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2019 EC³

10-12
JULY
2019

Proceedings of the 2019 European Conference on Computing in Construction

Venue
Location:

MINOA PALACE HOTEL
CHANIA, CRETE, GREECE

2019 EC³

2019 European Conference on Computing in Construction

Chania, Crete, Greece

July 10-12, 2019

2019 European Conference on Computing in Construction

Proceedings of the 2019 Conference of European Council on
Computing in Construction (EC³)

July 10–12, 2019

Chania, Crete, Greece

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PREFACE

The 2019 European Conference on Computing in Construction was held in the Minoa Palace Hotel, Chania, Crete, Greece during 10-12 July 2019. The conference had 91 attendees that presented work and exchanged ideas in the areas of the conference. This book contains the paper that were submitted to the conference and were accepted after a rigorous peer-review process.

The biennial EC³ conference will be a core activity of EC³. Conference organisation is managed independently by a group of volunteers. The present conference is the 1st biennial event, an important milestone for EC³.

The EC³ 2019 proceedings include an illustrated review of the program, the names of organizations and persons who contributed to the technical program. The peer review process consisted of two phases. Firstly, we received 28 optional abstracts that were reviewed by the respective area chairs. Following a rigorous full paper peer review process (with each full paper being reviewed by at least two reviewers drawn from the scientific committee of international experts, and final decisions being made collectively by the corresponding track and programme chairs), 55 outstanding full papers (from 21 countries) were ultimately included in the proceedings and presentation at the conference. The manuscripts were presented during 3 plenary sessions and 11 technical sessions, including topics that focused on:

- Data Acquisition, Analysis, Simulation & Resilience
- Smart Structures
- Energy Modelling & Monitoring
- Product and Process Modelling
- Systems Engineering
- Virtual and Augmented Reality
- Education, Policy and Standardisation

Please note: All EC³ proceedings and session recordings are available at no cost from <https://ec-3.org/publications/conferences>. *All conference papers now have a unique DOI and are comprehensively meta-tagged to ensure easy discovery by commonly used search and indexing services.*

Two further sessions allowed participants to communicate embryonic or thesis-related work through sessions dedicated to:

- Late-Breaking Abstracts, and
- Thesis-related work in the form of a Thesis-in-3 competition for students.

Additionally, the conference included four sessions dedicated to the technical committee work of the EC³ and these included:

- Data Sensing and Analysis (DSA) Committee
- Standards Technical Committee
- Education Committee
- Human-Data Interaction (HDI) Technical Committee

The Industry Day brought Industry professionals together with practitioners and researchers to discuss the latest challenges in the industry. The focus of the Industry Day was on the Digital Transformation of the construction industry and explored the potentially transformative impact of such a transformation.

In addition to the technical content, the conference also provided opportunities for fellowship and networking in informal settings. The EC³ programme opened on the evening of July 10th 2019 with a welcome reception. The conference offered optional day trips to: 1) Balos and Gramvousa Island and 2) Elafonissi Beach and a conference dinner with a folklore night at the Botanical Gardens of Crete.

We would like to thank the EC³ scientific community, including both academic and industry members for their contributions and support; the scientific committee (see specific acknowledgements below); as well as Efi Galanaki, Margaret Balothiari and their team at Mitos Event Management, who managed the

local organization matters of the event. Last, we would like to thank Usman Ali and Kyriakos Katsigarakis, for their invaluable support with the conference digital presence and preparation of the conference proceedings.

To all EC³ 2019 attendees: we sincerely appreciate your participation and involvement in this conference. We hope your experience provided opportunities to renew friendships and professional relationships, forge new ones, spark exciting new research ideas, and enjoy the scenery and surroundings in Crete!

James O'Donnell, Ph.D., University College Dublin, EC³ Programme Chair, and
Dimitrios Rovas, Ph.D., University College London, EC³ Chair.

EC³ SPONSORS

We would like to thank our sponsors and academic partners for their generous contributions to the congress, in support of awards and the industry day.

2019 EC³

2019 European Conference on Computing in Construction

Chania, Crete, Greece

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The **European Council on Computing in Construction (EC³)** is a recently established society of construction professionals, academics, researchers and national Professional Bodies, aspiring to become the leading European forum in the area of information technology in construction engineering and management.

Role of EC³

The **European Council on Computing in Construction (EC³)** advances professional knowledge and improves engineering practice in the built environment by fostering research, education and policy in current and emerging computing and information technologies.

EC³ is founded on the following four pillars and corresponding Technical Committees:

- DSA: Data Sensing & Analysis
- M&S: Modelling & Standards
- HDI: Human Data Interaction
- EDU: Education

EC³ interacts strongly with other Architecture, Engineering, Construction and Facility Management (AEC/FM) societies in related areas, strengthen the collaborations between academia and industry in topics related to EC³'s mission, spearhead research on such topics, identify and promote effective ways to advance the state of knowledge and the level of education and practice in these topics, assist in the making of policy, and support existing and new related specialty conferences and publications.

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The role of all technical committees is to:

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The organisers would like to thank the Area Chairs and the Scientific Committee members for their contributions to the paper review and selection process. We would also like to thank the Technical Committee members for their invaluable contributions and hard work to deliver the Industry Day and all other activities that took place in addition to the mainstream paper presentations.

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Data Acquisition, Analysis, Simulation & Resilience

BIM APPROACH FOR DECISION SUPPORT: CASE STUDY FASTENING SYSTEMS IN FACTORY ADAPTATION PLANNING

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Abstract

Increasing and changing product requirements demand a permanent readiness for efficient factory adaption. Considering necessary construction adaptations as well as conventional construction planning processes in the context of the factory adaptation process, standard planning methods are unable to support in a fast and efficient way. By application of the BIM method a Building Information Model, which contains all the needed information in one database is generated. BIM is a method for achieving targets, such as selecting the right type of construction technology or building material to evaluate the adaptation measure. The challenges by putting all information in one model are dealing with the amounts of data, identifying data quality and determining the current use case which should be examined. In this publication, the necessary data base is identified and implemented into a Building Information Model to investigate the right fastening system for an Industry 4.0 case study. The use case describes an integration of a robot into a factory in the life cycle phase operation to evaluate, which fastening system is most suitable as a part of taking adaption intelligence of a building to a higher level.

Introduction

A key result of the digitalization of construction industry are feature-rich Building Information Models that include semantically annotated parts for a growing number of building types, including factories (Delbruegger et al., 2017). BIM-Models have the potential to be used for a wide variety of tasks around the lifecycle of a building and handle them more efficiently. Nevertheless, there are a lot of challenges by using the BIM-method. The essence of the challenges is located in the variety of different file formats that are not or only partially related to each other (Gralla et al., 2018). However, a true potential lies in the data analysis and by getting the data of different systems like building parts, as the floor-slab, building materials, as a fastening system and an Industry 4.0 use case, as using a robot in a factory together. For this, all relevant data are analysed and put together in one BIM-Model. In addition, different rules are defined and software-based checked in a model-checker in order to be able to identify the interfaces and dependencies, to finally find an approach for semi-

automated BIM-based decision support for choosing the right fastening system. The case study introduced here is a BIM approach for semi-automatic decision support for factories that combines data of different building categories, as building parts and building materials with data of an Industry 4.0 use case in a Building Information Model and investigates interfaces and dependencies.

Utilized Technologies

This section presents a couple of basic technologies and the different types of data that are used in our case study.

Building Information Modeling

Building Information Modeling (BIM) is a method in the construction industry that includes the generation and management of digital representations of physical and functional characteristics of a building (Egger et al., 2013).

Building information models represent a database that provides a reliable knowledge base for decisions throughout a building's life cycle – from initial planning to demolition. BIM also offers the ability to optimize processes related to the life cycle of a building. The basis for the integration of different processes is a consistent virtual building model that is updated through the different phases of planning and building (Delbruegger et al., 2017).

Figure 1: Building Information Modeling vs. conventional planning (Gralla et al., 2017)

As figure 1 illustrates the BIM method is separated from conventional planning methods at the point from planning in three dimensions by using just geometric

data to three dimensions combined with other information e.g. data like quality information or maximum loads. At this stage it turns from a building model to a building information model, where information about time and costs are associated into the fourth and fifth dimension.

Data analysis of floor slab

The relevant data relating to the floor slab is divided into four categories. These four categories, shown in table 1, contain several information respectively data about the floor slab which is needed to evaluate the Industry 4.0 use case.

Table 1: Data analysis floor slab

category 1 – geometric information	
thickness: 200 mm	concrete cover: 35 mm
category 2 - material	
reinforcement: s = 150 mm, d = 10 mm, B500B	concrete quality: C30/37, XC 2
category 3 - loads	
distributed load: 500 kg/m ²	single load: 750 kg/216 cm ²
category 4 - surface	
surface treatment: smoothed	flatness: DIN 18202 table 3/ line 4

Data analysis of robot

For interdisciplinary consideration the data of the used robot is analysed. For this evaluation there is a versatile, high-speed, 6-axis robot used, which can handle a payload of 50 kg and uses a workspace of 2.061 mm. The given information respectively data of the manufacturer are collected and categorized in table 2.

Table 2: Data analysis robot

category 1 – geometric information	
maximum workspace: 2,061 mm	
category 2 – environmental conditions	
temperature: 0 – 45°	humidity: 20 - 80 %
category 3 - loads	
dead load: 550 kg	ultimate load: 50 kg
category 4 – maximum torque	
axis S: 0 Nm	axis U: 0 Nm
axis T: 147 Nm	axis B: 216 Nm
axis L: 0 Nm	axis R: 216 Nm
category 5 – maximum speed	
axis S: 180 °/sec.	axis U: 178 °/sec.
axis T: 360 °/sec.	axis B: 250 °/sec.
axis L: 178 °/sec.	axis R: 250 °/sec.
category 6 – maximum workspace	
axis S: 180 °	axis U: +251 ° / - 170 °
axis T: 360 °	axis B: 125 °
axis L: +135 ° / - 90 °	axis R: 360 °/sec.
category 7 – maximum moment of inertia	
axis S: 0 kg x m ²	axis U: 0 kg x m ²
axis T: 11 kg x m ²	axis B: 28 kg x m ²
axis L: 0 kg x m ²	axis R: 28 kg x m ²

Problems among analysing the data are the uncertainty about the exact workflows of the robot which is mostly not known during the planning on the one hand. On the other hand, the exact payload during

the workflow often is not available at the planning. By considering figure 2 the six different axes of the robot can be recognized. Though there is no information about the weights of the different parts, whereby the dynamic forces caused by the movement and acceleration of the robot cannot be determined exactly. The exact workflow combined with the real used payload and the different weights of the parts are essential information for making the right decision, which fastening system is the best to use and which forces act on the robot, the floor slab and especially on the fastening systems. By not knowing the exact workflows and payload an efficient and economic use of fastening systems is impossible.

Figure 2: Working range and axes of the robot (Yaskawa, 2018)

Data analysis of fastening systems

In this step the data of the fastening system as link between the building part floor slab and the Industry 4.0 case robot is analysed. Moreover, the data of the other systems (floor slab and robot) which are influencing the dimensioning of the fastening system are identified.

As such, the BIM environment can help in avoiding conflict at the interface represented by the fastening, as for example clashes of the borehole with reinforcement, or inadequate dimensioning of the fixture plate. At the same time the data provided from both adjunct systems at the fastening, i.e. the substrate (floor slab) and the attached element (robot – including its base plate), are used as input for the fastening design. Table 1 provides the necessary concrete structural properties, while the loading can be delivered based on the information of table 2. Here it should be noted that the loading characteristics are of particular importance for the design of fasteners and robot foundations, since they are complex dynamic loads, often in various combined directions. This

information is vital for an efficient design against fatigue loading, and it can serve as a basis for service life prediction and maintenance (Hoepfner et al., 2018). However, it is often lost in the transfer of information from the robot programmer to the fastening designer and specifier, over various other technical and management intermediate disciplines. A solution of this problematic based on BIM integration forms part of the present case study.

The structural design of the fastening based on the load envelope discussed above, can then deliver not a single, but a multitude of appropriate fastening products for the given fixture arrangement as dictated by the 3D Building model. The final selection of the fastening can then be delivered with consideration of a second periphery of information, related to the cost, delivery and work logistics, and life-cycle management. The initially qualified elements may remain in the database to facilitate change orders. As regards life-cycle management, besides the long-term structural reliability of the fastening product, important information is the possibility of inspection and testing of the fastening element during its service life, and an appropriate decommissioning and removal. Since fastenings are construction products they are typically delivered with specifications by the manufacturer (e.g. Declaration of Performance), and an associated approval/assessment document. Once the final selection is concluded, the following information should be conveyed into the multi-dimensional BIM model.

Fixing-point specific:

- Product name and description
- Location
- Installation date and crew
- Installation deviations and confirmation of pre-testing (as-built input)
- Maintenance intervals and expected service life

Indexed information:

- Performance specification and/or approval document (CE and ETA in Europe)
- Installation instructions
- Sub-contract and procurement details
- Project/designer's specification
- Possible alternatives (initially selected elements)

Fastenings can then be included in the BIM model at different Levels of Detail (LOD) (Mahrenholtz et al., 2017). A precise definition (LOD 300+) of the fastening as distinct individual elements is particularly necessary when the fastening element is critical to human safety, physical damage, interface conflicts, or life-cycle management issues.

Considering the undisrupted functioning of the robot

as a vital part of the factory operational profits, the preselection of fastenings based on the structural calculations, and the final decision based on integrated information are showcased herein. In this context, a total number of five different fastening systems, including four bonded anchors and an undercut anchor, are considered for adapting the robot in the through-setting design and tested for the specific use of this case study. The static calculation based on the physical motion processes of the robot and the resulting dynamic loads. In this case, these were determined by a motion analysis in position and time and then calculated on the basis of dynamic motion equations and the assignment of individual masses to load functions (figure 3).

Figure 3: Load functions of the fastener 1

In comparison, this precise and sometimes elaborately determined information is often missing in practice, with the result that only conservative approaches are used and the reference to the three-dimensional position and time is completely non-existent. Above all, the process time, respective acceleration and the direction of the resulting load vector represent disproportionately high influencing factors for an adequate and reliable dimensioning of the action.

In addition to these mechanical boundary conditions, geometric axial and edge distances, concrete member and fixture thicknesses, as well as material-technical factors in the form of concrete strength classes must be considered and controlled.

Data analysis of fastening systems

As in chapter I. described all the information of the data analysis is united in one Building Information Model. For that, the geometric information of different components have to be modeled in a BIM capable CAD software. In this case study Autodesk Revit is used for the modeling step. Subsequently, the information respectively data is inserted, which is based on the components generated in the several analyses.

Figure 4: Data composition with BIM

For checking the whole system in terms of interfaces and dependencies afterwards the model-checking software Solibri, which is able to insert several rules for individual control options is used. In order to check the system regarding the effects of different variants of fastening systems on the parameters cost and time the calculation software system RIB iTWO is used. The software environment and dataflow are illustrated in figure 5.

Figure 5: Software environment and dataflow (Autodesk, Solibri, 2017)

Investigation of potentials with BIM

In order to determine whether there is potential in the design of fastening systems by using the BIM-method, it is necessary to examine existing interfaces between the software applications as well as interfaces and dependencies between the building components.

Interfaces and interdependencies

After all components to be investigated, the robot, the different fastening systems and the floor slab have been created in Autodesk Revit, the combined model has to be imported into the Solibri Model checker. Therefore the IFC format (Industry Foundation Classes), which is an open standard in the building industry for the digital description of building models, is used. The IFC format can transport the geometric and semantic information through different BIM capable software environments. In this case the “IFC 2x3 Coordination View” format is used. To ensure that all the necessary information is available in the IFC-file, various configurations are required while creating the file by exporting the model from the CAD-software.

The interfaces resulting from the assembly of the components can be checked by suitable rules in the Solibri Model Checker. Furthermore, the existing

dependencies between the components (robot, fastening system, floor slab) are mainly influenced by the different usable anchors. Decisive parameters are shown in the data sheets and building control approvals of the fastening systems. In order to be able to evaluate these model-based, they are attached as information to the various components in the BIM-model. For checking the interfaces and interdependencies in the Solibri Model checker there are rules created which consider the following parameters which are important for the dimensioning of the anchors.

- Bonding depth of the anchors and edge distance of the anchors to the floor slab
- Concrete quality
- Collision between anchors and reinforcement
- Thickness of the mounting plate
- Accessibility for using a torque wrench
- Centre distance of the anchors

The various rules are described and analyzed hereafter.

2018-08-02_Ruleset_ICCCBE		
\$	bonding depth of the anchors and edge distance of the anchors to floor slab	SOL/234/1.2
\$	concrete quality	SOL/230/1.1
\$	collision between anchors and reinforcement	SOL/1/5.0
\$	thickness of the mounting plate	SOL/234/1.2
\$	accessibility for using a torque wrench	SOL/226/1.0
\$	centre distance of the anchors	SOL/222/4.0

Figure 6: Created rules for analysis

The interdependencies “bonding depth of the anchors” and “edge distance of the anchors to the floor slab” are put together in one rule. It examines the distance of the anchors to the edge and bottom edge of the floor slab. Therefore, the components and their names are used for testing. It is also necessary to define minimum and maximum distances to the edge and bottom edge of the floor slab, as shown in figure 7. It is not possible to define a variable value via an attribute with the software, but only to check static lengths, which makes it necessary to adjust the distances for each anchor variant.

Figure 7: Definition of minimum and maximum distance

With the rule “concrete quality” a check, if the concrete quality is sufficient to use the anchor in the floor slab is possible. For this, there is a rule defined, which verifies that the given concrete quality of the floor slab is within a range of the suitable concrete quality of the anchor.

The third rule can be used to check whether there is a collision between the fastening system and the reinforcement. For this requirement, the geometric information of the selected components is used and issues an error message as soon as these components

collide. Furthermore, the conflicting components are graphically highlighted to be able to identify them quickly, as visualized in figure 8.

Figure 8: Detected collision between fastening systems and reinforcement

The thickness of the mounting plate is an important information for the dimensioning of the appropriate fastening system. Due to that, there was a rule created which checks if the thickness is suitable for the used fastening system. To check this requirement the robot gets the semantic information of its floor slab thickness.

The rule is used to check whether the characteristic of the thickness of the mounting plate does not exceed the limit value specified by the fastening system used. Unfortunately, it is not possible to use variable values within the rules. For this reason, it is necessary to create the requirements within the rule separately for each type of anchor fastening system. To check the accessibility to use a torque wrench for final assembly, a rule has been created that proves that there is enough space around the nut of the fastening system. As in the other rules, the several components will be addressed by their designations. In this rule, those components can be defined that are not to be taken into account. This makes sense for the component floor slab, because it is located under the nut of the fastening system but is irrelevant for the test because it does not obstruct the assembly.

Figure 9: Determination of the free space around the nut

The last rule “centre distance anchors” checks the distance between two components in the model. To check the centre distance, there is the need to add up the diameter of the anchor to the defined distance in the rule, because otherwise only the distance from edge to edge of the two components will be tested. Beside that it is necessary to define the components which have to be checked. This can be ensured by adding the dowels as source component and target component within the rule so that it will check all components with the contained word “dowel” in its name. The created rules can be reused, reducing the

time and effort for audits in other projects.

Variant comparison

Now that all variants of the fastening systems have been evaluated for their basic suitability for application in this Industry 4.0 case study, the model has been prepared for further processing in the iTWO software. For this purpose, the model was exported as a CPI-XML file from Revit for analysis in iTWO with the aim of evaluating "4D" costs and "5D" time.

After verifying the required model quality for processing in iTWO, so-called QTO-queries (quantity-take-off-queries) were developed, with which a model-based generation of the quantities is possible. In addition, a partial service-catalogue was created for the automated preparation of a bill of quantities, which reflects in detail the various processing steps involved in the installation of a fastening system. The part performance catalog contains all service specification items with the corresponding costs in order to link them to the model and to make an evaluation of the cost differences visible.

1 fastening systems					
1.	fastening system V1.0				
1.1.	fischer (bonded anchor)				
	specification				
1.1.10.	hammer drilling incl. rework	4,000	4,000	St	1.13
1.1.20.	whiff (two times per anchor)	4,000	4,000	St	0.25
1.1.30.	brush (two times per anchor)	4,000	4,000	St	0.50
1.1.40.	whiff (two times per anchor) incl. rework	4,000	4,000	St	0.87
1.1.50.	injection with mortar FIS HB	4,000	4,000	St	9.50
1.1.60.	screw in dynamic anchor FDA	4,000	4,000	St	0.25
1.1.70.	hardening process	4,000	4,000	St	4.37
1.1.80.	final assembly t inst	4,000	4,000	St	3.25

Figure 10: Example bill of quantities fastening system iTWO

In the last step, a timetable generated in MS-Project for the different variants of the fastening systems was imported into iTWO in order to finally be able to link the individual scheduling processes with the model as well. Figure 11 shows that the decisive processes for the entire assembly time can be identified in the several hardening process (highlighted red).

Figure 11: Example timetable fastening systems

The combination of the model with the corresponding cost and time approaches enables a comparison of variants with the use of simulation as decision support for the selection of the most suitable fastening system in iTWO. The BIM approach for semi-automatic decision support in this case study shows differences between the investigated fastening systems in terms of quality, costs and the installation time.

Figure 12: example simulation fastening system in iTWO

It can be assumed, similar to the use of the different rule sets in Solibri, that the generation of the QTO-queries, combination of the model with the part performance catalogs and timetables as well as the creation of these must only take place once conceptually and can subsequently be adapted to the respective use case, which reduces time and efforts in the factory adaptation planning.

Evaluation matrix of possibilities

Based on the analysis delivered above, it is possible to quantitatively assess the various solutions and perform a multi-objective optimized decision on the most appropriate system. In this case, the selection is performed based on a co-evaluation of four main criteria, namely geometrical assembly of the item fastening (3D+i), costs (4D), time (5D), and utilization factor (UF), as discussed above.

The first criterion reflects a grading against geometric collisions and project-product compatibility requirements. In particular, the following items are checked: bonding depth, concrete class, collision between anchors and reinforcement, thickness of the mounting plate, accessibility, and center distance. The decisive parameter in this comparison appears to be the embedment depth. Costs and time are evaluated per product, and with consideration of the labor cost and time required for installation; there is also a correlation between these two criteria. Finally, the design utilization factor according, indicates if the anchor's structural capacity is utilized, particularly in this case against steel failure.

The utilization factor for the relevant types of concrete failures (concrete cone failure, splitting, pull out and pry out) are calculated and verified, but not stated below, as the values is of secondary importance with a maximum utilization of 19 % in this specific case study. This indicates on the one hand that the assessment is reasonably economical. Inversely, it indicates the residual safety reserves of the system. The grading for all criteria is then normalized to a 0-100 scale.

For the cost and time criteria, the normalization is performed against the fastening system with the highest value respectively. The normalization of the

utilization rate is carried out in such a way, that the value 100 reflects the total load-bearing capacity utilization (LCU) of the respective fastening system and theoretically, the increase greater than 100 represents a failure. The results are provided in Table III, and they are illustrated in a spider-graph, to facilitate the decision procedure. The qualified fastening system is V 4.0, with slightly higher costs than V3.0, though with best scoring in all other criteria against all other options.

Table 3: Evaluation summary

evaluation fastening system	3D+i grading*	4D costs**	5D time**	load capacity utilisation
V 1.0	91.67	69.55	53.04	75.00
V 2.0	91.67	90.70	93.91	62.00
V 3.0	83.33	100.00	66.52	97.00
V 4.0	91.67	99.31	100.00	96.00
V 5.0	100.00	71.28	65.22	87.00

Figure 13: Evaluation summary on spider-graph as decision tool

Conclusion

Based on the study presented herein, it becomes evident that implementation of the comprehensive digital tool for the design of a fastening system in the Industry 4.0 environment is particularly efficient. Through the process proposed herein, the data input for the design is substantially richer in quantity and quality, allowing for higher precision, transparency, and thus a safer, and more economical design. Furthermore, duplex tasks are avoided since they are combined and handled simultaneously (e.g. check of anchor location and geometry against the reinforcement, the slab thickness, the mounting plate, or other project specifications). Since the database is commonly accessible by all disciplines, it serves as a

key element in the collaboration and adaptation requirements of the work at hand. Finally, it is made evident that, including a digital data sheet (standardized e-document) with the procurement of construction products, in this case fastening systems, is of particular advantage for design and construction in the future.

Outlook

Based on this study, significant attributes of digital planning on the basis of multidimensional Building Information Models are disclosed. This requires the establishment of basic requirements in the digital documentation discussed above. At a further step, we aim to identify how different layers (from different disciplines involved) can be further combined and incorporated in the model. This is shown herein on the basis of interconnecting the structural engineer, fastening specifier and procurer, robot manufacturer, and production planner. A further endeavor is to integrate control of the installation defects risks through BIM models, including geometry and location checks of the fixture in relation to ergonomics.

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A TOOLCHAIN FOR AUTOMATED ACQUISITION AND PROCESSING OF AS-BUILT DATA WITH AUTONOMOUS UAVs

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Abstract

BIM-driven projects depend on structured as-built information with high availability, but the acquisition process for visual data involves too much manual labour. Apart from acquisition, the generation of data with laser scanners and other methods requires computationally intensive registration processes. Unmanned Aerial Vehicles (UAVs) have gained attention for all applications that involve remote sensing, but still require piloting personnel. UAVs with newly developed reactive autonomy, guided by stereo cameras in addition to standard GPS, enable both automated operation and, more importantly, the generation of structured data that is aligned with the model. This work proposes a toolchain for producing structured point clouds of construction elements in progress.

Introduction

Building Information Modeling (BIM) and its temporal variant 4D-BIM are the conceptual foundation of a standardised, model-based construction planning and management. Planning staff can only make informed decisions on the basis of rich as-built information. The collection of information on the current state of construction projects is a vital aspect of this paradigm (Bosché et al. 2014, Xiong et al. 2013). The need for rich data and a high level of availability correlates with the complexity of large building projects. Therefore, the costs for maintaining timely and comprehensive as-built information increase in larger construction projects. As a consequence, any decision and judgement depends on a model that provides accurate, timely and insightful information. Apart from quantitative and qualitative facts, such as delivery dates, delays, volumes, and progress notifications from subcontractors, visual data provides the highest degree of information to a human operator. Not only should as-built information be insightful to the human viewer, but more importantly, offer information for spatial analysis and automated comparison with as-planned model data. An ideal method for comparing as-planned and as-built status is able to determine the state of distinct BIM objects and present it in a meaningful way. An automated information generation workflow is a premise for automated progress reports and highlighting of issues per process. With the availability of photogrammetry and terrestrial laser scanners (TLS), point clouds have become an invaluable data structure for measuring as-built status. Point cloud data is both the basis

for meaningful 3D visualisation and moreover an adequate data structure for spatial analysis of BIM objects. However, TLS- and imaging-based approaches involve substantial manual labour, and therefore (multiple) daily updates are not feasible without disturbing ongoing processes and unreasonable amounts of man hours (Bosché et al. 2014).

Unmanned Aerial Vehicles (UAV), often referred to as drones, have recently gained attention for their ability to quickly gather information, predominantly photographs, especially in locations hard to reach. UAV is a broad term that applies over a wide range of aircraft, from winged plane-like types with several metres wingspan to helicopters that fit in the palm of a hand. Multirotors, the kind of UAV referred to in this work, are the preferred form factor for applications that require stable flight behaviour, vertical takeoff and landing, ability to carry payloads, and hovering in place for steady sensing. Research efforts on employing UAVs for monitoring (Eschmann et al. 2012), quality control (Wang et al. 2015, Morgenthal & Hallermann 2014), and digital reconstruction (Wetelscheid et al. 2011) leverage these advantages. Apart from enabling better and quicker remote sensing, the real advantage of UAV-based sensing lies in the potential of autonomous operation. Autonomy denotes a breaking point at which an effort to gather as-built information is not anymore measured per scanning operation, but instead is only necessary once for an arbitrary number of subsequent operations. Therefore, the UAV-based approach has the potential to make as-built measurements more efficient, with the scan rate possibly being increased from weekly to multiple times a day. Few examples of UAVs for inspection purposes have made practical use of autonomous capabilities in terms of avoiding obstacles and automatic flight towards inspection targets. Recent developments in the Robot Operating System (ROS) and the PX4 flight stack, however, reveal robust autonomous functionality for UAVs. The software for autonomous navigation used in this project has been proven to work on real UAVs and encourages a development workflow with simulator tests prior to outdoor flight tests. An open source ecosystem of robotics software is the foundation for this research work, incorporating the advantages of autonomous flight, state-of-the-art sensor technology, and BIM-driven workflows as the data model for detecting change in structural construction.

Prior to this work the authors investigated the feasibility of using UAVs with pre-computed flight missions to capture

photographs on construction sites. The UAV's navigation capabilities were limited by using only GPS for localisation purposes.

Contribution

This research work proposes a toolchain for as-built data generation, making use of autonomous UAVs. The toolchain is a combination of existing robotics tools and new ones, developed in the course of this project. In combination, these tools enable a UAV to automatically capture visual information of structural elements on the level of BIM objects. This work is part of an ongoing research of employing UAVs for inspection and monitoring purposes. The toolchain is under active development, as is the underlying autopilot and robotics codebase. Following this stage of development and simulator tests, this project will reach an evaluation stage with practical case studies. This work continues to employ the open source PX4 flight stack which was used in prior work (Freimuth & König 2018), but replaces GPS navigation, which is unaware of its environment, with reactive autonomy. Vision-based environment sensing, implemented in ROS, is used for safe navigation and path planning in an environment that is partially known. The toolchain that constitutes the autonomous UAV and the automated as-built data generator is a combination of modules, developed specifically for path-planning on BIM and scanning construction objects, based on a stack of open source robotic modules from the ROS and PX4 software projects. The known environment is derived from BIM, either as an as-planned model for a specific date and time or as an as-built model from a previous scan. The point cloud processing toolchain, implemented in the course of this research, produces point clouds with colour information that are aligned with the underlying BIM. Furthermore, by eliminating all points of objects known from the previous state, the point clouds produced by the proposed method represent only new or modified objects. Effectively, the toolchain substantially reduces the amounts of data to store and provides a per-object view on the deviations between as-planned and as-built. The resulting object point clouds represent distinct groups of points that belong to semantic objects, which is beneficial to further processing methods from the scan-to-BIM domain.

Research Background

3D information of existing structures is highly anticipated. The data is required for progress tracking (Son et al. 2015, Bosché et al. 2015, 2014), structural health monitoring (Klein et al. 2012, Jiang et al. 2008), quality assessment (Chen & Luo 2014, Ilang et al. 2011, Kim et al. 2015) and as-built modeling (Ilang et al. 2010). The importance of efficient measuring methods becomes evident, as each of

these applications depends on as-built data input and can only be executed as often as new data can be generated. Huber et al. (2011) describe the process of creating as-built data as time-consuming and error-prone and one of the key barriers to the widespread use of as-built BIMs in industry.

Taking photographs of objects for state documentation purposes is ubiquitous. However, taking images for structured analysis and as-built BIM purposes imposes special requirements. There are two major approaches for acquiring the state of a construction project with photographs. The first method takes images of objects and registers them by estimating the camera pose, with which the image was taken. This camera pose is then applied to a virtual camera inside the corresponding 3D model space, or from a 4D model at investigation time. A comparison of the virtual image and the real one then exposes differences between model and reality. By applying computer vision techniques, features in images or differences between the as-built and the as-planned images may be identified (Lukins & Trucco 2007, Golparvar-Fard et al. 2009, Ibrahim et al. 2009). Such techniques can produce various results like qualitative statements about surface properties (e.g. cracks in concrete slabs), detection of BIM objects (e.g. image contains slab), and clash detection (e.g. pipes cannot be installed as planned; clash with cable harness). The second method applies Structure from Motion (SfM) to derive 3D geometry in the form of dense point clouds. Dozens of images must be taken for each object and the SfM process itself takes several hours, even when using specialised commercial software and GPU-acceleration. Golparvar-Fard Mani et al. (2015) present a machine learning-based plane matching with Support Vector Machines (SVM) that relies on SfM. Klein et al. (2012) conducted a study on generating exterior and interior as-built models with photogrammetry methods. The authors acknowledge limitations regarding measurements of outer structures in upper stories, a limitation that applies to all inspection methods carried out by surveyors.

Terrestrial Laser Scanning (TLS) is an alternative method for generating 3D geometry. TLS is generally more accurate than image-based reconstruction, mostly due to the implicit error of the triangulation approach of SfM (Ilang et al. 2010, Wilkinson et al. 2016). However, conventional TLS only provides 3D points without colour information. Other approaches combine TLS and camera systems, which provide colour by mapping pixel values to points of the laser scan. TLS devices need to be mounted stationary for each scan, during which non-occluded surfaces will be captured. As a consequence, partially occluded and free-standing objects require multiple scans. When dealing with multiple scans of the same object, individual point clouds must be joined in a registration process. Automatic

registration can be achieved with heuristic approaches like the Iterative Closest Point (ICP) algorithm or other approaches like the 4-Points Congruent Sets method (Hight et al. 2013, Theiler et al. 2014, Besl & McKay 1992).

Concluding the data acquisition methods, laser scanning and image-based approaches (e.g. photogrammetry) have greatly improved the measurement process over the manual method and mitigate the risk of modeling errors (Ani et al. 2013). However, despite producing richer data with improved accuracy, the sensors still require manual effort for each scanning task. Setup and operation of TLS- and camera-based inspections are time-consuming and cause interferences with other construction tasks (Lang et al. 2010). With data generated in an automated manner, the number of scans could be increased from weekly to daily intervals.

Regardless of the method, TLS or SfM, point cloud data has no inherent alignment in the model space. In the context of BIM-driven construction the sole collection of unordered 3D information is not sufficient. Markerless registration of as-built point cloud data with BIM mesh data is a necessity for automated progress monitoring. The aforementioned 4-Points Congruent Sets method was adapted as 4-Plane Congruent Set algorithm with robust results (Bueno et al. 2018).

After registration, a point cloud is still an unstructured mass of data that resembles a whole scene. In order to make semantic decisions, point clouds need segmentation, preferably on a structural object level. Various segmentation approaches for structural objects have been investigated. A colour-based segmentation coupled with region growing yielded good results, but depends on colour information and therefore also on suitable lighting conditions (Zhan et al. 2009). Approaches based on shape detection (Ning et al. 2009) yield good results for detection of surfaces, but fall short in the segmentation of semantic objects with individual forms. The Point Cloud Library (PCL) implements several methods for segmentation and clustering (Rusu & Cousins 2011), including colour-based and plane-based methods, which will be investigated in upcoming research work.

Concept

The objective of this paper is the development of a novel method for measuring the as-built status with autonomous UAVs. The integration of UAVs requires a technological bridge between model information and controlling the autonomous aircraft. Control in this context means being able to interface with the path planning unit of the UAV's flight control.

Choosing a suitable platform for UAV development

Common (commercial) UAV platforms allow for manual control and mission control, with missions being sequences of GPS waypoints. For the sake of usability these platforms offer mobile applications with limited functionality. The envisioned integration and automation however poses the requirement of full programmatic control over the aircraft. Some commercial manufacturers offer optional development programs in the form of Software Development Kits (SDK). Committing to a single manufacturer creates an unnecessary dependency towards the company that maintains the SDK, but lifespan and support may be limited. This work is based on PX4, an open source software and hardware platform for UAVs. It was originally started as a research platform for vision-based autonomy and became a robust UAV platform. PX4 gives developers full control over the UAV and extensive compatibility with the Robot Operating System (ROS). The PX4 firmware is under active development and testing by researchers, industrial partners, and enthusiasts. An active community of developers and testers provides feedback on proposed changes to the system and analysable flight logs. This makes for a significant advantage in quality control over many other platforms. The sub project *PX4/Avoidance* (2016) is another basis of this work, focused on reactive autonomy with path planning in known and unknown environments.

The Robot Operating System (ROS)

ROS was started in 2007 at the Stanford Artificial Intelligence Laboratory and became part of the Open Source Robotics Foundation (OSRF) in 2012. It is an open source framework for the development of and execution on actual robots. At the core of the ROS concept is a graph architecture, which considers all robot-related processes and entities as distinct nodes while messages passed among nodes are considered edges. Apart from this architectural aspect, ROS is also a large collection of established robotics modules that come from an international community. Abstraction of message types and networking communication allows single modules of robotic systems to be executed on different computer systems. Furthermore, the modular architecture makes nodes exchangeable under the premise of conformity with the required message protocol. This is an essential aspect for research purposes, as it allows developers to change certain functionality of a robot with little effort. Iterative changes in code need testing and verification, but conducting outdoor experiments for every test is impracticable. Malfunctioning code could destroy hardware or even put humans in danger, when testing flying robots. Therefore, simulation driven development and testing has become an indispensable requirement.

Simulation in robotics

Simulation plays a major role in the development of robots, especially with autonomous UAVs, where malfunction on the device causes crashes, destroying hardware and possibly causing harm to bystanders and objects. Outdoor experiments with untested features significantly slow down the development process and pose unwanted risks and costs. For these reasons the robotics community established a development method that employs realistic simulations up to a point of validation where real world experiments can be conducted (Visser et al. 2011, Symington et al. 2014, Olivares-Mendez et al. 2014). Gazebo was created for exactly this purpose and is a popular simulator with deep integration in ROS (Koenig & Howard 2004, Meyer et al. 2012). The simulator can be configured to use exchangeable physics engines and a plugin system enables integration of new virtualised sensors. Within the simulation, the flight controller receives virtual sensor data including the UAV's attitude, axis rotation rates and acceleration. Instead of controlling actual motors, the flight controller feeds the simulation with actuator commands. The real benefit here is that experiments carried out in the simulation run the same code as the real UAV in outdoor usage. When transitioning from simulator experiments to outdoor execution, only the virtual sensors need to be replaced by their real counterparts.

Simulating the UAV for automated as-built scans

In the scope of this work generation and processing of point cloud data is also based on simulation data. A camera plugin in Gazebo provides the toolchain with images from the perspective of the UAV's stereo camera. The simulation environments are defined in world files, which describe the composition and properties of physical objects including the ground profile, building structures, and robots.

Fig. 1 shows the simulated autonomous UAV navigating around two examples of building models. The building models represent the construction site at scan time. They were created by converting an IFC file to a Collada 3D asset file. Collada is a modern and open 3D asset exchange format which is maintained by the Khronos Group. The conversion is achieved with the IfcBlender tool (Krijnen 2011). This converted model is necessary for the simulation scene to resemble what the real construction site looks like. The definition of simulation scenes is straight forward, however one additional step was found necessary in the preparation of experiments. During the first trials with the vision-based flight stabilisation, the UAV behaved erratically when its cameras were oriented towards the building. It was found that some of the converted building models had only few visible surface features, which are needed for the stereo cameras to create a disparity

(a) Example of a building model with complex geometry.

(b) Example of a building with realistic textures. The additional surface features greatly improve the vision-based depth sensing.

Figure 1: The simulated UAV autonomously navigates around virtual BIM-derived building scenes.

map. The building models were augmented with realistic surface textures (i.e. the brick surface wall in Fig. 1b) which immediately restored the stable vision-based flight behaviour.

Gazebo provides a plugin to access virtual camera streams of the 3D scene. Simulated cameras are defined by various properties such as resolution, field of view, frame rate, distortion and noise. These parameters make the virtual cameras configurable to resemble the properties of real cameras. Furthermore they are linked with the simulated UAV model, providing pictures from its point of view. This allows working with synthetic visual sensors as input for robot perception.

Instead of using the common mission flight modes of PX4, a path planner in ROS takes over control. The planner node is responsible for navigating the UAV towards its navigation goal. Currently, there are two instances of planning nodes available, *local_planner* and *global_planner*. The local planner is able to navigate in a previously unknown environment and find ways around obstacles that come up during its course. The local planner makes decisions based on the 3D Vector Field Histogram (3DVFH+). The 3DVFH+ is a computationally efficient two-dimensional array of potential motion directions that are either free or blocked. The elements of the array are projected on a polar sphere around the UAV and represent 3D motion vectors in all directions. The cell's values are updated in real-time

Figure 2: The component architecture of the proposed toolchain. Nodes represent individual software modules, arrows indicate data flow between the modules, with solid arrows marking the flow of point cloud data.

by determining if a certain path is blocked or free in the octomap (Vanneste et al 2014). The *global_planner* additionally recognises a previously known environment and maintains a global representation of the previously known environment. Both variants of the planner continuously exchange messages with the *mavros* node, which is the communication interface between ROS and the PX4 instance that runs independently, for example on a real-time microcontroller instead of the development machine.

Components of the toolchain

The software architecture of the toolchain is in accordance with the modularised structure of ROS. It makes use of existing structures from the PX4/avoidance project with additional modules developed specifically for the purpose of measuring the as-built status of construction sites and BIM.

Fig. 2 provides an overview of the toolchain with an emphasis on the data flow between its modules. Each node in the graph is a software component that handles a certain task and will be presented individually in the following subsections. The relations between nodes depict which

Figure 3: A visualisation of the generation of the disparity map (right) from the stereoscopic camera images (left). The color gradient in the disparity map represents perceived depth.

nodes exchange data with each other and therefore resemble dependencies. The top group *Input* includes nodes that generate the required stream of stereo images. This stream either comes from actual stereo cameras on the UAV (e.g. Intel RealSense), or from virtual cameras that adapt the real device by capturing images with comparable properties in the 3D simulation environment. This is the main input for the group of *ROS* nodes that process the stereo images for navigation and create the desired point clouds that represent the as-built status.

The *stereo_image_proc* node (included in the standard ROS distribution) is responsible for processing the stereo image stream. In its initial stage it computes a disparity image, in which each pixel value represents the depth of the same pixel in the rectified input image. Fig. 3 shows an example of the binocular camera image and the resulting colour-coded disparity map with a gradient between blue (near) and red (far). With depth information and color available, the node is further capable of producing a ROS typed `sensor_msgs::PointCloud2` message. `sensor_msgs::PointCloud2` is the default type for all further message passing of point cloud data and is compatible with the `pcl::PointCloud2` from the PointCloud Library, which offers mature point cloud processing methods. The flow of the resulting point cloud data splits at this point, as it is being used as input stream for both the planner node (local or global) and the nodes in the subgroup *pointcloud_proc*. Devices like Intel RealSense can compute disparity maps on their own. The accuracy and performance of these will be evaluated in upcoming work, but an integrated solution is expected to make the processing chain more CPU-friendly.

The subgroup *pointcloud_proc* encapsulates software modules for real-time processing of point cloud streams. The first notable node in this subgroup is *pcl_filter*, which is a PCL-based passthrough filter for eliminating all points outside a certain range in one dimension. In this case, the passthrough filter is used to eliminate all points near ground. Ground points are relevant to navigation applications, but since the objective of this toolchain is the mea-

(a) Example building in Gazebo

(b) Corresponding octree for navigation and point cloud processing

Figure 4: The simulated building scene and its corresponding octree, used on the UAV as a computationally efficient representation of navigation space.

surement of building structures, data of the ground is of no further interest. Such filtering processes significantly increase the performance of all subsequent operations. PCL implements further filtering routines. The statistical outlier removal is one notable filter in which point clouds can be freed from outlier points that do not represent solid structures. The next node in the processing flow is the *pc_subtractor* node.

The point cloud subtractor

The *pc_subtractor* node is the second to last stage in the *pointcloud_proc* subgroup and is responsible for reducing and separating input point clouds into groups of points that belong to objects of interest. During each flight, the UAV captures extensive amounts of point cloud data. Subsequent point cloud messages are assembled at the end of the toolchain with the intention to create complete views on objects from all perspectives. Although the input rate can be throttled to a value lower than that of the navigation system, it should be fast enough to ensure that no objects are overlooked while the UAV is moving. The information of single frames, accumulated intervals of frames or

even whole flight sequences is too large to make sense to a human operator when simply displayed on a screen. When considering a structured storage and processing of the data, it is also advisable to have point cloud data that is already clearly registered with individual objects in BIM. Therefore the inspection system automatically reduces the input data to solely represent new structures that weren't present during the last scan. The method requires accurate as-planned data for the automatic identification of new structures. This concept assumes that the data of each inspection is added to the existing as-planned data and therefore constitutes the as-planned model for the next inspection. In technical terms, the information on existing structures is extracted from BIM. In a 4D-BIM workflow this means that each inspection is executed on the current state of the model data and its result will be used to create the next iteration. Inside the *pc_subtractor* node the existing structures are processed as octree representations. The octree is generated directly from the mesh data of the BIM with the open source programs *binvox* (Min 2004, Nooruddin & Turk 2003) for voxelisation and *binvox2bt* (Hornung et al. 2013) for creating an octree file from the voxels.

Fig. 4 shows an example simulation with a building model derived from IFC and its corresponding octree representation. The building's octree is used as initial input to the dynamic octomap, which is constantly updated in flight.

Preloading the octomap with the known occupied space of the building model has a positive effect on the UAV's capability of finding a shortest viable path, since all known structures are automatically included in the path planning of the local planner. The octree is an adequate data structure to efficiently represent the spatial extent of geometric objects. The current environment is managed in Octomap (Hornung et al. 2013), an octree-based environment representation for robot navigation. Alignment and scaling of the input point clouds is a further requirement. The UAV inspection concept of this work makes use of the autopilot's self localising capability, a key feature of the autonomous flight system. The point clouds that are used for obstacle detection and avoidance receive accurate transforms (translation, scale) from the autopilot that constantly signals its current position in space to the *mavros* node.

Fig. 5a shows the initial status of data as it arrives in the node. The existing structures are displayed as boxes with thick solid outlines and the input data is illustrated by red points. The boxes represent leafs of the octree, which is an efficient discretisation of the building geometry. Some points are placed within a box of the octree, others are outside the octree. Since the octree is a discretised representation of the as-planned model, all points inside the octree shall be discarded. The goal is to efficiently identify all points, that lie outside the octree. The *pc_subtractor* node

Figure 5: Illustration of the point cloud subtractor using the octree to subtract points that are outside of known structures.

makes use of the PCL data structure `OctreePointCloud` and its function `isVoxelOccupiedAtPoint` to test each input point within the octree and keep a set of outlier points, marked as blue points in Fig. 5b, Fig. 5c.

The result of this operation is a point cloud frame that represents only objects that are new or modified compared to the previous model of as-built or as-planned status. Fig. 6a shows an example of a point cloud before processing in the subtraction node. In this case, the wall was part of the known structure and the staircase is not yet known to the as-built model. Fig. 6b shows the point cloud after processing. The points in the ground region were removed by the passthrough filter and the subtractor node removed the wall of the building. The expected result of this process is a point cloud with an isolated representation of the staircase. This isolated representation is easy to comprehend at a first glance. Furthermore, the size of the point cloud in storage is significantly smaller with similar benefits for subsequent processing operations. Most importantly though, the point cloud is semantic as it only represents one object. This is an advantage for further operations like reconstruction of meshes from point clouds. The `pc_subtractor` node is followed by the `pc_assembler` node, used for combining subsequent frames of point clouds.

The point cloud assembler node

Each point cloud frame, regardless of it being generated by a TLS or a flying stereo camera, can only represent points visible from the location of the sensor. For 3D mesh reconstruction purposes, point clouds of objects should be complete. In order to create complete point clouds of physical objects, point clouds must be created from multiple perspectives and then these frames must be aligned and joined. The autonomously flying UAV continuously captures point cloud frames while navigating around construction objects. The `pc_assembler` node collects a certain number of frames together with their respective transforms, an ROS description of pose, orientation, and scale of objects. It takes care of joining those frames and outputs a single, accumulated point cloud. The last step is

(a) Point cloud before subtraction

(b) Point cloud after subtraction of points

Figure 6: Visualisation of the subtraction operation on point clouds. The points of the staircase remain, ground and facade points are eliminated.

the `pcd_export` node, which receives point cloud messages and writes artifact files in the common PCD file type.

Observations

The Gazebo simulation application loads meshes for arbitrary objects from Collada files. This also applies to the geometric representation of the known building elements, which are derived from an Industry Foundation Classes (IFC) file to Collada format. The model files are converted with the `IfcBlender` plugin for Blender (Kritzen 2011). Initial tests on converted building models yielded poor results due to the plain surfaces of the Collada exports. The material properties of IFC objects have no realistic visual representations in the form of textures. Visible surfaces are defined by colors that will also define the material descriptions of the Collada assets. The resulting surfaces were found to have negative effects on

the depth perception in the stereo image proc node, which relies on visual surface features to compute a meaningful disparity map. As a result the simulated UAV would not be able to navigate properly. The problem was solved by adding photorealistic pattern textures of bricks and gravel stone to facade elements. This is a limitation that only applies to the simulation. Camera input from physical objects under natural lighting exposes more visual features than a simulation.

Conclusions and Outlook

This work is a study on automating and improving the process of as-built data generation. The proposed toolchain is capable of automatically guiding a UAV around building structures, effectively enabling it to capture as-built info on an object level. By automating the process of data acquisition, the toolchain effectively reduces repetitive manual labour which is needed for collecting visual data of structural elements. The self-localising UAV significantly improves the process, as scanned point clouds can inherit the UAV's position information for each frame. Therefore, no additional point cloud registration is needed. Furthermore, the toolchain's ability to eliminate all points of known or unmodified objects greatly improves the value of the as-built data. Despite being under active development, the open source autopilot software and the Robot Operating System provide a solid foundation for practical applications like the one presented here.

This is a work in progress. Following the simulation-based tests, the toolchain will be evaluated on real hardware and in practical case studies. The isolated groups of new or modified objects will be used for automated progress monitoring of processes in 4D-BIM.

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TOWARDS A METHODOLOGY FOR QUANTIFYING THE BENEFITS OF BIM

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Abstract

The adoption of Building Information Modelling (BIM) which offers integrated software and processes for digital delivery, is becoming imperative for the UK construction industry. Literature thus far is unclear if the benefits claimed by the industry are exaggerated for commercial reasons. Our exploratory study investigates how the benefits of adopting BIM can be quantified. The findings reported through a focus group of industry experts specialising in digital innovation offers a reality check at project/firm/sector level to scrutinize the benefits and costs of BIM. The key results offer four areas the construction sector could further investigate to report monetary benefits and costs of BIM. The study thus provides insight into how businesses can develop a robust but adaptable methodology for capturing BIM costs and benefits.

Introduction

The British Standards Institution (BSI, 2014) defines a Smart City as one where “there is effective integration of physical, digital and human systems in the built environment to deliver a sustainable, prosperous and inclusive future for its citizens”. Novel digital technologies and particularly Building Information Modelling (BIM) as a form of systemic innovation (Succar and Kassem, 2015) promise to revolutionise the way buildings and infrastructure are designed and operated. The vision for upgrading infrastructure and developing (digital) skills is of significant national importance in the UK (BEIS, 2017). At the same time, the UK Industrial Strategy (BEIS, 2017) prioritises innovation and increasing productivity as key areas for strengthening the economic performance of cities across regions, beyond the South East and London that pull performance around the country. To this end, British industry and policy players recommended BIM as a solution to improve productivity and efficiency (Azhar, 2011). By enabling improved collaboration and coordination, BIM has the potential to deliver project benefits such as better control, as well as enhanced project and asset performance (Love et al., 2013; Love et al., 2014; Papadonikolaki et al., 2017; Papadonikolaki and Wamelink, 2017). Recent developments such as the vision of the Digital Built Britain strategy (BEIS, 2015) which focuses on charting digitalisation, including and beyond BIM, and the Smart Cities agenda indicate that unbiased and scientific assessment of the benefits and costs of BIM adoption is needed.

An early effort to capture and operationalise the benefits and return on investment from using digital technologies started in the UK in 2002 known as the Avanti project (CPIC, 2013). The Avanti project showed that while digital technologies – back then called computer-aided – necessitate substantial learning, integrating these technologies with the complex, interdependent work in the construction industry is challenging (Morgan, 2017). According to the Department of Trade and Industry, Avanti reported a number of promising benefits.

Nevertheless, although the Avanti project demonstrated the potential use of Information Technology (IT) and became the basis of the BIM British Standards (BS) 1192, it relied on technology which is now redundant. The proposed study aims to operationalise the benefits and costs of the digital based on updated information from current technologies and practices.

This study provides an appraisal of BIM costs and benefits during the design, construction and operation phases of infrastructure. It aims to provide demonstrable appraisal of BIM costs and benefits to support the industry into adopting a digital way of working. It builds on the success of previous initiatives, which focused only on the design phases, by extending the scope to construction as well and investigating the impact of recent technological advancements in digitalisation across the construction supply chain.

Quantification of BIM costs and benefits

Various scholars have studied the benefits of BIM in development and operation asset life (Love et al., 2014, Krystallis et al 2015). However, BIM benefits are neither fully operationalized nor measured in a quantitative manner. The result is a lack of tangible and demonstrative outcomes able to further dis-incentive construction firms or their customers, who are still reluctant in adopting BIM and transforming digitally their businesses. For instance, in a study commissioned by the UK government, the BIM experts shared that “application of BIM is expected to have a 10% capex reduction for Small Modular Reactors which is consistent with savings achieved for other industries. And, the capex reduction can even go up to 20% in some cases” (BEIS, 2015). Accordingly, they expect proportionally similar benefits for new large reactors.

Looking at the scientific and practitioners' literature is clear that the claims about BIM benefits are mostly anecdotal, provided by stakeholders with a vested interest, and might be subject of "cherry picking", i.e. reporting only favorable outcomes. A recent report prepared by PwC on a methodology to evaluate the performance of BIM Level 2 provided results of savings of 3% in total, with savings deriving mainly from the operational stage (5.5%) and only validated through two cases (PwC, 2018). Also, a recent international study supported by the Danish government showed cost reductions up to 7% by using an online digital communications platform and BIM on large-scale construction projects (Lambrecht, 2017). This ambiguity justifies further research in cost and benefits of BIM. Indeed, in the UK and abroad, policies and major investments are decided using data and information about BIM benefits that might be unreliable. Based on this, the UK BIM and the Digital Built Britain strategies should avoid the pitfall of previous "deterministic change agendas" (Dainty et al., 2017).

Methods

The study builds on data collected through a focus group. In July 31st, 2018 the authors organised a stakeholders engagement workshop. All participants had professional experience in the UK construction sector. The focus group workshop aimed to explore the actual monetary cost savings/cost implications of adopting BIM. Ten senior experts from the UK industry, government, academic and research organisations participated. The participants were carefully selected because of their leading capacity in driving digitalization in their organizations. A total of four activities were organised into discussion topics (presented in detail below). For the first three activities, the participants were split into three groups. This allowed the team to investigate each topic in depth by carrying three rounds of data collection, whilst also minimising potential authority bias (Milgram, 1963).

The focus group workshop was divided into four key topics of discussion as summarised in Figure 1.

In term of data analysis, emergent theme analysis was applied to analyze and interpret the data (Creswell, 2017). Each of the co-authors acted as a facilitator for one of the four topics and was responsible for reporting the findings.

Figure 1. Workshop activities sequence

Results

In the remainder of this paper, we report the findings from the focus group. The findings are organized in four areas.

BIM costs

The quantification of key monetary BIM costs requires analyzing both upfront and maintenance costs, looking at the full building/infrastructure life cycle. In terms of upfront costs, the main streams are a) software and technology acquisition; and b) staff training according to the focus group. The implementation of BIM requires a complete shift from the linear system to parametric modelling, that is mostly based on new software, which requires both upfront costs such as license purchasing and staff training, as well as maintenance costs for license updating. The new routines involve the analysis of a larger number of data, which also requires powerful Internet connections and hardware, up to the adoption of cloud-computing.

The focus group indicated that the introduction of BIM has strongly differentiated the typology of their work within design and construction companies. Indeed, together with more traditional figures of architects, engineers, the new system requires people capable to perform program tasks, as well as capable of working on different platforms that can operate in parallel or in sequence. Therefore, higher investments are needed for training of current employees, investment in new highly skilled IT individuals and the involvement of technical support teams that can constantly allow the development of new skills, in a fast-evolving environment. Indeed, knowledge is fast evolving, and constant updates of protocols are required.

A good example was provided by the engineering company representatives, which envisages all information generated across contributing engineering disciplines to be made available between all design platforms through common means known as Common Data Environment (CDE) (Gerrish T., 2017). To reach this goal, the supply chain is aiming to develop their team's capabilities across four knowledge levels, as detailed in Table 1.

The industry is dealing with taking everyone to move from Level 1 to 2 as shown in Table 1, and is introducing individuals with coding skills, so that in the long-term, a large percentage of models will live in the CDE.

The application of BIM in the design phase is associated with the development of projects from the initial design, across architecture, structure and mechanical systems, to onsite work. However, one of the claimed BIM strengths sits in its implementation for the management of the building/infrastructure during the operation and end of life phases. Considering that, in the design and construction phase, the maintenance procedure can be defined and stored in the BIM platform, the maintenance procedure is defined according to lifetime scenarios. However, the scenarios often change in real life.

Table 1: Knowledge levels

Knowledge levels	Details
Level 1: Opening a protocol	The ability to open a BIM file and read and understand its context. Basic information can be obtained only.
Level 2: Creating a protocol	The ability to create a BIM file from established company BIM templates. The user can create a parametric BIM 3D model and use the company's BIM library of components.
Level 3: Writing code	The ability to use graphical programming tools that allows the user to customize the building information workflow.
Level 4: Creating models for the Common Data Environment (CDE)	The ability to create company and project-wide templates so users can work in common standards. The 3D model's metadata are formatted so users can carry interrogations in the CDE.

Therefore, updates of the maintenance procedure are required, with the necessity of including, in some cases, special works (such as retrofit) to be undertaken under exceptional circumstances. These situations can be caused either due to hazards (i.e. flooding, hurricanes), strong degradations, or change of usage. All these unpredictable events will strongly alter the physical asset's function and use and, therefore, the digital twin associated with it, should be updated. The complex lifecycle scenarios of the asset still pose many challenges and uncertainties in the real functioning of maintenance and accuracy of its digital

twin. Therefore, actual asset's lifecycle costs are difficult to be quantified and to a large degree, are arbitrary.

BIM benefits

In the development and execution phases, the main improvements from BIM lie in it being a major enabler for stakeholders to collaborate. Stakeholders can access the latest designs and models, improving the synchronization and therefore coordination in the information sharing and the visualization of the future building/infrastructure. This leads to benefits including:

- Reduction of mistakes and therefore rework and waste. Better information sharing, visualization and synchronization prevent many of the underpinning causes leading to mistakes (e.g. working with old design).
- Better collaboration, creating less misunderstanding, leading to a better relationship between the stakeholders reducing the opportunities for conflict and litigation
- Better time management: often designers use all the available time to produce a design up to when they provide construction documents to the contractor or the customers. Changes in the final phase, straight before the documentation delivery, can imply delays and a waste of the hours spent in making the original design. With the adoption of BIM, contractors and customers can visualize the proposed project earlier in the design process, with the consequent possibility to provide early feedback about both constructability (the contractor) and operation (the user).
- The quality intended as the satisfaction of the operator/end user implicit and explicit need of the "end product" (i.e. the building/infrastructure) is higher.
- BIM is an enabler for the offsite construction/factory fabrication and modularization. Offsite construction and modularization can generate time and cost savings because the operations are more efficient, the quality is higher and the number of mistakes lower (Mignacca et al., 2018).

In operations, a BIM model can keep track of the story of the building/infrastructure collecting valuable data for the decision making. This dataset can include information for example, about equipment failing, and maintenance routines, with consequences in:

- Reduction of maintenance costs. A key advantage of adopting BIM is the possibility to give the right information to the right person at an appropriate time.
- Reduction of retrofitting costs. Keeping track of the history of each BIM element, system and ideally module can provide valuable information about when and how retrofitting is needed. BIM can be used as a

simulation tool to test different possible retrofitting solutions.

- Energy and other operations cost reductions: Use of smart systems that know when a certain service is needed. For instance, a room used only for limited hours a day can be programmed to be warmed during these hours, thus resulting in energy costs savings.

BIM process evaluation methods

The focus group findings on how to measure the benefits/costs of BIM adoption fell largely into two distinct categories: internal metrics – whereby organizations develop their own approach to evaluate benefits and costs; and external organization metrics – whereby organization employ methodologies found in the market and embed in their routines. The internal metrics and measurements methodologies, first included firm-wide developed assessment tools for measuring BIM outcomes. Azzouz et al. (2016) shows as at least seventeen assessment tools developed globally, both in academia and practice. The pluralism of these various BIM assessment methods relates to different firm strategies and in-house performance tracking routines as well as the myriad of interpretations regarding BIM. Another source of internal metrics to evaluate the performance of BIM adoption was suggested as being data from Human Resources such as payment data and “time spent on projects”. However, the participants agreed that performance evaluation processes hardly ever take place in firms because they are not ingrained in company culture. Finally, workshop participants suggested as a source of data for measuring BIM benefits/costs the utilization of data on documents’ revision and change management as well as data from clash reports to compare projects with and without BIM implementation.

Regarding the use of external tools and methodologies, the participants suggested the use of the methodology developed by PwC (2018), although there is no proof that the methodology has been used to date. The methodology can be applied to estimate economic benefits that may be realized across the asset lifecycle. A limitation is however that the methodology does not consider the costs of implementing BIM. Similarly, some participants mentioned regular use of the tool developed by Scottish Futures Trust (2018) on assessing Return of Investment (ROI) from BIM implementation. Additionally, the participants displayed an awareness of the Avanti Project but acknowledged that the benefits reported there were about how to map technology in a process, however BIM changes the process of working. Finally, the participants suggested the organizational portfolio of new and repeated businesses as a way for defining the cost and benefits of BIM adoption.

Applicability

This section describes the key characteristics a construction project should have that would help realize the investigation about the monetary benefits and costs of BIM. According to the experts, the opportunity to investigate the monetary costs and benefits of BIM exists in projects that carry the following characteristics:

Complexity: The greater the complexity of the project, the greater the need for the project to be developed and executed in a BIM environment. The more complex the project, the greater the benefits but also potentially greater the costs of implementing this kind of technology.

Multi-disciplinary projects: Future investigations should look at projects that are multi-disciplinary in nature. Because of the involvement of multiple stakeholders, it is anticipated that greater benefits will be achieved with BIM.

Type of project: Future investigations should consider construction projects in general not just buildings. According to the experts, infrastructure projects provide better data compared to building projects.

Next, the experts discussed approaches regarding the development of the methodological approach of capturing the monetary costs and benefits. The following features were discussed:

Project phase: According to the experts capturing monetary BIM benefits is difficult during the operation phase. Because it is difficult to gather data, estimation of BIM costs and benefits becomes more challenging compared to the design and construction phases. As a result, the value of the findings decreases, and the research methodology would provide questionable results.

Set of projects: The collection of data should include multiple cases, not rely on the validity of outputs resulting from just a few projects. This should help tackle the uniqueness issue often identified in the sector. As such, the research methodology would offer a balanced approach and findings can be generalized to all construction projects with the characteristics mentioned above.

Requirements capture: The methodology should be flexible to capture and document various benefits and costs. The tool should have flexibility built in to accommodate various sets of benefits as one project’s vision could be different from another. Thus, this needs to be reflected in the way benefits are reported.

Procurement route variation: The methodology should have the capacity to measure BIM costs and benefits from projects of various procurement routes. For example, design and build projects are very different compared to Private Finance Initiative (PFI)

projects in various fronts. Thus, the costs and benefits are expected to be different in these two project types. The tool however could benchmark whether BIM benefits in a PFI project outperform the benefits found in a project delivered by a Design and Build contract.

Non-BIM Vs BIM comparative cases to measure BIM benefits/costs: The methodology could leverage a cross-case study between BIM and non-BIM projects that are identical in most aspects and use this as a baseline.

Client engagement: Further engagement was suggested, especially capturing the views of the respective project client to further shape and balance the inputs/outputs of the methodology.

Deployment approach: The methodology/tool should include handbooks, toolkits and on-site mentoring about how benefits are collected, measured and tested.

Table 2 illustrates a summary of key findings from the workshop.

Conclusions

Concerns that construction projects are not delivering full value to the public has called for Government action to mandate BIM in the construction sector as a digital-driven change initiative that promises better gains for public sector investments. Evidence suggests that the process upon how the monetary costs and benefits of BIM are captured remains a black box in the industry. The review suggests that it is still not clear in the construction sector what are the monetary costs and benefits of BIM. A reality check is needed at

project/firm/sector level to shed light whether the benefits of BIM are reaped.

The importance and urgency of developing a robust but flexible methodology for measuring these costs and benefits is presented in this paper. In this context, the types of benefits, costs, evaluation methods and projects to be tested was presented. Such a methodology would prove useful to both client organizations and supply chain organizations who wish to invest in BIM or indeed have incorporated BIM in their business and questioning the validity of its use. In terms of limitations and future research, the study's findings are grounded in the context of UK construction sector, and stakeholders reflections looked particularly how BIM is adopted and measured in the UK context. As such, the findings presented in this paper are applicable only in a UK construction sector. Future research should test if propositions in this paper are true. A comparative multi-national case study would be appropriate as way forward.

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Table 2: Summary of key findings from the focus group

BIM costs	BIM benefits	BIM evaluation methods	Applicability
<p>Upfront costs due to:</p> <ul style="list-style-type: none"> Software acquisition and updates Hardware (e.g. cloud computing) for increasing data capacity Existing Staff training Hire of skilled IT staff Development of processes, templates, workflows including maintenance Client education 	<p>Cost reductions in construction due to:</p> <ul style="list-style-type: none"> less rework due to design or construction errors limited scope change <p>Cost reductions in operation due to:</p> <ul style="list-style-type: none"> improved maintenance enhanced optimal usage of the asset 	<p>Internal tools and data:</p> <ul style="list-style-type: none"> In-house developed evaluation matrices Human Resources payment data Revisions and change management data Clash reports data <p>External tools:</p> <ul style="list-style-type: none"> Scottish Future Trust Avanti methodology BRE project KPIs <p>Other indicators:</p> <ul style="list-style-type: none"> Repeat businesses Profit 	<p>The methodology needs to reflect:</p> <ul style="list-style-type: none"> Project complexity level Project Multidisciplinarity Project type variation Project Phases Requirements capture flexibility Procurement route BIM – non-BIM project cases Client input Deployment package

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WHAT DOES “REAL-TIME” PROJECT CONTROL REALLY MEAN?

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Abstract

It is proposed that the application of real-time monitoring technologies requires an integration and mutual adjustment of planning and control processes as well, for the automation to be effective. An approach for integrating planning, monitoring and control is presented, and demonstrated in examples of schedule and safety control. Similar solutions can also be developed in other domains. The introduction of automated monitoring technologies can thus lead to future research that will revolutionize planning and control processes, and construction management in general.

Introduction

The need for real-time monitoring and control of construction projects stems from the fact that nearly all projects display significant discrepancies between their actual execution and their plans. The monitoring of large projects is currently a challenge when carried out manually (Isaac and Navon 2014). Consequently, the updating of construction plans according to the actual progress in projects is often carried out intermittently, and largely post factum. Automation presents a possible solution to this problem, by enabling real-time project monitoring. A large number of studies have consequently focused on the application of novel technologies, such as laser scanning, computer vision technology, radio frequency identification, and others, to enable real-time automated monitoring and control (Yang et al. 2015; Omar and Nehdi 2016).

Significant progress has thus been achieved in the testing of automated monitoring technologies. But challenges can still be expected in their application in construction projects. So far, these studies have typically focused on the use of technologies to collect and process large amounts of data, under the assumption that this information can be related to existing construction plans, and utilized for control purposes. They have implicitly been based on a decomposition of project management into a set of distinct and relatively independent processes, which include project planning, monitoring and control. However, manual monitoring cannot be expected to be simply substituted with automated monitoring without requiring the adjustment of other related processes in construction as well.

Past experience from other domains in which automation has been introduced, such as flight deck systems and operating rooms, indicates that the integration of automated components in a management system is not trivial. Sarter et al. (1997) have named this phenomenon the “substitution myth”, stating that “[t]he assumption was that new automation can be substituted for human action without any larger impact on the system in which that action or task occurs, except on output”, but that “investigations of the impact of new technology have shown that these assumptions are not tenable”. The result of this misconception has been that the expected benefits of automation were often only partially achieved, and the workload for human operators only partially relieved, due to the introduction of new tasks.

A number of challenges can be expected in the actual application of automated systems:

- A challenge of incorporating frequent changes that are made in the plan, and novel, unexpected circumstances, within the automated system (Dekker et al. 2002).
- A lack of clarity as to when automated systems should initiate communication with human operators and require their intervention (Sarter et al. 1997).
- Problems of data overload, especially on those occasions when something has gone wrong, which requires human operators to quickly digest and interpret large amounts of relevant data as the events in the project unfold (Woods 1996).

The problem of data overload can be particularly vexing. Automated systems have shown a tendency to increase in scope over time, especially in complex environments, and to become more and more demanding in terms of administrative burdens. There is always a danger of crossing a line, whereupon the system turns from an aid into a hindrance, which users will try to avoid since it takes up too much of their time. With an automated “real-time control” system that is based on large amounts of monitoring data, and may contain practically limitless inputs, this danger becomes particularly relevant. This paper discusses what can be done to avoid such a risk, and how the opportunities of automation can best be realized, by adjusting all the relevant project management processes.

Proposed approach to real-time project control

A clear definition of the exact meaning of the terms *project planning*, *project monitoring* and *project control* could be a helpful first step in addressing the challenge that has been presented in the previous section, since these terms are often inconsistently used. The term “project control”, for example, can be used to refer either to the execution of corrective actions to minimize deviations (e.g. (Al-Jibouri 2003, Hegazy and Petzold 2003, Lee, Pena-Mora and Park 2006)) or to the process of both identifying deviations and addressing them with corrective actions (e.g. (Diekmann and Al-Tabtabai 1992, Ballard and Howell 1998, Love et al. 2002)). In this paper the different terms are used as follows:

- *Project planning* – the allocation of resources (such as time, space and manpower) required to execute construction activities.
- *Project monitoring* – the identification of deviations from the planned budget, schedule and owner requirements in the actual execution of the project.
- *Project control* – the execution of actions necessary to correct or minimize significant deviations identified in the monitoring process.

These processes are interdependent, and will therefore affect each other (Figure 1). Project monitoring involves a comparison of data that is collected on the construction site with the planning data, an identification of any discrepancies between the two datasets, and an updating of the plan in order to analyze the implications of those discrepancies that have been identified.

Figure 1: The relations between project planning, monitoring and control

Project control involves the proposal of actions to cope with deviations that have been identified in the monitoring process, and to prevent a further deterioration. This requires an analysis of proposed actions to identify their impact on the project, and an implementation in the project plan of approved actions that are identified as having the desired impact.

The execution of these processes may not be straightforward, since the significance of a deviation may eventually depend on both corrective measures taken by the project management team, such as rescheduling tasks, requesting design changes and allocating additional resources, and on knock-on effects that may cause additional deviations in the future. The team has to determine that such actions will not have a negative indirect impact on the entire project, which could eventually cause a further deterioration (e.g. when additional tasks are executed simultaneously to overcome a delay, and this causes conflicts which result in additional downstream work and further delays).

Given the interdependencies between the automated monitoring process and the largely manual planning and control processes, an integration and mutual adjustment of all three processes is required for the automation to be effective. Thus, existing planning methods will have to be adjusted with the adoption of novel monitoring technologies, in the same way that the application of these technologies will have to take into account those planning practices. In particular, this will require a synchronization of the planning and real-time monitoring methods, which currently address completely different time-scales (Isaac and Navon 2014). For example, schedules are defined, and ideally (but rarely in practice) updated on a daily basis, whereas monitoring technologies can provide data at intervals of minutes or even seconds. In addition, monitoring technologies address projects at a much more detailed scale than do current schedules (Han et al. 2015). For example, an activity such as “Form/Rebar/Pour/Strip Concrete Walls” in the schedule contains, in practice, a number of different sub-activities related to different components (walls), each of which need to be separately defined and addressed by automated monitoring methods.

This paper proposes that the integration of planning, monitoring and control processes requires the following systematic analysis:

- What information is required for control purposes?
- What data can realistically be provided through automated monitoring technologies?
- How can this data be processed in real-time to provide useful information?
- How should project planning and control processes be accordingly revised?

In the following sections, examples of the implementation of such an analysis and integration is briefly described, concerning schedule and safety control.

Example 1 – Schedule Control

Automated progress monitoring solutions have not been integrated up till now with innovative project-wide planning and scheduling methods. Instead, they have largely relied on schedules defined with the conventional Critical Path Method (CPM) (e.g. Turkan et al. 2012). However, it is almost impossible to correctly revise a schedule according to monitoring data while using the existing CPM. The main causes for this are the following:

- The CPM currently assumes that the production rate in construction activities is constant, resulting in linear progress functions. In practice, actual production rates fluctuate, due to variations in the project's design (affecting the complexity of the
- work), on the construction site (e.g. soil conditions), or in the allocation of resources (e.g. the introduction of additional equipment).
- With the current CPM, activities can only be controlled at their end-points (Start or Finish), since the traditional precedence relations connect activities through their end-points alone. This can lead to instances in which deviations occur while an activity is being executed, after it has started but before it has finished, without the CPM providing any means to revise the schedule accordingly. This can happen despite the fact that such a deviation may potentially affect other activities that are executed in parallel, and the project as a whole.

Figure 2. Assessment of production rates and definition of control points

It is proposed that a key to ensuring effective automated schedule control processes is the correct definition of control points for each activity in the schedule (Figure 2). The progress that has been made during the execution of the activity can be monitored at those points, and the future progress can be predicted. This is especially important given the expected variability in the actual progress when construction activities are carried out. Recent innovations of the CPM provide opportunities to overcome these problems, in particular the development of point-to-point relationships between activities (Hajdu and Isaac 2017). Such point-to-point relationships allow a discrete monitoring of a specific number of control points during the execution of the activity. The automated monitoring can thus be scheduled to be carried out at those points.

The definition of control points for an activity can be carried out in the following steps:

- a. Definition of an “ideal” production rate of an activity according to its relevant attributes (e.g. allocated resources and their productivity) (Figure 2a).
- b. Adjustment of the “ideal” production rate for specific segments in consideration of activity-level attributes that may change the amount of work in those segments (e.g. resource allocation, soil conditions, complexity of work) (Figure 2b).
- c. Further adjustment of the production rate for initial segments of the activity according to an assessed learning curve (Figure 2c).
- d. Definition of control points (Figure 2d):
 - i. When production rates change
 - ii. When a sub-activity is completed
 - iii. According to control points in related activities
 - iv. At certain intervals if required

Once the activities, composed of segments with control points at their ends, have been modeled as piecewise functions, relationships are defined between the control points of different dependent and overlapping activities (Figure 3). Corresponding control points may have to be defined for overlapping activities, and this may consequently require the definition of additional points. For example, an additional control point is defined for the predecessor activity in Figure 3 in order to link it through a point-to-point relationship with the successor activity. The relationship is connected to a control point where a new segment of the successor activity starts, with a different production rate.

Once the actual progress that was made at the control points has been recorded in the schedule according to the monitoring data, the remaining work can be updated. In order to analyze the implications of a changing production rate that was observed for an activity on the remainder of that activity and on the production rates of successor activities, there is a need to identify the attributes causing the change in the completed segments of the activity. For example, activity-level attributes (e.g.

unexpected soil conditions) are differentiated from project-level activities (e.g. low-skilled manpower).

Figure 3. Definition of point-to-point relationships

Based on this, a prediction can be made whether the remaining segments and the successor activities will also be affected by the same attributes:

- If the attributes causing the observed change are relevant only for the completed segments, then the production rates of the remaining segments and of the successor activities don't need to be changed.
- If the attributes are activity-specific, then the production rates of the remaining segments may need to be changed, but not those of the successor activities.
- If the attributes affect the entire work package or project, then the rates of all remaining work may need to be changed.

Once the remaining time for ongoing and planned activities has been defined, additional control actions can be taken in order to reduce deviations from the planned schedule:

1. An activity can be stopped and delayed to satisfy the relationship.
2. Resources can be added or reallocated to change production rates for specific segments of activities.
3. The relationship can be adjusted in case neither one of the points on the activities has been reached yet.
4. The schedule can be manually adjusted.

The proposed approach can support the synchronization, according to the predefined control points on activities, of planning, monitoring and control. This will allow them to be carried out at the same required time intervals, through a combination of both automated and manual processes.

Example 2 – Safety Control

The previous section presented an approach that could be suitable for progress monitoring and the updating of the project schedule. While that example put more of an emphasis on the need to adjust the planning and integrate it with the automated monitoring process, other research by the author has focused on the adjustment of control

processes as well, in the context of automated safety monitoring with real-time location tracking of workers (Isaac and Edrei 2016, Edrei and Isaac 2017).

Previous studies on automated safety monitoring usually adopted a deterministic planning and control approach involving the “virtual fencing” of high-risk areas (resembling existing approaches with physical fences), and alerts whenever an unauthorized worker penetrated into such a high-risk area. This planning approach might not however be suitable for real-time monitoring, which should support proactive alerts. Instead, an alert should be provided sufficiently early before an accident occurs, when it is still possible to carry out a preventative action. In order to be able to do so, there is a need to detect those instances in which a worker has increased his exposure to hazards because he is moving nearer to a high risk area (Figure 4), or because he is exposing himself for too long a time to a low or moderate-level risk factor (such as noise).

Figure 4. Tracking a worker approaching a safety hazard

In Isaac and Edrei (2016), a statistical model was presented that supports a more dynamic form of safety planning and control, which better utilizes the real-time tracking data. The model relied on data that was received from a wi-fi-based location tracking system. The new planning approach included not only the definition of high-risk areas which are off-limits for all non-authorized workers, but also of medium-risk areas, in which a certain degree of risk exposure is tolerated. While medium-risk areas may appear to be free of critical or immediate hazards, a presence in such an area may harm a worker after some time, or indicate that he is moving too close to a high risk area.

The proposed model provides statistical alerts when the risk exposure of a worker has exceeded tolerable levels. This is enabled through the application of a number of statistical rules that detect an increase in the exposure to hazards, and provide an alert before a critical exposure occurs. To enable this, statistical safety zones are defined in the model. Each statistical zone is related to a risk area on the site, and reflects the expected probability of a worker being located in this risk area. The statistical zones are based on a predefined maximum allowable exposure to the safety risk that has been identified. In other words, an

area in which the exposure of workers to a safety risk is higher, should have a correspondingly lower probability that the worker will be located in it. In this way, the model can be used to control the movement of workers on the site, and to proactively impose certain limits to their risk exposure.

The planning and control process that was developed can prevent potential accidents from occurring, without unnecessarily affecting the efficiency of the activities carried out on site. On the one hand, transgressions of medium-risk areas on the site are likely to be frequent, implying that the creation of alerts whenever such a transgression occurs would excessively restrict the workers, and probably lead to them ignoring the alerts. On the other hand, the new process is not limited to providing alerts once a worker has already penetrated a high-risk area, which can have only a limited impact in terms of preventing accidents and injuries. The new process can thus ensure the health and safety of workers, and at the same time the efficiency of the construction work, by restricting the size of the areas that are defined as being of high risk, and therefore off-limits for most workers on site.

The new process allows site managers to control the exposure of construction workers to safety risks that accumulate and change over time, providing alerts when workers approached risk factors too closely, and ensuring their health by preventing excessive exposure over time to such factors. This required, however, a novel planning framework based on the definition of medium-risk areas, and a novel control process based on statistical rules.

Conclusions

The integration of automated monitoring with planning and control processes is crucial in order to fully exploit the benefits of the automated technologies. Such an integration will require mutual adjustments of all these processes. It has to be applied in a wide range of domains, each involving distinct requirements.

Two examples were briefly described of the implementation of such an integration, for schedule and safety control. Similar solutions can also be developed in other domains, such as quality control and cost management. By requiring the adjustment of conventional planning and control processes, the introduction of automated monitoring technologies can therefore be seen as an opportunity for future research to revolutionize those processes as well, and thus the practice of construction management in general.

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ADAPTIVE MINIMIZED COMMUNICATION PROTOCOL BASED ON BIM

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Abstract

The early conceptual architectural design phases are characterized by a constant interplay of creating variants and assessment of those variants as well as their consistent detailing. Variant comparison plays a significant role in achieving the desired final building. Objectifiable criteria used for the evaluation and comparison of design variants can be used to legitimize decisions and selections as the design process proceeds. Moreover, using these criteria, such as the results of simulations and analysis performed by various domain experts, most likely leads to building designs with better performance. One major challenge in practice today is the management of design information and collaboration between several actors in a building project.

A large portion of the Architecture, Engineering, and Construction (AEC) industry still deals with conventional methods to exchange design information. The growing use of building information models is promising, but even the most recent developments and practices still rely heavily on human-readable protocols and issue management systems (Beetz 2009; Borrmann et al. 2018). Considering the potential of schematized computer-readable communications to be analyzed and used for future references and case-based reasoning systems, this paper proposes a novel minimized communication protocol based on BIM, which aims to introduce a computer-readable, yet adaptive universal method/function which works on schematized information exchange requirements (templates) for different use cases. Furthermore, this concept will be explained and demonstrated using an example scenario.

Introduction

Decisions made in the early phases of building design significantly affect subsequent design tasks and efforts, such as the end products realization and performance. As we move on from initial conceptual design phases into more and more detail-oriented planning and subsequently precise technical design for construction, the cost and effort to change the overall design or modify previously taken decisions increases dramatically (MacLeamy 2004; Davis 2013). In other words, the architect's ability and freedom to affect the building design decreases intensely.

In the early, yet essential phases, usually only vague

and incomplete information is available in the form of fragments from the client's requirements, building regulations, and environmental necessities. The problem of this procedure is that in the early phases, even though the information is little, nearly all the crucial decisions must be made at this point. The process of designing a building is characterized by a constant interplay of creating variants, their assessment and consistent detailing (Zeiler, Savanovic & Quanjel 2007). During these initial phases, the architect as the designer mainly relies on his personal experience and know-how for detailing, evaluating and comparing design variants. The sheer load of design decisions leaves the architect to decide on a large number of details early on and sometimes without enough knowledge about their consequences (Derelöv 2004).

One way to improve this approach is to integrate, as early as possible, other domain experts into the assessment and evaluation of different aspects of the design. This creates the need for frequent and proper communication as well as the exchange of design information between different disciplines and their respective actors. Studies show that the AEC professionals become so occupied with managing design information, including manually integrating and coordinating domain-specific design information and representations that, in the end, they manage to create only few design alternatives (Flager et al. 2009).

The unique nature of the Architectural, Engineering, and Construction (AEC) industry puts a high demand on communication and workflow management and its optimization. The current trend in AEC follows Building Information Modelling (BIM). BIM is a model-based process for the development, integration, and management of all semantical and geometrical information related to construction projects. One significant advantage of BIM is the ease in which exchanging semantically rich 3D-models between different disciplines is possible. This feature in BIM enables new possibilities for the exchange of information in a digital format between different actors, such as architects and consultants. Thus, improving access to computer-aided analysis from the early stages of design. This encourages the early involvement of varying domain experts and thereby enhances the efficiency and overall quality of the design process (Borrmann et al. 2018).

In an attempt to address this gap, the DFG-FOR2363 research group develops methods for evaluating architectural design variants in the early stages of their development by adaptive detailing strategies that allow the detailing, evaluation, and assessment of alternative building design variants, which may be partially incomplete and vague.

In the next section, a brief overview of the state of the art research related to this work is prepared. Following this short literature review, the concept of BIM-based adaptive Minimized Communication Protocol is discussed. Later on, the adaptive universal Feedback function along with its related arguments is described, followed by a demonstrative example. In the end, a brief conclusion along with future steps is addressed.

State of the art

As the design of a building evolves, many experts from different domains are needed for evaluating various aspects of the design. Moreover, challenges in early design phases are uncertainties (vagueness and incompleteness) both in the model quality (degree of detailing and abstraction) of the design variants and in the results of the combined analysis and simulation procedures, which arise from assumptions taken to perform the analysis. In the concept of adaptive detailing corrections and modifications or so-called detailing of the BIM model can be suggested or provided by the domain-expert or the architect. But without the architect's acceptance, no change will be acknowledged. The corrections and criticism offered by the architect can be assumed as reflexive design, based on experience/know-how, or even based on references and similar models, and could include both objective and subjective aspects of design.

On the other hand, the criticism, corrections and suggested detailing from the domain-experts to the architect is referred to as **Feedback**. The feedback can also be delivered by the expert planners using objective criteria such as simulation/analysis results. The feedback from the domain-expert can include simulation results and design options (Zahedi & Petzold 2018a).

The development of design variants represents a vital aspect of the process of designing a building. Starting with the requirements that the architect receives from the client, followed by external restrictions and regulations, the architect designs possible variants. As the planning process proceeds, more suitable and preferred variants are elaborated in more detail while other drafts are rejected or discarded. Mattern & König (2018) introduce a concept for the model-based management of design variants. The developed idea eliminates the need to use separate models for partially similar and yet different design variants and thus avoids redundant information. So-called option categories are introduced to organize the possibilities

that might evolve when going forward in the design process. Then Graph models are proposed for managing design variants and their interdependencies. However, due to complex interdependencies and restrictions, the authors suggest that the creation of invalid combinations are to be avoided (Mattern & König 2018). This paper aims to utilize the concept as mentioned above later on in its backend system during the temporal development between options and design variants.

A major complication for using BIM in early design stages is that despite the insufficient information available in these phases, a BIM model appears precise and specific. Abualdenien & Borrmann (2018) introduce a multi-LOD metamodel for defining information exchange requirements as well as addressing information uncertainty during the early stages of design using BIM models. Their suggested metamodel has two layers of a data-model level and instance level. The concept is implemented as a web-server with a user interface (UI), providing the possibility for managing and checking exchange requirements between different domains (Abualdenien & Borrmann 2018). These exchange requirements defined using the multi-LOD metamodel of Abualdenien & Borrmann are being used later on in this paper as the aLODx templates. Using this concept depending on the analysis type and the design stage, which corresponds to a level of development, each domain expert will ask for a list of building components plus their proper attributes. Further explanations are given later on in this paper.

Considering the importance of collaboration and internal communication between the parties involved in building design, open BIM Collaboration Format (BCF) was first introduced in 2010 (bcfXML v1) and then further developed in 2014 (bcfXML V2.1). BCF enables BIM-based workflow and communication as an open standard, between different actors and different software vendors (buildingSMART 2019). Using BCF, the project participants create topics (such as issues, proposals, and change requests) that contain various attributes like type, description, comments and many other types of communication information. Each topic is then connected to a model element as well as a viewpoint and possible screen-shots. This eliminates the need to exchange entire bulk digital BIM-models between software applications. Each issue in BCF version 2 could also be equipped with a new feature called BIM-Snippet. BIM-snippets enable the exchange of schematized files. A BIM-Snippet could be another partial IFC file (buildingSMART 2017).

There's no doubt that BCF is a well-established and -supported communication protocol that is vendor-neutral and opensource. Almost all commercial BIM software have implemented BCF in their systems too. However, BCF XML is dominantly used for grasping

human-readable data regarding issue management. Even though BCF v2.1 is capable of encompassing so-called BIM-Snippets to encapsulate schematized arbitrary data, BCF is still mostly used to address human-readable issue management in AEC and examples of implementing BIM-Snippets are not yet commonly introduced. The authors of this paper, while not arguing the reputation and usefulness of BCF, merely intend to present another approach for BIM-based communication and workflow in early stages of design.

In the meanwhile, the authors believe that knowledge, especially in complex projects, is a socially attained phenomena (Zhang & El-Diraby 2011) and acquiring proper information for better decision-making in early design phases is achieved by integrating as many domain-experts as possible in the process. Nevertheless, aiming for computer-readable communications doesn't necessarily eliminate the need for social interactions. Still, in our protocol, there is room for comments and freestyle text and explanations. However, since the AEC industry is fragmented with many small and medium-size companies, and in most cases, collaborations between companies are limited to the duration of one project, we believe that being able to learn from the partnerships and communications of various building projects might be of great help to improve this less advanced industry.

Minimized BIM-based Communication Protocol

Through the early phase of design, we assume that when the architect requests an analysis from any domain-expert, there could be three different outcomes as following:

- The model is still incredibly immature and not qualified for analysis. So in this case, the response is a simple no, and maybe some general guidelines, most probably in the form of text or predefined categorical responses.
- The analysis could be performed, and the results would be presented to the architect.
- Some details within the model are missing, and these missing details would be reported back to the architect.

Reporting back the missing details to architect confronts him with the decision on which and what details to choose to develop his model further. The problem at this point is that the designer has to decide on so many things which he might not have enough knowledge about them. What could be of great help to the architect at this point is to provide him with some suggestions and enable him to compare them? Who is better to suggest these options to him than the experts and consultants in each domain? Other than being

more informed and knowledgeable compared to the architect in that specific field, they are also more familiar with common practice choices and decisions that are taken by other designers and architects when facing these decisions.

This paper differentiates design variants and options. Variants are the design models developed by the architect as proposed solutions, whereas options represent the feedback and suggestions provided by the different experts. In this concept, Options are partial design models that are being suggested (sent back as feedback) to the architect by the domain-expert as common practice examples to fulfill the shortcomings of his design model for analysis compatibility. These are to be used (accepted or rejected or even reasoned & argued & discussed with the domain-expert) by the architect as a source of inspiration, suggestion or a possible solution provided by a specialist (whom might have better understanding and knowledge in that specific matter or domain, than the architect). Our approach is to establish a common data environment (CDE) between the architect and multiple consultants to communicate and provide the architect with options to choose for further detailing his design variants. This so-called “feedback” that the architect receives from the domain-expert is consist of the following possibilities:

- report on the missing details in the design model
- possible options that could serve to fulfill the shortcomings in the design model
- the results of analysis or simulations when each of those options is selected

In this way, the architect would be provided with possible options to overcome design decisions while being informed about the consequences and outcome of those choices. Throughout the design process, the architect is the responsible team leader and can create and modify the design model/variants, and each updated state of design is done only through architect's final acceptance or upon his determination.

The proposed communication protocol focuses on staying as minimized as possible, which means avoiding to send back and forth any actual digital BIM files (Zahedi & Petzold 2018b). Even partial models (as options) will rest on the CDE, and the protocol will only inhale their links and globally unified IDs (*GUID*). In the case of updating/suggesting attributes and properties for already existing building components in the digital design model, these alphanumerical values will be included in the messages. But in the case of creating/suggesting new building components/objects, they will be only referred/linked to inside the messages.

The proposed communication system is consisting of two parts. One part would be an issue tracking system

Figure 1: BIM-based Minimized Communication Protocol

or so-called ticketing system. Via this part, just like any other ticketing system, requests and responses will be managed, and their progress will be controlled. Priorities can be set for each ticket, and their responsive person can also be traced back. Multiple tags can be assigned to tickets, which makes the coordination and communication more seamless and transparently traceable. The other part would serve and inhale the essence of the feedback provided by various consultants and domain experts. Figure 1 demonstrates this combination.

The architect will create the request for a specific type

of analysis and sent to the responsible domain expert. This request contains the desired nature and scope of analysis. In the next step, the domain expert will check the content of the sent BIM model and create a feedback report for the architect. This feedback report contains the missing building components and attributes within the BIM model that are essential for the analysis to run. In response to this report, the architect not knowing precisely what he should choose to fill in for the missing details, asks the domain expert for suggestions or in the context of our research group so-called Options. Proceeding, the domain expert will provide the architect with some common practice

suggestions for filling in the missing details in the design model along with the proper analysis results, using those suggested details. This way the architect can be informed about the consequences resulting from each of those options and choose them wisely. In the next step, a universal method/function called "feedback" will be defined to implement the exchange of missing components and attributes along with proposed values for them as options.

Feedback Function

This adaptive feedback function in its method signature is as follows:

Feedback (actionType, optionGroupID, GUID, aLODx, objectID, propertyID, value)

This universal method, based on its use case, will receive different arguments. These arguments are explained one by one as follows:

actionType: The first argument is called *actionType*. It represents the use case of the feedback function. Possible *actionTypes* are as follows:

missingObject: This action type deals with general use case scenarios, where some building components are missing overall, e.g., reporting back to the architect that all the openings (windows) are missing.

missingObjectProperty: This action type refers to an attribute needed for a building component that is empty and needs to be fulfilled by the architect.

createNewObject: This action type refers to a newly created building component (probably as part of an option) by the domain-expert (consultant), which is subject to the acceptance or disapproval of the architect. This volatile, newly created component nevertheless will have a GUID that is unique and will be used to refer to this object (explained later on).

deleteObject: This action type is used when the consultant suggests an unnecessary building component to be deleted by the architect.

updateObjectProperty: This action type is used to indicate a value to the architect, provided by the domain-expert, to fill in a missing property.

optionGroupID: The next argument in the feedback function is not mandatory and is used to group multiple suggestions. The proposed details could either be individually suggested, or they could be grouped. This could be achieved with an optional argument inside the feedback function. This argument provides the possibility to arrange some modifications together in a package called option so that the architect can choose to either accept the whole package, with all the included changes, or none of it. These packaged suggestions could not be and should not be handpicked to preserve the consistency and effectiveness of the suggested option.

GUID: This argument refers to the Globally Unique ID of a particular building component inside a given BIM model on the BIM server. In case the *actionType* in the feedback function is *missingObject*, then this argument (*GUID*) would be the unique id of the building component that is to contain the missing objects. Like with the example of all the openings being absent, then this GUID could be the Building's GUID. But when the *actionType* is *createNewObject* then this argument will be the GUID of the temporarily newly created object that is suggested to the architect by the domain-expert. With the *missingObjectProperty* and *updateObjectProperty* as *actionType*, then this argument is the *GUID* of the building component that accordingly has a missing property, or a new value is suggested for its lacking property. And finally, when the *actionType* is *deleteObject* then this argument is the GUID of the building component which is recommended for deletion by domain-expert. The use of this argument would be apparent upon explaining the demonstrative examples.

aLODx, objectID, propertyID: In each design stage and depending on the level of development, the individual domain experts request detailed requirements of exchanging building information models. Based on the explicit exchange requirements that are essential for each analysis type (examples in our research group are the Life Cycle Assessment (LCA) & Structural Analysis), a specific scheme will be defined, which contains all the essential components (spatial and semantical building components) with their corresponding crucial attributes and LOD within the BIM data model. This, in turn, formulates a certain aLODx for a specific analysis regarding a particular building project type. The following template, called aLOD1-TP4, illustrated in Figure 2, shows an example of the scheme (aLODx) for information required from TP4 (Life Cycle Assessment-LCA) in our research group.

Figure 2: aLOD1-TP4

To define these requirements, this paper uses the multi-LOD metamodel introduced by (Abualdenien & Borrmann 2018). aLODx acts as a dictionary, which contains the required information/details by different domain experts for their simulation engines to work. Inside our concept, the aLODx serves as an adaptive lookup table (using ObejectID & PropertyID) that both the architect and the domain expert will refer to when they are communicating with each other. This way, they can both be sure about what type of building component (object) and what sort of attribute (property) they are talking about.

value: This argument, if present depending on the actionType, will inhale the suggested values in the form of different options for the architect. Through the demonstrative example in the next section, the use of this argument will be more clarified.

Demonstrative Example

Figure 3 shows the conceptual framework of this minimized communication protocol using an example scenario for LCA. The scene starts when, at some point during the early design stages, the architect requests for an LCA analysis. By doing so, a ticket will be

Figure 3: Example Scenario for LCA

issued and a lite message mainly in the form a link, which clarifies the scope of the requested analysis, will be sent to the LCA specialist.

But on the other hand, not being sure of his choice about the outer-walls material, he asks for suggestions from the domain expert, together with the proper evaluation of the suggested options. The specialist creates four possible options for outer-walls material, namely steels, bricks, wood, and concrete. Then he

evaluates them and sends back the results along with their comparison to the architect. This way, the architect can decide intuitively for the better option according to the evaluation results and the system will automatically add the details (outer-walls material) to his model.

In agreement with our minimized communication protocol, the feedback function will be used in two stages. The first one is when the feedback function is

Figure 4: The use of Feedback function based on the example scenario for LCA

used for reporting the missing details (that are essential for the requested analysis) in the design model. In this example, using the *missingObjectProperty* as the *actionType*, the feedback function mentions two individual missing properties in the building (the argument *GUID* refers to the whole building). By pointing to the *aLOD1-TP4*, interpreting *objectID* 3 leads to the *OuterWall* and *propertyID* 2 and 3, point out respectively Window to Wall Ratio (WWR) and Material Group as missing properties. The upper part of Figure 4 illustrates this feature using the feedback function.

The second time the feedback function is used for suggesting four different material groups proposed for

outer-walls to the architect. This time the *updateObjectProperty* is used as the *actionType*, and each *value* for the material group is represented as an option via the *optionGroupID* argument. The lower part of Figure 4 demonstrates the usage of the feedback function for suggesting the options as mentioned earlier to the architect.

Feature work

Through this paper, an example was explained using the minimized BIM-based communication protocol for LCA analysis. Next steps include the use of feedback function and the minimized BIM-based communication protocol for structural analysis and the proper example options suggested by domain-experts

in this field. Right now, a relational database is designed and developed in MySQL to store the history of communications based on this minimized BIM-based protocol. Furthermore, developing a plugin for Revit is in progress, which enables the communication to happen inside Revit based on this minimized protocol and be stored in the established database.

Conclusions

This paper introduced a concept for a BIM-based minimized communication protocol to enhance the collaboration and transparency of the communication during the critical early phases of design. This BIM-based communication protocol is built on schematized information requirements that are adaptively defined by domain experts depending on analysis type, building project type and a suitable level of development of the digital design model. The goal is to store the history of these communications and use this accumulated data (since this data is structured and is machine-readable) for supporting decision making (e.g., via case-based reasoning) in future use cases.

Utilizing this lite protocol, computer-readable communications take place, which can be filtered and analyzed for future use cases. Using this protocol, all communications, variant evaluations, and decision-making will be documented and traceable afterwards for further use cases.

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FREEWAY WORK ZONE TRAFFIC STATE ESTIMATION WITH FAULT DIAGNOSIS

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Abstract

Freeway work zone can cause disruption to local traffic and have adverse impacts on mobility and safety of road users and those who work in the work zone. To ensure an effective traffic management strategy, it is essential to accurately and instantaneously estimate the traffic states at the work zone area. While many traffic state estimation methods are proposed by previous studies, few of them consider the occurrence of freeway sensor faults, which may result in a large deviation in state estimation and potentially lead to an inappropriate traffic management strategy. To overcome the impacts of sensor faults and provide accurate traffic state estimation, this study presents an approach using sensor fault diagnosis for traffic state estimation at freeway work zone area. Considering the capacity drop, the switching mode model with Kalman filter was used to estimate the traffic states. With the analysis of the density residuals generated by traffic sensors and probes, the fault diagnosis can detect the type of sensor faults and reconfigure the estimation model. The proposed system is implemented and evaluated in traffic simulator SUMO under a realistic freeway work zone environment. The results show that the developed system can accurately identify the type of fault in short time. An accurate traffic state estimation is provided and fairly maintained under fault-free and sensor-fault scenarios respectively.

Introduction

With the aging of freeway infrastructure, numerous construction work zones are added to freeway for projects such as barrier replacement, road resurfacing and road expansion every year. These work zones with lane closure can easily lead to traffic congestion and cause high safety risks and costs associated with wasted time and fuel. In 2014, 888 million hours and over 310 million gallons were wasted due to construction work zones (FHWA, 2014). To reduce the impacts of freeway work zones and mitigate the traffic congestion, many traffic management strategies are developed. The variable speed limit control was designed to dynamically change the speed limits upstream of a work zone so as to restrict the traffic inflow and maintain the maximum work

zone throughput (Papamichail et al., 2018; Du et al., 2019). A lane changing control strategy for work zone was proposed to reduce the lane merging conflicts and improve safety near work zone area (Qi et al., 2017). Hou et al. (2015) designed a traffic flow forecasting system to analyze the impact of planned work zone. However, an accurate traffic state estimation is essential to ensure the effectiveness of the traffic management strategies.

To provide an accurate traffic state estimation, various studies have utilized the freeway stationary sensors or a combination of stationary sensors and connected vehicles which act as probe sensors. The performances of traffic state estimation were compared between a sliding mode observer and an extended Kalman filter by using the loop detectors (Majid et al., 2015). By estimating the penetration rates of connected vehicle, the traffic density was calculated under mixed connected vehicles and conventional vehicle environments (Bekiaris-Liberis et al., 2016). Chu et al. (2018) developed the stochastic Lagrangian traffic flow model to estimate and predict the traffic congestion using lagrangian traffic data. The smart work zone was also built to acquire a better performance of queue and travel time estimation (Li et al., 2018). However, the aforementioned studies greatly relied on fault-free sensors which can consistently detect the traffic condition without disruption. In reality, a large part of data samples is missing due to sensor malfunction. It is reported that only 60% of the sensor network in California can provide reliable traffic measurement (Rajagopal et al., 2007). With the absence of reliable traffic measurement, the accuracy of traffic state estimation is greatly affected.

Since the sensor faults have detrimental effects on traffic data quality, many researchers have proposed a number of methods to detect the sensor faults and impute the missing data. The matrix and tensor based methods were designed by Asif et al. (2016) to learn traffic patterns so as to fill in the gap of the speed data. Chen et al. (2003) developed the diagnostics algorithm by using the time series of data samples based on linear regression method to estimate missing values. A modified k-nearest neighbour method and genetic algorithms were also utilized to improve the performance of the data imputation in missing traffic

data by Tak et al. (2016) and Tang et al. (2015) respectively. A better traffic state estimation is achieved in the previous studies by considering faulty sensors and missing samples, however, the designed diagnosis algorithms demand large historical data samples which are not always available especially in the cases of short-term work zones. Meanwhile, the previous diagnosis methods cannot provide sensor fault detection and adjust the state estimation algorithms online. Consequently, this makes it difficult to incorporate aforementioned traffic state estimation algorithms in traffic management strategies as real-time traffic condition is needed to make appropriate decisions.

To overcome the impacts of sensor faults on the traffic state estimation and provide accurate fault diagnosis and traffic condition, this study focuses on developing a traffic state estimation method with sensor fault diagnosis algorithm. The study includes: 1) designing the traffic state estimation model which can accurately generate the traffic condition using the stationary sensors and probe sensors; 2) developing a fault diagnosis algorithm which can detect the types of sensor faults and reconfigure the state estimation model; 3) implementing and evaluating the designed system in traffic simulator SUMO under realistic freeway work zone environment.

The rest of this paper is organized as follows. First, the system framework is presented. Then the traffic flow model is developed using the switching mode model with capacity drop. With the developed traffic flow model, the Kalman filter is utilized to estimate the traffic states. Following that, the fault diagnosis algorithm is built using the residual analysis. Afterwards, the effectiveness of the proposed system is evaluated in a traffic simulator environment. The conclusions and future work of this study are discussed in the end.

Methodology

System Framework

The proposed system mainly consists of three components: the traffic flow model, fault diagnosis and Kalman filter as shown in Figure 1.

In this study, connected vehicles are used as probe sensors in addition to other traffic sensors that can be used in fixed locations. The traffic measurements such as vehicle speed and traffic flow rate, which are detected by these two types of sensors, are sent to the traffic flow model, to estimate the traffic states and to be used for one-step state prediction. The capacity drop that further decreases the work zone capacity is also considered in the designed traffic flow model. The Kalman filter is used to improve the accuracy of the estimation by using one-step prediction and the traffic measurements collected by sensors. Then the improved traffic state estimation is generated and also

sent back to the traffic flow model to be used in the next time step estimation. During the process of state estimation, the fault diagnosis algorithm collects the traffic measurements from two types of sensors to determine whether a sensor fault occurs and to reconfigure the estimation model in the presence of a sensor fault.

Figure 1: System framework

Traffic Flow Model

Freeway work zone with lane closure can cause the loss of the road capacity. As a result, a queue easily forms upstream of a work zone when the traffic demand is larger than the work zone capacity. To estimate traffic states such as traffic density and speed near work zone area, traffic sensors and connected vehicles are used at work zone area as shown in Figure 2.

Figure 2: Layout of freeway work zone

Due to construction work zone, one of three lanes is closed in Figure 2. The mixed traffic flow which has conventional vehicles and connected vehicle travels from the left side to right side. In this study, connected vehicles are considered as probe sensors due to their ability to transmit positions and speeds. We assumed the drivers' behavior for conventional and connected vehicles is the same. Two traffic sensors stations TS 1 and TS 2 are located next to each other near work zone area. Because of the loss of road capacity, traffic congestion easily occurs when the demand exceeds the work zone capacity and a queue forms the upstream of the work zone.

Since traffic management strategies such as variable speed limit control and lane merging control are mainly implemented 1 km to 2 km upstream of work zone (Yang et al., 2017; Qi et al., 2017), the traffic state estimation in this immediate upstream of work zone area is crucial. Therefore, this upstream area is studied and the layout of this part of freeway is shown in Figure 3.

Figure 3: Layout of freeway segments

The section between TS 1 and TS 2 can be divided by several segments. Without the loss of generality, two segments with the same length are selected and the following proposed method can potentially apply to more segments. The traffic inflows of segment 1 and segment 2 are expressed as q_0 and q_1 respectively. q_d represents the traffic demand and q_2 is the work zone throughput. The variable v_i and ρ_i where i equals 1 or 2 are the average speed and density respectively in segment i which need to be estimated.

The traffic density $\rho_i(k)$ in segment i at time step k can be updated using the conservation law (Lighthill and Whitham, 1955; Richards, 1956)

$$\rho_i(k+1) = \rho_i(k) + \frac{\Delta T_s}{L} [q_{i-1}(k) - q_i(k)], \quad i=1,2 \quad (1)$$

where ΔT_s is the sample time interval and L is the length of segment. Under the assumption of triangular fundamental diagram (Newell, 1993), the traffic flow can be calculated as

$$\begin{cases} q_0(k) = \min\{q_d(k), q_{\max}, \omega(\rho_j - \rho_1)\} \\ q_1(k) = \min\{v_1(k)\rho_1(k), q_{\max}, \omega(\rho_j - \rho_2)\} \\ q_2(k) = \min\{v_2(k)\rho_2(k), q_{\text{md}}\} \end{cases} \quad (2)$$

In Equation (2), $q_{\max}$ is the maximum flow rate while q_{md} is the maximum flow rate with capacity drop. ω and ρ_j , which represent the backward propagating wave speed and jam density respectively, are the parameters in fundamental diagram as shown in Figure 4.

Figure 4: Triangular fundamental diagram

The two branches with the slopes of free flow speed v_{free} and backward propagating wave speed ω show the free and congested statuses respectively. The capacity C of three-lane freeway is reduced to be $C^b = 2/3C$ due to one lane is closed at the work zone

area. However, the reduced capacity C^b decreases further when a queue forms upstream of a work zone (Hall et al., 1992; Chung et al., 2007). This is known as capacity drop phenomenon and the maximum flow rate with capacity drop q_{md} becomes βC^b where β is the capacity drop factor.

The traffic density evolution equation can be described by

$$\mathbf{x}_{k+1} = \mathbf{A}_k \mathbf{x}_k + \mathbf{B}_k \mathbf{u}_k + \boldsymbol{\varepsilon}_k \quad (3)$$

where $\mathbf{x}_k = [\rho_{1,k}, \rho_{2,k}]^T$ is the state vector, $\mathbf{u}_k$ is the system input and $\boldsymbol{\varepsilon}_k$ is the system process noise assumed to be zero-mean Gaussian signal with the covariance matrix $\mathbf{Q}_k = E[\boldsymbol{\varepsilon}_k \boldsymbol{\varepsilon}_k^T]$. $\mathbf{A}_k$ and $\mathbf{B}_k$ are system matrices.

Since the nonlinearity introduced by $\min$ function in Equation (2) makes it challenging to estimate the traffic state, the switching mode model is developed based on the traffic status (Munoz et al., 2003). This developed model can eliminate the nonlinearity and establish linear density evolution equations under different traffic statuses. The fixed head queue is considered in this study, while the tail of queue can move towards either upstream or downstream of work zone. Therefore, the status of the segment 1 and segment 2 can fall in the set {FF, FCu, CCu, CCd, FCd} where the first two letters indicates the status of segment 1 and segment 2. The letter u and d represent the moving direction of the tail of the queue. F and C signify the free status and congested status respectively.

By differentiating the traffic status, only one value is selected from the $\min$ function in Equation (2) such that the nonlinearity is eliminated. The Equation (4) – (8) show the density evolution of status FF, FCu, CCu, CCd and FCd respectively.

$$\begin{bmatrix} \rho_{1,k+1} \\ \rho_{2,k+1} \end{bmatrix} = \begin{bmatrix} 1 - \frac{\Delta T_s}{L} v_{1,k} & 0 \\ \frac{\Delta T_s}{L} & 1 - \frac{\Delta T_s}{L} v_{2,k} \end{bmatrix} \begin{bmatrix} \rho_{1,k} \\ \rho_{2,k} \end{bmatrix} + \begin{bmatrix} \frac{\Delta T_s}{L} q_{d,k} \\ 0 \end{bmatrix} + \boldsymbol{\varepsilon}_k \quad (4)$$

$$\begin{bmatrix} \rho_{1,k+1} \\ \rho_{2,k+1} \end{bmatrix} = \begin{bmatrix} 1 & \frac{\Delta T_s}{L} \omega \\ 0 & 1 - \frac{\Delta T_s}{L} \omega \end{bmatrix} \begin{bmatrix} \rho_{1,k} \\ \rho_{2,k} \end{bmatrix} + \begin{bmatrix} \frac{\Delta T_s}{L} (q_{d,k} - \omega \rho_j) \\ \frac{\Delta T_s}{L} (\omega \rho_j - q_{\text{md}}) \end{bmatrix} + \boldsymbol{\varepsilon}_k \quad (5)$$

$$\begin{bmatrix} \rho_{1,k+1} \\ \rho_{2,k+1} \end{bmatrix} = \begin{bmatrix} 1 - \frac{\Delta T_s}{L} \omega & \frac{\Delta T_s}{L} \omega \\ 0 & 1 - \frac{\Delta T_s}{L} \omega \end{bmatrix} \begin{bmatrix} \rho_{1,k} \\ \rho_{2,k} \end{bmatrix} + \begin{bmatrix} 0 \\ \frac{\Delta T_s}{L} (\omega \rho_j - q_{\text{md}}) \end{bmatrix} + \boldsymbol{\varepsilon}_k \quad (6)$$

$$\begin{bmatrix} \rho_{1,k+1} \\ \rho_{2,k+1} \end{bmatrix} = \begin{bmatrix} 1 & \frac{\Delta T_s}{L} \omega \\ 0 & 1 - \frac{\Delta T_s}{L} \omega \end{bmatrix} \begin{bmatrix} \rho_{1,k} \\ \rho_{2,k} \end{bmatrix} + \begin{bmatrix} \frac{\Delta T_s}{L} (q_{d,k} - \omega \rho_j) \\ \frac{\Delta T_s}{L} (\omega \rho_j - q_{md}) \end{bmatrix} + \boldsymbol{\varepsilon}_k \quad (7)$$

$$\begin{bmatrix} \rho_{1,k+1} \\ \rho_{2,k+1} \end{bmatrix} = \begin{bmatrix} 1 - \frac{\Delta T_s}{L} v_{1,k} & 0 \\ \frac{\Delta T_s}{L} v_{1,k} & 1 \end{bmatrix} \begin{bmatrix} \rho_{1,k} \\ \rho_{2,k} \end{bmatrix} + \begin{bmatrix} \frac{\Delta T_s}{L} q_{d,k} \\ -\frac{\Delta T_s}{L} q_{md} \end{bmatrix} + \boldsymbol{\varepsilon}_k \quad (8)$$

In the case of the speed estimation, since the connected vehicles in this study are only used as probe sensors, the average speed of connected vehicles is utilized to estimate the average speed in segment 1 and 2.

As stated before, traffic sensors and connected vehicles are utilized to detect the traffic condition. Therefore the measurement equation can be designed as

$$\mathbf{y}_k = \mathbf{C}_k \mathbf{x}_k + \boldsymbol{\zeta}_k \quad (9)$$

where $\mathbf{y}_k$ is the sensor measurement with noise $\boldsymbol{\zeta}_k$ assumed to be zero-mean Gaussian noise with the covariance $\mathbf{R}_k = E[\boldsymbol{\zeta}_k \boldsymbol{\zeta}_k^T]$. $\mathbf{C}_k$ is the system matrix. More specifically, Equation (9) can be written as

$$\begin{bmatrix} \frac{Co_{1,k} - Co_{2,k}}{L} \\ \frac{q_{0,k}}{v_{1,k}} \end{bmatrix} = \begin{bmatrix} 1 & 1 \\ 1 & 0 \end{bmatrix} \begin{bmatrix} \rho_{1,k} \\ \rho_{2,k} \end{bmatrix} + \boldsymbol{\zeta}_k \quad (10)$$

In Equation (10), $Co_{1,k}$ and $Co_{2,k}$ are the traffic count from TS 1 and TS 2. Since the queue spills back towards upstream, the traffic flow rate detected by TS 1, which is located upstream of segment 1, is utilized to calculate the density of segment 1 via dividing by average speed in segment 1.

Therefore, the traffic state estimation model can be derived by combining the Equation (3) and (9). However, there are some noises in both density evolution equation and measurement equation which have negative impacts on the accuracy of traffic state estimation. Thus, the Kalman filter discussed in the following section is used to improve the estimation accuracy.

Kalman Filter for Traffic State Estimation

The Kalman filter is a recursive estimation algorithm which consists of two steps: the prediction step and measurement update step (Bar-Shalom et al., 2001). The following equations are utilized to update the traffic state:

$$\mathbf{x}_{k+1/k} = \mathbf{A}_k \mathbf{x}_k + \mathbf{B}_k \mathbf{u}_k \quad (11)$$

$$\mathbf{P}_{k+1/k} = \mathbf{A}_k \mathbf{P}_k \mathbf{A}_k^T + \mathbf{Q}_k \quad (12)$$

$$\mathbf{K}_k = \mathbf{P}_{k+1/k} \mathbf{C}_k^T (\mathbf{C}_k \mathbf{P}_{k+1/k} \mathbf{C}_k^T + \mathbf{R}_k)^{-1} \quad (13)$$

$$\mathbf{x}_{k+1} = \mathbf{x}_{k+1/k} + \mathbf{K}_k (\mathbf{y}_k - \mathbf{C}_k \mathbf{x}_{k+1/k}) \quad (14)$$

$$\mathbf{P}_{k+1} = (\mathbf{I} - \mathbf{K}_k \mathbf{C}_k) \mathbf{P}_{k+1/k} \quad (15)$$

After the one-step state prediction $\mathbf{x}_{k+1/k}$ and state covariance prediction $\mathbf{P}_{k+1/k}$, the filter gain $\mathbf{K}_k$ is calculated. The prediction is corrected in Equation (14) by using the traffic measurement from traffic sensors and connected vehicles together with filter gain $\mathbf{K}_k$. Then the covariance is also updated in Equation (15). Thus the traffic state estimation can be updated every time step with the measurement.

Fault Diagnosis Scheme

The fault diagnosis scheme is developed to identify the type of sensor fault, and then reconfigure the traffic state estimation model based on the type of faults. This study focuses on the stationary sensor faults, which are TS 1 and TS 2 in Figure 2. There are many types of stationary sensor faults. For example, it is found the sensor malfunction with zero flow rate is the leading fault among all the loop detector failure (Chen et al., 2003). Therefore sensor fault that causes the zero flow rate with the presence of vehicles is mainly considered in this study. However, there are 2 traffic sensors stations located upstream of the work zone. The different combinations of faulty sensors are categorized as different types of faults shown in Table 1.

Table 1: Types of sensor faults

Fault Number	Description
Fault 1	Only TS 1 is down
Fault 2	Only TS 2 is down
Fault 3	Both TS 1 and TS 2 are down

The fault diagnosis utilized the measurement from traffic sensors and connected vehicles to achieve the fault diagnosis. The process of the diagnosis is demonstrated in Figure 5.

It can be seen from Figure 5, the density estimation can be acquired from two ways. One is to use the measurement Equation (9) to fuse the measurement from both sources: stationary traffic sensors and connected vehicles. The other is to use the fundamental diagram in Figure 4 to calculate the density $\rho_{1,k}$ and $\rho_{2,k}$ via the average speed of connected vehicles. The estimated densities using

connected vehicles alone act as the redundant information. Then the redundant information is fed into the block of residual calculation together with the density estimation from both sensors. After the residual calculation, the residual analysis and the model reconfiguration are performed as shown in Figure 6.

Figure 5: Fault diagnosis

Figure 6: Residual analysis and model reconfiguration

As it can be seen from Figure 6, the identification of faults is achieved by the comparison between the density residual and the density estimated by connected vehicles, together with the comparison between current fault type and the saved fault type at $k-1$. α and γ are selected as the thresholds to consider the model uncertainties and noises. Too large thresholds can delay the time when the fault is detected or even make the fault undetectable, while too small thresholds can cause false fault detection. Different combinations of the thresholds are tested in this study to select the appropriate values. The current fault type and saved fault type from last time step are compared to avoid false fault detection. When the

type of the fault is detected and identified, the appropriate measure will be taken to reconfigure the estimation model. Though fault 1 and fault 3 can be successfully be distinguished, one more time step is required to confirm which fault occurs. However, both faults share the same reconfiguration action and there will be no time delay after the detection of either fault.

Experiment and Results

Experiment Setup

The proposed traffic state estimation for freeway work zone with fault diagnosis system is evaluated on a 4.8 km (3 mi) segment of I-15S freeway in California, US. The selected segment has the maximum legitimate speed limit 113 km/h (70 mi/h). A construction work zone was setup starting from State PM (postmile) 40.2 and extending to State PM 37.6 on July 22, 2016. The selected segment has one lane closed due to this work zone. Two loop detectors located at State PM 41.6 and 40.1 act as the TS 1 and TS 2 in this study. As shown in Figure 7, the bold (blue) line is the segment selected to evaluate the proposed system. The thin (red) line inside the bold line represents the work zone area where one of three lanes is closed. The upper (purple) marker and bottom (yellow) mark are the positions of two loop detectors used in the experiment.

Figure 7: Traffic network with work zone

In this study, the traffic network was first built in the traffic simulator SUMO. Then the microscopic model was calibrated and validated using the real traffic data provided by California PeMS (Freeway Performance Measurement System) database (PeMS, 2016).

After the traffic network was built, the fundamental diagram was calibrated using the generated traffic flow. The details of the calibration can be found in SUMO user manual (Krajzewicz et al., 2012). The capacity C , capacity drop factor β , jam density ρ_j , free flow speed v_{free} and backward propagating wave speed ω are selected as 4800 veh/h, 0.94, 270 veh/km, 108 km/h and 21 km/h. According to the realistic traffic data statistics analysis (Bekiaris-

Liberis, et al., 2016), the standard deviation of the noises of stationary sensors and probe sensors were selected as 25 veh/h and 3 km/h respectively. All sensors are sampled every 30 s. Both segment 1 and segment 2 have the length of 1.2 km (0.7 mi). The threshold α and γ are selected as 0.8 and 5 veh/km.

Results

To evaluate the effectiveness of the fault diagnosis scheme, 4 scenarios under different connected vehicle market penetration rates are designed: 1) no fault; 2) Fault 1; 3) Fault 2; 4) Fault 3. 20% and 5% are selected as the high and low connected vehicle market penetration rates respectively.

The simulation was run for 1 h. The first 5 minutes is the warm-up period and simulation data for these 5 minutes is discarded. During the simulation, an artificial fault is created at time step 1400 s for all the scenarios. Due to the paper length limitations, only results under low connected vehicle market penetration rate 5% are presented for the residual analysis and fault detection in Figure 8, 9, 10 and 11.

Figure 8: Residual analysis without fault

Figure 9: Residual analysis with fault 1

Figure 10: Residual analysis with fault 2

Figure 11: Residual analysis with fault 3

It can be seen from Figure 8 - 11 that all the faults have been successfully detected. In the scenario without any fault, the residual ratio in segment 1 is kept below 0.8 all the time before and after the artificial fault occurs. Although the residual ratio in segment 2 is larger than the threshold at some time steps, there is still no fault detected as no same fault type is detected between two consecutive time steps. The residual ratio in segment 2 exceeds the threshold some time because of the speed estimation error caused by low penetration rate and traffic merging disturbance at the immediate upstream of work zone. In Figure 9 and 11, either Fault 1 or 3 is detected at time step 1440 s because the fault type same as that at last sample time step 1410 s is detected. Though the specific type of the fault is confirmed one sample time interval later at the time step 1470 s, the reconfiguration command is able to generate promptly. In the case of Fault 2, the sensor fault is detected at time step 1500 s, which is later than the detection time of Fault 1 and Fault 3, as the density in segment 2 does not have a rapid change when the TS 2 fails. It requires some time for the fault diagnosis to identify the abnormal density increase in segment 2. However, the results for density and speed estimation in the following part show that this delay does not have a significant impact on the accuracy of traffic state estimation under Fault 2 scenario.

To assess the accuracy of the traffic state estimation, the state estimation is compared with the ground truth as a reference using the Equation (16) RMSE (root mean square error). The ground truth can be acquired via built-in functionality in SUMO.

$$RMSE = \sqrt{\frac{\sum (x_i - x_{i,r})^2}{n}} \quad (16)$$

where x_i is the estimation and $x_{i,r}$ is the reference value. n is the total number of the measurement.

The results of traffic speed and density estimation are shown in Table 2, 3 and 4. Since the average speed is estimated using the connected vehicles which will not be affected by the faulty sensor, the RMSE results for speed estimation are only presented with different connected vehicle market penetration rates.

Table 2: RMSE for speed estimation with different connected vehicle market penetration rates

Segment	Connected Vehicle Market Penetration Rate	
	20%	5%
Segment 1 (km/h)	3.8	6.7
Segment 2 (km/h)	8.3	14.6

Table 3: RMSE for density estimation with 20% connected vehicle market penetration rate

Fault Type	Density (Penetration Rate 20%)	
	Segment1	Segment 2
No Fault (veh/km)	4.4	10.1
Fault 1 (veh/km)	13.7	16.6
Fault 2 (veh/km)	4.4	16.5
Fault 3 (veh/km)	13.6	16.6

Table 4: RMSE for density estimation with 5% connected vehicle market penetration rate

Fault Type	Density (Penetration Rate 5%)	
	Segment1	Segment 2
No Fault (veh/km)	11.4	10.4
Fault 1 (veh/km)	14.1	19.3
Fault 2 (veh/km)	12.1	15.4
Fault 3 (veh/km)	15.2	19.3

From Table 2, it can be seen that RMSEs are smaller in both segment 1 and segment 2 under high connected vehicle market penetration rate because generally more probe sensors can acquire more accurate estimation. Though speed estimation in segment 2 is larger than the estimation in segment 1, the overall speed estimations in both segments have a small error and a good performance.

As we can see from Table 3 and 4, there is a small error (from 4 veh/km to 12 veh/km) in the density estimation without any fault. One potential reason can be the length of segment 1 and 2 is slightly large. Longer segment will make the segment stay at mixed status between free flow and congestion for longer time. This mixed status may affect the switching

mode model and potentially influence the accuracy of density estimation.

Table 3 and Table 4 show that Fault 1 and 3 have more impacts on the estimation than the impacts of Fault 2. Since both loop detectors are not used when TS 1 is down, more information of traffic condition from loop detectors is lost compared with Fault 2 scenario. Thus the performance of Fault 1 and 3 can be slightly worse. Meanwhile, only using the density measured by connected vehicles can also introduce some error because of the uncertainty in fundamental diagram.

The comparison of density estimation under high and low connected vehicle market penetration rates shows that higher penetration rate has better performance but the difference is not very significant. This can be attributed to the performance of speed estimation under different penetration rates.

In general, the results indicate that both the speed and density estimation provide a good accuracy of estimation. The performance is also fairly maintained under all types of faults especially when it is compared with the unusable estimation without fault diagnosis scheme.

Conclusions and Future Work

To improve the accuracy of estimating the traffic states for freeway work zone, a state estimation system with fault diagnosis is developed in this study. The switching mode model with the Kalman filter can provide sufficient accuracy of the speed and density estimation. Three types of faults are successfully detected and identified. According to the detected faults, the fault diagnosis scheme can reconfigure the estimation model and a fairly good performance is maintained with the presence of sensor faults. The proposed system shows the ability to consistently provide accurate traffic state estimation for freeway work zone even with the sensor faults.

In this study, two segments were selected and only stationary sensor faults were considered. The impact of the length of segment on the state estimation was not analyzed. The communicate delay or bad samples from connected vehicles can also affect the accuracy of state estimation. In future work, more segments and faulty probe sensors will be studied and incorporated to achieve a better estimation.

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AUTOMATED MODEL CHECKING FOR TOPOLOGICALLY COMPLEX CODE REQUIREMENTS – SECURITY ROOM CASE STUDY

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Abstract

A review of the state of the art in the field of automated code compliance checking revealed that existing applications are limited in the scope of clauses they are able to check. While some building code clauses are straightforward, requiring direct checking of parameter values, others depend on the topological relationships among objects, making automated checking of BIM models more challenging. Moreover, existing applications require the user to extensively preprocess the model in preparation for checking. We propose applying semantic enrichment for preprocessing the BIM models. The goal of a semantic enrichment process in support of automated code compliance checking is to derive the needed clause test values automatically and to represent them explicitly. A successful semantic enrichment process can therefore widen the scope of requirements that can be checked automatically. This work demonstrates such a process for checking code clauses involving topologically complex requirements. Although semantic enrichment proved to be successful for several purposes in previous research, dealing with complex topologies involves different types of semantic enrichment tasks. We explore the subject through a test case of requirements from the Israeli code for security rooms.

Introduction

In a visionary paper describing a computerized Building Design System (BDS) published in 1975, Eastman predicted that “*Designing would consist of interactively defining elements...Thus BDS will act as design coordinator and analyzer, providing a single integrated database for visual and quantitative analyses, for testing spatial conflicts and for drafting. ... Later, one can conceive of a BDS supporting automated building code checking in city hall or the architect’s office*” (Eastman, 1975). While all the other specific capabilities described in that paper have been realized with modern BIM systems (Sacks et al., 2018), automated building code checking remains limited to a narrow class of building code requirements, restricted almost entirely to those that impose numerical constraints on explicitly defined parameters of model objects. Furthermore, the discipline-specific nature of most commercial BIM systems means that their internal data schemas are specific to the discipline they serve. When models are

exported to the ISO 16739:2013 Industry Foundation Class (IFC) open file format (ISO, 2013), much of the semantics remain implicit, and thus inaccessible to generic model review systems which require explicitly defined parameters, aggregations, connections and other topological structures. Semantic enrichment offers an automated interface to represent the implicit information in an explicit form, as well as supplement BIM models with missing information for a specific application or need (Belsky et al., 2016).

IFC for automated code checking and the need for Semantic Enrichment

In the 1980s and 1990s, researchers envisaged future automated building design review systems based on two developing technologies: building product modeling (BPM) and artificial intelligence (AI). Building Product Modeling is concerned with development of the object-oriented data schema considered essential for explicit digital representation of the form and function of buildings and their constituent components and systems (Eastman, 1999). The ‘General AEC Reference Model’ (Gielingh, 1988) was among the early building product models. Björk laid out the guiding principles for modeling spaces, space boundaries and the building envelopes (Björk, 1992). The RATAS project model (Björk, 1994), a model developed in the EU COMBINE project (Augenbroe, 1994) and CIMsteel (Crowley & Watson, 1997) all followed. This development culminated in the Industry Foundation Classes (IFC), an open building model schema based on the ISO STEP standard (ISO 10303). The current version of IFC is IFC4 Add 2 and it has become an international standard (ISO, 2013).

Existing applications for automated code compliance checking rely mostly on information extracted from the model in conformance with the IFC schema. Dealing with complex code clauses in an automated code checking process requires higher levels of semantic information to be explicitly represented in the models (Solihin et al., 2004). Retrieval of required information in its correct representation is one of the challenges in every existing automated code checking application (Eastman et al., 2009; Preidel & Borrmann, 2015). To overcome this problem, a manual pre-processing stage, often called ‘normalization’, is required for most rule based code checking routines (Eastman et al., 2009). In addition

to being labour intensive and prone to errors, a manual pre-processing stage limits the degree of automation we can achieve in code checking. A semantic enrichment process is an alternative approach that offers to automate the interface. As the definition of semantic enrichment is the use of domain expert knowledge to infer the semantics of a given model, dealing with topologically complex code clauses requires an extensive semantic enrichment process to reach specific clause test values corresponding to the clause requirements.

Semantic Enrichment with rule inferencing and Machine Learning

Current automated code compliance checking applications such as Solibri and SMARTreview (SMARTreview APR, 2017; Solibri, 2017) use hardcoded rule sets that represent specific code clauses. Each rule set requires an explicit representation of the relevant information to support evaluation of the clause test value. Sacks et al. laid out a spectrum for code checking strategies and the required pre-processing for each strategy (Sacks et al., 2019). The strategies for checking range from traditional rule inferencing (Eastman et al., 2009), at one end of the spectrum, to the use of deep learning algorithms to classify building models, at the other end. Hypothetically, deep learning might eliminate the need for semantic enrichment to support automated compliance checking, because the patterns linking a model's topology and a classification of pass or fail for any given clause may be identified by the system. However, this is still largely unexplored territory in terms of research to date, and there are major unsolved challenges in its application to building models.

Research on semantic enrichment to date has focused on inferring meaningful information that was implied in a BIM model and explicitly adding its representation in the IFC file. The 'SEEBIM' system has been used successfully to demonstrate application of rule-inferencing to enrichment tasks such as classification of building objects, aggregation of building systems, unique identification and numbering, and reconstruction of occluded objects (in the case of models compiled from point cloud data) (Sacks et al., 2017). More recent work (Bloch & Sacks, 2018) has shown that some SE tasks can be performed more efficiently using supervised machine learning techniques. These experiments led to the conclusion that there are several types of semantic enrichment tasks with distinct characteristics and that the approach for SE should be chosen based on the nature of the problem.

To make progress in the field of automated code compliance checking, it is important to make progress in the field of semantic enrichment. While previous research focused on solving specific semantic enrichment tasks for different purposes, we strive to

understand the structure and characteristics of semantic enrichment problems typically required to support an automated code checking process. The general idea is that a better understanding and characterization of the problem will lead to discovery of suitable solutions. The approach is to explore a range of test cases corresponding to a variety of regulatory codes and requirements. The expected result is a general framework for SE to support automated code checking. In this paper, we describe one such test case that involves complex topology.

The paper begins with an explanation of the code clauses and identification of specific semantic enrichment tasks to support an automated compliance check of models for conformance to them. We then describe each semantic enrichment task, detailing its implementation and results. The next section describes the compliance checking process using the results obtained in the semantic enrichment step. Finally, we report an experiment conducted using a model of an eight story residential building to validate the rule-sets compiled to implement semantic enrichment and code checking for the test case.

Security Room Code Requirements

A security room is a reinforced concrete space designed to protect its occupants from shrapnel and blast impacts from conventional weapons and from chemical weapons. Every residence built in Israel is required to have a security room, or alternatively, a larger security room must be provided to serve all apartments on a floor. The design requirements for security rooms are defined in a design code (Home Front Command, 2010). The code includes both simple geometric clauses, such as minimum wall thicknesses, and clauses that depend on topologically complex relationships between objects, such as requirements for intervening concrete walls to protect security room doors from line-of-sight exposure to windows.

Checking the supported area of walls

In this paper, we treat the requirement that security rooms must be stacked one on top of the other to form vertical shafts, and that at least 70% of any given security room's walls must be continuous and reach the structural foundations.

Figure 1 illustrates the general requirement and provides examples of pass and fail cases. The structural walls at the foundation level support a security shaft containing three security rooms, one on each floor. The rooms on the first and second floors pass, since more than 70% of the walls are continuously supported and reach the foundation. For the security room above the third floor, the north wall is missing and the east wall is discontinued on the first floor, meaning only 50% of the walls are continuously supported, and it is therefore non-compliant.

Figure 1 explanation of the requirement that 70% of the security room walls must continue to reach the structural foundation.

Semantic enrichment tasks

The first step to implementation of an automated code checking routine is to analyse the code at hand to recognize all objects, attributes and relationships that might be used during checking. The concepts are compiled and detailed in the format of a formal Model View Definition (MVD). Once we identify all needed information, we move on to compose specific semantic enrichment tasks. Since we aim to enrich a model to a point we can automatically check its compliance to the code, the exact requirements for enrichment have to be defined. Thus, we first compose a checking routine for a specific code clause and draw all required concepts for enrichment from that routine.

To explore the abilities of the semantic enrichment process in the case of topologically complex code requirements, we aim to fully enrich the model. Thus, the checking process will include a single logical rule applied on an explicit clause test value we provide during enrichment. In this case we aim to enrich the model so that each security room explicitly contains the value of total supported walls percentage. This essentially dictated all the requirements for semantic enrichment, which consists of the following steps:

- identify all enclosed spaces (rooms) in a model, and where objects representing the spaces are missing, create them;
- uniquely identify the security rooms and classify them;
- explicitly associate all of the walls belonging to a security room with it;
- identify any walls or foundations that support each wall and associate them with it;
- for walls supported by foundations, identify the portion of their cross section that is supported, and store this supported area;
- for walls supported by walls below them, identify the portion of their cross section area that is supported by the lower wall's supported area, and store it;
- calculate the value of the total supported area of walls for each security room.

This final test value needs to be stored as an attribute of each security room. These SE tasks are explained in detail in the next section of the paper.

Semantic Enrichment Steps

Classification tasks

Bloch et al. (2018) demonstrated that classification of room types in residential apartments is a task better solved with a ML approach than with rule inferencing. From this work we can conclude that dealing with classification of physical elements with distinct geometry, like bridge elements (Ma et al., 2016) is different than classification of abstract elements with a similar box-like geometry. Since we are only interested in security rooms for the checking of the code at hand, we defined a less complex task of a two-class classification. In other words, we classify all spaces in the apartment as 'security room' or 'not security room'. Although this specific ask can be solved by both rule inferencing and machine learning, we continue to treat problems of room type classifications with a machine learning approach. Using a two class decision forest algorithm we reach 96.6% accuracy in classification on a cross validation set.

Association tasks

Once all spaces in the model are classified and the security rooms are tagged, we proceed to associate the walls bounding each security room to the security room. To make this association explicit, we do not create relationships between the walls and the spaces but tag the walls with the IDs of the spaces they bound. During the association, we also compute and store each wall's initial cross section area as an attribute of the security room.

IF *object 1* is an element of type IFCSPACE AND
object 1 description is "Security Room" AND
object 2 is an element of type
 IFCWALLSTANDARDCASE AND
object 2 centroid elevation is between *object 1*
 minimum elevation and *object 1* maximum
 elevation
 THEN
object 2 description is "Security Room Wall" AND
object 2 tag := *object 1* tag AND
object 1 user field "Area" := *object 2* Area

To enable the next step, in which the supported area for each wall is computed, we need to compare every two walls that are in contact but above one another to find the overlap between them (the calculation itself is detailed in the next section). To form those pairs of walls we need to take into account the fact that every pair of walls is separated by a slab that can vary in thickness. This makes it difficult to use an operator which tests for "contact" between two walls. To overcome this problem, we explicitly associate the slabs to each security room and use them to find the correct pairs of objects for the calculation.

IF object 1 is an element of type IFCFOOTING
AND
object 2 is an element of type
IFCWALLSTANDARDCASE AND
object 2 is made of "concrete" AND
object 1 is in contact with object 2
THEN create IFCRELAGGREGATES object 1
"supports" object 2

IF object 1 is an element of type IFCSLAB AND
object 2 is an element of type
IFCWALLSTANDARDCASE AND
object 2 is made of "concrete" AND
object 1 is in contact with object 2 AND
object 1 is above object 2
THEN create IFCRELAGGREGATES object 2
"supports" object 1

IF object 1 is an element of type IFCSLAB AND
object 2 is an element of type
IFCWALLSTANDARDCASE AND
object 2 is made of "concrete" AND
object 1 is in contact with object 2 AND
object 2 is above object 1
THEN create IFCRELAGGREGATES object 1
"supports" object 2

Notice that if a non-structural wall bounds a security room, which clearly denotes a modelling or design mistake, the wall will be associated to the room but will not be used to calculate the walls' overlapping areas, which is the correct interpretation.

Computation tasks

The next step is the calculation of overlapping area between every pair of supported objects. Starting from the overlap between the structural foundation walls to the room bounding walls that rest on them, we first compute the bounding box representing the overlapping area between each pair of walls (or pairs of slabs and walls) where one is immediately above the other. The same computation is implemented until we reach the top of the building. The procedure is illustrated in Figure 2 below. This computation requires association of all pairs of walls (or pairs of slabs and walls) where one is immediately above the other.

Once the supported area of all security room walls is computed, we compute the overall percentage of support for each room. This is the sum of the supported areas divided by the sum of the gross areas for the set of walls belonging to any given room. This value is stored in a user-defined 'walls_to_foundation_ratio' field for each security room.

IF object 1 Aggregates("supports") object 2 AND
object 1 longest dimension is parallel to object 2
longest dimension

THEN object 2 user field "Support Area" :=
calculate_supported_area of object 1 and object
2.

Figure 2 calculation of overlap between walls using their bounding boxes

Compliance Checking Step

Since we have enriched the model to contain an explicit clause test value, the checking itself consists of a single rule to check if the final calculated test value is greater than 70%.

IF object 1 is an element of type IFCSPACE AND
object 1 description is "Security room" AND
Object 1 walls_to_foundation_ratio >= 70%
THEN object 1 user field support_clause_flag :=
TRUE

Once the checking is complete, the results are stored in the IFC file. This enables reporting in various forms, including viewing of a colour-coded model.

Validation

To validate the results, the entire process of enrichment and checking was applied to a construction project of a residential building in Tel Aviv. The building contains eight floors with six apartments on each floor, and three underground floors for parking. Every floor is designed to contain a public security room that serves all six apartments on that floor. Figure 3 shows a typical floor plan.

Although the security rooms are similar on every typical floor, there are some significant differences on the ground floor and the underground levels, where the walls have openings to facilitate parking spaces. These openings are most significant for the code check at hand, adding geometric complexity to the topological complexity of the minimum foundation support clause case. Figure 4 (a) illustrates the configuration of a typical security room, and (b) the configuration of the security room's walls with the openings on level -3. Notice that there is an opening in the north wall and in the east wall, meaning the walls are not entirely continuous to the structural foundations.

Figure 3 A typical floor plan

(a)

(b)

Figure 4. (a) A typical security room. (b) The security room's supporting walls on level -3.

As the building had already been granted a construction permit, we expected the model to be compliant to the code clause, which was indeed the result of the enrichment and checking process in SEEBIM. To further explore and validate the proposed procedure, we introduced several changes to the model's geometry to create cases that were not compliant to the described code clause.

To create and test a case similar to the one illustrated in Figure 1, we introduced two changes to the original model. First, we changed the material of a single wall of the security room on floor four from cast in place

concrete to masonry concrete blocks. This should have the same effect on the particular code clause as removing the wall entirely. As can be seen in Table 1, in the row for floor 4, according to manual calculations, this will lead to 70.2% of the security room's walls on floor four being continuous to the structural foundation, which is still compliant.

The second change introduced to the model was to create a 123cm wide opening in the north wall of the security room on floor six. Again, based on the manual calculations shown in Table 1, we expect the result of checking the supported wall area to be only 64.3% for the security room on floor six, making it not compliant to the code requirements. Subsequently, the supported wall areas of security rooms on floors seven and eight will also be 64.3%, meaning those security rooms are not code compliant as well.

Info					
Space.17.5 : Security Room[1148]					
Space Boundary Areas	Classification	Hyperlinks	Pset_SpaceCommon		
Identification	Location	Quantities	Profile	Relations	Space Boundaries
Property	Value				
Model	Test 25_12_18_V6_1st Level Boundaries and 2d ...				
Discipline	Architectural				
Name	Security Room				
Number	1148				
Type	Security Room				
Type Name					
Description	security room FAIL				
Occupant					

Info					
Space.15.6 : Security Room[1132]					
Space Boundary Areas	Classification	Hyperlinks	Pset_SpaceCommon		
Identification	Location	Quantities	Profile	Relations	Space Boundaries
Property	Value				
Model	Test 25_12_18_V6_1st Level Boundaries and 2d ...				
Discipline	Architectural				
Name	Security Room				
Number	1132				
Type	Security Room				
Type Name					
Description	security room PASS				

Figure 5. A view of the building model with tags for security rooms that pass and that fail the foundation support clause.

The model with modified geometry was exported as an IFC 4 design transfer view and used as input for the SEEBIM engine. The file size of the original REVIT file was 122 MB; the corresponding IFC 4 reference view file was 45 MB; the run time in SEEBIM was ~3 minutes (although the time to write the export file using the IFC Engine is some 60 minutes). The rule sets detailed above were used in SEEBIM to complete all of the described semantic enrichment tasks and to perform the compliance check. Results received from SEEBIM match the expected results as described in Table 1.

Figure 5 illustrates a view of the model using an IFC file viewer software, in which users can visualize the results of the code compliance check for minimum continuous wall foundation support for security rooms. The illustration shows results for the security room on floor four, which is compliant to the clause and on floor six, which is not compliant. All of the security rooms were evaluated correctly, both in the original building model obtained from the developer, and in the model in which the researchers intervened to create cases in which the security rooms on floors 6-8 failed the code check.

Technical Implementation

As described above, the rules sets were implemented in the SEEBIM 2.0 inferencing engine. The interface is illustrated in Figure 6.

The rules were compiled directly in the user interface, without any need for programming. Rules can be compiled directly in the user interface, by selecting from a set of pre-coded operators to apply to every pair of IFC objects in the model (see Figure 7).

Users can upload any IFC file and apply any of the existing rules to that model. Rules can also be aggregated into rule sets, in this case including all the enrichment and checking rules needed for checking the compliance of the security rooms wall supported area. Once the user runs a set of rules on a specific file, a new, enriched IFC file is created, which can be downloaded and opened in any compatible platform.

Figure 6 The SEEBIM 2.0 user interface

Figure 7 Compiling new rules directly in the user interface

During the validation experiments, a number of challenges arose which shed light on the process as a whole. These included:

- Unexpected and non-uniform modelling practices on the part of the design team. For example, some walls were left 'unconnected' to the slabs above them, so that they protruded through and above the slabs (apparently a result of changes to the levels of slabs during design); structural foundations were modelled as floors.
- Omission of objects and technical errors in the IFC files exported by Revit 2018: walls with openings were absent from IFC4 reference view export.
- Unforeseen design situations. For example, in some places in the parking levels, designers modelled floor to ceiling openings in concrete walls by placing two wall sections rather than one section with an opening. This meant that the cardinality of the 'structural support' relationship between walls was m:n rather than 1:1, as had been implicitly assumed (such situations were not contemplated in the simple lab models used when compiling the rules).

Discussion and Conclusion

A set of rules was compiled and implemented for checking compliance of a building model to a building code clause that requires evaluation of complex geometry and topology. The rules were evaluated using the SEEBIM forward chaining inference engine. The successful application of the rule sets demonstrates the feasibility of replacing normalization - the manual process for pre-processing a model to populate it with the specific information concepts needed for code compliance checking - with an automated procedure. By defining a specific clause test value and the corresponding concepts in an MVD, we can define semantic enrichment tasks that will lead to explicit representation of that test value in the BIM model. Once all semantic enrichment tasks are complete, simple logical rules can perform the

compliance check itself. The overall development procedure can be broken down into three stages: a) establish the interim concepts and define them as targets in an MVD; b) compose the SE rule sets and implement them in the inference engine or in ML processes, c) test and validate the resulting system.

Through this experiment, we demonstrate that it is feasible to compose a set of rules that chain together to fulfil the semantic enrichment that is needed. The rules progressively add the concepts that are needed, such as 'supported area' for each wall, as the rule inferencing engine is cyclical, repeating all of the rules on each and every pair of objects on the model, until such time as no new information is added in a full cycle. This is an effective method for enrichment of concepts that involve complex geometry as they require a progressive chain of calculations based on the relevant

geometric features.

Once the SE process is complete, the rule checking reduces to a simple IF THEN rule evaluation for each space. We assume that this is the case for all code clauses with a single test case value that can be represented explicitly in the BIM model either directly in the design phase or through semantic enrichment. The result emphasizes the importance of progress in the field of semantic enrichment.

In general, the selection of a rule-based or a machine learning approach will depend on the nature of the problem and the amount of effort that is needed for compiling the code checking solution. In ongoing research, we are testing the machine learning approach to the same clause, with a view to learning more about alternative approaches.

Table 1. Validation test case values.

Floor	Supported Wall Areas [m ²]					Ratio of supported walls
	North	East	South	West	Total	
Whole room	1.41	1.21	1.41	1.21	5.24	100.0%
-4	1.41	0.41	1.41	1.21	4.43	84.6%
-3	1.06	0.41	1.41	1.21	4.08	78.0%
-2	1.06	0.41	1.41	1.21	4.08	78.0%
-1	1.06	0.41	1.41	1.21	4.08	78.0%
G	1.06	0.41	1.41	1.21	4.08	78.0%
1	1.06	0.41	1.41	1.21	4.08	78.0%
2	1.06	0.41	1.41	1.21	4.08	78.0%
3	1.06	0.41	1.41	1.21	4.08	78.0%
4	1.06	0.00	1.41	1.21	3.68	70.2%
5	1.06	0.00	1.41	1.21	3.68	70.2%
6	0.75	0.00	1.41	1.21	3.37	64.3%
7	0.75	0.00	1.41	1.21	3.37	64.3%
8	0.75	0.00	1.41	1.21	3.37	64.3%

The unexpected modelling conditions encountered in the validation underline the need for effective semantic enrichment. Despite being modelled by a highly skilled and professional design team, the model still contained object compositions that were not foreseen during SE rule compilation. The essentially unlimited diversity of possible modelling practice raises a question concerning the feasibility of a purely rule-based approach to SE. Machine-learning may be superior in dealing with diverse object compositions. The same can be said for unforeseen design situations.

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DO VEHICLES SENSE PAVEMENT SURFACE ANOMALIES?

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Abstract

Nowadays, pavement monitoring agencies typically assess pavement quality approximately only once per year. The main reason for this low frequency of inspections is the fact that current methods are expensive and laborious. The paper presents a data-driven framework and related field studies on the use of pattern recognition techniques and smartphone sensor technologies for the detection, classification and georeferencing of roadway pavement surface anomalies. The proposed system provides continuous and reliable information about the five most common roadway pavement surface anomalies which are valuable for pavement management systems and public safety.

Introduction

One of the most significant indicators for road quality is the pavement surface condition, which is determined by the anomalies in the pavement surface that influence the ride quality of a vehicle. Pavement surface anomalies can damage vehicles, cause unpleasant driving and sometimes be the cause for traffic accidents, injuries and/or fatalities.

Further, the condition of pavement surfaces is not time-invariant, as pavements deteriorate in time from causes linked to location, materials used, traffic, weather, etc. Identifying road anomalies related to pavement surface cracks, rutting, raveling, patching and potholes can improve road condition quality. Distributed mobile sensing with connected vehicles and smartphones could provide a viable solution to the problem at a much lower cost compare to current methods which are expensive and laborious.

As a result of the fast and intense development and usage of smartphones in current years, smartphone technology has gained noteworthy consideration within the transportation, infrastructure, and automotive industries. Smartphones can be utilized in the collection of smartphone and vehicle sensor data, since they come with a range of built-in sensors such as accelerometer, gyroscope and GPS sensors. Further, OBD Bluetooth devices coupled with specialized smartphone applications enable the real-time monitoring of, among others, GPS latitude and longitude, forward and lateral acceleration, vehicle roll and vehicle pitch. This paper investigates the use of smartphone applications, in the interest of

Figure 1: System Components

improving the condition evaluation and management of roadway pavement surfaces, and by extension it examines the possibility that smartphone-based data and tools may contribute to efficiently monitoring the condition of transport infrastructure.

The goal of roadway anomaly detection by utilization of smartphone technology is set in parallel with the hypothesis that such technology can be used for crowd-sourced data collection and analysis in GIS-based pavement management systems (PMS). A general depiction of a PMS is shown in Figure 1, with the focus of this paper highlighted in shaded shapes. As aforementioned, this study focuses on the data collection from smartphones and OBD-II devices for the detection and classification of roadway pavement anomalies. An adequate number of vehicles collecting this crowd-sourced data can then be used to generate a georeferenced event at points where vehicles encounter pavement surfaces anomalies on a roadway network. Even though multiple vehicles may probably provide conflicting data concerning pavement surface conditions, the joint knowledge given by participatory sensing delivers an accurate model of the pavement surface in relation to how an average user experiences the roadway condition.

Further to this introduction to the paper's subject matter, a short literature review section presents an outline of past and ongoing work related to pothole detection using smartphones. A section on methodology describes the developed data collection system and methods, while the results and discussion section includes the processes and tools used to classify the data and experiment outcomes. The paper concludes with key findings and future research directions.

Literature Review

Roadway pavement defect detection – State of knowledge

The American Association of Highway Transportation Officials (AASHTO 1993) states that the “...function of a PMS is to improve the efficiency of decision making, expand its scope, provide feedback on the consequences of decisions, facilitate the coordination of activities within the agency, and ensure the consistency of decisions made at different management levels within the same organization.” The investment in a PMS is worthwhile as it provides the tools an agency needs in rational resource allocation, optimal use of funds, pavement rehabilitation cost reductions, pavement treatment selection, pavement life extensions, and increased credibility with stakeholders (Washington Department of Transportation 1994). It is essential to understand the benefits and related cost of any expenses in pavement management before starting the process (Khattak, Baladi et al. 2008). In developed countries, PMS are specialised structures supplied with expensive equipment installed on specialised Pavement Evaluation Vehicles (Seraj, van der Zwaag, Berend Jan et al. 2014). The costs linked to a PMS include software (purchase and installation), data collection, database building and system maintenance, as well as, updates,

consultant services, employee training, personnel time and actual expenditures on the pavement and rehabilitation (AASHTO 1990).

State of knowledge in automated roadway anomaly detection

At present, the methodology used for the collection of pavement distress data utilises surveys which address an evaluation or a detailed measurement of distress (Walker, Entine et al. 2002). The collection of the road surface condition data can be either manual (from a moving vehicle, or by “walking” the pavement), or automated (by the use of vehicles fitted with specialized cameras and sensors). Two of the most prominent broad categories of data collection are (1) vibration-based methods and (2) vision-based methods.

The succeeding sections present past and ongoing research work related to the automated detection of roadway pavement surface anomalies by use of low-cost technologies (such as smartphone-based accelerometers and gyroscopes). A summary of these efforts and their findings is listed below, in thematic areas and in chronological order.

Vision-Based Methods

With regards to vision-based methods, the most relevant work can be found in the works, amongst others, of Radopoulou et al. (Radopoulou, Brilakis et al. 2016), Radopoulou and Brilakis (Radopoulou, Brilakis 2016), Li, Yuan et al. (Li, Yuan et al. 2016), Hadjidemetriou et al. (Hadjidemetriou, Christodoulou et al. 2016, Hadjidemetriou, Vela et al. 2017) and Christodoulou et al. (Christodoulou and Kyriakou et al. 2019).

In Radopoulou et al. (Radopoulou, Brilakis et al. 2016), video data collected from a car's parking camera was used to detect defects in frames, coupled it with elevation signals collected from accelerometers attached to the car to reconstruct the profile of the road, and classified detected defects according to their type and severity. The researchers reported that the initial identification of frames including defects produced an accuracy of 96% and approximately 97% precision, and that further experiments on such frames, aiming at the detection of potholes, patches and three different types of cracks resulted in over 84% overall accuracy and over 85% precision.

Further, Radopoulou and Brilakis (Radopoulou, Brilakis 2016) presented an application of the Semantic Texton Forests (STF) algorithm for automatically detecting patches, potholes and three types of cracks in video frames captured by a common parking camera, reporting over 70% accuracy in all of the tests performed, and over 75% precision for most of the defects.

A vision-based approach was employed by Li, Yuan et al. (Li, Yuan et al. 2016) who proposed a method to integrate the processing of two-dimensional images and of ground penetrating radar (GPR) data for pothole detection. The images and GPR scans are first preprocessed and a pothole

detector is designed by investigating the patterns of GPR signals, and then the position and dimension of the detected potholes is estimated from GPR data and mapped to the image to enable a localized shape segmentation. The researcher reported a precision, recall, and accuracy of 94.7%, 90% and 88%, respectively.

Hadjidemetriou et al. (Hadjidemetriou, Christodoulou et al. 2016, Hadjidemetriou, Vela et al. 2017) presented a method based on image processing and Support Vector Machine (SVM) classification. The feature vectors used in the classification consist of an image histogram and two texture descriptors, and the output is a binary image where each image block is classified as “patch” or “no-patch”. The performance of their proposed method is rated by a detection accuracy of 81.97 %, a precision of 64.21 %, and a recall of 91.21 %.

Finally, Christodoulou et al. (Christodoulou, Symeon E., Kyriakou et al. 2019) presented a big-data driven methodology for the detection of roadway anomalies, utilizing smartphone-based data and image signal streams. The methodology uses a vision-based method with entropic texture segmentation filters and SVM classification for the detection of patch defects on roadway pavements. The presented system pre-processes video streams for the identification of video frames of changes in image-entropy values, isolates these frames and performs texture segmentation to identify pixel areas of significant changes in entropy values, and then classifies and quantifies these areas using SVM. The developed SVM is trained and tested by feature vectors generated from the image histogram and two texture descriptors of non-overlapped square blocks, which constitute images that include patch and no-patch areas. The outcome is composed of block-based and image-based classification, as well as of measurements of the patch area.

Vibration-Based Methods

With regards to vibration-based methods for the assessment of roadway pavements, relevant work can be found in the works, among other, by Chen et al. (Chen, Tan et al. 2016), Jang et al. (Jang, Yang et al. 2016), Singh et al. (Singh, Bansal et al. 2017) and Allouch et al. (Allouch, Koubâa et al. 2017).

A crowdsourced approach using hardware modules mounted on distributed vehicles was utilized by Chen et al. (Chen, Tan et al. 2016). Low-end accelerometers and GPS devices were used to obtain vibration patterns, locations, and vehicle velocities. Further, a light-weight data mining algorithm was utilized to detect road surface events and transmit potential pothole information to a central server. The researchers reported a case-study deployment of their system on 100 taxis, and pothole detection accuracy of 90% with nearly zero false alarms.

Jang et al. (Jang, Yang et al. 2016) proposed an automated method to obtain up-to-date information about potholes by using a mobile data collection kit mounted on vehicles. In each mobile data collection kit, a triaxial accelerometer and global positioning system sensor, collects data for the

detection of street defects. At a back-end server, a street defect algorithm, which relies on a supervised machine learning technique and a trajectory clustering algorithm, enhance the performance of the proposed monitoring system by integrating data collected from multiple sensor-equipped vehicles.

Sigh et al. (Singh, Bansal et al. 2017) presented a smartphone based sensing and crowdsourcing technique to detect the road surface conditions. The in-built sensors of the smartphone like accelerometer and GPS have been used to observe the road conditions. The motivation of their work is to improve classification accuracy of detecting road surface conditions using Dynamic Time Warping (DTW) technique which has the ability to automatically cope with time deformations and different speeds associated with time data. Their technique shows detection accuracy rate of 88.66% and 88.89% for potholes and bumps respectively.

Allouch et al. (Allouch, Koubâa et al. 2017) motivation was to create a real-time android application ‘Roadsense’ that automatically predicts the quality of the road based on a triaxial accelerometer and a gyroscope, show the road location trace on a geographic map using GPS, and save all recorded workout entries. Decision tree classifier was applied on training data to classify road segments and to build their model. Their experimental results show consistent accuracy of 98.6%.

Related work published to date by the paper’s authors

The works of Kyriakou et al. (Kyriakou, Christodoulou et al. 2016) explored the use of data, collected by sensors from smartphones and automobiles’ onboard diagnostic (OBD-II) devices while vehicles are in movement, for the detection of pavement transverse defects, longitudinal defects and potholes/manholes. The smartphone-based data collection was complimented with artificial neural networks detecting and classifying identified roadway anomalies. Thirty-one factors were used for the detection (subsequently reduced to nine, without loss of accuracy). The proposed method and system architecture were checked against three types of roadway defects and validated against hundreds of roadways run (relating to several thousands of data points) with above 90% accuracy rate. Their study’s results confirm the value of smartphone sensors in the low-cost (and eventually crowd-sourced) detection of roadway anomalies.

Kyriakou et al. (Kyriakou, Christodoulou et al. 2018) discussed the development of a low-cost pavement assessment method and a geographic information system (GIS)-based decision support system (DSS). Data were collected by means of a smartphone and then analyzed for anomalies by use of artificial neural networks, robust regression, and various classification algorithms. The researchers reported pothole-detection accuracy levels of about 90%.

Kyriakou et al. (Kyriakou, Christodoulou et al. 2017a, Kyriakou, Christodoulou et al. 2017b) presented a study on the use of low-cost technology for data collection,

detection and georeferencing roadway patches and potholes by use of smartphone's accelerometers and gyroscopes, while vehicles are in movement. The proposed approach, which leads itself to participatory-sensing applications, utilises readily available and low-cost sensing technologies found in contemporary smartphones, coupled with robust regression analysis, various algorithms and bagged trees classification model to analyse in near-real time the signal of a vehicle's roll and pitch values as the vehicle traverses roadway pavements. The proposed patch and pothole detection method has been piloted on an urban roadway network showing a detection accuracy rate of over 90%, and it is currently expanded to cover larger datasets and a bigger number of roadway defect types.

Proprietary commercial efforts

The 2014 Mercedes-Benz S-Class used a Light-Detection-and-Ranging (lidar) scanner to measure pavement roughness as a component of an active suspension system. Recently, the Jaguar Land Rover automaker announced that is examining a new connected vehicle technology which permits a vehicle to point dangerous potholes in the road and then allocate this data in real time with other vehicles and road authorities (O'Donnell, Mc Conomy 2017).

Literature review summary and concluding remarks

The aforementioned systems show that pavement condition assessment by use of smartphone sensors is technologically feasible.

Among the most noteworthy limitations of existing vision-based methods are the need for noise filtering, shadow removal and background illumination correction. These methods either rely on complete 3D surface reconstruction, which comes along with high equipment and computation costs, or make use of acceleration data, which can only provide preliminary and rough condition surveys. Finally, and most important, existing vision-based methods require large storage space and extensive computation for image processing.

The most important limitation of existing vibration-based methods is that they are constrained by tire-hitting paths and by vibration-inducing pavement anomalies (i.e. they are dependent on how the road surface anomaly is hit by the tire, and on the speed of travel). Despite hardware differences in terms of GPS accuracy and accelerometer sampling rate and noise, pothole detection is possible. However, the detection of softer vibration-inducing pavement anomalies has proven difficult. Finally, a speed dependence removal approach must be utilized, especially for the cases involving sudden stops or sudden changes in motion acceleration.

The undertaken research is vibration-based in order to avoid the limitations of vision-based methods and utilizes a new approach to pavement anomaly detection that uses gyroscope readings (roll and pitch values), which are scientifically proven to govern 3D rigid body dynamics, in order to avoid speed dependence and false indications

when there is a sudden motion. The suggested system targets the detection of five roadways anomalies (instead of 2-3 of the existing vibration systems) and the development of a GIS-based pavement monitoring system.

Methodological setup

The section focusses on the detection of five types of common roadway anomalies in six different sections of local roadways and two highway roadways (of 80Km total distance, ~ 10 data points per geographical location, 3349 data points of cracks, 1401 data points of rutting and ravelling, 1770 data points of patches and 2770 data points of potholes), which examines in tandem, albeit being part of a larger effort on the detection of vibration-inducing pavement anomalies, as documented in Kyriakou et al. (Kyriakou, Christodoulou et al. 2016, Kyriakou, Christodoulou et al. 2018, Kyriakou, Christodoulou et al. 2017b, Christodoulou, S. E., Kyriakou 2018, Christodoulou, Symeon E., Kyriakou et al. 2019).

According to the Federal Highway Administration (FHWA) (Miller, Bellinger 2003) there are longitudinal, transverse, block and alligator cracks. FHWA states that ravelling is a progressive loss of pavement material, rutting is displacement of material creating channels in wheelpaths, patches are original surface repaired with new asphalt material and potholes are holes or loss of pavement material caused by traffic loading, fatigue and inadequate strength (Miller, Bellinger 2003).

Data on these types of pavement surface anomalies were collected in-situ by use of a car equipped with a smartphone (mounted on the car's windshield) with its sensors turned on, and with an OBD-II reader attached to it. The smartphone was also fitted with the DashCommandTM application for recording (and exporting) sensor readings of taken data. Vehicle system data transmitted through the OBD-II reader to the smartphone device and then transferred for either processing or storing, via a digital cellular connection or other means. Further, for visually verifying the existence of a pavement surface anomaly (as detected by the sensor data), the smartphone had also its video camera active for recording the routes travelled.

The data, collected at intervals of 0.1 seconds, included a total of 31 uni-dimensional (e.g. X, Y, Z accelerations, speed, etc.) and two-dimensional indicators (e.g. the smartphone's roll and pitch values). At the back-end server, defect detection algorithms based on robust regression analysis, various algorithms and bagged trees classification model enhances the performance of the proposed monitoring system, by integrating data collected from multiple sensors and deducing knowledge from these participatory sensors.

Mathematically, the proposed method is based on rigid-body dynamics. Any three-dimensional rotation can be described as a sequence of yaw, pitch and roll rotations (Figure 2). Pitch is defined as counter clockwise rotation of θ_{pitch} about y-axis. Roll is defined as counter clockwise rotation of θ_{roll} about x-axis. Yaw is defined as counter

clockwise rotation of θ_{yaw} about z-axis.

Figure 2: Yaw, pitch and roll rotations (Kyriakou, Christodoulou et al. 2017b)

(a)

(b)

Figure 3: Smartphone's (a) roll and pitch directions and (b) relation to car's wheels' differential (Kyriakou, Christodoulou et al. 2018)

The smartphone's roll and pitch values (Figure 3a) can be associated with the host car's roll and pitch values (Figure 3b). In essence, the roll metric refers to a car's acceleration variation between its left and right front wheels, while the pitch metric refers to a car's acceleration variation

between its front and rear wheels. Concurrently, the roll and pitch values define the way in which the host car is off balance (sideways and front/back).

Robust regression analysis is used to detect the most significant variables and the underlying regression equation. Tukey's Biweight robust influence function was used. It is an M-Estimator that uses iteratively reweighted least squares. This M-estimator completely downweights observations with large outliers until their weight is set to zero. It provides protection against heavy-tailed error distributions. The regression analysis outputs are shown below (Table 1), listing the most important statistical variables (with p-values ≤ 0.05).

Table 1: Most important variables according to robust regression

Variable	Variable Description
VAR_1	Forward Acceleration (Gs)
VAR_2	Lateral Acceleration (Gs)
VAR_3	Vehicle Pitch ($\hat{A}^\circ$)
VAR_4	Vehicle Roll ($\hat{A}^\circ$)

Robust regression determines the coefficients β_i of each factor x_i , and the residual error ϵ_j for each observation j , in the equation

$$y_j = \beta_0 + \beta_1 x_{1j} + \beta_2 x_{2j} + \dots + \beta_p x_{pj} + \epsilon_j, \quad (1)$$

which is expected to link the dependent variable, y_i , to the independent variables, x_i . The independent variables are the 31 parameters mentioned above, and the dependent variable relates to the classification status of the pavement ('1' for no defect, '2' for cracks, '3' for rutting and ravelling, '4' for patching and '5' for potholes). The subscript 'j' denotes the observation (row) number (nearly 3,000 data rows were used in the analysis). Robust regression was selected instead of other regression analysis, because it analyses highly contaminated data by detecting outliers from both dependent and independent variables.

Results and discussion

The collected raw data exposes the difficulty of the detection problem, as variables such as the lateral acceleration assumed to highlight roadway anomalies are not as definitive as originally thought. A plot of lateral acceleration (Figure 4) helps reveal the absence of any pattern in the taken readings. The vertical variability is random even at a point of known pavement surface anomaly.

Despite the fact the plots indicate areas of suspicion (highs and lows, away from the running average values), they are not reliable indicators. Further, the plots fail to provide information on other running parameters which could affect the accuracy of the data (e.g. the forward and lateral acceleration).

Figure 4: Lateral Acceleration over time

Figure 5: Classification models architecture

Bagged Trees Classification model

Classification can be achieved with supervised machine learning in which an algorithm "learns" to classify new observations from examples of labeled data. In order to classify and validate the data, supervised learning algorithms for multiclass problems were used and an evaluation comparison was conducted between various classification algorithms to check their performance, including decision trees using various classifiers, discriminant analysis, support vector machines, logistic regression, nearest neighbors, and ensemble classification. Performance was evaluated for both training and validation datasets.

Supervised machine learning was performed by supplying a known set of input data (observations or examples) and known responses to the data (i.e., labels or classes). The abovementioned datasets were fed into classification models consisting of 4 observations and 5 responses. The classification model observations are the parameters listed

in Table 1, while the responses are the values of '1' for no defect, '2' for cracks, '3' rutting and raveling, '4' patching and '5' potholes. The data used for training the model is the basis for the generation of predictions in response to new data. The classification model architecture (shown in Figure 5) was implemented in MATLAB™.

Classifier Type	Train Accuracy (%)	Classifier Type	Train Accuracy (%)
Complex Tree	99.4%	Fine KNN	99.6%
Medium Tree	99.4%	Medium KNN	98.9%
Simple Tree	91.4%	Coarse KNN	88.5%
Linear Discriminant	79.5%	Cosine KNN	98.1%
Quadratic Discriminant	95.3%	Cubic KNN	99.0%
Linear SVM	87.4%	Weighted KNN	99.6%
Quadratic SVM	99.6%	Boosted Trees	71.5%
Cubic SVM	99.6%	Bagged Trees	99.7%
Fine Gaussian SVM	99.6%	Subspace Discriminant	82.5%
Medium Gaussian SVM	99.6%	Subspace KNN	99.6%
Coarse Gaussian SVM	92.7%	RUSBoosted Trees	93.8%

Figure 6: Classifier type training statistics

After cross-validating the various classification systems and comparing the resulting cross-validation errors of each method, the best model was selected to be the bagged trees classification model (Figure 6). Bagged trees procedure is simple: (1) takes a sample from the dataset, (2) fits the tree to this data set, (3) repeat steps 1 and 2 many times (typically 50-1000), and (4) makes predictions for new data using each of the fitted models and average the predictions. Bagged trees use Breiman's 'random forest' algorithm. 'Random forests are a combination of tree predictors such that each tree depends on the values of a random vector sampled independently and with the same distribution for all trees in the forest. The generalization error for forests converges to a limit as the number of trees in the forest becomes large' (Breiman 2001).

True Class	1	100%					100%	
	2		100%				100%	
	3			100%			100%	
	4				100%		100%	
	5			1%		99%	99%	1%
		1	2	3	4	5		
		Predicted Class						
							True Positive Rate	False Positive Rate

Figure 7: Bagged trees confusion training matrix (cracks, rutting and ravelling, patching and potholes)

As shown in Figure 7, the bagged trees classify the three roadway anomalies (target classes '2', '3', '4' and '5') while also distinguishing the 'no defect' condition (target class '1'), consequently discriminating normal and abnormal roadway pavement surface conditions. For each pavement surface anomaly, data is used for training, for validating and for predicting the bagged trees, with an outline of the obtained classification results presented in Figure 8.

Classifier Type	Accuracy	Total (data)	True (data)	False (data)	(%)
Bagged Trees	Train	17291	17290	1	99.95
Bagged Trees	Validation	17301	17300	1	99.99
Bagged Trees	Prediction	11851	11832	19	98.84
		46443		21	

Figure 8. Bagged trees training, validation and predictions statistics for the various roadway anomaly cases examined (cracks, rutting and ravelling, patching and potholes)

Spatial DSS and pavement condition-assessment mapping

Ongoing work involves the development and completion of a spatial decision support system (DSS) for pavement surface condition-assessment mapping. The outcome of the bagged trees analysis and the resulting pavement surface condition assessment score will be mapped spatially, point out the areas of concern and in need of rehabilitation activities (Figure 9).

Further, the generated heatmaps will be used by the pavement agencies to investigate the condition of roadway surfaces and to prioritize their rehabilitation actions according to their budgets.

Conclusions and future work

This paper focuses on efficiently and cost-effectively appraising the surface condition of roadway pavements and on developing a GIS-based system for roadway anomaly detection and classification. The thesis proposed methodology was designed to provide information and data for analysis, so that highway managers make more consistent and defensible decisions related to the preservation of a pavement network. The suggested

Figure 9. Spatial condition-assessment mapping

system can collaborate to surveying road condition quality, because is able to identify and classify cracks, rutting, ravelling, patching and potholes on the pavement surface. As a result, this system can raise the value of road surface, protect vehicles from damage and improve traffic safety.

The paper suggested system gives the opportunity to agencies to monitor their roadways networks without buying specialized expensive vehicles which cost over one million dollars, extra software or hardware acquisition and consulting services. The proposed system collected automated pavement surface condition data by using typical passenger vehicles and typical smartphones. Contemporary and future primary datasets of the thesis low-cost pavement monitoring system will be different in form from traditional pavement condition data. Even though connected vehicle data is not likely to directly provide us with traditional assessment metrics (such as IRI and PCI), new metrics might supplement and eventually supplant traditional metrics. An application will be developed in order to collect the specific metrics from the probe-vehicles.

The most important advantage of this system is that pavement surface condition data can be collected and analyzed on a daily base so that suitable treatments can be timely applied. Future work will include also the development of suitable treatments for each roadway anomaly and cost analysis of the corresponding maintenance works. Further, trigger values will be applied for distinguishing different types of cracks, rutting, ravelling, patches and potholes. Discrete ranges could be converted into a numerical (1-5, 1-10, etc.) scale.

The applied methodology is instantly available, low-cost and precise, and can be utilized in crowd-sourced applications leading to roadway assessment and pavement management systems. The presented study documents the detection of common pavement surface anomalies, exhibiting accuracy levels higher than 90%. The proposed methodology is currently field-tested with larger datasets and a higher number of roadway defect types, with links created to GIS mapping and database management systems for the use of the proposed methodology in PMS.

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SORTING THINGS OUT? MACHINE LEARNING IN COMPLEX CONSTRUCTION PROJECT

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Abstract

This research includes answers from 324 main contractor representatives and 256 clients for a survey in Sweden, 2014. The literature review covers project management success in construction projects. A statistical correlation method is used to select the features that are strongly correlated with three performance indicators: cost variance, time variance and client- and contractor satisfaction. A linear regression prediction model is presented. The conclusion is an identification of the most correlating factors to project performance, and that human related factors in the project life cycle have higher impact on project success than the external factors and technical aspects of buildings.

Introduction

Construction projects are usually affected by multiple and interrelated factors which have a direct impact on projects performance and productivity; for example, factors such as poor management practices, unclear goals, performance measure, and crises orientation, are all contributing to poor productivity and cost overruns (Forbes and Ahmed, 2010). Construction projects suffer from scheduling problems related to the best sequencing for activities and resource allocation (Wauters and Vanhoucke, 2014). There are also problems associated to uncertainties in design, construction management and decision making, and these can be dependent on mathematics, mechanical calculations, and practitioners' experience (Lu et al. 2012). Regardless of emerging new performance measures such as safety and environmental performance, cost and schedule are still considered the most important to evaluate construction project performance (Chan and Chan, 2004).

Artificial intelligence (AI) is currently considered a solution superior to traditional systems used in studying complex systems such as construction project cost and time performance, (Lu et al. 2012). AI is a branch of computer science involved in the research, design and application of intelligent computers, and a comprehensive discipline, which was developed based on the interaction of several kinds of disciplines, such as computer science, cybernetics, information theory, psychology, linguistics, and neurophysiology. It is now used in different fields, such as expert systems, knowledge base system, intelligent database system,

and intelligent robot system and it solves problems such as knowledge management and decision making, (Lu et al. 2012). However, Walker (2016) argues that despite the innovative advancement in the construction industry in terms of knowledge management and organization learning, the full potential of high-capacity computing power is not fully utilized. Walker's perspective is that intelligent machines are to be the new construction management means to be utilized along with knowledge management and organizational learning, promising the combination of human learning with intelligent machines to solve construction problems and improve performance.

The aim of this paper is to develop prediction models for cost variance, time variance and satisfaction of the contractor and the client. With the utilization of a literature review of the subject of cost and schedule performance in the construction industry and empirical results utilizing a machine learning-based prototype. The literature review covers the possible causes for cost and time overrun. Then, this knowledge is transformed to empirical survey factor selection and linear regression results.

The structure of the article commences with the framework of understanding, the literature review for project success and performance indicators and predicting performance, and then moves to the sections containing method, limitation, the experimental results, the discussion, the conclusions, recommendations for future research, and the contribution.

Framework of Understanding

This paper follows on the model presented by Josephson (2013), see (Figure 1). This productivity report undertakes the debate of measuring productivity and elaborates on that by measuring productivity in cost per square meter for different building types. The model visualizes the relationship between input and output. In Josephson's report (2013), and in Koch and Lundholm (2018), project input depends on project conditions, and then the production stage continues causing costs to finalize construction work. Productivity is the output and it is measured by SEK (Swedish Krona) per square meter of total gross area, and by hours per square meter of total gross area. The construction project is also dependent on the performance of project organization, which represents

the most significant stakeholders in the project. The framework presented by Josephson (2013) is used in this paper to categorize factors behind project success or failure in the body of literature that discuss the subject. According to Tangen (2005), productivity is part of the broader term of performance, the assessment of which is aimed at. Therefore, it is suggested to replace productivity by performance, and then use this as an output. Time, cost, and satisfaction are the three performance measures.

Figure 1: Productivity measurement basic model.
Presented by Josephson (2013)

Literature review

Project success and performance indicators

Projects success can have more than one definition for different stakeholders, (Ogunlana and Toor, 2009; Chan and Chan, 2004). According to Frödel et al. (2008), success is when project-planned goals are met, and projects accomplished are on budgeted cost and schedule, as well as keeping high quality and technical performance. Sanvido et al. (1992) refer to project success as when the expectations for all parties (e.g. client, contractor, engineer or end user) are met or exceeded. De Wit (1988), suggests that a distinction should be made between project success and success of project management effort. The term “project success” is when the project objectives are met, judged from the perspective of all possible stakeholders, whereas project management effort is usually measured using cost, time and quality.

Most popular KPIs are cost, time, and quality, commonly known as the “iron triangle”, (Ogunlana and Toor, 2009; Chan and Chan, 2004). Client satisfaction, the number of defects and the accuracy of the predicted project outputs are also presented as possible KPIs (Ogunlana and Toor, 2009; Alias et al., 2014). According to Xiong et al. (2014), to facilitate good collaboration among the members of the project team, the satisfaction of the contractor is especially

important.

KPIs can be categorized into *subjective* and *objective* measures. *Objective* KPIs are, for example, time and speed of construction, rate of accidents, time variation, and cost variation. *Subjective* ones are quality, client and construction team satisfaction (Chan and Chan, 2004). Cox et al. (2003) categorize key performance indicators into *qualitative* and *quantitative*. The *quantitative* ones cover construction cost, units per man hour, cost per unit, on-time completion, and amount of rework. The *qualitative* ones are related, for instance, to safety, turnover, or workers motivation. The research effort and analysis presented in this paper considers evaluating the project in terms of satisfaction of clients and contractors, as well as the percentage of cost and time variance. The interpretation of cost and time over- and underrun is made based on Freeman’s and Beale’s (1992) description of the relationship between the sponsor (client) and the project manager and if the contract is based on fixed price. From the client’s perception, if the project is finished before the due date, it creates revenues, while it is considered a failure if the project exceeds the timeframe. Also, cost overrun will not affect the sponsor, but for the project manager, cost overrun is regarded as a loss, whereas cost underrun is a gain. Therefore, schedule and cost underruns are considered success criteria in construction projects.

General project conditions

As shown in Figure 1, general conditions consist of project attributes and external factors. Project attributes are characteristics specific for the project; size, material, type of building, prefabrication, structure type, and contract and procurement route (Josephson, 2013; Chan et al., 2004; Koch and Lundholm, 2018). According to findings by Josephson (2013) and Al-Momani (2000), site conditions also play a role in project performance; for instance, lack of space affects delivery of goods and adequate storage space on site, thus making production more complicated. Technical complexity is mentioned by Lam and Wong (2009), project performance in terms of cost, time, quality and safety is highly affected by construction buildability. Ground conditions are mentioned by Josephson (2013), as the location of the project indicates the type of ground work to be performed, such as blasting work or piling.

External factors that affect the results of a project are presented in the framework by Chan et al. (2004), which categories the external environment of a project to its social, physical, economic and political dimensions. Weather is also seen as an external factor causing delays in a project, Jha and Iyer (2006), and Al-Momani (2000). For Josephson (2013) and Koch and Lundholm (2018), the Swedish weather is one of the most frequently mentioned disturbance by surveyed specialists. Moreover, geographical location,

market conditions such as material price fluctuations, competition, and aggressive tendering, are seen to impact the production. For example, Jha and Iyer (2006) found that aggressive tendering and high competition can have a negative influence on the quality performance of the project.

Project organization attributes

Project organization in the model (see Figure 1) is represented by the clients, the contractors, the consultants, and the subcontractor. This organization contributions in the project has an impact on its outcome. By the distinction made by Chan et al. (2004) and Alias et al. (2014), human related factors are represented by knowledge, skills, relationships and commitment with the project organization. The conclusion made by Jha and Iyer (2006) is that human-related factors are very important to achieve good quality in a construction project.

Frödell et al. (2008), Chan et al. (2004), agree on that client decision-making is a factor behind project success. Josephson (2013), found that in the main contractor's view, clients lack the experience to give clear messages and to plan the projects, although they can indeed create a collaborating environment and make decisions. Odeh and Battaineh (2002), show in a survey that slow decision making by the client is a common cause to delays. Another aspect of the client role are changes made by the client to the design and scope of the project, which are found to be considerably prominent in causing cost and time overruns (Al-Momani 2000; Attalla and Hegazy 2003). The client is required to have the ability to collaborate, manage the relationships within the project organization, such as the construction management and the design team (Walker 1995). Findings made by Koch and Lundholm (2018) show that the type of client has an impact on the productivity of the construction project. The procurement criteria that the client priorities in the contractor offer are also presented by the authors; whether the client emphasis on low price, high quality, time limit or special competence.

The category of contractors, consultants and sub-contractors, is also perceived to have a contribution to the project's performance. A common reason for bad performance is the contractor's relevant experience for a project, which can cause both time and cost overruns (Odeh and Battaineh, 2002). Managerial skills are highly valued throughout the literature as being important for achieving cost and time goals, solve problems with scheduling, (Attalla and Hegazy, 2003), and inadequate planning (Sambasivan and Soon, 2007). The good planning aspect can be associated with good planning for the specific design and construction phases; the skills of the designer are important for the project performance (Alias et al., 2014). The design team's communication with the

construction management and client's representative teams is one of the most important factors (Walker, 1995). The support that the contractors get from their own organizations is also highlighted (Josephson, 2013; Koch and Lundholm, 2018). In Koch's and Lundholm's (2018) report, support such as providing enough workforce, the priority of the project, and the degree the site-manager's involvement in choosing subcontractors and suppliers, were presented.

It is also found in Jha's and Iyer's (2006) work, that the high competence of the project manager has a positive impact on the quality of a project. The ability to organize, give feedback, plan, communicate and coordinate the project, as well as motivating the staff, are key to success (Frödell et al., 2008; Chan et al., 200). On the construction site, management and supervision, (Sambasivan and Soon, 2007); contractor's productivity during construction (Odeh and Battaineh, 2002), and workforce competence, commitment and participation in the project (Frödell et al., 2008), are important factors for project success.

Sambasivan and Soon (2007) present that problems with subcontractors, supply of material and labor, are some of the most common causes behind delays. In the report made by Koch and Lundholm (2018), the results of the study show that, when asked, the site managers claim that the performance of the ventilation and piping subcontractors are not satisfying. Conversely, the subcontractors are not fully satisfied with the site managers either. In specific, it is the main contractors' time planning that the subcontractors are not satisfied with, according to Koch and Lundholm (2018).

Predicting project performance

As stated by previous authors, for instance Alias et al. (2014), and Chan et al. (2004), it is possible to predict the level of a project's performance if the relationships between such a performance and the factors influencing it are established. Lowe et al. (2006), Kim et al. (2004) and Attalla and Hegazy (2003), used regression and neural networks in attempts to predict project cost at early project stages. Cost has been the center of attention for authors who have built different models for prediction. In these efforts, the focus had been on facts like duration, building type, finishing grades, type of installation, floor area, total units, procurement type, building function and type of client, which were turned into input variables.

Chi et al. (2012), proposed a decision support framework using data mining strategies, and utilizing a case study consisting of 193 projects submitted from 2008 to 2010. The data used reflect the degree of utilized technology and cost performance in construction projects. Chi et al. (2012) used four different ranking algorithms for project work functions, and chose the highest-ranking attributes showcasing the highest capability for predicting cost

performance. Attributes are; planning and execution, estimating, process and architectural engineering and definition, project scoping, detailed engineering and specifications, supplier qualification, warehouse and laydown yard, quality assurance (QA)/quality control (QC) systems, subcontractor's management, and customer satisfaction.

Another approach in the literature utilizes the earned value management methodology and support vector machines in forecasting estimate at completion and budget at completion, (Cheng, 2012; Wauters and Vanhoucke, 2014). This type of forecasting is based on data collected from different stages of the project; such as the schedule performance index, the earned duration and the earned schedule. Both studies conclude that forecasting models using AI outperform traditional methods used in estimate at completion calculations. However, so far, such models do not provide deeper understanding for project performance.

Previous models fail to fulfil the appraisal of the impact of the management performance on project success. Studying the impact of project management on project success lacks mathematical evidence. Therefore, it is necessary to find the link between project management performance and project success (Mir and Pinnington, 2014) which this study effort is attempting to provide with the utilization of machine learning as a method to study the assumptions about construction projects success. Mir and Pinnington (2014) concluded that project management (PM) performance in terms of PM leadership, PM staff, and PM life cycle management processes, has great impact on project team. More significantly, PM KPIs were proven to have great correlation with project success. In this research effort, the collected literature knowledge is transformed to tangible relationships between the factors contributing to project performance and project success.

Method

The data in Koch and Lundholm (2018) was collected through telephone interviews supported by questionnaires. In this way, answers are based on the respondent's own perspective as is always the case with questionnaires (Koch and Lundholm, 2018). The buildings included in the survey are primarily premises and group-built houses. Premises are buildings (such as day care centers, schools, office buildings, administrative buildings, sports and recreation facilities, hospitals and long-term care, church buildings, and elderly homes), stores, industrial properties, and others. In addition, civil engineering construction projects within the survey include pipelines, roads / streets / squares, railways, bridges, landfills, port facilities, fencing, plank and water

pipelines.

In each project, the client's project manager and the site manager of the contractor were asked within October-November 2014 to answer questions. The questions covered aspects about the product, such as the relative processes, the organizational structure, costs, times, the way the work progressed, and the way the project teams performed (Josephson, 2013). The clients received 23 questions and the site managers 21, in the respective questionnaires. The surveys were sent to 1000 individuals, with the valid responses amounting to 580, indicating an overall valid response rate of 58%. The survey was answered by 324 contractor representatives, displaying a 72% response rate, and 256 clients with a 62% response rate. The data used in this analysis contain information regarding the project number, location, structure type, client type, type of the construction method, the area of the building, and the phone numbers of respondents. Also, questions regarding the performance of clients, consultants, main contractor and subcontractors, are included. The datasets are also separated into two categories: the pre-construction phase consisting of the project program, pre-design phase, design phase, procurement and contracting of main contractor, and the construction phase covering external factors, construction site aspects, and the performance of the main contractor and the consultants.

In this study the same framework of understanding used by Josephson's report (2013), and in Koch and Lundholm (2018), was utilized, but productivity was replaced with cost variance and time variance as outputs. If cost variance and time variance are reduced, this implies savings in both cost and schedule. In other words, fewer costs and less time taken to complete the project, translate into fewer Swedish kronor (SEK) and fewer working hours per square meter.

Limitations

The limitations in this study are mainly due to the survey was pre-designed by others, and the data was not gathered by the authors of this research effort. It is possible that there were entry mistakes and missing values in cases that were not known or answered by the respondents. Such mistakes were tackled by checking and understanding the context and the ranges of the available gathered data and deleting incomplete answers. Moreover, the questions asked in the survey focus on cost and time, as well as performance of project teams.

Extreme projects that show high cost overrun or extreme savings are minority in the data. This implies that they are harder to have their outcome predicted. If that is the typical distribution of the data, then increasing the data size will actually not result in improvements in the prediction in future developed models. Such projects should be individually studied

further. There is also a possibility that there are factors that we are not aware of, which caused unlikely result for a project.

Experiment and results

The experiment includes the utilization of feature selection, linear regression, n-fold cross-validation, and Quantile-Quantile plot analysis. The tool that used in this study is Weka (Waikato Environment for Knowledge Analysis), which is a data mining and machine learning software, (Frank et al, 2016). The software contains a variety of methods for common data mining problems such as regression, classification, clustering, and attribute selection. Weka provides tools for data processing, feeding data into learning schemes and analysing the results, without writing any code.

Understanding the data is trying to know what it features contains, range of attributes, what the values represent, investigate output variables and detect outliers, (Han et al., 2011). Clearing the data off of noisy instances such as features that lack more than 20% of its values and projects lacking to be answered. The main contractor dataset consists of 17 input variables and 2 dummy variables in the pre-construction phase. The construction phase dataset consists of 25 input variables. And, the client data set consist of 58 input variables (of which 21 dummy variables) related to pre-construction and 11 input variables related to construction phase. The features selected with the CfsSubsetEval “correlation-based feature selection” method. It is a method to reduce the number of input variables used to build a prediction model, and to find the attributes with the most distinctive predictive capability in relation to the output, (Witten et al., 2011). The output variables used in this study are project cost-variance, time-variance and satisfaction of clients and contractors. Literature reviews about KPIs, for instance by Chan and Chan (2004), cost- and time variance as well as participants’ satisfaction, are important measures for project performance and still represent the most popular in the industry. Therefore, these three performance indicators are suitable as performance measures in this report. Also, in the data set used in this report, cost- and time variance and satisfaction of the client and the contractor are the only variables that can be identified as relevant ‘‘outputs’’, and it was decided to follow on the data availability.

The regression analysis is made using the selected features and resulted in 10 models. The models are validated with n-fold cross-validation for n=10 folds of the data sets. The 10-fold cross-validation is, by a large number of experiments, agreed to be the most appropriate for a good error estimate, according to Witten et al. (2011). The final error estimate is the average of the 10 error estimates (Witten et al., 2011). The error estimate used in this analysis is the root mean

square error (standard deviation of residuals), which is defined as the root of the square value of the difference between the predicted value and the actual value, (Witten et al., 2011). If the standard deviation is low, then the data observations are closer to the ground truth value.

The regression results are presented in Table 1. The RMSE results show that the best prediction model is the cost variance of the construction phase with an error of 9.8%. On the other hand, time variance and satisfaction are harder to predict with error rates up to 16.0% for pre-construction time variance and 16.6% for predicting satisfaction of the contractor based on pre-construction data.

Table 1: Testing the adequacy for prediction model

	Prediction model	RMSE
Pre-construction	Contractor - cost variance	10.1%
	Contractor - time variance	16.0%
	Contractor - satisfaction	16.6%
	Client - cost variance	12.8%
	Client - satisfaction	13.5%
Construction	Contractor - cost variance	9.8%
	Contractor - time variance	15.3%
	Contractor - satisfaction	15.1%
	Client -cost variance	13.1%
	Client - satisfaction	12.5%

The plot to plot analysis shows that the data is normally distributed, which is a good indicator since the error is centred around 0 standard deviation. However, there also appear heavy tails in the error distribution (large error). Such projects were not explained by the input; for example, a project might have good indicators such as good collaboration and high quality, but still be overbudgeted or have low satisfaction and vice versa.

Discussion

General project conditions

Since the attributes presented in each model, (see Table 2) are those with the highest correlation with the output (cost variance, time variance, satisfaction), the observation is that general project conditions do not have a correlation with the satisfaction of the client or the contractor. On the other hand, cost variance in the client survey is influenced by project attributes such as “main procurement criteria - reference project”, “Main procurement criteria - environmental aspects” and “Type of contract = trades contract”. Cost variance in the contractor statistical analysis is influenced by “Contract type = traditional contract”. Naoum and Egbu (2016), argue that the design process in traditional contracts is more influenced by the designer, hence the contractor’s task is to do the

construction without being involved in the design. The fragmentation between the design and the building process cause rework and changes and produce higher costs for the projects.

It is important to investigate the underlying reason for criteria such as the “earlier collaboration with the contractor” or the “specific competence of the contractor” do not show any significant impact on project cost underrun. It could be explained by that the contractor with specific competence will not be identified in the correlation-based feature selection if such a contractor is more expensive. According to Alzahrani and Emsley (2013), contractors with relevant experience from previous projects can have positive impact on the success of a project.

This effort analysis finds that “environmental aspects” as a procurement criterion, have a positive impact on the project cost variance. Naoum and Egbu (2016), show that the emphasis on procuring a contractor according to environmental criteria can increase project performance because the environmental requirements call for more collaboration which lead to an overall performance gain. It is even argued that design- and build contracts are better organizational environments to achieve sustainability requirements.

Moreover, cost variance in the contractor statistical analysis is influenced by, “Gross area” and” project technically challenging and advanced”. Time variance

is influenced by the “Percentage of prefabrication”, “extensive blasting works” and “project technically challenging and advanced”. It is observed that a technically challenging and advanced project induce time- and cost overrun. As stated by Lam and Wong (2009), construction buildability is highly affecting project performance (time, cost, quality and safety). Table 2 shows that the amount of prefabrication influences time variance but not cost variance. It is therefore reasonable to believe that prefabricated constructions save time but does not lead to lower costs due to being more expensive when compared to situ-built structures, (Josephson, 2013).

The client survey shows that “Design phase - absence of disturbances” is important factor to the cost variance, it has a decreasing effect. “Absence of disturbances” is also shown to be correlated to the decrease of the construction phase cost variance and the increase the satisfaction of the client and contractor. Weather conditions and ground conditions appearing to be some of the most important factors behind project performance according to Swedish studies as well as international studies, (Kock and Lundholm, 2018). However, these factors are not distinguished in the statistical analysis of this study effort. The reason is that the output (cost-, time variance or satisfaction) is not changing accordingly with the complication of groundwork or bad weather.

Table 2: Selected features (input variables)

Pre-construction phase	Construction phase
<p>Cost variance – Client data set</p> <p><i>x1: Main procurement criteria - reference project</i></p> <p><i>x2: Main procurement criteria - environmental aspects</i></p> <p><i>x3: Pre-design phase - investigation of plot</i></p> <p><i>x4: Design phase - absence of disturbances and problems</i></p> <p><i>x5: Design phase - follow time plan weekly</i></p> <p><i>x6: Design phase - performance of architect</i></p> <p><i>x7: Type of contract - trades contract</i></p> <p>Satisfaction – Client data set</p> <p><i>x1: Project program - follow time plan weekly</i></p> <p><i>x2: Project program - good result</i></p> <p><i>x3: Pre-design phase - conducting risk analysis</i></p> <p><i>x4: Pre-design phase - well thought-through description of goals</i></p> <p><i>x5: Pre-design phase - analysis of suitable type of contract</i></p> <p><i>x6: Design phase - good collaboration within project team</i></p> <p><i>x7: Design phase - good results</i></p> <p><i>x8: Design phase - performance of ventilation consultant</i></p> <p><i>x9: Design phase - performance of architect</i></p> <p>Cost variance – Contractor data set</p> <p><i>x1: Client - planning the project well</i></p> <p><i>x2: Client - good decision-making</i></p> <p><i>x3: Contract type - traditional contract</i></p> <p><i>x4: Own company - production people involved in choosing</i></p>	<p>Cost variance – client dataset</p> <p><i>x1: Construction phase - good collaboration within the project team at site</i></p> <p><i>x2: Construction phase - absence of disturbances and problems</i></p> <p><i>x3: Construction phase - good results</i></p> <p><i>x4: Main contractor - good cooperation</i></p> <p>Satisfaction – Client data set</p> <p><i>x1: Construction phase - good collaboration within project team at site</i></p> <p><i>x2: Construction phase - absence of disturbances and problems</i></p> <p><i>x3: Construction phase - good results</i></p> <p><i>x4: Main contractor - innovative production method</i></p> <p>Cost variance – Contractor data set</p> <p><i>x1: Client - giving clear message on time</i></p> <p><i>x2: Construction phase - good collaboration within project team at site</i></p> <p><i>x3: Construction phase - absence of disturbances and problems</i></p> <p><i>x4: Construction phase - follow time plan weekly</i></p> <p><i>x5: Quality of documents - piping consultant</i></p> <p>Time variance – Contractor survey</p>

<i>subcontractors and suppliers</i> <i>x5: Subcontractors - office workers duration</i> <i>x6: Gross area</i> <i>x7: Project technically challenging and advanced</i> <i>x8: Limited time to prepare production</i> Time variance – Contractor data set <i>x1: Client - planning the project well</i> <i>x2: Client - encouraging innovation</i> <i>x3: Project technically challenging and advanced</i> <i>x4: Percentage of prefabrication</i> <i>x5: Own crew - craftsmen duration</i> Satisfaction – Contractor data set <i>x1: Client - planning the project well</i> <i>x2: Client - encouraging innovation</i> <i>x3: Client - good decision-making</i> <i>x4: Client - clearly presenting goals of the project</i> <i>x5: Own company - production people involved in choosing subcontractors and suppliers</i> <i>x6: Own company - support of administrative work</i> <i>x7: Subcontractors - office workers duration</i>	<i>x1: Quality of documents - architect</i> <i>x2: Ventilation subcontractor - innovative production methods</i> <i>x3: Construction phase - extensive blasting work</i> <i>x4: Construction phase - absence of disturbances and problems</i> <i>x5: Construction phase - follow time plan weekly</i> Satisfaction – Contractor survey <i>x1: Client - good cooperation in project</i> <i>x2: Ventilation subcontractor - work to minimize disturbances and problems</i> <i>x3: Ventilation subcontractor - result according to expectations</i> <i>x4: Construction phase - good collaboration within project team at site</i> <i>x5: Construction phase - absence of disturbances and problems</i> <i>x6: Construction phase - follow time plan weekly</i>
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Project organization attributes

By examining the results in Table 2, it is observed that “client planned the project well” has a decreasing influence on cost variance and time variance as well as increasing influence on contractor’s satisfaction. Moreover, “client showing good decision making”, “encouraging innovation” and “clearly presenting the goals of the project” are all contribute to project success in the pre-production phase. Construction phase is affected most by “client achieved good cooperation in project” and “giving clear message on time”. These findings align with Walker (1995) and Chan et al. (2004) as they argue that the client’s ability to collaborate with the design- and construction and contribution are factors behind project success. Boyd and Chinyio (2008) explain the complexity in understanding the client requirements as the building exceeds being only technical structure.

The variable “pre-design phase - investigation of plot” has decreasing effect on cost variance if well performed. The client’s ability to contribute to and manage the design stage is highlighted in the theory, (Chan et al.,2004). The performance in the design phase is represented several times by different variables. “Design phase - compliance with time plan”, “Design phase - good collaboration within project team” and “Design phase - good result”. This is in compliance with the findings made by Koch and Lundholm (2018), which show that problems with the design are sources behind disturbances in construction projects.

The result of the statistical analysis of the client survey show “Project program - compliance with time plan”, “project program - good result” have correlation with

the client satisfaction and will increase the client satisfaction if fulfilled.

Poor site management is one of the most common factors behind unsatisfactory performance in construction projects (Jha and Iyer, 2006; Sambasivan and Soon, 2007; Odeh and Battaineh, 2002). This is compatible with the results found in the statistical analysis in terms of good production on site and good collaboration on site aspects. It is also observed that the factor “compliance with time plan” increases satisfaction as well as it lowers cost and time. Satisfaction of a contractor is affected by “own company production people involved in choosing subcontractors and suppliers” and “own company support administrative work”. It is generally known that site managers have a large load of administrative work that consumes time. When the company provides support for administrative work, site managers seem to work more effectively. Chan et al. (2004) suggest that one of the factors behind project success is the support and provision of resources that the project team leaders get from the own organization. This argument is aligned to the findings when the duration of contractors’ own craftsmen is higher, the time variance is lower. The last aspect to be discussed about the contractor factors is “own company production people involved in choosing subcontractors and suppliers”. This aspect has a positive influence on the site managers’ satisfaction, as well as it can increase cost variance. Hartmann et al. (2009) finds that contractors tend to value the lowest price when choosing subcontractors and suppliers regardless of their previous trusted relationships. One explanation for the finding is that involvement of production team might

bring trust criteria back to decision making and value it over price.

It can be argued that the architect is one important actor in the project brief and the design phase. The regression analysis of the client survey, shows that a well performing architect in the design phase, contribute to lower cost variance as well to higher client satisfaction. Also, the results of the contractor survey show that the quality of the architect's documents lower time variance. But it must be noted that it might be not the skills what hinders the architect's performance. Boyd and Chinyio (2008), state that the design flaws are the result of hard competition caused by clients' focus on lower cost and therefore the architect provide incomplete drawings to keep the cost down. It is found in Table 2 that the performance of the ventilation consultant in the design phase is important for the client satisfaction. And the piping consultant documents is one of the influential factors behind lower cost variance. Thereafter, the consultant's performance is reflected in the quality of drawings, which can also be a source of disturbances at the construction site. In Table 2, the results show that the performance of the ventilation subcontractor is influential to contractor satisfaction. Ventilation subcontractor worked to minimize interruptions and result was as expected are such factors that are highly correlated with contractor satisfaction. Ventilation subcontractor using innovative production methods is one factor that is correlated to construction time variance.

Predicting project performance

The purpose of the prediction models developed with machine learning is to improve performance by increasing predictability of important KPIs. But, it is difficult to know exactly how the models can be deployed in the industry, especially if it is used as a consultancy tool for decision making. Also, if undesired project outcome is predicted and corrective actions are taken, the project outcome has the possibility to improve and therefore it will be hard to assess the predictability of the models. One way is to test the model on unseen data and use the data for new training. Cross validation is a valid method to develop the most generalized model (Witten et al., 2011). The lowest prediction error is the one associated with predicting contractor cost variance of construction (9.8%). It has been shown that predicting satisfaction is the hardest; RMSE 16.6%. Satisfaction is subjective, and each person have different criteria for being satisfied about a project. (Chan and Chan, 2004).

The outputs of the analysis, cost variance and time variance have high variation. For example, time variance ranges from +100% to -55.55%, This makes instances highly deviating from the average and thus

standard deviation (error) will be higher. As a result, the prediction is approximate and not absolute.

Finally, challenges in inference. Just because time or cost variance is smaller for some projects, it does not automatically mean that they perform better or have higher productivity than other projects. A low variance sometimes tells a project's ability to meet the planned cost and time or the result of inaccurate estimations of the project cost in the early phases. Some projects have low cost variance by nature such as design and build contracts. It can be that the cost in these projects, by nature, are more easily predicted. However, it does not mean that these projects perform better. However, it is generally believed that construction contractors do not particularly want to give unnecessary high price offers, since it is often competition during tendering. Therefore, low cost variance does not equal good project performance unless the original tender was low.

Conclusion

In conclusion, a statistical evidence for what factors that are important to consider is provided. The identification of the most correlating factors can be used to build prediction models. It is proved that, the obtained models in this report can provide predictions when testing the formulas on the originate dataset. It can be learned that machine learning concepts are suitable method for understanding project performance.

This paper has identified the most influential factors behind project performance in Swedish construction projects. External factors, such as weather conditions, are broadly mentioned in the theory as causes behind bad performance and project failures. In this paper, this type of factor is not found to be highly correlated with project performance. The technical aspects of a building are found to be of importance and highly suitable for predictions. It can be concluded that prefabrication saves time, but not necessarily cost. Extensive blasting work is one factor that is shown to be correlated to time overrun. Projects, in which contractor feel that the client has not planned the project well and that the time for preparing production is limited, are most likely to show unsatisfactory results.

Although external factors and technical aspects of a building are important for project success, the most recurring factors behind project performance can be derived to human related factors. It can be concluded that construction projects tend to be more expensive when traditional contracts are used and there are presumably many reasons behind this finding. The work behind this. A contract or criteria that facilitates collaboration and communication between parties will

per se contributes to fulfilling or solving several of the other factors behind project performance. Added to this, a common goal the parties can strive for, such as environmental requirements, makes performance likely to be satisfactory for the involved project team.

Factors that are recurrent in the statistical result of the contractor's survey are client's ability to plan the project, make decisions and communicate as well as to encourage innovation. It can be concluded that the client is a very important actor for project success, not least in the early stages of a project where the client should be clear about the project scope and to select a suitable type of contract for carrying out the project. Disturbances in the construction phase are often caused by design flaws. Architects and consultants are often blamed for this. However, it is the client's role to address what is wanted and to pay for the design.

Recommendations for future research

It is suggested to conduct research that focus on one particular aspect beside the more general studies. Because it was found that it is challenging to establish a full understanding of the single practice or interaction attribute unless it is fully defined or put into detailed lens of objective measures. Especially "collaboration", "client decision making" and "satisfaction". Moreover, approaches of machine learning in this research are helpful for quantifying soft aspects and making them more measurable. Focusing on one process such as design, project brief, site management, are subject for machine learning model's development. It is also possible to focus on a certain type of contract to study its features.

Contribution

The contribution to the construction research and practice is the illustration of machine learning as a method to study project performance. The causes of delays and cost overruns continue to be of interest in the construction industry when aiming to optimize and increase efficiency. The factors behind success or failure are elaborated in the literature can be more comprehensively understood with feature selection methods and while being used in prediction using machine learning methods (such as linear regression, in the case of the current paper). Contractor satisfaction is a new addition to the literature as it is not a traditional performance indicator and it has been used as an output for projects in this effort.

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PLANNING AND SCHEDULING BRIDGE GIRDERS FABRICATION THROUGH SHOP-FLOOR OPERATIONS SIMULATION

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Abstract

In modular and offsite construction, structural components are prefabricated in a fabrication shop resembling a manufacturing plant in order to accelerate field construction processes. However, the dynamic nature of such fabrication operations often demands frequent adjustments to original production plans so as to fit actual project start-finish schedules in terms of completion dates and budgets and accommodate changes in design details. It is a daunting task to minimize disruptions to ongoing workflows while realizing high efficiency in utilization of shop production resources. In reality, such situations constantly press production managers to take prompt decisions without having analytical decision support in exploring available options, potentially resulting in loss of productivity on the shop floor and missed deadlines. This research introduces a structured approach to communicating shop-floor operations simulation at various management levels. The paper focuses on the representation of project schedules and production plans resulting from simulation in straightforward, role-specific “bar charts”. The applicability of the proposed approach is demonstrated with a case in the setting of a steel girder fabrication shop.

Introduction

Advances in engineering technology and requirements for sustainable development are main drivers for changes and innovations in the current construction industry. The paradigm shift to modular and offsite construction is moving conventional field construction efforts into the controlled environment of an offsite manufacturing facility (Pasquire et al., 2002). This lends a significant advantage to execution of fast-paced construction projects, making construction schedules better organized, shorter, and less susceptible to environmental factors, while substantially reducing the number of skilled craft workers on site and improving quality and safety performances (Lu and Liska, 2008). Despite all the advantages of offsite construction, planning and

scheduling operations at offsite production facilities still present distinctive challenges due to one-of-a-kind product design, concurrent execution of multiple projects, and finite limits of skilled trades and space available in a fabrication shop (Liu and Lu, 2018). Herein, shop production planning is similar to planning a conventional project in the field, which entails establishing the workflow logic between all the jobs and allocate sufficient resources to complete planned jobs within limited budgets and finite timeframes (Halpin and Riggs, 1992). In fact, planning made-to-order operations in a typical fabrication shop is no lesser a challenge than planning construction operations in the field, subject to varied product designs from different projects, limited skilled laborers, finite space resources and client-imposed deadlines. Thus, a well-formulated production plan for a structural steel fabrication shop is vital to deliver bespoke structural components on site by respective deadlines while keeping production costs within budget limits (Song and AbouRizk, 2006). The general process of such planning process is illustrated in Figure 1.

This research highlights a unique planning problem in bridge steel girder fabrication to illuminate the reasons why the identified problem does not lend it well to existing solutions for construction planning. Main characteristics of the offsite fabrication problem are summarized as follows:

- A lot of variations: This shop floor problem features variations in product design specifications and fabrication processes; a product goes through a unique process. The basic lean principle of reducing variation (i.e. *six sigma*) is not applicable (Dedhia, 2005; Nakhai and Neves, 2009).
- Product sequencing is key: The problem is tightly constrained by resource use (labor intensive), space, and material handling systems - similar to established problems in construction planning. Nonetheless, product sequencing plays a crucial part in shop production planning,

Figure 1 Planning process of any typical offsite steel bridge girder fabrication shop

dictated by construction technology (splicing) and site demand (delivery timing.)

- Site client demands lean: The site demand can be a hard constraint (just in time delivery is demanded as there is no buffer space on site; late delivery penalty would be imposed due to idling field crews and project completion delay; early delivery penalty would incur due to laydown yard cost and extra material handling cost).
- Shop processing demands lean: The inventory cost and extra material handling cost in the shop are significantly high due to size of product and space limit. So, once production starts, the sequence of products is not flexible to change.
- Avoid idling expensive resources: The trades and assets in the shop are limited resources, expensive; hence, it is critical to have workface plan formulated beforehand, which effectively guides allocating work to trades/stations while ensuring utilization of resources as fully as practically possible.
- No cost-effective analytical tool: It is crucial to have a simulation model to assist project managers in evaluating the impact of site demand changes, the impact of resources/space provisions.

In this paper a simulation-based approach is presented for project scheduling and production planning at a structural steel fabrication shop, considering major constraints typically imposed on a fabrication facility, which simultaneously serves field construction needs from multiple projects. Particular

emphasis is placed on representing and interpreting simulated production plans in customized schedules of various details in an attempt to cater for the needs of different stakeholders involved at various management levels. The applicability of the proposed approach is demonstrated with a case in the real-world setting of a steel girder fabrication shop.

Problem Statement

Importance of Planning

Planning is the key to keep workforce engaged in a productive production process (AbouRizk and AbouRizk, 2009). Project planning includes work package breakdown, definition, organization and allocation down at the construction site or shop floor level. Project Management Institute (PMI) defines *work package* (WP) as the lowest level Work Break Structure (WBS) used to group the activities, where work is scheduled and estimated, monitored, and controlled (PMI, 2017). Construction Owners Association of Alberta (COAA, 2013) promotes “Workface Planning” as the best practice for the success of any construction project, which is “*the process of organizing and delivering all elements necessary, before work starts, to enable craft persons to perform quality work in a safe, effective and efficient manner*”.

To ensure a worker’s uninterrupted process, it is always crucial to ensure that required raw materials, detailed fabrication design, and equipment or tools are available on site, at the right time. At the same

time, to deliver the highest productivity, a worker must be informed before starting the work on how to structure the day, which milestone to reach, plus an order of time events to accomplish those milestones (Hendricson, 2008). Therefore, a good plan is not just limited to making all tasks organized but also depends on effective communication of defined scope and content (Warner, 1989).

A good work plan can only be effective if it is expressed in the form of a well-organized schedule addressing specific needs relevant to particular stakeholders. Then, the individual worker's job schedule needs to be linked with project resource allocation schedule, resulting in a flawless work plan (Ahuja et al., 1984). At the same time, the work plan needs to be role-specific, contain no redundant information and straightforward to the worker or manager to act on. If any change emerges at any stages of the project lifecycle, that change should be well reflected in every level of schedule in both ways of the plan structure: *bottom up* and *top down*. The ensuing sections will illustrate good practices in (1) project planning and scheduling and (2) work planning and communication using a girder fabrication shop which services multiple bridge construction projects. As an example, Table 1 below summarizes requirements for different levels of plans and schedules for maintaining operation flow, execution motoring and project control in bridge girder fabrication.

Table 1 Project schedule required for different management functions.

Role	Plan Required	Responsibility
Program Manager	Project Schedule	All projects owned by the company
Facility/Shop Manager	Production Schedule	All projects under one facility
Shop Superintendent	Work plan	Work plans for individual trades and workstations in the shop
Trade	To do list	Work on different work packages

Challenges in Bridge Girder Fabrication Planning

Bridge girder fabrication processes are as tightly constrained as field erection of structural steel with regards to resource use, space, and safety. Each girder piece has a similar appearance but is indeed one-of-a-kind structural element with special features (such as shop splice, field splice, stiffeners, studs, number of drill holes, weld thickness, etc.) These features play a vital part in dictating the specification of work packages and processing sequences for each

girder to go through workstations on the shop floor.

During the pre-bidding stage, the upper-level program schedule (timeline for different projects to be handled by the shop) is established first by estimating work content of jobs associated with each unique product (girder). The production efforts (in labor-hours) associated with processing, handling and assembling the individual component are calculated. This labor-hours estimate based on detailed material takeoff is further assessed against the existing shop production capacity prior to determining final budgeted labor-hours and project duration. The current practice relies on the use of critical path scheduling to establish activity predecessor relationships and adapt all the constraints in planning the fabrication program. Furthermore, this program schedule can be adjusted considering the client's deadline and shop resource (journeyman, workstations, machinery, etc.) constraints in identifying the time windows for the fabrication shop to handle particular jobs (Liu and Lu, 2018). Afterward, this schedule is passed on to the shop operation planner/manager with start and finish milestones specified for major work packages, subject to which, detailed activity by activity operation schedule is created and communicated to the shop floor operations personnel. In the beginning, with defined work content, the shop production planner is responsible for breaking down work packages into sufficient detail ready for execution in the shop (Hu and Mohamed, 2014). Therefore the shop production planner assigns resources on each activity in a project scheduling platform (e.g., Microsoft Project, P6) and defines activity predecessor relationship one by one.

Shop floor operations schedule consists of repetitive workflows to be performed on non-uniform work units (girders). The mainstream planning tool of Critical Path Method (CPM) represents activity breakdown and predecessor relationships in the form of Activity on Node (AON) diagram, which has proven to be cumbersome and ineffective, potentially resulting in an extra-large, overwhelmingly complex AON network model in representation of repetitive workflows performed on non-uniform work units (Hyari and El-Rayes, 2006). Again, performing such scheduling tasks can be tedious, usually takes time and largely depends on the planner's experience and expertise (Song and AbouRizk, 2006). The scheduler is also responsible for representing schedules in the interest of different stakeholders (e.g., Journeyman, shop floor manager, station manager). In reality, the scheduling process becomes a daunting task, updating obtained schedules in a short turn-around time would be practically infeasible when a need to change operation logic and resource constraints arise. In reality, it is not realistic to keep in halt the production until the CPM schedules are updated. There is not

sufficient time to update CPM schedules at different levels and probe “what-if” alternative scenarios in resequencing job production and generating an updated set of jobs (*to do list* for the trades).

To tackle the above-identified limitations, this research study proposes a simulation enabled job planning approach. The simulation model is established based upon the three-tiered methodology proposed by Lu et al. (2019). In the case study, the Simplified Discrete Event Simulation Approach (SDESA) is used (Lu, 2003) as a platform for dynamic and resource-constrained process mapping and simulation purpose.

Simulation-Based Planning and Scheduling

To adapt the process-interaction simulation paradigm to better cater to construction simulation needs and simplify construction operations modeling, Lu (2003) formalized the simplified discrete-event simulation approach (SDESA). It is an activity-based simulation method, which mimics the common practice of using CPM in construction planning but requires less modeling efforts inadequately representing complicated construction operations. It is important to note by SDESA the processing sequence of each activity/job is prioritized by first-in first-out rule. Thus, the start time of any activity is delayed until demanded resources are available and other logical conditions as specified are satisfied.

SDESA was enhanced further resulting in the development of a generic process mapping and simulation methodology for integrating site layout and operations planning in construction. Since its introduction, SDESA has been successfully implemented in many cases for planning and academic research purposes. For instance, it was used to model the process of erecting the prefabricated structural elements using cranes in the construction of the steel structure of a stadium (Lu, 2009) and to model the operations of installing the precast deck segments considering site constraints of limited site space and logistics on a precast viaduct construction project in the real world (Chan and Lu, 2008).

Process Flow of Steel Girder Fabrication

Steel plates of different dimensions and grades are transformed into steel girders as per engineering design in the constrained space of the fabrication shop. The fabrication operation mainly consists of the following main steps or work packages (WPs): (1) receiving plates, (2) flanges preparation, (3) web preparation and (4) stiffener preparation, (5) assembling girder by fitting and welding flanges to web, (6) stiffener fitting and welding, (7) studding, (8) field splicing, (9) sandblasting and finishing. The logical interdependencies among these WPs are shown in Figure 2 in the form of AON diagram.

Figure 2 Typical Steel girder fabrication process cycle

The simulation model developed in this study is based upon a similar strategy for the real-world abstraction of workflows of the fabrication shop (Hu and Mohamed, 2014). The top tier interface of the applied three-tier modeling architecture of the SDESA model allows the modeler (being production planner) to change job processing order and quantities of finite resources available to the shop, without the need of expertise in computer programming and simulation modeling.

This paper takes advantage of the developed model of the steel bridge girder fabrication shop, as changing model parameters and updating the simulation can be easily achieved given the flexibility offered at the top tier of the simulation model. Schedules in support of multiple management functions are generated from the simulation.

Various Management-Function Schedules

For steel bridge girder fabrication, the operation schedule for one particular girder consists of nine WPs (Figure 2); which can be elaborated into a total of eighty-nine fabrication activities processed in the shop floor simulation with over one hundred technology constrained precedence relationships plus even more implicit resource constrained precedence relationships. In practice, one project consists of multiple girder lines; and each girder line is made up of several girders. In addition, the shop floor needs to handle multiple bridge projects simultaneously in a limited timeframe. So, if the total number of bridge project one shop needs handle is, n and the total girder lines and associated girders in each line become, l_i and m_j respectively, then the total amount of activities (Na) one shop manager needs to account in planning is estimated by Eq. 1:

$$Na = (nl_i m_j) \times 89 \quad (1)$$

Hence, it is not practical to apply CPM (P6 or MS Project) to handle a great quantity of activities along with inter-activity relationships for shop-floor operations planning and scheduling.

Here, different stakeholders have different perspectives with respect to planning and schedule of this fabrication shop. The fabrication program manager is mainly interested in tracking the number of projects he or she is handling along with progress on each. The fabrication shop manager under the

program manager is concerned with sequencing and completion times on each girder line and progress on associated girders. The floor station superintendent needs to know which girder arrives at the station at what time and the welder (trade) needs to know when he needs to perform welding on which girders (to do list), at which stations. These multi-levels of schedule representation are further explained in ensuing paragraphs with an example case of shop splicing (WP8).

Shop splicing is one critical fabrication stage involving heavy equipment use and demanding sufficient shop floor space for safety. Hence, two adjacent girders in the same girder-line are placed together in the same way as they would be placed in the field in order to confirm the accuracy of connection details (Figure 3). Suppose the shop is handling just one girder line consisting of three girders: G1A, G1B, and G1C as shown in Figure 3. Here, G1A and G1C need to be spliced just once on one end, but G1B needs to be spliced twice on both ends. Thus, the production logic is presented in the

flow chart shown in Figure 4.

Now, assuming the shop can handle one splicing operation at a time, there should be two adjacent girders of the same girder line ready for splicing trial assembly need to be ready at the same time. So, girder G1A and G1B will be spliced together at first, and then in the second round, G1B and G1C will be spliced together. Note, each splicing job (WP8) includes nine unique activities to be performed by a crew of two journeymen (J1, J2 or J2, J3) on the individual girder. Here, the shop manager's interest is mainly to track the progress of individual girders. Whereas, the splicing station superintendent needs to track all the activities occurring on the splicing stations. These two schedules of different levels are generated from the simulation and presented in Figure 5. Besides, Figure 6 shows the trade-specific project schedule, which includes job start-finish times and the location and type of each job to be conducted by each journeyman. Ideally, such different plans for different management functions can be automatically produced from the simulation model.

Figure 3 Field splice of a typical Steel plate girder.

Figure 4 The middle tier of the workflow model: operation logic for field splice

Figure 5 Schedule for the shop production/fabrication manager.

Figure 6 Trade specific for splicing job.

Case Study

A case study was conducted on a steel bridge fabrication shop located near Edmonton, Alberta. The girder configuration is shown in Figure 7. The SDESA shop-floor workflow model –which corresponds with the middle tier in the proposed simulation modeling framework-, was developed according to the shop space configuration, resource use, and availability constraints. Simulation logic was then face validated by domain experts involved in the partner company. It is worth mentioning this study was the initial attempt to generate the project plan through the bottom-up approach (Activity Level: shop floor activity under individual work package < Work Package Level: work packages under each girder < Project Level: all the girders in a project < Program Level: all the projects under the same program). The model's logic was carefully validated through tracing computing details in simulation step by step. Thus, only constant values for activity times were used in scheduling which was provided by shop manager), instead of collecting sample data and defining statistical distributions.

The case study consisted of a total of 6 individual

girders making up three girder lines on one bridge. So, as according to Eq. 1, the shop manager is responsible to plan for five hundred thirty-four activities by tackling more than six hundred technological constraints. Plotting AON for such activities considering all resource and technological constraints in any existing CPM tool to produce project schedule is practically infeasible. SDESA in this case basically provides a cost-effective alternative to produce this enormous bar chart like schedule with one click effort.

Figure 7 Girder configuration for case study project

In this case study, all the girders were classified into four design types based on girder features (i.e., length, depth, stiffener quantity and locations, field splice type). The same simulation model was then

used to evaluate shop performances in various what-if scenarios for formulating shop production plan by changing the top tier console only. Attributes (1. length, 2. weight, 3. no of required field-splice) of each girder were assigned in the computer platform accordingly. This top tier console also allows arranging for the fabrication order of the girders in a visual way. In this case, both girders of the same girder line (GL) are fabricated as in the order of A – B. Processing order between different GL is changed as part of what-if analysis in order to find the most efficient plan. Simulation results were used to identify the optimum number of crews and the best fabrication order of the girder lines. Results from simulation experiments are given in Table 2, which would help the production manager to decide the number of crews and the production sequence.

For this case, if the production manager's objective is to minimize the total man-hours spent in this project, he or she can choose the production sequence GL1 – GL2 – GL3 with five journeymen engaged in the production process (ID 5 of Table 2). Whereas, if there is a deadline to meet, an alternative solution can be considered. Once the job processing sequence along with appropriate resource allocation is determined, project managers simply extract all the necessary plans from the simulation result in the form

of customized schedules for various management functions. A screenshot directly taken from SDESA showing start to finish for all the activities in the simulation is shown in Figure 8. It is worth mentioning the bar chart schedule in itself can be overwhelming for effective communication even if the demonstration case is simplified. Considering a realistic setting for the fabrication shop investigated, in which the number of projects (identical) is three (3), the number of girder lines in each individual project is ten (10), and the number of girders in each line is five (5), the total number of activities to be scheduled in the simulation is at least 13,350 based on Eq. (1). One major research contribution is to interpret the bar chart resulting from simulation to the need of different decision makers involved at various management level.

Figure 9 shows the program level schedule (start-finish time for individual girder for the case project) extracted from the simulation model. The work plan for a particular station in the shop can also be generated. Material receiving deadline for each girder is shown in Table 3 as an example. Besides, a *to-do-list* for a particular worker (trade) can also be generated. Table 4 presents the activity by activity work schedule for Journeyman ID 1.

Table 2 Experimentation results with fabrication shop model

ID	Job Sequence	Journeyman No.	Man hours	Utilization Rate	Project Duration
1	GL1 – GL2 – GL3	9	1578	59.06%	175 hr.
2	GL1 – GL2 – GL3	8	1450	62.24%	182 hr.
3	GL1 – GL5 – GL2	7	1425	65.36%	204 hr.
4	GL1 – GL2 – GL3	6	1363	68.32%	227 hr.
5	GL1 – GL2 – GL3	5	1339	68.22%	267 hr.
6	GL1 – GL2 – GL3	4	1365	68.24%	341 hr.
7	GL1 – GL3 – GL2	5	1344	69.14%	270 hr.

Table 3 Raw material delivery schedule (schedule for superintendent)

Collecting Raw Plates for Girder	Material Delivery Date (Job start date: Fri 01/11/19)
G1A	11 January 19
G1B	15 January 19
G2A	17 January 19
G2B	24 January 19
G3A	31 January 19
G3B	6 February 19

Figure 8 Activity by activity plan for the bridge girder fabrication project (screenshot from SDESA simulation platform)

Figure 9 Timeline for processing individual girder (Schedule for program manager).

Table 4 Task to do list (trade specific) for the first day (11 January 19) for journeyman ID 1.

ID	Task Name	Duration	Start Time	Finish Time
1	Unloading Plates	2 hrs	1/11/19 8:00 AM	1/11/19 10:00 AM
2	Move: Web Splicing	0.25 hrs	1/11/19 10:00 AM	1/11/19 10:15 AM
3	Web Edge Cutting: Camber	0.7 hrs	1/11/19 10:15 AM	1/11/19 10:57 AM
4	Preset Plates for Camber	0.47 hrs	1/11/19 10:57 AM	1/11/19 11:25 AM
5	Cut Flanges	2 hrs	1/11/19 11:25 AM	1/11/19 2:25 PM
6	Move to Flange Straightening Station	0.25 hrs	1/11/19 2:25 PM	1/11/19 2:40 PM
7	FPL-Straighten	1.4 hrs	1/11/19 2:40 PM	1/11/19 4:04 PM
8	Move back to Shop	0.25 hrs	1/11/19 4:04 PM	1/11/19 4:19 PM
9	Turn Web	1 hr	1/11/19 4:19 PM	1/14/19 8:19 AM

Conclusion

This paper introduces a simulation-based production planning approach for a structural steel fabrication shop, considering major constraints typically imposed on a fabrication facility simultaneously serving field construction needs from multiple projects. Particular emphasis is placed on representing and interpreting simulated production plans in customized schedules of various details in an attempt to cater for the needs of different stakeholders involved at various management levels. Taking advantage of the developed model of the steel bridge girder fabrication shop, schedules in support of multiple management functions are generated from the simulation. The applicability of the proposed approach is demonstrated with a case in the real-world setting of a steel girder fabrication shop.

Once the job processing sequence along with appropriate resource allocation is determined, project managers simply extract all the necessary plans from the simulation result in the form of customized schedules for various management functions. The Simplified Discrete Event Simulation Approach (SDESA) is used as a platform for dynamic and resource-constrained process mapping and simulation purpose. The shop-floor activity bar chart produced from SDESA simulation shows start to finish for all the activities. However, it is worth mentioning the bar chart schedule in itself is overwhelming for effective communication even if the demonstration case is simplified. One major research contribution is to interpret the bar chart resulting from simulation to the need of different decision makers involved at various

management level. As such, production plans based on the same simulation model are represented and communicated in straightforward, role-specific formats (such as "bar charts" or "to-do lists"), thus facilitating execution of different management functions by relevant stakeholders involved.

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PRECISE RECONSTRUCTION OF GEOMETRIC PRIMITIVES IN BUILT ENVIRONMENTS

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Abstract

Precise reconstruction of the built environment is very useful for the management of the construction site. As far as the reconstruction of large-scale built environments is concerned, the reconstruction effect still needs to be further improved. Considering that most of the structures are piece-wise planar/linear in the built environment, this paper proposes a method for reconstructing the geometric structure of the scene that display its appearance precisely. This method focuses on reconstructing objects with plane and edge structures, such as buildings, to achieve the reproduction of their geometry. The paper introduces a new dense reconstruction algorithm, the patch based stereo matching algorithm to refine a sparse point cloud to produce a dense point cloud. This method further merges three-dimensional (3D) line into the dense point cloud to optimize the geometric line of the model. The experiment demonstrates that the improved method has a flawless reconstruction effect on the geometric primitives of buildings.

Introduction

The technique of three-dimensional (3D) reconstruction has become an important tool and is being widely used to develop infrastructure and landscape models to better manage cities and assets. This technique can be used for a variety of purposes such as providing the spatial information needed to operate and maintain infrastructure (Kim et al., 2005), recognising structural components and monitoring their progress (Son et al., 2010), inspecting bridges (Lattanzi et al., 2014) and creating retrospective 'as-builts' of historic buildings (Yang et al., 2010; Arayici, 2007).

Currently, the precision of the reconstructed model based on the state-of-the-art technology has attained cm-level for the image-based modeling technique or mm-level laser scanning technology for simple scene or single object (Ma et al., 2018). Reconstructed scenes have been typically simple objects such as single-span bridge and a set of items on the desktop. For a large range of scenes with multiple building entities, the effect of model reconstruction needs to be improved. These models can well realize the visual maintenance and management of the construction site (Kim et al., 2005). In order to better reconstruct the built environment, a method for reconstructing its

important geometric structure is proposed. Most of the structures of the built environment are piece-wise planar/linear (Raposo et al., 2014). If the edge and surface reconstruction precision can be improved, this can better display important elements such as buildings and roads in the built environment, which will be very useful for the application of 3D models.

Therefore, this paper proposes an improved algorithm for generating a point cloud to achieve a fast and precise reconstruction of the 3D structure of the built environment. Specifically, an improved dense reconstruction method, the patch based stereo matching algorithm, is introduced to quickly process images (especially high-resolution images) to generate a precise point cloud (Shen, 2013). Further, for built environment, this paper incorporates a 3D line extraction algorithm for dense point clouds to optimize the geometric structures of the model (Hofer et al., 2015).

The paper commences with a review of point cloud reconstruction method (Section 2). Newly developed algorithms for reconstructing 3D structure are then presented (Section 3). The algorithms are then tested and discussed using experiments (Section 4). Finally, the contributions and implications for future research are identified (Section 5).

Reconstruction of point cloud

The image-based 3D reconstruction method is a relatively popular technique for reconstructing the built environment and involves two key steps: (1) Restoring the structure from the motion (SFM) (Wu, 2013); and (2) Multi-view Stereo (MVS) (Jensen et al., 2014). The SFM technology restores the camera motion parameters and scene structure using low-level features (point features) from multi-view images to reconstruct sparse 3D scenes. Common feature extraction algorithms include Scale-invariant Feature transform (SIFT) (Chang et al., 2008), Speeded Up Robust Features (SURF) (Bay et al., 2008), and Fast Retina Keypoint (FREAK) (Alahi et al., 2012).

The sparse point cloud that is composed of seed points in areas with rich textures can only reflect the discrete state of the scene and therefore it must be densely reconstructed to improve its integrity and precision. This has been typically undertaken using three MVS based methods identified in Table 1.

Table 1: The methods for dense reconstruction

Method	Specific algorithm	Characteristics
Voxel-based	Voxel coloring framework (Seitz et al., 1999) Space Carving (Kutulakos et al., 2000) Graph-cut optimization (Cipolla et al., 2005)	A series of regularly stacked cubes or polygon surfaces
Feature point growing-based	Region growing (Otto et al., 1989) PMVS (Furukawa et al., 2009)	To expand sparse seed points to weakly textured areas
Depth-map merging-based	Window-based (Goesele et al., 2006) Markov Random Field optimization (Campbell et al., 2008) DAISY feature matching (Tola et al., 2012)	To find a depth map of each image, and merge them

Voxel-Based Methods include Voxel coloring algorithm, Space Carving algorithm and son on. These methods need to provide a better initial volume, such as Visual hull, otherwise the optimization may converge to a local minimum. Voxel resolution affects the accuracy of reconstruction. However, increasing the resolution of voxels will cause the storage space to grow at lot, which consumes a lot of computing

resources. Nowadays, the most popular feature point growing-based methods is PMVS algorithm, which ranks in the forefront of dense reconstruction method in terms of model integrity and precision. However, for multi-planar scenes, images often exhibit a single, repeating texture so that the reconstructed model by PMVS algorithm will have many holes. The DAISY feature descriptor is an efficient tool for calculating depth maps in depth-map merging-based methods. It can quickly realize the reconstruction of high-resolution images. The depth-map merging-based methods is particularly suitable for the reconstruction of large scenes. The higher the resolution of the image is, the denser the reconstructed point cloud will be.

Although MVS-based reconstruction has been greatly developed, it still needs to be further improved. In the DTU standard database, a large number of clips, holes, etc. can be found in the point cloud of different scenes reconstructed by several popular algorithms (Furukawa et al., 2009; Tola et al., 2012).

Precise Reconstruction of 3D Structure

Akin with previous studies, pictures of the scene were collected from different angles to create a 3D model (Zheng et al., 2016). An SfM pipeline is performed to obtain the corresponding camera poses and a sparse point cloud. Based on the sparse point cloud, the patch based stereo matching algorithm is introduced to recover the details of the scene by generating additional points and eliminate noise. Then perform 3D line extraction from the sparse point cloud. Finally, the 3D line is merged with the dense point cloud to generate a complete point cloud of the scene for built environment. Figure 1 shows the generation process of the point cloud.

Figure 1: The improved point cloud generation process

For SfM pipeline, specifically, feature point extraction is performed using the SIFT algorithm. Then, match these feature points with its nearest k neighbours by using the k -d tree algorithm (Zhiliang et al., 2018). Then calculate the parameters of the camera for sparse reconstruction and finally adjust the camera's positional parameters to get a sparse point cloud.

Dense Reconstruction

After obtaining the internal and external parameters of the camera, the reconstructed data of the sparse 3D scene can be obtained, along with generating a sparse point cloud. The patch based stereo matching algorithm is introduced (Shen, 2013). This algorithm is based on the existence of a satisfactory spatial neighbourhood near the projection plane. Unlike the conventional method of obtaining decentralised, discrete depth maps (e.g., stereoscopic vision), a continuous depth map of a precision subpixel is reconstructed. The patch based stereo matching algorithm consists of four steps: stereo pair selection, depth-map computation, depth-map refinement, and depth-map merging. The patch based stereo matching algorithm spatial depth-map propagation algorithm could be easily parallelized at image level.

We first find its reference picture for each image. A good candidate reference image should have a similar viewing direction as the image, and have a suitable baseline. The baseline should not be too short, otherwise it will generate a lot of information redundancy. The baseline should not be too long to have less common coverage of the scene. After forming its image pair for each image, we calculate the depth map for the image, which is to calculate the depth for each pixel in the image.

Each pixel in the input image needs to find a good support plane which can minimize aggregated matching costs between the pixel of the image with the corresponding pixel in its reference image. The support plane is essentially a local tangent plane of the scene surface. A square window $n \times n$ centered on the pixel in the given image is used to calculate its support plane. The other pixels in the window on the image is projected onto the reference image R by homography. The photometric consistency of pixels between the image and its reference image can be compared by the Normalized Cross Correlation (NCC) (Yoo et al., 2009). We can find a patch plane with the lowest matching cost. Each pixel in the picture corresponds to a 3D plane. The initial 3D planes are then refined by slightly adjusting the parameters of the 3D planes, including its angle and position, to achieve a smaller matching cost. Finally, all depth maps are merged to obtain a dense point cloud.

Extraction of 3D Lines

The rich information features of line segments are often lost or unclear when models are re-built using point features. For example, straight line segments at the edges of a model are sometimes uneven and poorly represented (e.g. roof plane). Thus, the 3D line segments need to be extracted from the model.

In line with previous studies 3D lines are generated based on the 3D sparse model, containing a sparse set of 3D points $P = \{P_1, \dots, P_K\}$ and camera poses. A set of 2D line segments is found on each image, and each 2D line consists of two endpoints. Specifically, we use the line segmentation operator LSD to get the 2D line segment on each image (Gioi, 2012).

The 2D lines segments extracted in different images are matched to associate 2D line segments corresponding to the same 3D line on the object. We use epipolar matching constraints to establish a set of potential correspondences for each line segment individually (Hofer et al., 2014). To simplify the calculation of the match, we only match the 2D line segments on the image to the 2D line of its nearest neighbours. After these matches, we built a series of line segment correspondences.

For all matches of 2D line segments, we need to further rule out the wrong matches. We use a novel similarity measure based on positional- and angular reprojection errors between a 3D hypothesis and 2D segments. Specifically, for each line segment correspondence, find its corresponding 3D line. The 3D line is projected on other images to obtain projected line segments. The more similar the projected line is to the 2D line extracted on other images, the more likely the 3D line is to be seen by the image. If the 3D line can be seen on more images, the more reliable the 3D line is. Retain 2D line segment correspondences that form these reliable 3D lines. According to this rule, we can clarify whether the matching of a 2D line segment is credible.

A 2D line segment does not correspond to a 3D line hypothesis, but the 2D line on each image can only be a projection of a 3D structure. Therefore, we have to calculate the most likely 3D position for each 2D line. Based on the above calculations, we determine the position of each 2D line, which is the one that can be seen by most images and has the highest similarity among all the assumptions of the 3D line. We can select the most plausible correspondence for each 2D segment as its 3D position hypothesis. Finally, we perform clustering 2D segments based on their spatial proximity in 3D to obtain the final correspondence set and 3D model.

Fusion of 3D Lines and Point Cloud

After the 3D line is extracted, the reconstruction of the entire point cloud is achieved by fusing the 3D line with the dense point cloud. The method of fusion is to extract the points on the 3D line and draw a set of points. The number of points to be extracted needs to take into account the point density of the point cloud. The greater the density of dots, the more points are extracted from the 3D line.

Reconstructing the 3D point cloud after combining the 3D line reconstruction method and depth propagation algorithm significantly improves the quality of the model. On the one hand, 3D line reconstruction can show sharp straight-line features of some edges of the model. Dense reconstruction of point cloud by depth propagation algorithm, on the other hand, can often contain more modelling information that can correct inaccurate 3D lines.

The following steps are processing the point cloud, including the elimination of interference, surface mesh reconstruction and texture synthesis. The mesh reconstruction method initially performs a Delaunay triangulation on the dense point cloud (Fang et al., 1995). After constructing the Delaunay tetrahedron, the model surface is determined. Then use the plane-sweeping principle to remove hallucinated surfaces

that are often related to missing cameras. That leads to cleaning the space and the hallucinated surfaces are further generated from sparsely distributed false positive points. To enhance the visualization, texture synthesis arises when a picture of an object is projected back on to the corresponding surface of a model.

Experiments and Validation

The proposed method in this paper could reconstruct the built environment. In order to test the reconstruction effect of the method on the geometric primitives of a built environment model, a set of residential buildings was selected as the experimental scene. Then the box girder scene was reconstructed to quantitatively evaluate the effects of the proposed method.

Visual effect

This experiment qualitatively shows that the proposed method can reconstruct large and complex scenes. Figure 2 shows a model of a group of housing construction scene. The proposed method can faithfully reproduce the building and its surroundings. Whether it is a building, a road, a car, or a tree, they can maintain a good shape and texture in the model. Except for some trees, their structure is too irregular to be fully expressed.

(a) The entire model

(b) Small objects in the model, which are house, car, road & meadow, tree

Figure 2: 3D model of a group of housing construction scene

Quantitative Experiment

The proposed method is compared with some mature software packages or products, including Visual SFM + CMVS (Teeravech, 2013) and Autodesk Remake (the original 123d Catch) (<https://www.autodesk.com/products/remake/overview>) and Kinect and Laser scanning technology (Leica Scan Station P30 / P40) by a box girder scene. Figure 3 shows the models for all methods.

We can see the overall appearance of all models in Figure 3, and the models of the proposed method, Kinect and laser scanners are quite perfect. We further evaluate the quality of the point clouds using the following criteria: (1) point density (ρ); (2) average error (ϵ). The point density refers to the number of points in the unit cube. The density distribution of the points is counted by calculating the percentage of regions with the same number of point density. Average error refers to the difference between the point cloud generated by several methods and the

ground truth.

Figure 3: The reconstructed model

Laser scanning is currently a high-stability and high-accurate technology. The laser scanner selected in this experiment is FARO Focus3D X130 and its ranging error is ± 2 mm with a resolution of up to 70 million pixels. The point cloud generated by laser scanning are taken as a ground truth. The average error ε are defined as (1).

$$\varepsilon = \sqrt{\frac{\sum_{i=1}^n (\Delta x_i^2 + \Delta y_i^2 + \Delta z_i^2)}{n}} \quad (1)$$

Where n is the number of matching points. $\Delta x_i = x_i^* - x_i$, $\Delta y_i = y_i^* - y_i$, $\Delta z_i = z_i^* - z_i$ represents the spatial coordinates (x_i, y_i, z_i) of the laser point cloud minus the spatial coordinates (x_i^*, y_i^*, z_i^*) of the corresponding points in Visual SFM+CMVS/ Autodesk Remake/ Kinect and the proposed method.

Then the all point clouds are converted to the same coordinate system by registration alignment. The alignment results are shown in Figure 4. We calculate the point-to-point errors by comparing every other point cloud with the Laser point cloud.

Figures 4: The point cloud aligned to the laser scanning point cloud

Figure 5 shows the density distribution of their point cloud. Then we can calculate the average error, point density. Table 2 represents the average error, the point

density reconstruction time and model type for the four methods (Visual SFM+CMVS, Autodesk Remake, and the proposed method and Kinect).

Table 2: Average error (ε), Point density (ρ), Reconstruction time and Model type for four methods

Method	ε (cm)	ρ (pt/cm ³)	Time (min)	Model type
Visual SFM+CMVS	Match failed	Invalid	3.5	Point cloud
Autodesk Remake	Match failed	Invalid	6.3	Mesh
The proposed method	6.3931	1.1515	8.5	Mesh
Kinect	6.5592	6.5169	6.1	Point cloud

Figure 5: The point distribution of the point cloud for Kinect and the proposed method

As shown in Figure 4, the proposed method and the Kinect align well with the laser point cloud, while the others fail to do so. Except for this reason that there are not enough points for the point cloud generated by Visual SFM+CMVS, Autodesk Remake, many points in the point cloud are very different from the ground truth and have a big error.

In Figure 5, it can be seen that the point density of the point cloud generated by the proposed method is relatively sparse, concentrated at 1 pts/cm³. The number of points for point cloud generated by the Kinect is large and the density distribution of the points is quite different, and the point density varies from 1 pts/cm³ to 12 pts/cm³.

For these four models, the models generated by Autodesk Remake and the proposed method are mesh model. Generating mesh models (Autodesk Remake and the proposed method) takes longer than generating point cloud models (Visual SFM+CMVS and Kinect), because point clouds need to perform grid reconstruction and texture synthesis. Mesh model is usually able to meet more visualization purposes than the point cloud model. Of four methods, the proposed method shows the best precision.

In general, the proposed method outperforms the Visual SFM+CMVS, Autodesk Remake, and Kinect. The model generated by the proposed method has a small error and have a great visual effect.

Conclusions

Based on the existing image-based 3D reconstruction method, this paper improves the process of dense reconstruction, and focuses on improving the accuracy of geometric primitives (plane and line) reconstruction in built environments, which helps enlarge the applications of 3D reconstruction techniques in civil engineering. In the experiment, the approach presented in this paper is very good for achieving precise

reconstruction of planes and lines. Compared with several existing methods, the reconstruction performance of the proposed method is also very good.

Regarding future work, we plan to use more means to test the performance of the proposed method. In this paper, the quantitative experiment was not carried out using the built environment scene, but was replaced by a box girder scene composed of lines and planes, which may lead to the advantages of the proposed method not shown. In addition, the comparison methods selected in this experiment are several easy-to-obtain methods, and the comparison between the proposed methods and the more advanced methods needs further study. We also research further to improve the reconstruction performance of geometrically irregular objects.

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AUTOMATIC DETECTION OF PLAN SYMBOLS IN RAILWAY EQUIPMENT ENGINEERING USING A MACHINE LEARNING APPROACH

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Abstract

Exact data in the form of technical drawings and plans of built assets are a significant requirement for the successful operation and reconstruction of such assets. When the consistency between this data and the real world situation cannot be assured, the data is not reliable and needs to be updated by comparing plans and reality. Depending on the size and number of assets this may involve an enormous amount of manual effort. In the scope of this research, an approach for supporting and automating such a process by utilizing concepts developed in the field of machine learning was developed. This paper focuses on the interpretation of technical drawings in terms of detecting and classifying plan symbols as this is a time intensive and error prone process when done manually. It is described how the capabilities of Convolutional Neural Networks are employed in analyzing images to automatically detect important plan symbols in the field of Train Traffic Control and Supervision Systems and how those networks are trained without the need for a time consuming-manual labeling process.

Introduction

The railway network in Germany, which consists of more than 30.000 kilometers of railway, is mainly operated and managed by the DB Netz AG. As this integral part of German infrastructure has grown over the last century both tracks and railway equipment are of various technological levels. This is also the case for corresponding technical drawings and plans. However, management, operation and especially rebuilding and reconstruction of railway infrastructure rely heavily on the availability of such technical drawings which need to be exact and up to date. In a vast railway network of several thousand kilometers that has grown over decades, discrepancies between archived drawings and the actually built infrastructure are almost inevitable due to various circumstances. As the purely manual effort required for comparing and updating the stock data consisting of technical drawings and plans involves an enormous amount of manual effort, we devel-

oped an approach for supporting and automating parts of this process by utilizing concepts developed in the field of machine learning.

The research presented here is part of the RIMcomb research project (Railway Information Modeling: Equipment technology for rail infrastructures (Vilgertshofer et al. 2018)). Among the main goals of the research project is the digitization of the information on conventional 2D-drawings depicting railway equipment. While most drawings are available as digitally stored images by now, the interpretation of these plans and, most importantly, the various symbols they contain has to be undertaken manually to create a semantically rich digital railway representation.

Our approach aims at supporting this process in order to reduce the manual effort by automating at least parts of this image interpretation process. The first step towards this goal is the automatic recognition and highlighting of plan symbols on a given drawing and the subsequent storing of their count and location. To achieve this, we employed Convolutional Neural Networks (CNN) and developed a process in which to train these networks without the need for a time-consuming manual labeling process to generate training and testing data. The results can then be compared to the actual situation on the track in order to check for inconsistencies or confirm the accuracy of a plan. Naturally, this comparison process also requires the recognition of infrastructure elements on the track as a counterpart. In the scope of the RIMcomb research project, a second approach for automating this process has been developed and is summarized in the following section (Genc et al. 2018). The combination of those approaches is currently underway and will result in a semi-automated process of the otherwise highly labor intensive comparison of the as-planned and as-built situation of railway infrastructure.

This paper is structured as follows: In Section 2 we will discuss existing approaches to detect and classify symbols in technical drawings. We will further describe the technological background that our approach involves. Additionally, we will give an overview of a related development that focuses on the recognition of railway equipment in

images/videos and acts as a counterpart to our approach. Section 3 provides a detailed description of our methodical approach and the conducted research work, while Section 4 focuses on our implementation work and the general quality of our results. In Section 5 we show how we apply our approach on a set of real-world technical drawings to deliver a proof of concept. Finally, we will sum up our findings and describe how we will further develop our approach.

Related research and theoretical background

Symbol recognition in technical drawings is a well-known challenge in the engineering field. In technical drawings, symbols often appear to be strongly distorted or overlapped with other objects, making their recognition a significant challenge. Therefore, numerous solutions to this problem have already been proposed.

Luqman et al. (2009) describe a method which represents symbols by their graph-based signatures and a Bayesian network is trained to encode the common probability distribution of symbol signatures. The Bayesian network is trained in two phases – the structure learning phase and the parameter learning phase. Another approach is described by Weber & Tabbone (2012), where a template matching operator HMTAIO (Hit or Miss Transform Adapted to Information Overlapping) is used. The advantage of this approach is its robustness against occlusion and overlapping. Another interesting approach for symbol spotting is proposed by Rusiñol & Lladós (2005). The authors describe their approach as follows: “In this paper, we present a method to determine which symbols are probable to be found in technical drawings using vectorial signatures. These signatures are formulated in terms of geometric and structural constraints between segments, as parallelisms, straight angles, etc.” (Rusiñol & Lladós 2005). Different symbol recognition methods are also described by Le Bodic et al. (2012) and Nayef et al. (2012).

Although many approaches have been proposed, they could not deliver satisfactory results for detecting railway equipment symbols. In our approach, we train artificial neural networks to recognize symbols in engineering plans. This method shows promising results and can be used in various contexts. It is not only invariant of scale and rotation operations, but it also works for heavily distorted symbols. The approach recognizes many types of symbols, thus demonstrating its practical applicability.

Convolutional Neural Networks (CNNs)

Artificial neural networks are used for different tasks such as text, speech and image recognition, and even self-driving cars. Convolutional neural networks (CNNs) have

been used here, as they appear to be very useful for image recognition. One of the first CNNs developed is the LeNet (LeCun et al. 1998), and since its creation, there has been a tremendous improvement in the field of image recognition and object recognition in general.

CNNs use filters to detect patterns in an image. An image is searched for these patterns, and a value is saved, which represents how good each pattern matches the images at specific locations. In this way, an image can be inspected for features such as horizontal or vertical lines. Via combination, they can represent more complex shapes such as symbols. Figure 1 shows an example for two filters of a horizontal and a vertical line on the left side and how they are matched in the image on the right-hand side.

Figure 1: Searching for filters in an image

Each filter pixel is multiplied with the corresponding pixel from the image, and the resulting values are added up. Afterward, this value is divided by the pixel number of the filter. If the filter is found in the image with a 100% accuracy, the result for this location of the image is 1 (upper filter with the blue box in the image). On the other hand, if the filter has no common values with the current location in the image, the result is -1. The overall result is a map which represents where the different features occur in the image. A ReLU activation function can then be used to normalize the values in the feature map that was calculated, which improves the training process (Figure 2).

Figure 2: Max pooling

Images usually consist of thousands or even millions of pixels, which can make the training of a CNN computationally expensive, as bigger images result in a bigger feature map. Therefore, an operation is introduced that reduces the size of the feature map. We chose the so-called max pooling operation. It takes only the maximum value of a given window and saves it at the correct location in a new, smaller feature map (Figure 2). These techniques can be used multiple times in so-called layers, where each layer takes as input the output of the previous layer. The image gets more filtered for each convolution layer and smaller for each pooling layer (Stoitchkov 2018).

The extracted features are then fed into the neural network. A very simplified example neural network can be seen in Figure 3. By adjusting the weights (marked with a W in Figure 3) between the neurons, an output is calculated from a given input. In the training process, the neural

Figure 3: Neural network structure

network tries to minimize the difference between the output it has generated and the ground truth result which is targeted. In order to reach a good accuracy, meaning exact recognition, thousands of images are required. However, one of the biggest challenges of training a neural network is to prevent overfitting. Overfitting occurs when the training images are similar to one another, and the network is extremely optimized in recognizing these images but fails to recognize a new set of images. Instead of learning, the model then starts to memorize the training data.

Recognition of infrastructure elements in video data

As already mentioned Genc et al. (2018) have developed an approach that also relies on the use of CNNs in order to automate the process of detecting and cataloging infrastructure elements on railway tracks. In contrast to the method presented in this paper, their approach focuses on video data, that was obtained by filming the tracks with a camera positioned at the front of a train. While these videos have been used to manually detect existing infras-

tructure elements in the past as a basis for maintenance or reconstruction tasks, they are now used as the basis for an automated process. Figure 4 gives an impression of the types of objects that are recognized (ETCS balises, light signals, and switches) and the general results of the approach. The findings in this research can now be used to analyze infrastructure data to save cost and time compared to a manual process.

Figure 4: Application of object recognition (Genc et al. 2018)

Methodical Approach

The project NNdips (Neural Network for the detection and interpretation of plan symbols) aims to facilitate the detection of plan symbols for large amounts of technical drawings, i.e., plans of train tracks. The process is composed of three main parts, namely the import and preprocessing of data, the training of CNNs and the detection of symbols using the CNNs. All steps have been automated and thus provide a technique that does not require classification by users. We were provided with a large data set of real technical drawings and plans of railway tracks by the DB Netz AG. These formed the basis of our research in terms of data and are especially important as they were used for validating our results.

In the first stage of this project, the framework for the research was set. As there are numerous ways to utilize neural networks, it was decided at first which type of neural network was to be used and how it should be applied to the data. Considering that the aim was to detect plan symbols in railway plans – usually image files – we decided on using CNNs. As mentioned before, CNNs are particularly suitable for image recognition, and their use has been successfully tested for symbol recognition purposes by Stoitchkov (2018).

The symbols that need to be recognized are tiny compared to the complete plan and do not occur in large numbers.

Also, on most technical drawings there is much white space where it is unreasonable to scan for a symbol as nothing is depicted. Therefore, it makes sense to “cut” the plan into small pieces, so-called regions of interest (ROI) and to scan only those ROIs, which are not empty. In other words, white ROIs are ignored to minimize the amount of data and thereby the computational effort.

The size of those ROIs is a critical parameter, as the computational effort increases disproportionally when very small ROIs are used. In the case of large ROIs, the training time increases drastically while at the same time the detection accuracy decreases. At the same time, it is crucial how the plan is divided into regions. It is possible that a significant symbol is located on a border between two regions of interest and thus will not be detected, as the partial symbol cannot be recognized by the CNN in either of the two regions. We found that the simplest solution for this problem is an overlap of the ROIs at the expense of some computational overhead.

Generation of training Data

Providing thousands of input images for the training process is usually a big challenge and can result in tedious work if the images have to be selected and classified by hand. In the case of plan symbol detection, training images can be generated artificially due to the inherently repetitive nature of drawing symbols. This generation process is done in the following steps.

In a first attempt, a large background image was created by lumping some random image parts together, such as parts of technical drawings, text elements, and random patterns. Subsequently, thousands of smaller images containing the symbol to be detected and having the same size as the ROIs in the recognition process were created. This was done by copying random parts of the same size from the background image and placed the symbol on each of them. To ensure that a large variety of images was generated, this process was entirely randomized by choosing arbitrary parameters, such as the position and rotation of the symbol relative to the image (cf. Figure 5).

After many tests, which did not yield sufficiently accurate prediction results, we concluded that an improvement of the generation process was necessary. A first attempt adapted the background image and made sure it mostly contains elements such as line shapes, numbers, and text that may occur in the technical drawings that should be scanned later on. The random patterns, which were put in the background image before, did not provide any increase in training accuracy. The plan elements (such as line shapes), however, helped to reduce the detection of false positives drastically.

Figure 5: Cutting the background image into ROIs and placing training symbols in different configurations

Afterward, the symbol placement was also improved. For this, a set of variations of the symbol the CNNs was supposed to recognize was created. This was achieved by resizing and stretching the symbol. These measures increase the detection capabilities of the trained CNNs and therefore reduce the number of false negatives.

For every symbol that the network is being trained for, the same background image may be used. However, to improve the training accuracy, the background image was modified by placing plan sections containing markings similar to the target symbol to reduce false positives and increase the specificity of the resulting classifier.

At the same time, training images were also created to generate the output data which contains the exact information that the CNNs are supposed to predict. For each training image, the information is stored separately.

Training process

Before the training process could be initiated, it is necessary to compile a CNN model. To create this CNN model various parameters have to be adjusted, such as the amount and type of layers, the number of filter types, the mask size of the filter (kernel size), the type of activation function, loss function (error calculation) and optimizer.

As there is no single perfect solution to set up the model, the best parameters had to be determined by systematic experimentation. In this regard, we created different model

setups by changing one parameter per setup, trained and tested them for accuracy. The models with the best results were then further refined until we obtained a model setup with every good recognition capabilities. In each of these refinement stages, we trained with only a reduced amount (a few hundred) of input images, as this process otherwise would have been inappropriately time-consuming.

After that, we trained a CNN with the obtained model setup and a few thousand input images and applied it on real plans of train tracks. The results of these scans revealed that the model still could not match the expectations, as it failed to detect symbols which are located close to each other.

To further increase the detection accuracy, the CNN was split into three more specialized CNNs. The first CNN is supposed to detect how many symbols are located within the detection range (Region of interest) and then to initialize one of the other CNNs, which are responsible for predicting the location of the symbol center of one or two symbols (cf. Figure 6).

Figure 6: CNN types

In a final refining process, we changed the loss function of the number recognition CNN to a classifying method rather than a mean square error evaluation.

Overfitting

Because the training images are generated artificially, there is a high chance for overfitting. Therefore, two types of input symbols are required. The first type (the training symbol) is a set of up to five images depicting different variants of the symbol we want to detect. With these images, we generate the training data set. The other testing symbol is cut out from a real, presumably slightly distorted plan and we generate another set, also with a different background image – the testing data set. From the training data set we take 15% as validation data, which is also used for calculating the accuracy. We measure the accuracy for both the validation and testing data set and take the average as our final accuracy.

In the training process, we train one epoch, pause, apply the trained neural network on both image sets, measure the

accuracy and save the neural network only if it yields the best accuracy compared to the prior epochs. If the neural network overfits over the epochs, the accuracy of the test data will decrease and, because of the averaging with the training data set, the overfitted network will be discarded.

Implementation and results of the training process

Facilitating the training and recognition process

We implemented the derived algorithms into a GUI (Graphical User Interface) in order to simplify their usage. It allows for importing plans in several formats, such as .pdf, .png or .tif and the detection of pre-trained symbols in the imported plans. Positions and other results are visualized and can be exported as text files or as annotations at the positions of detected symbols in PDF-files. Another feature is the option of training the necessary CNNs automatically for new symbols. This can be done by using the predefined parameters or using advanced options that control, e.g. ROI size, number of epochs or kernel size.

Provided that the user has already trained at least one set of CNNs, the workflow of our software is straight forward. The technical drawings that should be evaluated are imported, then assigned an ID and displayed for the user to check if any mistakes happened in the conversion process. After that, the plan is scanned for a chosen symbol by using the respective set of CNN. The results of the scan are then presented on the same screen in a list box with an ID and their respective position in pixel coordinates. All results can be selected one by one, and on selection, their position on the plan will be visualized with crosshairs as well as a zoomed image. At this stage, the user can manually delete falsely detected symbols and check the overall quality of the scan. Finally, the user can export the obtained and reviewed results. Figure 7 illustrates the workflow schematically.

Figure 7: NNdips workflow

Used software

To build the CNNs we chose the TensorFlow¹ framework for Python. TensorFlow is an open-source software library for dataflow and contains a symbolic math library. It is frequently used for building neural networks and is released under the Apache 2.0 open-source license. To enable fast testing, the Keras API² was used in this project, which is an API that runs inside TensorFlow. We avoided conflicts with the compatibility of different programming languages by writing the GUI with the TkInter³ library, which is the standard GUI in Python.

Accuracy

The accuracy is measured in two different ways. For the number of symbols, it is measured in percent, where the recognized number is compared to the ground truth number of symbols in the ROI. It returns 1 for matching numbers or else 0 and the sum divided by the total number of images gives the percentage of the correctly predicted number of symbols. On the other hand, the accuracy for the location of a symbol is measured as a distance in pixels, where the distance denotes the deviation from the recognized coordinates to the ground truth coordinates of a given symbol.

Figure 8: Accuracy for the number of symbols

Figure 8 shows the accuracy of the detected number of symbols, and it can be seen that the network learns very fast for this specific task. Figure 9 displays the learning curve for the location of one symbol. Here the learning happens slower and more time is required for accurate results. We explain this by the complexity of the problem, since deciding between 0, 1 or 2 is an easier task than to find the exact x and y coordinates in a ROI. Both figures were

¹<https://www.tensorflow.org/>

²<https://github.com/keras-team/keras>

³<https://wiki.python.org/moin/TkInter>

Figure 9: Accuracy for one symbol

created in the scope of the training process with the default values of the ROI size (160x160 pixels) for 15 epochs and an amount of 23.996 training images, 4.235 validation images, and 4028 testing images. Tests were conducted on different symbols, and the accuracy was consistently above 99% for the recognition of the number of symbols in a ROI and less than 2 respectively 4 pixels deviation for one respectively two symbols. However, when the neural network is applied on a plan, there are thousands of ROIs to be searched and the error multiplies with the number of ROIs.

Figure 10: Visualization of the results in a PDF file

Proof of concept and use-case scenario

The output of the CNNs is the coordinates for each found symbol. These can be visualized by marking the position in the associated plan. Figure 10 shows an example for the output in a PDF file. The positions are marked as annotations. Another possibility is the export of a TXT file. We expect users to supervise the outputs and allow deleting and commenting on single results in the GUI.

So far we tested our networks with over 25 different plans

	Plans	manual count	Nndips	doubles	false +	false - [%]
18	215	366 (197)	169	9	12,56 (27)
1	4	7 (4)	3	0	0 (0)
4	22	55 (35)	20	16	13,64 (3)
4	13	42 (37)	5	25	7,69 (1)
4	37	70 (34)	36	2	13,51 (5)
10	28	51 (30)	21	2	0 (0)
6	16	24 (14)	10	0	12,50 (2)
4	96	156 (90)	66	0	6,25 (6)
7	20	43 (21)	22	1	0 (0)
22	29	74 (49)	25	20	0 (0)
26	43	133 (76)	57	36	6,98 (3)

Figure 11: Results of the verification process

provided by the DB Netz AG. In those plans, we selected more than ten symbols to verify our previously described method. Figure 11 summarizes the results of this verification process. Each line shows the actual number of symbols present in a set of plans (column *manual count*). The column *Nndips* shows the number of hits that the CNN produced. Since we usually have multiple hits for the same symbol, the number in parenthesis shows the actual number of symbols found - without counting the multiple hits. The number of multiple hits is shown in the column *doubles*.

In some cases the CNN produced a falsely positive result (a hit at a position where no symbol is present) - the respective number is given in the column *false +*. Unfortunately, the CNN does not recognize a symbol at all times. Such false negatives are shown in the column *false -* as percent values (the actual number of symbol which were not recognized is given in parenthesis; the percent value is calculated by dividing the number of false negatives by the number of actually present symbols, e.g., $\frac{27}{215} = 12,56$ in the first row).

While those results are not perfect, they nonetheless indicate that our approach shows promising possibilities - especially in regard to the very short time required for training the CNNs (see below). We are currently working on further improving the general accuracy and also on automatically removing the unnecessary multiple hits.

Challenges

Training CNNs for the detection of symbols in technical plans pose multiple challenges. Previous knowledge about the occurrence of the symbols is essential. In the given technical plans, we found the occurrence of multiple symbols closely together. One issue that results is the multiple detection of the same symbol in various ROIs. This is a well-known issue especially in object detection in videos. Other works such as Breuers et al. (2016) tackle this by deleting multiple hits by calculating an overlap-area-ratio of bounding boxes around the detected objects. We did not apply any of the possible techniques here, as the plan data yields cases where multiple symbols are incredibly close together, and a minimal distance approach or a bounding box overlap could delete distinct hits. Further investigation of this phenomenon could minimize the amount of multiple detection of symbols.

Another challenge is the rare case of more than two symbols in a single ROI that are not detected by the overlap of ROIs. We built a fourth CNN for the task of the detection of three symbols in a ROI but found lack of accuracy. The fourth CNN worsened the amount of multiple found symbols, referred to as false positives. If in further testing, symbols are overlooked by the algorithm due to more than two symbols in a ROI, this error can presumably be corrected by merely reducing the ROI size.

Time of training and recognition

When using the parameters and symbols shown in this paper, the time for the training process of a single symbol took between 20 to 30 minutes on a Computer with an 8 core i7-7700 CPU at 3.60GHz and an NVIDIA Quadro P2000 graphics card. The recognition process, which consists of the calling of the trained model and drawing of the symbols on a single plan took about ten seconds on the same machine. Similar results could be achieved on a laptop with an NVIDIA GeForce 940MX; thus the training can presumably be done within a reasonable time on any modern graphics card.

Summary and outlook

This paper has introduced a method to automatically recognize important symbols in technical drawings of railway infrastructure by using a Convolutional Neural Network. The authors have shown how their approach was developed, implemented and tested in order to reduce the manual effort that would otherwise be necessary in order to obtain digital information from the aforementioned technical drawings. This information can then be further used as the basis for planning purposes or to check the accuracy of the drawings against the actual as-built situation. Since the accuracy of the method is only at approx. 90 % at the moment we are continuously improving the automated training process. In regard of the fact that the training process does not require a large number of manually labeled images and is automated as well as fast, we conclude that the accuracy of the approach shows the possibility of reducing the manual effort in recognizing plan symbols. Furthermore, we plan to combine our method with the approach by Genc et al. (2018) to enable a semi-automated consistency check of technical drawings. For this purpose, we are currently acquiring video data as well as plan data for a specific stretch of railway track. By applying both approaches to the data and comparing the results we plan to show the applicability of the combined approach.

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MANAGING MISTRUST IN CONSTRUCTION USING DLT: A REVIEW OF USE-CASE CATEGORIES FOR TECHNICAL DESIGN DECISIONS

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Abstract

Blockchain, or more general distributed ledger technology (DLT), is seen as an opportunity to integrate digital information, management, and contracts to increase trust and collaboration within the construction industry. However, little research has analyzed and confirmed this linkage through case-studies. There seems to be a gap between use-case ideas and the technical system implementation. This paper aims to reduce this gap through a review of both DLT and its applications in construction. It proposed six use-case categories through clustering of analyzed use cases and a basic framework to match the categories to a suitable DLT design. For that, the trust level of the user group was used as a proxy for the needed fundamental properties of the system. The categories and framework can lead to a more connected and structured thinking between technological properties of DLT's and use cases in construction.

Introduction

Construction project teams often work in cross-functional, geographically distributed teams (Zolin et al. 2004) composed of complex and fragmented supply chains. The successful completion of complex projects requires the development of trust and mutual confidence between the interacting parties (Pishdad-Bozorgi and Beliveau 2016). This has been found to be a major challenge for large, complex projects that rely on the interdependent actions of numerous stakeholders (Zolin et al. 2004). Without a strong foundation of trust, it is difficult to reach consensus and information exchange in a meaningful manner (Hall et al. 2014). Mistrust leads to guarded behaviors and conflict within project teams and results in individuals pursuing and protecting their own interests instead of the benefit of the overall projects (Pishdad-Bozorgi and Beliveau 2016). Furthermore, the construction industry suffers from longitudinal fragmentation that occurs when project teams disband at the end of projects and are selected on future projects by competitive bidding. They are thus unlikely to work with the same set of partner firms on future projects. Consequently, team members lose tacit knowledge about how to work together effectively (Dubois and Gadde 2002) and organizations are unable to build long-term trusting relationships across firm boundaries. It is therefore not surprising that project sponsors and clients list a primary concern to be "trust and integrity in the construction process" (Thomsen et al. 2009).

Scholars and practitioners argue that digital transformation can help overcome challenges of mistrust and fragmentation in order to increase the overall productivity of the construction industry (Agarwal et al. 2016; Whyte and Hartmann 2017). Digital tools such as Building Information Modelling (BIM) promises potential in this regard. BIM allows designers and builders to design, visualize, and coordinate construction systems with greater efficiency through the use of three-dimensional modelling tools and processes. While helpful for individual firms, BIM provides significantly more value when it can integrate information across multiple firms and organizations in the supply chain (Papadonikolaki and Wamelink 2017). However, the use of a shared model requires again trust in the other project participants that originally created the model (Hall et al. 2014); this trust is often not found in BIM practice (Miettinen and Paavola 2014; Papadonikolaki 2018). Despite its potential, the adoption of BIM has lagged as project teams struggle with trust and liability concerns associated with sharing information on the project (Hall and Scott 2019). It seems that new technologies such as BIM are important but can only offer a partial solution to trust and liability.

The emergence of Distributed Ledger Technologies (DLT), also known as blockchain, offers an opportunity to increase trust and collaboration within the construction industry by integrating digital information with management and contracts. It can help making the construction process more efficient, transparent, and accountable between all involved participants (Penzes 2018). Past research has identified and summarized specific use cases where DLT can be applied to construction (e.g. Li et al. 2018). However, DLT is an emerging concept. Previous reviews of DLT have determined lists of single use cases but have not clustered applications into higher-order categorizations. Furthermore, past reviews of use cases lack consideration of the fundamental design decisions made for DLT's. DLT's can be chosen with different levels of decentralization according to the need of the users, which also impacts a DLT's ability to overcome issues of trust. Much existing literature in construction does not take the technical design of DLT's into consideration when reviewing its potential use cases.

This paper attempts to further refine the understanding of potential use cases for DLT in construction. To do so, we

review nine papers that identify multiple potential use cases for DLT in construction. From these papers, we identify 22 use cases. These use cases are then clustered into six higher-order use-case categories. For each of the six use-case categories, we map the technical requirements of the DLT's onto the design decisions. The resulting framework is useful for researchers and practitioners to identify the technical design decisions required for future use-case implementations of DLT in construction.

Distributed Ledger Technology

Bitcoin as a blockchain-based crypto-currency introduced by Satoshi Nakamoto (2008) emerged as a combination of existing technologies (e.g. distributed ledgers, public-key encryption, merkle tree hashing, consensus protocols) (Tasca and Tessone 2017). Often called a disruptive technology, blockchain enables application beyond the specific case of Bitcoin as peer-to-peer money. It is possible with this new kind of distributed software architecture to operate a trusted, unchangeable ledger. Parties can execute and store any kind of peer-to-peer transactions over the internet without the need of a trusted intermediary party. However, the Bitcoin blockchain is unlikely to meet the requirements for all usage scenarios (Xu et al. 2017). This is why various other implementations and combinations of the technology emerged for different requirements. Blockchain is a new technology and the accepted terminology is still evolving. In this paper, we use the term distributed ledger technology (DLT) as an overarching term (Hileman and Rauchs 2017) that can capture all potential design options.

Application of DLT's has been structured into three categories: Blockchain 1.0, 2.0, and 3.0 (Swan 2015). Blockchain 1.0 includes the initial use case of blockchain as a currency. Blockchain 2.0 refers to all applications using transactions combined with smart contracts for business related cases. Shermin (2017) points out that DLT's have the potential to become the new economic layer on top of the internet. From a business perspective, DLT is likely to impact finance and accounting, sales and marketing, legal affairs, and raising capital (Tapscott and Tapscott 2016). Therefore, DLT affects the main institutional pillars of industries and potentially disrupts business models by authenticating traded goods, improving operational efficiency, and facilitating disintermediation (Nowiński and Kozma 2017). This is in line with the main advantages for business processes of DLT showed by Viryasitavat et. al. (2018), namely enabling trust, faster transactions, and cost reductions through disintermediation. In conclusion, most literature agrees that DLT should not be neglected when looking at future business development. On top, blockchain 3.0 includes applications beyond finance, economics and markets, particularly in the areas of government, health, science, literature, culture, and art (Swan 2015). Finally, London et. Al. (2018) stated that apart from the purist or academic value coming from DLT's, they can also be used as a banner to modernize an industry from a digitization and collaboration perspective. DLT is gaining traction around the world in different industries. The report of

Digital Catapult (2018) and Hileman and Rauchs (2017) give empirical evidence for the UK and global market respectively.

Technology Stack

The goal is to identify factors influencing the DLT design decision by focusing on the most important aspects. Detailed explanations on the underlying base technologies for DLT's can be found for example in Wattenhofer (2017). Furthermore, various scholarship (Ballandies et al. 2018; Tasca and Tessone 2017; Xu et al. 2017) introduce taxonomies for DLT's and provide detailed information on different components. They were used as sources for this section. The information was structured based on an adapted version of the technology stack (Shermin 2017), pictured in Figure 1. The internet acts as the base technology for information sharing. A DLT, sometimes also referred to as *protocol layer* (Hileman and Rauchs 2017), is built on top of the *internet layer* with three main components impacting its characteristics: Ledger, P2P Network, and Governance. An *application layer* is possible, if code can be executed on the *protocol layer*.

Figure 1: Technology stack (adapted from Shermin 2017)

- Ledger:

The ledger represents the data structure of the DLT and can be, as in the case of Bitcoin, a *blockchain* with sequential entries and total order (Ballandies et al. 2018). Another type of ledger is the *directed acyclic graph* (DAG) with a stream of individual transactions entangled together (e.g. IOTA, see iota.org). Various elements of a ledger can be defined, such as the storage capabilities or data encryption, which is beyond the scope of this paper. Most importantly, if the ledger supports turing complete language on the *protocol layer*, an *application layer* for coded relations is possible (see Figure 1). This enables the use of *smart contracts*, described the first time by Szabo (1996). These self-executing and unchangeable codes open up a large scope of applications. They allow for automated and self-executing conditions based on the state of the ledger. Many smart contracts can be combined to build so-called decentralized applications (DApps) or decentralized autonomous organizations (DAOs), also described in the analysis part of this paper. Furthermore, so-called *tokens* for all kind of (mostly financial) purposes can be introduced (see Token Alliance 2018).

- P2P Network:

The ledgers are distributed on different nodes in the network. These nodes can be either *permissionless*, meaning everyone could set up a node and write transactions to the ledger, or *permissioned*, by limiting

write-access to the ledger. The second distinction is between *public*, meaning everyone can read the ledger, or *private*, where only defined members can access transactions on the ledger. The distribution and ownership of nodes impacts the decentralization of the system. *Public permissionless* DLT's naturally lead to higher decentralization, as everyone can set up a node, leading to more nodes and higher variability in interests of the participating users.

- Governance:

The governance of the DLT defines the set of rules for users interacting with the system. The most important component is the consensus mechanism, responsible for defining how to write, validate, and agree on entries to the ledger. Next to proof-of-work, which was the real innovation behind Bitcoin (see Nakamoto 2008), also other consensus mechanism have been introduced such as proof-of-stake (see e.g. Tasca and Tessone 2017). A consensus mechanism for a *public* DLT is enabled by a crypto-economic design (CED). A native coin of the DLT incentivizes participants to behave in the interest of the system. This is important to prevent attacks, but also to compensate miners for their expenditures in running nodes and adding transactions. Multiple properties of a CED can be defined, influencing the DLT's governance (see also Ballandies et al. 2018). A *private* DLT might not necessarily need a CED, as consensus is often based on permissions. This can have an impact on the cost structure for users when interacting with different systems. Often, users pay for transactions on a *public* DLT with transaction fees in its native token. In contrary, for *private* DLT's costs for the acquisition and maintenance of the infrastructure are predominant, while making transactions involves mostly no fee.

Fundamental Properties

The fundamental properties of DLTs are immutability, non-repudiation, integrity, and transparency (Xu et al. 2017). If the network is decentralized and protected through a working consensus-mechanism, the chain is immutable. Each transaction is added only once, which

leads to non-repudiation of the stored data. The cryptographic tools support data integrity, allowing to verify that all the data is complete and as initially written into the ledger. Public access for everyone ensures transparency, and equal rights allow every participant the same ability to access and write to the ledger. *Public permissionless* DLT's are able to achieve the highest level of trust. Trust in the DLT is achieved because the participants rely on the fundamental properties of a DLT itself rather than on trusted third-parties. The more permissions, the less trust in the technical system can be accomplished. Even though integrity can also be maintained through cryptography, permissions have an impact on the other aspects of the fundamental properties. In private DLT's, immutability and non-repudiation are often ensured through verifying nodes or permission-based consensus algorithms, with lower decentralization and increased possibility to act in self-interested behavior. Moreover, restricting read access to the ledger decreases transparency. This lowered trust in the technical system needs to be compensated by trusting the involved parties or a third party. Table 1 adapted from Xu et. Al. (2017) summarizes this for central databases and three typical design decisions of DLT's: *private*, *public permissioned*, and *public permissionless*. The fundamental properties are less favorable with more permissions. Having said that, in some use cases this high trust in the technical system might not be needed. A more centralized system offers a better performance (scalability and latency), as fewer nodes are involved and it does not need to continuously reach consensus with resource intensive algorithms. In addition, privacy can be of concern with public DLT's, if data encryption is considered too weak of a protection or parties want to have the possibility to control more aspects of the DLT (e.g. for easier implementation of system changes).

Opportunities for DLT in Construction

One vision for a digitized future construction process is described by some scholars as a combination of DLT, BIM, and the Internet of Things (IoT). IoT describes an environment where physical objects connect with the digital world, having sensors and connected devices

Table 1: Impact on DLT-related design decisions: fundamental properties and performance, using a spectrum from low (+) to high (+++++) (adapted from Xu et al. 2017).

Design Decision	Comment	Examples ¹	Impact	
			Fundamental Properties	Performance
Fully Centralized	Central databases with a single or alternative providers	-	+	++++
Private DLT	Private DLT's with permissions on both read & write of transactions	Hyperledger Fabric / Corda	++	+++
Public Permissioned DLT	Public DLT's (permissionless read access) & permissions for write-access	IOTA	+++	++
Public Permissionless DLT	Public DLT's (permissionless read access) & permissionless write-access	Ethereum	++++	+

¹ Examples classified by Ballandies et. al. (2018): Ethereum (www.ethereum.org), IOTA (www.iota.org), Hyperledger Fabric (www.hyperledger.org/projects/fabric), and Corda (www.r3.com).

allowing to monitor and sense the environment with high spatial and time resolution (Fleisch 2010). Ye et al. (2018) describe in their conference paper a so-called “cup of water theory.” They compare the technological environment with the analogy of a water glass and state that DLT will be the “cup wall,” which is responsible to hold the data produced by IoT in a transparent, secure and convenient environment. The “cup-bottom” and base for the new technologies is BIM as the main tool to digitize construction project data. The combination of the three would link the digital models to the physical buildings, enabling real-time digital twins to automate procedures. Additional literature implicitly aligns with this viewpoint. Mathews et al. (2017) list the required ingredients for a DLT adoption in the construction sector. Main ingredients include BIM and IoT. Additional consultancy reports (Kinnaird and Geipel 2017; Penzes 2018) concur that a future industry state will be characterized by the “circular economy of BIM things.” The produced data from projects and IoT can be fed into a common data environment managed and visualized through BIM, enabling a digital twin over the whole life cycle of a building. Benefits of these digital twins exist for the planning and construction process as well as in the operational phase (Penzes 2018). Having a digital model from the very beginning in the project throughout the construction phase can reduce efforts for the operation of the facility over its lifecycle. As more activities become digitalized, DLT’s offer a way for business process optimization and automation on the transaction level through the use of smart contracts for higher efficiency and accuracy. Furthermore, DLT could benefit construction with higher transparency in the project and supply chain due to data immutability and traceability.

Challenges Facing DLT in Construction

Despite the potential benefits of DLT in construction, many challenges exist for its successful application and adoption. Apart from technical barriers of DLT, various challenges regarding the nature of the construction industry and the involved humans exist, among them lack of awareness, skills, as well as resistance to change (Wang et al. 2017). Some scholars see the coding of relations into smart contracts as an especially challenging area in construction. Mason (2017) lists construction contracts of all kinds and investigates if a transition to smart contracts would be possible. He notes that smart contracts work best where they are short-term or are of instantaneous effect. This is sometimes at odds with the complicated and long-running nature of construction projects. He believes that certain aspects of the construction contract cannot be fully intelligent, and the best that can be achieved in the short to medium term is a semi-automated position with human involvement. He found in a survey that construction industry participants mostly doubt that full automation with smart contracts is possible (Mason and Escott 2018). Furthermore, Kinnaird and Geipel (2017) emphasize that transaction entries in the DLT do not verify the correctness of data itself, therefore moderators might need to be involved to resolve disputes related to data sources. Belle (2017) summarized this saying that two kind of

transactions are difficult for smart contracts: 1) ambiguous situations where third party expertise is needed; and 2) when turning a task, negotiation, or contract terms into algorithms is difficult. That is why some authors (e.g. Kinnaird and Geipel 2017; Mathews et al. 2017) propose to look more into oracles, which are third party or external information sources that interact with a smart contract. This can be human interaction, data from sensors or third-party services. Oracles might offer a solution to deal with problems of wrong or ambiguous information and implementation. These challenges has been summarized using three dimensions: technical, political, and social in Li et al. (2018).

As DLT has developed, academics and consultants have theorized the potential use cases for the technology. These use cases are a helpful starting place to understand how DLT can benefit the construction industry. However, there is an emerging gap between the described use case ideas and the technical system implementation required for DLT (Ye et al. 2018). To solve the emerging challenges described above, applications of DLT in construction must take the appropriate DLT design options into consideration. Yet no literature was found investigating what technical design option might be best suited for which use case in construction. Turk and Klinc (2017) started to think about a possible technical layout for the connection of blockchain and BIM. However, the proposed scenarios do not distinguish between different DLT’s. The question remains: how does one know which DLT to design for a certain use case? Furthermore, how can these use cases be clustered into broader categories based on their technical requirements for DLT?

Methodology

To answer these two questions, this paper conducts a review of recent papers written about DLT use cases. Because literature on DLT in construction is still limited, both scholarship and consulting reports were considered. The literature review conducted by Li et al. (2018) was used as a starting point to identify relevant papers. We then refined the papers reviewed based on relevance to the construction industry, and limited the literature to papers published in 2017 or later. In total, we identify nine papers written about DLT use cases (see Table 2).

Table 2: Literature for use-case analysis (S: scholarly papers, C: consulting reports)

#	Literature	Type
[1]	(Belle 2017)	S
[2]	(Heiskanen 2017)	S
[3]	(Kinnaird and Geipel 2017)	C
[4]	(Mason 2017)	S
[5]	(Mathews et al. 2017)	S
[6]	(Penzes 2018)	C
[7]	(Turk and Klinc 2017)	S
[8]	(Wang et al. 2017)	S
[9]	(Ye et al. 2018)	S

From these nine papers, we identify 22 individual use cases (see Table 3). Afterwards, use-case categories were

identified based on the clustering of use cases regarding similarities in their user group and/or their higher level application. If no use case was left without a category, it implied that they were able to capture the current state of DLT applications in construction.

In a second step, the categories were evaluated according to their technical requirements based on the characteristics of the respective user group. If the requirements of one category varied from the other categories, each category was needed. The assessment from both the use case and technical view point leads to a robust argument that the proposed use-case categories are eligible for a first assessment regarding their technical design decisions.

In the end, we identify six use-case categories. For each category, we describe the overarching characteristics identified in the literature, as well as the specific use case applications. Finally, we propose a basic framework and analysis to identify which DLT design is best suited for each use-case category.

Findings

Six final use-case categories were identified (Table 3):

1. Internal Automation of Administrative Processes

According to Wang et. Al. (2017), DLT could be used for storage and perfect notarization of each creation, deletion, and updating of files across an inter-organizational system (Table 3, 1.1). This can simplify and automate administrative processes. Wang et. Al. (2017) mentions the recording of quality data or resource consumption data as examples.

2. Transaction Automation & Optimization Between Stakeholders

This use-case category focuses on the automation of transactions with smart contracts between different stakeholders, instead of one stakeholder as in the first use case category. The most mentioned use case in this category was the automatic triggering of payments (Table 3, 2.1), as delays for monetary transactions have been mentioned repeatedly as a factor causing conflicts and disputes (Eastman 2011). This can be generalized to trigger various deliverables from contracts (Table 3, 2.2). Once a smart contract is written, its behavior is unambiguous and predictable. This can be used for self-

executing contract administration (Table 3, 2.3), such as monitoring and updating of the contract status (Wang et al. 2017). Smart contracts are also mentioned as a way to enable automated information and data sharing in projects (Table 3, 2.4), ensuring consistent reporting for (sub-)contractors and owners. Combined with digital signatures (Table 3, 2.5), decisions can be quickly approved and automatically trigger subsequent action. These use cases are independent of the project phase and can be applied for procurement and supply chain activities for higher accuracy and efficiency.

3. Record of Transactions, Changes, Ownership

The focus lies here on the immutability and transparency a DLT can provide by timestamping value transactions (Table 3, 3.1). The most mentioned use case is the record of changes and ownership (Intellectual Property) of digital models and components, especially in combination with BIM (Table 3, 3.2). Moreover, the ownership of physical property can be registered on a DLT (Table 3, 3.2). One other often mentioned use case is the tracking of supply chain logistics, including procurement, transportation, and storage of goods (Table 3, 3.4). Penzes (2018) expanded this towards use cases such as the tracking of project progress and worked hours (Table 3, 3.5), maintenance and operations data of buildings (Table 3, 3.6), health & safety incidents (Table 3, 3.7), and machine operations data (Table 3, 3.8).

4. Decentralized Applications (DApps)

DApps enable direct user interaction with a DLT, typically through web user interfaces. Even though it is possible to create web applications for the use cases in the previous categories during a project, we refer with DApps in this category to long-term and global users. They might be unknown and involved in various projects simultaneously. Different use cases for DApps are mentioned, such as managing identities (ID's) of people or organizations on a DLT (Table 3, 4.1) for clear and trustworthy identification and reputation (see e.g. *civic.com* as an existing DApp for managing ID's). Similarly, material and product passports with provenance-related information (Table 3, 4.2) can be maintained throughout the supply chain. This can be used for quality assurance in global construction projects (Wang et al. 2017) or to enable the reuse of materials at a later stage of a building towards a circular economy

1. Internal Automation of Administrative Processes					2. Transaction Automation & Optimization					3. Record of Transactions, Changes, Ownership				
	+	++	+++	++++		+	++	+++	++++		+	++	+++	++++
1)					1)					1)				
2)					2)					2)				
3)					3)					3)				
LoT					LoT					LoT				
4. Decentralized Applications (DApps)					5. Decentralized Autonomous Organizations (DAOs)					6. Coins/Tokens as Payment or Incentive Scheme				
	+	++	+++	++++		+	++	+++	++++		+	++	+++	++++
1)					1)					1)				
2)					2)					2)				
3)					3)					3)				
LoT					LoT					LoT				

Figure 2: Assessment for level of Trust (LoT) from low (+) to high (++++). 1) Are users unknown (+) or known (++++)? 2) Do users have opposite (+) or aligned (+++++) interests? 3) Is the data used long-term (+) or short-term (++++)?

Table 3: Use-Case clustering into six categories, based on the literature listed in Table 2.

Use-Case Category	Literature								
	[1]	[2]	[3]	[4]	[5]	[6]	[7]	[8]	[9]
1 Internal Automation of Administrative Processes									
1.1 <i>Notarization of Documents</i>								X	
2 Transaction Automation & Optimization Between Stakeholders (Procurement & Supply Chain)									
2.1 <i>Smart Contracts to Trigger Payments</i>			X	X		X		X	X
2.2 <i>Triggering Contract Deliverables</i>			X	X		X			
2.3 <i>Self-executing Contract Administration</i>						X		X	
2.4 <i>Automated Data/Information Sharing</i>			X			X			X
2.5 <i>Approval of Work Packages with Digital Signatures</i>			X			X			
3 Record of Transactions, Changes, Ownership									
3.1 <i>Timestamping of "Value" Transactions</i>		X			X				
3.2 <i>Record of Changes and Ownership in BIM (IP-Rights)</i>	X		X	X		X	X		X
3.3 <i>Record of Physical Ownership (e.g. Property)</i>			X	X		X			X
3.4 <i>Tracking of Supply Chain Logistics</i>		X	X			X		X	X
3.5 <i>Tracking of Project Progress and Worked Hours</i>						X			
3.6 <i>Record of Maintenance and Operations Data</i>						X			
3.7 <i>Tracking of Health & Safety Incidents</i>						X			
3.8 <i>Record of Machine Operation Data</i>						X			
4 Decentralized Applications (DApps)									
4.1 <i>Digital Identities for Reputation (People, Contractors)</i>	X		X			X			
4.2 <i>Product Passports (Material & Product Provenance)</i>			X			X			
4.2 <i>Decentralized Market Places</i>			X					X	
4.4 <i>Decentralized Common Data Environments (CDE)</i>			X						X
5 Decentralized Autonomous Organizations (DAOs)									
5.1 <i>Automated Building Maintenance Systems</i>	X					X			X
6 Coins/Tokens as Payment or Incentive Scheme									
6.1 <i>Payments in Cryptocurrencies</i>								X	X
6.2 <i>Shared Accounts & Insurances (Multi Party Risk)</i>				X					
6.3 <i>Token as Incentive over Whole Building-Lifecycle</i>					X				

(Kinnaird and Geipel 2017). Also, certification of products and buildings can profit from the availability of this trusted data. Decentralized marketplaces (Table 3, 4.3) can be set up based on the ID's for objective data of the best-qualified person or company in tendering, without the need to disclose sensitive data to third parties (Belle 2017). Lastly, decentralized common data environments (CDE) as a combination of cloud storage and DLT (see e.g. *sia.tech* or *storj.io*) are proposed to store digital models without the need to trust a third party server provider or run private servers vulnerable to attacks (Ye et al. 2018).

5. Decentralized Autonomous Organizations (DAOs)

DAOs represent a fully autonomous organization based on smart contracts, only running on a DLT without any human involvement. Governance rules are coded in smart contracts and incentive mechanisms are implied through crypto-economic design (CED). Even though fully automated construction companies seem futuristic, three sources (Belle 2017; Penzes 2018; Ye et al. 2018) mentioned automated building maintenance systems as one possibility for a DAO (Table 3, 5.1). The idea is that building performance can be monitored through sensors (IoT) in combination with BIM, enabling an automatized

reaction to certain conditions based on predefined rules. This can include automatic ordering of spare parts or regulating technical installations.

6. Coins/Tokens as Payment or Incentive Scheme

This last use-case category includes all financial and incentive related use cases based on DLT's. An obvious use case is the payment in cryptocurrencies (Table 3, 6.1), which allows to send money across borders instantly and with small fees. Shared risk and reward structures with shared bank accounts and insurances could be further application (Table 3, 6.2). Finally, Mathews et al. (2017) propose the use of an #AECoin as a token to reward project contributors for the value of an artefact over its full life cycle. This should create superior value for the project, as contributors are incentivized to work better in order to earn from the value creation after the project handover to the client.

Framework for Technical Design Decisions

Having identified the categories based on use-case clustering (Table 3), we analyze them regarding their technical requirements. As seen in Table 1, Xu et al. (2017) structures different DLT design options according

Table 4: Identification of suited DLT design options for each use-case category. Range of “level of trust” (from Figure 2) and “fundamental properties” from low (+) to high (++++).

Use-Case Category	Level of Trust	Fundamental Properties	Design Decisions for DLT's			
			Fully Centralized	Private	Public Permissioned	Public Permissionless
1 Internal Automation of Administrative Processes	++++ to +++	+ to ++	X	X		
2 Transaction Automation & Optimization Between Stakeholders	+++ to ++	++ to +++		X	X	
3 Record of Transactions, Changes, Ownership	++	+++			X	
4 Decentralized Applications (DApps)	++ to +	+++ to ++++			X	X
5 Decentralized Autonomous Organizations (DAOs)	+++ to +	++ to ++++		X	X	X
6 Coins/Tokens as Payment or Incentive Scheme	+	++++				X

to their fundamental properties. With favorable fundamental properties, trust in the system is established, which is needed for use cases with low trust. Therefore, we introduce the needed *level of trust* for a use-case category as an inversely related proxy to the fundamental properties of a DLT. The *level of trust* was quantified for each category in Figure 2 based on three questions, which relate to two different kinds of trust identified. 1) *Are the users known or unknown?*, and 2) *Do they have aligned or opposite interests?*, relate to the participants behavior and relationship in a use case. Unknown users and unaligned interests lead to less trust. Question 3) *Is the data used long-term or short-term?*, relates to the required trust and transparency in the data. Data used long-term across project boundaries or over the whole life cycle of a building requires more trust. The final proxy *level of trust* was assigned based on an approximate average of the three questions from low (+) to high (++++). As the *level of trust* is inversely related to the fundamental properties of a DLT, we derive the needed fundamental properties of the specific use-case category as the opposite of the *level of trust* (e.g. the *level of trust* is high (++++), then the required *fundamental properties* are low (+)). Using the relationships introduced in Table 1, this results in one or more of the four introduced design decisions for each use-case category. The analysis is shown in Table 4 and discussed in the following section.

Discussion

The qualitative assessment of trust is not always clearly assignable and the assessment was based on the author's evaluation. The first category involves single organizations or few known stakeholders. Trust is therefore rather high and a DLT-solution not necessarily needed. A cloud service or versioning servers such as git (git-scm.com) could be alternatives. Having said that, a DLT could enable later integration with other stakeholders (second use-case category) or might make sense if interests internally are not aligned. The second category involves multiple stakeholders with different interests.

However, these stakeholders normally work on the same project and know one another. Data is mostly needed during the project and does not cross project boundaries. Dependent on the specific use case, both a public or private ledger could be suited. In contrast, use cases in the third category are more likely to store data long-term for transparency and accountability reasons. Furthermore, the network can be more global and complex as e.g. in supply chain tracking, and participants are often unknown. At least a public permissioned DLT is desirable. Having said that, one should be careful if the record is relevant for conflicting parties. E.g. for use cases in Table 3, 3.5-3.8, if this data is only relevant for one party, a private DLT or even centralized database might be sufficient (see also first use-case category). DApps (fourth use-case category) involve long-term and global users that do not know each other across project boundaries with various interests. A public DLT is for this case favorable. For DAOs (fifth use-case category), the case is more complex. A DAO for building maintenance could be only for one particular building, still owned by a company. For such cases they could be set up on private DLT's. If they are autonomous, representing their own organizational entity, a public DLT makes sense. The payment or incentive use cases in the sixth category require high trust in the technical system, preferably with a public permissionless DLT.

The proposed six use-case categories capture the current state of proposed use cases in the construction industry (Table 3). Furthermore, they differ in terms of prerequisites for DLT design, because the respective user group varies in terms of *level of trust* (Figure 2 and Table 4). This leads to a robust assessment that these use-case categories are complete and the proposed framework is suited to identify DLT design options for construction use cases.

However, we note the findings presented above should be considered with the following limitations:

- The literature of DLT in construction is still limited

and the categories cover the current state of knowledge. Hence, use cases might evolve in the coming years and the categories should be revised.

- The framework is sensitive towards the qualitative proxy *level of trust*. With a different viewpoint on the user group, this might lead to other assessments of suited DLT design options than in Table 4.
- The nature of the proxy *level of trust* generates results found in a certain range rather than an absolute value. This leaves the decision makers with the freedom to adjust the final DLT design solution regarding other factors.
- As the framework is only based on one proxy, other important factors such as scalability, privacy, and the cost structure are left out. Major research efforts are currently put into the advancement of DLT in technical regards, and scalability and privacy implications between DLT design choices might become less decisive in the future. Nevertheless, a more detailed framework with additional factors could be a topic of future research.
- The selection of design options is limited to four cases (see Table 1). This can be of course refined, also considering combinations between several design options (hybrid-solutions).

Despite above limitations, the proposed use-case categories together with this basic framework can lead to a more connected and structured thinking between technological properties of DLT's and use cases in construction. They allow a first assessment of DLT design options based on a simple proxy: the *level of trust* of the user group. It is important to consider technical aspects of DLT's when thinking about use cases. With this, the authors hope to contribute towards more case-studies of DLT in a construction context to further advance the research in this field. Even with our basic assessment, different requirements for DLT in construction are identified. This might imply that a future connected ecosystem of DLT's could be preferable over a one-size-fits-all DLT solution for construction.

Finally, based on the literature review of both DLT and its construction-related applications, the following future research areas were identified:

- An extended framework beyond the introduced metric *level of trust* to connect DLT use cases to the best suited DLT design option.
- Interoperability of different DLT's together with existing software solutions in construction.
- Establishing DLT standards for the specific needs of the construction industry.
- Best practices for coding construction applications into smart contracts and the role of oracles.
- Quantitative assessment of use-case feasibility through case-studies.
- More general impact of DLT on the construction industry ecosystem in a socio-economic context.

Conclusion

This paper reviews literature regarding DLT and its applications for construction. It was found that the benefits of DLT theoretically align with some of the trust problems facing the construction industry. The overall research is still limited and various challenges for implementation remain. Furthermore, there is no evidence for the socio-economic benefit of DLT's in construction yet. Especially, case-studies of use cases in construction are missing. Therefore, this paper proposed and described six use-case categories through use-case clustering. The paper then provides a basic framework to link use-case categories to possible design decisions of DLT's based on the trust-level in the user group. The resulting framework can be used by practitioners and academics to reduce the gap between DLT use-case ideas and technical system implementation.

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CONSTRUCTION PROGRESS VISUALIZATION FOR VARIED STAGES OF THE INDIVIDUAL ELEMENTS WITH BIM: A CASE STUDY

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Abstract

Building information modeling (BIM) is an intelligent 3D design and modeling process that gives architects, engineers, construction and facility managers the ability and tools to plan, design, construct and manage buildings more effectively and efficiently. Currently, the construction progress is monitored by comparing the baseline project schedules, which include the planned dates and resources, with the actual dates in the updated schedules. 4D scheduling is used in the construction industry for linking individual model elements with the schedule activities to visualize the progress of construction activities. However, the limitation of this approach is a need for the creation of a dedicated activity for monitoring each model element, which can result in an excessive number of activities. This paper presents a construction progress visualization method, which uses a custom developed add-in to present the status of building elements (e.g., planned, installed) without linking them with the schedule. The new tool enables a visual presentation of the progress of each element within the BIM model during different stages of the construction process to increase the decision-making capabilities. A case study is used to demonstrate the capabilities of the developed BIM add-in tool for construction progress visualization.

Introduction

Updating the project schedules requires actual progress data collection from the site (Abdelsayed and Navon, 1999). For example, the comparison between the actual and planned progress shows the project deviations, whereas the automated progress monitoring enables an equitable measure of the project performance and each activity actual dates can be defined more precisely (Turkan *et al.*, 2012). One of the most important tasks of construction management is to track the progress and take corrective actions required on time. Software packages such as Microsoft Project and Oracle Primavera are widely used in the construction industry for this purpose. Planning software is based on activities defined in different work breakdown

structures with planned and actual dates for each activity. In addition to the dates, many other parameters can be loaded to the activities, such as resources or quantities for reporting purposes. It is possible to receive a planned versus actual data from the software and also report activities that are in the critical path of the project. All these reports created by using the software are limited with the activities defined that do not include a visual representation of the project.

Updating the schedules with actual progress at the site and creating reports requires the necessary skills in using the related software. Moreover, progress is monitored based on activities. Consequently, it is not possible to monitor each stage in the project or each status of the activities in a large-scale project due to the excessive number of activities. However, in some cases, it is necessary to monitor the critical building elements at this level of detail to make proactive decisions. Reinhardt *et al.* (2004) developed an approach to collect data for the project management tasks by employing navigational models as well as identified that the interaction between data at different levels of detail is one of the needs for progress monitoring.

4D scheduling is another method that combines the schedule with the BIM model elements to visually represent the progress at the construction site. Visualization of the progress increases the decision-making capabilities of project managers through the latest data collected from the progress performance (Golparvar-fard *et al.*, 2009). Furthermore, 4D scheduling has been utilized for the planning and constructability review as well as for the improvement of the coordination and collaboration between the projects' stakeholders (Mahalingam *et al.*, 2010). Software packages, such as Autodesk Navisworks Manage, Synchro Pro Software, and Vico Office have functionalities for linking the model elements automatically with the work schedule through a common parameter (Figure 1, and Figure 2). Although 4D simulations are commonly used in the construction industry for the last decade and provide valuable information to decision-makers, a limitation is that they are based on schedules, which have a limited number of manageable activities. Since

the number of activities is limited, the granularity of the progress data is low. As a result, the representation of all statuses and stages of a large scale project is often not possible due to a large increase in the number of activities in the schedule.

The majority of studies that updated the BIM model based on the progress of building elements performed this update automatically by matching the activity ID and the 3D element ID. Kim et al. (2013) proposed a methodology for automatic updating of the 4D model by using image processing to monitor construction progress. Tutas et al. (2014) presented two approaches for automatic monitoring of the construction site, firstly generation of as-built data, and secondly comparison between planned and the as-built data. Getuli et al. (2016) described a workflow using apps and mobile devices for information exchange in construction. However, this approach only allowed visualization of the installation activities and required properly structured schedule information. In contrast, we present an approach for progress monitoring of the various status of building elements without the need for integration with the schedule information.

Several strategies for automatic collection of the construction progress data using advanced technologies have been explored by the researchers (Turkan et al., 2012; Shih and Wang, 2004; Golparvar-fard et al., 2015; Son and Kim, 2010). These studies used remote-sensing technologies (e.g., laser scanning) and demonstrated that visual information from the site could be collected as a point cloud data and compared directly with a building information model of the project. For example, Park et al. (2017) developed a real-time web and database-supported visualization method for presenting the latest information in 4D BIM models. Also, Chen and Luo (2014) proposed to integrate the construction quality management system and 4D BIM application for improving the current processes.

However, the previously developed methods for automatic collection of the construction progress data can only be used for verifying the construction progress percentage or checking whether the element is installed, and they do not provide information about other stages of the elements (e.g., tested or inspected). Moreover, the tracking methods of the construction progress that are used in the industry - even with emerging technologies- are based on the activities defined in the work schedules of the project which includes planned or installed status only.

The goal of this paper is to define an element based tracking method for the visualization of the actual progress of each element (i.e., the lowest level of detail in the model, for different custom status). The four main statuses of mechanical and electrical services during the construction phase, (i.e., planned, installed, tested and inspected) are represented for

each element in the building information model to demonstrate the potential use of the approach. These statuses were chosen since they are the ones that are challenging to track efficiently for electrical and mechanical components (Love et al., 2019). The other component statuses that can be potentially used for this purpose include “ordered”, “shipped”, “received”, “critical”, “waiting for inspection”, or “on hold”. Color coding is defined for each status and visualized in the 3D model based on the status of each element.

Figure 1: Sample view of Synchro software

Figure 2: Sample view of Autodesk Navisworks software

The BIM software, Autodesk Navisworks Manage (2018), was used for development of the new add-in. This software package was selected for two main reasons: (1) it is compatible with different software packages, and (2) it does not allow users to make any model revisions. The former provides access to all data collected from a wide range of file formats, whereas the latter prevents any unintentional model changes.

The developed add-in is user-friendly, simple to use and can be easily facilitated for different buildings construction progress visualization with the flexibility to define new status definitions. The BIM model of data center facility, which includes structural, architectural, mechanical and electrical elements, is used as a case study for the demonstration of the developed BIM add-in technology. A detailed description of the methodology including

demonstrations from the case study is presented, and the findings and conclusions are provided.

Description of case study building

The case study is a data center building that is under construction in Turkey and aimed to be completed in 2019. The facility is constructed on 75,486 m and includes 52,000 m of data center space, 3,000 m of conference space, 10,500 m of underground carparks, and 34,000 m of landscaping. Four floors of the data center building are selected as the case study to demonstrate the application of the developed add-in.

The main reason for selecting a data center building as a case study is its' unique requirement for monitoring of the construction progress. The data centers are value-added services that offer resources for processing and storing data on a large scale for organizations of any size. They have complex mechanical and electrical systems to operate 24 hours and seven days a week and are equipped with fire protection systems. Moreover, the data centers' electrical and mechanical services are tested by the international standards, whereas installation sequences need to follow the completion of commissioning. Also, the site inspections following the testing are the predecessor for following installations and need to be monitored and recorded. While the visual representation of the completed installation, testing, and inspections present very valuable information for the data center construction, it also improves the construction planning.

Methodology

Autodesk Revit (2018) was used as BIM authoring software since it is one of the most commonly used BIM authoring tools according to the surveys conducted by the National Building Specification (NBS) for last three consecutive years (NBS, 2016; NBS, 2017; NBS, 2018). Additionally, the same software supplier provides other tools fully compatible with their BIM authoring software. The main goal of our approach is to develop a custom add-in for an element based status tracking method that allows for updating multiple statuses at once. The used Autodesk Navisworks Manage 2018 comes with application programming interface (API) and software development kit (SDK). The add-in is developed in MS Visual Studio 2015 for Autodesk Navisworks Manage 2018. Moreover, Autodesk Navisworks Manage is used for visualizing, clash detection and 4D work schedule integration.

Each model element has specific parameters loaded from BIM authoring software, and their values are represented in the Properties tab after selecting the individual elements. These properties are grouped in different tabs based on the BIM authoring software use. It is possible to include progress data of each

building element (e.g., statuses) by adding custom parameters and values. However, it is not possible to select multiple elements and add custom parameters to these elements at the same time. Consequently, since there are high numbers of elements in the project, updating the statuses of elements is a tedious process when performed by hand.

The add-in is created using windows for the application template of MS Visual Studio with .net framework 4.5.2. Firstly, in the software, a connection is created between .net and .comapi for writing new parameters and their values to the elements (Figure 3). Next, the defined property category data is added to each selected model element and a control operation is defined to prevent any duplicated information (Figure 4).

```

COMAPI .net connect
Dim mState As Autodesk.Navisworks.Api.Interop.ComApi.InmQState10
mState = Autodesk.Navisworks.Api.Interop.ComApi.InmQState10Bridge.State

'create new Property Category Vector
Dim newVec As Autodesk.Navisworks.Api.Interop.ComApi.InmQPropertyVec
newVec = mState.ObjectFactory(Autodesk.Navisworks.Api.Interop.ComApi.InmQPropertyVec, eObjectType_m0aPropertyVec)

'propertycategory vector
For Each row As DataRow In dtProperty.Rows
    'create new property
    Dim newP As Autodesk.Navisworks.Api.Interop.ComApi.InmQProperty
    newP = mState.ObjectFactory(Autodesk.Navisworks.Api.Interop.ComApi.InmQProperty, eObjectType_m0aProperty)

    'set name, username and value of the new property
    newP.name = row.Item("Property_Name")
    newP.UserName = row.Item("Property_Username")
    newP.value = row.Item("Property_Value")
    'add the new property to the new Property Category
    newVec.Properties().Add(newP)
Next

```

Figure 3: Code for connection between .net and .comapi

```

Dim oItem As Autodesk.Navisworks.Api.ModelItem
Dim oDOC As Autodesk.Navisworks.Api.Document
oDOC = Autodesk.Navisworks.Api.Application.ActiveDocument

'add property category to each item selected
For Each oItem In oDOC.CurrentSelection.SelectedItems
    'select path of the item
    Dim oItemPath As Autodesk.Navisworks.Api.Interop.ComApi.InmQPath
    oItemPath = Autodesk.Navisworks.Api.Interop.ComApi.InmQPathBridge.ToInmQPath(oItem)
    'select Property Category from path
    Dim PropCat As Autodesk.Navisworks.Api.Interop.ComApi.InmQPropertyNode2
    PropCat = mState.GetObjectFromPath(oItemPath, True)

    If CheckBox1.Checked = True Then
        Dim PropCatAtt As Autodesk.Navisworks.Api.Interop.ComApi.InmQAttribute2
        Dim checkAtt As Boolean = False
        For Each PropCatAtt In PropCat.Attributes()
            If PropCatAtt.ClassName = TextBox1.Text() Then
                checkAtt = True
                MsgBox("You Selected Existing Tab " & TextBox1.Text() & " to remain." & vbCrLf & "Please give a unique TAB NAME to prevent duplicate data." & vbCrLf & "Sample: " & TextBox1.Text() & ".1",
                    MsgBoxStyle.OKOnly, "BIMCAVE")
                TextBox1.Text = TextBox1.Text() & ".1"
                Exit Sub
            End If
        Next
        'If the PropertyCategory does not exist add it
        If Not checkAtt Then
            PropCat.SetUserDefined(0, TextBox1.Text, TextBox1.Text, newVec)
        End If
    End If

    If CheckBox2.Checked = True Then
        Dim PropCatAtt As Autodesk.Navisworks.Api.Interop.ComApi.InmQAttribute2
        Dim Index As Integer = 1
        For Each PropCatAtt In PropCat.Attributes()
            If Not PropCatAtt.UserDefined Then Continue For
            If Not PropCatAtt.ClassName = TextBox1.Text() Then
                Index += 1
                Continue For
            End If
            PropCat.RemoveUserDefined(Index)
        Next
        PropCat.SetUserDefined(0, TextBox1.Text, TextBox1.Text, newVec)
    End If

Next
MsgBox("PROPERTIES LOADED UNDER NEW TAB " & vbCrLf & TextBox1.Text, MsgBoxStyle.OKOnly, "BIMCAVE")

```

Figure 4: Code for adding the property category data

The user can select multiple elements at the same time based on the status of each element (i.e., planned, installed, tested and inspected). Elements can be selected manually from the model or by using find items in-built functionality of the Navisworks. Element selections can be saved for future references and used through search or selection sets. While the selection sets are used to store the selected elements, they do not refresh the selection. Instead, the search sets refresh the selected elements based on the defined criteria in each run. On the other hand, the individual element selection enabled to change the

status of each element based on the progress at the site.

A custom tab name, parameter name and parameter value can be defined using the Add-in for the selected elements. The workflow for loading custom parameters is aimed to be simple and user-friendly with three basic steps: (1) selecting elements, (2) specifying the parameter values, and (3) loading to the elements, as the user form illustrated in Figure 5. It is also possible by the software in-built functionalities to filter elements based on the custom parameters loaded as well as change the visual properties, such as making transparent or change color temporary. Appearance profiler built-in functionality of the Autodesk Navisworks software is used for changing the elements' visual properties based on the defined values of their parameter. In the case study, the following set up was used: transparent for the planned elements, green for the installed elements, blue for the tested elements, and red for the inspected elements.

Figure 5: Add-in user form view

Structural and architectural model elements are selected manually from the model and progress status of the elements were entered to the model. Search sets used for loading the actual status to the elements are created for electrical and mechanical elements based on their installation, testing and inspection sequences. A sample room with a total area of 538 m2 was selected for visualizing the results of our approach using the developed add-in and in-built functionalities of Navisworks. In addition to structural and architectural elements, the sample room has 2,080 elements including cable trays, bus bar system, electrical equipment, sprinkler and ductwork for the ventilation. The status of each

element is loaded using the add-in for compliance with construction progress for six consecutive months.

Results

The work schedule used for this project has 1,855 activities including the contractual, design, and construction activities. The construction phase only includes the installation activities, whereas the hand-written daily reports monitor the status of tested or inspected elements. It is a common practice to define the installation activities of the work schedules based on floor, system or zone. Consequently, the monitoring for individual elements is not possible with the existing work schedule breakdown. Besides, the project has 131,952 model elements that need to be monitored. As a result, a large number of building elements prevents the creation of the individual activities for each element, and the installation progress monitoring is limited with the activities defined in the work schedule. Table 1 presents a summary of the status change of the model elements for six months. Furthermore, Figure 6 presents the visualization of the monthly status change of model elements. The model elements that are monitored using this approach can also be more specific. For example, the hanger and support of the piping systems can also be monitored. This level of detailed information provides the decision-makers with a higher level of understanding of the progress at the site.

Table 1: Status change of model elements for six months

Model Elements	Months					
	1	2	3	4	5	6
Structural System	Installed	Installed	Installed	Installed	Installed	Installed
Cable Trays	Planned	Installed	Tested	Inspected	Inspected	Inspected
1,000A Busbar	Planned	Planned	Installed	Installed	Tested	Inspected
3,000A Busbar	Planned	Planned	Installed	Installed	Tested	Inspected
4,000A Busbar	Planned	Planned	Planned	Installed	Installed	Inspected
5,000A Busbar	Planned	Planned	Planned	Installed	Installed	Inspected
Sprinkler system	Planned	Planned	Planned	Planned	Installed	Tested
HVAC system	Planned	Planned	Planned	Planned	Planned	Tested
Main Equipment	Planned	Planned	Planned	Planned	Planned	Installed

During the construction phase, the progress data is collected using 2D drawings, daily reports, site photographs (e.g., laser scanning). In 4D process, all this data for individual elements collected from the site is not effectively used. The progress is only represented if it is related to a dedicated activity in the schedule. Therefore, the data available for individual elements are not used for visualizing the construction progress. Instead, only the progress based on the activity definitions can be visualized. The results of the proposed approach show that it is possible to visualize the construction progress data based on each element.

Figure 6: Visualization of 6 months progress: (a) first month progress; (b) second month progress; (c) third month progress; (d) fourth month progress; (e) fifth month progress; (f) sixth month progress; (g) color coding for status; (h) 3D model of the case study room

The visualization of the case study results shows different status of the elements in a 3D environment.

The two main advantages of the developed approach are: (1) it allows selection of individual model

elements and loading data to these elements, and (2) it supports the selection of the model's elements from different systems and monitoring progress status of each element. In our case study, we defined two additional status 'tested' and 'inspected.' On the other hand, the use of the 4D scheduling method would require the creation of the additional 263,904 activities next to the existing installation activities.

Conclusions

In the common practice, visualization of the 4D process is limited with the activities defined within the construction schedules, and it is not possible to define the activity of each element status. This paper proposes a new add-in method for visualization of the status progress of the building elements (e.g., inspected, tested) within the BIM models. The add-in is developed in Navisworks, and it enables project monitoring based on the individual elements. The effectiveness of the developed method is tested using the complex data-center building as a case study. A sample room with a large number of elements is selected to present the monthly construction progress visualization over the six months. The results show that it is possible to successfully monitor construction progress based on the individual elements in the model. This approach increases the planning ability of decision makers and allows easier foreseeing of the potential problems.

One of the limitations of our approach is the requirement of Navisworks software. However, Navisworks is a widely used tool in the construction industry, and it comes with other Autodesk products. Another limitation of the proposed approach is that the construction progress is monitored based on the elements that do not have any relation with the construction schedules (e.g., actual dates). While the main goal of this paper is to propose the new method for visualization of the construction progress based on the model elements, separate parameters within the developed add-in can be used to load actual dates for the elements.

The future work will include the expansion of the proposed method to allow instant data integration with handheld devices, which can be used for the updating of the element parameter values. Furthermore, further integration will be developed - using the unique ID of model elements and work breakdown structure codes of schedules- between construction schedule software and proposed method for updating the actual schedule data from the add-in. Future work will include adding additional parameters such as the actual dates, related entity names, and reference document links to the individual elements. This approach will enhance the visualizations of the construction progress and create a valuable database for the project handover and facility management.

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BIM-BASED HOLONIC SYSTEM FOR REAL-TIME PATHFINDING IN BUILDING EMERGENCY SCENARIO

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Abstract

Emergency management can benefit from advanced information and communication technology (ICT), since they can support officers in charge with rescue operation to deal with urgent decision within a really short deadline. Further enhancement can derive from the application of holonic systems, inherited from the manufacturing industry, to tackle unforeseen scenario. The aim of this research is to develop a BIM-integrated technology for the real-time pathfinding during emergencies. A virtual reality platform, exploiting building topological data from the digital model, can support the standard emergency approach if an unexpected event voids the network of pre-determined paths. The developed system has been tested in a large mixed-used building assumed as case study.

Introduction

Building Management Systems

Building automation systems (BAS), also known as building management systems (BMS), denote a wide range of computerized building control systems, from special-purpose controllers, to standalone remote stations, to larger system including central computer stations. A BAS comprises several subsystems which are connected in various ways to form a complete system. The system must be designed and engineered around the building itself to serve the services systems for which it is intended. Consequently, although the component parts used may be identical, no two systems are the same, unless they are applied to identical buildings with identical services and identical uses (Wang S., 2009). BMS, with their typical hierarchical structure, are usually able to reach their goals in an efficient way and with no faults, whereas they fail to stick to pre-determined targets in the presence of disturbances. In fact, traditional systems cannot pursue the assigned task if any unforeseen events occur. Their rigid structure makes it very difficult to tackle unexpected scenarios. As low-level modules have to consult higher hierarchy levels in case of a disturbance, their reactivity becomes weak. Furthermore, global decision-making is often based on obsolete information (Valckenaers et al., 2016). Building services include HVAC systems, electrical systems, lighting systems, fire systems, security systems and lift systems. In industrial buildings they may also include the compressed air, steam and hot water systems used for the manufacturing process (Wang S., 2009).

In this paper, fire and security systems for the emergency management will be studied in depth in order to overcome the limits of the traditional BMS. Emergency management, since directly affects safety of people, represents a relevant issue in each phase of building lifecycle, from a foresighted design of buildings and infrastructures to the elaboration of emergency plans according to specific regulations. Emergency scenarios are even more relevant as case studies, if the high frequency of unexpected events affecting them is considered. The traditional approach to the emergency management is based on a deterministic forecast of main scenarios. The emergency plan resulting from them has a key role, although it does not consider the totality of possible scenarios. As a consequence, it is regardless of contextual, changing and unexpected events that may happen and seriously affect the effectiveness of emergency measures. The limits of such a knowledge-based approach are confirmed by several examples of complications in the emergency operations. To name one, during the emergency response to the September 11, 2001 attack on the World Trade Centre, commanders on the scene were unable to communicate to '911' Public Service Access Points (PSAP) that people should evacuate the building (Uliuru et al., 2006). As a result, PSAP operators complied with New York City's standard operating procedure for hi-rise fires and advised callers to stay in impacted buildings. The '911' system was inadequate for handling a major disaster and could not adapt to the emergency. The final death toll 2749 may have been substantially reduced if the PSAP's were adaptive in coping with the overload. Moreover, commanders trying to evacuate fire fighters from the north tower during the World Trade Centre disaster were seriously hampered by ineffective radio communications; the final death toll 343 of New York fire fighters may also have been substantially reduced if the system controlling the radio communications was also adaptive (Uliuru et al., 2006). To name another example, the Grenfell Tower fire produced a high number of victims not only for technical reasons, due to the employment of a not proper cladding system and to a lack of separated fire boxes into the building, but also to a mistake in the emergency evaluation (Lane, 2018). The "stay put" strategy, led by a tardive declaration of the situation as a major incident with the consequent delay of one hour in the evacuation process, has revealed as a fatal mistake in the rescue operations (Lane, 2018). Furthermore, a traditional emergency plan does not facilitate the

operational use. In fact, it remains as a plain-text document which is difficult to consult during an excited situation due to an oncoming danger. In other words, a way-out plan hung on the wall cannot help incisively to find a viable exit route. The fire in the Rhode Island station club represents an example of how a not profound knowledge of the building in which people were located affected the evacuation process: a study has demonstrated that people did not use alternative ways-out since they ignored their presence (Grosshandler et al., 2005). While the main exit doors were obstructed by the smoke presence, there were no indication to use alternative paths to escape from the building; therefore, the evacuation process was affected by a fatal delay (Grosshandler et al., 2005).

Most traditional studies about pathfinding for fire emergency evacuation considers only 2D navigation and find it difficult to respond to the ever-changing emergency circumstances due to their limitations in utilizing real-time building information. Recent researches introduce the BIM-based pathfinding to detect traditional exit routes; a common feature is the manual pre-processing phase which extracts from the IFC project all the needed building information. Amongst them, Wang et al. (2014) focus on the evacuation training; Xu et al. (2017) compares the results from a 2D and 3D spatial navigation; Ismail et al. (2017) applies graph databases and graph theory concepts for advance analysing of BIM models as well as pathfinding.

Starting from the above-mentioned shortcomings and previous researches, the current one proposes a contingent approach which exploits a BIM-based holonic technology to overcome the limits of the traditional BMS in real emergency scenarios. The building digital model, imported in an environment endowed with physics engine, provides all the necessary data for 3D ways-out detection in real-time. The developed holonic architecture introduces resilience and emergent collaboration in order to tackle unexpected events by means of alternative and unconventional escape solutions. This paper is organized as follows. The following section provides a description of the system architecture. Then, a section describes the Virtual Reality Platform. The next one provides a description of the BIM integration. Afterwards the Bayesian Selector is described. Another section provides a description of Real-Time Pathfinding and shows the simulations results. The last one is devoted to conclusion.

Holonic Theory

The holonic concept, which is the basis of holonic management systems, is the key enabler to tackle unexpected events and overcome the limits of the traditional BMS. The holonic theory was introduced in 1967 by Koestler (Koestler, 1967) to explain the evolution of biological and social systems. Likewise, in the real world, where almost everything is at the same time a part and a whole, each holon can be part of another holon (Valckenaers et al., 2016). In fact, the word holon is the combination of “holos”, which in Greek means “whole”, and the suffix “on”, which suggests a part (Wang L. et al., 2015), (Verstraete et al., 2006), (Giret et al., 2004). In the

manufacturing field, holons are autonomous and cooperative building blocks, since they can both control the executions of their own strategies and develop mutually acceptable plans (Valckenaers et al., 2016). Furthermore, holons consist of an information-processing part and often a physical-processing part (Valckenaers et al., 2016), (Wang L. et al., 2015), (Verstraete et al., 2006). The former is responsible for high-level decision making, collaborating and negotiating with humans and other holons, while the latter is a representative of its linked physical component and responsible for transferring decisions and instructions to it (Wang L. et al., 2015). According to Koestler, a holonic system or holarchy is then a hierarchy of self-regulating holons that function (i) as autonomous wholes in supra-ordination to their parts, (ii) as dependent parts in subordination to control at higher levels, and (iii) in coordination with their local environment (Valckenaers et al., 2016), (Koestler, 1967), (Giret et al., 2004). Therefore, holonic architecture combines high and predictable performance, which distinguishes hierarchical systems, with the robustness against disturbances and the agility typical of heterarchical systems (Verstraete et al., 2006). In this way, systems' resilience is guaranteed. Holonic management systems, which have been successfully applied in the manufacturing field, can constitute a novel technology to tackle unforeseen scenario variations. Indeed, the autonomy and cooperation of their elementary units, the holons, makes it possible to avoid the rigid structure of hierarchical systems and therefore respond quickly to disturbances (Valckenaers et al., 2016).

System Architecture

The architecture of the developed holonic system, depicted in Figure 1, supports fire emergency management and rescue operation, detecting the most effective way-out. Its aim is not to substitute the actual approach foreseen by regulations, rather to enhance the standard emergency plan, detecting unconventional path to exit the building, if an unexpected event occurred. The architectural principles are shortlisted as follows:

- *Real-time effectiveness*: it must regard both the information flow and the decision-making process. Since the system is continuously evolving, especially in complex scenarios like emergencies, it is not feasible to represent all the changing status it assumes, in order to provide the proper solution to the occurring situations. Moreover, the response of the system must be sufficiently reactive in order to result effective to face the situations that are in place.
- *Proactive and unconventional problem solving*: on the basis of the information gathered in a real-time manner, in order to be sufficiently resilient, the system must be capable to extract the information useful to reach its objectives also by general data, as well as to provide escape solutions with the employment of unconventional means.

- *Resilience*: the system must be reactive and adaptive to the new possible configurations that may occur, without compromising its primary function of managing the emergency scenario. Failure, interruptions, damages to the standard communication backbone systems, as well as injuries or obstructions to the usual evacuation means, must not impede the main objective of keeping people safe during emergencies.
- *Emergent cooperation*: the system architecture embodies the capability of the holons to cooperate in temporary associations, namely the holarchies, introducing the “emergent cooperation”. This concept can be described using a metaphor: the behaviour of these agents is similar to the one belonging to the birds of a flock; no one is able to manage flock’s shape and dimension, but everyone takes care of maintaining flock’s trajectory, flock’s speed and minimum distance from its fellows. Although no one of the birds has a complete view of the scene, the behaviour described above is the result of a “emergent collaboration”. This kind of cooperation is not so onerous for birds because it is supposed to be integrated within their DNA and, therefore, instinctive. The same functioning characterizes the agents inside the developed architecture.

The system architecture is composed by different layers interacting each other according to a publish/subscribe scheme, whose central concept is the notion of *topic*: each node/layer of the architecture subscribes and some other

publishes information on the *topic*. In other words, the *topic* is simply the database content itself without intermediate language adapters: the unique language is the database language and its queries. Hence, the architecture layers behave like a human being that only subscribes to interesting events/information and publishes relevant events/information, which are specifically useful for the occurring situation, complying to the actual needs (Bonci et al., 2017).

The different layers can be clustered by function according to the PROSA reference architecture (Valckenaers et al., 2016), a conceptual architecture for manufacturing control, that has shown great potentialities to be applied also in different context. The acronym PROSA stands for product-resource-order-staff architecture and refers to the different types of holons. Three basic types of holons can be distinguished: product holons, resource holons, and order holons. Staff holons are optional and can be added to provide the other holons with expert knowledge (Valckenaers et al., 2016). In PROSA, the holons’ physical part belongs to the world of interest, that is the part of reality which falls within a certain scope relevant for the application (Verstraete et al., 2006). In Figure 1, the PROSA analogy is highlighted identifying resource, product and order holons. Finally, the environment is the real-world scenario where the holons operate, namely the fire occurring and the countermeasures to be taken at the end of the elaboration process. The highest architecture layers, namely the General Safety Objectives and the Generic Metaplans, correspond to the order holon, which

Figure 1. System architecture of the developed holonic management system.

in the manufacturing system represents a task that needs to be executed, for example the delivery of a package (Valckenaers et al., 2016). The General Safety Objectives represent the always valid target: “save all the people inside the building”. As a consequence, the Generic Metaplans are triggered and fed with real-time data from the Virtual Reality Platform. The output of this elaboration are the general processes to be executed, which may be represented by the generic instruction “stay in/go out” and are published to the following layer. Thanks to the generality of the high-level setting, the resilience architectural principle is guaranteed and the resulting system is applicable for every building, without the need to configure it manually every time. This is a key feature that distinguishes the developed architecture from classic BMS.

Virtual Reality Platform

The Virtual Reality Platform (VRP) is the heart of the resource holon which corresponds, in the logistic context, to resources like all transport means and material handling equipment (Valckenaers et al., 2016). In the developed system the VRP is implemented using the Unity 3D game engine. It has been selected as the most suitable tool because of the following characteristics:

- high interoperability with other software, including the capability to integrate several functional mockups afferent to different engineering disciplines;
- presence of a physics engine that provides physical behaviour to the components of the scene, basically the correct acceleration and the affections by collisions, gravity and other forces, making the simulation of a great likelihood with the real world;
- possibility to introduce artificial intelligence by scripts, based on C# or Java programming languages, or by means of visual programming.

In other words, Unity 3D offers an extremely realistic environment to simulate a fire emergency scenario of the case study and building occupants' behaviour using artificial intelligence. The VRP constitutes a dynamic hub able to collect IFC data from BIM and real-time data from pervasive sensors distributed in the real world. The interconnection with the BIM software Autodesk Revit has been established through an IFC Loader, based on the IFCEngine DLL Library (RDF Ltd., 2006). This component makes it possible to easily import topological information, materials properties and all semantic information from the digital model, once exported in IFC format. The interconnection with sensors, which has not been tested in this research step, is one of future developments. The technological solution to this issue is ASP.NET Core SignalR, an open-source library that simplifies adding real-time web functionality to apps. Real-time web functionality enables server-side code to push content to clients instantly (Microsoft Corp., 2018). As depicted in Figure 1, the VRP acts as a collector of heterogeneous data and represents the proper environment where the required knowledge can be produced and published. In this way, real-time data are available for each

subscribing layer of the architecture.

A* Pathfinding Project Pro (A*PPP) (Granberg, 2017), is one of the most popular dedicated pathfinding Unity assets and the benchmark for quality pathfinding in Unity. Unlike Unity default NavMesh (Unity 3D Doc., 2018), it supports dynamic updates of the graphs at runtime. Hence, A*PPP, applying the A* algorithm, detects in real-time the most effective way-out. If the usual escape route is obstructed by smoke, fire, collapsed building elements or other kinds of accidents, the A* algorithm can detect unconventional ways-out through internal doors.

BIM integration

The system architecture integrates the BIM technology with the aim to improve the context awareness during the emergency management. The building digital model, coherently updated during the whole lifecycle, provides in real-time accurate building information, that goes further beyond the static and poor information usually contained in emergency plans. In fact, a BIM organizes and stores contextual, geometrical and materials information, facilitating the consultation at any time, especially by users and rescuers during excited moments. Building digital information lay the basis for automatic detection of alternative path outwards, whether pre-determined standard routes result unviable. Moreover, BIM is proposed not only as a comprehensive provider of the building data, but it is subjected to a proper *semantic enhancement*: some building elements can be exploited in an unusual way in respect of their main purpose and become evacuation means in an unconventional manner. These contributions appear even more relevant, if we consider the possibility to have random visitors inside building affected by a poor awareness of the spatial distribution. Furthermore, the building information model, once imported in the VRP, can be updated with data about the monitored spaces deriving from sensors deployed on site. Real-time location systems (RTLS), integrated with BIM, provides real-time information about a relevant aspect like the position of people trapped during an emergency. As mentioned in the previous section, BIM data can be leveraged within the VRP by means of an IFC Loader, completing the role of the resource holon.

Bayesian Selector

The Bayesian Selector (BS) is conceived as the translation into a Bayesian network of an expert's knowledge. Bayesian networks, which constitute a powerful mean to represent phenomena affected by a high level of uncertainty, are a probabilistic graphical model that uses Bayesian inference for probability computations. They aim to model conditional dependence, and therefore causation, by representing conditional dependence by edges in a directed graph. Through these relationships, one can efficiently conduct inference on the random variables in the graph through the use of factors (Soni, 2018).

Figure 2. Bayesian Selector.

In the fire emergency management, the BS, fed by real-time data from the VRP, detects which strategy or plan is probabilistically the most effective to exit safely the building in fire. As shown in Figure 1, it is composed by a generic part and a specific one, respectively linked to Plausible Plans and Multi-Target Partial Plans. The Generic BS suggests the most effective preliminary escape strategy (called also Generic Plausible Plan) amongst those ones valid for any building. The Specific BS detects the most promising escape plan (called also Specific Plausible Plan), instantiated for the analysed building. All these layers, according to the PROSA analogy, constitute the product holon, which contains the knowledge on how instances of a specific task type (represented by order holons) can be executed by the resources (Valckenaers et al., 2016). In Figure 2, BS's orange node, namely "Fire Scenario", constitutes a Boolean variable, which notices the occurring fire. Green nodes represent the Generic Plausible Plans; for example, "Stairs and Emergency Door" represents all the exit routes which exploit stairs and emergency doors.

They comprise not only the standard exit route suggested by the emergency plan, but also alternative and unconventional ways-out through internal doors connecting adjacent rooms. Purple nodes are the Specific Plausible Plans, automatically instantiated for the case study building exploiting the technology described in (Bonci et al., INDIN 2018) and (Bonci et al., ETFA 2018) and on the base of real-time data published by the VRP (for example, "Roof and Helicopter" stands for "lead people to the roof and pick up them by a helicopter"). Finally, blue nodes represent building's features (for example "Flat Roof" stands for "is the building's roof flat?") whereas yellow ones represent resource availability (for example "Stairs Available" stands for "are the building's stairs available/viable?").

Real-Time Pathfinding

In order to implement and test the developed architecture, the mixed-use building Eustachio, located in Ancona

Figure 3. BIM of Eustachio loaded in Unity 3D (VRP) in order to simulate a fire scenario.

(Italy), has been chosen. The building belongs to a major complex occupied by the Faculty of Medicine of Polytechnic University of Marche. This eight storeys-building presents a quite regular shape with two major blocks on the north and south side, containing spaces devoted to heterogeneous scopes: classrooms, scientific laboratories, administrative offices for students, a library, books storage rooms, services. The two main blocks are connected by the two double stairwells of the building. The choice has fallen on this edifice for its characteristic of public building with several uses that may involve variable flow of different people inside it: estimated between 100 and 2320 individuals and characterized by several age ranges and, more specifically, owning a different level of knowledge of the building. Finally, the presence of inflammable substances in several laboratories leads to simulate the fire scenario in this building (see Figure 3), since this is one of the most common and disruptive emergency situations, often affected by unexpected events and mistakes in the management of the evacuation process.

The Eustachio's standard emergency plan, provides a network of pre-determined ways-out, indicated on site by dedicated panels. For example, as shown in Figure 4, the black line points out the route to reach the stairwell and so the safe place outside. If a fire occurs in a room and expands up to the hallway, the standard exit route is blocked and the user cannot rely on the emergency plan to

reach the closest safe place (see Figure 4). In cases like this, it is not easy for the user to search for an alternative way-out, because he could be a random visitor with limited

knowledge of the building. Moreover, the smoke, which expands throughout the hallway, limits visibility and the possibility to get oriented, also in a familiar place.

Figure 4. Eustachio's emergency plan: example of standard way-out (black line) obstructed by fire and smoke.

Figure 5. Standard way-out detected by A*PPP, coherently to the emergency plan for a normal scenario.

Figure 6. Alternative way-out detected by A*PPP for an unforeseen fire scenario.

The developed system, utilizing building updated data, hosted in BIM and loaded into the VRP (see Figure 3), is able to carry out a real-time pathfinding to tackle emergency scenarios, unforeseen by the standard emergency plan. The switch from the standard way-out (see Figure 5) to the alternative one (see Figure 6) occurs automatically, as soon as the fire is detected by sensors and simulated in the VRP. A*PPP, detecting all the connected floors surfaces (highlighted by purple color in Figure 5 and Figure 6), finds rooms internally connected by doors. The alternative path circumvents the zone affected by fire and smoke and leads the endangered users towards the closest stairwell. In order to readily inform them about the ever-changing plan, a dynamic signage system (Galea et al., 2014) and a directional sound system (Plocher et al., 2011) can be integrated. If signage disappears behind the smoke, directional sound system continues to be effective. In fact, it uses verbal messages and a broadband multifrequency-based noise that allows the brain to work out exactly where the source of this sound is located. At the same time, the fire commander, equipped by a ruggedized tablet (Luyten et al., 2006), is informed about the evolving scenario and able to coordinate other firefighters by radio communication.

Conclusions

The holonic management system, described in this paper, improves the usual emergency management approach, leveraging more updated and significant information. Since a complete representation of every incidental events that may occur is not feasible, the current work proposes to move from a knowledge-based approach to a contingent one. Exploiting data from BIM and deployed sensors, the VRP computes real-time pathfinding to tackle scenarios unforeseen by the standard emergency plan. The approach described in the current paper is able to detect in real-time alternative and unconventional ways-out to be applied during emergency. Applying holonic theory and Bayesian inference, an effective emergent collaboration between low level holons makes it possible to get away safely; it can be done if a semantic enrichment labels some building elements as evacuation means. The developed system architecture tested in a large mixed-use public building, shows its potentiality through the contribution given to officers in charge of emergency management. More in details, the results of real-time pathfinding, support endangered users as well as rescuers, dealing with urgent decision within a really short deadline.

In future researches, a continuous update of IFC data will be tested in order to guarantee system functionality also after building refurbishment. Moreover, the connection between sensors and VRP and the implementation of the BS represent relevant matters of work in order to automate the functioning of the whole system.

Nomenclature

ICT (Information and Communication Technology),

BIM (Building Information Modeling),

BAS (Building Automation Systems), B

MS (Building Management Systems, HVAC (Heating, Ventilation and Air Conditioning), PSAP (Public Service Access Points), VRP (Virtual Reality Platform), BS (Bayesian Selector), PROSA (Product Resource Order Staff Architecture), IFC (Industry Foundation Class), A*PPP (A* Pathfinding Project Pro).

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DEVELOPMENT OF A SOFTWARE PROGRAM TO GENERATE A WBS FOR EARTHWORK PROJECTS

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Abstract

It is very important while creating a schedule plan for any project, to have a suitable work breakdown structure. It is well known that in earthwork projects, there are several criteria that effects the WBS as soil type and level of excavation. The present research shows the steps of the development of a software program using matlab and Microsoft excel. Taking into consideration the topography of the ground and the soil type. The research work aims to create an automated software program that calculates the most economic platform level and creates a WBS for Earthwork projects. The results of the software had been used to be exported to Microsoft Excel in an easy way to be used in the planning stage. In addition, an interface was created in order to make the software program user-friendly and easy to use. The software has been validated by two tests, a theoretical area and a real case study.

Introduction

Background

Early planning is very important in order to create the best combination of price, quality, and time. Earth work can be one of the main activities of most mega projects. One of the early tasks is to choose the best platform levels to begin construction especially in rough terrains. The detailed calculation of the cut and fill volumes are the basics of an effective and economic design. The best way to organize such a big task is to create a Work breakdown structure (WBS) which categorizes the main points of the work. Among different ways to create a WBS, the computerized process can help to reach the most economical solution in short time avoiding the possible manual errors. Therefore, the best approach is always an automated generation that calculates and categorizes all project components in a logical procedure.

In this study, earthworks for large areas (e.g. large industrial areas, compounds, resorts, and huge landscapes) have been considered. This is referred to a mass-haul problem as the project task will be moving materials from one location to another. It would be catastrophic to start such a big task without a detailed earth work plan considering areas and volumes of cut and fill as well as type of cut materials

and specifications of the fill materials. Such a study can help the engineer to define the amount of reused cut material and the amount of required imported materials. This procedure can develop an economic and time-saving project.

Software

This study shows the development of a software that calculates the cut and fill quantities with the most economic Platform level of the area. The program is based on only one platform for the whole project area. The program was validated using a real case study.

Literature review

There are different methods for calculating the Volume of a shape. Among many methods, Section method, Simple prisms method, Layer thickness method, Complex prisms method, and cross-sectional method are commonly used.

Different techniques can be explained as follows (Janić et al., 2015):

Section method

For linear objects, the common used method is the cross-sectioning method. This method can be used for surface objects as well, and is used as a control method. The advantage of this method is that visually depicts conducted excavations and embankments, and disadvantage is insufficient accuracy for large profile intervals.

Simple prisms method

This method consists in summing volumes of simple three-sided prisms formed from a network of triangles. TIN triangles are used to form the vertical three-sided prism to some reference elevation, usually zero elevation. In the case of calculating the volume between two terrains surfaces, i.e. upper and lower, their difference is the volume of excavation or embankment. The disadvantage of this method is that both models must have identical external border, and it is not possible to get the information separated for excavation and embankment. If the excavated material is dumped within the common external border, this method will give the volume of zero, which is not correct. This method is applicable only when the excavation is transported outside the

external border.

Layer thickness method

In this method, the points on the first model (vertices of triangles) are projected to the second model and calculated height differences are thicknesses in the points of the first model. Also in the points of the second model similarly are calculated height differences to the first model that also give the thicknesses in these points to the first model. The third set of points consists of the polygon boundary vertices, where the layer thicknesses between two models are also calculated. Thus, obtained thickness now serve as input data for the thickness model formation, where the points of both models and the layer thickness in them as variable Z , forms a model, whose volume should be determined. This method has the advantage over the previous one, because both models do not necessarily have identical external border, and which gives information separately for excavation and fill. The disadvantage of this method is that the upper and lower model may not have big changes in elevations. It is recommended to calculate the volume of ore reserves from the exploration boreholes.

Complex prisms method

This method gives the best results, because it takes into account all the inputs from both terrain models: points and break lines. It consists in projecting a network of triangles of the first model to a network of triangles of the second model, resulting in a set of polygons

Cross-sectional method

The cross-sectional method is most commonly used for calculation of site excavation on sites where the grade around the building changes dramatically (Peterson 2012). Like the average-width-length-depth method, the average-end method, and the modified-average-end method, the cross-sectional method produces an approximate volume and is less accurate than the geometric method. The following steps need to be completed to calculate the volume using the cross-sectional method:

Step 1: Divide the site into grids.

Step 2: Calculate the cut or fill at each grid intersection.

Step 3: Separate the cuts and fills with a zero line.

Step 4: Calculate the volume of the cuts and fills.

Methodology

Method used in the software

Following the literature review, and comparing different methods in terms of the calculations and suitability, the “Cross-section (grid) Method” was

found best suited for large open areas because it is not complicated and gives results with high accuracy. This method divides the area into a network of small simple four-sided rectangular. The dimensions of the developed mesh are fixed to a square with fixed side width. The volumes will be calculated from the area of the rectangular multiplied by the difference between the upper and lower surfaces. The upper surface represents the natural ground level and the lower surface is the Platform level that can be defined via an iteration process. The volume calculation is classified into “Volume cut” and “Volume fill” depending on the sign (positive or negative respectively). The start value of the platform level is chosen equal to the average of the z -coordinates of the points (height of the ground surface), and then it will be increased or decreased by a certain value (e.g. in this work 0.15m) in an iteration process till the value of the cut and fill volumes are nearly equal. The details of subsoil conditions are defined through the boreholes conducted as part of the site investigation. As shown in Figure 1, the fill volume is divided into three parts as follows: the distance between the finishing level to the foundation elevation will represent the so-called “foundation depth” and will be assumed 1.5m and consists of silica sand; compaction will be done for every 0.25m lift. 3m under the foundation elevation will be filled with 1:1 sand and crushed stone which will be compacted every 0.3m. And the rest, till the initial natural ground surface, will be filled with well grades material of size from 0 to 15cm and compacted every 0.5m.

Figure 1: Fill material details

There is also the possibility of getting a volume value of zero, that means that the initial ground surface and the platform elevations are identical at this cell.

Work procedure

Flowchart construction:

After collecting the data and deciding how the calculations will be performed, a flow chart was developed. This flowchart shows the steps and the approach that the program will take.

The software will start with taking following input

data:

- Area dimensions
- Spot point coordinates
- Borehole data

Then the calculations are made in the software:

- 1st assumption of the Platform level by taking the average of all spot point heights
- Calculating the Volumes and classify it into 'Volume cut' and 'Volume fill'
- Modification of the platform level depending on the differences between the volumes
- Final calculation of cut and fill Volumes
- Calculation of volume details

The software shows following output data:

- Three 3D-Graphs
- WBS in form of an Excel-document with sheets for 'Platform level', 'cut', 'fill' and 'no work'.

Program development:

There are lots of methods for writing a software-code. It was decided to write a MATLAB-code considering its advanced graphic opportunities. A case study was calculated manually to validate the software and to check its accuracy (see chapter 6 "Case study"). At the end, a graphical user interface was developed to help the user to enter the inputs and understand the calculated results easily in a visible format (see chapter 5 "Graphical User Interface").

Program limitations

The program has some limitations. The following list clarifies the limitations of the software:

- The area that will be calculated should be rectangular with a length and width multiple of 50m.
- Grid dimensions are 50X50m.
- The whole area should have only one platform.

Basic assumptions:

- The origin of the area will be in the lower left corner.
- In every grid, there is a spot point and a Borehole point.
- The unit used in the program are all in SI unit

Software development

Theoretical case:

To create the software and write the code it is always better and easier to have a test with its results to verify step by step everything that will be calculated. This test was assumed as an area with size 350x250m.

Manual test results:

Before writing the code, manual calculations were done to have values for comparison while writing the code step by step. These manual calculations were done with the help of an excel sheet.

Graphical User interface

Definition of "Graphical User interface" (GUI)

The software was developed using MATLAB and a graphical user interface was developed to let the software be user-friendly.

Shape of the GUI

The designed shape of the GUI is shown in Figure 2.

Figure 2: GUI shape

1.1. Inputs:

1. The dimensions of the area
2. The coordinates of the spot-points
3. The borehole data

1.2. Outputs:

1. The three 3D graphs (initial topography, the calculated platform level, and the combination of both).
2. The excel document with all calculated details in 4 different sheets (platform level, cut, fill and no work).

Case study

Any program that is developed has to be tested on a real project with logical values to check that the software is working right and to approve the software.

A real resort project near the beginning of the Alexandria road was chosen as a verification

example. The surface topography was given in an AutoCAD file with the x,y,z-coordinates of each point and the borehole-data taken from the site. The area has a highly irregular shape as shown in Figure 3. To simplify the required work, only a part of the project is considered from the test as shown in Figures 4 and 5. The 50x50m grids were drawn inside this area and everything else was deleted from the file to work on the chosen part (see Figure 5). Three boreholes were applied to represent the whole subsoil conditions of the studied area (Figure 6).

Figure 3: Original area of the real test

Figure 4: Small area taken from the map

Figure 5: The Grids and data used in the software

Figure 6: Borehole data of real test

Software results

The software results associated with the case study project are presented below in figure form. In particular, Figure 7 presents the ground level surface graph, Figure 8 the platform level graph while Figure 9 the combined picture of the previous graphs.

The software produces automatically an excel document that is divided into 4 sheets that includes all the calculated volume amounts and their different materials. By comparing those results with the manual calculations done, the software was proven to work accurately.

Figure 7: 3D graph of ground level

Figure 8: 3D graph of the platform level

Figure 9: Combined 3D graph with platform level and ground level

Conclusions

Overview

In conclusion, this work shows the development of a software that provides an automated work break down structure. The software uses the dimensions of any rectangular-shaped area, the x,y,z-coordinates of the spot points, and the borehole-data of an area to calculate the most economic platform level with the cut and fill volumes and their details.

Benefits of the developed software

The results of the software are accurate, as the software was tested a lot. The results can help construction managers to plan the earthwork of large open areas. The three graphs that are created by the software helps to understand the process of working on the area, which can be used to present the work. The excel document with all the detailed amounts is very easy to read and shows all the details of the site activities and their locations according to the grid numbering system. The details are very useful for the construction manager to estimate the cost that will be needed to prepare for bids. One of the main objectives is to develop a user-friendly program and to present the results in a simple format.

Recommendations for future studies

This software has some limitations that should be addressed in the future:

The areas calculated by the software has to be rectangular with a length-dimension of multiplies of 50. That could be improved through future studies.

In the developed software only one platform-level is created to fit more site environments, the area could be divided into more platform-levels.

The software works with one borehole in each grid, which means in each spot; this could be changed into a calculation of three-dimensional geotechnical model that can be developed depending on the conducted boreholes.

The software could be linked to an excel sheet that contains all the input data instead of entering them manually.

The software can be further developed to consider both one dimensional (linear) projects such as highways as well as three dimensional projects in one package with all features described in this paper.

Comparison between the developed software and similar work

After searching a lot for similar papers to gain more information and experience regarding the topic, I could not find similar papers that hold the same address or content.

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BUILDING INFORMATION MODELS ARE DIRTY

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Abstract

Building Information Modelling (BIM) processes imply an intensive use of information. Nevertheless, several studies revealed critical issues in the data quality of information models. While some studies presented interesting works in the evaluation of model quality with reference to IFC. The analysis of the data quality issues in native models remains a research gap as well as the understanding of where these issues are generated. This research proposes an analysis of four information models to evaluate and classify data quality issues according to three dimensions, i.e. accuracy, coherence and completeness. Results highlighted user behaviours and/or technological limitations in real-world applications.

Introduction

Building information modelling (BIM) is transforming the way construction projects are developed, delivered and managed. Information models are characterised by the aggregation of both geometrical and non-geometrical information in composing objects (Eastman *et al.*, 2011). BIM implies an intensive use of information and its uses can be specified according to the needs of the processes defined e.g. in the project context and/or in the company context. This information represents a central asset in the construction process. Nevertheless, several aspects including technical and cultural ones can limit the use of information. In this context, interoperability, i.e. the process to exchange and use information between two or more systems (IEEE, 1990), can be identified as one of the main open issues.

Since 1995, the BuildingSmart consortium (formerly known as International Alliance for Interoperability until 2008) is working on the Industry Foundation Classes (IFC), a common data model to represent and describe building processes (Laakso and Kiviniemi, 2012). Moreover, starting from early 2000s researchers start to explore the use of semantic web technologies to enhance the information exchange processes (Pauwels, Zhang and Lee, 2017). Nevertheless, a common point in the existing studies is the need to start from a building information model developed through a specific BIM authoring tool. This is the case both in the use of IFC, where the IFC model is obtained translating the native model, and in the use

of semantic web technologies or graph databases. These translating processes can introduce informative issues in the resulting models as already broadly explored in the literature for IFC (Sacks *et al.*, 2010; Törmä, 2013; Hu *et al.*, 2016). Hence, the quality of the exchanged models and the processes used to obtain these models is of central importance. However, according to the well-known concept Garbage-in-Garbage-out (GIGO), also the quality of the input models needs to be assessed to guarantee the quality of the exchanged ones.

The increasing number of experimentations based on the use of information contained in models is progressively highlighting the importance of data quality in BIM. For example, Sacks *et al.*, (2017) underlined how processes of semantic enrichment of building information models are subject to the quality of the input data. In the same way the experiment proposed by Farias, Roxin and Nicolle (2018) showed wrong results in the output of the proposed algorithms due to data quality issues derived from the input models.

The broad area of data quality is well known in the field of database management and is now gaining increasing interest in the Architecture, Engineering, Construction and Operations (AECO) industry research field. While can be found in the literature some studies focused on the analysis of IFC models and related processes quality (Solihin, Eastman and Lee, 2015), few studies have been developed in the understanding of the possible issues that can be encountered in the native models. The existing studies in the IT field showed that it is extremely difficult (if possible at all) obtaining a completely error-free database. Hence, due to the inherent data quality issues that can be found in BIM processes, their evaluation plays a critical role also in the development of automated processes to information use (e.g. rule checking processes) and to propose structured (and automated) processes to verify models' quality.

According to Donato, Lo Turco and Bocconcino, (2018), the quality evaluation of BIM processes involves two main aspects, namely the quality of the processes and the quality of the models. Moreover, the quality of the models can be related to the quality of the entire models (including e.g. clash detection and models coordination) and to the quality of the objects

composing each model including the information contained in the objects and their coherence with the project (and information) requirements. The research proposed in this paper focuses on this last quality evaluation.

The scopes of the research are twofold. On the one hand, the study highlights the types of data quality issues that can be encountered in real world models according to three data quality dimensions, namely accuracy, consistency and completeness. On the other hand, the analysis focuses on the understanding of the quantity of data that can be generated in a building information model. The identification of possible critical data quality points in a structured analysis can help developers in the study of automated means to limit the highlighted issues and pave the way for future studies in this area. Hence, the proposed research is not focused on the measurement of data quality of information models but on the understanding of the possible issues that can affect the data quality of these models.

The rest of the paper is organised as follows. The background section introduces the concept of data quality and proposes a brief literature review of the existing studies related to data quality in BIM. The methodology section explains the processes followed in the development of the study and how the analysis was organised. The case study section presents the results of the analysis. The discussion section proposes a critical explanation of the evidences emerged from the study. Finally, the conclusion section reports the summary of the research and possible future works.

Background

Real world data is dirty (Hernández and Stolfo, 1998; Fan, 2012). In general dirty data means either missing data or wrong data or non-standard representations of the same data (Kim *et al.*, 2003). The management of data quality represents a fundamental area to guarantee the quality of analysis based on data. The definition of data quality proposed by Wang and Strong (1996), i.e. “*data that are fit for use by data consumers*”, underlines its complexity and dependency from the context. It is still relevant as highlighted in recent studies on data quality measurement (Mocnik *et al.*, 2018). Hence, the extent for which the quality of data needs to be evaluated depends on the context of use of the data. This evaluation can be based on more than 170 dimensions described among others by Wang and Strong (1996), Naumann and Rolker (2000), Delone and McLean (2003). Nevertheless, the most used objective dimensions are:

- Accuracy: i.e. the extent to which data are correct, reliable and certified.
- Consistency: i.e. the satisfaction of semantic rules defined over a set of data items.
- Completeness: i.e. the degree to which a

given data collection includes the data describing the corresponding set of real-world objects.

- Timeliness: i.e. the extent to which data are sufficiently up-to-date for a task.

In addition, a well-known issue in database analysis is the interpretation of *null values* (Zaniolo, 1984; Neumann, 2018). Empty cells or null values are difficult to interpret and can reduce the readability of a database. In fact, null values can be interpreted both as *unknown*, i.e. the value exist but it is not known or as *nonexistent*, i.e. the value does not exist. Moreover, there is no way to understand if the null value is related to one of those interpretations or it derives from a mistake in the development of the model.

According to the increasing need of understanding and evaluating the quality of BIM (both in terms of models and processes), in the literature can be found some recent studies in this direction. Solihin, Eastman and Lee (2015) presented a study analysing and detailing the concept of quantifiable IFC validation. The study was based on the understanding of the possible issues related to the export and import phases in the IFC process. The possibility of data quality issue in the native models is mentioned but not explored. Lee, Eastman and Solihin (2018) presented a set of product data exchange requirements, the rules of IFC data translation and exchange, the scenarios of each rule checking process, and the logic of their checking implementation creating the basis for the development of the IfcDoc (Building Smart, 2018) application that can be used to check IFC models against specific Model View Definitions (MVD). Zadeh *et al.* (2017) defined a framework for information quality assessment of building information models focusing on facility management needs. Donato, Lo Turco and Bocconcino, (2018) proposed a method for quality assessment of building information models through a structured and quantifiable BIM quality control based on a BIM quality assurance analysis. Moreover, focusing on the information flow, Tribelsky and Sacks (2010) proposed a process to measure and evaluate inefficiencies and issues. Kouhestani and Nik-Bakht (2018) proposed an automated process to collect and analyse event logs during design phases including process mining techniques to highlight procedural issues and optimise the development of the design process. Beside these studies, a systematic analysis of the user behaviour in generating models and/or of the technological limitations that can bring to data quality issue seems lacking in the literature. Hence, the proposed study focuses on these factors to improve the comprehension of the existing data quality issues that can derive from native models.

Figure 1: Methodology

Methodology

According to the scope stated in the introduction, i.e. the understanding of data quality issues focused on the objects composing information models obtained from real-world applications, this study was designed to allow the comparison between similar models developed by independent design teams. This allows the identification of common issues shared by different design teams identifying these as critical ones. Following the definition of data quality that highlights its variability according to the objectives and the needs of the process where data quality is evaluated, it is required the definition of a common background and common objectives shared by all the design teams involved in the experimentation. Hence, as reported in Figure 1 the methodology starts from the development of the original Design of a medium-large building with a basic specification of the requirements in terms of performance. Moreover, to guarantee the coherence between the building information models developed by the independent teams during the process was defined an Employer Information Requirements (EIR) (BSI, 2013) were the informative needs were described. Looking at the information requirements for the objects composing the models, the EIR specified the obligatory use of the USA BIM Forum (BIMForum, 2016), requiring the LOD 300 for all the modelled objects (architectural, structural, MEP, etc.).

These two main documents were shared with four design teams in the industry. To maintain the comparability of the models, the use of a specific BIM authoring tool (i.e. Autodesk Revit) was defined. Hence, each team started with the same design guidelines, the same BIM requirements and the same objective, that was win the competition proposing the best project in terms of performance and quality of the design and of the models.

Starting from this point, each design team developed a BIM execution plan (BEP) (BSI, 2013) to support the proposed models and a project proposal defined

through the development of building information models.

Collected the BEPs and the models, the analysis phase started. The analysis focused on the models objects according to the four main data quality dimensions described in the background chapter. Because of the proposed methodology, timeliness was not relevant for the study. In fact, the study is focused on a static analysis in a fixed time and with fixed objectives. Hence, not up-to-date issues can be highlighted. Comparing to other means of data quality evaluation, the proposed dimensions provide a consolidated structure to discuss data quality issues that is the focus of this work.

In the proposed case study, the organisational structure defined by each design team was considered as a black box focusing on the final outputs (i.e. the building information models and all the related documents) and not on the generation process. To maintain the privacy of all the subjects involved in the case study, every reference to the original models has been omitted and the models are numerated from 1 to 4. Each design team defined more than one model according to different internal rules. Hence, in the term “model” are comprises all the models composing the design developed by a specific team (e.g. “Model 1” includes the architectural, structural, and destination of use models).

Case study

According to the proposed methodology, the case study herein presented is based on the analysis and comparison of four projects developed using BIM processes to identify common and/or relevant issues in terms of data quality in each project and to provide insight about how real-world models are developed. In the following, for each data quality dimension, i.e. accuracy, consistency and completeness are identified issues and peculiarities revealed during the case study analysis.

Accuracy

The database structure embedded in BIM authoring tools is limited and can produce incoherent data. In the market can be found different tools some more flexible and other more rigid where the inclusion of only predefined information is allowed. Nevertheless, in contrast with traditional relational databases, the data structure of BIM authoring tools can present relational issues. Moreover, except for some basic constraints in the data structure such as the data type, there is not the possibility to define embedded constraints to limit the introduction of erroneous data. Unfortunately, this kind of issues is not quantifiable in quantitative terms because its evaluation requires a manual exploration of the model due to the difficulties in defining general rules that can be executed automatically. Nevertheless, it is possible to identify some common issues revealed in the analysed models classifying these issues in four main points:

- Inconsistency between information fields.
- Precompiled information fields:
 - The information is not known.
 - The information is known but the designer does not use it.
- Other human related accuracy issues (e.g. typos).

Starting from the first point, the most widespread issue is the inconsistency between the name of objects and their informative contents. Technically, in this case the semantic structure of the BIM authoring tool is coherent. However, the inclusion of redundant information in the name may cause this type of accuracy issue.

The issues related to precompiled values can be divided in two cases. On the one hand, some information field cannot be eliminated from the data schema and cannot be defined as empty value. Hence, the designer is obliged to leave the precompiled value if he or she does not know the information. In this case, if this situation is not explicitly defined in the BEP, it is not possible to know if the information can be used or not. A diffused example in the analysed model are the information fields “absorptance” and “roughness” associated to walls that are always compiled even if the information is not known.

On the other hand, it may happen that the designer knows the information but this last is not used in the process. Once again, the designer leaves the precompiled value in the specific object. An example diffused in the analysed models is the “function” field that is usually maintained on “exterior” even in interior elements.

Consistency

During the experimentation have been found several issues that can be related to the consistency dimension.

These issues, as in the case of accuracy, cannot be evaluated through a quantitative approach but it is possible to identify some common terms in the analysed models. Can be listed three main critical points.

- Misuse of the object categorisation provided by BIM authoring tools.
- Introduction of information in the wrong information field.
- Not coherent use of the same information field.

About the first point, BIM authoring tools provide a defined semantic structure that aims to improve information exchange processes and to limit the interpretability of information. However, the structure proposed in commercially available BIM authoring tools is limited and does not include all the elements that can be required in the development of a building model.

This issue together with a limited vision of the personnel involved in the construction sector on the possible future uses of data, can bring to the incorrect use of the semantic structure provided by BIM authoring tools. Some examples related to this issue are following listed.

- To model vertical wood elements related to the fixed furniture of an open space has been used “concrete pillars” characterised by wood material.
- To simulate the skirting have been used walls characterised by wood material.
- To define complex railings have been used curtain walls.

The second and third points are shared with the accuracy dimension, but they imply an incorrect use of the semantic structure embedded in BIM authoring tools. The misuse of information fields can be identified as the introduction of information in the wrong information field. Typical examples that have been found during the research are the use of text free fields such as comments or descriptions to include a performance or a dimensional parameter creating possible inconsistency e.g. with the parameters based on the geometry of the object. With reference to the third point, have been found some cases where the same information field has been used to include different data types. For example, once the specific field contains the thermal transmittance of the object and in another object the same information field contains a generic comment, or the dimension of the element.

Completeness

The completeness dimension can be related to two factors. On the one hand, one can measure if the models satisfy the information requirements defined in

the EIR. For example, in this case study all the objects contained in the building information models need to reach LOD 300 according to the USA BIM Forum (2016 version). On the other hand, the completeness dimension can evaluate the information structure that has been defined to satisfy the requirements. In this case it is of interest the evaluation of the volume of information generated in an information model and if the configuration defined in the models can cause data quality issues.

A first analysis revealed the misalignment between the USA BIM Forum requirements and the information included in the models. Table 1 reports the completeness rate analysis focused on three object types comparing the minimum information required according to the USA BIM Forum and the related information included in each object.

Table 1: Completeness rate according to USA BIM Forum 2016 version

Object type	U.B.F	M1	M2	M3	M4
Interior fixed partition	8	7	6	6	6
	100%	87%	75%	75%	75%
Exterior window wall	5	4	4	3	4
	100%	80%	80%	80%	80%
Structural frame concrete	12	4	3	4	4
	100%	33%	25%	33%	33%
Legend U.B.F.: USA BIM Forum specification 2016. The column reports the minimum information required. M1, M2, M3, M4: Model 1, 2, 3 and 4. The columns report how many information requirements have been satisfied with reference to the specific U.B.F. requirements. The percentage indicates the completeness rate for the specific object type.					

Even if it is possible to individuate a common behaviour in the inclusion and/or exclusion of information, every design team defined different information structures to reach the defined requirements.

Figure 2 (next page) shows the relation between the number of objects and the number of fields respectively in models 1, 2, 3, and 4. Number of objects and number of fields are divided according to a logical (and technical) subdivision of the models. In the graphs are reported data for the architectural models (circle), the structural models (X), the materials (square), and the spaces (plus). Focusing for example on the architectural models, the number of objects per model ranges from around 3.400 to around 5.500, while the number of fields range from around 110.000 to around 200.000. Nevertheless, the

correlation between number of objects and number of information fields is not linear between the four models. The ratio between the number of objects and the number of information fields vary from around 29 (model 3) to around 50 (model 2). This situation can be related to the introduction of information fields defined ad hoc by each team to satisfy the requirements imposed by the EIR. To understand this configuration in the different models it is possible defining a matrix to highlight how personalised fields has been added to specific object types.

Table 2 reports the comparison between the number of fields that are inherently defined in the specific BIM authoring tool in four classes of elements, namely walls, windows, pillars and materials, and the number of fields derived from the analysed models.

It is clear how each design team defined a different structure of data to reach the required LOD. This behaviour can cause critical issues related to the accessibility and interpretability of the information because of the not standard structure defined for each model.

Table 2: Identification of the number of information fields per object in the different models

	Walls			Windows		
	S	M	Δ	S	M	Δ
Model 1	62	89	27	58	75	17
Model 2	62	87	25	58	76	18
Model 3	62	62	0	58	70	12
Model 4	62	67	5	58	65	7
	Pillars			Materials		
	S	M	Δ	S	M	Δ
Model 1	59	75	16	42	47*	5
Model 2	59	89	30	42	50*	8
Model 3	59	61	2	42	42*	0
Model 4	59	64	5	42	42*	0
Legend S: number of parameter in a standard model (i.e. number of information fields that the specific BIM authoring tool contains as starting point) M: number of parameter in the analysed model (i.e. number of information fields calculated for each object classes in the analysed models) Δ : $\Delta = M - S$ *: the number shows the material completed with physical and thermal properties (these are not included in all the materials included in the model)

Figure 2: Analysis of the relation between number of objects and number of informative fields included in each model. The analysis is divided in four main classes of objects, i.e. architectural objects, materials, rooms (spaces), structural objects

Nevertheless, the proposed table highlights that it is possible to reach similar levels of information on the object with a very different number of information fields, in some cases even without including additional information fields in the embedded structure of the BIM authoring tool.

This situation is further emphasised in Figure 3 (next page) where are identified the number of objects (vertical axes) and the number of empty information fields (horizontal axes) in the architectural models. As mentioned in the background chapter, empty fields can cause several issues in the use of the models and can be listed as data quality issues with reference to completeness. Hence, a high number of empty fields brings to a low data quality evaluation due to the

difficulties in the use of model information. Moreover, calculating the percentage of completeness for each model (intended as how many fields have been compiled), many information fields included in the models were useless with reference to the objectives and scopes of the models. For example, Model 2 shows a percentage of completeness equal to 52,4 % that means that around 85.680 fields were left empty. At the same time, the model does not satisfy the information requirements related to LOD 300 (Table 1).

Figure 3: Analysis of the relation between number of objects and number of empty fields. The percentage under each circle indicates the percentage of completion of the informative fields in each model. The graph is limited to the architectural objects

Discussion

Considering the existing studies in the field of quality assessment of information models, we proposed a specific analysis devoted to understanding the possible data quality issues in the source information models, i.e. information models in their native format focusing on the component's objects. The results of the experimentation highlighted several critical points in the management of data quality in BIM revealing common user behaviours and/or technological limitations in real-world applications. In comparison to existing studies, this paper proposes a detailed identification of data quality issues generated in real world models highlighting not only procedural and technical problem e.g. related to IFC export processes but also the behaviour of the industry in the development of information models. The authors believe that the evaluation of the societal context is of critical importance in BIM data quality area.

Some of the issues highlighted in the paper can be identified as software dependent issues that means that are issues related to the specific software and not to BIM in general. Nevertheless, because building information models are developed using specific software, it is useful to know possible related issues to improve the quality of the software and to improve the quality of the research linking the results to the peculiarities of each source instrument.

In the following, we discuss the results according to technical and procedural issues exploring possible

solutions e.g. using standard and shared structures. In fact, even if the processes used to generate the models were considered as black boxes, the results highlighted a correlation with the processes that play a fundamental role in improving data quality performance. It is worth mention that standard and shared information structures can be seen as means to limit data quality issue. This does not mean that there is always a direct link between specific standards and the data quality evaluation. Data quality can be evaluated even without considering specific standards, while these lasts can be identified as valuable means to improve the control of information models data quality.

Technical issues

The misuse of information field highlighted in the consistency dimension brings to the impossibility to develop automated algorithms and/or applications based on the data contained in information models because it is not possible to know where to find the right information and if a specific information field reports always the same information type. Moreover, the inconsistency between information fields, underlined in both accuracy and consistency, can limit the reliability of information models with the direct consequence that information is not used, losing value.

The analysis focused on completeness highlighted the misalignment between the EIR requirements and the information included in the analysed models. This

issue may be analysed by different perspectives. On the one hand, the direct use of information requirements defined for foreign markets (USA BIM Forum) can generate difficulties in the interpretation and in the alignment with the national regulation. On the other hand, the knowledge background (also related to the societal aspects) of the personnel involved in the development of the model can create the highlighted limitations.

Procedural issues

Some issues that have been underlined in the different data quality dimensions can be related to procedural components. Most of the data accuracy issues revealed during the analysis can be limited (and probably eliminated) identifying precise processes to develop new objects. In the same way, this can help in limiting consistency issues because the responsible for the development of the objects should guarantee for their consistency according to the objectives of the model. Moreover, the variety of data structures used to reach the required LOD can be limited through a structured process that, starting from the client, defines a rigid matrix of information with specific name, data type, semantic, etc.

Nevertheless, in many cases the application of these rigid and structured processes in the construction industry demonstrated to be all but easy. In fact, due to the complexity of the construction products (buildings, infrastructures, etc.) it is not possible to think through the entire process from the beginning with the consequent need to introduce changes and adjustments on the way in a reduced time lap. Moreover, some data quality issues related to human factors cannot be eliminated and they must be considered in the analysis and use of information models.

Conclusions

The implementation of BIM can provide effective means in the management of data quality in the construction processes. However, the inclusion of geometrical and non-geometrical information in an information model imposes new issues related to the verification and validation of the model quality. Evaluating and controlling the quality of information models is a significant challenge and requires further research. In order to address this gap and with the scope of understanding data quality dimensions in building information models developed in native formats, a systematic analysis of real-world models is presented in this work. Data quality issues were classified according to three dimensions, namely accuracy, coherence and completeness. This structure provides the background to explore and discuss technical and behavioural issues in the processes of information models development.

The authors believe that the proposed results can represent a good starting point to understand where

data quality issues are generated and how (and if) these issues can be limited or solved. They can be used in different applications, for example to improve existing and future studies that are based on intensive data use of BIM objects such as export procedures (from native to IFC, from native to graph databases, from native to OWL, etc.), expert systems, machine learning and artificial intelligence applications, design support systems, etc. evaluating the sources of errors and including possible processes to limit their influence on the results. Moreover, understanding the typical sources of errors in native models can help in the evaluation of exporting processes highlighting issues related to the input models and those related to the export and/or import processes. Moreover, relating this study with the concept of Model View Definition (MVD) it is possible to optimise the research devoted to automate and optimise the translation process used to share information. Existing studies highlighted the dependency between data quality and performance of the translation process. Understanding the nature of the input errors can help in defining better algorithms and information flows.

On the other hand, the proposed analysis can be used by the industry to improve the existing modelling processes, i.e. the rules that can be defined in a project team and/or in a collaborative environment to guarantee the quality of the overall process that cannot forget the quality of every subject (people) and of every object (models) that are included in the process.

As a future work, we envision to apply the same experimentation structure to other BIM authoring tools to highlight software dependent issues and/or issues that are shared among different tools. Moreover, it would be interesting to develop the same experimentation in a different societal context to highlight how different knowledge and contextual backgrounds can affect the process development with reference to data quality.

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IMAGE-BASED 3D SURFACE RECONSTRUCTION OF COLD-FORMED STEEL C-SECTIONS

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Abstract

The use of cold-formed steel (CFS) members in construction have increased significantly due to the recent advances in cold-formed steel research and the developed design guidelines. CFS construction provides affordable, light, efficient, and resilient building systems. CFS members are obtained by forming thin steel sheets into several different cross-sections. Due to transportation, installation, and even production, geometrical imperfections may occur on the thin steel sheets that form the CFS members. These geometrical imperfections affect the predicted physical response of CFS members. Thus, in order to efficiently compute the physical response of a CFS member, it is necessary to determine the geometric imperfections and investigate their effect on the member behavior. In this paper, a low cost methodology for extracting the 3D surface data of CFS members from 2D images that could be later used for geometric imperfection extraction is proposed.

Introduction

CFS members diverge from the ideal as-design geometry due to various reasons. Geometric imperfections form due to these deviations from the ideal geometry and they are common in cold-formed steel members. Both strength and buckling behavior of CFS members are affected by the geometric imperfections. Thus, it is important to characterize these geometric imperfections and include their effects in the design in order to predict the behavior of these members accurately. However, the current methodologies used for extracting geometric imperfections involve collecting geometric data by using advanced 2D or 3D data collection equipment. Thus, it is necessary to develop an easy-to-use, low-cost solution.

In recent years, there have been several studies that focus on geometric imperfection measurement, extraction, and modeling. The influence of imperfections on the behavior of CFS members is investigated by Dubina and Ungureanu (2002). They also discussed the effects of the different types of local-sectional imperfections on the buckling

resistance. Zeinoddini and Schafer (2011) measured the global imperfections and dimensional variations in CFS members. Certain imperfection types that are the global bow, camber, and twist are determined. The geometric imperfections that occur due to the manufacturing process are then investigated by Zeinoddini and Schafer (2012). Three approaches, which are Traditional Modal Approach, 2D Spectra Approach, and 1D Modal Spectra Approach, are used for simulating the imperfections. The 1D Modal Spectra Approach is found to be the most accurate approach for predicting the strength, axial flexibility, and failure mechanism of the members. The procedures for processing three-dimensional point clouds that are generated by laser scanning of CFS members in order to measure cross-section dimensions and extract imperfections, as well as to perform finite element simulations using the as-measured geometry, are discussed in Zhao et al. (2017). Selvaraj and Madhavan (2018) collected the surface data of 188 CFS members with varying cross-sectional geometries are collected with a 3D laser scanner and the related geometric imperfections are extracted. It was observed that the imperfections in the CFS members are in correlation with geometric properties such as slenderness ratios, torsional constant, and plate slenderness.

This paper focuses on developing a low cost method that enables 3D surface data extraction from 2D images. The surface data, which can also be referred to as point cloud, could then be used for geometric imperfection extraction in future studies. First, images of a CFS C-section mounted on a special test setup are collected. The collected images are then calibrated and enhanced for 3D surface data generation. The quality of the enhanced images is tested by performing keypoint extraction and matching. Finally, the quality controlled images are used for generating the surface mesh of the investigated CFS member.

Experiment

Camera properties

The camera used in this study is a Nikon D7100 with a DX-format 23.5 mm x 15.6 mm CMOS image

sensor. In order to capture 2D images, this camera is positioned on a stationary tripod at a certain distance from the test setup. Each captured image consists of 24.1 Megapixels.

Cold-formed steel C-section

A C-sectioned CFS member is investigated in this study. In total 36 images, which cover the 360° around the member, are collected. The collected images are then converted into a surface mesh. In order to check the accuracy of the generated surface mesh, first, the actual dimensions of the CFS member are recorded with a micrometer. The measured dimensions are then compared with extracted dimensions. Figure 1 shows the locations from where the micrometer measurements are taken. Table 1 presents the measured dimensions related to the investigated CFS member. The extracted dimensions are presented in the following sections of the paper.

Figure 1: Measurement locations for dimension extraction of the C-section (dimensions are in cms).

Table 1: Dimensions of the C-section.

Measured Dimensions											
Point A						Point C					
Web Width (mm)		Flange Width (mm)	Lip Width (mm)		Web Width (mm)		Flange Width (mm)	Lip Width (mm)		Lip Width (mm)	
S1	S2	-	S1	S2	S1	S2	-	S1	S2		
45.9	45.7	73.9	9.5	9.5	45.8	45.6	73.9	9.5	10.0		
Point B						Point D					
Web Width (mm)		Flange Width (mm)	Lip Width (mm)		Web Width (mm)		Flange Width (mm)	Lip Width (mm)		Lip Width (mm)	
S1	S2	-	S1	S2	S1	S2	-	S1	S2		
45.9	45.6	73.9	9.5	10.0	45.8	45.9	74.4	9.5	9.8		

It should also be noted that since the original state of the investigated CFS member has a uniform and shiny surface texture, the surface the member is patterned. The pattern is generated by randomly spraying the surface of the member with a black dye from a distance of 1m. A permanent black dye suitable for metal surfaces is used. The generated surface pattern is later used for keypoint extraction and matching.

Test setup

Test setup consists of two plates attached to a ball-bearing. The plated located at the bottom is fixed and the plate on the top is free to rotate. There are 36 holes on the perimeter of the bottom plate, which are 10° apart from each other. On the top plate, however, there

are only 4 holes. These 4 holes are used to secure the top plate on which the element is secured during image capturing process. 4 bars are placed in these holes and the bars are then inserted into the corresponding bottom plate holes.

There are one straight and two L shaped perforated plates located on the top plate. All the plates are free to move. The locations of the plates are determined based on the centroid of the investigated C-section. Once the CFS member is located on the top plate, the moving plates are positioned to secure the member in place.

The test setup is located in front of a white surface in order to generate contrast and a calibration sheet is attached to the white background. An image is recorded and the top plate is rotated 10°. This is repeated 36 times to collect 36 photos that cover the entire surface of the CFS member. Figure 2 presents the test setup on which a sample CFS member is attached from two different viewpoints.

Figure 2: Images of the test setup from two, (a) and (b), viewpoints.

Calibration and image enhancement

The collected images are calibrated as the first step of the surface mesh generation. To perform this, the Camera Calibrator application of MatLab (2018) is used. This application is capable of estimating the camera intrinsics, extrinsics, and lens distortion parameters. The obtained parameters are then used to remove the effects of lens distortion from the collected images. In this study, the known physical properties of the checkerboard image attached to the background are used for calibration. Figure 3 shows one of the calibrated images that belong to the collected 36 image set. The image contains the test setup, the attached CFS member, and the calibration paper.

The images are cropped to include only the test setup once the calibration process was completed. In order to crop the images to a certain size, the *imcrop* function of the MatLab is used. A location for a cropping rectangle is obtained from the first image and used on the rest of the 35 images.

Flash is not used during the image capturing due to the shiny surface of the CFS member, only cold light sources were used as additional lightening. As a result, the collected images are rather dark. In order to continue with further processing, it is required to enhance the quality of the images by making them more suitable for keypoint extraction. This requires increasing the contrast of the images. The images are first converted into grayscale images and the *imadjust* function of the MatLab is then used for adjusting image intensity values. The final image set is exported in *tiff* format. Figure 4 shows (a) a cropped image, (b) a grayscale image, and (c) an adjusted image.

Figure 3: One of the calibrated 36 images that include the test setup, the attached CFS member, and the calibration paper attached to the wall behind.

Figure 4: (a) Cropped image, (b) grayscale image, and (c) adjusted image.

Keypoint detection and matching for image quality verification

In this study, Regard3D (2018) is used for keypoint extraction and matching. This step is performed to ensure the quality of the enhanced images.

Regard3D (2018) is a structure-from-motion software that enables creating 3D models from objects using a series of photographs taken of an object from different viewpoints. For each image, keypoints that have a high

probability of existence in a successive image are detected. Later, a mathematical descriptor based on local intensity order pattern is calculated for each keypoint. This descriptor has invariant characteristics that are present in successive images with different viewpoints. The descriptors from different images are matched and geometrically filtered. Figure 5(a) shows the keypoint detection results and Figure 5(b) shows the tracks in between the matched keypoints in two successive images. These results are used to confirm that the obtained images are sufficient for generating the 3D surface mesh of the investigated CFS member. The threshold for the number of keypoints for a successful match is taken as 8000.

Figure 5: (a) Detected keypoints are shown on the member and (b) two successive images are matched based on the previously detected keypoints.

3D mesh generation

The next step of the method described in this paper is the surface mesh generation. This is achieved by using the Meshroom (2018) software. This software performs 3D surface mesh generation using overlapping 2D images collected from different viewpoints. Meshroom allows users to run a photogrammetric pipeline that starts with image insertion and ends with textured mesh generation.

The Meshroom software follows a 12 step analysis scheme. The first step of the process is feature extraction that is performed via scale-invariant feature transform. The aim is to extract discriminative patches in an image that can be compared to discriminative patches of a successive image irrespective of rotation, translation, and scale. Feature extraction is followed by image matching; the extracted features are matched by photometric matching. The software then runs the structure-from-motion algorithm. As an intermediary step; camera correction is performed automatically. The depth map extraction that is followed by depth map filtering is executed later. The software then performs meshing and mesh filtering. Finally, the generated surface mesh is covered with texture through texturing.

Figure 6 shows the end result of the mesh generation process. The surface mesh, which represents the CFS member, is in the middle of the screenshot. This surface mesh is surrounded with the camera locations from which the 36 images were captured. The camera locations are shown with white rectangles centered with white cubes.

Figure 6: Generated mesh along with the camera poses for all of the 36 images used for processing.

3D mesh refinement

As the final step, MeshLab (2016) is used to improve the quality of the generated surface mesh and exclude the redundant regions. MeshLab is an open source system for processing and editing 3D triangular meshes. It provides a set of tools for editing, cleaning, healing, inspecting, rendering, texturing and converting meshes. Figure 7 presents the finalized surface meshes. Figure 7(a) and 7(b) show vertex presentations from two different perspectives that cover interior and exterior views. Figure 7(c) and 7(d) on the other hand represent smoothed surface meshes from two different perspectives that cover interior and exterior views.

Figure 7: Vertex representation for (a) interior and (b) exterior and smoothed surface mesh representation for (c) interior and (d) exterior.

Discussion and results

The accuracy of the generated surface mesh is verified by performing a dimension comparison between the micrometer measurements given in Table 1 and the

dimensions extracted from the generated surface mesh. These dimensions are given in Table 2.

The surface mesh is then converted into a 3D point cloud in order to extract the necessary dimensions: web, flange, and lip. This point cloud is then used to extract the listed dimensions. However, it should be noted that it is not possible to extract lip dimensions from the generated point cloud due to noise. The error associated with the extracted web and flange dimensions is around 5%. Details of point cloud processing and dimension extraction can be found in Guldur (2014).

It should be noted that the accuracy of the generated 3D point cloud is directly related with the sensor used for image collection, the selected mesh generation algorithm, and the parameters chosen for meshing procedure.

Table 2: Dimensions extracted from the generated surface mesh.

Extracted Dimensions					
Point A			Point C		
Web Width (mm)	Flange Width (mm)		Web Width (mm)	Flange Width (mm)	
S1	S2	-	S1	S2	-
48	49	74	47	48	74
Point B			Point D		
Web Width (mm)	Flange Width (mm)		Web Width (mm)	Flange Width (mm)	
S1	S2	-	S1	S2	-
48	48	74	47	47	75

Conclusions

The geometric imperfections that occur on CFS members due to various reasons such as transportation, production, etc. could significantly change the physical response of the member. Thus, it is important to determine these imperfections and take their effect into account prior to construction.

This study focuses on developing a low cost methodology that uses 2D images to generate a 3D surface mesh by performing 3D image processing. The generated surface mesh is then used to extract the as-is dimensions of the investigated CFS member. It has been verified by the comparison of the measured vs. extracted member dimensions that the generated surface mesh is in good agreement with the as-is geometry of the investigated CFS member.

In future studies, the developed methodology will be tested on several CFS members and the generated surface mesh will be used to automatically extract geometric imperfections such as the bow, camber, etc.

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PREDICTING THE IMPACT SIZE OF UNCERTAINTY EVENTS ON THE CONSTRUCTION COST OF HIGHWAY PROJECTS USING ANFIS

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Abstract

This study examines the use of Adaptive Neuro-Fuzzy Inference System (ANFIS) as a machine learning technique in the prediction of the impact size of uncertainty events on construction cost of highway projects and whether this technique is more accurate than the classical statistical methods. The rationale for the study stems from the availability of several techniques such as regression analysis and machine learning for developing predictive models of relationships of various variables in the construction industry. However, there has been limited research undertaken to compare the accuracy of the available techniques. The success or failure of prediction depends on the credibility of the prediction method. In this study, the predicted impact size of 76 uncertain events on the construction of highway projects using ANFIS as an intelligence machine learning method and Stepwise Regression Analysis (SRA) as a classical statistical method were compared to delineate the ability and accuracy of the ANFIS prediction technique. The comparison of calculated R-Value and two error tests for ANFIS and SRA show that the constructed ANFIS model has a higher performance than the SRA method in both fitness and reliability of the prediction model. Also, the performance comparison showed that ANFIS is a good tool for predicting the impact of uncertainty events on construction project cost. Based on these findings, the study concludes that the use of intelligent methods such as ANFIS will minimise the potential inconsistency of correlations in construction cost and time prediction. The model developed enables cost engineers to estimate the construction cost with a higher degree of accuracy.

Keywords: Accuracy, ANFIS, Construction Cost, Impact size, Predictability, SRA

Introduction

Providing accurate estimates of cost on construction projects is a difficult task because construction projects are subject to risks and uncertainties, especially in the planning phase of the project when sufficient data and information about the project is unavailable (Ökmen & Öztaş, 2010). Typically, in the estimation of construction project resources, several variables are not known since uncertainties populate construction projects. According to El Khalek et al. (2016) various uncertainties are existing in construction projects that affect construction

performance differently. A project is regarded as successful if it is completed on time, within budget and to the level of quality standards specified during the planning stage (Chan & Chan, 2004).

Estimating construction cost at the early stage of project development represents a prediction provided by the cost engineer based on available information and data. Cost estimating is defined as that area of construction practice where the cost engineers' experience and judgment are utilised in the application of scientific principles and techniques to the problem of predicting and controlling cost of projects (Ng & Zhang, 2008). The ANFIS model enables the ability to accurately predict the impact size of uncertainty events on construction cost which has always been one of the most critical challenges of cost engineers (Antunes & Gonzalez, 2015). This advantage enables cost engineers to estimate the construction cost with higher performance by predicting the accurate impact amount of uncertainty events on construction cost using tailor-made effect values table for individual projects (PMI, 2013). However, the success or failure of prediction depends on the credibility of the prediction method.

The intelligence machine learning techniques based on Fuzzy Inference System (FIS) is used in modelling the qualitative aspects without employing precise quantitative analyses, it provides standard practical methods for transformation into rule based as well as effective methods for turning Membership Functions (MF) for better performance index (Chai et al., 2009). ANFIS combines the strengths of Artificial Neural Network (ANN) with Fuzzy Inference Systems (FIS) to create an efficient method for analysing complex problems. ANFIS has the capability to handle nonlinearity, uncertainty, and complex problems which are involved in predicting the impact size of uncertainty events on construction cost (Jin, 2010).

ANFIS has been used in various fields of engineering. For instance, Ugur (2017) used ANFIS to estimate the costs of the residential building. While Fragiadakis et al. (2014) used ANFIS to assess the occupational risk in the shipbuilding industry; Ebrat and Ghodsi (2014) applied ANFIS to evaluate the risk in construction projects; Li et al. (2011) forecasted building energy consumption using hybrid ANFIS; Güneri et al. (2011) used ANFIS to overcome supplier selection problem in construction projects; Shahhosseini and Sebt (2011) used ANFIS to establish a fuzzy adaptive decision-making model for selection and assignment of human resources to construction projects based on

competency; and Wang and Elhag (2008) developed an ANFIS based risk assessment model for bridge maintenance projects.

On the other hand, classical statistical methods such as regression analysis are quite common in predicting different variables in construction management. Regression analysis methods are relatively easy to implement, and the main advantage of these methods are that the relationship between the input variables and output variables is easy to comprehend. Stepwise Regression Analysis (SRA) is an extension of Multiple Regression Analysis. The SRA model is a mathematical model used in estimating the relationship between a dependent variable and independent variables with a strong mathematical background. SRA models have been used extensively in different areas of construction management. For instance, assessing the critical factors affecting cost performance of public construction projects (Sinesilassie et al., 2017); modelling the construction risk ratings and estimating contingencies in highway projects (Diab et al., 2017); identifying the success factors for public, private partnership projects (Yun et al., 2015); evaluating project risks (Ebrat & Ghodsi, 2014); evaluating the risk factors leading to cost overrun in highway construction projects (Creedy et al., 2010); analysing the risk perception of build–operate–transfer road project participants (Thomas et al., 2003); developing models to forecast the actual construction cost and time (Skitmore & Ng, 2003); and designing a multivariate analysis technique to rank project success factors (Chan et al., 2001).

The primary objective of this study is to evaluate and compare the performance of machine learning technique (ANFIS) with the classical statistical method (SRA) in the prediction of the impact size of uncertainty events and to determine a reliable and accurate prediction technique. The prediction technique involves developing a model, estimating the value and evaluating the performance (reliability and fitness) of predicted value to the real data. According to PMI (2013), the impact amount of uncertainty is a function of the impact size and effect value (See Equation 1).

$$\text{Impact amount}_i = \text{Impact size}_i \times \text{Effect value}_i. \quad (1)$$

By predicting the accurate impact size of events on the cost of the project it is possible to estimate the exact impact amount of events on the construction cost of the project (PMI 2013).

However, there are limited researches undertaken using ANFIS in the field of construction management and limited studies have compared the accuracy of ANFIS as a technique for predicting the impact size of uncertainty events on construction cost to available classical prediction techniques such as SRA.

The novelty of this study is that it examines the predicted impact size of uncertainty events on the construction cost of highway projects using ANFIS as an intelligence method and SRA as a classical statistical method based on the standard impact matrix, and thereafter compares the ability and accuracy of the two prediction techniques. Therefore, this study shows the ability of ANFIS technique as an intelligence method in predicting the impact size of uncertainty events on the construction cost of highway projects on important step in cost estimation. Thereafter the study compares the reliability and accuracy of the ANFIS to the ability and performance of SRA as a classical prediction method. This approach is straightforward and provides the accurate impact size of uncertainty events on the construction cost of highway projects and a holistic overview of the advantages of the ANFIS to the classical prediction methods.

Uncertainty Events on Highway Projects

Uncertainty means an unknown phenomenon that is associated to the location and is project specific and has no root causes that can be generalised (Ramanathan et al., 2012). Therefore, there is an obvious need to effectively anticipate, identify and classify the uncertainty events on different locations and projects to assess their influence on the objectives of construction projects. Moghayedi and Windapo (2018) identified 76 uncertainty events as affecting the construction of South African highway projects under seven major groups namely Economical, Environmental, Financial, Legal, Political, Social and Technical as illustrated in Figure 1. It can be seen from Figure 1 that more than half (41) of the uncertainty events are attributed to Technical factors.

The 76 uncertainty events identified by Moghayedi and Windapo (2018) was used in the current study to evaluate the performance of proposed techniques for predicting the impact size uncertainty events on construction cost of highway projects.

Methodology

The hierarchy structure of the model developed for predicting the impact size of uncertainty events consists of four main steps; 1. determination of uncertainty event attributes; 2. data collection; 3. developing the prediction models; and 4. comparison and recommendation. The process begins with a determination of criteria for uncertainty assessment. The magnitude influence of uncertainty can be assessed by two parameters, probability of occurrence and severity (ISO, 2009; PMI, 2013). To model, the impact of uncertainty events, the ISO 31000 (International Standard Organization) impact matrix was used (ISO, 2009). Figure 2 shows the probability of occurrence and severity as two input variables and relevant impact size as output of prediction models.

To model the impact of uncertainty events on

construction cost and predict the impact size, the probability of occurrence and severity of the event were obtained from all 32 available professional project managers with a minimum of 20 years of work experience in South African highway construction projects recommended by The South African National Roads Agency SOC Ltd (SANRAL) using the five-point linguistic Likert scale questionnaires.

The ANFIS and SRA were used as intelligent and classical prediction models to predict and assess the

impact size of 76 uncertainty events on construction cost. To evaluate the prediction performance of each techniques the two controlling indicators were adapted. The indicator to measure the reliability of techniques are Mean Absolute Percentage Error (MAPE) and Root Mean Square Error (RMSE). Regarding the fitness and efficiency of each technique, the model is indicated by the correlation coefficient (R). The ideal technique has RMSE and MAPE score of 0 and R-value close to 1

Source: Moghayedi and Windapo (2018)

Figure 1. Uncertainty event

		Severity				
		Insignificant (1)	Minor (3)	Moderate (5)	Major (7)	Catastrophic (9)
Probability of Occurrence	Rare (0.1)	Minimal (1)	Minimal (1)	Low (2)	Low (2)	Moderate (3)
	Unlikely (0.3)	Minimal (1)	Low (2)	Moderate (3)	Moderate (3)	High (4)
	Possible (0.5)	Low (2)	Moderate (3)	Moderate (3)	High (4)	High (4)
	Likely (0.7)	Low (2)	Moderate (3)	High (4)	High (4)	Extreme (5)
	Almost Certain (0.9)	Moderate (3)	High (4)	High (4)	Extreme (5)	Extreme (5)

Source: ISO (2009)

Figure 2: Probability of Occurrence of the Event and Severity

Adaptive Neuro-Fuzzy Inference System

ANFIS refers to combinations of Artificial Neural Networks (ANN) and Fuzzy Inference System (FIS). Fuzzy modelling and ANN have been recognised as powerful tools that can facilitate the effective development of models and integrate information. These two tools were combined to achieve readability and learning ability at the same time. ANFIS, trained to develop fuzzy rules and determine Membership Functions (MF) for input and output variables of the system is an intelligent system which is able to estimate the variables and fuzzy rules intelligently and does not require a systematic method for design of fuzzy systems. Also, neural network fuzzy systems interpret the human knowledge and deduce it into a mathematical model (Negnevitsky, 2005). The Neuro-Fuzzy has two major categories: linguistic fuzzy modelling which is focused on interpretability

(Mamdani), and precise fuzzy modelling which is focused on accuracy (Takagi-Sugeno) (Lughofer, 2011). In this study, a first-order Takagi-Sugeno fuzzy inference system is employed to accurately assess the impact size of uncertainty events in construction cost of highway projects. In this inference system, the output of each rule is a linear combination of two input variables added by a linear term of “AND” logic. The final output is the weighted average of each rule’s output. Figure 3 illustrates the Takagi-Sugeno ANFIS structure which was developed for this study. To model this ANFIS following 25 fuzzy rules “If-Then” are considered (See Equation 2).

$$\text{If } (P \text{ is } p_i) \text{ AND } (S \text{ is } s_i) \text{ Then } f_i = a_i p + b_i s + r_i \quad (2)$$

Where P and S are numerical inputs while p_i and s_i are numerical variables. a_i , b_i and r_i are parameters that determine the relation between input and output

Figure 3. Proposed Takagi-Sugeno ANFIS structure

ANFIS is modelled in MATLAB to predict the impact size of uncertainty events. Eighty percent (80%) of the data collected from the research participants was used for training of the FIS, while twenty percent (20%) was used for checking and testing the neural network which set the system parameters. To evaluate the performance of 76 models developed by ANFIS (a model to fit each uncertainty event was developed), the RMSE, MAPE and R-Value of the predicted impact size of uncertainty events are calculated and the results are presented in Table 3. The minimal error scores of RMSE ($e < 0.3$) and MAPE ($e < 0.1$) proved the high reliability of ANFIS models (Veerasamy et al., 2011). Furthermore, the extreme closeness of R-Values to 1 verified the excellent fitness ($r > 0.9$) of predicted impact sizes of all models to the real data (20% of observed data) (Moore & Kirkland, 2007).

Stepwise Regression Analysis

The impact size of uncertainty event as the dependent variable is a function of two independent variables namely probability of occurrence and severity of relative uncertainty (ISO, 2009) shown in Equation 3.

$$\text{Uncertainty Impact}_i = a_i p + b_i s + r_i \quad (3)$$

Where p is probability of occurrence, s is severity of event, r_i is a constant value, a_i and b_i represent regression coefficient of independent variables

The linear regression analysis was used to generate correlations coefficients of the two independents variables (probability of occurrence and severity) of uncertainty events by using the SRA in the MATLAB. An SRA technique was selected due to the low correlation between the independents' variables and dependent variable as presented in Table 1. The general SRA model for predicting the impact size of uncertainty events has been developed based on the matrix impact in Figure 2. The SRA model test details are presented in Table 2.

Table 1. Correlation matrix among input and output variables

	Probability	Severity	Impact
Probability	1		
Severity	0	1	
Impact	0.685061	0.685061	1

Table 2. Regression test details

Regression Statistics				
Multiple R	0.968822			
R Squared	0.93861607			
Adjusted R Square	0.93303571			
Standard Error	0.31622777			
	Coefficients	Standard Error	T Stat	P-value
Intercept	0.18	0.170294	1.056996	0.030198
Probability	2.9	0.223607	12.96919	8.82E-12
Severity	0.29	0.022361	12.96919	8.82E-12

The regression test revealed the correlation coefficient value of the model is close to 1 which verifies the close fitness of the estimated output model with real data (impact matrix). Also, the low value of P-value (<0.05) indicates the statistically significant relationship of each independent variable to the dependent variable of the model. The developed SRA model for general uncertainty impact size is outlined mathematically in Equation 3.

$$\text{Impact Size} = 0.18 + 2.9 \times p + 0.29 \times s \quad (3)$$

The similar process was repeated to generate the SRA uncertainty impact models for each event. To predict the impact size of uncertainty the optimum values of probability of occurrence and severity of events are

identified using sensitivity analysis and incorporated into SRA models. The impact of uncertainty events on the construction cost of highway projects was predicted.

To evaluate the performance of SRA models' on predicting the impact size of uncertainty events the (RMSE), (MAPE) and R-Value of developed models were calculated, and the results are presented in Table 3. The small error scores of RMSE and MAPE proved the reliability of SRA developed models. However, the fitness of the predicted values to real data varies from 0.367 to 0.816. Only three models have good fitness ($0.9 > r > 0.8$), nine models have acceptable fitness ($0.8 > r > 0.7$), and the other ten models have a low fitness ($r < 0.7$) to the real data.

Table 3: ANFIS and SRA predicted impact size of uncertainty on cost of project and performance evaluation

Event	ANFIS				RSA			
	Impact Size	RMSE	MAPE	R Value	Impact Size	RMSE	MAPE	R Value
EC1	4.02	6.05E-08	1.35E-08	1.0000000000000000	4.16	0.213	0.0484	0.659
EC2	4.08	1.07E-07	1.73E-08	0.9999999999999999	3.94	0.246	0.0547	0.647
EC3	2.98	6.88E-08	2.14E-08	0.9999999999999999	2.88	0.268	0.0857	0.506
EC4	3.88	1.27E-07	2.06E-08	0.9999999999999999	3.69	0.247	0.0597	0.582
EN1	3.03	2.53E-07	6.02E-08	0.9999999999999994	3.06	0.301	0.0943	0.649
EN2	3.84	1.39E-08	2.94E-09	1.0000000000000000	3.84	0.251	0.062	0.665
EN3	4.21	3.36E-08	7.08E-09	1.0000000000000000	4.09	0.228	0.0449	0.444
EN4	3.52	8.03E-08	1.62E-08	0.9999999999999999	3.5	0.222	0.0513	0.821
FI1	3.22	2.16E-08	6.59E-09	1.0000000000000000	3.13	0.253	0.0725	0.62
FI2	3.52	4.58E-08	1.05E-08	1.0000000000000000	3.5	0.254	0.0666	0.766
FI3	3.13	7.55E-08	1.43E-08	1.0000000000000000	3.5	0.249	0.0749	0.638
FI4	3.48	4.34E-08	1.03E-08	1.0000000000000000	3.47	0.241	0.0595	0.789
FI5	3.75	2.65E-08	6.07E-09	1.0000000000000000	3.75	0.249	0.0623	0.739
FI6	3.8	2.41E-08	5.99E-09	1.0000000000000000	3.78	0.251	0.0613	0.785
FI7	3.65	2.41E-08	5.69E-09	1.0000000000000000	3.63	0.233	0.0535	0.799
LE1	3.49	6.91E-08	1.49E-08	1.0000000000000000	3.44	0.203	0.0472	0.851
LE10	3.3	6.85E-08	1.06E-08	1.0000000000000000	3.31	0.249	0.0535	0.856
LE2	3.01	7.90E-08	2.45E-08	0.9999999999999999	2.91	0.238	0.0607	0.801
LE3	1.7	1.20E-07	4.82E-08	0.9999999999999996	1.75	0.168	0.07	0.954
LE4	3.19	7.37E-08	1.42E-08	0.9999999999999999	3.09	0.243	0.0696	0.559
LE5	2.92	1.04E-07	3.05E-08	0.9999999999999999	2.78	0.321	0.1133	0.664
LE6	3.15	2.49E-08	6.99E-09	1.0000000000000000	3.28	0.278	0.0818	0.773
LE7	2.81	2.05E-07	4.97E-08	0.9999999999999995	2.72	0.28	0.0989	0.76

LE8	2.98	9.11E-08	2.47E-08	0.999999999999999	3	0.244	0.072	0.644
LE9	3.29	5.77E-08	1.40E-08	1.000000000000000	3.19	0.331	0.0959	0.78
PL1	3.77	8.27E-08	1.33E-08	0.999999999999999	3.59	0.251	0.0633	0.718
PL2	3.21	5.84E-08	1.66E-08	1.000000000000000	3	0.268	0.0761	0.78
PL3	4.27	3.09E-08	5.91E-09	1.000000000000000	4.06	0.236	0.0502	0.803
SO1	2.73	2.20E-07	5.87E-08	0.999999999999994	2.78	0.269	0.0868	0.694
SO2	2.56	1.14E-07	4.53E-08	0.999999999999998	2.47	0.244	0.0668	0.784
SO3	3.72	5.31E-08	1.40E-08	1.000000000000000	3.69	0.238	0.0554	0.782
SO4	3.65	4.66E-08	1.17E-08	1.000000000000000	3.53	0.243	0.0618	0.782
SO5	4.11	3.59E-08	7.38E-09	1.000000000000000	4.03	0.193	0.0337	0.816
SO6	3.82	5.06E-08	1.26E-08	1.000000000000000	3.78	0.232	0.0539	0.739
SO7	4.17	7.54E-08	7.99E-09	1.000000000000000	4.09	0.252	0.0559	0.61
TCR1	2.98	5.54E-08	1.66E-08	1.000000000000000	2.81	0.166	0.0333	0.884
TCR2	3.22	4.58E-08	1.43E-08	1.000000000000000	3.03	0.254	0.0733	0.615
TCR3	3.1	1.70E-07	4.29E-08	0.999999999999996	2.81	0.26	0.0856	0.754
TCR4	3.7	7.50E-08	1.70E-08	1.000000000000000	3.53	0.253	0.0657	0.765
TCR5	3.77	8.73E-08	1.33E-08	0.999999999999999	3.72	0.244	0.0604	0.748
TCR6	3.08	9.19E-08	2.05E-08	0.999999999999999	3.19	0.267	0.0705	0.693
TCR7	3.04	1.65E-07	2.97E-08	0.999999999999997	2.84	0.254	0.0811	0.785
TCS1	2.63	2.09E-07	5.16E-08	0.999999999999994	2.53	0.28	0.0921	0.772
TCS2	3.57	7.36E-08	1.27E-08	1.000000000000000	3.53	0.214	0.0503	0.833
TCS3	3.72	6.65E-08	9.68E-09	1.000000000000000	3.56	0.248	0.0605	0.768
TCS4	3.63	8.04E-08	1.70E-08	0.999999999999999	3.56	0.233	0.0486	0.842
TCS5	3.05	6.74E-08	1.74E-08	1.000000000000000	3.03	0.25	0.079	0.73
TCS6	4.59	4.79E-08	7.51E-09	1.000000000000000	4.56	0.255	0.0524	0.81
TCS7	2.89	1.42E-07	3.29E-08	0.999999999999997	2.78	0.281	0.0829	0.694
TCS8	2.75	1.38E-07	4.16E-08	0.999999999999998	2.81	0.269	0.0931	0.752
TCS9	2.4	1.03E-07	4.14E-08	0.999999999999998	2.38	0.155	0.0328	0.907
TE1	2.9	1.61E-07	4.83E-08	0.999999999999997	2.78	0.25	0.084	0.757
TE2	1.35	1.99E-07	6.60E-08	0.999999999999982	1.34	0.215	0.1304	0.855
TE3	2	1.77E-07	6.00E-08	0.999999999999993	1.97	0.216	0.0733	0.896
TE4	2.14	1.37E-07	5.85E-08	0.999999999999996	2.09	0.207	0.0812	0.858
TG1	1.5	2.04E-07	6.61E-08	0.999999999999985	1.56	0.23	0.155	0.844
TG10	2.21	1.13E-07	5.83E-08	0.999999999999997	2.16	0.195	0.0821	0.865
TG11	4.97	1.13E-08	1.78E-09	1.000000000000000	4.97	0.145	0.0163	0.367
TG2	3.31	2.00E-07	4.46E-08	0.999999999999997	3.28	0.241	0.0657	0.786
TG3	3.66	7.51E-08	1.55E-08	1.000000000000000	3.56	0.25	0.0664	0.77
TG4	3.25	5.94E-08	1.58E-08	1.000000000000000	3.06	0.26	0.0764	0.768
TG5	3.61	1.85E-07	3.93E-08	0.999999999999997	3.53	0.259	0.0701	0.755
TG6	3.47	1.19E-07	2.61E-08	0.999999999999999	3.53	0.291	0.0787	0.767
TG7	3.31	7.49E-08	1.50E-08	0.999999999999999	3.28	0.255	0.0718	0.726
TG8	3.1	1.56E-07	4.83E-08	0.999999999999997	2.81	0.237	0.0687	0.594
TG9	3.86	2.50E-07	3.44E-08	0.999999999999995	3.72	0.257	0.0649	0.649
TL1	3.57	7.40E-08	1.55E-08	1.000000000000000	3.53	0.252	0.0662	0.769
TL2	2.34	1.06E-07	4.38E-08	0.999999999999998	2.31	0.16	0.0416	0.892
TL3	2.93	1.60E-07	4.30E-08	0.999999999999997	2.84	0.281	0.0829	0.742
TL4	3.2	1.72E-07	4.30E-08	0.999999999999997	2.91	0.275	0.0801	0.749
TM1	2.84	1.36E-07	4.53E-08	0.999999999999998	2.69	0.24	0.0649	0.777
TM2	2.46	1.03E-07	3.99E-08	0.999999999999998	2.47	0.281	0.0456	0.756
TM3	3.59	6.02E-08	1.20E-08	1.000000000000000	3.56	0.215	0.053	0.866
TM4	3.12	9.14E-08	2.90E-08	0.999999999999999	2.91	0.252	0.0768	0.63
TT1	3.65	7.25E-08	1.20E-08	1.000000000000000	3.56	0.255	0.0657	0.761
TT2	3.51	7.78E-08	1.20E-08	1.000000000000000	3.53	0.261	0.0717	0.753

Discussion of Findings

This study employs ANFIS as an intelligent machine learning technique to predict the uncertainty events in the construction cost of highway projects and thereafter compares the prediction performance of ANFIS to the SRA as a classical statistical technique. The success or failure of prediction depends on the credibility and performance of the prediction technique. The comparison of calculated R-Values from ANFIS and SRA (Table 3) revealed that the R-value of intelligent machine learning method is significantly close to 1, which means the predicted impact size of uncertainty events by ANFIS has a higher fitness to the real data. For Instance, the fitness of predicted impact size of event EC1 (fluctuation of prices) is improved from low fitness (0.659) to perfect fitness similarly for all the events.

Also, it emerged that intelligent machine learning technique improves the reliability of prediction by reducing both error indicator scores. Table 3 shows the two minimal error values of ANFIS on predicted impact size (very close to 0). For Instance, the RMSE score of event EC1 is decreased from 0.213 to 6.05E-08 similarly the MAPE score is reduced from 0.0484 to 1.35E-08. Therefore, the minimal error indicator values and the extreme closeness of the R-Value to 1 for ANFIS technique manifests the higher credibility and accuracy of intelligent machine learning methods in predicting the impact size of uncertainty events when compared to the classical statistical method. Furthermore, the comparison of the predicted impact size of the uncertainty events from SRA and ANFIS techniques revealed that the SRA technique generally underestimated (62 out of 76) of the impact size of uncertainty events by an average of -6.5%.

Conclusions

This study examines the capabilities and credibility of ANFIS as an intelligence machine learning method for predicting the impact size of uncertainty events on construction cost of projects. The results show that intelligent machine learning method (ANFIS) is more accurate than the classical mathematical method (SRA) in both fitness and reliability of the prediction model. Also, the research results suggest that intelligence machine learning methods such as ANFIS could be used as a superior technique for predicting the impact of uncertainty in construction projects mainly when the input data are ambiguous or subject to relatively high uncertainty. The hybrid intelligent learning ability of Fuzzy Inference System (FIS) empower the ANFIS in learning, modelling and analysing the qualitative aspects of data such as human knowledge. The strength of the hybrid intelligent learning methodology provides a simple and efficient approach over other conventional methods of prediction such as classical statistical techniques including Regression Analysis. Besides accurate

prediction and evaluation of uncertainty impacts, the ANFIS also reduces the potential inconsistency of correlations.

The study advances that the use of ANFIS technique could be extended to the management of uncertainties in various sectors of the construction industry. Also, that managing the uncertainties on projects could be executed more systematically using the advantages of the designed FIS and higher performance of predicted size by ANFIS. The use of a similar approach in evaluating the performance of intelligent machine learning methods as a predictor of various variables in the construction industry such as project complexity and project performance is recommended as the focus of further studies.

This study provides an accurate impact size of uncertainty events on the cost of highway construction projects as a baseline for future studies. By using this baseline and tailormade effect value for each impact size class it is possible to estimate the exact amount of construction cost of highway projects. In this study, the ANFIS was applied to assess the impact of uncertainty events on the cost of highway construction projects, due to its effectiveness in predicting, learning and modelling human knowledge. The strength of the proposed methodology provides a simple and efficient approach over other conventional methods of impact assessment which can be used by other researchers as a new research direction to explore the advantages and reliability of machine learning on other areas of construction management over the standard and classical methods.

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BIM LOD FOR FACILITY MANAGEMENT TASKS

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Abstract

Building information modeling (BIM) widely adopted in design and construction phase of the buildings, holds undeveloped possibilities for supporting Facility Management (FM) tasks in Operation & Maintenance (O&M) phase. The purpose of this paper is to define appropriate Level of Development (LOD) for different FM areas in order to enable FM-BIM for existing buildings during O&M phase. To do so, the customized LOD have been defined by existing literature review and facility experts. Then the required properties for each FM areas are implemented in two case studies. Conclusion demonstrated that more than 60 percent of properties defined as LOD500 are unnecessary to execute FM tasks. Besides, the categories of Services including Mechanical, Electrical and Plumbing (MEP) and fire systems requires more properties comparing with another categories and it needs specific LOD to leverage BIM in O&M phase.

Introduction

Throughout the lifecycle of the buildings, the highest costs occur during the phase of Operation & Maintenance (O&M) (Brito and Pereira 2017) since some reports (Akcemeti et al. 2010c; Teicholz 2013a) show that more than 60 percent of a total project cost is related to this phase which emphasize the importance of Facility Management (FM) tasks.

Building information modeling (BIM) has been emerging as a potential solution for Facility Managers (FMs) to address the challenges of information reliability, interoperability and usability in providing the project to endorse the lifecycle of their assets' information (Liu and Issa 2016). One of the advantages of BIM is to share data among multiple systems during the O&M phase (Motawa and Almarshad 2013). BIM has potential to support FM tasks by acting as a data repository, by locating equipment within a facility, and by coordinating information from multiple systems (Becerik-Gerber et al. 2012a). In order to enable BIM for FMs, it is absolutely crucial to access appropriate and reliable information to operate and maintain equipment and

systems efficiently in the building to extend the lifespan of equipment, to support decision making, to improve maintenance activities, to make energy more efficient, and to minimize labor time and equipment downtime (Cavka et al. 2017). Despite the numerous benefits offered by BIM, its utilization for the O&M phase remains significantly limited (Pishdad-Bozorgi et al. 2018). A serious hindrance to enabling BIM for FMs is the challenge of identifying and formalizing the information requirements needed to support FM tasks (Cavka et al. 2017) especially for existing buildings.

International Facility Management Association (IFMA) defined Facility Management as a profession that encompasses multiple disciplines to ensure functionality of the built environment by integrating people, place, process and technology. International facility management ISO standards presents different areas of FM (IFMA 2016) such as Asset Management (ISO 55001), Energy Management (ISO 50001), Safety Management (ISO 45001), Security Management (ISO 27001), etc.

According to Becerik (2012), these areas could be implemented in a BIM model and taken advantage of BIM during O&M phase, on the basis of the feedback gathered from the current and future implementers of BIM-enabled FM practices, and from persona and expert interviews.

In an effort to enable FM-BIM, each one of these FM areas demanded precise information (Becerik-Gerber et al. 2012a) which required defining Level of Development (LOD) (Leite et al. 2011). The LOD designation for project milestones determine geometric and non-geometric attribute information offered by a model component ((AIA) 2008). For instance, the Construction Operations Building information exchange (COBie) defines a LOD for technical equipment for commissioning maintenance functionalities with respect to type, location, serial numbers, tag, installation date, warranty, plan of maintenance necessity (The National Institute of Building Sciences 2013). However, LOD specification does not objective what FM tasks require as facility information (Dias and Ergun 2016). Most of researchers (Bruno et al. 2018; Chen et al. 2018; Lijun

et al. 2016; Pärn et al. 2017; Pishdad-Bozorgi et al. 2018) allocated LOD 500 for FM tasks which possess too much information, whilst having too much of unrequired information makes it challenging to manage (Cavka et al. 2017).

The aim of this paper is to overcome these challenges and determine appropriate LOD for different areas of FMs (Asset Management, Energy Management, Safety Management, Security Management, Space Management, Maintenance, Operation and Monitoring) so as to be able to take advantage of full value of BIM in O&M phase of the buildings.

Background

BIM in project lifecycle

The utilization of BIM in the design and construction phases has been conducted by enormous researchers and the professional communities. Researchers have focused on implementing BIM on design (Eastman et al. 2008; Kiziltas and Akinci 2010), automated cost estimation, visualization of process (Babič et al. 2010; Sacks et al. 2010). Enabling BIM for keeping and maintaining information has also been one of the most commonly researched areas in O&M phase (Hwang and Liu 2010). Moreover, BIM implementations have also been extended to energy analysis (Chew et al. 2004; Stumpf et al. 2009) and sustainability (Arayici et al. 2011; Barnes and Castro-Lacouture 2009; Sacks et al. 2009). Recently, using BIM in the other fields has been central in research such as valuable 'as-built BIM' (Volk et al. 2014), maintenance of warranty and service information (Arayici 2008; Becerik-Gerber and Rice 2010; Singh et al. 2011), quality control (Boukamp and Akinci 2007), assessment management and monitoring (Arayici 2008; Becerik-Gerber et al. 2012b), energy management and space management (Becerik-Gerber et al. 2012b; Cho et al. 2010), emergency management (Arayici 2008) or retrofit planning (Mill et al. 2013). Furthermore, making decisions on preventive maintenance plan (Akcemete et al. 2010a; Becerik-Gerber et al. 2012a; Teicholz 2013b), building systems analysis (Becerik-Gerber et al. 2012a; Weygant 2011), and commissioning processes (Becerik-Gerber et al. 2012a; Jiao et al. 2013; Weygant 2011), emergency planning and strategies plan (Becerik-Gerber et al. 2012a; Zou and Wang 2009) can benefit from BIM in O&M phase.

FM-BIM for new and existing buildings

Recently, with the growing interest in enabling BIM for FMs, many researchers (Akcemete et al. 2010b; Pishdad-Bozorgi et al. 2018) have focused on transferring information from design phase to O&M phase. For this purpose, some standards are used to transfer information from design phase to O&M phase such as Industry Foundation Classes (IFC) (IFC 2016), COBie (COBie 2017), etc. The Industry Foundations Classes (IFC) is an open, neutral and standardized specification for Building Information Models allows AEC to utilize various software during whole lifecycle

of the buildings. According to National Building Specification, COBie is a non-proprietary data format for the publication of a subset of BIM focused on delivering asset data as distinct from geometric information. It reduces the time and effort that the FMs spend on entering building information manually. However, it allows to possess too much information result in overloading (Anderson et al. 2012; Thabet et al. 2016) Accordingly, COBie needs to be customized for facility information as a means to building operation (Dias and Ergan 2016).

In contrast, for existing buildings, if BIM model is not available, the buildings should be modelled from the scratch. In this regard, techniques of data capture or survey are applied (Donath 2009). However, These kind of information is spread out and might not be available in many existing buildings due to lack of as-built, CAD files (Becerik-Gerber et al. 2012b; Gursel et al. 2009) along with imperfect and deficient, obsolete or disintegrated building information (Gursel et al. 2009). If BIM model is available, it comes from design and construction phase of the buildings which typically do not contain the necessary information for executing FM tasks (Dias and Ergan 2016).

LOD for FMs

Some researchers (Dias and Ergan 2016; Liu and Issa 2016; Sattenini et al. 2011; Terreno et al. 2015; Thabet et al. 2016) have attempted to determine LOD needed for O&M phase by interviewing experts. Liu and Issa (2016) conducted a survey questionnaire to define a list of maintenance problems such as Lack of equipment accessibility, poor design of equipment layout, lack of adequate space for mechanical room, lack of space designed in the ceiling to contain MEP systems, limited space for AHU filter access that ought to be deliberated in design phase. Sattenini et al. (2011) interviewed with facility managers of Auburn university for defining required information to be included in a BIM model. Thabet et al. (2016) depicted workflow for collecting information defining who is responsible and when data should be collected during project lifecycle. Regarding maintenance management area of FM, Akcemete et al. (2010) have been utilizing BIM model in an university campus for enabling maintenance planning and linking maintenance history to facilitate decision making. Cavka et al. (2017) developed owner information requirements for enabling BIM to assist maintenance (preventive schedule-periodic reactive), building systems monitoring (operation/monitoring and tracking) and asset management. Accordingly, there is a lack of generally LOD that can apply to each kind of FM areas to manage the buildings efficiently.

Methodology

In order to determine the appropriate LOD for the different areas of FM, each element of the building (such as Air Handling Unit, chiller, steam boiler, floor, etc.) should have suitable geometric representation and

properties extracted from Omniclass, COBie, Specifiers' Properties information exchange (SPie) to be included in BIM models. Based on detailed examination of Omniclass, COBie, Spie, the authors allocated facility properties represented in these standards for each elements (Figure 1).

The authors focused on the most important elements that are common or typically seen in different buildings. The Unifomat classification is used to classify elements into five categories: 1) Substructure; 2) Shell (Exterior, Windows, Doors, Roof, Column, and Beam); 3) Interiors (Wall, Ceiling); 4) Services (HVAC, Plumbing, Air handling unit, Chiller, Electrical); 5) Equipment & Furnishing. Table 1 shows the elements in each categories based on Unifomat classification.

Figure 1: Process of creation a matrix

The focus group was conducted with twelve FM experts including engineers, architects and technicians who were involved in FM services and consultancy (Bortolini and Forcada 2018) both to define FM areas and eliminate unnecessary properties (to avoid heavy model so as to be used in FM tasks). The experts included 8 industrial engineers, one architect, two quantity surveyors, and one technical engineer.

Experts agreed that the most relevant FM areas include: Asset Management, Energy Management, Safety Management, and Security Management, Maintenance, Space Management, Operation and Monitoring. Based on these FM areas, elements and properties, the elements-LOD matrix is created (Figure

1). The FM experts identified what properties with their geometric representation are relevant in BIM model so as to leverage BIM for FM areas. Figure 2 shows the elements-LOD matrix with respect to FM areas.

The feasibility of implementing the proposed LOD was then validated in two case studies by collecting the required elements' properties from two university buildings from the Universitat Politècnica de Catalunya (UPC), Spain.

Table 1: Elements in each categories

Categories	Group Elements	Individual Elements
Substructure	Foundation	Foundation
Shell	Superstructure	Column
		Beam
		Floor
	Exterior Enclosure	Wall exterior
		Curtain wall
		Window
		Door
	Roofing	Roof
Interiors	Interior Construction	Wall interior
	Interior Finishes	Ceiling
Services	Conveying	Elevators & Lifts
	Plumbing	Plumbing Fixtures
	HVAC	Air handling unit
		Chiller
		Steam boiler
		Water heater
	Fire Protection	Fire protection systems
	Electrical	Electrical systems
Equipment & Furnishing	Equipment	Objects
	Furnishings	Fixed furnishing

Elements-LOD		FACILITY MANAGEMENT									
CHILLER		FM areas									
Information Item		Maintenance	Space management	energy management	security management	Asset management	Safety management	Operation & monitoring			
6	Nominal Size										
7	Type										
78	Material										
79	Maker Name										
80	Manufacturer										
81	Serial Number										
82	CSI Uniformat Number										
83	Inventory Number										
84	Model Number										
85	Order Number										
86	Product ID										
87	Product Name										
88	Production Year										
89	Accessories										
90	Shipping Weight										
91	Purchase Information										
92	Retail Cost										
93	Retail Cost Unit										
94	Installation Cost										
95	Set Assembly Cost										
96	Location of Manufacture										
97	Certified Green Item Selected										
98	Fabrication Time										
99	Construction Means & Methods										
100	Installation Time										
101	Installation Sequence										
102	Installation Start Date										
103	Installation End Date										
104	Shipment Delay										
105	SafetyTaskID										
106	TroubleTaskID										
107	ServiceTaskID										
		D30 Equipment-Mechanical	D30 Air Handling Unit	D30 Chiller	D30 Steam Boiler	D30 Water Heater					

Figure 2: The elements-LOD matrix

Results

The properties collected from OmniClass, COBie, SPic for LOD500 contain approximately more than 8000 properties. After eliminating those properties that FM experts found irrelevant for managing buildings, the number of properties fell dramatically to approximately 3000 properties. It shows that more than 60 percent of properties are unnecessary to execute FM tasks.

Figure 3 illustrates the properties for each categories based on FM areas. For the Operation and Monitoring activities, a huge amount of information (elements' properties) within the "Services" category is needed. Monitoring electrical, gas, water consumptions are also important for this FM area.

In the area of Safety management, the categories of

“services” and “shell” are those that require more properties. Taking into account that it is urgent to access the information organized and displayed logically to respond and take appropriate actions during an actual emergency (Becerik-Gerber et al. 2012b), most of the properties requirements for safety management are of a spatial nature (e.g. evacuation routing position). Other properties are related to Fire Resistance, Fire Prevention, Disability Access, Occupancy/Capacity, Means of Egress, Fire Rating Requirement, Building Type Selection, and Position of fire extinguishers and defibrillators.

In the area of Asset management, “equipment and furnishing” is the category that requires by far more properties. These properties mainly include Maintenance history, Maintenance schedule, schedule ID, Approve By, Delivery, Schedule Activity,

Figure 3: Properties for each categories based on FM areas

Inspection report, system lists, equipment lists, Component ID, Component Name, Component Description, Attribute ID, System Reference ID, Maker Name, Manufacturer Serial Number, installation manual, Inventory Number, Model Number, Order Number, Product ID, Maintenance history, Purchase Information, Retail Cost, Retail Cost Unit, Installation Cost, Type, Material, Availability, etc. Whether public or private sector, and whether assets are physical, financial, human or 'intangible', asset management could maximize value-for-money. It involves coordinated and optimized planning, asset selection, acquisition/development, utilization, care and ultimate disposal or renewal of assets and asset systems (Asset management standards).

For the management of security, all categories except "substructure" require approximately a similar amount of properties for "equipment and furnishing", "interiors", "services" and "shell". Security in operation typically addresses certain aspects of IT or data security.

In the area of Energy management, the most relevant properties are related to the categories of "services". "Interiors" and "shell" held the same amount of properties. The most relevant properties for Energy management are, Air Infiltration, Low E Glazing, Energy Efficiency Ratio, R-Value, U-Value, System performance, Absorption-Value, Radiation Exposure, Green Material Type, Green Material Specification, Power consuming, Recycled Content, Post-Industrial Recycled Content, Pre-Consumer Recycled Content, Post-Consumer Recycled Content, Carbon Footprint, Certified Green, Item Selected, Coefficient of Performance, etc. Using energy efficiently helps organizations save money as well as helping to conserve resources and tackle climate change.

In the area of Maintenance, the "services" requires more properties as might be expected followed by the category of "equipment & furnishing". In this case, the LOD properties for "Services" consist of Shape, location of panel and valves, Component ID, Room Number, Room Name, Story Number, Manufacturer Name, Product Name, Type, Acquisition Date, Bar Code, Serial Number, Assembly Place, Production Year, Warranty Identifier, Warranty Start Date, Warranty End Date, Warranty Period, Contact, etc. Building maintenance combines actions to keep the building in an appropriate condition for use (Shohet et al. 2003), including technical building inspections that characterize a building's pathological state.

In the area of Space management, the category of "equipment & furnishing" demands more properties. FMs are able to optimize the physical utilization of the spaces and related assets. Remodeling or renovating of existing buildings is also considered in this area (Space management). Facility ID, Facility, Name, Length, Width, Height, Area, Volume, Maximum Size, Story Number, Zone/Space Name, Zone/Space Number,

Room Name, Room Number, Floor ID, Floor Name, Space Volume, Room Name Tag, Glazing Requirements, Net to Gross Space Requirement, Ceiling Height, Building Story Information, space ID, Space Number, Coordinate ID, Coordinate Type, etc. are the most relevant properties for Space management.

The findings indicate that there are huge amount of information which are not necessary for implementing FM tasks and it causes heavy BIM model (creating model navigation and computer memory issues). Generally, the elements which require more properties are related to the categories of "Services" including Mechanical, Electrical and Plumbing (MEP) and fire systems and they need specific LOD to be used in BIM model. "Equipment and Furnishing" is also important for asset management and space management.

Case study

The feasibility of implementing the proposed LOD is validated by collecting the required elements' properties from two university buildings from the Universitat Politècnica de Catalunya (UPC), Spain. Both buildings (TR5 and Gaia) are located in Campus Terrassa and are managed by the same Facility Management department. The campus includes 25 buildings of different typologies and construction ages. There are buildings with more than 100 years and buildings with less than 10 years. About 98% of the buildings have the energy consumption monitored, 60% of the buildings have automated HVAC systems and only 20% of the buildings have automated lighting (Bortolini et al. 2016).

The majority of the building characteristics of the campus (age of construction, location, type of materials, technology of the equipment, etc.) are stored in pdf files in an intranet platform called Somdoc. This platform also includes maintenance reports, guarantees, etc.

Building monitoring and control data (temperature, humidity, energy consumption, etc.) is automatically captured by sensor, sent to a Building Management System (BMS) (TAC VISTA Schneider) and visualized in an intranet application.

The water and energy consumption is monitored by Power Studio® and visualized on the intranet platform called Sirena (System of Information on Consumption of Energy Resources and Water).

Regarding the maintenance management, the university campus uses Archibus® system, which consist of a Computer Automated Facility Management (CAFM) and Integrated Workplace Management System (IWMS) for FM. The visualization of information is text based and includes 2D drawings of the buildings. For asset management, UPC campus adopted a standardized classification of elements. All building elements and systems are classified with a predefined code based on COBie. The structure of information has a standard classification and it is organized by: campus, building, floor, room and type of element.

Figure 4: TR5 modelled in Revit

TR5 was built in 1960 and is mainly used for classes. Although having temperature and humidity sensors in different areas of the building, the automation of the systems is low. There is neither light control nor automatic HVAC system. Only architectural and systems CAD drawings are available. These drawings include very basic information such as the location of equipment but without specifying their characteristics. These CAD drawings are not updated and might contain dimensional errors. Figure 4 shows TR5 modelled in Revit based on existing information.

Figure 5: Gaia modelled in Revit

Gaia was built in 2006 and is mainly used for offices. It is a highly automated building with HVAC and lighting control. As-built drawings and maintenance manuals are precise. The architectural BIM model is also available, although some construction properties and building systems are missing. Figure 5 shows Gaia BIM model.

Table 2 demonstrate the available properties in each building. As it can be seen, Gaia has nearly most of the properties required in each category. On the other hand, TR5 needs more properties to leverage BIM for

FM areas. The available properties for the service category is only 40% in TR5. Hence, facility managers miss necessary properties for FM operation.

Table 2: Available properties in TR5 & Gaia

Categories	TR5	Gaia
Substructure	67%	90%
Shell	64%	87%
Interiors	58%	84%
Services	40%	72%
Equipment & Furnishing	70%	84%

The available properties of each category in TR5 and Gaia buildings are compared. The results show that Gaia building has approximately all the necessary properties and has potential to improve the building performance by implementing other FM areas, while TR5 needs more properties which requires either time or specific tools to obtain that properties since it does not have an as-built document. Moreover, most of the available properties in TR5 are obsolete and need to be updated. Although Gaia has got most of the properties, these properties are stored in different platform and needs to be store in one platform to be more useful for other FM areas. For instance, facility managers can make decision on replace equipment or remodel a building if they have an access to reliable information provided in BIM.

Figure 6: The available properties in TR5 and Gaia with respect to space and safety management

Regarding Space management and safety management in both buildings (Figure 6), the availability of properties in the category of interiors are quite the same. The same situation happened in Equipment & Furnishing category where TR5 and Gaia buildings possess the same amount of properties with respect to FM areas (space and safety management), even though space management area requires more properties other than safety management area in this category.

As it can be seen in Figure 6, the significantly different

in properties available between TR5 and Gaia buildings are related to the service category. Table 3 illustrates more than 70% of properties are not available in TR5 for service category in order to implement safety management area.

Table 3: Available properties in TR5 & Gaia with respect to Space and Safety management areas of FM

Categories	Space management		Safety management	
	TR5	Gaia	TR5	Gaia
Substructure	73%	98%	52%	86%
Shell	84%	95%	78%	97%
Interiors	71%	95%	60%	90%
Services	49%	87%	29%	88%
Equipment & furnishing	71%	83%	82%	91%

Safety management area is ignored in both buildings, however, Gaia has potential to implement this FM area based on the properties available, 86% in substructure, 97% shell, 90% interiors, 88% services, 91% equipment and furnishing. Although space management area in TR5 and Gaia buildings is already implemented, it is becoming more evident that both buildings can improve this area activities with having more certain properties.

Figure7: The available properties in TR5 and Gaia with respect to maintenance and energy management

Regarding Maintenance and Energy management (Figure 7), the Gaia building has got approximately 80% of the properties in each categories for maintenance area. However, more than 50% properties in TR5 building are not available and FMs will not be able to execute maintenance tasks completely.

Table 4: Available properties in TR5 & Gaia with respect

to Maintenance and Energy management areas of FM

Categories	Maintenance management		Energy management	
	TR5	Gaia	TR5	Gaia
Substructure	50%	83%	33%	67%
Shell	47%	67%	34%	57%
Interiors	39%	79%	36%	64%
Services	36%	81%	48%	82%
Equipment & Furnish	45%	91%		

The properties available for energy management in both buildings are quite low (Table 4). FMs should come up with getting information so as to implement energy management area.

Discussion

The LOD defined for each areas of FM can bring benefit to FMs to utilize BIM model with full value. For example, the availability of the relevant properties on "Services" can not only improve the maintenance area but also the energy management area. The location of plumbing can not only be used for maintenance but also can be used for safety and energy management areas. Hence, facility managers knows what properties are missing and they would be able to decide whether they require it or not with respect to FM areas. BIM model, which contain appropriate LOD, can be used for maintenance activities, monitoring energy consumption, and etc. Having all these necessary information conjointly will enable FMs to make decisions. For instance, having information about consumption, occupancy, façade along with historic information about complains for one room, FMs would find out where the problem comes from and decide whether it is better to stop the air conditioning or replace the window to reduce energy consumption.

Figure 8 shows the difference BIM creation between new and existing buildings. In many existing buildings, BIM is not available and the properties should be collected from existing information (Paper, maintenance history, walk through the building, etc.) which might not be reliable or updated. Even if the BIM model is available, it might not be used for FM tasks in O&M phase. For instance, In design phase, generally, the architectural model might lack adequate detail and information about building systems and equipment data, many facility elements are not modelled due to either complexity of the modelling process, or they are considered nonessential to design drawings and visualization (Sacks et al. 2018). In

Figure 8: FM-BIM creation for New and Existing buildings

construction phase, the construction model normally contains too much information about construction details that have no relevance to FM, lacks proper definitions for space management, and lacks systems connectivity information and equipment data needed for FM (Sacks et al. 2018). The best way for modelling BIM used for FM tasks in new buildings is to define necessary LOD by FMs in an early phase to be included in their BIM models since BIM offer new opportunities to improve FM tasks and enhance building performance during O&M phase of the buildings. For existing buildings, this research will assist FMs by defining what information should be made readily available for FM operation.

Conclusions

In order to use BIM for existing building in O&M phase, it is absolutely crucial to access appropriate and reliable LOD to operate and maintain equipment and systems efficiently in the buildings. This paper has defined the appropriate LOD for each areas of FM for existing buildings in order to utilize full potentially BIM for FMs in O&M phase. The results show that more than 60 percent of properties are nonessential for implementing FM tasks. Among 40 percent, “service” category is required specific LOD with more detail. The case study illustrates although the “service” category is the most important one and requires more properties, approximately 60 and 30 percent of properties are missing in TR5 and Gaia respectively. However, the properties for “Shell” and “Equipment & furnishing” categories are nearly available in both buildings. Concerning properties for each FM areas, warranty start date, warranty end date, assessment date, assessment condition, and service life duration is not required for space or security management purposes, but information about assignable area, net to gross space requirement is important for managing space. Material Safety Data Sheet (MSDS) information is important for safety management area.

Regarding asset, maintenance and energy management, the elements description, where it is installed, manufacturer name, serial number, acquisition date, (nominal power consumption, coefficient of performance in case of a chiller); (nominal air flow rate, fan speed, fan Ext pressure drop in case of a fan); and efficiency, humidifier capacity in case of an air handling unit for each elements are highly important for asset, maintenance and energy management. The case studies also illustrate difficulty to obtain information for TR5 building because the information is not updated. Some equipment like Laser scanning, thermal camera, etc. could be used to obtain these kind of information but it is necessary to evaluate the costs and benefits of acquiring information beforehand. Future research will evaluate the costs and benefits to make decision whether to obtain information or not.

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AN IFC DATA PREPARATION WORKFLOW FOR BUILDING ENERGY PERFORMANCE SIMULATION

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Abstract

Accurate building energy performance simulation model generation from IFC data files require the input IFC data to be correct and complete. To ensure such data quality conditions, methods integrating IFC data correctness and completeness checks, under a common architecture, are introduced. IFC data correctness is supported by the use of a dedicated geometric error detection tool, which identifies and reports back to the building designer, errors affecting the building's 2nd-level space boundary topology. IFC data completeness is performed by the use of a dedicated for building energy performance simulation Model View Definition schema. The quality checking results are reported in a BIM collaboration file format.

Introduction

The accuracy of Building Energy Performance Simulation (BEPS) results is determined by the quality of its input data, mainly comprising the building geometry, its construction's materials, internal loads, HVAC systems and components, weather data, operating strategies and schedules, and simulation specific parameters (Maile et al. 2007).

In current practice, to develop a BEPS model, modelers gather and combine 2D drawings such as Architectural and Mechanical Electrical Plumbing (MEP) plan views, material data and other information, and manually transform them into the specific input data, required by the respective BEPS engine. This process has two strong weaknesses: a) it is very time-consuming, often requiring more time than is available due to project's deadlines; and b) it is a non-standardized process that produces BEPS models whose results can significantly vary from one modeler to another according to their experience (Berkeley et al. 2014), even given the same initial building design information. A methodology for automated creation of BEPS models could make the BEPS modeling process much more expedient and therefore, less vulnerable to modeling errors. Building Information Models (BIM) are information-rich repositories that could be used to streamline and expedite the collection of such information. Hence, recent

research studies focus on BIM-based BEPS models generation (Andriamamonjy et al. 2018, Thorade et al. 2015, Wimmer et al. 2015, Giannakis et al. 2015).

BIM is an object-oriented digital representation of a building, which also can capture part of the information required for generating a BEPS input data file. Relevant open-BIM data schemas include the Industry Foundation Classes (IFC) (ISO 16739-1 2018) and the green-building XML schema (gbXML). Concerning building geometry, IFC supports three dimensional representations, while gbXML supports only planar geometry. For this reason, a plethora of recent studies focuses on developing a methodology to automatically generate geometry inputs for BEPS from IFC files. Additionally, IFC appears to be a more suitable choice as its rich content enables interoperability among different software environments and can easily be updated following a building's life cycle (Hitchcock & Wong 2011).

However, applying an automated data transformation from IFC data to input data of BEPS tools is not a straightforward but a tedious task often due to imperfections of the provided IFC files. Although commercial BIM authoring tools (RevitTM, ArchicadTM, VasariTM) support exportation of IFC files, their quality is not acceptable in the context of BEPS input data generation. Even RevitTM, and its IFC4 Design Transfer View (DTV) exporter, which currently seems to be the most mature tool, is far from being perfect: while IFC schema can capture data about material thermal properties, internal gains (schedules and densities) and 2nd-level space boundaries (Bazjanac 2010), requested from the BEPS perspective, relevant information is missing or incorrect in the exported IFC4 DTV files.

Proposed IFC4 workflow

To examine and eliminate these IFC data imperfections, in this work an IFC4 data workflow is introduced. This workflow aims at delivering error-free IFC4 files ready for BEPS input data generation. The workflow starts with the BIM preparation and the IFC data exportation processes (first block of Figure 1). Since the lack of training of the BIM designer contributes to data inaccuracies, a set of de-

sign guidelines have been developed to help the designer to define properly all the requested information during the BIM preparation process. After the BIM data are prepared, the IFC data exportation process follows. However, due to issues mentioned above, the exported IFC file is of poor quality (as for the 2nd-level space boundary information) or lacks valuable information (as for the material thermal properties and internal gains); for the latter, RevitTM's IFC4 DTV exporter has been modified to correctly populate such information.

Figure 1: Overview of the proposed IFC data workflow

After the BIM preparation and IFC exportation processes, the IFC4 data workflow continues in three main stages. During the first stage (IFC data geometric check) the architectural geometric content of the IFC file is examined using the GED tool (Lilis et al. 2015), for possible errors which affect the BEPS model generation process and if found they are reported in BIM Collaboration Format (BCF). In the second stage (IFC data enrichment) the IFC file is enriched using the Common Boundary Intersection Projection (CBIP) tool with the necessary for BEPS 2nd-level space boundary information. Similar enrichment tools, such as the SBT tool (Rose & Bazjanac 2015), have been developed using graph-based methodologies. In the final stage (IFC data completeness check) several checks are performed on the IFC data to ensure acceptable quality for BEPS input data file generation. The checks are performed using the Model View Definition (MVD) Checking

tool. For its development, other supporting tools, relevant libraries and an MVD XML for conventional BEPS have been created. Other attempts in this domain have been primarily focused on developing a MVD XML for conventional and advanced BEPS (Pineiro et al. 2018). The initial processes and the three main stages of the workflow are described analytically in the following sections.

IFC data preparation and exportation

To help the BIM designer on creating an error-free (or error-reduced) BIM, from which the maximum level of BEPS information can be exported, a document that presents a set of design guidelines as they apply for RevitTM has been developed – similar guidelines can be developed for other BIM authoring tools.

The guidelines are provided as a set of modelling rules belonging to two broad categories: Static and Dynamic Data. Static data rules cover the building geometry, construction materials, glazing information, building services, and so forth, while dynamic data rules cover the specification of time-varying parameters such as occupancy schedules, internal gains schedules, use of equipment, or occupant actions. A subset of these guidelines are briefly presented below.

Note here that concerning HVAC systems data representation, while IFC is the most widely used openBIM schema, it suffers from limitation in the description of HVAC system in the context of BEPS. Commonly, HVAC modelling in BEPS engines require further information than what is available in an IFC file. Hence, the presented BIM design guidelines, are mostly focused on building energy demands estimation aspects.

Spaces and HVAC zones

Accurate heating- and cooling-loads simulation can only be accomplished when spaces are created in all internal building closed areas to account for the entire volume of the building model. Spaces should be defined for each closed area of the building, including unoccupied closed air volumes such as plenums. Following the definition of spaces, a checking that they are properly bounded must be performed using floor plans and section views, to guarantee that a) there are no overlaps between the space volume and the attached building elements, and b) there are no void volumes (common case when the space volume is not attached to building elements).

HVAC zones comprise one or more spaces that have common environmental or design requirements. Spaces that are on different levels can be added to the same zone. Zones are rather important for BEPS as they define the granularity of the approximation. Grouping spaces into zones in RevitTM is required to ensure manageable com-

plexity of the BEPS model. When a space has not been assigned to a zone, a new zone for this space is defined automatically.

Material thermal properties

In a broad sense, two main material categories exist: Opaque and Transparent. Knowledge of material thermal property values is required in the modelling of the various energy transfers this includes absorbed solar shortwave radiation flux, conduction heat transfer through walls, convective transfer to the space (or outside) air and fraction of sunlight transmitted to building interiors.

For Opaque materials, knowledge of the following thermal properties is required: Thickness, Conductivity, Density, Roughness, Specific Heat, Thermal absorptance, and Solar absorptance. Transparent materials require definition of the following parameters: U-factor and Solar Heat Gain Coefficient (SHGC). In Revit, these material properties can be defined by the designer and can be subsequently accessed through the Revit API. To define and retrieve such information, the BIM designer must activate the thermal properties population for each material through the "Thermal" tab.

Most IFC-to-BEPS methods currently use construction and material thermal properties of building elements from fixed predefined libraries (Thorade et al. 2015, Wimmer et al. 2015). However, as mentioned above, this information can be explicitly prescribed in the Revit™ model, and can also be represented in IFC (e.g. IfcThermalConductivityMeasure for thermal conductivity). Surprisingly, the default Revit IFC-exporter is not able to export such information.

Internal gains and operation schedules

Building equipment's operation (artificial lighting and electrical equipment), as well as the occupants' presence and the building infiltration rate, contribute to the overall internal gains and can be represented as time-varying functions, called herein internal gains schedules and assigned to every building's space.

The IFC schema includes classes for representing the internal gains schedules (IfcTimeSeries). Objects of these classes can be attached to individual space instances. However, concerning the existing BIM-authoring tools, these schedules can be selected from predefined variants. In Revit™, such information can be defined in building and/or space scale as follows: a) define the building type, which sets a predefined template for the internal gains (schedules and densities), and its infiltration class; b) define the people, artificial lighting and electric equipment (density and schedules) at each space by selecting the space type. At this point, it is worth-mentioning that the designer is allowed to edit/modify non-schedule parameters

(densities), but not modify existing schedules, since these schedules have been defined according to relevant standards (ASHRAE 90.1 2010); if a new schedule is required the modeler must define a user-defined schedule and edit its values properly.

IFC exporter modification

To overcome limitations of the default Revit IFC4 DTV exporter on exporting information about thermal properties of each building entity's construction material and internal gains (schedules and densities), which have been properly set following the aforementioned guidelines, and to guarantee correct exportation of such information, the default exporter (which is an open source component) has been modified to create a bespoke OptEEmAL version that addresses these shortcomings. The OptEEmAL IFC Exporter supports the latest version of Revit™ (2018.3).

Exportation setup

Assuming that the BIM data insertion according to the guidelines and the OptEEmAL IFC exporter's installation have been accomplished, the BIM designer proceeds with the exportation setup where few of the defaults IFC-exporting options are modified properly to retrieve the requested information.

The first modification is the rooms exportation's deactivation. Utilizing the Revit IFC4 DTV exporter and/or its modified version, both spaces and rooms are exported as IfcSpace instances. While spaces definition throughout the models is prerequisite, rooms definition is not: information that a room object could provide is not usable in the context of BEPS. Hence, to avoid duplication of IfcSpaces' geometry representation, the designer must deactivate the rooms' exportation. To this direction, designer must change the IFC options by editing the rooms Revit™ category and setting "Not Exported" in the respective "IFC Class Name".

Setting the rooms as not exported elements, the file is ready to be exported: the IFC4 Design Transfer View is selected as MVD, while a) the Revit™ property sets and b) the IFC common property sets exportation are activated.

IFC data geometry check

After the IFC file export geometric errors that affect the IFC data enrichment stage (stage 2 Figure 1), (Lilis et al. 2015) must be detected automatically and corrected manually. These errors belong to a subset of all possible errors in IFC data files (detected by commercial IFC data checking software such as Solibri Model Checker, TEKLA and others) and a dedicated Geometric Error Detection (GED) tool have been developed for their detection.

Errors that are detected by the GED tool belong to mul-

multiple categories. For example, an architectural construction (e.g. wall, slab, etc.) that intersects with a building space volume, renders the 2nd-level space boundary surface related to this construction and space undetectable (see example in part I of Figure 2). Two intersecting wall opening volumes next to each other, attached to the same building space (see example in part II of Figure 2), produce 2nd-level space boundaries which also intersect with each other (space boundary surface duplication). For all of these reasons, methods for detection and semi-automatic correction of these inaccuracies have been proposed (Lilis et al. 2015).

Figure 2: Geometric errors detected by GED tool

The GED tool reports the detected errors back to the designer in a BCF file format (part III of Figure 2). The BCF error report file contains the 3D geometric definitions of the architectural elements involved in a geometric error as well as the set of surfaces and line segments indicating at the exact location of the error in the building's three dimensional space.

IFC data enrichment

After the designer's manual corrections of the aforementioned remaining geometric errors, the exported IFC file is ready to be enriched with the necessary for BEPS geometric content, which is essentially the 2nd-level space boundary surface topology (Bazjanac 2010). This topology contains surfaces through which thermal energy flows among internal building spaces and the building environment (air or ground) and are required in order to assess total thermal energy balance of the building (see example in part II of Figure 3). This surface topology cannot be obtained directly from the geometry of the architectural elements (e.g. walls, slabs, etc.) as the building spaces are not perfectly aligned vertically and horizontally. Addi-

tionally, most IFC exporters do not or export this topology or they export it with errors.

Figure 3: 2nd-level space boundary surface generation of CBIP tool

Consequently, to produce this topology in a consistent and precise way, CBIP tool has been developed (Lilis et al. 2017), which performs the necessary geometric transformation operations on the existing IFC architectural geometric content (part I of Figure 3), calculates the 2nd-level space boundary surfaces (part II of Figure 3) and enriches the input IFC file with the required geometric data of these surfaces and their associations to building space volumes and material constructions. As illustrated in the example of part III of Figure 3, CBIP correctly decomposes the floor surface into multiple sub-surfaces depending on the location of the building spaces underneath the slab.

Although the geometric content of the enriched IFC file might be adequate for BEPS model generation (the necessary 2nd-level space boundaries are present with the correct associations to related building elements), additional information related to thermal properties of the materials and time schedules of entities which change state (people, devices, openings, etc.), required for BEPS model generation, might be missing. Consequently, an IFC data completeness checking stage, following the model view definition approach, appears to be necessary, as described in the following section.

IFC data completeness check

For an IFC-to-BEPS model data transformation, presence of certain IFC data is prerequisite. More specifically, IFC data have to satisfy the exchange requirements of the BEPS input data generation; hence, certain subsets of the IFC schema are validated by evaluating the IFC entities and their attributes in terms of existence, correctness, uniqueness and conditional dependencies (Chipman et al. 2014). There are two main approaches of developing an IFC validation tool. First using an IFC library, the developer can build static rules by querying the IFC entities and checking their attributes. This approach has some weaknesses: a) it does not support reusability of the defined rules; and b)

it requires advance programming skills to validate the relations of the IFC entities under a certain IFC subset. The second approach is the development of an IFC validation tool that supports the Model View Definition (MVD) automated checking (Zhang et al. 2015). An MVD describes the subset of the IFC schema that is needed for a data-exchange in a specific domain, which can be formalized using the mvdXML open standard that has been released by buildingSMART International. The IFC validation tools which support MVD checking use the mvdXML format to import the IFC subsets known as templates and the defined rule sets known as concept to perform an automated validation of the IFC data. To develop such a tool, in this work some supporting tools and libraries have been developed, described in the following sections.

EXPRESS Parsing Tool

The proposed EXPRESS Parsing Tool is a standalone program written in Java using the code model library and is suitable to generate IFC java classes from the corresponding EXPRESS files which have been released by buildingSMART International. The tool can parse successfully the most frequently used IFC releases, from IFC2x3 TC1 to IFC4x1 final. In the first step, the EXPRESS data are transformed into in-memory objects. Consequently, the defined mapping rule set is applied on top of this in-memory representation to initialize the corresponding Java code model. The mapping rules are summarized in Table 1.

Table 1: Mapping rules between EXPRESS schema and Java model

EXPRESS Model	Java Model
ENTITY	Java Class
SELECT	Java Interface
ABSTRACT SUPERTYPE	Java Abstract class
TYPE	Java Class
	Enumeration class
	Custom list wrapper
	Custom array wrapper
	Boolean wrapper class
	Logical wrapper class
	Real wrapper class
	Integer wrapper class
	String wrapper class
	Binary wrapper class
INVERSE	Set Collection

The Java code model has a built-in method to generate the defined IFC classes and to organize them into packages based on the version of the given EXPRESS schema. Each IFC Java class implements some standard methods which

are summarized as follows:

- Public constructor without arguments: instantiates an object of an IFC class;
- Public constructor with arguments: the constructor includes all the defined properties (IFC attributes) as well as the properties which are defined in upper levels (IFC abstract classes);
- Public method to initialize the properties of an IFC class;
- Public method to initialize the collections set of the inverse properties;
- Public getters/setters for each property;
- Public method to generate the step line of an IFC class.

Furthermore, the EXPRESS Parsing Tool generates the IFC factory class which allows the instantiation of the IFC objects by using the IFC class names.

IFC Library

The proposed IFC Library provides the possibility to parse efficiently the IFC-SPF data and to instantiate in-memory the IFC model of the corresponding IFC file. An embedded API is used for the loaded objects manipulation, providing the developers with useful functionalities such as adding new IFC instances, modifying existing instances or querying the IFC model. The core of this library comes from the output of the EXPRESS Parsing Tool and is organized in multiple packages to handle effectively the supported versions of the EXPRESS schema. The current version of the IFC library can handle a wide range of different IFC schemas (IFC2x3 TC1 to IFC4x1 final). Additionally, the IFC library can initialize the properties of the inverse relations by adding the instance of a class to the set collection of the inverse connected property. The initialization of the inverse relations is archived by calling a specific public method as listed next:

Listing 1: Part of IfcMaterialProperties class

```
public IfcMaterialProperties(){
}

public void inverse(){
    if( this.materials != null &&
        this.material.getHasProperties() != null){
        this.material.getHasProperties().add(this);
    }
}
```

Listing 2: Part of IfcMaterialDefinition class

```
public IfcMaterialDefinition() {
    this.associatedTo =
        new HashSet<IfcRelAssociatesMaterial>();
    this.hasExternalReferences =
        new HashSet<IfcExternalReferenceRelationship>();
    this.hasProperties =
        new HashSet<IfcMaterialProperties>();
}

public void inverse() {
}
```

Using the inverse set collections, it is possible to get the `IfcMaterialProperties` instance from the inverse method `getHasProperties()` of the `IfcMaterial` class. In this example, the `IfcMaterial` class is subtype of the `IfcMaterialDefinition`. The inverse method is called for each IFC instance after the deserialization process.

MVD Checking

One of the main goals of the MVD specification is to help the community develop BIM tools that allow the automatic validation of IFC data against rule sets that are based on the mvdXML standard. Mainly, three steps are needed to achieve automatic validation of IFC data: a) the preparation of the rule set (mvdXML) using buildingSMART certified tools such as the `ifcDoc` (see figure 4); b) the model checking service that applies the given rules to the loaded IFC instances; c) the report generation service that generates reports based on open standards such as the BCF. For the creation of valid mvdXML files the `ifcDoc` software is used. This software has been developed by buildingSMART International in order to improve the consistent and computer-interpretable definition of the MVD specification. The user can easily create a custom model view and assign new concepts under it. Each concept has an applicable entity (IFC class), a connection to an existing template (subsection of the IFC schema) and the applied rules based on logical operations (IFC entities or attributes that are checked by type or by value under certain conditions).

The proposed MVD checking tool is a standalone service written in pure Java without having external dependencies to third party libraries. The main goal was to achieve a clean end-to-end design where the different parts are separated based on their functionalities. Thus, the EXPRESS Parsing Tool is used to generate the IFC Library which in its turn is used internally by the model view checking process. There are two main features that the checking process uses from the IFC Library: a) the IFC-SPF serialization/deserialization feature to load the IFC data in-memory and to perform queries; and b) the inverse connections of the IFC entities to validate the existence of an IFC schema's subset starting from an applicable IFC root entity. The MVD checking tool takes as an input the IFC-SPF data as well as the MVD-XML data. The output of the tool is the boolean result of the validation for each given concept. The serialization of the results can be represented in a graphical environment or using open standards such as the BCF that supports workflow communication in BIM processes.

From a BEPS viewpoint, the partition of building construction (interior/exterior walls, floors, roofs) and opening (door, window) surfaces into 2nd-level space boundary (Bazjanac 2010) surfaces is a prerequisite. This process

is performed by the CBIP tool. The result of the CBIP tools execution is the enrichment of the IFC file with relevant 2nd-level space boundary information (`IfcRelSpaceBoundary2ndLevel` class population).

The 2nd-level space boundary content of the enriched IFC file is checked by the model view checking process, using the following four checking rules, which are implemented under the same concept using multiple template rules:

1. The existence of the 2nd-level space boundaries is checked by examining the presence of the `IfcRelSpaceBoundary2ndLevel` class instances in the enriched IFC file.
2. For each `IfcRelSpaceBoundary2ndLevel` populated instance, the presence of its related building element is examined.
3. For each `IfcRelSpaceBoundary2ndLevel` instance, the related building elements type, the value of the `ExternalOrInternal` property, the corresponding space boundary (if the space boundary is INTERNAL) and the parent space boundary (if the space boundary refers to an opening) are examined.
4. For each `IfcRelSpaceBoundary2ndLevel` instance the relating space index, is checked.
5. Finally, the last rule checks if there is an `IfcRelSpaceBoundary2ndLevel` instance with `ExternalOrInternal` property value "EXTERNAL_EARTH".

If any missing or invalid information is detected the corresponding template rule fails to validate the defined parameters. These parameters are summarized for different space boundary types (internal, external, corresponding and parent) and related building elements (wall, slab, door, window, plate, opening and virtual element) in Table 2.

Table 2: Space boundary checking rules

Applicable IFC Entity	Boundary Condition	Corresponding Space Boundary	Parent
IfcWall	Internal	Missing	-
IfcSlab	Internal	Missing	-
IfcDoor	External	-	Missing
	Internal	-	Missing
	Internal	Missing	-
IfcWindow	External	-	Missing
	Internal	-	Missing
	Internal	Missing	-
IfcPlate	External	-	Missing
	Internal	-	-
IfcOpening	External	-	-
IfcVirtualElement	External	-	-

Figure 4: ifcDOC tool

As mentioned above, other IFC data that are required in the context of BEPS include the space occupants presence, artificial lighting, electrical equipment operation (which act as thermal sources in terms of BEPS) and related operation schedules. These data are exported by the modified IFC Revit™ exporter by populating a new Pset class, named Pset_Space InternalGainsDesign, assigned to each IfcSpace class. The properties of this new class are checked against the property name and the entity type as listed in Table 3.

Table 3: Space checking template rules of Pset SpaceInternalGainsDesign

Property name	Entity type
OccupancySchedule	IfcIrregularTimeSeries
LightingSchedule	IfcIrregularTimeSeries
EquipmentSchedule	IfcIrregularTimeSeries
HeatGainLighting	IfcPropertySingleValue
HeatGainEquipment	IfcPropertySingleValue
AreaPerOccupant	IfcPropertySingleValue
HeatGainPerOccupant	IfcPropertySingleValue
InfiltrationRate	IfcPropertySingleValue

BEPS require a number of properties to be assigned to materials for various building constructions as well. These properties, depending on the material type, are: for opaque materials Conductivity, Density and Specific Heat; for transparent materials U-factor and Solar heat gain coefficient (SHGC). Two new MVD concepts depending on the building element type are applied: a) Opaque materials (e.g. walls, floors, roofs); and b) Transparent materials (e.g. windows, plates, doors).

The properties under the opaque and the transparent materials classes are checked against the property name and the entity type as listed in Table 4 and Table 5, respectively.

Table 4: Opaque material property rules

Property name	Property type
SpecificHeatCapacity	IfcPropertySingleValue
ThermalConductivity	IfcPropertySingleValue
MassDensity	IfcPropertySingleValue

Table 5: Transparent material property rules

Property name	Property type
Visual Light Transmittance	IfcPropertySingleValue
Solar Heat Gain Coefficient	IfcPropertySingleValue
Heat Transfer Coefficient (U)	IfcPropertySingleValue
Thermal Resistance (R)	IfcPropertySingleValue

Conclusions

The automated BEPS model generation from IFC data has received lately considerable attention. However, imperfections of the provided IFC files prevent the BIM-to-BEPS data transformation process from being widely and automatically applicable.

The focus of this work has been the proposal of an IFC data quality checking workflow towards populating IFC files ready for BEPS input data generation. The proposed workflow consists of four main stages: a) data preparation and exportation; b) geometric data correctness check; c) data enrichment; and d) data completeness check.

Describing these stages concisely, in the first stage, design guidelines along with a modified IFC exporter are provided to enable exportation of information about materials thermal properties and internal gains. In the second stage, geometric errors that affect the correct 2nd-level space boundaries population are automatically detected and reported in a BCF file. These errors are corrected

manually by the designer and an geometric error-free IFC that includes information about materials thermal properties and internal gains is exported to be processed by the third stage; here, the IFC data are enriched with the 2nd-level space boundaries data. In the final stage, a data completeness check is performed for the enriched IFC file to ensure that the BEPS information that the IFC schema could capture is present.

The presented workflow has been focused strictly on data preparation for building energy demands estimation aspects, since HVAC data inclusion have not been thoroughly investigated. A concrete implementation of such data in the proposed workflow remains the main subject of future work.

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SEMANTIC DATA MINING AND LINKED DATA FOR A RECOMMENDER SYSTEM IN THE AEC INDUSTRY

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Abstract

Even though it can provide design teams with valuable performance insights and enhance decision-making, monitored building data is rarely reused in an effective feedback loop from operation to design. Data mining allows users to obtain such insights from the large datasets generated throughout the building life cycle. Furthermore, semantic web technologies allow to formally represent the built environment and retrieve knowledge in response to domain-specific requirements. Both approaches have independently established themselves as powerful aids in decision-making. Combining them can enrich data mining processes with domain knowledge and facilitate knowledge discovery, representation and reuse. In this article, we look into the available data mining techniques and investigate to what extent they can be fused with semantic web technologies to provide recommendations to the end user in performance-oriented design. We demonstrate an initial implementation of a linked data-based system for generation of recommendations.

Introduction

Building data: BIM and semantic web technologies in a sensor world

Recent years have presented significant research efforts accentuating the environmental impact of the built environment and methods for its mitigation. That has amended design practice and has made it strive towards implementing sustainability principles as fundamental and not merely complementary. Simultaneously, the rapid technological developments have allowed powerful computational techniques to emerge in support of architectural design and engineering. Such technologies allow to represent buildings semantically (Pauwels et al. 2017) and discover implicit knowledge about their performance through pattern recognition and knowledge discovery techniques (Fayyad et al. 1996). With regards to data representation in Architecture, Engineering and Construction (AEC), Building Information Modelling (BIM) allows the creation of semantically rich building models (Sacks et al. 2018).

Recently, semantic web technologies (Berners-Lee et al. 2001) have received major attention in the attempt to break open the isolated information silos and connect the semantically rich building data with other meaningful data about the building, its occupants, environment, etc. These further reaching semantic models are the building blocks of Linked Building Data (LBD) and provide a decentralized source of information (Pauwels 2014). On the other hand, Building Monitoring Systems (BMS) play an essential role in building operation, by allowing the collection of operational data through a myriad of sensors and devices (Fan et al. 2015). Advanced analytical methods are hereby of high value, as they help uncover hidden knowledge in the data, and highlight its potential to the future of building design and performance improvement (Fan et al. 2015, Miller et al. 2018).

Despite the availability of knowledge bases, many of the decisions taken during the design process are based on ‘rules of thumb’ and previous experience (Heylighen et al. 2007), and not on data and evidence contained in building performance, BIM models or LBD knowledge graphs. If such data were used more efficiently, significant potential would be uncovered in reaching performance targets currently associated with gaps between design and actual performance (de Wilde 2014). The target of this research effort is to bring knowledge from previous projects into future design environments to achieve both a sustainable end product and a holistic sustainable design process. Previous works also investigated how Knowledge Discovery in Databases (KDD) (Fayyad et al. 1996) can be used to retrieve patterns and association rules from available building data (Petrova et al. 2018a,b). These works also showed how it is possible to build a knowledge graph that includes (1) semantically rich building data (topology, properties, etc.), (2) 2D and/or 3D geometry, (3) sensor data, and (4) motifs and association rules obtained from the sensor data. The resulting graph provides a valuable resource for evidence-based design recommendations. Therefore, the objective of the current article is to investigate the potential of linked data-based recommendation retrieval in the design environment, including performance patterns discovered in sensor data, thereby utilizing the available

and ever-growing knowledge bases to achieve an evidence-based design process.

Linked data-based recommender systems for improving sustainable design decision-making

This work explores the possibility of building a system that relies on knowledge discovered in building data and stored in knowledge graphs to make recommendations towards the design team. Considered here is evidence-based feedback in response to design requirements, yet the recommender system is conceived as user-centered and can provide any feedback requested by querying the available knowledge base(s). Recommender systems can be subdivided in content-based and graph-based (Musto et al. 2017), where content-based systems provide recommendations based on direct similarity and graph-based ones link user nodes to user-tailored recommendations.

Several research efforts investigate recommender systems based on linked data and the wealth of data provided by the Linked Open Data (LOD) cloud¹(Oliveira et al. 2017, Musto et al. 2017). Research in the area of LOD-based recommendations takes its roots in the field of ontology-based recommender systems introduced by Middleton et al. (2004). When linked data and ontologies are used for the disambiguation of content, recommendation systems become semantics-aware (Boratto et al. 2017). The use of linked data for user-centered recommendations was introduced by Passant (2010), who proposed a recommender system based on semantic similarity calculations. This research relies on a set of measures to compute the semantic distance in linked data, thus exploiting the abundance of links among the resources. Recent works (Oliveira et al. 2017, Boratto et al. 2017) typically follow the software architecture displayed in Figure 1 where user profiling is on focus.

Recommender systems nowadays are usually associated with user profiling and recommendations based on previous interactions, social relations, likes, etc. The aim is to match the user's demands (profile) with the highest possible level of similarity, while still diversifying the recommendations. In the case of building design, the similarity matching aspect should also be the starting point, but it should be equally balanced with diversification driven by design and performance requirements. For example, if a user indicates high interest in residential nearly zero-energy buildings (NZEB), the recommender system should also be able to suggest other NZEB building types or other residential building types, etc. Of course, the richer the original dataset, the easier it is to obtain and make alternative recommendations.

Recommendation engines are not unknown to the AEC

Figure 1: Semantics-aware content-based recommender system (based on Boratto et al. (2017))

industry. However, these usually suggest predefined objects hosted in a database when a certain level of similarity with the current design is achieved (content-based). As a result, one of the fundamental goals of this research is to investigate the level of feasibility for application of linked data-based recommendations utilizing dynamic knowledge bases in changing context. The dynamic knowledge bases can be new buildings projects, which may include continuous incoming streams of sensor data and new LBD graphs. The changing context then refers to continuously updating user profiles.

To achieve the above-stated objectives, this paper starts with a state of the art review in the areas of KDD, semantic web technologies and data stream processing. The article continues with the approach used to achieve the objectives of the current study. We then outline the necessary steps towards a linked data-based recommender system for improvement of decision-making in sustainable building design and perform initial tests. Finally, the paper discusses the results, presents the main conclusions and outlines future work.

State of the Art

Knowledge Discovery in Databases (KDD) according to data type and purpose

Fayyad et al. (1996) define KDD as an overall process, in which knowledge is the end product of data-driven discovery. They outline five main steps, namely selection, pre-processing, transformation, data mining and interpretation/ evaluation of the results. In that context, Hand et al. (2011) define data mining as "the analysis of large observational datasets to find unsuspected relationships and summarise the data in novel ways so that data owners can

¹<https://lod-cloud.net/>

fully understand and make use of the data". Fayyad et al. (1996) also summarise six main data mining categories, i.e., classification, clustering, association rule mining, regression, summarization and anomaly detection. Han et al. (2012) divide these into two main categories: predictive and descriptive. Descriptive analytics use data aggregation and mining to provide insight into the past and make it interpretable by humans. Predictive analytics use statistical models and forecasting to understand the future and provide actionable insights. With regards to the input, Lausch et al. (2015) distinguishes between (numerical and categorical) data, text, web, media, time series and spatial data mining.

Knowledge discovery in Architecture, Engineering and Construction

Petrova et al. (2018c) provide an extensive definition of KDD approaches according to the type of building data (semantic BIM data, geometric data, sensor data, etc.) and the knowledge discovery purpose. Due to the abundance of spatio-temporal data, the AEC industry can benefit from mining temporal data (time series) and spatial data. Shekhar et al. (2010) rightfully indicates that extracting interesting patterns and associations from such complex and multidimensional data with plenty of dependencies and spatio-temporal correlations is more difficult than mining traditional numeric and categorical data. In AEC, spatio-temporal data mining approaches can be valuable in cases where spatial data is augmented with time series data from sensor networks in buildings.

Data mining applications for building performance improvement and sustainable building design usually relate to energy use and demand prediction (Wang & Srinivasan 2017), prediction of occupant behavior (D'Oca & Hong 2014), fault detection for building systems (Cheng et al. 2016), improvement of building operation and control strategies (Xiao & Fan 2014), as well as discovering and explaining energy use patterns (Miller et al. 2015). Other researchers have investigated the use of semantic data modelling, neural networks and data mining for building energy management (McGlinn et al. 2017). As can be seen from these categories, the use of KDD is usually related to the improvement of building operation. Using such approaches to improve future building design processes have not been investigated in such detail.

Limitations in the application of data mining

"Classic" data mining techniques typically focus on isolated "silo" data. As stated by Lausch et al. (2015), in such cases, the conclusions remain limited and do not span interdisciplinary and complex data. Additionally, data selection and treatment resides in the hands of the analyst, who is responsible for variable selection and data prepa-

ration to fit the needs of the mining algorithms. In case of incorrect decisions, the results can be influenced negatively, e.g. hidden patterns and novel knowledge may not be discovered or registered.

Therefore, Lausch et al. (2015) propose to mine data using linked data technologies. Such an approach allows opening silos and integrating data across disciplines, and provides an opportunity for analysis of interdisciplinary datasets. This broad overview can lead to insightful analyses, especially in a semantically rich domain such as AEC. Nevertheless, how these analyses are obtained is very different from the methods used in data mining, in the sense that the linked data realm is governed by queries and rules. These methods can be considered graph mining or matching techniques, and therefore potentially similar to pattern recognition. However, the types of graphs and patterns used in semantic queries and rules are very different from the patterns uncovered using data mining techniques, and both should not be perceived as identical.

Knowledge Graphs, Linked Data and the Semantic Web

Further to the evolutions in KDD, a lot of progress has been made in the formalization of knowledge using web technologies. From a web of documents, the World Wide Web has evolved into a 'Web of Data' (LOD cloud) (Bizer et al. 2009). The term linked data was coined by Tim Berners-Lee in 2006² and has enabled worldwide publication of 5-star open data³. This implies defining data according to the Resource Description Framework (RDF)⁴ data model and interlinking it with other RDF datasets available on the web. The Web of Data relies on ontologies so that data is typed and can easily be used in combination with query and rule languages such as SPARQL. Ontologies can be defined using RDFS and OWL⁵ and give 'meaning' or 'semantics' to the data, thereby constituting the Semantic Web as conceived in Berners-Lee et al. (2001).

Due to their potential, linked data and semantic web technologies have received major attention in the AEC industry. A comprehensive overview of this topic can be found in Pauwels et al. (2017). Among the most notable initiatives is the early work on transforming the Industry Foundation Classes (IFC) into an OWL ontology (ifcOWL) (Pauwels & Terkaj 2016). The ifcOWL ontology was built to match the original EXPRESS schema as closely as possible, thus allowing a round-trip conversion process (lossless conversion). However, this has led to a very big ontology, which resembles the IFC schema almost entirely, i.e., difficult to extend, complex, and not modular.

²<http://www.w3.org/DesignIssues/LinkedData.html>

³<http://5stardata.info/>

⁴<http://www.w3.org/TR/2014/NOTE-rdf11-primer-20140624/>

⁵<http://www.w3.org/TR/2012/REC-owl2-primer-20121211/>

This led to research initiatives aiming at ontologies for Linked Building Data, which do not rewind to IFC, yet cover similar ground.

Figure 2: An example LBD graph.

An ecosystem of smaller domain ontologies is currently available, each covering parts of what can also be handled with IFC (Figure 2 and 3). A central Building Topology Ontology (BOT) Rasmussen et al. (2017) captures terms as ‘Building’, ‘Site’, ‘Space’, etc. and aims for standardisation of these terms within the W3C LBD CG. Starting from BOT, alignments with various domain ontologies (Schneider 2017) can then be made. As a result, the industry can rely on a modular set of ontologies, yet still have a stable standard at the core. Besides topology, other ontologies in the W3C LBD CG cover products, properties, and geometry McGlinn et al. (2019).

Semantic Data Mining

Standard data mining algorithms usually use statistical models on data to discover patterns and provide actionable insights. According to Lavrač et al. (2011), in these cases, data is treated as meaningless numbers and attribute values. In other words, data by itself does not convey any semantics and needs to be interpreted to present meaningful information, which is usually done by domain experts. Such processes are associated with an abundance of raw data, but the underlying knowledge is scarce. Considering that KDD and data mining are knowledge-intensive processes, they can significantly benefit from enrichment by domain knowledge and the relations between objects. As further stated by Lavrač et al. (2011), that can be achieved by adding semantic annotations to the data and use of domain ontologies. This concept has caused a paradigm shift in data mining, expressed in a transition from mining the raw data to mining the knowledge directly. An overview of how semantic web technologies can be used in data mining and KDD is given in Ristoski & Paulheim (2016).

The increased interest in the fusion of data mining and semantics has also highlighted the main technical challenges and opportunities that this union presents. For instance, classic data mining is powerful for extracting patterns and association rules from large traditional datasets. Yet, as Nebot & Berlanga (2012) state, the different na-

ture of semantic data presents challenges, which cannot be tackled by traditional machine learning approaches, as they target mostly homogeneous data composed by transactions (sets of items). Since annotated data does not follow a rigid structure, instances, which are a part of the same class may still have a different structure. That causes a challenge of structural heterogeneity. Together with the heterogeneity of data sources, this leads to the necessity of dedicated approaches for pattern discovery in semantic data. This includes reasoning capabilities that allow inferring the implicit knowledge residing in the ontology itself (subclassOf relations, rules, inverse relations, etc.). For those reasons, researchers have engaged in defining the pathway towards effective association rule mining in knowledge bases (Barati et al. 2016).

Storing and processing sensor data

An important body of work in the semantic web domain, which is also of particular relevance in this paper, lies in the context of sensors and actuators. Sensor nodes are placed in precisely determined locations with a particular purpose of observation, thereby monitoring building use and performance in a real-time manner. This typically results in significantly large amounts of data, often captured in data lakes. Such data can be used in RDF graphs (Semantic Sensor Networks), and thus be directly included as separate modules complementing the modular LBD cloud. Example ontologies that can be used for this purpose are SOSA⁶, SSN⁷ and SAREF⁸.

Calbimonte et al. (2012) state that the heterogeneity of sensor data sources and environments is an important issue related to the realization of a connected sensor world. Monitored data is usually represented in different ways by different networks, and data models and schemas differ as well. That leads to several compatibility and representation issues. To tackle those, research efforts propose various solutions such as semantic annotation of sensor data (Sheth et al. 2008), providing ontology-based access to data (Calbimonte et al. 2010), etc.

Storing the vast amount of data directly in the RDF graph typically leads to a "swollen" graph, and takes down query and reasoning performance. Hence, Petrova et al. (2018a,b) propose to maintain sensor data within their common non-RDF based data stores, yet link directly from the RDF graph to the web API providing access to the sensor data. When relying on web technologies for application development, these HTTP links can be consumed to give a custom and on-demand access to the raw sensor data. However, several studies suggest that further opportunities may arise from using SPARQL queries with streaming ex-

⁶<http://www.w3.org/ns/sosa/>

⁷<http://www.w3.org/ns/ssn/>

⁸<http://ontology.tno.nl/saref/>

Figure 3: Conceptual overview of the modules and ontologies in a linked building data cloud, based on the work in the W3C LBD CG.

tensions to access observations (Calbimonte et al. 2012). RDF stream processing may give an opportunity to publish and analyze real-time data streams while avoiding the "swollen" graph issue and still make sensor data a part of the LBD knowledge graph. Della Valle et al. (2009) state that achieving that would require moving from storing data and querying it on demand ("one-time semantics") to using continuous queries ("continuous semantics"). Barbieri et al. (2010) state that focus needs to be put on "stream reasoning", i.e., making sense of multiple real-time heterogeneous data streams. Llanes et al. (2016) define three main stages in the publication of RDF streams, i.e. conversion from sensor data streams to RDF streams, storing RDF streams, and linking them with other data sources. That requires the selection of relevant ontologies, defining the mapping language for conversion, selection of continuous query languages (e.g. Continuous SPARQL (C-SPARQL) and SPARQLstream (Barbieri et al. 2010), (Calbimonte et al. 2012)) and choosing other appropriate datasets to link to.

Semantic Data Mining and Linked Data for a Recommender System in the AEC Industry

Conceptual framework

Based on the review, we conclude that in the implementation of the recommender system (1) knowledge graphs can be accessed using semantic queries, (2) sensor data can

be mined with traditional data mining techniques, (3) semantic data mining can be performed on the LBD graph, and (4) RDF graph mining can also be used for pattern matching in combination with RDF stream processing.

Furthermore, a recommender system can rely on data sources both without and with explicitly embedded semantics. In the latter case, recommender systems rely directly on semantic analysis techniques, thereby directly exploiting the semantics in the linked data graph. In the current context, in which the modular LBD graphs consist of both graph data (topology and product data) and non-graph data (geometry and sensor data), both traditional and semantic data mining can be used. Mining of raw sensor data implies discovery of performance patterns by the use of classic data mining methods. The knowledge interpretation is strictly related to obtaining understanding about the performance through the discovered patterns, not through the raw data. The RDF frequent pattern discovery, on the other hand, is data structure oriented and considers the graph predicates instead of data values.

Applying these techniques results in the conceptual system architecture in Figure 4. The following sections explain this architecture focusing on (1) how patterns are discovered and added to the graph, (2) how user profiles can be built and benefit from the system, including feedback, and (3) how recommendations can be generated. We present an example for RDF pattern discovery in a semantic data stream by implementing a method suggested

by Belghaouti et al. (2016) and discuss its potential feasibility. Finally, we demonstrate an initial implementation of a linked data-based recommender system by applying the concept of Linked Data Semantic Distances proposed by Passant (2010).

Pattern discovery and representation

First, data about existing buildings is retrieved and transformed into linked data. We hereby suggest to rely on the overall LBD approach documented earlier in Petrova et al. (2018a,b). This process is displayed on the bottom right in the system architecture diagram in Figure 4. For describing sensors, the LBD graph can be enriched with sensor node instances and sensors, as can be seen in Figure 2. Listing 1 lists all namespaces and prefixes used in the following examples.

```
@prefix rdf: <http://www.w3.org/1999/02/22-rdf-syntax-ns#> .
@prefix xsd: <http://www.w3.org/2001/XMLSchema#> .
@prefix foaf: <http://xmlns.com/foaf/0.1/> .
@prefix rdfs: <http://www.w3.org/2000/01/rdf-schema#> .
@prefix bot: <https://w3id.org/bot#> .
@prefix buildings: <https://www.example.com/data/buildings/> .
@prefix people: <https://www.example.com/data/people#> .
@prefix ls: <https://www.example.com/voc/linkset#> .
@prefix bmeta: <https://www.example.com/voc/buildingmetadata#> .
```

Listing 1: Namespaces and prefixes used in the following examples

As previously indicated, including sensor measurements can be done by pointing to an SQL store via a Web API or by including the sensor measurements explicitly in the graph. In this case, pattern discovery can be done using traditional data mining, which works with data batches and uses the previously discussed predictive and/or descriptive models. As explained in Petrova et al. (2018a,b), the resulting performance patterns can also be stored directly in the graph.

Alternatively, it is possible to convert the sensor data streams into RDF streams and perform semantic data mining on the resulting graph. Ideally, the RDF graph is first completed, which requires reasoning through the data and ontologies, and inferring all implicit data (e.g. subclassOf relations). To analyze how RDF stream processing would affect the recommendation concept, we employ the method described by Belghaouti et al. (2016), who identify frequent RDF patterns in RDF streams by mapping the graphs to adjacency matrices based on the graph predicates. Using this method, one is able to construct bit vectors, which describe the graph structure. Each bit vector is constructed from the predicates in the graph. The graph in Figure 2, for example, would lead to a bit vector (1111) that indicates each of the four predicates ('rdfs:label', 'gig:hasSensorNode', 'rdf:type', and 'fog:asObj- v3.0-obj'). All predicates and corresponding bit vector indices are recorded in a predicate hash table,

which detects the patterns in the streams based on the bit vectors present in the graphs (e.g. 1111, 11101, 101, etc). Finally, a graph hash table is constructed, which records the frequency of occurrence of each bit vector. In this case, considering that all observations in the stream are modelled with the same predicates as in Figure 2, only one pattern would be included in the graph hash table, even though very diverse observation measurements are present. This has a big impact on pattern discovery, as the RDF frequent pattern mining is data structure oriented and considers the graph predicates instead of data values, as opposed to traditional data mining, which focuses only on data values.

User profiling and feedback

User profiling is a required feature for a well-functioning user-centred recommender system. We have set up the profiling system in a way similar to the one proposed in Boratto et al. (2017) (top of Figure 4). At user registration, a *Profile Initiator* component fills an RDF-based *User Profile Store*. These RDF-based profiles are built using the FOAF⁹ ontology, and the result is an initial RDF graph identifying a user and its key metadata (Listing 2). The user is served recommendations through the *Recommendation Filter* component. All actions that the user takes in direct interaction with the recommender system are logged through a *Profile Learner* component. These actions serve as 'feedback' to the system, and they may come from a user clicking a 'like' button, a 'category' button, an 'annotation' button, or any other form of interaction. The Profile Learner component feeds back user profile data and user logs into the back-end of the recommendation system, which contains the *User Profile Store* and the *User Log Store*. In other words, the User Profile Store gets modified incrementally under the effect of the user interactions. The interactions of highest relevance are those related to recommendations, which are used by the end user in the project, especially if they respond directly to specific design requirements and performance targets.

```
people:EkaterinaPetrova
  a foaf:Person ;
  foaf:name "Ekaterina Petrova"^^xsd:string ;
  foaf:givenName "Ekaterina"^^xsd:string ;
  foaf:familyName "Petrova"^^xsd:string ;
  foaf:nick "epetrova"^^xsd:string .
```

Listing 2: People profile data

Feedback from user interaction goes into the User Logs and User Profiles, but the links between specific user profiles and relevant items in the *Building Data Store* are also kept, thereby aiming to enable a context-aware system. This means that we store links between user profiles and building identifiers in a separate RDF linkset (Listing 3).

⁹<http://xmlns.com/foaf/spec/>

Figure 4: System Architecture for a linked data-based recommender system in the AEC industry.

This linkset serves as a hash table with identifiers from user profiles and the building data repository. Note that Listing 3 only includes `ls:like` relations, but other, more specific relations could be used as well, depending on how user interaction and feedback is tracked.

```
people:EkaterinaPetrova
ls:likes buildings:building_987d706d-877a-4b1d-80f6-6
ee89d856319 ;
ls:likes buildings:building_af41d889-f50c-456e
-9625-96655150838d .
```

Listing 3: Linkset between buildings and people.

We have applied this principle to the Building Data Store, User Profile Store, and Linkset Store as follows. Through user interaction and KDD, implicit data is retrieved about the buildings in the building data repository. As such, the buildings can be enriched with metadata tags. The result is displayed for two example buildings in Listing 4. Whereas this example only includes four simple metadata tags (buildingType, designedBy, energyLabel, sustainabilityCertificate), many more metadata tags can be used, e.g. category, occupancy data, mined performance patterns, design requirements, energy source, etc. These metadata can be used to form categories of design references, to compose queries in the database, to sort search results in a certain dimension, etc.

```
buildings:building_00dd6c87-6a6e-f482-7490-e6613659708a
a bot:Building ;
bmeta:buildingType bmeta:theater ;
bmeta:designedBy people:architectX ;
bmeta:energyLabel bmeta:A ;
```

```
bmeta:sustainabilityCertificate bmeta:LEEDPlatinum .
buildings:building_2e0dcc1c-b981-4c47-adb4-2b9887f10481
a bot:Building ;
bmeta:buildingType bmeta:theater ;
bmeta:designedBy people:architectY ;
bmeta:energyLabel bmeta:A ;
bmeta:sustainabilityCertificate bmeta:DGNBGold .
```

Listing 4: Example building data in TTL format.

In summary, the system holds three RDF-based data stores (besides the User Log Store): the User Profile Store, the Building Data Store, and the Linkset Store. It is now possible for an end user to query each of these stores for relevant data. For example, an end user may query for all buildings of a particular type, category and/or with a specific energy label (Listing 5). In this case the `bmeta` tags are used in the query. Of course, it is also possible to include user preference (Linkset Store) or user profile (User Profile Store) data in the queries. The returned results can be displayed to an end user, who is then able to sort the results using the available attributes and categories.

```
SELECT *
WHERE {
  ?b a bot:Building .
  ?b bmeta:buildingType bmeta:theater ;
  ?b bmeta:energyLabel bmeta:A .
}
```

Listing 5: Query for buildings of a particular building type.

Generating recommendations

As stated in the state of the art section, recommender systems can rely on the computation of semantic distance, i.e. the semantic relatedness between resources. Instead of limiting only to queries from within the end user environment, our recommender system should also make suggestions of buildings that are semantically close to, for example, a building that is considered to be most relevant to an end user at some point in time. Such buildings are the generated recommendations.

A set of measures were proposed in Passant (2010) to represent the 'Linked Data Semantic Distance' (*LDSD*) between two concepts (values between 0 and 1). This includes Direct, Indirect, and Combined Semantic Distance (*LDSD_d*, *LDSD_i*, *LDSD_c*), each either weighted or not. These semantic distances are used in recommender systems to find out what else users may like based on their user profile, search behavior, favorites, etc. The smaller the semantic distance between two related concepts, the higher the related concept is ranked in the set of n top related concepts or recommendations.

The semantic distance can be computed using all outgoing and incoming links of two concepts. For example, two different buildings might both be of type `theater`, which connects them to the same node for the `bmata:buildingType` predicate, and makes them semantically closer. Determination of LDSD for recommendations starts as soon as an end user clicks a building from a result set that was previously returned with a simple query. In other words, the Recommendation Filter component is set up to look for 'bot:Building' objects that are semantically close to each other. The calculation hereby relies on all incoming and outgoing links for specific buildings, which are linked in the Building Data Store and the Linkset Store. Essentially, the simple indirect distance as a matrix between one building and all related buildings is calculated (Passant 2010).

This is illustrated in a simple example in Table 1, which shows the semantic distances for one of the buildings in the Building Data Store. As the `bot:Building` tag is present for all concepts, it is disregarded. Of course, in this limited example with 6 buildings and 3 relations (`buildingType`, `designedBy`, `energyLabel`), values are quite far apart (1/3, 1/2, 1, or 0), because only three links are considered. In an actual Building Data Store, semantic distances are much more interesting and diverse.

For each of the retrieved buildings, any available data can be displayed. This may also include sensor measurements and patterns found in them, metadata and user data in support of the end user, etc. Of course, this data needs to be displayed in an appropriate end-user interface, which is out of scope here.

Challenges and limitations

In terms of effectiveness of the proposed system, potential challenges need to be overcome, which can be related to user behaviour or the method that the recommendations are based on. Besides the knowledge base, the users play an important role in a recommender system. Important to consider are changes over time in the user profiles and preferences, which need to be taken into account continuously. End users may have similar profiles, but different behaviour and preferences depending on their context. These phenomena can affect the accuracy of a recommendation system, as the wrong user preferences may be considered. Anomalous behaviour such as disliking of recommendations also needs to be analysed and factored in. Another limitation may stem from the fact that despite being efficient, the LDSD approach only computes the semantic distance between two resources that are directly or indirectly linked through an intermediate resource. Therefore, enhanced LDSD algorithms may need to be used to expand the range beyond the two links distance. Also, the current system only considers semantic distances between buildings. Other semantic distances may be used as well, to configure and refine the recommendations.

Conclusions

Recent years have shown a rapid increase in technology uptake aiming to help reduce the negative environmental impact from buildings. This research attempts to minimise the negative contribution by informing the design with evidence-based feedback stemming from the existing building stock through a recommender system. Research on recommender systems has a long history, but is seldom implemented in the AEC industry. We attempt to overcome this challenge with data mining and linked data technologies. The article presents a state of the art review in the areas of KDD, semantic web technologies, stream processing and recommender systems. We investigate how to make sensor data streams efficiently available to the end user in addition to knowledge discovered in the data through semantic sensor technologies, web API connections, and/or sensor data stream processing. We outline the necessary steps towards a linked data-based recommender system, thereby drawing on the techniques that have been identified as most promising in the literature review. The software architecture of the proposed system consists of triple stores, as well as mechanisms for feedback handling and recommendations, data mining, and user interaction. Future work should focus on further implementation in practice including identifying how metadata tags can be inferred in the most intelligent way. Furthermore, the way sensor data are combined with semantic data, so that they can be used effectively in recommendation filtering, needs to be further investigated.

Table 1: Simple indirect semantic distances computed for https://www.example.com/data/buildings/building_00dd6c87-6a6e-f482-7490-e6613659708a.

Building	Cio	Cii	LDS
https://www.example.com/data/buildings/building_2e0dcc1c-b981-4c47-adb4-2b9887f10481	2	0	0.3333
https://www.example.com/data/buildings/building_987d706d-877a-4b1d-80f6-6ee89d856319	1	0	0.5
https://www.example.com/data/buildings/building_43576e80-cf8c-11e1-8000-68a3c4d40f59	1	0	0.5
https://www.example.com/data/buildings/building_af41d889-f50c-456e-9625-96655150838d	0	0	1.0
https://www.example.com/data/buildings/building_aac3427f-eeb0-460c-ba47-14fd44c8be74	0	0	1.0

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BIM-DRIVEN MISSION PLANNING AND NAVIGATION FOR AUTOMATIC INDOOR CONSTRUCTION PROGRESS DETECTION USING ROBOTIC GROUND PLATFORM

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Abstract

Reconstructing a complete and accurate 3D representation of indoor construction scenes is an important step towards automated visual monitoring of construction projects. For fast access to construction's as-built visual data, construction drones are programmed to autonomously navigate the outdoor space and collect the data. However, due to limited satellite signal indoors, ground rovers provide safer and more reliable autonomous navigation in the narrow cluttered indoor space. In this paper we present a novel pipeline for 4D BIM-driven mapping of the as-built state of indoor construction site. 2D Light Detection and Ranging (LiDAR) sensors are mounted on an Unmanned Ground Vehicle (UGV) for Simultaneous Localization and Mapping (SLAM). The developed method consists of (1) BIM-driven data collection planning; (2) automatic mission navigation; (3) LiDAR data collection and (4) dynamic obstacle avoidance. Experiments show the applicability of the developed data collection strategy and the improved safety of automatic mission execution using UGVs.

Introduction

Reality visual data is commonly collected to document the as-built state of construction site and provide clear communication between project parties (Golparvar-fard et al. 2012). Various devices are utilized to collect construction visual data. Hand-held cameras and mobile phones are commonly used by site personnel or hired professionals to collect informative images and videos. Stationary Pan-Tilt-Zoom (PTZ) cameras are installed on the job-site or mounted on tower cranes for real-time access to construction visual feed. Recently, remote controlled unmanned aerial vehicles (UAVs) are operated manually by drone pilots or automatically using drone mapping software to manually create visual data collection plans. These data collection plans aim to collect data that visually cover the constructed structure vertically and horizontally.

Construction progress reporting requires fast access to visual data frames that observes changes in the constructed structure at expected progress locations to detect the construction progress. The state-of-practice manual methods

for videos and images collection are very slow and do not guarantee visual coverage to the locations of expected progress. Adding to that, the raw collected visual data requires cumbersome and resource intensive visual analysis tasks to organize and localize the data.

High end laser scanners are used to provide more accurate and complete as-built geometry of the job-site, these devices can collect dense and accurate 3D reality models using time-of-flight technology. The resulted pointcloud data is organized temporally and aligned with as-planned BIM models to visually communicate and analyze the construction progress. However, collecting reality data using laser scanners is associated with the challenges of:

- *Manual data collection planning* which is slow and inefficient as the fast pace of construction progress requires high frequency data collection planning to define scanning configurations according to the locations of expected changes.
- *No visual quality feedback* that is needed to assure complete visual coverage to the in-progress elements.
- *Inaccurate execution* of the data collection plan due to poor communication of the collection plan or inability to localize the laser scanner on the job-site.
- *Registration of local scans* that requires placement of visual tags at specific locations before scanning leading to extra costs, increased data collection duration and additional post-collection tasks.
- *High investment costs* associated with purchasing or renting the scanning devices and hiring professionals to operate the devices and analyze the data.

To overcome such challenges, automated data collection platforms -for instance ground rovers- are investigated for fast and accurate retrieval of construction visual data. Recently, several reports showed an increase in the adoption of construction drones in order to automate outdoors visual data collection (Drone Deploy 2018, Skyward 2018). Using Global Navigation Satellite System (GNSS), drones can automatically navigate waypoints according to the manually planned missions to collect the data. However, the limited GNSS signal and the narrow cluttered indoor

construction environment reduce the accuracy of localization and increase the risks of mid-air collisions. On the other hand, Unmanned Ground Vehicles (UGVs) are more reliable for indoor data collection due to the aforementioned collision risks. Adding to that, these platforms can be programmed for dynamic obstacle avoidance to prevent collision with moving objects on the job-site. UGVs have also higher payload capacity allowing them to carry multiple visual sensors that are needed to improve the accuracy of autonomous navigation and provide a variety of as-built data.

Related Works

Automatic progress detection requires accurate geometric representation of the as-built geometry of the construction site. State-of-the-art methods utilize the daily collected images and videos to reconstruct 4D reality models using Structure-from-Motion (SfM) algorithm (Schönberger & Frahm 2016). SfM algorithm outputs a colored pointcloud model that can be used as-is or converted to a meshed model using Poisson surface reconstruction (Kazhdan et al. 2006) for better interpretation of the data. Geometries of the reality models are compared with that of the as-planned 4D BIM to detect construction progress (Golparvar-fard et al. 2012).

To assure the accuracy of geometry-based progress detection, the visual quality of the collected data has to be evaluated before execution. However, state-of-practice data collection planning approaches do not provide visual quality feedback leading to bad quality of the collected data. Bad quality visual data results in incomplete and inaccurate 3D reconstructed models (Ibrahim, Golparvar-Fard, Bretl & El-Rayes 2017). These challenges are only reported after post-processing of the collected data and reconstructing the 3D as-built geometries. To improve the visual quality of the data and shorten their acquisition duration, change-driven visual quality metrics are utilized to provide visual quality feedback for the data collection plans before execution (Ibrahim, Roberts, Golparvar-Fard & Bretl 2017).

Light Detection and Ranging (LiDAR) sensors are also used to collect high quality 3D as-built geometries. Such sensors are utilized to directly collect dense and accurate reality pointcloud models relying on hardware capabilities. LiDAR data collection plans are defined by specifying locations and configurations of the sensor inside the construction site. The data collection plans aim to provide full 3D mapping of the construction site to record the state of progress (Zhang et al. 2016).

However, collecting LiDAR data still requires manual relocation and readjustment of the LiADR platform several times to place the device at the planned scanning loca-

tions. So in order to improve the speed and the quality of the data collection process, autonomous unmanned vehicles are being investigated to accurately execute the data collection plan and automatically collect the as-built visual data. These autonomous platforms can be categorized -according to their navigation strategies- into (1) GNSS-based platforms and (2) SLAM-based platforms.

GNSS-based platforms

Global Navigation Satellite System (GNSS) is used to localize the autonomous platform by triangulating the position of the mounted GNSS receiver with respect to multiple detected satellites. Such technology is mainly used for outdoor data collection using camera-equipped drones (Tahar & Kamarudin 2016, Ibrahim, Roberts, Golparvar-Fard & Bretl 2017, Rakha & Gorodetsky 2018, Freimuth & König 2018) or multi-sensory autonomous ground rovers (Kim et al. 2003, Ramanagopal & Ny 2016, Haala et al. 2008, Srinivasan Ramanagopal et al. 2018). To improve the accuracy of localization and mapping, fiducial tags are usually placed at pre-defined locations to provide ground truth survey points.

SLAM-based platforms

Simultaneous Localization and Mapping (SLAM) pipeline is used to create a map of the environment -2D or 3D- and concurrently estimate the location of the robotic platform relative to the map. For instance, Hector SLAM (Kohlbrecher et al. 2013) uses 2D LiDAR to build a navigation map and Iterative Closest Point (ICP) algorithm (Censi 2008) to detect the location of the LiDAR relative to the map. ORB SLAM (Mur-Artal et al. 2015) uses a monocular camera to detect the 3D locations of binary visual features and localize the camera with respect to these features through Visual Odometry (VO). SLAM algorithms are mainly used for indoor navigation due to limited GNSS signal indoors. However, SLAM is associated with drift errors leading to geometrical inconsistencies in the reconstructed map and incremental localization errors. To reduce the errors, several sensors -as wheels odometers and internal measurement units- are fused with VO to improve the platform's state estimate using Extended Kalman Filter (EKF) (Einicke & White 1999) for fused state estimation.

A prior model or a 3D representation of the construction scene is required for creating and evaluating a data collection plan. A visual quality feedback during data collection planning assures good visual coverage to the in-progress elements. Taneja et al. (2016) defined BIM-based indoors navigation models using Industry Foundation Classes (IFC) that stores the model's geometric information and the relationship between the model's elements. These networks can be used for indoors localization given

that the utilized BIM has high level of details (LOD) and is up-to-date. Hover et al. (2012) used low resolution models to plan for complete high resolution mapping of a ship-hull using visual and acoustic sensors. Jing & Shimada (2018), Baik & Valenzuela (2018) used simple geometric models to represent the structure's topography and thus enable planning for complete visual coverage of the structure using camera-equipped drone. Ibrahim, Roberts, Golparvar-Fard & Bretl (2017) used 4D BIM model to create and simulate flight plans for outdoors data collection. Nevertheless, other methods are developed for navigation without a prior model, for instance exploration policies are used to automatically navigate a robotic platform in the unknown space (Taylor & Kriegman 1995, Ramanagopal & Ny 2016). However, exploration-based navigation methods are not tailored for construction change-driven data collection planning and thus not considered in this research.

Collection Platform

In this research, we used a Clearpath Jackal ground rover for automated indoors data collection. The rover is equipped with wheels odometer and an IMU for supporting accurate localization. To reduce the overall cost of the collection platform, two 2D LiDARs are mounted orthogonal to each other for accurate mapping and navigation as shown in Figure 1. The first LiDAR has longer range (16 meters) installed horizontally to create 2D occupancy grid map used for navigation. The second LiDAR has shorter range (10 meters) and oriented vertically to create cross section scans of the structure during navigation. The ground robot also provides the following capabilities:

- Large payload capacity that allows the installation and fusion of multiple sensors
- Good computational power with the high performance on-board computer
- Dynamic obstacle avoidance and safer operation with stop in-place fail safe strategy
- Longer operating duration with a battery that can last for 2 ~ 3 hours

Data Collection Pipeline

Hector SLAM Kohlbrecher et al. (2011) algorithm was chosen for localization and navigation due to the lack of GNSS signal inside the constructed structure. Hector SLAM utilizes sensory observations from the long range LiDAR to create an accurate and high resolution 2D occupancy grid map. The map is initialized with cells (grid) marked as unknown and then each cell is identified as empty or occupied by detecting fixed obstacles around the robot while it is in motion. For each horizontal 360° scan,

Figure 1: The indoors robotic collection platform

the scan points are matched against the global occupancy map using Iterative Closest Point (ICP) algorithm to detect the configuration of the sensor (location and orientation). The estimated configuration is then used to transform the latest scan points to the global map frame for updating the global occupancy map in real-time.

To create 3D pointcloud model, the rover navigates the data collection path automatically using pre-defined waypoints. Each new vertical scan retrieved from the LiDAR is converted to pointcloud and then registered to the global pointcloud using the synchronized robot pose calculated using Hector SLAM localization module (Figure 2). To synchronize the LiDAR data with the robot's pose, time stamps associated with the scan data and the robot pose estimation are used. Where the time stamp of each observed scan data (message) is used to query for the robot pose with the same time stamp. If the queried time stamp lies between two successive poses, the accurate pose is retrieved by interpolating the translation and rotation values of the two poses. Adding to that, when the rover reaches a waypoint, it performs a 360° in-place rotation to assemble 2D vertical scans into 3D pointcloud at the location of the waypoint.

To enable automatic navigation, an initial navigation map - occupancy grid map - has to be created manually by driving the ground robot inside the indoors space. After the space is mapped completely, the occupancy grid map is saved to be used for future mission planning. The initial map is also used for automatic navigation by localizing the robot with respect to navigation waypoints that are defined inside initial map. Details of planning and autonomous navigation are discussed in the following sections.

Figure 2: Vertical scan points displayed with red color registered to the global pointcloud colored in white

Planing

Model-driven data collection planning is utilized to define waypoints that visually observe the locations of expected changes. 4D BIM is used to identify such locations by color coding the elements with expected progress and creating navigation waypoints close to these elements. Since the plan's waypoints are defined in 2D, a 2D floor plan is retrieved from the BIM model by creating a cross section at the data collection floor. The user then defines the locations and orientations of the waypoints preferably in the middle of each room/space that contains in-progress elements.

To transform the data collection plan to the navigation map's coordinates, a 2D transformation matrix is calculated through manual registration of the 2D floor plan and the navigation map. During the registration process, the user defines pairs of points -at least two- that create correspondences between the floor plan and the navigation map. The corresponding points are used to solve for the translation, rotation and scale parameters that are then used to transform all waypoints from the 2D floor plan frame to the navigation map frame. The transformed collection plan is then uploaded to the rover's on-board computer and executed on the job-site.

Autonomous Navigation

Given the initial navigation occupancy grid map and the transformed waypoints, LiDAR-based SLAM is used to localize the robot in the occupancy grid map. A path planner is used to define a navigable path between the robot's current configuration and each waypoint successively using A* algorithm (Hart et al. 1967). The A* algorithm uses heuristics-based search to detect the shortest path along the unoccupied cells of the map connecting between the robot's location and the location of each waypoint. The robot then navigates the defined path using the mounted Micro Controller (MC) unit that controls the wheels' rota-

tion to drive the robot according to the planned path.

Obstacle Avoidance

Due to the presence of dynamic obstacles on the job-site -for instance moving personnel-, a local path planner is used to locally alter the global planned path. The local path planner uses the same A* heuristics to create detours along the main path to navigate around the obstacles. A local occupancy grid map with finer resolution is used for high frequency detection and avoidance of obstacles. The user also defines a safe offset distance that inflates the obstacles' footprint in the navigation map to avoid unexpected collisions resulting from localization errors. An escape policy is also defined to drive the robot away from moving obstacle in case an obstacle is moving towards the robot.

Experimental Setup and Results

The introduced indoors data collection pipeline is tested using the data collection robotic platform. Robot Operating System (ROS) framework (Quigley et al. 2009) is installed on the robot's on-board computer to communicate the robot's state estimate, the observed sensory data and the developed algorithms in real-time. The framework also sends navigation actions to the robot's Micro Controller (MC) unit for mission execution. Stitching local vertical LiDAR scans and transforming them to 3D reality model is developed and integrated with ROS as part of this research. Hector SLAM, autonomous navigation and dynamic obstacle avoidance modules are integrated using open source software packages available online.

Two indoors experiments were conducted to (1) validate the applicability of the developed pipeline; (2) evaluate the safety of autonomous execution; and (3) assess the quality of the reconstructed 3D reality model in terms of density and accuracy of the model.

The first experiment was conducted in a structural university lab. The lab simulates a cluttered indoors construction space with the presence of built-up structural elements, small equipment and personnel. An initial occupancy map (Figure 3) was created manually by driving the robot around the lab. The collected reality model is then retrieved and visualized in Reconstruct web platform that offers 3D visualization of BIM and reality models (Figure 4). The dynamic obstacle avoidance module was tested by having a person walk in front of the robot while executing a simple two waypoints autonomous mission.

After testing the platform in the lab and ensuring its safe operation, a second experiment was conducted on a real construction site. Adding to that, data collection operation was performed after working hours to mitigate any interference between the autonomous mission execution

Figure 3: Occupancy grid map collected for the first experiment

Figure 4: Collected Reality pointcloud model for the structural lab

and the on going construction work. The platform was deployed to collect reality model on the second floor of a building during indoors partitioning construction phase. The floor is composed of a long corridor connecting 10 residential units. An initial occupancy grid map was created manually and then used to navigate the ground robot to collect data. Data collection plan was defined using the 2D floor plan of the building visualized using Reconstruct web platform. The data collection waypoints are placed manually to navigate the robot through 20 waypoints -two waypoints per unit- to collect reality data covering the in-progress elements. Using Reconstruct platform, the 2D floor plan was registered to the occupancy map by manually picking six corresponding points that align the floor plan with the occupancy map. The retrieved transformation matrix from the previous step is used to transform the 20 waypoints from the BIM Cartesian coordinates to the navigation map frame (Figure 5).

The collected pointcloud data is then evaluated for quality by measuring the density and accuracy of the points. The density of the model at a specific location is measured by counting the number of neighboring points within a

Figure 5: Transformed waypoints from 2D BIM floor plan at the top to the navigation map at the bottom

unit surface area at that location. The later calculation is conducted for each point's location of the reality model and the distribution of the density across the model is reported (Figure 6). For accuracy calculation, the reality model is registered with the project's BIM model (Figure 7), and the distance between each point and the closest BIM element is used to measure the accuracy.

Figure 6: Density distribution for the reality model collected in experiment 2

Evaluation of the model's density reported a mean density of 6.85 pts/m^2 with 4.05 pts/m^2 standard deviation and 6 pts/m^2 median. Evaluating the model's accuracy reported a mean accuracy of 0.51 m with 0.65 m standard deviation and 0.3 m median. Also, results show that locations with

Figure 7: Pointcloud model collected for the second experiment and overlaid on BIM model for visualization

high density results in better accuracy detected through improvements in the mean and standard deviation of the measured accuracy (Figure 8).

Figure 8: Distribution of reality model's accuracy with respect to points density

The results also show that the low detected density and accuracy of the reality model are affected by:

- The low resolution and accuracy associated with the utilized 2D LiDAR device. The choice of such LiDAR was a compromise to reduce the overall cost of the collection platform.
- The few number of waypoints and manual placement of the waypoints result in poor visual coverage to some regions on the constructed floor.
- Placement of waypoints in the middle of rooms to improve visual coverage and navigation safety resulted in lower density of points associated with far walls as the spacing between the scanned points increases with the distance.
- Drift errors associated with the SLAM pipeline led to incorrect registration of some local points to the

global pointcloud model.

- Utilizing manual registration of the pointcloud model with the BIM model led to lowering the model's accuracy due to registration errors.

Conclusions

In this paper we presented a novel pipeline for automated indoor data collection using LiDAR sensors mounted on an Unmanned Ground Vehicle. The developed pipeline utilizes 4D BIM-driven data collection planning to define waypoints that capture the as-built state of the job-site at the locations of expected progress. LiDAR-based SLAM is used for localization and navigation by constructing an accurate and high resolution pointcloud map. To enable automatic navigation, an initial navigation map is created by manually driving the robotic platform. The initial map is then used for automatic navigation to follow user-defined data collection waypoints localized in the map's coordinate system.

A 2D LiDAR sensor is mounted vertically on the ground robot to collect 2D cross section scans of the indoor space during autonomous navigation. the cross section scans are converted to local pointclouds that are registered to a global pointcloud map using the synchronized pose of the sensor. During autonomous mission execution, the robot navigates the shortest safe path between waypoints while collecting data. Adding to that, at each waypoint the robot performs a 360° in-place rotation to create a 3D model from the cross section scans.

Results from the first experiment show the applicability of the framework for safe indoors navigation while dynamically avoiding moving obstacle. The experiment also shows the scalability of Hector SLAM for mapping large indoor construction spaces and the usability of the resulting occupancy map for autonomous navigation. The second experiment reported the quality of the reconstructed pointcloud model with a mean density of 6.85 points per m^2 and mean accuracy of 0.51 m . It was also observed that locations with higher pointcloud density are associated with improved accuracy.

Future work will focus on automating the process of indoor mission planning to further reduce the duration of data acquisition. Visual quality evaluation will be conducted before data collection execution to assure complete visual coverage of in-progress elements and improve the quality of the reconstructed reality model. To provide semantic information for the collected pointclouds, frames captured from a mounted omnidirectional camera will be used to color the scanned points. In addition, the accuracy of collected pointcloud model will be improved by using fiducial tags to reduce drift errors.

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AUTOMATED UNDERSTANDING OF CONSTRUCTION SCHEDULES: PART-OF-ACTIVITY TAGGING

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Abstract

Nowadays, construction planning practices, whether conducted by human planners or artificial intelligence (AI) systems, rely heavily on manually elaborated descriptions of construction means and methods. As part of envisioning a new planning system that automatically learns construction knowledge from previous projects' schedules, this paper introduces Part-of-Activity (POA) Tagging: a construction-specific word-category disambiguation method for decoding the constructional functionalities encoded in activity names. These functionalities represent the roles each token, i.e. word, in an activity name plays in understanding that activity from a construction point of view. The model is built using Bidirectional Long Short Term Memory Recurrent Neural Networks (BI-LSTM RNN). After training on a manually annotated dataset of more than 7000 activities, the model achieved a token accuracy of ~92%. The significance of this method lies in its ability to allow an AI System to decipher construction schedules. This schedule understanding opens the door for further applications such as the automated elaboration of weekly work plans and alignment of master schedules to weekly work plans.

Introduction

The automated generation of construction schedules is a well-established research area in construction literature (Levitt & Kunz (1985), Hendrickson et al. (1987), Darwich et al. (1989), Fischer et al. (1994), Aalami & Fischer (1998) Dong et al. (2012), and Morkos (2014) among others). While this literature is very rich when it comes to construction knowledge formalization (Han et al. 2015, Koo et al. 2006), previous artificial intelligence (AI) systems depend on knowledge databases that are elaborated manually. However, given the variety of construction means and methods and the differences in practice between different companies, the manual population of these databases is tedious and impractical. On the other hand, many construction companies have already established procedures to propagate their construction scheduling knowledge between different projects. This accumulated knowledge, typically rooted with accomplished construction planners, is maintained in Critical Path Method (CPM)-based project-level construction schedules, lookahead schedules, and weekly work plans. Nowadays, given the progress in Natural

Language Processing, Data Mining, and Machine Learning, mining this semi-structured data offers a new opportunity for learning scheduling knowledge automatically and building structured company-specific scheduling knowledge bases. To take advantage of this opportunity, Amer and Golparvar-Fard (2019) proposed a new system that automatically mines company-specific construction sequencing knowledge from previous schedules and stores it in Dynamic Means and Methods Templates. This paper extends their work by detailing a method for decoding activity constituents using only activity names as written in construction schedules.

The model presented in this paper parses an activity name, tokenizes it (i.e. splits it into individual tokens (words)), and identifies the constructional functionality of each token. The constructional functionality is defined here as the role each token plays in understanding the activity from a construction point of view. These functionalities reveal the constituents encoded in that activity name. For example, the activity "*place CIP columns level 1*" is split into the following tokens: "*place*", "*CIP*", "*columns*", "*level*", and "*1*". The constructional functionalities of these tokens are respectively "*Action*", "*Object*", "*Object*", "*Location*", and "*Location*". The descriptions of different activities can include all or a subset of the constituents required to understand the task in hand. The level of details of these descriptions vary between different schedules and between different activities of the same schedule. For example, the activity "*prime and paint*" only encodes the action to be done, without explicitly describing the element to be painted, the location where the painting needs to take place, nor the resources required for painting. On the other hand, "*fire sprinkler main laterals area a*" describes the physical elements to be modified and the location of that modification without reciting the exact action to take nor the party responsible for conducting that action. The amount of information that can be learned about a given activity is therefore dependent on its available constituents.

Additionally, the constituents of different activities can in some cases reveal the dependencies among them. For example, "*place CIP columns level 1*" and "*place CIP columns level 2*" differ only in their location constituent. This suggests a resource-based precedence dependency as opposed to a logical means and methods dependency. While the authors envision an AI system that can learn construction knowledge from previous company-specific

schedules, such system needs to understand these schedules and the types of dependencies among their activities. In other words, this system needs to have the capacity of decoding construction activities and pinpointing their constituents. This paper therefore presents a supervised machine learning based method for mining construction activity constituents from raw schedule data.

The following sections will (1) highlight the research methodology and provide a formal definition of the problem, (2) review related literature, (3) detail the proposed method, and (4) validate the model and discuss the results.

Research Methodology and Problem Definition

Knowledge Gap

Currently, construction literature lacks a method that can automatically reason about the different constituents of a construction activity given only its name as written in a construction schedule. Moreover, a corresponding formal definition of the activity constituents that can be learned from an activity name and constructional functionalities that different tokens in an activity name can take is also missing.

Problem Definition

Given an activity, we aim at extracting all the activity constituents encoded in the activity name by tagging each token in that name with its constructional functionality. Formally, let's define F to be the set of all possible constructional functionalities, C to be the set of all possible constituents such as $C \subset F$, V to be the vocabulary or the set of all possible tokens, and $f: V \rightarrow F$ to be the function that maps individual tokens in an activity name to their respective constructional functionalities. The aim of this paper is therefore to define C and F and to learn the function f given V .

The reason C and F are not identical is that there exists tags in F such as "Preposition" that are not part of C . For example, some tokens such as "in" which is almost deterministically a "Preposition" are also an "Action" or "Object" as for "in" inside the phrase "rough in".

Literature Review Approach

In order to define C and F , a literature review of the definition of construction activity constituents is conducted and discussed in the following section. On the other hand, given the similarity between this paper's problem and the Part-of-Speech (POS) tagging problem which is well known in the Natural Language Processing (NLP) and Linguistics communities, this work reviews the POS tagging problem definition, the most recent and successful models for solving it, and its coverage in the construction literature specifically.

Data

Similar to the supervised POS tagging problem, learning the mapping function f requires training data. In this paper,

7300 activities were collected from 3 construction schedules of actual construction projects. The dataset was then built by annotating the data based on the pre-defined F and using a custom-built annotation tool. An example of the annotated data can be found in Figure 1.

Validation

Validating the model followed a typical machine learning model validation procedure. The labeled data was split into training and testing sets. The model was trained on the training set and then tested on the testing set. The metrics used for validation are Token Accuracy, Sentence Accuracy, Precision, and Recall. These metrics are calculated as follows:

$$\text{Token Accuracy} = \frac{\sum_{i=0}^T I(y_i = \bar{y}_i)}{\sum_{i=0}^T I(y_i = \bar{y}_i) + I(y_i \neq \bar{y}_i)}$$

where T is the total number of tokens, I is an indicator function that takes a value of 1 if its argument is correct and 0 otherwise, y_i is the true label for token i , and $\bar{y}_i$ is the model prediction for token i .

$$\text{Sentence Accuracy} = \frac{\sum_{i=0}^S I(s_i = \bar{s}_i)}{\sum_{i=0}^S I(s_i = \bar{s}_i) + I(s_i \neq \bar{s}_i)}$$

where S is the total number of activities (sentences), s_i is the vector of true labels of the tokens activity i , $\bar{s}_i$ is the vector of the model predictions of the tokens of activity i .

$$\text{Precision}_j = \frac{\sum_{i=0}^T I(\bar{y}_i = y_i = j)}{\sum_{i=0}^T I(\bar{y}_i = j)}$$

Precision of label j is equal to the ratio of the number of tokens correctly predicted as j to the total number of tokens predicted as j .

$$\text{Recall}_j = \frac{\sum_{i=0}^T I(\bar{y}_i = y_i = j)}{\sum_{i=0}^T I(y_i = j)}$$

Recall of label j is equal to the ratio of the number of tokens correctly predicted as j to the total number of tokens that have j as their true label.

Literature Review

Construction activities have been widely discussed in construction literature and especially in the construction scheduling automation and optimization communities. In terms of defining the constituents of those activities, Darwich et al. (1989) defined Object, Action, and Resources as the main arguments required to define and represent an activity. Similarly, Fischer et al. (1994) and Aalami & Fischer (1998) defined these constituents to be Components, Actions, Resources, and Sequencing Constraints. These definitions were also adopted by more recent works such as Dong et al. (2012), Morkos (2014), and Garcia-Lopez (2017). This paper builds on top of these definitions and tailors them towards information that can be mined solely from activity names as opposed to having more contextual data or domain expertise.

On the other hand, In Linguistics and NLP, Part-of-Speech (POS) Tagging is the process of identifying the syntactic

part of speech, i.e. Noun, Verb, Adjective, etc., of any token in any given context. Similar to POS Tagging, this paper introduces Part-of-Activity (POA) Tagging where the aim is at identifying the constructional functionality of each of the terms that appear in an activity name as opposed to their syntactic roles. Research in POS Tagging started in the 70s where rule-based models and finite-state models were mostly implemented (Greene & Rubin 1971). These models were deterministic in their nature, and they took advantage of preset rules and manually designed features. On the other hand, the next generation of models was stochastic. Hidden Markov Models (Cutting et al., 1992, Kupiec, 1992) and Maximum Entropy Models (Ratnaparkhi, 1996) became the state of the art and achieved token accuracies of ~96%. These models still used predefined features combined with probabilistic distributions over tags and tokens. More recently, Neural models such as Huang et al. (2015) and Choi (2016) achieved state of the art performance with accuracies above 97.5%. This paper implements one of the neural models tested in Huang et al. (2015) which is the Bidirectional Long Short Term Memory Recurrent Neural Network (BI-LSTM RNN). The reason this model was chosen is its high performance combined with its intuitiveness which makes it ideal for a baseline prototype.

In construction literature, POS Tagging has been used as part of NLP pipelines for information extraction for compliance checking (Zhang & El-Gohary, 2014, 2015a, and 2017, Zhou & El-Gohary, 2017, Li et al., 2016), contract requirements extraction (Zhou & El-Gohary, 2016), IFC schema extension (Zhang & El-Gohary, 2016), and information retrieval from Building Information Models (BIM) (Zhang & El-Gohary, 2015b, Lin et al., 2016, Oraee et al., 2017). However, to the best of the authors' knowledge, using approaches inspired by POS tagging to decipher construction activities was never attempted before.

The following section (1) defines activities' constructional functionalities and constituents, (2) describes the dataset used for training the model, and lastly (3) details the model architecture.

Proposed Method: POA Tagging

Constructional Functionalities (F) and Activity Constituents (C)

As seen in the literature review section, construction activities are often defined by an Action, Object/Component, Resources, and Sequencing Constraints. Since the aim of this research is to ultimately learn construction scheduling knowledge by mining existing schedules, the sequencing constraints constituent of an activity is already available through the precedence links provided by those schedules. Therefore, formalizing a schema for learning sequencing constraints from individual activity names is not necessary. The focus of this paper is therefore on the Action, Object, and Resources constituents of an activity. More specifically, Resources are further split into Location and Responsible Party and the set of possible constituents is defined as:

$$C = \{Action, Object, Location, Responsible Party\}$$

While the Action and Object constituents provide a strong indication on the type of the ongoing activity and allow for generalization across different projects, Location and Responsible Party are more project specific.

Moreover, as mentioned earlier in the problem definition section, activity names include ambiguous terms such as "in" which can be part of the Object or Action, or it can simply be a Preposition. Therefore, the set of constructional functionalities F expands on C , and it is defined as follows:

$$F = \{Action, Object, Location, Responsible Party, Conjunction, Preposition, Extra Information\}$$

where Conjunction, Preposition, and Extra Information are only complementary tags that help in the identification of activity constituents.

Dataset

Using the predefined set of constructional functionalities and constituents, the authors built a labeled dataset of 7300 activities from 3 different schedules. Each activity name is tokenized and manually tagged as shown in Figure 1. This labeled dataset is split into training (85%) and testing (15%) sets.

Figure 1: Labeled Dataset Example

As shown in Figure 2, the distribution of different tags in the original training dataset is skewed. While more than 47% of the tokens are labeled as Object, only ~1% are labeled as Responsible Party. Additionally, while 84% of the activities include an Object, less than 4% of all activities include an explicit indication of the Responsible Party.

To target this data imbalance problem, the original training dataset was augmented by randomly pulling from the subset of activities that include Responsible Party but does not include Object. The new tags distribution can be seen in Figure 3. While data augmentation also increased the portion of tokens labeled as Action, the distribution of different tags is more uniform when compared to the original dataset: the standard deviation of the number of different tags in the augmented dataset is 5.6 as opposed to being 16.5 in the original dataset.

Figure 2: Tags Distribution in the Original Dataset

Figure 3: Tags Distribution in the Augmented Dataset

Model Architecture

The model architecture is shown in Figure 4. After preprocessing and tokenization, the input list of tokens is fed to a pre-trained embedding layer that transforms each token into a vector.

The output of the embedding layer is then fed into a BI-LSTM which is composed of two LSTMs that parse the input sequence both from left to right and from right to left. Additionally, each LSTM is stacked vertically to form a 4-layer deep LSTM (illustrated as layers 1 to k in Figure 4). The number of layers is based on empirical testing and fine tuning. The bi-directional parsing allows the contextual information to be better learned, and it is particularly useful for the purpose of this paper given the non-standardized and inconsistent writing conventions of activity names in the construction industry. The power of LSTMs lies in their ability to model sequential data by passing information from one time step to the following one while implementing the same set of weights to the input token at each time step. This means, irrespective of the length of the input sequence, which in this case is the number of tokens in an activity name, the model can handle that sequence without the need to change the architecture. This flexibility cannot be achieved with feedforward networks for example where the length of the input features must be fixed a priori.

The output of the BI-LSTM is used as input for a fully connected (FC) layer that reduce the dimensionality of the output vector into the size of set F . A Softmax layer is then

applied on the output of the fully connected layer to create a probability distribution over F . For each token, the model returns the constructional functionality with the highest probability given the activity context.

Figure 4: POA Tagger Model Architecture

Preprocessing and Tokenization

Before passing an activity name into the model, it goes through a preprocessing and tokenization step. During preprocessing, punctuations and unwanted characters such as $\{()?!*\$ \# \}$ are removed, the characters are set to lower case, and numbers are replaced by a special token among other preprocessing steps. This preprocessing takes advantage of a predefined dictionary of construction-specific terms to be skipped in the cleaning process such as 'f/r/p' (which stands for form/reinforce/place). Additionally, the tokenization step splits the input string ' $W_1 W_2 W_3 \dots W_4$ ' into a list of individual tokens ' W_1 ', ' W_1 ', ..., ' W_4 '.

Embedding

After tokenization, each token of the activity name is first represented as a vector using an embedding layer trained specifically on construction scheduling data. These vectors are formally known as Word Embeddings in the NLP community (Mikolov et al. 2013). The idea is to learn n -dimensional vectors that capture the semantic similarities between different words in a given corpus (set

of documents or schedule activities in this case).

Figure 5: Learned Embedding Example - "place" and its nearest neighbors

While there are many existing trained word embeddings for different languages including English, these models do not capture the specifics of the construction scheduling terms. An example is "place" and "pour" which have very different meanings in English, but they are both used in construction to describe concrete related activities. Moreover, some of the technical terms used in construction such as "f/r/p" are also missing from a general English model. Building a specific construction scheduling model is therefore essential to the proposed approach. Details related to building and training the embedding model used in this paper can be found in Amer and Golparvar-Fard (2019). An example of the embedding results is shown in Figure 5 displaying a three-dimensional plot of the word vectors after reducing their dimensionality using t-SNE (t-Distributed Stochastic Neighbor Embedding) (Van Der Maaten & Hinton, 2008). It can be seen in the figure that the nearest points to "place" were found to be {"concrete", "form", "reinforce", "strip", "reshore", "pour", "deck", "cure"}.

BI-LSTM RNN

After the input activity name is vectorized, it is fed to the two LSTMs. The first parses the input vectors from left to right, and the second parses it from right to left independently. Each cell in both LSTMs is characterized by a set of "gates" that control the importance of different pieces of information. There are exactly 8 sets of weights for each cell: input (W_{ig}), output (W_{io}), update (W_{ii}), and forget (W_{if}) weights applied to the current input, and (W_{hg}), output (W_{ho}), update (W_{hi}), and forget (W_{hf}) weights applied to the previous "hidden state". This hidden state is responsible for maintaining important information from previous time steps to capture distributional dependencies. The function graph along with the different computations and definitions of individual LSTM cells can be found in Figure 6. At each time step, the cell hidden state combined with the current input token contribute to the prediction of the constructional functionality of that token.

Figure 6: LSTM Cell Configuration and Computations

Fully Connected and Softmax Layers

The FC and Softmax layers are the last step of the tagging pipeline. The FC layer is used to reduce the dimensionality of the BI-LSTM output to the size of set $\mathcal{F}$ which is equal to 7. Softmax is then used to normalize the output of the FC layer and create a probability distribution over all 7 possible constructional functionalities.

Mapping function ($\mathcal{f}$)

The mapping function $f: V \rightarrow F$ is therefore the entire learned model that takes an activity name “a” and identifies the constructional functionalities of its individual tokens by passing it through the neural network layers: Tokenization, Embedding, BI-LSTM, FC, and Softmax.

Results

Qualitatively, sample results of the proposed model are shown in Figure 7. Examples 1 and 2 illustrate the model’s ability to accurately predict both “Install” and “Installation” as Actions irrespective of their location in the sentence and their different inflections. Similarly, examples 1 and 3 showcase how “level 1” and “lv 1” were both predicted as Location irrespective of the abbreviation used by the planner while writing “lv”. Moreover, “drywall” in example 1, “Doors hardware” in example 2, and {“walls”, “columns”} in example 3 were all correctly labeled as Object irrespective of their location in the sentence and their relative location when occurring together in the same sentence.

(1) Install drywall at level 1
[Action, Object, Preposition, Location, Location]
(2) Doors hardware installation
[Object, Object, Action]
(3) f/r/p walls and columns at lv 1
[Action, Object, Conjunction, Object, Preposition, Location, Location]

Figure 7: Examples of Qualitative Results

Quantitatively, as shown in Table 1, the model achieved a token accuracy of 92% and sentence accuracy of 72%. A sentence in our context is an activity name. It is considered correct only if all of its individual tokens are correctly predicted as previously described in the Research Methodology section.

Table 1: Token and Sentence Accuracies

Token Accuracy	Sentence Accuracy
0.92	0.72

The Precision and Recall of different constituents are illustrated in Figure 8. As previously described in the Research Methodology section, Precision illustrates the model’s accuracy in predicting each of the constituents out of the total number of times each constituent was predicted. It is equal to the number of True Positives (TP) divided by the sum of TP and False Positives (FP).

Figure 8: Constituents Precision and Recall

Recall on the other hand represents the model’s efficiency in retrieving each correct constituent out of the number of times each constituent should have been predicted. It is therefore equal to the number of TP divided by the sum of TP and False Negatives (FN). In the context of this paper of TP, FP, True Negatives (TN), and FN are defined per label as shown in Figure 8 and as discussed in the Research Methodology section.

(1) Insulation level 5
True Labels: [Action, Location, Location]
Prediction: [Object, Location, Location]
(2) Elevator inspections
True Labels: [Object, Action]
Prediction: [Location, Action]
(3) re pave alley north
True Labels: [Action, Action Object, Location]
Prediction: [Action, Object, Object, Location]

Figure 9: Examples of incorrect predictions

On the other hand, Figure 9 displays some of the incorrect predictions made by the model. For example “Insulation” is labeled as Object by the model. For example “Insulation” is labeled as Object as opposed to being correctly labeled as Action in this context. In the dataset, “Insulation” can take both Action and Object as labels depending on the context. In the activities where another action is specified such as “install insulation”, “insulation” will be an Object. However, in the contexts where no explicit Action is specified, “insulation” reflects the Action of “installing insulation” more than reflecting the insulation Object itself. Similarly, “Elevator” can be either a Location or an Object depending on the context. Moreover, “pave” in “re pave” should reflect an Action, but the model mistakenly classified it as an Object.

In terms of FN and FP, classifying “Elevator” as Location in the second activity will add 1 to the count of Object FN and 1 to the count of Location FP. In other words, this prediction of Location instead of Object decreased the Precision of Location and the Recall of Object.

Conclusions and Future Work

As part of the authors’ vision for a new construction planning system that can automatically learn construction knowledge from previous projects’ schedules, this paper presented a new method for deciphering construction activities and automatically understanding their different constituents. This paper defined {Action, Object, Location, and Responsible Party} as the main constituents of a construction activity that can be directly learned from the activity name. Inspired by POS Tagging, the paper also presented a Part-of-Activity (POA) tagging model that built on a BI-LSTM RNN architecture to identify activity constituents with high accuracies. This work constitutes a part of an envisioned overall automated schedule generation and revision system that can leverage the available construction scheduling knowledge encoded in schedules of previous projects. Moreover, when used as a part of project control system, the automated understanding of construction activities as described in this paper allows for the identification of similar activities across multiple schedules, the alignment of short term and long term plans, and for the elaboration of weekly work plans from master schedules. Future work will focus on improving the robustness of the proposed algorithm and merging it with a larger system for learning scheduling knowledge from previous projects.

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RISK MANAGEMENT IN CONSTRUCTION PROJECTS USING BUILDING INFORMATION MODELLING

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Abstract

Risks reduction in construction projects is feasible through Building Information Modelling (BIM) according to the respective literature; however, so far, BIM-based risk management (RM) has not been addressed in a systematic way. This paper attempts to formalize BIM-based RM by suggesting and demonstrating the performance of a three-stage methodology. The methodology is applied on two risk scenarios in a building project through four commercial software applications that perform in combination, a full risks analysis regarding time and cost levels for the building project. The advantages and disadvantages of the proposed methodology and risk management in construction projects using BIM are presented.

Introduction

Building Information Modelling (BIM) methodology and technology is a way to digitalize planning, design and operation of buildings and infrastructures (EU BIM Task Group, 2017). The majority of large construction enterprises, worldwide, use BIM software for their projects (Lam et al., 2017), while adoption of BIM is increasing year after year, as the AECOO (Architecture, Engineering, Construction, Owner and Operator) industry recognizes the advantages and potential of this technology (Farnsworth et al., 2015).

BIM offers a user-friendly environment for designing and modifying a project's 3D model. Moreover, what constitutes the biggest advantage of this methodology and technology is the data that is contained in the created model (Eastman, 2008) that can describe the geometry and the attributes of the model's elements and can be useful to all phases of the project (Volkov & Kuzina, 2016). Another critical aspect is that BIM ensures the interoperability of information among different parties involved throughout a project's life cycle (Jupp, 2017).

Based on these features BIM can be a very effective

platform for performing risk management (Bråthen & Moum, 2016; Farnsworth et al., 2015; Kelly & Ilozor, 2016; Lam et al., 2017; Eadie et al., 2013; Bryde et al., 2013; Ciribini et al., 2016), which is one of the most important aspects when planning and developing a construction project (Zou et al., 2017). BIM can specifically help in handling the high complexity which is inherent in modern constructions at the development and operation phases and hinders control of quality, time and cost in a project (Bryde et al., 2013). BIM also facilitates communication among the project's participants, which is a prerequisite for having a successful risk management (PMI, 2013). Finally, it contributes to project's coordination, through a great number of available collaboration tools for the project's stakeholders (Jupp, 2017).

To investigate the current level of use of BIM tools into risk management and identify the benefits and improvements that they offer, a literature review was carried out. Zou et al., (2017) have presented thoroughly the state-of-the-art concerning the use of BIM for risk management. Their conclusion was that while BIM-based risk management is a growing research interest for the AECOO industry, the last still, largely, depends on manual, empirical and cognitive processes for managing risks. Furthermore, they identified that BIM-based risk management tools are still in their infancy, while they are not covering the whole spectrum of risks but rather focus on specific types of them (e.g. safety risks) (Zou et al., 2017).

Following the Risk Breakdown Structure proposed by El-Sayegh (2008), Table 1 associates different types of risks sources with previous research efforts on the use of BIM for risk management in construction projects. As shown in Table 1, BIM technology has so far been addressed to tackle with internal risks, i.e. risks associated to the main stakeholders in developing a project, namely the designers, contractors, and suppliers. Some examples of such applications are: a) the use of BIM by Zhang et al. (2013) to reduce risks of

injuries through automated hazards identification on the site, and b) the use of BIM in conjunction with Geographic Information Systems (GIS) by Irizarry, Karan and Jalaei (2013) to reduce late deliveries of materials on the site.

Table 1: An overview on how BIM is addressed for managing risks in construction projects

	Source	Citation
Internal Risks	Owners	-
	Designers	Peckienė & Ustinovičius, 2017; Kelly & Ilozor, 2016; Al Hattab & Hamzeh, 2015
	Contractors	Peckienė & Ustinovičius, 2017; Bråthen & Moum, 2016; Kim, Cho & Zhang, 2016; Barazzetti et al., 2015; Whong & Zhou, 2015; Chen & Luo, 2014; Bryde et al., 2013; Zhang et al., 2013;
	Suppliers	Irizarry et al., 2013
External Risks	Political, Social & Cultural, Economic, Natural, Others	-

Therefore, the conclusion from the conducted literature review is that two main issues are interesting for further investigation: a) the use of BIM for managing external risks of construction projects is very limited if any, and b) the use of BIM for risk management is rather case-based as there is no description of a clear methodology in order to apply BIM for risk management (Zou et al., 2017). Both identified limitations prevent BIM from fully supporting and becoming a standard approach for risk management for construction projects. The goal of this paper is to propose such a methodology and demonstrate its application through an example of a building project.

Methodology and analysis

The project's lifecycle can be generally distinguished in four phases, namely initiation, planning, implementation and closing (Volkov & Kuzina, 2016). The project's pre-selection phase is when conducting the respective feasibility studies, whose assumptions and baselines become the critical data that define along with existing regulations the project's requirements at the design phase. Furthermore, the design's requirements define for the project's developers the objectives to achieve during the implementation phase. BIM technology may be applied even from the feasibility studies' phase, but it definitely applies at the very early stages of the design phase. The initial drafts are usually designed in 2D plans, which then elaborate to 3D plans and BIM models that follow in the next versions. The created BIM models contribute to several

calculations related to quantities of materials, tasks' schedules, costs and budget, etc., while they facilitate site planning and management. At the implementation phase, BIM models are required for organizing and controlling the construction process by monitoring activities, controlling outflows and timeline, etc. At this phase, BIM models are very critical for the project's development as they can provide adaptations of the design to real time conditions, something which is crucial in the dynamic environment of a construction project. Required changes of a qualitative or/and quantitative nature can be early identified, investigated for their impact and adopted properly in the context of a monitoring, risks management or facility management processes towards ensuring the project's unhindered development.

Managing risks with the use of BIM, currently, requires a combination of software solutions that should include:

- a BIM software program for designing the project's 3D model,
- a software program for project management,
- a software program for risk analysis, and
- a software program for construction management.

There are several criteria of choosing such solutions, including cost, easy use, etc.; however, the fundamental criteria are interoperability and compatibility of the various file formats of different software programs. In order to decide about the proper software solutions to apply, proper information flow (i.e., inputs and outputs of different nature to the modules of a fully automated model) between them is required. Figure 1 depicts the types of software programs used to support this information flow in BIM-based risk management in construction projects.

Figure 1: Information flow of software combination

As shown in Figure 1 the final model produced is an n -dimensions model, where n depends on the information that is included in the model. For instance, a 4D model includes information about geometry and time, a 5D model about geometry, time and cost, and so on. An example of a combination of software programs that was actually applied in the case study described in the Simulation section is the following:

- Revit 2017 by Autodesk for designing the 3D BIM model,
- MS Project by Microsoft for project management,
- Risky Project by Intaver for risk analysis, and
- NavisWorks 2017 by Autodesk for construction management.

The software products combined in this research are very well-known and used in practice, thus indicating that an integrated and largely computer-aided conducting of risk management is feasible for common practitioners that possess the appropriate respective theoretical background.

Proposed methodology

The proposed methodology consists of three stages, which are described in detail below.

Stage 1

The plans of the project are designed in 2D CAD software that must be compatible with a BIM software. For example, AutoCAD by Autodesk allows 2D and 3D designing, while its .dwg format can be imported into Autodesk's Revit, ensuring the required interoperability. The BIM software must produce an integrated unique model of the project with as many details as possible; therefore, several add-ins facilitating structural analysis, photorealistic rendering, energy analysis, etc. should be added to it. The output of the first stage is a BIM software's file (e.g., rvt in the case of Revit) with the project's full model. Figure 2 depicts the information flow at Stage 1.

Figure 2: Information flow of Stage 1

Stage 2

Once the building's model is at hand the project's details must be inserted to allow project management. All necessary project tasks and their attributes (i.e. prioritization, start and finish times, resources, etc.) must be inserted through another software suite that allows scheduling, resources assignments, budget calculations and controls, etc. MS Project is an example of such software that was also used in this research.

As project management software does not allow full risk management (and whenever it does, this software is not compatible with BIM software), another software suite is required for managing project risks. This suite must be compatible with and operate either as a standalone program or as add-in to the project management software suite used. An example of such software solutions is RiskyProject that allows an integrated schedule and cost risk analysis of a project, along with a sensitivity analysis on risks, cost, duration, tasks' finish times, etc. Co-ordination of these software solutions produces a full file of project and risk management as shown in Figure 3.

Figure 3: Information flow of Stage 2

Stages 1 and 2 are independent and can be run either simultaneously or asynchronously; however, it is helpful if Stage 1 precedes Stage 2, because changes in the building model affect the input at Stage 2.

Stage 3

The final stage integrates the outputs of previous stages with the use of a third appropriate software tool that enables such integration. In this case, NavisWorks by Autodesk, is selected as it is compatible with both. rvt and .mpp formats.

At this stage every scheduled task is assigned to the respective objects of the BIM model thus allowing simulation of different scenarios of the construction process showcased in respective videos. Figure 4 depicts the information flow at Stage 3.

Figure 4: Information flow of Stage 3

The total proposed methodology is depicted in Figure 5.

Figure 5: Information flow of proposed methodology

When the study team wants to examine and compare more than one scenario, the implementation of Stage 2 must be repeated as many times as the different

scenarios. Figure 6 shows the implementation of Stage 2 for n different scenarios.

Simulation

The proposed methodology is demonstrated through an example that represents the construction of a ground floor residence of 120m².

Firstly, the top view is designed in AutoCAD and the dwg file is imported to Revit to create the 3D model. Figure 7 showcases the BIM model with screenshots

Figure 7: Screenshots of creating BIM model

A new parameter, the 4D_Task_ID, is added to the model's objects' properties as shown in Figure 8. This extra parameter facilitates the connection between the model's objects and the project's tasks, which is introduced at the methodology's Stage 3 and is essential for addressing to the BIM model the risks related to the several tasks. Filling the parameter's field with the ID number of the proper task links the BIM model with the project's schedule and concludes the implementation of the methodology's Stage 1.

Figure 6: Information flow of Stages 2 & 3 for examining more than one different scenarios

Stage 2 includes the definitions of all tasks and their modelling in MS Project. Activities' sequence, duration and cost are set for every task. Then the program calculates the total project's duration and cost. The results are the following:

- Total duration: 135 days
- Total cost: 115,870.00€

Stage 2 proceeds with risk identification. In the presented case study, the most common - according to the literature presented in Table 1 – risks met during the construction phase of building projects are identified. These risks are listed in Table 2.

Figure 8: Adding the new parameter "4D_Task_ID" on Revit

Table 2: Identified risks of the current project

	Source	Risk
Internal	Owners	Change of design – Improper intervention
	Designers	Defective design – Deficiencies in drawings
	Contractors	Construction accidents
		Poor quality
		Low productivity
	Suppliers	Delay of material supply
External	Natural	Unexpected weather
	Economic	Rise material's value

The application of BIM technology can contribute to the mitigation of some of these risks (e.g. deficiencies in drawings can be minimized thanks to the integrated 3D BIM model).

The introduction of risks allows the creation of different scenarios based on the created BIM model; in the example's case, two scenarios are proposed, namely the optimistic and the pessimistic one. The optimistic scenario considers that the application of BIM technology can reduce to the maximum both the probability of the modeled risks and their impact on the project's duration and cost. On the other hand, the pessimistic scenario, considers that the application of BIM technology contributes only to a minimum reduction of them. To illustrate the studied example the arbitrary – yet plausible – values shown on Table 3 are used for an indicative subset of risks. The identified risks are then introduced into Risky Project and subsequently to MS Project where they are assigned to the several tasks. For each scenario a different file is created that addresses the different values of the risks' determinants (i.e. chance and outcome of the risk occurrence), and the simulations' results (i.e., duration and cost for different values of risks) are presented in Figure 9. The new durations and costs for each scenario are the following: a) for the optimistic scenario the total duration is 142 days and the total cost is 121,112.00€, b); for the pessimistic scenario the results are 163 days and 125,420.00€, respectively. Figures 9 and 10 depict the simulation results in Risky Project.

After the simulations three .mpp files are created each one corresponding to a different scenario, i.e. the no-risk, the optimistic, and the pessimistic one. These files constitute the final outputs of Stage 2.

Continuing with the methodology's Stage 3, the.mpp and .rvt files are imported to NavisWorks, thus, achieving every task's assignment to the proper objects in the model. The simulation in NavisWorks produces the videos of the construction process for each scenario. Figures 11 to 19 depict screenshots of these videos.

Conclusions

Risk management is one of the most important processes in planning and constructing a project. BIM technology can undoubtedly facilitate this process, thanks to its advantages. The – as accurate as possible - and in time risk assessment can reduce time and cost, while increase quality and safety of a construction project. The conventional methods of risk management require many hours of team work and a great amount of data. BIM software expedites the risk management process as the produced models include all the required information, in a uniform manner, thus facilitating the project's stakeholders' understanding and acceptance of the risk management process and outcome.

A three-stage methodology is proposed in this paper that introduces the combination of four software suites. At the first stage, the BIM model of the project is created, then, at the second one, the current risks are

Table 3: Chances and outcomes for every risk

		Pessimistic Scenario		Optimistic Scenario	
Risk	Type	Chance	Outcome	Chance	Outcome
Defective design	Relative delay	20%	20%	5%	5%
	Relative cost increase	20%	30%	5%	5%
Construction accidents	Relative delay	10%	10%	5%	10%
	Relative cost increase	10%	20%	5%	20%
Poor quality	Relative delay	20%	10%	10%	5%
	Relative cost increase	20%	15%	10%	15%
Change of design	Relative delay	20%	20%	5%	5%
	Relative cost increase	20%	30%	5%	30%

Figure 9: Risk assessment for the optimistic scenario

Figure 10: Risk assessment for the pessimistic scenario

identified and analyzed, and, finally, at the third stage, all elements are integrated to a single model and risk assessment arise. The advantages of the proposed methodology are that:

- It is applicable for all types of projects throughout their whole life cycle and especially at the implementation and design phases.
- The results are presented in a clear and comprehensible way and they can be studied even by non-specialists.
- Many different risk scenarios can be examined using a unique model for the project.
- The proposed software combination allows time and error reductions, especially during data transfer.

Figure 11: Simulation video's screenshots from 60th day for the no-risk scenario

Figure 12: Simulation video's screenshots from 60th day for the pessimistic scenario

On the other hand, there are several shortcomings that need to be confronted, including the following:

- Only internal risks of the project can be fully managed with the use of BIM software. External risks are generally non-technical and while - some of them - can be modelled through BIM, they can be mitigated only by attempting to keep

low the impact of their consequences upon occurrence, rather than taking precautionary methods to deal with their sources.

- Risk identification is not automated and specialist's experience is required.
- Risks that cannot be assigned to the model's objects require a different approach to get included in the analysis. In this way the risks management process becomes fragmented and complicates co-ordination.

Figure 13: Simulation video's screenshots from 60th day for the optimistic scenario

Figure 14: Simulation video's screenshots from 120th day for the no-risk scenario

Figure 15: Simulation video's screenshots from 120th day for the pessimistic scenario

- The whole process of the methodology is not fully automated as several imports and exports of files are required.
- Different software programs' versions may obstruct information flow (e.g. Revit and NavisWorks should have common year's versions to collaborate) as, often, software updates result to incompatibilities between older and recent versions of the same product.

Future work could focus on the further development of the proposed methodology especially regarding: a) the inclusion of a more comprehensive list of risks that would address also more risks typologies (including external ones), b) the further limitation of manual processes most probably with the use of augmented reality, and c) the inclusion in the methodology of a well-defined decision-making process to select the appropriate software. Future work could, also, include the application of the methodology to construction projects of different types (e.g., infrastructure), level of complexity and demands.

Figure 16: Simulation video's screenshots from 120th day for the optimistic scenario

Figure 17: Simulation video's screenshots from 180th day for the no-risk scenario

Figure 18: Simulation video's screenshots from 180th day for the pessimistic scenario

Figure 19: Simulation video's screenshots from 180th day for the optimistic scenario

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OPTIMUM TOPOLOGICAL CONFIGURATIONS OF SENSOR NETWORKS

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Abstract

Placing sensors at appropriate locations is an important task in the dynamic assessment of the mechanical systems and its role is central in structural health monitoring. All sensors have to be placed on the structure so that all sought system features be obtained from the experimental tests. Sensors network design is rather diffused in laboratory applications, but there are scarce investigations on real civil structures and they are not so well documented. In order to give a contribution in this framework, the present paper deals with the optimal sensors placement problem on lattice towers. With reference to six of the most diffused existing optimum criteria and according to mechanical and energetic formulations, several sensors network configurations are calculated for two example broadcasting antennas, adopted as benchmark cases of studies. The final topological configurations of the networks are compared and the most relevant differences are discussed. Moreover, the information content behaviour is computed to investigate the connection between sensors network topology and its ability to withstand the presence of undesired signals (e.g., noise) during the measurements. The results here illustrated may be useful for sensors network design for this special class of structures.

Introduction

The dynamic assessment of real mechanical systems is possible only if a minimum amount of information (the structural response under natural or artificial dynamic loads) is acquired. In this aim, the investigated system must be equipped with a minimum number of sensors. However, this is not the only “constraint” of the problem: others, of economic and technological nature, impose the installation, of a maximum number of sensors, too. In order to monitor the most significant information it is all too evident that sensors must be accurately positioned. In this sense, from a mathematical standpoint, the optimal sensor placement (OSP) is a constrained topologic combinatorial (or mixed) optimization problem. As for any optimization problem, the optimum criterion (the objective function of the optimization problem) should be defined for the goal of the sensors positioning and should be selected with reference to the investigated

mechanical system. Thus, its role is fundamental and it is not surprising that great efforts have been exerted in the last two decades to define suitable formulations.

One of the most used approaches is the so-called Effective Independence Method (EIM) presented in (Kammer and Brillhart 1996) and developed for in-orbit modal identification of large space structures. This method uses the determinant of the Fisher information matrix to define the optimal sensors array. In order to maximize the measured kinetic energy of the mechanical system, a modified version of the EIM, the Kinetic Energy Method (KEM), has been developed in (Wang et al. 1998): in this case, the original Fisher information matrix is weighted with the mass matrix to compute the energy matrix.

Different from the methods based on the Fisher information matrix, in (Papadimitriou 2004) an entropy-based concept is developed to formulate an optimum criterion for the OSP problem: the Author uses the entropy measure (a decreasing function of the total sensor number) to characterize the amount of useful information contained in the available set of measured data. Alternative methods for sensors and actuators placement are based on controllability and observability measures, see for instance (Gawronski et al. 1997) or (Shih et al. 1998). Damage-based optimum criteria can be formulated for the OSP problem, as well: in this case, the goal is to find an optimal configuration of sensors that will best predict structural damage. For instance, in (Shi et al. 2000) sensors are positioned according to their damage localization ability evaluated by means of the eigenvector sensitivity method.

For the sake of completeness, it is necessary to remark that existing approaches differ also for the solution strategies. This is not a marginal question in the OSP, especially if a large number of candidate positions have to be examined. A very competitive technique is the sequential sensors placement: in this case, degrees-of-freedom (DOFs) to equip with a sensor are selected one at a time, according to the adopted optimum criterion. This strategy can be applied in several methods, either based on the Fisher information matrix or on the entropy measure. An alternative way can be proposed by adopting a global search in solving the OSP problem. For instance, the use of genetic

algorithms for the OSP is proposed in (Guo et al. 2004) and (Liu et al. 2008). Artificial neural networks and other non-classical combinatorial optimizers are used in the OSP for fault detection in (Worden and Burrows 2001), while the “ant colony algorithm” is performed in (Overton and Worden 2004).

Generally speaking, due to the existence of a wide number of optimum criteria, it is advisable to produce several sensors arrays using different formulations and to compare the obtained configurations according to some performance indicators. For example, (Meo and Zumpano 2005) analyze the difference between several criteria for the optimal sensors positioning on the Nottingham bridge. In this paper, the comparison between six different optimum criteria has been performed with reference to two example broadcasting antennas. The final topological configurations are presented and the principal differences are discussed. Robustness of the sensors arrays against undesired signals (e.g., noise) during the measurements is evaluated. Results here illustrated may be useful for sensors network design of this special structures.

Optimum Criteria For Sensors Placement

In this Section, we briefly illustrate the adopted criteria for the OSP in deterministic mechanical systems with linear behaviour.

Effective Independence Method

The EIM deals with the goal to maximize both the spatial independence and signal strength of the target mode shapes by maximizing the determinant of the associated Fisher information matrix. For a linear system, in modal space the structural response y can be expressed as

$$y = \Phi q + w \quad (1)$$

where Φ is the matrix collecting N target mode shapes, q is the coefficient response vector and w the zero mean White Gaussian Noise (WGN) vector

$$w \sim N(0, \sigma I) \quad (2)$$

and I is the identity matrix. In (2), σ is the standard deviation of the random noise (without loss of generality, it is assumed equal for any measurement point).

The linear assumption is generally fulfilled in usual dynamic testing especially if one is interested to monitor the system response under small or moderate dynamic loads. By evaluating the coefficient response vector q through an efficient unbiased estimator, it is possible to estimate the covariance matrix as follows

$$C_q = E[(q - \hat{q})(q - \hat{q})^T] = \sigma^2 (\Phi^T \Phi)^{-1} \quad (3)$$

that results the inverse of the Fisher information matrix, according to the Cramer-Rao Lower Bound (CRLB) theorem ($E[\cdot]$ denotes the expected value operator). In virtue of the fact that the best estimation of q occurs when the Fisher information matrix is maximized, the procedure for selecting the OSP is to unselect candidate sensor positions such that its particular crisp value (trace or determinant) is maximized.

In an iterative manner, from a computational point of view, the analysis starts by computing the effective independence distribution (EID) vector

$$\varepsilon = [\Phi \Psi] \times [\Phi \Psi] \Lambda^{-1} \mathbf{1} \quad (4)$$

In (4), Ψ is the eigenvector matrix of $\Phi^T \Phi$ and Λ the associated eigenvalue matrix, symbol $\times$ denotes the Hadamard product (term-by-term matrix multiplication), $\mathbf{1}$ is the $N \times 1$ vector with all elements equal to one. Operatively, the selection procedure sorts the element of ε and removes the smallest one in each iteration. Thus, the effective independence distribution vector (4) is updated, according to the new modal shapes matrix. The process is restarted until the number of remained sensors equals a desired value.

Driving point residue method

The modal participation factor or Driving Point Residue (DPR) is a mechanic optimum criteria (Doebling 1995). The DPR for the i -th DOF can be evaluated by using this expression

$$DPR_i = \sum_{j=1}^N \frac{\varphi_{ij}^2}{\omega_j} \quad (5)$$

where ω_j is the j -th target mode frequency (φ_{ij} is the i -th nodal displacement of the j -th mode shape). In this case, sensors will be placed where the DOF is characterized by the highest average response over all of the target modes. This method has been adopted by (Meo & Zumpano 2005) coupled with the EIM strategy (EIM-DPR method). In fact, by multiplying the candidate sensor contribution of the EIM with the corresponding DPR coefficient in (5), it is possible to avoid candidate positions with low energy content.

Kinetic energy based method

In KEM the objective is to maximize the measure of the kinetic energy of the structure. In this case, the Fisher information matrix is weighted with the mass matrix M and so, the kinetic energy matrix V can be defined as follows

$$V = \Phi^T M \Phi \quad (6)$$

Decomposing the mass matrix into lower (denoted L) and upper (denoted U) triangular Cholesky factor matrices

$$\mathbf{\Gamma} = \mathbf{U}\mathbf{\Phi} \quad \mathbf{M} = \mathbf{L}\mathbf{U} \quad (7)$$

the kinetic energy matrix can be defined as the product of the matrix $\mathbf{\Gamma}$ and its transpose

$$\mathbf{V} = \mathbf{\Gamma}^T \mathbf{\Gamma} \quad (8)$$

After the evaluation of $\mathbf{\Gamma}$, the OSP process is identical to that described for the EIM.

Eigenvalue vector product method

Eigenvalue Vector Product (EVP) is a mechanic type criteria (Doebeling 1995). This criteria forms an indicator consisting in the absolute value of the product of every eigenvector. This product can be written for the i -th structural DOF over the measured modes as

$$\text{EVP}_i = \prod_{j=1}^N |\varphi_{ij}| \quad (9)$$

Following this criteria, the best locations are those with the highest EVP. The main advantage of this criteria is that it is able to prevent the location of sensors (but also of actuators) on nodal lines of a vibration modes, so that the maximization of their vibration energy is expected.

Non-optimal driving point method

It is an energy-based method, generally used to find the optimal location for actuators. Non-optimal driving point based method (NODP) is based on the well-known concept that the amount of vibration energy of any mode shapes depends on the relative positions of the excitation sources.

Following this way, the proposed methodology looks for the OSP by adopting an iterative procedure that unselects the candidate sensor having the smallest target mode shape displacement, that is:

$$\text{NODP}_i = \min_j |\varphi_{ij}| \quad (10)$$

Numerical Applications

A wide class of engineering applications deals with the use of metallic lattice towers. They can be adopted in telecommunications, radio and television broadcasting, observation, power transmission and lighting supports, just to name some of the most diffused uses.

Different from other kind of engineering structures, the occurrence of the failure event generally does not involve the loss of human life, unless the tower is placed in a densely populated area. On the other hand, it is well known that also moderate dynamic loads can lead to temporary but frequent malfunctions, for instance, due to the loss of pointing accuracy in the installed equipment or devices. Moreover, the presence of acceleration-sensitive instruments could require the reduction of the detrimental inertial forces

induced by vibrations. In order to measure the structural response, an efficient OSP is required because the off-line conditions in these structures is often economically relevant.

Under this auspicious, EIM, EVP, NODP, DPR, EIM-DPR and KEM will be used to define appropriate topological network configurations for two example broadcasting antennas. All analyses for resolving the OSP problems are carried out by means of SAP2000 (version 11).

Tower A

The finite element 2D model and ten modes for Tower A are depicted in Figure 1. The FE model has 146 joints and two nodes connected to the base (total number of DOF is 288). It is constituted of 16 different type frames with area in the range $430 \text{ mm}^2 \div 3000 \text{ mm}^2$.

Figure 1. Finite element model for Tower A and first ten mode shapes

By using ten modes and the above listed optimum criteria, we obtain the configurations indicated in Figure 2.

Figure 2. Sensors configurations for Tower A

Figure 3. Fisher information matrix determinant for Tower A

One can observe that EVP and NODP select the sensors placements in reduced zones of the tower and the NODP selects a great number of vertical DOF to monitor. The most degenerate configurations is obtained by means of DPR: in this case, horizontal DOF are progressively selected from the top to the bottom of the tower. By combining the EIM and DPR, some of the sensor on the lower part of the tower (selected by means of the EIM) are removed and “placed” on the top. The most regular configurations are obtained by using the EIM and the KEM: final configurations leads to a quasi-uniform and quasi-symmetric geometry of the arrays. Moreover, it is possible to observe that sensors arrays obtained by means of the EIM and the KEM are quite similar.

A comparative analysis for studying the difference between the obtained sensors arrays is based on the strength of the acquired signals: in fact, to reduce the influence of the noise, it should be as high as possible.

Therefore, to evaluate how the network topologies withstand the presence of disturbs, the Fisher information matrix determinant is a useful and efficient performance index.

In Figure 3, the Fisher information matrix determinant dimensionless value is plotted against the progressive number of the dropped candidate sensors for Tower A. It is possible to observe that the worst configurations are obtained with the NODP and the EVP. The EIM and EIM-DPF behave very well in comparison to the others criteria for a wide number of deleted sensors.

Intermediary performances are achieved by using KEM.

However, it should be remarked that these curves change their relative positions when the number of removed sensors increases (see the zoom on the corner).

Tower B

The finite element 2D model of Tower B is depicted in Figure 4. The FE model has 90 joints and two nodes connected to the base (total number of DOF is 176).

It is constituted of 14 different type frames with area in the range $691 \text{ mm}^2 \div 15280 \text{ mm}^2$. In Figure 5, it is possible to observe that topological configurations are quite similar to the previous lattice tower: also in this case, the EIM and KEM appear to give a quite uniform distributions of the sensors along the height of the antenna. In the same way, the others configurations have some criticalities.

With reference to the Fisher information matrix determinant (see Figure 6), the optimum criteria based on the NODP provides the most sensible configuration against the noise. On the other hand, the EIM remains the best optimum criterion.

Figure 4. Finite element model for Tower B and first ten mode shapes

Figure 5. Sensors configurations for Tower B

Therefore, general guidelines from these benchmark cases of study can be extrapolated. Optimum sensor arrays obtained by using EIM and KEM are suitable in these structures for two reasons.

Firstly, they approximately lead to fairly uniform and symmetric sensors configurations, so that a greater capability to capture the dynamic response of the structures (especially in the modal operational analysis) is attended. Secondly, the Fisher information matrix determinant indicates a good behaviour against the noise. With reference to the horizontal DOF, one can observe that both criteria give final configurations not excessively dissimilar. Diversely, with reference to the vertical DOFs, it is interesting to note that EIM always selects the nodes on the top while KEM chooses the nodes on the upper part of the towers but not in the same positions. This result can be analyzed with reference to the nodal mass distribution: in fact, KEM privileges nodes with greater mass, in virtue of their greater kinetic energy.

These considerations and these results could be a valid technical support to decide number and locations of the sensors. Firstly, the designer chooses a compromise between sampling frequency and number of sensors to install, taking into account the unavoidable economical and technological constraints. Subsequently, it is always advisable to perform the EIM or the KEM to define the optimum placements for the sensors and to evaluate the expected covariance matrix of the coefficient response vector by means of (3). The standard deviation σ of the

Figure 6. Fisher information matrix determinant for Tower B

WGN can be found in the sensors data sheets or from preliminary laboratory tests.

However, in evaluating the economic efforts, it should be kept in mind that not only the number of sensors define the total cost (positions and others characteristics of the networks can sensibly modify this value).

CONCLUSIONS

The optimum design of the sensors arrays in lattice towers is addressed in the paper. Within the framework of the structural identification problems, six different optimum criteria are selected to calculate six configurations for the sensors arrays. The applications regarding two broadcasting antenna demonstrate that each optimality criteria leads to configuration very different in comparison to the others.

From a topological standpoint, the application of the EIM and KEM provide very regular arrays, so that we can expect a better performance in modal identification problems. On the other hand, the EVP, NOODF, DPR and EIM-DPR conduct to critical configurations. In order to appreciate the robustness against the noise, the performance of the calculated sensors configurations are evaluated with reference to the Fisher information matrix determinant.

In both towers, we observe that the EIM is more robust than the others optimality criteria for a wide range of sensors deleted. From our study, the EIM is the most appropriate approach for sensors placement in lattice towers, while the performance of the KEM are sufficiently good and then acceptable for this goal. The other optimality criteria appears not appropriate for sensors placement in lattice towers.

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PAVEMENT CONDITION AND TRAFFIC INDICES FOR PRIORITIZING ROAD MAINTENANCE

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Abstract

Maintenance prioritization is a regular challenge that transportation departments face. They periodically have to choose among many roadway sections the ones that take precedence over others when it comes to the order of rehabilitation. They typically follow methodologies that consider only pavement condition for prioritizing roadways, without considering the number of the users. Presented herein is the way information provided by automated techniques for pavement and traffic evaluation is transformed into a numerical metric that can be utilized for maintenance prioritization purposes. The contribution of the proposed system can be summarized in: (1) the implementation of two entropy-based classification approaches (change-point detection and thresholding) for detecting “distressed pavement” areas; (2) the development of a pavement condition index that is a continuous variable; and (3) the creation of maintenance prioritization index based on both pavement condition and traffic.

Introduction

Maintenance prioritization of roadway sections is essential, especially in case of budget constraints. Departments of Transportation (DOTs) select amongst several road sections the ones that take priority over others when it comes to the order of maintenance. Most DOTs follow procedures that take into account only pavement condition (Bandara and Gunaratne, 2001; Pantha et al., 2010) for prioritizing roadways of the same type (e.g. highways). They utilize the International Roughness Index (IRI) measurement, a pavement condition index, or a combination of the two.

The former is the most commonly used index for measuring road roughness, defined as the divergence of a roadway surface from a planar surface, affecting vehicle dynamics, drainage ride quality, and dynamic loads (ASTM International, 2012). The latter is normally calculated based on the type, severity and extent of specific defects, existing in the examined section. PASER and PSCI are two examples of pavement condition indices. The former consists the condition index for Michigan DOT (Walker, 2002), while the latter is used by the (Department of Transport, Tourism and Sport, Government of Ireland, 2013). PACER and PSCI are numerical indices

between 1 and 10, with 10 indicating excellent condition and 1 showing failure.

However, in recent years several researchers have reconsidered the maintenance processes, claiming that a priority-of-work analysis should be a multi-criteria procedure that determines the optimal ranking list of candidate segments for maintenance based on numerous factors (Shah et al., 2014).

Ndume and Mlavi (2017) claimed that the most important factors affecting road maintenance prioritization should be: traffic, population served, production centers, social services, connectivity, road class and tourism. Though, this study does not consider pavement condition, ignoring that if a road section is economically important but in an excellent condition, it should not be prioritized over a section that is less economically important but its condition threatens passengers' safety.

Reddy and Veeraragavan (2001) developed a maintenance priority index concept that is based on an overall distress index model and traffic adjustment factors. In addition, Moazami et al. (2011) claimed that the factors needed to be included in a prioritization model consist of pavement condition index, traffic volume, maintenance and rehabilitation cost, as well as road width. Another study named the following elements to be considered by a priority ranking model: pavement serviceability and condition index, traffic level, functional classification, and agency cost (Fwa, 2005). However, these studies do not include all information needed on the procedures of collecting and processing data to estimate these variables.

Pavement condition and traffic volume, which comprise the common factors in the aforementioned studies, are those that require the most time and cost to be estimated. Several researchers have attempted to contribute on automated pavement condition and traffic assessment since current manual techniques are time-consuming, subjective and pose safety risks for surveyors (Bianchini et al., 2010).

Pavement evaluation methods in literature can be divided based on the way data is collected. Data can be collected via vibration-based sensors that are embedded in smartphones and vehicles, or via cameras and laser scanners positioned on moving vehicles, followed by data processing using computer-vision techniques. Lakušić et al. (2011), Yu and Yu (2006),

Ngwangwa et al., (2014) and Harris et al. (2010) utilized accelerometers to estimate road roughness or characterize road profile, without classifying specific defect types. Mednis et al. (2011), Douangphachanh and Oneyama (2014), and Kumar et al. (2017) utilized accelerometers embedded on android smartphones. The former study detects potholes, while the other two relate road roughness condition with acceleration vibration. The exploitation of gyroscopes, combined with other sensors embedded on smartphones, was investigated by Seraj et al. (2014) and Mohamed et al. (2015), detecting severe pavement defects. Vibration-based methods have been proved effective in estimating road roughness and detecting “elevation” defects, such as potholes. However, they miss pavement defects if the moving vehicle, equipped with the sensors, do not pass over the defects, they are unable to detect defects which are not related to elevation differences (e.g. bleeding) and to classify the severity of defects that is based on visual characteristics (e.g. width of cracks).

A noteworthy number of researchers have concentrated on vision-based methodologies to avoid the aforementioned limitations. Zhou et al. (2006), Lokeshwor et al., (2014) Doycheva et al. (2016), (Yan and Yuan (2017), and Banharnsakun (2017) developed algorithms that detect distressed pavement areas, without classifying defect types. A significant number of other studies have concentrated on directly classifying specific defect types, such as cracking (Amarasiri et al., 2010; Huang and Xu, 2006; Ying and Salari, 2010), potholes (Koch et al., 2012; Ryu et al., 2015), patching (Hadjidemetriou et al., 2018; Hadjidemetriou et al., 2016) and raveling (Mathavan et al., 2014). A few studies have attempted to classify multiple pavement distress types simultaneously (Radopoulou and Brilakis, 2016; Xu et al., 2016). Li and Wang (2016) used an emerging 3D pavement data collection system to detect cracking with a multiseed fusion algorithm, while Zhang et al. (2018, 2017) developed the CrackNet, a deep-learning based software, for detecting pavement cracks on 3D asphalt pavement surfaces. Nonetheless, the aforementioned studies do not describe the way this information can be used for rating pavement condition and prioritizing road maintenance.

Numerous other studies concern with automated traffic monitoring. One of the most widespread practices in automated traffic monitoring consists of sensors embedded in the pavement, with the majority being inductive loop detectors. Nevertheless, this practice suffers from high installation and maintenance costs (Zhang et al. 2011). Chen et al., (2001) as well as Gupte et al., (2002) designed vision-based systems that automatically detect and track vehicles.

The current paper describes work in progress on the

development of procedures for rating asphalt pavement condition of a road section using vision-based identification of distressed areas, and for grading traffic using vision-based detection and classification of vehicles. Lastly, it aims to combine the two grades providing a final rating, which can be used for prioritizing maintenance of roadway sections.

Methodology

Entropy-based Pavement Condition Index

A vision-based method for distressed pavement areas detection (Hadjidemetriou and Christodoulou, 2019), provides the data needed for the development of the novel pavement condition index described below. The input of this method consists of collected pavement surface videos from which frames are extracted, along with their geospatial location. Shadows are removed from the grayscale images using a method developed by Gong and Cosker (2016), which upon testing on images of pavements with shadows showed almost perfect performance in removing such shadows. The shadows were eliminated in 519 frames (95.8%), partially removed in 13 frames (2.4%), and remained in 10 frames (1.8%) after processing 542 frames extracted from the collected videos for the presented distressed-areas detection algorithm.

The subsequent phase of the developed system consists of the calculation of entropy, in the context of image-processing, as firstly introduced by Shannon (1948).

$$E \equiv \text{entropy}(I) = - \sum_{i=1}^N * \log_2(p) \quad (1)$$

The parameter p in Equation 1 stands for the probability of occurrence and N represents the number of classes in the analysis. In the current case of a grayscale image, p is the number of pixels per color on a scale of 0 to 255 divided by the total pixel count of the frame, while N is the number of color values in the analysis (256). Entropy reaches maximality at the equiprobability state (i.e. when all classes have equal probability of occurrence) and minimality when all events are assigned to a single class (Christodoulou et al., 2009). Given a grayscale image, entropy maximality corresponds to an equal number of pixels in each gray shade, and minimality corresponds to all pixels having the same grayscale shade (for instance a completely black image). Thus, the worse the pavement condition is, the higher the entropy value gets. This is a result of the smooth texture of healthy pavement (which includes similar shades of gray and consequently a low entropy value) and the rough texture of distressed pavement (which contains a higher number of gray shades and therefore a greater entropy value).

Video frames of healthy and distressed pavement were

analyzed to automatically separate the two classes. Thus, the solution space and the complexity of the problem will potentially be reduced since transportation authorities will have to deal only with the images including anomalies. The “distressed pavement” frames detection was initially performed by use of the relative unconstrained least-squares importance fitting (RuLSIF) method (Liu et al. 2013; Yamada et al. 2013). RuLSIF is a statistical change-point detection algorithm based on non-parametric divergence estimation between signal samples from two retrospective segments. The algorithm uses the relative Pearson divergence as a divergence measure and a method of direct density-ratio estimation.

Figure 1 and Figure 2 show two examples of the video signals analyzed, with the corresponding anomaly detection results from the RuLSIF method. Video signal 1 was known to have transverse cracking and raveling in frames 1215-1269 and 1578-1622, respectively, while video signal 2 included patching, cracking (longitudinal and transverse) and raveling in frames 343-367, 531-574, and 656-670, respectively.

Figure 1: Entropy signal and change-point score of sample video 1

Figure 2: Entropy signal and change point score of sample video 2

The RuLSIF method identifies frames that have a significant change compared to the previous frames (regions where the change-point anomaly scores peak). In the current example, the algorithm proved accurate in identifying frames including anomalies (True Positives). However, in several cases it indicated healthy pavement areas as distressed areas (False Positives), when moving from a high number of consecutive “distressed pavement” frames to “healthy pavement” frames. False Positives increase the number of frames that authorities have to deal with, without achieving the initial aim of reduced time and complexity. Further, RuLSIF, as most change-point detection methods, even though better than traditional outlier detection methods (such as the moving average), fail when the transition between states is smooth and thus the pace of change (from one image to another) is small. In this case, there are “distressed pavement” frames identified as “healthy pavement” pavement frames (False Negatives). To avoid wrong indications and to increase the detection accuracy, the change-point detection approach was supplemented with a thresholding approach, as described below.

The final approach classifies frames into two classes, named “healthy pavement” and “distressed pavement”, based on their entropy values. Frames that exceed a predefined entropy threshold value are classified as “distressed pavement”. Figure 3 illustrates the entropy signal of a sample video with X-axis and Y-axis presenting the frame serial number and the frame entropy value respectively. The entropy-thresholding process extracts the “distressed pavement” frames, along with their geospatial location, with a classification accuracy of 89.2 % (Hadjidemetriou and Christodoulou, 2019).

Figure 3: Entropy signal of the sample video, with annotations on the observed roadway defects (Hadjidemetriou and Christodoulou, 2019)

The aforementioned detection process provides the data needed for the development of a novel pavement

Table 1: Comparison between PASER, PSCI and EPCI

Section	Description of condition	PASER	PSCI	Average frame-entropy	EPCI
A	New construction	10	10	5.42	1.00
B	Recent overlay, like new	9	10	5.45	4.54
C	Low-severity raveling	7	8	5.69	32.82
D	Medium-severity longitudinal cracking	6	6	5.72	36.36
E	High-severity transverse cracking, low-severity longitudinal cracking	5	5	5.76	41.07
F	Low-severity patches	5	5	5.8	45.79
G	High-severity raveling, medium-severity patching	4	5	5.98	67.00
H	High-severity patches, high severity longitudinal and transverse cracking, high-severity raveling	3	3	6.08	78.79
I	High-severity alligator cracking	2	2	6.16	88.21
J	Road disintegration of surface. Pavement failure	1	1	6.26	100.00

condition index, as presented below. The entropy values are normalized to a 1-100 scale and used as a condition rating index, while also calibrated against two of the most widespread pavement condition indices, called Pavement Surface Evaluation and Rating (PASER) and Pavement Surface Condition Index (PSCI). The pavement condition indices of PASER and PSCI were selected because: (a) they are currently used by transportation authorities; (b) the way they are used as well as their description for each level of the scale are clear; (c) they consider almost all possible pavement defects of asphalt pavements. The developed index is also divided into severity levels, with each level including possible pavement defect types.

The proposed system was tested by use of videos collected from roads (of approximate total length of 10 km), separated into lane sections of 50 m. The selection of the 50m-lane sections was based on a review of 56 different pavement manuals used by different DOTs, and on interviews of pavement engineers/experts. The entropy value of each frame is calculated using Equation 1, followed by the calculation of the average of entropy values for all images of the 50m-section. The average frame-entropy is then normalized to a scale from 1 to 100 (Equation 2) and compared with the PASER and PSCI indices. Figure 4 shows 10 representative frames collected from 10 different sections. Table 1 presents the defects that exist in these sections, the pavement condition rating by PASER and PSCI, the average frame entropy and its normalized value.

$$x' = a + \frac{(x - A)(b - a)}{(B - A)} \quad (2)$$

where:

x' : normalized value

x : initial value

A: lowest entropy value in the dataset (i.e. 5.42)

B: highest entropy value in the dataset (i.e. 6.26)

a: lowest normalized value (1)

b: highest normalized value (100)

The comparison in Table 1 clearly shows that as the values of PASER and PSCI decrease, the normalized entropy value increases. Thus, the latter can be used as a pavement condition index, with similar results with the other two indices. It also has the advantage of being a continuous variable, compared to the other two indices that are integer and have only ten possible values. After reviewing all collected data, Table 2 was created to divide the entropy-based pavement condition index (EPCI) into levels. Each level characterizes the general pavement condition, while Table 2 also includes the possible pavement defects that might exist in every level, along with their severity level (low (L); medium (M); high (H)). The values of EPCI corresponding to possible defects were defined based on the conducted case study (10 km-length road network). It should be noted that the current paper presents work in progress. Thus, these values need validation, testing the developed system in other road sections.

Table 2: Entropy- based pavement condition index

Entropy-based index	Pavement defects	General pavement condition
1-32	No defects.	Healthy
33-35	Raveling or bleeding (L). Longitudinal or transverse cracking (L).	Very good
36-40	Raveling or bleeding (M). Longitudinal or transverse cracking (M). Block cracking (L)	Good
41-55	Raveling or bleeding (M). Longitudinal or transverse cracking (H). Block cracking (M). Edge cracking (L). Patching (L)	Fair
56-70	Raveling or bleeding (H). Longitudinal or transverse or block cracking (H). Edge cracking (M). Patching (M). Shoving or rutting or distortion (L).	Fair
71-80	Raveling or bleeding (H). Longitudinal or transverse or block or edge cracking (H). Alligator cracking (L). Patching (H). Shoving or rutting or distortion (M). Potholes (L)	Poor
81-95	Alligator cracking (M or H). Patching (H). Shoving or rutting or distortion (H). Potholes (M or H)	Very poor
95-100	Disintegration of surface	Failed

Figure 4: Frames from the examined roadsections

Traffic Volume Index

A vision-based method for traffic monitoring, provides the data needed for the development of a novel traffic volume index (TVI) (Figure 5). An already developed algorithm, called “Detecting Cars Using Gaussian Mixture Models” (The MathWorks, Inc., 2010), included in the Computer Vision System Toolbox of

MATLAB, formed the basis of the automated traffic monitoring system. The initial algorithm was modified so that it is able to classify vehicles into three classes (Figure 6) and count the number of vehicles belonging in each class.

Firstly, a video is imported, from which frames are extracted, with the first frames being used to initialize the foreground. Moving objects (foreground) are segmented from the background. The algorithm utilizes the morphological “opening” to remove the noise and to fill gaps in the detected objects. Figure 6 shows the initial foreground mask computed by the detector as well as the improved foreground mask (after the application of morphological opening) for a two-wheeled vehicle, a light vehicle, and a heavy vehicle.

The following step finds the bounding box of every connected element corresponding to a moving vehicle, using the Matlab command “vision.BlobAnalysis” that tracks and computes statistics for a set of connected points in a binary image. Once detected, the vehicles are classified into one of three classes based on the number of connected pixels. The minimum and maximum number of connected pixels, for the examined video resolution (640 x 360), for each class are the following: 4500 and 11000 for two wheeled-vehicles; 11000 and 30000 for light vehicles; and more than 30000 for heavy vehicles, respectively. These numbers were arrived at through a search over the range of 3,000 to 40,000 connected pixels in increments of 100, to identify the best performing district connectivity count based on the performance of the testing set. Finally, the vehicles of each class are counted. This method has an overall recall of 94.07 %.

Figure 5: Main stages of the proposed traffic monitoring system

Figure 6: Initial foreground mask and improved foreground mask for: (a) a two-wheeled vehicle; (b) a light vehicle; and (c) a heavy vehicle

Presented herein is the way the counted vehicles are used to estimate the novel TVI. The three different classes of vehicles are transformed into Passenger Car Equivalent (PCE) to estimate traffic flow. Additionally, the daily proportion of PCE/hour is normalized to a scale from 1-100. This value is combined with the EPCI to form the final maintenance prioritization index (MPI).

PCE is a metric used in Transportation Engineering, to evaluate the traffic flow rate on a roadway. A PCE represents the influence that a mode of transport (vehicle type) has on the traffic variables of headway, speed and density, compared to a single car (light-vehicle) (Ahuja, 2007). Various research studies estimated the PCE of different modes of transport. Table 3 represents the PCE values of the three vehicle classes examined by this paper, as introduced by

(Webster, 1958), Tiwari et al., (2000), Minh and Sano, (2003), Prasetijo (2007) and Partha et al. (2009). The median PCE value of these studies, for each class, is used for the purpose of this study (last row of Table 3).

Table 3: PCE values, proposed by various research studies and the current work

Study	Two-wheeled vehicles	Light vehicles	Heavy vehicles
Webster (1958)	0.3	1	2.25
Tiwari et al. (2000)	0.4	1	2.4
Minh and Sano (2003)	0.29	1	-
Prasetijo (2007)	0.3	1	3.1
Saha et al. (2009)	-	1	2.16
Proposed system	0.3	1	2.3

After automatically counting all vehicles of each class and calculating the daily proportion of PCE/hour for an examined road lane, a traffic volume index is calculated. Lane capacity varies due to a number of conditions, such as lane width, neighboring lanes, elements next to the road, number of driveways, presence of parking and speed limits. The range of lane capacity is between 1000 and 4800 PCE/hour. Normally lane capacity is between 1500 and 2400 passenger cars per hour (Austroads, 2013).

The aforementioned lane capacity numbers serve as guides for the normalization of the proportion of PCE/hour to a range between 1 and 100 (Equation 2). The maximum number of 4800 PCE/hour is transformed into the value of 100. Additionally, 2400, 1500, and 1000 PCE/hour are converted into the traffic volume index values of 90, 80, and 70, respectively. Everything in between is normalized accordingly. For instance, the values of vehicles/hour between 4800 and 2400 are normalized into the TVI values between 100 and 90, while the values of vehicles/hour between 2400 and 1500 are normalized into the TVI values between 90 and 80.

Maintenance prioritization index

This paper proposes the evaluation of pavement condition and traffic, dividing a roadway network into lane sections of 50 m. Every section is rated by the proposed EPCI and TVI. The combination of the two indices provides the final MPI, which also ranges from 1 to 100. The weighted arithmetic mean is utilized for calculating the MPI (Equation 3).

$$\text{MPI} = \frac{w1 * \text{EPCI} + w2 * \text{TVI}}{w1 + w2} \quad (3)$$

A weighted arithmetic mean is estimated by data points that do not contribute equally to the final average. In case of all weights being equal, then the weighted arithmetic mean equals the arithmetic mean. The current paper proposes an equal contribution of traffic and pavement condition, after advised by pavement experts. However, transportation authorities can utilize the proposed maintenance prioritization method, selecting the weights of EPCI and TVI according to their needs and priorities (pavement condition or traffic volume of a section).

A case study was conducted to test and validate the presented MPI in the roadway network of Nicosia, Cyprus. The EPCI was tested by use of videos acquired from roads of total length of 10 km, with a classification accuracy of 89.2 %. However, the TVI was tested in a portion of these roads (of total length of 1 km), with an overall recall of 94.07 %. Thus, the final MPI, which depends on both EPCI and TVI, was estimated for the common 1 km-length roadways. These roads were divided into 20 equal road sections of 50m-length. Firstly, EPCI, TVI and MPI were calculated for each section, and secondly, sections maintenance was prioritized, with the section with the highest MPI being first in the prioritization list.

Conclusions

Transportation authorities normally have to select the road sections that they will be maintained amongst many sections, due to budget constraints. This paper proposes a maintenance prioritization technique for 50 m-length sections of roadway lanes. Each section is rated by a novel index (MPI), which is a combination of the proposed pavement condition (EPCI) and traffic volume (TVI) indices. The following characteristics summarize the advantages of the proposed method compared to existing maintenance prioritization systems:

- The EPCI is a continuous variable with a range from 1 to 100.
- The MPI considers not only pavement condition but also traffic volume.
- The maintenance prioritization system provides not only the theory on the calculation of the MPI based on the EPCI and TVI, but also the vision-based tools for automated assessment of pavement condition and traffic.

Future work includes the investigation of other factors that might be taken into account for the prioritization, such as maintenance and rehabilitation cost, and road width. The weights given to each considering factor for calculating the weighted arithmetic mean will also be explored. The final proposed solution should be tested and validated by a greater case study in a real road network.

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Education, Policy and Standardisation

ONTOLOGIES AND LINKED DATA FOR STRUCTURING PUBLISHED BIM ARTICLES

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Abstract

In the last decade, Building Information Modeling (BIM) has been of broad and great interest in both the academia and industry. Massive amounts of BIM researches have been published in academic journals, books and conference proceedings. However, more than half of the published researches are not cited, and some researches with similar questions and outputs are published. In this research, the Linked Data paradigm is utilized with ontologies to provide a structured database of the different articles of BIM and mapped to different BIM aspects in a semantically meaningful format. The proposed ontologies and Linked Data can accelerate and enhance systematic reviews and metadata analysis for future BIM studies. Also, it can assist young researchers to define the gaps that need to be filled in BIM studies and avoid repetitive researches.

Introduction

Since the idea of Building Information Modeling (BIM) has been coined in 1978 (Eastman et al, 2011), BIM has been increasingly implemented in the Architecture, Engineering, and Construction (AEC) sectors and recently in the Operation and Maintenance (O&M) sectors (Farghaly et al. 2018). BIM is evolving as an approach driven by technology for generating, managing and exchanging a well-structured facility's data throughout its lifecycle (Succar & Sher, 2014). In the last decade, BIM has been the new international benchmark for better efficiency and collaboration in the AEC and O&M industry (Arayici, 2015). Several public and private sectors have mandated BIM for all their projects. This leads to the publication of public policies and standards, and also academic publications to improve the implementation of BIM in the AEC and O&M sectors.

At present, there is a massive amount of BIM researches in academic journals, conferences, books and master theses. Based on the Web of Science (WOS) database, 1836 journal articles contain the keyword "BIM." Figure 1 represents the number of articles that have been published in five of the main journals in the AEC fields during the last ten years; namely, Automation in Construction, Advanced Engineering Informatics, Journal of Computing in Civil Engineering, Journal of Construction, Engineering and Management, and Journal of Information Technology in Construction. It also shows

how exponentially the number of articles is increasing.

Figure 1: Number of articles published related to BIM in the main five journals in AEC domains.

Due to this massive amount of literature, BIM is reaching maturity in some aspects, and the quality and complexity of recent papers are significantly high (Santos et al, 2017). However, it is hard to establish which BIM aspect has been covered and which still has gaps to be filled. This leads to similar and repeated research questions, objectives and outputs. Moreover, several researchers do not provide much literature on the identified problem and do not evaluate it critically. Instead, they provide general literature and rush to the formulation of research objectives and methods.

Providing a structured database of the different articles of BIM could assist researchers to identify and select the appropriate articles for their research problem and objectives. BIM researches can be classified based on several aspects, such as BIM tri-axial framework (Succar, 2009), project phases, project types, BIM uses, and BIM dimensions (Charef et al, 2018; Succar, 2009). To overcome the barrier of the different classifications, it has been argued that Linked Data (LD) and ontologies could improve interdisciplinary research through linking between different domain-specific knowledge bases (Schmachtenberg et al, 2014). LD aims to define a process to publish and share machine-readable interlinked data on the web, based on a set of design principles. The implementation of LD in the AEC and O&M sectors is still in its infancy (Radulovic et al, 2015). Pauwels et al. (2015) categorized the work of LD in the AEC sector to three main groups based on aims and barriers to overcome; namely, interoperability, linking across domains, and logical inference and proofs. Several publications implemented LD with BIM for better

building operation and maintenance (Curry et al, 2013), efficient management of building energy activities (O'Donnell et al, 2013), sharing construction defect information (Lee et al, 2016), and linking Industry Foundation Classes (IFC) objects with the facilities management work information (Kim et al, 2018).

So far, as per the author's knowledge, there is no available work that has attempted to explore using LD and ontologies to publish structured data on the web related to all BIM articles. Therefore, this research proposes the different ontologies required to create reporting standards for BIM articles. It also recommends a framework of mapping the articles to the proposed ontologies and publishing them in the Web using LD.

Linked Data

Linked Data is the coding of data with semantic meaning for human and machine use (Dutta, 2017). LD works in the same way as relational data in conventional databases; they are stored, processed and queried by computers, not by humans (Bizer et al., 2009). The term Semantic Web was coined before Linked Data by Sir Tim Berners-Lee, "the inventor of the Web" at WWW (World Wide Web) in 1994 and documented in a scientific American article in 2001 (Berners-Lee et al., 2001). The semantic web is an extension of the current web where information (data and documents) is well defined to ensure better cooperation between computers and humans. The purpose of the semantic web is to achieve data universality and data linking with any other data.

However, Bernes-Lee (2006) noticed that some semantic data published on the web are not linked to other outside semantic data. Therefore, Bernes-Lee outlined four principles that need to be adopted to truly obtain LD. The four principles are (1) use URIs (Uniform Resource Identifiers) as names of things, (2) use HTTP URIs so that people can look up those names, (3) when someone looks up a URL, provide useful information using the standards, and (4) including links to other relevant URIs, so they can discover more things. In 2010, Bernes-Lee suggested a five-star deployment schema for Linked Data based on the four Linked Data principles. The five-star deployment schema is accumulative, it starts with one star, and the data earn more stars when proprietary formats are detached, and more links are added.

The web of Semantic Data, unlike the document web, requires standards to ensure a highly interconnected network where the huge amount of heterogeneous data has been given a well-defined meaning. Therefore, the World Wide Web Consortium (W3C) team has developed an ecosystem of standards named Semantic Web Stack, to support LD. The stack consists of several layers, and the first two layers are known as the

standard Internet technologies for providing data on the web. The combination of these two layers with Cryptography, which verifies the reliability of inputs such as the digital signature of the source's origin, forms the structure of the normal web. Resource Description Framework (RDF) layer is a semantic web core representation for data in graphical format. The RDF is a generic and flexible language that permits the presentation and integration of information from different knowledge domains. RDF is a framework based on triples subject-predicate-object that forms a graph of data. Each concept in an RDF graph where it is subject, object or predicate has its own URI (Uniform Resource Identifier). The RDF Schema (RDFS) contains the most basic elements in describing the ontologies built by the RDF triples, such as the description of classes, subclasses, comments, relationships and data types. Ontologies represent knowledge in specific domains and enable semantic interoperability by linking to other external data sources (Guarino, 1998). More rich and complex elements and greater machine interpretability for expressing ontologies and RDF statements are found within Web Ontology Language (OWL). For querying and manipulating RDF data as well as RDFS and OWL ontologies, Simple Protocol and RDF Query Language (SPARQL) is commonly used. It provides SQL-like operations the ability to retrieve knowledge from OWL. RDF(S), OWL and SPARQL provide the foundation to allow working with rules and proofs. Relying on rules and proofs, several applications can be built and could reach a precise level of trust.

Due to LD capabilities, it has enjoyed great popularity in different domains including biology, medical records, digital libraries, cultural heritage, finance, accounting, and social media (Schmachtenberg et al, 2014). There are three main benefits of utilizing LD in the research lifecycle of science; namely, to facilitate the serendipitous discovery of information resources and novel links, enhance the systematic review of the existing body of knowledge, and provide metadata openness and sharing (Alemu et al, 2012; Zaveri & Ertaylan, 2017).

Ontologies Development

The process of the development of an ontology consists of seven main steps as shown in Figure 2 (Noy & McGuinness, 2001). The first step is to define the covered domain and the scope. As mentioned before, this research concentrates on the articles in the BIM domain and present the different ontologies for BIM articles. The second step is to consider reusing existing ontologies. Several classifications have been taken in consideration as ontologies in this research such as BIM fields, and BIM stages (Succar et al, 2007) and n-dimensions developed by the University of Salford (Lee et al, 2005). Also, the RIBA plan of work stages is adapted to develop building lifecycle phases.

Figure 2: The process of ontology development

The third step is to enumerate important terms in the ontology. In this step, terms are extracted to form a list of concepts (classes, relationships, and slots) from the data schema regardless of any overlap between the concepts they represent. The names of the selected terms have to follow a specific strategy as specified in define resources-naming strategy task. In this stage, all the classes and their related instances are identified. Some of the terms are selected from existing taxonomies or classifications, and the author proposes the others. For example, Succar (2007) classified BIM fields in three interlocking nodes; namely, policy, process, and technology. That classification has been adapted to develop the class of BIM field and its related instances. On the other hand, the author has noticed the engagement of several technologies in the implementation of BIM, such as Geographic Information Systems (GIS), Virtual Reality (VR), Augmented Reality (AR), Linked Data and Big Data. Therefore, it is crucial to develop an ontology for the different technologies that can be integrated with BIM. The name of the class is “BIM with other technologies,” and it contains several instances representing the different technologies. Also, another ontology is identified with its own classes, instances,

and relationships for the articles. It consists of the main information required to classify the articles, such as the source, the year, the author and the country.

The fourth step is to define the classes and develop the class hierarchy. Several approaches can be used for developing a class hierarchy; namely, top-down, bottom-up and combination. Most of the ontologies are developed based on the top-down approach, which starts from an abstraction of a domain and continues to a concrete level. However, it has been argued that the bottom-up approach is more effective as the domain modeling is based on raw and evidential data instead of theoretical conceptualization (Zaveri & Ertaylan, 2017). One of the pros of integrating LD with ontologies is that it allows utilizing the bottom-up approach for the ontology development (Dutta, 2017). In this research, the top-down approach is used for the reusable ontologies and concepts, while the bottom-up approach is selected for the development of the new ontologies. For example, the BIM use and the BIM benefit classes developed starting with identifying the instances. The instances were identified based on the review of 100 of articles and classifying them based on BIM usage and BIM benefits.

The fifth and sixth steps are closely interconnected and are usually done together. The fifth step is to define the properties of classes (slots); while the sixth step is to define the facets of the slots. The values of slots are described in different facets such as; value type, allowed values, cardinality, and other facet features. The value type facet can be described in different value types, such as string, number, Boolean and enumerated. The allowed value facets define the range of slot and the cardinality facets define how many values the slot can have. In this research, the string value type is used for defining most of the slots for the classes’ properties. Finally, the seventh step is to create the instance of classes in the hierarchy. This step consists of three tasks respectively, which are – choosing the class, creating the instance of that class

Figure 3: Screenshot for the developed classes and instances using protégé.

and finally filling in the slots values. Figure 3 represents a screenshot for the developed ontologies using Protégé 5.5.0.

In this research, instances are used to represent the different attached individuals to a specific class such as BIM technology attached to the BIM field class, while individuals are utilized for the BIM articles. After the development of the different ontologies, a logical base approach is used to evaluate the ontologies syntactically. Syntactic evaluation aims to ensure that all defined concepts are viable from a technical viewpoint (Tomašević et al, 2015). Several SPARQL queries are executed to observe the credibility of obtained results and Hermit reasoner was used to validate the consistency with the used ontologies. Hermit is a reasoner for ontologies written using the Web Ontology Language (OWL), and it is a preinstalled Protégé plug-in.

Linked Data Development

A main step in developing and publishing data in the web is to provide crosslinking between the instances of an ontological source and the data ‘out there’ based on the background knowledge. LD mapping relies on setting RDF links between URI aliases in order to be able to track the different information referring to the same article. This stage aims to provide visible indicators that have not already been harvested such as the interconnections, incoming and outgoing links between the different BIM classifications. Figure 4 illustrates the link between the different ontological sources and a specific BIM article. The different relationships are color-coded and depicted in the bottom left of Figure 4.

Figure 4: An example of mapping all the BIM aspects to a journal article using Protégé OntoGraf plug-in

The selected journal paper, “A Taxonomy for BIM and Asset Management Semantic Interoperability” has

been mapped to predefined ontologies. Ten main relationships were identified using object properties to map between the ontological instances and the selected article. For example, the relationship “*itsBIMLenses*” links the instances related to the ontology of BIM lenses to the article. Since the BIM lenses class consists of three main subclasses – disciplinary, scoping and conceptual, three different instances were linked using the *itsBIMLenses*. Another relationship was developed using data properties such as *itsAbstract* and *itsIssueNo* (Data properties are not shown in Figure 4). Data properties describe relationships between individual and data values. For example, *itsIssueNO* relationship is assigned to the subclass *Journal* to identify the issue number where the article has been published.

The developed ontologies and the defined resource naming strategy can be utilized in the transformation process of the BIM articles from the different sources into RDF format. Figure 5 illustrates the proposed framework for data transformation of the different BIM articles. The first step is selecting and accessing the data sources. In the ongoing research, the articles were retrieved from the WoS core collection using two keywords: BIM and Building Information Modeling. The University subscriptions have provided the accessibility for the different journals sources. 1836 research papers were selected, accessed and analyzed at the end of this stage.

Figure 5: Proposed framework for the flow of data

The second step is to transform the datasets to RDF format. The data are exported from the WoS website in HTML (HyperText Markup Language) format and then converted to xls format. The exported data for the BIM articles were arranged in seven main columns; which are, research title, abstract, source, keywords, year, authors and issue no. OpenRefine with the RDF extension has been utilized to transform the xls data into RDF. To achieve the transformation, a mapping between the data and the ontology has to be defined

taking into consideration the defined resource-naming strategy. This has been achieved in several tasks; firstly, the preliminary transformations to the data made in order to correct errors. Secondly, mappings between the columns and rows in the table and the ontology and specifying the pattern for naming instances according to the resource-naming strategy (Radulovic et al, 2015). Consequently, the RDF syntax is chosen and the datasets are generated and evaluated semantically and syntactically. The Turtle serialization was selected as the research RDF serialization. More mapping is required between the datasets and the ontologies related to the BIM aspects. The author has manually mapped the different articles to their related instances in the different BIM ontologies. However, he believes that the authors of the selected articles can classify their work more accurately. Therefore, future work includes approaching the authors to classify their researches based on the developed ontologies.

Once all the data are transformed and integrated with the ontologies, the discovery of links between the data sets and the retrieving of required data are now possible using SPARQL queries. Finally, the proposed framework can provide outputs which are characterized by maximally findable, accessible, interoperable and reusable (FAIR) data (Zaveri & Ertaylan, 2017).

Conclusion

In both the academia and industry sectors, BIM has been the AEC evolving topic. Massive amounts of BIM researches have been published in academic journals, books and conference proceedings. Meanwhile, more students are enrolled in the BIM master's degree and required to conduct a research for their dissertations. The massive amounts of articles available mislead students to find related literature for their research questions, which leads to repetitive outputs and less contribution in the field of BIM.

Linked Data (LD) and ontologies can enhance interdisciplinary research by enriching knowledge through linking among multiple domain-specific knowledge bases. In this research, ontologies are utilized to organize and describe the BIM articles based on the different BIM concepts such as the tri-axial BIM framework, BIM dimensions and BIM uses, BIM benefits and technologies adapted with BIM. While LD is implemented to expose data in different integrated ways and enhance the Web through the addition of structured data. This paper is a part of an ongoing research; more outputs related to the datasets transformation will be presented in the future. More ontologies and relationships are going to be added to future works, and also a systematic review for the implementation of BIM in the Asset Management (AM) sector and meta-analysis of the articles based on the building phase where the implementation of BIM occurred.

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INVESTIGATING THE DROP-OUT RATE FROM A BIM FOR INFRASTRUCTURE COURSE

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Abstract

This research examines how personal time management relates to successful course completion or dropping-out from a high intensity building information modelling (BIM) e-learning course. The course has been developed during 2017-2018 and uses peer instruction to engage students with the intention of improving their performance. Students' activity data were captured and analysed according to their study groups and suggested study module completion dates. The findings suggest that distance learners had a higher drop-out rate than study program students and that lagging the suggested study module completion dates did not necessarily lead to dropping-out. This paper represents a first step in ongoing research to understand the effectiveness of peer instruction in high intensity BIM courses.

Introduction

Building information modelling (BIM) has been noted as a possible solution to improve the construction industry's poor productivity (McKinsey&Company, 2017). BIM supports the full lifecycle of built assets and has been in use from the early 2000s but, more than a decade later, we still need to address the fact that the full potential of BIM has not yet been realised. Existing research exploring the key barriers to successful BIM implementation (for example, Won et al., 2013; Halttula et al., 2015; Olawumi et al., 2018) has found that the steep learning curve and lack of understanding of BIM processes and workflows are significant challenges. To overcome these, we should focus on how BIM is taught (Sacks et al., 2018).

Numerous research studies have investigated BIM education program development (Sacks and Pikas, 2013; Forsythe et al., 2013). Built environment-related educational requirements have changed in order to meet emerging industry needs in terms of BIM-related topics, including new job roles (Abdirad and Dossick, 2016; Gustafsson et al., 2015; Lindblad and Vass, 2015; Succar et al., 2013; Uhm et al., 2017) and to enhance construction professionals' career paths (Wu and Issa, 2013; Uddin and Khanzode, 2014). Key considerations in developing university course programs for BIM include: (a) the availability of the software which helps to practice key workflows (Russell et al., 2014; Tuchkevich et al., 2015); (b) the need from the industry to push BIM topics into first- or second-year study programs (Vinšová et al., 2015) by eliminating the prerequisite of computer aided

design (CAD) topics as this will be a result from the BIM model and not the opposite (Sacks and Barak, 2010); (c) helping faculty members to redesign their courses according to industry needs due to the availability of BIM workflows (Russell et al., 2014; Peterson et al., 2011; da Silva Vieira and Neto, 2016) and, as such, removing a significant barrier to integrating BIM into current university programs in some countries (Abbas et al., 2016); and (d) focusing on workflows which involve several tools to be learned rather than narrowing the knowledge to a single product's features only.

Various broad educational theories (behaviourist, cognitivist, constructivist, etc.) have shaped the design of e-learning courses and more specific, theoretical models of e-learning have been developed (Ally, 2004). For example, Anderson (2011) proposed a robust online learning model where interactions of learning are divided between community/collaborative (communication) and self-paced instructional models. From a communication perspective, learning may be divided into: synchronous and asynchronous. Asynchronous learning is primarily self-learning with little support from the teacher. These include typical e-learning courses and commercially available examples of BIM e-learning which often focus on a single, specific topic/software (e.g. LinkedIn Learning, Coursera, Udemy) while some enhance this by setting a personal learning path first and then focus on specific topic/software learning content (e.g. Pluralsight). Common to these are the assumption that learners can self-learn without direct and continuous support. Since there are various types of learner, this type of learning may easily lead to learners dropping out from the learning path or gaining an incomplete (even misleading) understanding of key topics. More importantly, since such learning solutions typically focus on a specific topic or software, it also means that the BIM process through the facility's full lifecycle is not correctly understood and the development of essential collaboration skills suffers. (This point may be equally valid for face-to-face training where only one particular topic/software is dealt with.)

Synchronous learning, on the other hand, assumes that each student actively participates in the learning process and this implies that discussion is a key part for all. Active learning can be simulated in a classroom or an e-learning environment. It is mainly limited time that restricts the "all-involved" learning experience within the classroom, so e-learning tools can make

it easier to set the rules of active learning. Examples of e-learning that incorporate active learning components include massive open online courses (MOOCs) that run within a certain timeframe and ensure that all students are involved in the learning process (e.g. Adobe Education Exchange, Udacity).

Several research papers analyzed active learning vs classical lectures in terms of student performance in science, engineering and mathematics (Freeman et al., 2014). Active learning embraces various teaching methodologies. For example, peer instruction (PI) as an active teaching method was popularized by Harvard Professor Eric Mazur in the early 1990s (Mazur, 1997). The main idea of PI is to help students learn more from pre-class reading and to increase students' engagement in discussion sessions (Crouch and Mazur, 2001; Alcalde and Nagel, 2018). Teacher availability and readiness to answer questions from the whole group is widely valued by students as it helps them to develop during the course and this reduces the failure rate (Zingaro and Porter, 2014). PI as a teaching method is similar to other methods that share the same logic as flipped or inverted classroom (Bates and Galloway, 2012; Hsieh et al., 2015; Wang et al., 2018) or active learning (Lassen et al., 2018). Classical PI assumes that people in a PI session are equally involved (each and everybody is participating in discussions) but this is not always the case because it is not made compulsory. Therefore, special versions of PI have been developed in which each participant should ask a question before entering the discussion group as in the 'stepladder' technique (Rogelberg et al., 1992; Michinov et al., 2015).

The current research relates to BIM courses developed over the period of 2017-2018. These courses are BIM workflow-based active learning courses that incorporate PI throughout the semester. The wider research is intended to investigate how PI can enhance the BIM learning experience and reduce course drop-out rates thus promoting a better and more complete understanding of BIM and, ultimately, to help drive BIM adoption and quality in industry. This research paper presents a preliminary investigation of how students' personal time management throughout BIM course participation relates to the drop-out rate and successful course completion. In the following section, the design and development of the BIM for infrastructure course is described. The methods of data collection and analysis are then explained, and the results obtained are presented before conclusions are drawn.

Course design

Three separate BIM courses were developed during 2017-2018 in Tallinn University of Technology (TalTech). One with a focus on buildings, one for infrastructure and one for advanced BIM studies that combines both buildings and infrastructure topics.

In this research, the analysis is carried out for the second of these, "BIM for Infrastructure". BIM can be used as a general term for any building-related design discipline, if

infrastructure is in focus, several other terms are used, like civil integrated management or civil information management (CIM) or from the bridges context, bridge information modeling (BrIM). In general, bridges and buildings belong to the same, structures class, and have similar features, the key difference is in the construction process, operation and classification of parts (Costin et al., 2018). Vertical construction (building) differs from horizontal construction (e.g. bridge, road, tunnel, etc.), and each has different components, operations and techniques from planning through construction, operation and maintenance. BIM use in building-related projects is currently more advanced with BIM for infrastructure behind it in terms of development. The success of BIM deployment needs effort from both industry and academia. Although there are similarities, BIM implementation from the building or infrastructure perspective requires a different focus in terms of training, study programs, standards and guidelines. Recently, Estonia has adopted Finnish BIM for infrastructure guidelines to speed up the adoption and common understanding of BIM workflows for transportation infrastructure development.

In addition to TalTech, this course is given also at TTK University of Applied Sciences (TTK UAS). Due to new study programs, the course will be taught in TalTech from the 2020 spring semester, but in TTK UAS it has already been given for three semesters (2017 spring, 2018 spring and 2018 autumn). Therefore, this research focuses on the data that has been gathered from TTK UAS. It should be noted that in 2017-2018 the course was taken during students' fourth semester (second year), but from 2018 autumn a slight change was made to the study program and the course was rescheduled to the third semester (second year).

Table 1 shows how the "BIM for infrastructure" course evolved from 2017 spring to an updated version from 2018 autumn. The typical BIM course, if not based on one software package only, is usually a high educational density course, which means that it may include around 20 different tools to be learned (Fonseca et al., 2017). The course has been designed as an active learning course in a university wide Moodle e-learning system. It is divided into several modules (Table 2), each one of which has its own learning outcomes and assessments.

The core idea of the course is to teach the BIM process from the modelling perspective and to include collaborative exercises. The course begins with introductory lectures (usually during the first 2 weeks, 3 x 45 min at one time).

Table 1: Educational density of the “BIM for infrastructure” course in different study programs

Course name	Topics covered	Software packages and/or services included
Building Information Modeling (3 ECTS credits, up to spring 2018)	Introduction to BIM for infrastructure, BIM use in BIM for preliminary design to detailed design, intelligent planning, virtual design and construction, BIM for visualization (including virtual reality), model-based collaboration workflows.	9 major tools used (incl. Autodesk InfraWorks, AutoCAD Civil 3D, AutoCAD Map 3D, AutoCAD Raster Design, Autodesk Navisworks Manage, Autodesk 3ds Max, Autodesk 3ds Max Interactive, Autodesk Viewer, MAGNET Explorer)
Building Information Modeling (3 ECTS credits, from 2018 autumn)	In addition to previous list: BIM in road rehabilitation workflows.	10 major tools used (in addition to previous list: Autodesk ReCap)

At the same time, the students start to carry out individual tasks and assessments (Table 2). Peer instruction is simulated in an e-learning environment, where each student must formulate at least one question at the end of the course module and answer or discuss another student's

questions. This is a key differentiator from the classical lecture where only the most active students formulate questions/answers. The e-learning system ensures that each student has formulated one question and answered somebody else's question.

Table 2: Course learning modules (LM), assessments (version 2018 autumn)

Course learning module	Assessments
LM 0. Introduction	<ul style="list-style-type: none"> • Self-introduction forum (not graded) • Sample quiz (not graded) • Theoretical quiz • Question/answer forum
LM 1. From preliminary design to detailed design	<ul style="list-style-type: none"> • Homework (data flow from preliminary design to detailed design) • Theoretical quiz • Question/answer forum
LM 2. Intelligent planning	<ul style="list-style-type: none"> • Homework (creating intelligent information) • Theoretical quiz • Question/answer forum
LM 3. Virtual design and construction	<ul style="list-style-type: none"> • Homework (4D simulation) • Theoretical quiz • Question/answer forum
LM 4. Visualization and virtual reality (VR)	<ul style="list-style-type: none"> • Homework (visualization + interactive game) • Theoretical quiz • Question/answer forum
LM 5. Model based collaboration (updated in 2018 autumn)	<ul style="list-style-type: none"> • Question/answer forum (shared project model through a web service; commenting and answering to questions)
LM 6. Road rehabilitation (added in 2018 autumn)	<ul style="list-style-type: none"> • Homework (point cloud to road rehabilitation project) • Theoretical quiz • Question/answer forum
LM 7. Project	<ul style="list-style-type: none"> • Essay • Presentation of the project (based on previous modules)

As such, it may happen that, if only one student is active at the start of the course, she/he should wait at least until one other student has reached the same learning point. Due

to the flexible time management this is usually the case at the first learning module and it disappears once more students are involved. This issue can be resolved by setting

deadlines and the teacher can always step in and keep the discussion going if there are too few students active. These questions and answers are assessed based on their constructiveness.

Methods

Data collection

The data used for analysis were obtained from two sources: (a) the university's study information system (number of declarations, final grades) and (b) students' individual activities with the completion date from an e-learning environment. In addition, a feedback system at the end of the course was in place and responses were gathered. However, these course feedback responses cannot be fully used in the current research as key information, for example, whether student respondents "passed" or "failed" cannot be distinguished and, with the high drop-out rate, this may introduce bias into the analysis.

Data measures

The course in both years was taken by different study groups and it was intended to determine if student performance differs by study group. Division was made into 2 separate groups: (a) study program students; and (b) distance learning students. Although there could be many other variables affecting the drop-out rate (for example, previous knowledge) these are not taken into account in this preliminary analysis. In fact, the course did not have any compulsory prerequisites. The course in both years has been a compulsory subject for all student groups.

Data analysis

The preliminary analysis was carried out at two different levels of detail. Firstly, the key performance indicators of students' accomplishments were compared during the BIM course editions of 2017 spring and 2018 spring. Secondly, as more data was gathered during 2018, these were analyzed against learning outcomes where suggested

learning module completion times should be followed but are not made compulsory except for the final deadline at the end of semester. These data give insights into students' capability to manage their time.

Results

Core performance analysis (2017 vs 2018)

The BIM course layout has evolved in time (Table 1). Table 3 summarizes the core statistics of the BIM courses that were delivered during 2017-2018. Table 3 shows that study program students have improved their completion rate, but the opposite is true of the distance learners. Distance learners can be further divided into three dynamic sub-groups (based on their activity): (a) those who register to the course; (b) those who start the course; and (c) those who complete the course. We can see that the average drop-out in between those sub-groups is 25-33%. We explain this by the fact that the course needs more engagement and work during the semester and, if students fail to do it on their own, their motivation reduces.

Another possible reason that may explain the high drop-out rate is that, according to the policy of the university, a student who starts the course in one semester can declare it again if it has not been successfully passed. Since dropping out does not have any serious repercussions for the future, the high-density course can easily be postponed in the hope of having more time or motivation in the future. In this study we have not yet been able to investigate such cases where the student retakes the course at a later time. The first such successful case was recorded in the 2018 autumn course but, due to limited time, that timeframe is not yet analyzed in the current research. It should be also noted that various universities do have different policies in terms of retaking the course and these may affect students' conduct. For example, in Tallinn University of Technology, retaking any course may have financial implications and this may compel more students to finish the course on their first attempt.

Table 3: A summary of student basic activity during the course

	2017 spring		2018 spring	
	Study programme	Distance learning	Study program	Distance learning
Number of registrants (% from total)	19 (50%)	19 (50%)	15 (45%)	18 (55%)
First assessment (quiz) finished	18	14	15	12
First modelling task finished (preliminary design)	18	10	14	8
Course completed (% from study group total)	15 (79%)	8 (42%)	14 (93%)	6 (33%)
Average grade (max 5)	3.47	4.75	3.29	4.83
Number of various graded assessments	17		17	

This will be investigated in future research once the course has commenced in TalTech.

Motivation vs performance and time management (2018)

We take a closer look at how the motivation differs between those who finish the course and those who don't. "Motivation" here is defined in terms of a student's

continuous activity. The analyses are divided according to the two main groups defined above. Starting with the full-time study program students, Table 4 presents students' performance in terms of activity completion on-time. Positive numbers indicate the number of days ahead of time that an activity was finished, and negative numbers refer to learning activities completed after the suggested completion times (in days). It should be noted that the

course has only one strict deadline, at the end of semester. Therefore, each student was able to apply his own time management to finish the course on time. Only one student (Student ID 12) did not complete the course, and this drop-out occurred before the first assignment. We can clearly see that being behind the suggested completion date doesn't affect the possibility of finishing on time (for example, Student ID 7 began late and lagged the recommended schedule by almost 80 days). The final assignment's (7.2) assessment was carried out in the classroom. It was carried out in groups (2 students in one group) and at several dates.

The second study group, distance learning, is shown in Table 5. The first difference when compared with the previous study group, is the fact that only 33% of students reach the first assessment (which is also shown in Table 3). Either they do not start the course in Moodle at all or drop out in the introductory module (during assignments 0.1 – 0.4). Also, one clear difference here is the average completion time of assignments. We see that distance learning students' complete assignments in a much shorter time. There are only two students who lag the schedule, they then try to start again but drop out around mid-course (learning module 3). With distance learning students we

may connect the high drop-out with their daily duties because these students are participating in the course while also having (quite often) a full-time job.

Conclusions

During 2017-2018, a new BIM for Infrastructure course was developed for TTK UAS and TalTech as active learning courses. To reflect industry needs for students to develop a wide variety of skills, the course was created as a high-density course. This research focused on students' individual time management and how it relates to the course drop-out rate. It can be concluded that lagging behind the suggested learning schedule is not necessarily a problem and is not a major factor for explaining drop-outs. Peer instruction was used throughout the course and could be a possible explanation for students finishing the course on-time, even if they lagged during the semester. Although the drop-out rate is much higher in the distance learning group, those who finish have demonstrated good time management throughout the course (lagging behind by an average of only 10 days). Overall, their performance has also improved over two semesters (in terms of higher grades). When it comes to study program students, their performance has dropped but the proportion completing the course has increased

Table 4: Time management of a study group "study program"

Student ID	Learning module																					
	0.1	0.2	0.3	0.4	1.1	1.2	1.3	2.1	2.2	2.3	3.1	3.2	3.3	4.1	4.2	4.3	5.1	6.1	6.2	6.3	7.1	7.2
1	-1	-18	-4	-10	-1	-9	-10	-1	-3	-3	-29	-31	-31	-25	-29	-31					-29	-12
2	-2	-17	-3	-8	3	-1	-9	5	4	-4	0	-1	-1	-1	-8	-8					-8	1
3	-3	-17	-3	-9	-8	-8	-8	-17	-18	-23	-21	-22	-25	-30	-31	-31					-39	-8
4	-18	-18	-6	-9	-4	-4	-4	3	0	-7	-5	-13	-13	-16	-17	-17					-32	-4
5	3	-18	-5	-10	-39	-41	-41	-45	-48	-48	-50	-50	-50	-44	-44	-44	These modules have been added to the 2019 course but were not present in the courses of 2017-2018.				-40	-11
6	3	-1	-7	-14	-8	-8	-8	6	5	5	2	0	-1	4	3	-9					-28	0
7	-18	-18	-15	-79	-66	-67	-67	-58	-59	-59	-52	-53	-53	-46	-49	-49					-39	-12
12	-18	-18	-23																			
15	-1	-1	-1	-29	0	-1	-1	-1	-2	-2	3	2	-8	-3	-5	-5					10	10
16	-3	-18	-4	-14	0	-10	-37	-43	-44	-44	-37	-37	-37	-30	-54	-54					-40	-12
18	-3	-4	-2	-16	-8	-10	-24	-15	-15	-31	-24	-25	-29	-22	-26	-31					-38	-9
20	-18	-18	-7	-21	-18	-18	-18	-11	-15	-15	-11	-12	-27	-22	-24	-24					-39	-9
24	-3	-17	-3	-16	-10	-10	-11	-10	-11	-15	-16	-20	-20	-22	-22	-31					-39	-8
28	-21	-21	-7	-8	1	-2	-2	4	-2	-18	-11	-23	-23	-16	-17	-17					-17	5
29	-1	-18	-4	-32	-30	-52	-52	-44	-44	-44	-37	-38	-38	-31	-37	-38					-40	-12
Average	-7	-15	-6	-20	-13	-17	-21	-16	-18	-22	-21	-23	-25	-22	-26	-28					-30	-6

Table 5: Time management of a distance learning study group

Student ID	Learning module																			
	0.1	0.2	0.3	0.4	1.1	1.2	1.3	2.1	2.2	2.3	3.1	3.2	3.3	4.1	4.2	4.3	5.1	6.1	6.2	6.3
8	-23	-23	-9	-14																
9	-7	-7	0	-1	-4	-7	-7	0	-1	-1	6	5	-1	1	-1	-1				
10	-13																			
11	-15	-15	-1	-1	6	5	5	10	10	9	0	-1	-4	0	-1	-1				
13	-5	-5	-7	-14																
14	-29	-30	-16	-17	-3	-4	-4	7	6	6	-5	-8	-8	-3	-4	-4				
17	-8	-8	-2	-14	-9	-10	-64	-50	-51	-55										
19	-14	-92	-78																	
21	-14	-14	-13	-14	-21	-28	-30	-35	-39	-40	-35									
22	-8																			
23	-4	-65	-59	-59																
25	-3	-7	1	1	4	4	4	7	7	7	0	-7	-7	-4	-4	-4				
26	-24	-24	-10	-10	0	0	-7	7	6	6	4	2	-6	-6	-10	-10				
27	-7	-7	1	-12	-4	-15	-15	-14	-16	-16	-9	-11	-11	-8	-10	-10				
Average	-12	-23	-15	-13	-3	-6	-13	-7	-8	-9	-4	-2	-5	-2	-4	-4				

These modules have been added to the 2019 course but were not present in the courses of 2017-2018.

(from 79% in 2017 to 93% in 2018).

This may be partly explained in terms of the motivation associated with a study group because study program students see each other every week (through different courses) but distance learners see each other only once per month and their personal motivation is a key driver for them. To minimize the latter effect, both study groups were combined in Moodle into one big group, so that they were able to discuss each other's questions.

Future research and data analytics will focus more on the effectiveness of peer instruction, including: (a) how the number of a student's attempts to successfully complete an individual assessment change during the course as the amount of peer instruction increases (continuous support); (b) how the understanding of key terms develops through the course by carrying out text analytics of students' questions/answers given throughout the course. It is also crucial to compare the same methodology with other courses, that are built up in the same manner, in different universities and study groups.

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Energy Modelling & Monitoring

THE IMPACT OF DENSITY AND SCALE ON THE LIFE CYCLE COST OF NET ZERO ENERGY COMMUNITIES

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Abstract

It is widely agreed that expanding the Net Zero Energy concept to a community scale brings multiple advantages in terms of design flexibility, cost reduction, clean energy and resource management. However, it is less clear what the scale or the density of the community should be to utilize these advantages in the best possible way. The objective of this work is to study how the Life Cycle Costs of new Net Zero Energy communities are affected by changes in their density and scale. To achieve this objective, a model was developed for identifying the optimal configuration of energy technologies for each specific scale and density. The analysis takes into consideration the local climate and the types of buildings in the community. The results of the implementation of the model show that both urban density and scale have a direct impact on the costs of NZE communities, but in ways that depend on the local climate.

Introduction

A Net Zero Energy (NZE) building is one that combines energy efficiency and renewable energy utilization to reach a balanced energy budget over a yearly cycle (Voss, Musall, & Lichtmeß, 2011). To date, a standard definition or protocol of NZE buildings has not yet been defined, as the system's boundaries, scope and balance calculation methods differ between projects and countries. In this study, the concept of a NZE community was studied – a community that has reduced energy needs, so that the balance of energy requirements within the community is met by renewable energy (Carlisle, Geet, & Pless 2009).

The following categories of technologies are typically incorporated in NZE communities:

- High-efficiency building envelope components and Heating, ventilation, and air conditioning (HVAC) systems that will reduce the consumption to a minimum.
- Renewable Energy Systems to supply the remaining demand for energy from renewable sources, integrated at a building and/or at a community level.
- Energy management systems at building and community levels for optimizing the distribution and utilization of energy.

The enlargement of NZE concept to a community scale encompasses a number of potential advantages for the

incorporated technologies:

- Centralized and high demand for certain components or technologies allows to utilize the economies of scale.
- The requirement to achieve the NZE balance on a community rather than on a building scale allows the consideration of a larger variety of building forms, styles and building integrated (BI) technologies.
- The energy resources can be managed at a community level and shared between the buildings.
- The possibility to install technologies at a community level enables the consideration of multi-building systems, such as commercial Photo-Voltaic (PV) installations or bio fueled district heating centers. These systems can be installed on large structures such as parking facilities and commercial buildings, or in other available areas in the community.

Such multi-building systems have several advantages, including centralized maintenance, shared energy management and peak thermal load diversity – the simultaneous heating/cooling peak load of multiple buildings together is smaller than the sum of all individual building peak loads (DeBaillie 2012). Expanding the NZE concept to a community scale thus brings multiple advantages in terms of design flexibility, cost reduction, energy and resource management. However, it is less clear what the scale or the density of the community should be to utilize these advantages in the best possible way. In particular, it is not clear how the energy related costs of such a community can be minimized.

Literature review

There are many papers discussing and analyzing the design and implementation of energy production/reduction/ management systems in NZE neighborhoods. Marique & Reiter (2014) analyzed the implementation of the NZE concept at a community scale focusing on two aspects: (a) the impact of urban form on building energy requirements and the required capacity to supply it using on-site renewable energy production; (b) the effect of location on energy consumption for urban mobility. The study suggests that these aspects must be considered in an integrated manner in the design of NZE communities. Orehounig, Evins, & Dorer (2015) describe a method of integrating decentralized energy systems at a neighborhood scale. The method is based on the "energy

hub" concept by which the input and output energy flows are managed in order to optimize net energy consumption. A review of such modelling approaches, focusing on analytical tools for integrating energy systems at the district level while considering both building and urban scale aspects was given by Allegrini et al. (2015).

The intensive initial investments in the technologies that are later compensated by savings in operational costs of the building make the Life Cycle Cost (LCC) analysis an effective technique to evaluate and compare the economic feasibility of NZE buildings. Fuller & Petersen (1996) describe the LCC analysis as a structured approach to consider all the potential costs of a 'project' in a given period of time, including adjustments to reflect the value of money over time. The approach allows the identification of the most cost-optimal alternative among others once the LCC of all alternatives is analyzed under the same economic assumptions and service life time. The specific costs that the LCC of a project/product/system encompass can vary according to product type, industry, complexity and ownership model, but can always be summarized by the following three types:

1. Initial investment costs – the initial cost includes all the potential costs of a system before it was put into operation. It may include designing, planning, construction, acquisition, supply, assembly costs, etc.
2. Operational and Maintenance costs – these costs are all the potential cost of a system after it was put into operation. It may include energy costs, spare parts and labor required for maintenance – whether scheduled or due to failures, and in general all costs that appear from the first service date of the system and until its end of service life.
3. End of Life cost – these costs appear at the end of life of the system and may include its disassembly, demolition, recycling, and all the required costs needed to take the system out of service.

To consider the value of money over time the LCC is to be calculated in present value terms, which requires to discount all future costs to its equivalent present value, considering the interest rate and inflation in market.

The objective of the LCC analysis/optimization is to examine the feasibility of the whole project, therefore, the analysis will deliberately neglect the investment/income distribution among the stake holders. The capital distribution topic is typically addressed by business models, which are typically set before the LCC analysis/optimization is performed.

LCC analysis and design optimization of NZE buildings is widely covered by multiple researches, in different countries and climate zones (Hamdy et al. 2011; Marszal & Heiselberg, 2011; Marszal et al. 2012; Moran, Goggins, & Hajdukiewicz, 2017; Zakis, Zakis, & Arfridsson, 2016). However, LCC analysis of NZE neighborhoods has been discussed much less, probably due to their novelty and very few real-life implementations of the concept. It is expected that compared to a single NZE building, the previously described advantages of NZE communities will

have a positive impact on the LCC of the technological design. Consequently, the following questions arise:

1. How does the LCC change due to the enlargement of NZE concept from a single building to a community?
2. How does the scale, i.e. the number of buildings in a NZE community, affect the LCC?
3. How is the LCC affected by the density of the community and by the area available for the implementation of multi-building systems?

A model for identifying the optimal design of NZE settlements

The technological design of NZE communities is complex for the following reasons:

1. Multiple types of technologies that are interacting with each other are to be considered to effectively achieve the NZE balance
2. While some technologies perform better when installed at the building level, others perform better when installed at a community level. The cost-optimal level of implementation highly depends on the type of technology, the urban form of the community and the cost of land.
3. A bigger size of technologies is usually related to lower costs. However, in NZE communities most of the technologies are implemented inside the community, as part of the urban fabric. Therefore, large-scale technologies that are believed to be more cost effective may be unfeasible or eventually too costly to implement in NZE communities.
4. The same urban density may have a different impact on the cost and energy performance of different technologies. One example is heat distribution systems that perform better in dense areas vs. solar energy based technologies that require some space to reach the needed solar irradiation.

The objective of this research is to analyze how the LCC of new NZE communities are affected by changes in their density and scale, and what these should be in order to utilize the advantages of such communities in the best possible way. The results of this study could lead to a better understanding of the implications of NZE requirements for urban planning. Unlike a single NZE building where the technological design is set according to a given urban environment, the urban form of a NZE community is a variable that can be altered in the design phase and have huge impact on the energy and cost performance of the community. A precise urban form of NZE community will help to achieve cost-optimal technological design, high energy performance and the required cost reduction for a wide adoption of this concept.

Optimization model

To achieve this objective, a generic and comprehensive LCC optimization model was developed with which the optimal configuration of energy related technologies can be identified for each specific urban scale and density, while taking into consideration the local climate and the type of buildings in the settlement. This model can be used

as a tool to study the implications of NZE requirements for urban planning.

The optimization model was developed under the simplifying **assumptions** that all the buildings in the community are similar in shape, energy demands and potential of renewable energy production on rooftops. In addition, it is assumed that the buildings are spread uniformly across the community, and that all the energy centers at a community level have the same potential of renewable energy production. Community-level energy centers can be implemented within the community, in the free area between the buildings, parking lots, rooftops of commercial buildings, etc. While these assumptions are not entirely realistic, they are not expected to significantly affect the conclusions that can be derived from the results of the implementation of the model.

In addition, it is assumed that the buildings in the studied communities are connected to the electrical grid, as are the vast majority of buildings in Europe, and that when the generated renewable energy is higher than consumption the electricity is fed into the grid according to the Net Metering regulation. An analysis of the impact of the use of renewable energy sources on the grid (in terms of variability, capacity, etc.) was not included in the scope of this study, since it focused on the settlement-scale implications of achieving NZE performance.

The **objective** of the model is to minimize the LCC of energy related technologies incorporated in the community, per m² of net area of the buildings in the community. The LCC includes the initial, operational, maintenance and replacement costs in Present Value (PV) terms:

$$LCC = PV(IC) + PV(O\&MC) + PV(RC)$$

IC - Initial Cost - this cost includes all the potential costs of a system before it was put into operation. It may include designing, planning, construction, acquisition, supply, assembly costs, etc.

O&MC - Operational and Maintenance Costs – these costs are all the potential costs of a system after it was put into operation. It may include energy costs, spare parts and labor required for maintenance – whether scheduled or due to failures, and in general all costs that appear from the first service date of the system and until its end of service life.

RC - Replacement cost - in this work it's assumed that the replacement and demolition cost of a technology are equal to its initial cost. The only exception is land cost for the implementation of community integrated Renewable Energy Systems (RES) (if any). This cost will be excluded from the replacement cost because it's charged only once when initially purchased.

There are three types of **decision variables** in the model:

1. The inclusion or exclusion of a configuration of technologies that are required to support the regulated energy demand of the building. For example – air conditioning units for space heating and cooling with

solar thermal boiler and electric back up for water heating.

2. The number of units of a building integrated system for renewable energy production of a certain type. For example - small scale wind turbines.
3. The number of units of a community integrated system for renewable energy production. For example – PV installation on a parking lot's rooftop.

The objective function is subject to the following **constraints**:

1. The inclusion of one configuration of HVAC & water heating technologies in the optimal solution, to support the regulated energy demand of the building.
2. The rate of the annual regulated energy consumption of the building that must be supplied from renewable sources.
3. The available area on the rooftop of the building for effective installations of BI RES, which is changing per required energy type, i.e. solar, wind, etc.
4. The available area on the rooftop of the building for all BI RES installations.
5. The maximal allowed size of a single community energy center. It's assumed that community energy centers are integrated within the communities, therefore it can't be too big in order to fit in both functionally and esthetically. The maximum allowed area is changing according to the urban density of the community.
6. The total area of all community energy centers. The available area changes according to the urban density of the community.

The model can be easily adjusted and be subject to additional constraints according to local regulation or design decisions, e.g. capacity constraints, maximal initial cost, etc.

The **implementation** of the model was in Microsoft Excel software, using the Solver add-in. The model is partially nonlinear, yet smooth, both in the objective function and the constraints. Moreover, all the decision variables are Integers and Booleans, therefore the GRG (Generalized Reduced Gradient) Nonlinear Programming solving method was applied. The GRG Nonlinear method examines the gradient of the objective function as the values of the decision variables change. The method determines that an optimum solution is found when the partial derivatives are equal to zero. The disadvantage of this method is that it's highly dependent on the initial conditions and a locally optimum solution may be found instead of global optimum. To decrease the probability of this happening, a "Multistart" option was used in this study. With this option, the algorithm creates a random population of initial values that are evaluated using the GRG Nonlinear algorithm. The "Multistart" option highly increases the chance of finding a globally optimum solution (Young, 2018).

In this study, it is assumed that urban density has an impact on the following parameters:

1. The available area for establishment of energy centers at a community level.
2. The maximal area of a single energy center.
3. The cost of land for establishment of energy centers at a community level.

A sensitivity analysis was carried out to examine the implications of variations in certain parameters (such as the available area for energy centers, the cost of land for those centers, etc.) on the LCC. However, the possible implications of future technologies and of changes in the market over time were not analyzed and are suggested as topics for further research.

Application of the model

In order to apply the model with a realistic input, data was used from two case studies that are being constructed in the framework of the “Zero Plus” project – one in Cyprus and the other in France. Zero Plus is an EU-funded project aiming to develop a comprehensive, cost-effective system for NZE communities and to implement it in a series of case studies across the EU. In order to give this research a wider perspective, the two case studies that were chosen to provide data for the model have different characteristics, and are located in different countries and climates. The assessment of the energy consumption of the buildings and of the production potential of RES incorporated in the communities is based on simulations performed with EnergyPlus software in the framework of the Zero Plus project.

The generic model that was developed is applied to optimize the technological design of the communities while changing their urban density and scale artificially. The case studies, which in reality include the construction of a limited number of buildings, were thus used as a starting point to examine the implications of an implementation of the NZE approach at a much larger scale. In order to extend the variety of technologies available for incorporation in the communities, and to reflect the impact of changes in density and scale on the cost and performance of the technologies, some of the data was collected from the literature and official reports.

Cypriot case study

The first case study that was selected is situated on the outskirts of the village of Peyia, near Paphos in the south-west region of Cyprus. The building that is considered in this case study is a high-end single-dwelling villa that is being constructed in the framework of Zero Plus Project. Cyprus has a Mediterranean climate with very mild winters and hot summers. The average annual temperature on the coast is around 24 °C during the day and 14 °C at night. Warm temperature season lasts from April to November. In the remaining period, the temperatures tend to remain mild. The scale of the Cypriot community analyzed with the model varied from 1 to 50 single-dwelling buildings.

In all the examined variations in terms of scale and density, the optimal combination of technologies identified with the model includes the following technologies:

- Built-in unitary split air conditioning units of 3.5 kW size with heat pump version for heating and cooling.
- A solar water heating system for sanitary hot water production comprising of a 300 liters cylinder tank and 3 solar panels, with a 3kW electric back-up heater, installed on the roof of the building.
- A PV system implemented at a building and/or community level with an average capacity of 12.75kWp per building.

All the energy consumption of the community is covered by renewable energy sources, which makes the community Net Zero Energy. However, the split between the energy produced at a building and at a community level is affected by changes in density and scale, and has a significant impact on the costs of the technologies. As the community scale (no. of buildings) and the available area for community-level energy centers increases, so does the percentage of energy produced by community integrated RES. An increase in the energy generated by the community integrated RES in turn corresponds to a lower cost in terms of LCC/m² (i.e. the LCC of the community divided by the net area size of the case study).

The main results in Figure 1 show that the enlargement of the available area for community-level energy centers causes an increase in the percentage of energy produced by community integrated RES, and a decrease in the LCC/m² of the technologies of up to 15%. Moreover, the enlargement of the available area for community energy centers increases the rate at which a significant reduction of LCC/m² is achieved for the first time. The results are explained by the assumption that community integrated technologies are more cost efficient than building-integrated technologies since they share many components such as the inverter, cabling, etc. In general, the cost of PV systems decreases by 27% in larger installations (of 10kW-2MW) compared with a residential system in the range of 3-10kW (Fu et al. 2016).

The larger the area that is available for community energy centers in the community, the more community integrated systems are installed instead of BI systems, and a lower LCC/m² is achieved. However, the LCC/m² reduction is limited. The lowest LCC/m² is achieved when the value of the “available area” parameter is 75% (this parameter is measured using a proxy, in this case 75% of the buildings’ rooftops area in the community). The enlargement of the value to 100% has no further impact since the percentage of energy produced by community integrated RES has already reached its maximal possible value of 95%. The remaining 5% are produced by building-integrated solar water heating system and used for sanitary water needs. Further increase of energy production is cost inefficient due to the net metering tariff.

As presented in Figure 1, a significant LCC/m² reduction is achieved at a community scale at which the first energy center reaches its full possible capacity. The reason for this phenomenon is the assumption that the cost of RES per unit is decreasing as the total capacity of the installation is

increasing. The assumption is valid for each installation by itself, which is in this case – each energy center. Further increase of scale requires the establishment of a new energy center – basically a duplication of the achieved

technological design. The RES installed in the new energy center won't benefit from the reduced costs achieved in the existing energy center.

Figure 1: Cypriot Case Study, LCC/m² as function of community scale and the available area for community energy centers

Therefore, the establishment of a new energy center causes a slight increase in the overall cost of RES. This cost eventually decreases to the same level or to a slightly lower level when the new center reaches its full capacity as well. This cyclic effect continues as the scale of the community further increases. Although the highest LCC/m² reduction is achieved at bigger community scales, it's only slightly higher than the already achieved reduction at the scale of one full energy center.

Based on these results, both community density and scale have an impact on the LCC/m² of technologies implemented in NZE communities. The scale of the community has a significant impact on the reduction of LCC/m², but only up to the point at which the first community-integrated energy center reaches its full capacity. Further increase of community scale only have a minor impact and don't lead to a significantly further LCC/m² reduction. Lower density has a positive impact on the LCC/m² of technologies. The parameter which constrains the maximal rate of energy produced at a community level is the available area for community integrated RES. The LCC/m² reduction is achieved by the reduced costs of RES integrated at a community level.

French case study

The second case study chosen for this study is located in Voreppe, a city 15 km North-West of Grenoble, France. The building in this case study is an apartment building, with a total net area of 1005 m², and containing 18 dwellings. The climate in Grenoble is warm and temperate, and defined as 'Oceanic' according to the Koppen-Geiger climate classification. The temperatures

are highest in July with an average of 20.2 °C and a peak of around 26.4 °C, and lowest in January with an average of 1.7 °C and a peak of around -2.2 °C (CLIMATE-DATA.ORG, n.d.). The scale of the French community that was examined varied from 1 to 28 buildings (i.e. a range of 18-504 dwellings).

In all examined scale and density variations, the optimal combination of technologies identified with the model includes the following technologies:

- Low temperature radiators in each room, which are fed by hot water using the building's hot water distribution system
- A water heating boiler based on bio fuel - wood pallets - integrated at a building or community level.
- A community heat distribution system when a district heating is considered.
- A PV system implemented at a building and/or a community level.

In all cases, the renewable energy production of the heating boiler(s) covers the regulated energy consumption of the community. The difference between the optimal combination of technologies in the various options of density and scale is the level of implementation (building/community) of the heating boiler(s) and the PV systems. As the density and scale of the community increase, the bigger the boiler and the denser the heat distribution system that combine the district heating center, and consequently – the lower its cost.

Figure 2: French Case Study, LCC/m² as function of community scale and density characteristics

As described in Figure 2, the LCC/m² of the technologies in a high ‘inner city’ density at the scale of 5 buildings or lower is significantly higher than in the other two densities. This is explained by the following points:

1. A district heating system is available at a capacity of 0.5MW and higher, i.e. at least 4 of the buildings that considered in this study. Therefore, the design at the scale of 3 buildings or lower includes only building-integrated boilers, which are less cost efficient than district heating.
2. In an ‘inner city’ density, there is no available area for community-integrated PV systems except on the rooftop of the heating center, which causes an increased LCC/m² costs of the PV systems vs. the two other density options.

However, once the community scale increases above 5 buildings the LCC/m² is higher in lower densities, and ‘inner city’ density is LCC/m² optimal option out of the three examined. This result is explained by the following:

1. Unlike in the Cypriot case study, in the French case study all the regulated energy, which stands for ~71% out of the total energy consumption, is produced by the heating system. The PV systems are producing only ~29% of the total produced renewable energy. Therefore, the heating system has a bigger impact on the LCC/m² of the technologies than the PV systems.
2. A district heating system includes a heat distribution system and a heat production boiler. As previously described, the heat distribution system is more cost efficient in a denser environment due to lower capital and heat distribution costs. At the same time, the cost of a heating boiler is decreasing in higher capacities.

Therefore, in higher densities, a district heating system which includes a heat distribution system is more cost efficient than in low densities, which causes an earlier adoption of such system. As more buildings are connected to the system, the costs of the boiler decrease. Therefore, the inclusion of district heating in the optimal design in higher densities occurs in smaller community scales, and the costs keep decreasing as the scale increases. The cost efficiency achieved by the heating system overcomes the

low amount of area available for the establishment of community level PV centers. Moreover, some PV centers can be installed on the rooftop of the heating center as previously described, and partially overcome this constraint.

Once the district heating is included in the design, the LCC/m² of the technologies decreases as scale grows, and reaches its minimum at the scale of 14 buildings. As the community scale grows further, the LCC/m² of the technologies first increases and then decreases again. The reason is similar to the described phenomenon in the Cypriot case study. A scale of 14 buildings requires the establishment of a heating center with a wood pellet boiler at a nearly full capacity of 2MWp, the capacity at which the maximal cost reduction is achieved. Further increase in scale requires the establishment of a new heating center, which is basically a duplication of the achieved technological design. The new heating center won’t benefit from the achieved reduced costs of the existing heating center. Therefore, the establishment of a new energy center causes an increase in the overall cost of RES, which eventually reaches the same or slightly lower level when the new center reaches its full capacity as well. This cyclic effect continues as community scale grows further.

Based on the achieved results, the scale of the community has a significant impact on the reduction of LCC/m² only up to the point at which the first district heating center reaches its full capacity. Further increase of community scale doesn’t provide further significant LCC/m² reduction. The LCC/m² reduction is achieved by the reduced costs of RES integrated at a community level, in particular the district heating system. This result is in line with the results from the Cypriot case study. It’s noteworthy that the increase of community scale above the examined levels in this study would probably result in further LCC/m² reduction, due to the integration of high capacity wood chips heating boiler in a district heating center. However, the increasing and then decreasing LCC/m² phenomenon would occur at this scale as well, and its technological design would be duplicated, just like in smaller scales examined in this study. As opposed to the results from the Cypriot case study, higher density has a

positive impact on the LCC/m² of technologies at community scales of 6 buildings and higher in the French case study, due to the cost efficiency of the heat distribution system in higher urban densities.

Conclusions

The results show that both urban density and scale have a direct impact on the LCC/m² of the technologies implemented in NZECs. The LCC/m² reduction was achieved through the reduced costs of RES integrated at a community level.

As observed in both case studies, the enlargement of community scale causes a decrease in the LCC/m² of the technologies. However, the scale has a significant impact on the LCC/m² only up to a certain point. The most significant reduction in LCC/m² of the technologies is achieved at a scale at which the first feasible energy center reaches its full possible capacity. Although the lowest LCC/m² is achieved at bigger community scales, it's only slightly lower than the already achieved cost at the scale of one full energy center. The reason for this phenomenon is the assumption that the cost of RES per unit or kWp is decreasing as the total capacity of the installation is increasing. The assumption is valid for each installation by itself, which is in this case – each energy center. Further increase of scale requires the establishment of a new energy center, or in other words, a duplication of the achieved technological design. The RES installed in the new energy center doesn't benefit from the reduced costs achieved in the existing energy center. Therefore, the establishment of a new energy center causes a slight increase in the overall cost of RES, which eventually reach the same or slightly lower level when the new center reaches its full capacity as well. This cyclic effect continues as community scale grows further.

Considering the above, we suggest that the increase in community scale causes a decrease in the LCC/m² of the implemented technologies, however, the cost reduction is highly constrained by the size of the largest energy center of the community.

Unlike the scale of the community, urban density had an opposite impact on the LCC/m² of the technologies in the two case studies. While in the Cypriot case study lower density caused a reduction in the LCC/m² of the technologies, in the French case study the reduction was achieved as urban density increased. The difference is related to the local climate and the required energy to supply the HVAC & WH demand of the communities. The community in the Cypriot case study is located in a warm climate, and all of its energy requirements can be supplied by electricity. Therefore, 95% of the energy in this case study was supplied by PV systems, whose installations are known to require space. Consequently, as density decreased, more and bigger community-integrated PV centers could be installed, which resulted in lower costs. The parameter of the available area for community-integrated RES had an impact not only on the absolute value of the LCC/m² reduction, but also on the rate (in terms of community scale growth) at which this reduction

was achieved. It's noteworthy that the impact of density is limited by the following constraints:

1. Energy production regulations, which make over-production cost inefficient, as showed in the results of this study.
2. The assumption that very low urban density with very big energy centers would require intensive investments in the local electrical grid, which would negatively balance the cost reduction.

Unlike the Cypriot case study, the French case study is located in a colder climate, and all of its regulated energy is supplied by a heating system. As described earlier in this work:

1. The cost of heat distribution has a significant impact on the overall cost of the technologies in this case study
2. Heat distribution cost is decreasing as urban density is increasing
3. It's assumed that the heat production centers are located on the outskirts of the settlement and aren't constrained by lack of land in high densities

Therefore, the increased urban density of the French case study resulted in lower LCC/m² of the technologies. It's noteworthy that we assume that the positive impact of high density is limited due to the fact that:

- The design and construction of a heat distribution infrastructure in very high densities is physically complicated and capital intensive
- The lack of space may affect the effectiveness of other required technologies

Considering the above, we suggest that the impact of urban density on the LCC/m² of the technologies depends on the local climate and the energy types required to meet the regulated energy demand of the community. Low urban density has a positive impact on the LCC/m² in communities with electricity-based demand, while high urban density has a positive impact in communities with heat-based demand. In both cases, the effect of urban density on the LCC/m² of the technologies is limited due to renewable energy production regulations and energy distribution limitations.

The current workflow of urban planning, in which the technological design is performed only after the urban density, the unbuilt areas and the types of the buildings are already set, is constraining the type of the technologies that can be implemented and the energetic and financial efficiency that can be achieved. Following the presented results of density and scale implications on the LCC/m² of the technologies, we suggest that the consideration of the technological design is critical in the first stage of urban planning of energy efficient communities. The consideration of the technological design before the urban density, the unbuilt areas and the building types are set will contribute to a better definition of these parameters and assist to achieve better energetic and financial efficiency of Net or nearly Zero Energy Communities.

This is a first attempt to study the economic implications for urban planning of an implementation of the NZE approach at a settlement level. Further research is needed to gain a better understanding of this topic. Such research could include a relaxation of the assumptions that were made in this research, such as the uniform distribution of buildings, and the equal capacity of energy centers. Additional building types, locations and climates could also be considered.

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OPTEEMAL: IT-SUPPORTED DESIGN TOOL FOR THE GENERATION OF OPTIMISED ENERGY RETROFITTING SCENARIOS AT DISTRICT LEVEL

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Abstract

The EU strategies to reduce the carbon emissions highlight the importance of renovating the existing building stock as one of the major contributing sectors to these undesired emissions to the atmosphere. The existing practices to design energy efficient retrofitting projects are still too time consuming, unprecise and provoke, therefore, a lack of trust within the sector; especially to investors. There is a need to improve these practices through reducing the errors and the time required to evaluate retrofitting alternatives in order to select those most appropriate according to the stakeholders' priorities. In order to give an answer to this challenge, the EU funded project OptEEmAL has designed and deployed an integrated platform that delivers automatically some of the steps that belong to this process reducing thus time, errors and therefore costs, which will lead to increasing efficiency and creating confidence among the stakeholders.

Introduction

The design of energy efficient retrofitting projects poses an elevated number of challenges when evaluating candidate retrofitting alternatives. Apart from the fragmentation of the retrofitting sector, with several stakeholders with different and sometimes conflicting interests, from the technical perspective the selection of indicators, generation of candidate retrofitting scenarios or the related simulation models are sometimes too time consuming and prone to human errors (Berkeley, et al., 2015). These problems, that are evident at building level, grow exponentially when tackling greater scales, as the district level, where new interactions and flows appear, as well as new potential technologies to be implemented.

Acknowledging all these issues, the OptEEmAL project has designed and developed a platform that implements a number of processes to support the design of energy efficient retrofitting projects at district scale (García-Fuentes, et al., 2016). The main functionalities offered by the platform are the integration of data and generation of baseline data models, the simulation of the baseline conditions, the

generation of candidate retrofitting scenarios as a combination of Energy Conservation Measures (ECMs) – modelled and integrated within a digital catalogue –, and their evaluation and optimization against a set of District Performance Indicators (DPIs) that are weighted considering the users' preferences and conditions.

All these functionalities are delivered by a set of modules that have been deployed and connected through the appropriate interfaces to ensure the communication among them. With a distributed architecture, the OptEEmAL platform is able to interact with the users through a set of user-friendly Graphical Interfaces and to perform the steps that belong to the process of designing energy-efficient retrofitting projects. Thus, through delivering automatically processes that are manually performed in the Business-as-usual, this platform helps reducing errors, time and therefore costs to the stakeholders.

This paper presents the architecture of the OptEEmAL platform, describing its high-level architecture, functional modules and the testing activities that have been performed to ensure its functioning.

High-level architecture

Taking into account the main objective of the OptEEmAL solution, this section details a high-level overview of the specific functionality expected for all the key components associated with the OptEEmAL architecture. This architecture assumes a three-layer structure, i.e. the Data Layer, the Business Logic Layer and the Application Layer, which altogether offer a holistic service-oriented platform able to integrate interoperable modules/tools to generate optimized district retrofitting scenarios. On the other hand, the framework presented in this paper reinforces the commitment of all the involved stakeholders through an Integrated Project Delivery (IPD) approach in a collaborative and value-based process towards obtaining the most sustainable and efficient retrofitting solution for a refurbishment project.

In order to properly collect all these needs, a deeper analysis of the platform requirements is fundamental

as the starting point to the design of the OptEEmAL architecture.

On the other hand, when interoperability is required in the definition of ICT solutions, it can be reached by making use of existing technologies and standards (well-known and well-established communication protocols, data models and interfaces standard definitions). In the context of the OptEEmAL solution the interoperability requirement is desirable taking into account that the OptEEmAL system needs to be interconnected to different internal and external services, data sources and tools. A common data representation, in the form of a District Data Model (DDM), is also needed to obtain a common way of interacting among all these different elements. All these needs are presented in the following subsections.

Analysis of functional requirements

The OptEEmAL solution aims to develop an optimized energy efficient design platform for refurbishment at a district level, which delivers an optimized, integrated and systemic design based on an Integrated Project Delivery approach for building and district retrofitting projects, reducing time delivery and uncertainties, resulting in improved solutions when compared to business-as-usual practices.

To be able to reach the previous objective, the OptEEmAL platform requires to integrate five main pillars:

1. An IPD-based retrofitting design approach, to facilitate communication, knowledge sharing and consensus among interested stakeholders as the Owner, Primer Designer or Prime Constructor
2. A BIM-based information exchange approach to enhance collaboration between stakeholders and improve information flows within the design process.
3. A catalogue of Energy Conservation Measures (ECMs) considering scale of implementation and providing all the needed data for the evaluation of the design alternatives.
4. A Multi-Criteria Decision Analysis (MCDA) approach for decision making integrating the interest of the stakeholders and making use of well-established indicators at different scales.
5. A semantic data model and data mapping process to ensure interoperability among the platform components and consistency of communications.

These five essential pillars have been covered in the OptEEmAL project in different work packages, identifying in each of them the main requirements for the indicated functionalities (OptEEmAL Consortium, 2016-D5.1).

From the **end-user** point of view, a set of requirements has been collected related to the input data process to evaluate users' objectives and initial conditions (OptEEmAL Consortium, 2016-D1.2) (OptEEmAL

Consortium, 2016-D1.3). In that sense data needed to build the baseline model of the district and to compare district retrofit scenarios is required by the platform. To address the multiple objectives of the project, this data comes in four different forms: BIM models and CityGML models representing the district, contextual data (climate, energy prices, socio-economic data, etc.), and configuration data.

From the **data representation** point of view, requirements have been identified for the definition of the ontology used to generate the OptEEmAL District Data Model (OptEEmAL Consortium, 2016-D2.1). The DDM has to integrate all the data required to perform a refurbishment analysis of buildings within a district, including building data, district data, contextual data, District Performance Indicators (DPIs), intermediate results and targets, barriers and boundaries delimiting the project assessment.

Related to the **ECM catalogue**, a set of requirements have been defined (OptEEmAL Consortium, 2016-D3.1) to determine the kind of information the catalogue has to contain to feed properly the different steps of a project elaboration, the way the ECMs have to be store into the catalogue, and in which moments the catalogue is going to be queried to provide information to the modules/services of the OptEEmAL solution.

In the case of the **optimization process**, the specification of a set of parameters that adequately represent the refurbishment plan, the barriers and boundaries and the stakeholders' priorities with the aim to define the optimum scenarios have been established (OptEEmAL Consortium, 2016-D4.1).

From a **simulation** point of view, the tools and methodologies to evaluate the DPIs required by the process implemented in the OptEEmAL platform towards the identification of the best retrofitting scenarios according to stakeholders' priorities for each design project have been investigated (OptEEmAL Consortium, 2016-D4.4). As result, a set of requirements have been identified to guide the design of the OptEEmAL DPI calculation element of the platform, divided into two parts, building- and district-level calculation methodologies.

Finally, and in order to complete the analysis of requirements more related to the whole platform, different aspects have been analysed more deeply, comprising functional requirements and non-functional requirements such as performance, security, human-machine interaction, systems management (configuration and interoperability) and data management.

The translation of all these requirements into a set of Use Cases has been necessary to define the high-level architecture of the OptEEmAL solution presented in the following subsection.

High-level architecture of the OptEEmAL solution

With the aim of fulfilling the requirements and functionality expected for the whole OptEEmAL system, a three layer architecture is envisaged in Figure 1 (OptEEmAL Consortium, 2016-D5.2).

The **Application Layer** works as point of interaction between the OptEEmAL platform and the user. It is used for data insertion, showing results and providing outputs, as well as for other interactions (checking results, checking progress of the processes, etc.).

Figure 1: High-level architecture of the OptEEmAL platform

The **Business Logic Layer** contains the modules with major functionalities of the platform as the Data Insertion Module, the Data Management Module, the Simulation Module, the Optimisation Module and the Data Exportation Module. Moreover this layer contains the Communication Logic Layer that acts as the link of the different modules of the platform since it enables the communication between the Data Layer and the Services Layer.

Finally, the **Data Layer** represents the OptEEmAL Data Repository which is composed by five different repositories: the BIM, CityGML, Context, Project and ECM repositories. The Context, BIM and CityGML repositories store information about the districts to refurbish. On the other hand, the Project repository has information about the refurbishment projects (such as platform users and user's inputs, e.g., barriers, targets, boundaries, prioritisation criteria) and data generated within the platform such as District Performance Indicators, scenarios and simulation models (Energy, Economical, Environmental...) automatically generated. The ECM repository contains the Energy Conservation Measures (ECMs) used to generate the refurbishment scenarios to be optimized by the OptEEmAL platform, and also contains information about these ECMs to be exported in the final step.

In order to work properly, the OptEEmAL platform also needs to interoperate with other **external and existing services and tools** needed to support and

enhance part of the expected functionality to be offered mainly by the simulation module. These external tools comprise:

- **EnergyPlus:** It is an energy analysis and thermal load simulation program. Based on a user's description of a building from the perspective of the building's physical make-up, associated mechanical systems, etc., EnergyPlus is able to calculate the heating and cooling loads necessary to maintain thermal control set-points, conditions throughout an secondary HVAC system and coil loads, and the energy consumption of primary plant equipment as well as many other simulation details that are necessary to verify that the simulation is performing as the actual building would.
- **NEST:** for life-cycle and social District Performance Indicators calculation. NEST is a plug-in for Sketch-Up. It allows, from 3D modelling of the area, impact assessment and comparison of development scenarios.
- **Matlab Runtime Compiler:** MATLAB Runtime Compiler lets developers to share MATLAB scripts into standalone applications. Using this solution, it is possible to package M-Files as Java libraries used by the DPI computation process. The M-Files are organized into Java classes and each MATLAB function is provided as Java method.
- **Terrain data access:** in order to provide the user with a user-friendly view of the district, it is shown the terrain geometry mapped with satellite images around the district location. These data are obtained from open source third party services such as ASTER DEM and SRTM for the terrain geometry, and from OpenStreetMap and/or similar satellite imaging services for the satellite images.

Other ad-hoc implementations have been developed to cover the calculation of specific DPIs, as for example the **ECO tool**, for the calculation of economic indicators, and the **HVAC tool** for the simulation of the active elements of the building/district.

District Data Model for data representation

As it was mentioned previously, the interoperability of an IT solution is gained by using well-known communication procedures, common data models and standardized interfaces definitions. In the case of the data models, OptEEmAL uses the **District Data Model** (DDM) as a means to represent, in a common manner, all the input data of the platform (BIM/GIS models, contextual data, inputs from the users, etc.), ensuring the interoperability and understanding in their exchange among modules, components, services and external tools. Therefore, the DDM contains the data resulting from the recovery, integration and transformation of the input data. These data are

provided at each stage of the processes managed by the platform in the required representation.

In (OptEEmAL Consortium, 2016-D2.1), the DDM was described as an ontologies-based framework for district information representation. The DDM enables the intertwining of standardized data models (e.g., CityGML, IFC) with ontologies in domains related to building energy efficiency at the district level (energy, social, environment, comfort, urban morphology and economic). To be able to represent the data of all these domains, the DDM provides a semantically integrated data model including data about geometry, materials, equipment, and indicators, at the building and urban scales) that the platform needs to carry out the calculation of the optimized retrofitting scenarios.

More specifically, the data included in the DDM are represented according to the following six ontologies:

- **Urban Data Model.** This model represents the data about the relations between buildings, weather data, placement, population, total surface of buildings and relations to other data models (e.g. to which district energy system is a building connected).
- **Building Energy Data Model.** This model represents the data necessary to carry out energy simulations of buildings. It includes the geometry of the building, material properties, building energy systems, etc.
- **District Energy Data Model.** This model represents the data necessary to carry out energy simulations at district level. Basically, it includes the data of active systems.
- **Energy Carrier Data Model.** This model represents the data of energy carriers that can be selected for a project. Basically, it includes energy carrier costs.
- **Social Data Model.** This model represents the social data of a district. It includes number of inhabitants and their income.
- **ECM Data Model.** This model represents the data about the Energy Conservation Measures at building or district scale.

While the District Data Model assures the interoperability between the various data sources (BIM and GIS models, and contextual information), represented in different formats (IFC, CityGML), and a set of external tools used to perform building simulations, the **Data Management Module (DMM)** includes the necessary components to carry out the different stages required to transform and integrate the data to generate the District Data Model.

The DDM Manager, one of the two software components implemented in the Data Management Module, provides the necessary functionalities to carry out the corresponding data transformation and integration processes. These two processes are

identified as ETL1 and ETL2. The ETL1 process transform the input data models (e.g., IFC, CityGML) into semantic data models (RDF models), represented according to different data schemas (e.g., ifcOWL ontology). The ETL2 process integrates the data resulting from the ETL1 process where semantic data models are transformed into Simulation Data Models (e.g., RDF models represented according to the OWL version of the SimModel data schema).

Finally, the Simulation Module (represented in Figure 1) invokes the model input file generator process to create instances of simulation models from the Simulation Data Models obtained in the ETL2 process. An instance of simulation model is a set of data that fulfils the input data requirements of a specific simulation tool (e.g., EnergyPlus requires the input data in IDF format).

Platform design, implementation and deployment

In the platform design stage, the high-level architecture has been taken into account and the modules have been finely described, explaining their main **components** with the functionalities related and the **processes schemes** that identify the workflow following in the platform and also the information interchanged between the components (OptEEmAL Consortium, 2016-D5.2).

Once the platform has been designed the next steps are the implementation and the deployment of the platform. All these steps are explained in the following subsections.

Component diagrams and processes schemes

According to the workflow generated as part of the requirements definition, the functionality of the platform can be divided into three main processes:

1. Data insertion and diagnosis process
2. Scenarios generation and optimisation process
3. Data exportation process

Each one of these processes involved a set of modules. The processes schemes show the different components that constitute each module and the relationship between these components. They are explained below.

Data insertion and diagnosis process

This process, represented in Figure 2, provides as an output all the data needed to be introduced into the Optimisation Module. To this end, through the data insertion module, the user is able to introduce all the required data (**input data connector** component), which is checked (**data checker** component) and complemented with information coming from external geo-clustering services (**geo-connector** component). All these data are stored in the corresponding repositories through the corresponding connector of the communication logic layer.

Figure 2: Data insertion and diagnosis process scheme

Once the information is stored in the repository, the Data Management Module (presented in the section District Data Model for data representation) maps the information in order to create one instance of the baseline scenario. The simulation data models generated by the **data integration** component is stored in the project repository.

This information is retrieved later by the Simulation Module (simulation module input generator component), which will be in charge of configuring the simulation files and launching the simulation tools (private Cluster Computing component). With the result of this process the DPI calculation component calculates diagnosis DPIs, which are stored in the project repository.

The last step inside this process requires user interaction to validate the generated information. The results from the DPIs are extracted from the project repository and shown to the user along with the other information of the baseline scenario (data insertion module), who, taking into account these results, could reconsider the choices they have made with regards to their objectives. With these new list of targets, boundaries and barriers (or the same if the user has not changed their mind) the ECM catalogue is queried to provide the user with the list of applicable ECMs filtered according to their objectives. Through a specific GUI the user could discard the ECMs that they do not want to apply in their district or edit the applicable ones proposed by the platform (**strategies checker** component). This information will configure the optimiser input data to be used in the next process.

Scenarios generation and optimisation process

This process (see Figure 3) represents the core element of the platform, where scenarios are generated from different combinations of ECMs and the DPIs are calculated by launching simulations with external tools. These results are evaluated to be able to have as an outcome a series of optimised scenarios and the data generated along this process (García-Fuentes, et al., 2018) (Hernández, et al., 2017).

Optimiser input data generated in the previous process is introduced in the Optimisation Module (**scenario generator** component), which is in charge of generating scenarios by means of combining the applicable ECMs in the retrofitting project with a certain intelligence. It has as result a codification which generates a scenario vector that is mapped in the Data Management Module (**data integration – instance creator** component). This scenario vector is fed to this component with information coming from the ECMs data base to configure the simulation data models.

Once the simulation data models have been created the Simulation Module (**simulation module input generator** component), will launch the simulation tools (**private Cluster Computing** component) and the **DPIs calculation** component in order to calculate the simulation DPIs which will be directed to the data management module to be stored in the project repository.

Once the DPIs are stored, these can be retrieved by the Optimisation Module (**evaluator** component) in order to have one single, understandable and easy-to-handle

Figure 3: Scenarios generation and optimisation process scheme

value or grade for each scenario to be ranked in by the Optimisation Module. With the result of the objective function, the Optimisation Module (**optimisation algorithm** component) will either generate more combination rules and will continue the iterative process or the stopping criteria will be met and the optimiser output data will be generated and stored in OptEEmAL repositories.

Data exportation process

The last stage carried out in the platform is the data exportation process (see Figure 4), where the main objective is to process the information generated in the previous stage in order to generate exportable information that is relevant for the user to execute their retrofitting project.

Figure 4: Data exportation process scheme

The process starts in the Data Exportation Module, where the user can visualise through a GUI the ranking of scenarios generated in the optimisation process. Afterwards, through a different GUI and another

component (**scenario selector** component) they are able to select their desired scenario.

This selection will launch the **export data configurator** component (inside the data management module) which will be connected to the different repositories to extract the necessary information to be exported that has been indicated by the user. These data will be processed through several components (**IFC serializer**, **CityGML serializer** in the Data Management Module and **Text exporter** and **Charts exporter** in the Data Exportation Module) to end up in the **data exporter** component which will in the end enable the user to export the files with the information: IFC, CityGML and XLS.

Implementation and deployment

The OptEEmAL platform is composed by different modules and components described in the previous sections. In order to carry out their functionalities the modules need to communicate among them and with external tools and services. The module dependencies have been analysed and the logical interfaces between modules have been defined. It is important to highlight that the modules and the repositories of the platform have been developed by different companies, so the definition and development of the interfaces were essential steps in the implementation of the platform.

Red Hat JBoss Fuse has been used as an Enterprise Service Bus (OptEEmAL Consortium, 2018-D5.3), which role into the OptEEmAL platform is to synchronize different and asynchronous modules deployed on several environments and to have a base

control of it. This is an open source integration framework based on Apache Camel and it is a distributed integration platform that allows the integration of services, microservices and application components. This allows us to delocalize the different modules and repositories of the platform.

Figure 5: Deployment physical scheme

From a deployment point of view, Figure 5 shows the physical distribution of the different modules and repositories. As it is shown in the figure, the different modules and repositories are geographically distributed in three different premises and locations. In that sense, security and reliability in the communications is needed and guaranteed by the Enterprise Service Bus.

The repositories can be accessed through APIs in a remote way. Besides queues are used in order to send files that are too large to be managed by the APIs.

Graphical User Interfaces

For the OptEEmAL platform, the Graphical User Interface (GUI) is a web/browser-based solution that facilitates the human-machine interface with the functionality offered by the design tool. The canvas interface is a web site based on HTML5 and supported by a WebGL-based 3D visualization environment.

The GUI is composed of different components:

- **User data input module:** responsible of collecting data inputs from the users, for example: the login information, project data such as project name, description, CityGML and IFC files that will be used in the optimization phase.
- **2D visualization module:** this module will provide the user with all necessary data and interactive graphical interface such as web page in the forms of texts, charts, tables or similar representations.
- **3D visualization module:** a 3D representation of the district and buildings will be shown in this module.
- **Data communications module:** this module is responsible for data transport between the 2D and 3D visualization modules.
- **3rd party Digital Elevation Map service communications module:** this module acts as

an interface that obtains from third-party services the information required by the 3D visualization module to visualize the terrain geometry around the district.

- **3rd party Satellite Imagery communications module:** this module will act as an interface between the 3D visualization module and the third-party satellite imaging services to obtain the district satellite images that will be shown on top of the terrain geometry.
- **Unstructured Data Connector module:** in this module the users can search in the web for useful information related to the district to support the evaluation of the current scenario and its objective setting.

Navigation scheme

In this subsection, the navigation scheme followed by the OptEEmAL GUI is presented in 15 different steps. Figure 6 shows the site map of the OptEEmAL platform (*OptEEmAL Consortium, 2016-D5.2*).

Figure 6: Site map of the OptEEmAL GUI as a web site

The first page shown in the platform is the Visitor Overview with the login page for the platform users. From this point the end-user interaction in the GUI is required in the next steps:

1. Create new project
2. Create new IPD Group
3. Insert CityGML and IFC files
4. CityGML-BIM Matching
5. Baseline Energy Systems
6. Insert contextual Data
7. Energy Conservation Measures
8. Check Strategies
9. Baseline Performance
10. Insert Targets and Boundaries
11. Prioritization Criteria
12. Problem Summary
13. Optimisation Process
14. Select optimal scenario
15. Configure and export data

The data inserted by the users are checked for integrity and correctness by the system with a specific checking tool developed. This tool has 3 different checking operations: Consistency check (IFC4 schema compatibility), Completeness check (the required input data for the Building Energy Performance Simulation model by checking rules) and Correctness check (geometric error detection) (Lilis, et al., 2018). After all the information required by the system is collected and verified, the necessary processes are launched to obtain the initial performance of the district. The results of the calculations are presented to the users which can modify the targets, boundaries, barriers and prioritization criteria taking into account the results of the baseline district evaluation. After ECMs are shown to the users and are then selected or discarded by them, the scenario generation and optimization phase takes place in the platform core. Finally, after the optimization phase is finished, a number of best optimized scenarios for the district are shown to the users to select and export the best scenario for them. The users can go back to the target, boundary and barrier selection phase in order to change or fine tune their choices.

Example of use with a real case: Cuatro de Marzo district in Valladolid (Spain)

The platform has been tested and validated in different case studies or districts and in three different Technology Readiness Levels or TRLs, from TRL5 to TRL7. One of them is *Cuatro de Marzo* district located in Valladolid (Spain), demonstrated for TRL6 (platform prototype demonstration in relevant environment).

Figure 7: View of Cuatro de Marzo district
(Image ©2019 BingMaps)

For *Cuatro de Marzo* case study, five residential buildings (two towers and three individual blocks – see Figure 7) have been tested for the retrofitting project. In this district the information required and uploaded to the platform has been:

- Four IFC models (one IFC per block and one IFC for the two towers) and one CityGML model of the district. Figure 8 shows the interface where the user has to upload and check the models.
- Building Energy Systems related information (with a questionnaire), shown in Figure 9.
- Biomass prices. Figure 10 shows the climate, energy & Socio-Economic data included in the

Contextual Data interface with the biomass price data for this project.

- Targets and boundaries. Figure 11 shows the information completed for the project *Cuatro de Marzo*.
- Prioritisation criteria. Figure 12 shows the options to choose for the Prioritisation Criteria.

Figure 8: Insert CityGML and IFC files interface in the project *Cuatro de Marzo* with the user Data Input Module

Figure 9: 3D representation of the *Cuatro de Marzo* district with the 3D visualization module

Figure 10: Contextual data interface included in the user data input module

After the upload to the platform of all the information required, the optimization process is launched and the Pareto Front, shown in Figure 13, is obtained with the execution of ten iterations and ten scenarios for each iteration. With this case study, a complete validation of the platform prototype is obtained.

Some results related to one of the chosen optimal scenario (Scenario1) are presented in Figure 14 in comparison with the results for the baseline condition of the district.

Figure 11: Targets and boundaries interface.

Figure 12: Prioritisation criteria interface.

Figure 13: Select optimal scenario interface with the Pareto Front obtained in the project Cuatro de Marzo

Energy DPIs		
Name	Scenario 1	Baseline Value
Energy demand	239.75	242.74
Energy demand HEATING	131.11	134.10
Energy demand COOLING	108.64	108.64
Final energy consumption	78.17	141.81
Final energy consumption (thermal)	51.52	90.50
Final energy consumption (thermal - gas)	42.48	90.50
Final energy consumption (thermal - biomass)	9.04	0.00

Figure 14: Energy DPIs for the optimal Scenario1

A deeper analysis of the results obtained for the Cuatro de Marzo district can be done by comparing the

available information of the district coming from the [R2Cities project](#) and the proposal of ECMs provided by the OptEEmAL platform. This comparison is shown in Table 1 .

Comparing the results it is observed that OptEEmAL proposes similar ECMs than those actually implemented in the district. In the case of the OptEEmAL platform, internal roof and external façade insulations are proposed as well as monocrystalline photovoltaic panel connected to the grid instead of solar thermosiphon collectors for Domestic Hot Water (DHW). The total investment for the Scenario 1 would be of 453.592€ according to OptEEmAL calculations.

Table 1: ECMs comparison between actually implemented and proposed by OptEEmAL in Cuatro de Marzo district

Real ECM	ECMs proposed by OptEEmAL	
	Scenario 1	Scenario 2
Roof insulation below top slab (Rockwool 100mm)	Passive Roof Pitched Internal Insulation (Mineral wool 100mm)	Passive Roof Pitched Internal Insulation (Mineral wool 60mm)
Façade External Thermal Insulation Composite system (ETICs) EPS 120mm	Passive Façade External Thermal Composite System (EPS 150mm)	Passive Façade External Thermal Insulation Composite System (EPS 250mm)
Solar thermosiphon collectors for DHW	Monocrystalline photovoltaic panel connected to the grid, 320 W	Monocrystalline photovoltaic panel connected to the grid, 320 W
Efficient condensation low-temperature boiler for heating and support of DHW, 24kW	Condensing natural gas boiler with 24kW of nominal capacity	Condensing diesel boiler with 26kW of nominal capacity

Conclusions

This paper has presented the main objectives of the OptEEmAL platform and how the technical challenges to pursue these objectives have been tackled. Of particular relevance is the approach followed in the platform design, implementation and deployment, where a **SOA-EDA platform** using an Enterprise Service Bus to connect and synchronize different and asynchronous modules has been deployed on several environments. This connection and synchronization would not have been possible without relying on a **District Data Model** based on standards that can assure the interoperability among the modules of the platform. It enables to represent the baseline scenario

and the different enriched models including a combination of Energy Conservation Measures. Moreover, to be able to support the design of energy retrofitting solutions, an important advancement proposed by the OptEEmAL platform is the **automatic generation of scenarios** based on the combination of **Energy Conservation Measures** and the optimization based on previously performed simulations of the behaviour of the district, as well as considering the objectives and barriers defined by the user.

All these requirements have been reflected in this paper in the form of a **high-level architecture** comprising a set of modules, services, external tools and the interfaces among them. The way these elements interact to fulfil the different OptEEmAL functionalities has been reflected in several **processes schemes** representing the three main actions: the data insertion and diagnosis process, scenarios generation and optimization, and the data exportation. Finally, the **Graphical User Interface** for accessing to these functionalities has been presented by showing real results when applying the tool in the *Cuatro de Marzo* district located in Valladolid (Spain).

The combination of all these innovations will allow reducing time, errors and inconsistencies in the design and refurbishment of district retrofitting projects, and thus, lead to increasing efficiency and generating confidence among stakeholders. This will result, as a consequence, in a greater number of retrofits, which will contribute to the reduction of carbon emissions.

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BEMSERVER: AN OPEN SOURCE PLATFORM FOR BUILDING ENERGY PERFORMANCE MANAGEMENT

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Abstract

In the era of new technologies and with the growing need for reliable ecological energy supplies, researchers eyes are diverted towards reducing the energy consumption of buildings which becomes a major concern that requires a variety of actors being involved (e.g., building owners, energy/facility managers, occupants, data scientist), who have different expertise and need to use different tools

This paper introduces BEMServer, an open source Building Energy Management system solution built to ease the integration of data analytic and visualization services into building and energy domain applications. It handles heterogeneous data in a transparent way by providing a clear and unambiguous semantic representation of the modeled resources. To do so, BEMServer integrates the OntoH2G formal ontology at its core. The architecture of BEMServer, the design and use of OntoH2G in the solution, as well as the suitability of BEMServer as a middleware in the H2020 project Hit2Gap are described

Introduction

It is stated that buildings account for more than 40% of the energy consumed worldwide and for more than 30% of the global CO₂ emission, as already shown in [Shaikh et al \(2014\)](#), [Costa et al \(2013\)](#), and the [Commission \(2018\)](#). Reducing energy consumption in buildings is challenging in many respects. First of all, it is necessary to involve all building actors, from experts (energy manager, ESCOs, facility managers) to non-experts (occupants, building owners). Different users need different tools, therefore a building energy management system needs to be modular. Secondly, most of the currently monitored buildings are equipped with a Building Management System (BMS) to collect data from different sources, meters, sensors, actuators, or set points. BMSs are closed system, which are not service oriented, with poor evolution capacities: ex-

tracting and adding values to data stored in BMSs is often a tedious work; communicating with legacy sensors requires handling specific protocols such as BACNet, Modbus, or LonWorks, to mention some. Deploying solutions in various buildings can only be achieved by adopting open standards instead of proprietary technologies. Finally, developers of services need description on the data captured by the monitoring system in order to select those of interest for post-processing or visualization; for buildings which are equipped with hundreds of sensors, the task of energy or facility managers must also be facilitated by attaching a clear and unambiguous semantic to the different data sources.

On one hand, the amount of available information from buildings is dramatically increasing; on the other one, data science has brought novel solutions to add value to such a massive amount of information. Bridging data extraction and data treatment is required to accelerate the deployment of energy applications at a bigger scale. Moreover, all actors must be part of making buildings greener and the situation requires adapting tools to different types of users, while offering interoperability and the capacity of integrating different tools, applications, and protocols, through a semantic data model. To address the aforementioned drawbacks, BEMServer is presented as an open source platform to deploy Building Energy Management Systems (BEMS), with multiple layers of functionalities (see Figure [III](#)), aimed at providing:

- *Data abstraction.* BEMServer integrates a semantic data model to represent the monitored data collected from different sources; it also offers REST APIs to access, manipulate, and visualize those data; thus developers and end users do not need to know how data are collected but only focus on how valuable they are to them; the Semantic layer in Figure [III](#) acts as an abstraction layer;

Figure 1: BEMServer layers of functionalities

- *Services integration and interaction.* BEMServer ensures interaction between services, since results generated by different services can be reused by other external modules; this interaction facilitates a better collaborative work between complex modules (for instance, machine learning based services, energy simulation, front-end applications . . .), and the power of composing services to deliver the best output;
- *Data access control.* To protect confidential and sensible data, BEMServer implements a security layer that ensures a secure connection in a multi-tenant environment: users can only access data on specific buildings, and from specific services, and can perform operations according to the rights conceded.

The paper is structured as follows. We first provide a state of the art of solutions similar to BEMServer, and other ontologies similar to OntoH2G, the core data model used in BEMServer. We then provide details on the architecture and the main functionalities of BEMServer, with a focus on the semantic layer. The third section is dedicated to a demonstration of the suitability of the solution through its use in the Hit2Gap project¹, in which BEMServer is used to deploy smart monitoring solutions on four different sites. Finally, we point out conclusions and future works.

Related works

In this section, we provide a comparative study of different data models used for building monitoring purpose, as well as building energy management software.

Data models

The use of linked data has gained interest in recent years as a solution to the complexity of modelling buildings with information relevant to different domains (architecture, energy, structural engineering, . . .). As such, ifcOWL in Beetz et al. (2009), is an RDF translation of the IFC schema: it is therefore an important reference thanks to the high level of modelled information, but suffers from being too verbose and not domain specific, just as IFC files do.

¹<http://www.hit2gap.eu/>

More recently, the Building Ontology Topology (BOT)² model was proposed by Rasmussen et al. (2017) within the Linked Building Data W3C working group as the angular ontology that could be used to develop building-related domain ontologies on top of it.

At the operational level, different models have been proposed to describe sensors and building equipment that are monitored. The SOSA ontology proposed by Janowicz et al. (2018) describes sensors and actuators, and the SSN one in Compton et al. (2012) extends it to sensors networks. SOSA and SSN are now widely accepted as standards and are W3C recommendations. They also integrate concepts to store actual measure points, which is a questionable choice since triple stores (i.e. RDF-dedicated storage such as Jena or Stardog) perform poorly when dealing with a big amount of data, like monitoring time series data, while specific time series storage solutions exist.

Several ontologies focus on modeling building equipment. The BASOnt ontology, proposed by Ploennigs et al. (2012), integrates building infrastructure, devices, and data points but does not seem to address the role of occupant information in the overall building management, which could help authorities to elaborate newer management strategies or policies focused on specific building usage at different levels (operational, managerial, or technical). Additionally, it does not seem to be open.

The SAREF ontology, first designed by Daniele et al. (2015), integrates elements related to building equipment, such as HVAC systems, and monitoring devices. While many of these concepts can easily be used to align the SAREF ontology with ifcOwl or SOSA, the ontology seems quite incomplete in the description of building equipment, sensors locations, or occupants integration.

Haystack is a tagging model led by the Corporation (2014) and used to represent the metrology building information in a lightweight strategy. It is far from obvious how to link it with existing building data models like ifcOwl or BOT, since it is a tagging model and not a formal ontology (although an OWL translation of Haystack was proposed in Charpenay et al. (2015)). Moreover, no inference engine can be run on it in a straightforward way to create new relations.

The Brick Schema, presented by Balaji et al. (2016), can be assumed to be the most complete model. It is an RDF formatted ontology for building equipment and monitoring devices. A great number of concepts are described in the model; it is already aligned with both ifcOwl and BOT. Additionally, contributors of the model provide a bridge between Brick and Haystack, which is a popular system in commercial applications.

More recently, Terkaj et al. (2017) proposed a building au-

²<https://w3c-lbd-cg.github.io/bot/>

Table 1: Specific Domain Ontologies

Name	Dimensions	Language	Building Domain
ifcOWL	20644 (Axioms) 1315 (classes)	OWL	Generic
BOT	439 (axioms) 9 (classes) 14 (properties)	RDF/OWL	Generic
Haystack	–	–	Operation - Monitoring
Brick Schema	19365 (axioms) 313 (classes)	RDF	Operation - Monitoring
SAREF	1111 (axioms) 92 (classes) 36 (properties)	TTL	Operation - Monitoring
BACS	2165 (axioms) 244 (classes) 95 (properties)	OWL	Operation - Monitoring
CTRLont	144 (axioms) 13 (classes) 11 (properties)	TTL/OWL	Operation - Monitoring

tomation and control systems (BACS) ontology to model automation systems, building appliances, physical devices and their relations. It is aligned with other ontologies (such as SOSA, SSN, and BOT) and offers a detailed representation of automation states and functioning. The CTRLont, proposed by [Schneider et al. \(2017\)](#) also models building automation systems (i.e., devices that have the possibility to collect data, but also to control devices).

Table 1 shows a summary of these ontologies.

Energy building monitoring platforms

While many ontologies were developed to describe building monitoring systems, few energy management applications built on top of these models seem to exist.

[McGibney et al. \(2016\)](#), propose OpenBMS as an IoT-based architecture to manage blocks of buildings. An extension of the BASOnt ontology is used at the core of OpenBMS. BASOnt being aligned with ifcOwl, it makes OpenBMS a BIM-compliant system, although the integration of BIM data is not explicitly mentioned as a functionality of the platform. Additionally, there is no reference to the integration of some preprocessing services and how the data quality is handled in OpenBMS.

The BOSS (Building Operating System Services) architecture, proposed by [Dawson-Haggerty et al. \(2013\)](#), is divided into five layers: (i) the hardware presentation layer, that handles a direct communication with different on-site devices to expose the very same data to some standard REST APIs; (ii) the hardware abstraction layer that semanticizes collected data; (iii) the time series management layer to store and preprocess data points; (iv) the control transaction layer to be used by external services that can control buildings systems through a BOSS implementation; and (v) the authorization layer that handles control access. The integration of semantic into BOSS is not fully detailed and does not seem to rely on W3C recommendations, both on the technologies used (i.e. SPARQL query language) and on the models used (i.e. SOSA, ifcOwl).

While formal ontologies are relevant to associate some semantic to measure points, triple stores performance is low when handling actual time series values. To solve

this issue, a hybrid architecture is presented in [Hu et al. \(2016\)](#), where both semantic data and actual values of measure points are handled. The architecture is generic in the sense that different storage solutions can be handled and described into an RDF-based ontology (RDF-DB), to ease the integration of new storage solutions; in this work, time series data are stored in relational databases.

Other solutions, freely available or commercial, offer services to collect, analyze, and process data for energy management, but they do not implement a semantic data model. Such are the cases with the open source solutions from [Al Faruque and Vatanparvar \(2016\)](#) and [Pan et al. \(2015\)](#), and the commercial Skyspark [3](#) solution, which limits these solutions in terms of interoperability, and evolution. Nevertheless, Skyspark is interesting in many aspects: it has a capacity to handle a huge variety of proprietary protocols (e.g. KNX, BACNet) that are used in building monitoring systems, and to offer the possibility for end users to configure their own data visualization modules. It also integrates a rule-based language to generate alerts.

Finally, some initiatives to push the community towards using formal ontologies at the core of building energy monitoring applications exist. For instance, the Brick's consortium encourages to do so, but exposing data through a SPARQL endpoint is a barrier for application developers that would need to develop their own SPARQL queries, instead of using more popular SOAP or REST APIs.

BEMServer - Technical description

In this section, the overall architecture of BEMServer is introduced, its main functionalities are presented, and some insights on the semantic data model are given.

Overall architecture

BEMServer aims at being a core solution to deploy smart energy building solutions that are: (i) modular; (ii) extensible; and (iii) secure. A variety of data needs to be stored and exposed to end-users and connected services. Three main categories of data were identified: (i) time series

³<https://skyfoundry.com/product>

Figure 2: BEMServer architecture

data (i.e. sequences of timestamps/values pairs), which are data points collected by sensors/meters, set points on HVAC (Heating, Ventilation, and Air Conditioning) systems, and potentially data generated by services (such as predictive services); (ii) events which are elements generated by additional services, such as errors detected on sensors or identified potential energy savings; and finally (iii) metadata, which is information used to attach semantic to the data stored and exposed; as an example, metadata consist of all the data that is required to describe the value points collected by a sensor measuring the temperature of an exhaust air zone of an air handling unit. The management of metadata is one of the core functionalities of BEMServer, and it is detailed in the next subsection.

The functional architecture of BEMServer is depicted in Figure 2. It is composed of four layers: (i) the **Field Level**, where on-site data is collected from meters, sensors, BMSs, etc., but also from documents like IFC files; (ii) the **Extract-Transform-Load (ETL) Level**, that is used to connect the BEMServer services with the Field Level; this layer is in charge of collecting on-site data, from smart sensors/meters, to data stored in traditional BMSs, but also building descriptions through IFC files or *ad hoc* Excel files, and occupants answers to questionnaires; (iii) the **Storage Level** in charge of keeping track and semanticizing data; in this level, several technologies are used to deal correctly and efficiently with the heterogeneity of the data stored: a Time Series Database (TSDB) solution is used to store continuous monitoring data; the current implementation makes use of the HDF5 file format; a relational database (RDB) is used to store events; and (iv)

the **Management (Orchestration) Level**, where different services can be plugged to the BEMServer so as to deliver some added value to the data stored and shared within the platform; all the data handled in BEMServer are exposed via standard REST APIs, running over the HTTP protocol. REST APIs are widely adopted in the SaaS industry, and it ensures a homogeneous data access to BEMServer clients, hiding the complexity of using three different data storage solutions.

The secure access is provided through: (i) SSL encryption over HTTP communications; (ii) the delivery of cookie sessions to BEMServer clients; and (iii) the implementation of a Role-Based Access Control to reduce the scope of available resources and operations for registered users.

BEMServer has been developed to manage all these data in a transparent way for end-users and to connect the two sides of the same smart building coin: the Field Level and the Management Level.

The Semantic Data Model

Numerical values returned by sensors are useless without a meaning. In the double-blind architecture proposed through the BEMServer, it is necessary to attach semantic to the data extracted from sensors, smart devices, questionnaires, etc. OntoH2G, the formal ontology used at the core of BEMServer (presented in Chbeir et al (2018)), allows to describe building infrastructure, including physical and digital entities, as well as user-building interactions not only in the form of activities but also comfort requirements, user preferences, and other aspects that motivate users to interact with the building. In order to do so, different domain specific ontologies are aligned, among

⁴<http://www.buildingsmart-tech.org/specifications/ifc-overview>

which:

- SOSA (Sensor, Observation, Sample, and Actuator) ontology, a W3C recommendation used to describe sensors, actuators, and measures, while offering various concepts to ease the alignment with other ontologies;
- ifcOwl, used to describe building infrastructures and equipment; ifcOwl is the OWL version of usual EXPRESS formatted IFC files; as such it offers concepts covering many areas of interest in building descriptions, from infrastructure, energy equipment, measurement devices, to the geometry;
- Haystack, a tagging system developed by major BMSs vendors, and it is being increasingly adopted by smart building software industries, with the goal of becoming a standard so that new generations of smart measurement devices can integrate tags and attach them to the data points sent.

SOSA has the expressive and flexibility power of formal ontologies and can easily be linked to other ontologies, but it does not contain any information on building equipment and does not describe any of the relations that can be useful to monitor complex building heating or cooling assets, for instance. Thus, OntoH2G aligns SOSA with ifcOwl, to complement the semantic needed in BMSs. Additionally, ifcOwl is augmented with some features, and simplified to represent walls adjacency or space adjacency for instance. While SOSA can be used to store actual measures performed by sensors, those are stored in a time series storage solution, for performance reason. Each measure is then related to an ID to access actual time series, in the OntoH2G model.

The ifcOwl ontology, even if rich of concepts, is not specific to the building monitoring domain. In particular, relating an Observation with a particular element of an HVAC system cannot be done in an obvious way. To fill this gap, OntoH2G is augmented with concepts extracted from the Haystack project. Haystack is a simple tagging system, not a formal ontology and is therefore hard to bind to a formal building description, but it contains description of complex measurement types, that can be made in the context of building systems monitoring. Figure 3⁵ provides an example of an AHU (Air Handler Unit) discharge air temperature measure, using the Haystack tagging system. The measure is associated to a specific part of an equipment, (i.e., the discharge part of an air handling unit), a kind (i.e., number), a unit (i.e., degree Fahrenheit), a physical element (i.e., air), and an observation type (i.e., temperature).

⁵The example is taken from <https://project-haystack.org/tag/point>

```
id: @whitehouse.ahu3.dat
dis: "White House AHU-3
DischargeAirTemp"
point
siteRef: @whitehouse
equipRef: @whitehouse.ahu3
discharge
air
temp
sensor
kind: "Number"
unit: "°F"
```

Figure 3: Example of a measure representation in Haystack

In the scope of BEMServer, coupling SOSA and Haystack is done considering concepts in ifcOwl which share some concepts with both SOSA (i.e., Sensors) and Haystack (i.e., building HVAC equipment: air handling units, coils, heaters, boilers).

Our proposal for OntoH2G does not rely on a simple alignment of the Haystack ontology in Charpenay et al. (2015) with SOSA and ifcOwl, for efficiency reasons: both ifcOwl and the Haystack are verbose, being direct translation of some formats into OWL triples. This direct translation would have an impact on the complexity of an instance creation (because intermediate relations would need to be created) and on the response time on queries. Thus, the adaptation of OntoH2G for BEMServer, instead, is focused on enriching SOSA and ifcOwl with relations, classes, and individuals of relevance for BEMServer based on the information described in Haystack.

The following concepts from Haystack and ifcOwl are integrated into OntoH2G:

- *Spatial elements*: an observation may be related to some specific zones; it is particularly true for ambient sensors, i.e., those who perform some measurements like temperature, humidity, CO2 rate, in a specific zone of a building
- *Equipment*: in particular representing HVAC equipment, which are heavy energy consumers. Those systems are often monitored in big buildings to ensure they are not deteriorated, or even not badly programmed.
- *The type of observation*: observation type entails the physical measurement (e.g., temperature, energy, power) and also the physical medium (e.g., air, oil, water).
- *The unit*: that needs to be coherent with the physical measurement.

Figure 4: Classes and relations related to measures in OntoH2G

Additionally, more information needs to be modeled to assist end-users and services running on the time series to discriminate data:

- Is the observation a set point? A set point is a programmed value, not an observation (for instance, it can be the minimal temperature at which the heating system needs to be turned on). For services running simulations or energy consumption prediction, this data is particularly important and can be integrated in models.
- How is the observation made? Two modes are modeled in BEMServer ontology: observations performed at a fix frequency rate and those performed when a change of value is observed (for instance, a sensor checking the open/close status of a window, or valve). Such data are important in the BEMServer architecture and in particular for the missing data detection/correction services.

The final proposition is represented in Figure 4. The `sosa:FeatureOfInterest` concept was extended to model spatial elements, systems, and physical mediums on which the measure is performed. The `sosa:ObservableProperty` was extended to express the physical phenomenon that are measured. Finally, units are not modelled through the `sosa:hasResult` relation as expressed in the online documentation of SOSA because numerical values, are not modelled in the present ontology. Additionally, if some of the sensors can perform various measures, no measure can change units at runtime, but units need to be predefined and fixed at the installation of the sensors.

Services and data preprocessing

The Storage level of BEMServer is in charge of attaching a semantic to the data collected on sites. This, in addition to the REST APIs of the Orchestration level, provides an easy access to the data relevant to applications at the top level of the architecture. For instance one can obtain the list of air temperature measures in a certain zone using correct filters in a REST route: https://h2q-platform-core.nobatek.com/api/v0/measures/?location_id=XXXX&observation_type=Temperature&medium=Air⁶.

Such a functionality eases the integration of new applications; nevertheless, monitored data can also suffer from different issues that can prevent them from correctly running: sensors can be offline for some periods, can diverge from their initial calibration, or simply be measuring data with some undesired noise. These situations can cause corresponding time series to contain blanks (i.e., when no data is erroneously collected) and outliers (i.e., data that contain abnormal values). Developers of services at the Application Level, may not be energy building experts (for instance, front-end developers) and they should just care about working with values that are as-correct-as possible. In order to assist them in their tasks, the BEMServer embeds some preprocessing services so that:

- *Data cleansing*: blanks and outliers can be detected and corrected;
- *Resampling*: time series data can be resampled at a desired frequency;
- *Conversion*: time series values can be converted to a different value unit;

⁶The full list of APIs is available at <https://h2q-platform-core.nobatek.com/api/v0/api-docs/redoc>

- *Operations*: basic arithmetic operations can be performed so as to retrieve the minimum or maximum value of a time series on a given time range; to compute the mean value or the sum of a time series on a given time range; or to sum multiple time series.

In the case of arithmetic operations on multiple time series, all the data must be resampled at the very same frequency. Hence, the resampling and arithmetic services need to be combined. In a micro-service architecture, this issue is common and requires a services composition functionality. In BEMServer, this functionality is being developed in a semi-automatic way: services are described using an extension of the Hydra vocabulary presented in [Lanthaler and Güntel \(2013\)](#) and an API is available for end-users to specify the way services can be composed. This way, end-users can describe how to compose different services as workflows to get the desired preprocessed data. For example the data cleansing service can be first invoked, its output transferred to the resampling service, which prepares the data for the target arithmetic operation service. This tool is currently being integrated in the solution and has not been tested within the Hit2Gap project.

The Hit2Gap project: A Case Study

In this section, a description of real case study using BEMServer is presented, and some related conclusions are provided.

Description

The Hit2Gap project aims at reducing the energy gap at the exploitation phase of non-residential buildings. Four different pilot sites provide case studies in four different climate regions (Paris, Warsaw, Galway, and San Sebastian). The types of the sites vary from educational buildings (NUIG in Galway and Nanogune in San Sebastian), to an administrative office (Wilanow Town Hall in Warsaw) and a commercial private office (Challenger in Paris). BEMServer is the central solution used to monitor those four different buildings through the deployment of different types of services: (i) AI-based services for energy consumption prediction developed by [Massana et al \(2016\)](#), fault and detection diagnosis developed by [Burgas et al \(2018\)](#), and behavior modelling from [Calis et al \(2016\)](#); (ii) building performance simulation for the identification of potential energy savings and discomforts, model calibration by [Monari and Strachan \(2017\)](#); and (iii) data visualization services for different actors, from experts (i.e., facility or energy managers) to non-experts (building occupants).

A single instance of BEMServer was deployed to monitor the 4 sites, and 16 modules were plugged at the Management Level. Another module was plugged at the Field

Level as a bridge between proprietary communication protocols (e.g., Modbus, BACNet) and the HTTP protocol. Additionally, BEMServer is connected to OpenWeatherMap⁷, an external service that provides current and predicted weather data (for buildings that are not equipped with a weather station).

Table 2 gives an overview of the amount of data gathered by BEMServer in the Hit2Gap project. Note that more descriptive data (i.e. floors, spaces, walls, windows, surfaces, volumes...) are available for NUIG's building, than for the other three sites, since the information was extracted from an available IFC file for NUIG, while the other sites were manually described. In particular, information on façades, walls, slabs, windows, and windows covering could be retrieved in a straightforward way, while the same information is not modeled in BEMServer for the other sites.

The number of measure points also differs from one site to another: as shown in Table 2, a big amount of data is collected on the French site, which is the one equipped with an important number of sensors and meters (see column Sensors in Table 2). In the case of the Irish site, a high quantity of data points has been recorded because this site was connected to the BEMServer solution almost a year before the other ones.

Feedbacks from the experiment

The presentation of all the data handled in the storage layer through REST APIs was of great importance during the integration of the different modules, as the technical complexity was hidden to end users. For BEMServer developers, coding such APIs on top of a triple store is nevertheless time consuming. Several approaches are maturing to solve this issue, like the use of GraphQL for Linked Data in [Taelman et al \(2018\)](#) or the automatic generation of REST APIs on top of Linked Data as presented in [Schroder et al \(2018\)](#).

Preprocessing services reveal to be an important feature of BEMServer to help software editors to develop services, in particular for those with no expertise on building monitoring. It is important to remark that raw data is still available, so that experts can use their own preprocessing services.

The main efforts when deploying BEMServer is to collect metadata on building infrastructure and sensors. Such a task requires a close cooperation with building managers to get accurate data on measure types, units and locations. Extracting this data from an IFC file is most of the time important, as sensors are often not reported in BIM models, even though the schema offers concepts to do so.

The connection with the Field Level is not entirely man-

⁷<https://openweathermap.org/>

Table 2: Data storage in the Hit2Gap project

Site	Building Metadata	Number of Sensors	Number of Data points
Challenger, Paris	199	2494	57.061.659
Nanogune, San Sebastián	139	576	4.952.007
Wilanow, Warsaw	78	136	19.616.834
NUIG, Galway	9546	350	70.694.192

aged by BEMServer, but an intermediate software is used for its ability to connect to the main sensors protocols. Despite these limitations, this use case shows that BEMServer is suitable and adaptable to handle multi-sites and multi-tenant data in a secure way. A more complete connection to the Field level will be studied in the future, through the use of gateways between local networks protocols and web APIs, such as the one in [Bonino et al. \(2008\)](#).

Some performance leaks were also revealed during the project. For instance, HDF5 pilots do not handle concurrency, and a move to other solutions, such as InfluxDB or DruidIO, is being studied. Also, SPARQL queries will be optimized to offer a better response time.

Conclusion

BEMServer is an open source solution to deploy modular, secure, and semantic building energy management solutions. It is based on different standards from the Web (REST APIs, linked data), to ease the work of web services developers and different storage solutions to handle heterogeneous data. BEMServer is based on a semantic data model (OntoH2G), to describe measure points, as well as occupants and user information. Thus it offers a holistic model to represent the building and the human interaction impacting energy consumption. The deployment of the solution in the H2020 project Hit2Gap shows its suitability to monitor non residential buildings, and its robustness in a real case study. Its usage in residential buildings as the use of a semantic layer is perhaps not useful when few measure points are managed.

In the future, some performance issues need to be tackled to make BEMServer more efficient. Additionally, the use of the ifcOwl ontology made queries complex because of the complexity of this model, thus we wish to align our model to ontologies from the Linked Building Data W3C group, in particular the BOT ontology, which is more concise and made of direct relations between concepts, while keeping compliance with the IFC model. Additionally, the connection of BEMServer and Dog-Gateway will be evaluated to handle proprietary protocols. Finally, more preprocessing services will be developed to offer more quality of service to end-users, like blanks and outliers correction based on machine learning techniques.

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DYNAMIC DISTRICT INFORMATION SERVER: ON THE USE OF W3C LINKED DATA STANDARDS TO UNIFY CONSTRUCTION DATA

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Abstract

The evolution of ICT and BIM systems in the construction domain yield detailed views of buildings and their use throughout their lifespan. These systems also provide a structure around which information about buildings and their effect on surrounding infrastructure can be described in space and time. Thus, when aggregated, information provided by these systems can serve as a semantic structure through which other information can be stored and contextualized. While bespoke systems have explored these approaches in particular contexts, few if any systems have been constructed to provide a flexible, semantically rich structure that can be used to structure information about any urban landscape at district and regional scales. This paper describes such a system. The Dynamic District Information Server (DDIS) provides a core information structure which can be extended to store as yet undefined information structures and allow these to be reasoned about in the contexts that range from neighbourhoods to regions. In addition, the paper describes how the DDIS can serve as a coordinating process in a tool chain by providing a semantically rich and flexible notification system that allows tools in the chain to notify one another when steps in some information process have been completed.

Introduction

Technological advances are improving how we build, operate and renovate buildings. Advances in data measurement, collection and management are providing a rich picture of how buildings operate and perform. This information can be used by stakeholders such as owners and managers to improve a building's performance, and by planners and decision makers to plan future buildings and urban spaces. Such advances have never been more important as society begins to address the twin challenges of climate change and access to quality accommodation for ever denser population centres; both goals must be met within the strictures of emissions standards - both during construction and operation - while providing comfortable, affordable accommodation within an attractive, efficient urban environment. Other advances, such as cloud com-

puting, and access to reliable, robust software packages are making the use of such data for the development of decision support systems possible for all stakeholders.

While the use of building and environmental data is replete with benefits, challenges remain (Azhar et al. 2019). Cost of development, regulatory issues such as data protection, trust worthiness of results and technical challenges pose significant hurdles¹. While custom information management systems are accessible to large firms and operators of buildings, the cost of development, operation and maintenance of such systems are prohibitive and unjustifiable to many stakeholders. In light of public reaction to social media companies apparent misuse of individuals' data, awareness around privacy and data access is growing, and may cause individual building owners and organizations to be reluctant to share their information (Department of Communications & Resource 2014). Furthermore, government and EU regulation has defined significant punishments for misuse of users' data under General Data Protection Regulation (GDPR)² and other regulations; this has placed a burden on operators of software systems that may cause reticence about storage and use of data. In addition, this information often has commercial value.

Stakeholders are also more discerning and cautious about the promises of both organizations and technologies; for instance, it has been found that uptake of grant support for building renovation in Ireland has not been forthcoming unless users can see and trust the promised outcomes of these efforts³.

Finally, technological challenges exist. For example, over the course of time, development of building and urban data systems has diversified into task specific silos. Software systems and standards developed around these and so data exchange from within a specific silo to some other domain remains challenging; yet, such exchanges are key to proving decision support systems that are wholly informed Yoshida & Hirashita (2003).

¹<https://constructionprocurement.gov.ie/wp-content/uploads/BIM-Adoption-Strategy-Statement-of-Intent.pdf>

²<https://eugdpr.org>

³Introduction Part iii <https://www.dccae.gov.ie/documents/2017041220LTRS.pdf>

This paper presents and details a novel data management solution called the Dynamic District Information Server (DDIS) that uses W3C Linked Data standards and conventions to:

- Bridge various complimentary, yet diverse data standards (for example, CityGML and BIM IFC);
- Provide both data and process management for relevant tool chains;
- Preserve data ownership and privacy, and provide a mechanism to explain results in order to build users' trust in decision support outputs;
- Be affordable, both in terms of operation and expertise required to run the system. Furthermore the system seeks to be flexible, accommodating new data sources and tool chains with minimal refactoring.

It is anticipated that this system could serve as the nucleus to a data management and exchange system that informs decision support in building and urban planning environments.

Throughout this paper, a scenario will be used to illustrate how the server meets the goals described above. In this, a semantic bridge will be built between district data expressed CityGML and building data in IFC format. This information resource will then be augmented with data from other sources. The scenario will be described in detail later, and should be considered as just one application of the server. While this paper focuses on the use of these formats because of their use in the NewTrend Project⁴, preliminary work has been done to assess the feasibility of supporting additional formats such as W3C's LBD⁵.

The paper continues by briefly describing relevant systems and standards and introducing W3C Linked Data and related standards used in this work. The systems architecture will then be described, before concluding with an explanation of how the server was applied to manage information related to the scenario.

Background

(Boddy et al. 2007) presented an innovative visualisation of the Computer Integrated Construction (CIC) landscape that helped researchers place their systems in the context of research and industrial systems, as well as assist in the identification of axis of advance for research outputs. Their work divided the CIC landscape into four quadrants by proposing two key axis, shown in Figure 1:

- *semantic focus (from Data Structures through Semantic Description)* - which provides an axis to express

the semantic expressivity of a system, standard or protocol, from generic data structures which express little context to semantic standards that permit richer opportunities for synthesis of information;

- *application focus* - which provides an axis to express the scope of the work, from low-level APIs and monolithic applications to entire tool chains and complex processes.

These axes define four quadrants (from Software Application Interworking through Process Integration) - *Integration at data-application level*, *Integration at application-semantic level*, *integration at data-process level* and *integration at process-semantic level*.

In our discussion, we merge the *data-process* and *process-semantic* levels into a single data-process-semantic level. In the authors' opinion, these quadrants are about process integration either as a functional goal of the software, and to provide process-oriented software architectures; the goal of the DDIS is to admit an event driven architecture that advances both of these goals, as well as address related issues of trust and cost of running such a system.

Information Interoperability remains a challenging topic in CIC. While individual tools have evolved to provide complex functionality, the ability to pass information artefacts between these has relied on techniques as simple as manually passing files, often in intermediary formats that involve human intervention and loss of detail. This approach also has implications for data control, and in particular, handling information that is of a sensitive nature. Files that are manually passed may be subject to unauthorised access if the transfer medium is compromised - for example, a lost memory stick, or an email account compromised through use on an unsecured network (Belanger & Crossler 2011).

Automated information interchange was previously achieved through the use of shared databases, where a common schema was used by multiple software tools, and then through the use of Application Programming Interfaces (APIs). Both of these approaches enable information sharing. However, both approaches have issues; the most significant is inflexibility - with significant refactoring (re-design and re-implementation) required to extend in order to cater for new information requirements of new applications; while standards exchanges would require changes for any approach, these changes are less common.

The CIC landscape diagram described by Boddy et al is extended in this work to include semantic contributions in each quadrant. The authors contend that this is the natural extension of progress as semantic standards provide mature mechanisms to facilitate information exchange while systems interoperability offering information organisation options that facilitate data control. Semantic standards,

⁴<http://newtrend-project.eu/>

⁵<https://www.w3.org/community/lbd/>

Figure 1: Boddy et al's representation of CIC landscape

for example, Linked Data, are proposed and developed by the World Wide Web Consortium (W3C). These standards seek to enrich the ability to communicate information in machine readable formats, and have these standards widely adapted to ensure compatibility access across domains.

Linked data is increasingly being exploited in CIC (as promulgated by the broad range of research presented at the LDAC⁶ conference series). These standards offer both expressivity and connectivity, which are key requirements for interoperability. Several projects have been involved in using the semantic web and linked data in the building domain. The SWIMing project has examined over 100 EeB projects, analysing them in detail to identify where linked data and semantic technologies can be used to make information more accessible, exchangeable and easier to

exploit (Mcglinn et al. 2016).

Linked Data approaches have also been used to address privacy issues. It was recognized that linked data would pose challenges to privacy and data control. However, the standards developed to support information discoverability have addressed many of these concerns. In particular, efforts to make information discoverable has lead to a distributed architecture where it is possible to host information on servers that are managed by the data's controller, and exposing only the required subset. Information science has also developed best practices and methodologies that strive to guide organizations in striking a balance between information openness and control (*Big and Open Linked Data (BOLD) in government: A challenge to transparency and privacy?* 2015).

⁶<http://linkedbuildingdata.net/ldac2018/>

W3C Linked Data Protocols

This work describes the implementation of the DDIS that manages building related information at multiple scales. To do this, it leverages implementations of several protocols designed by W3C to manage linked data. This section describes the relevant protocols and how they are used by the DDIS.

Linked Data

Linked data is a set of design principles for sharing machine-readable data on the Web (Mihindukulasooriya & Munday 2012). It is made up of named data that can be exchanged and reasoned about. Data can be expressed statically as RDF or dynamically embedded in the format. This data is named using a unique Uniform Resource Identity (URI) that allows it to be found and shared across the web. The data can contain links to other named data sets and meta data about the relationship between these linked datasets. Given a rich enough network of data, a computer algorithm can reason about entities based on the contexts provided by their related data.

While the ability to reason about distributed data is in itself sufficient motivation to embrace the concept of linked data, the schema has further advantages. Because the data is distributed, maintenance is reduced and only expertise about data related to an organisation's expertise need be maintained. Furthermore, the data exposed need only be the subset that is relevant and permissible for an organisation's remit. Maintenance of data is distributed, while the linked data concept is infinitely extensible. While there is an overhead in re-expressing data in RDF format, the process can be largely automated and supported by mature software tools.

In this work, the server both exposes and describes related linked data to facilitate data exchange between attached software clients.

Data Cubes

W3C's RDF Data Cube Vocabulary makes it possible to publish a multi-dimensional dataset as part of a linked data schema (Cyganiak & Reynolds 2014). In this context, a dataset consist of the following data types:

- Observations or the raw data;
- Organisational Structure positions the observation in each dimension it is related to;
- Structured metadata provides metadata about the observation, such as its unit, or whether the value is estimated or measured;
- Reference metadata is used to describe the dataset as a whole, including its publisher, information about how

measurements were made and a SPARQL endpoint through which the data can be accessed.

The data cube vocabulary defines dimensions, attributes and measures. Dimensions provide organizational structure or context for an observation, for example, time of observation and location. Measures represent the value of an observation. Attributes describe structured meta data or information that allows us to interpret and reason about observations, for example units. Together this vocabulary can be used to reason about data contained in a data cube and also to facilitate its exchange with other services.

In this work, data cubes are used to associate external data with core entities, such as buildings. The data could be any related data including measurements from sensors or simulation results.

Data Catalogue

Data Catalogue (DCAT) is an RDF vocabulary that allows reasoning about online data catalogues (Maali & Erickson 2014). Its use promotes discoverability of data sources and admits consumption of catalogues' metadata. The vocabulary also provides metadata that can be used to reason about a dataset's provenance. The vocabulary provides a rich set of attributes that can provide context about a dataset and its versions. A catalogue entry can be maintained on a server that is remote from the dataset's SPARQL endpoint.

For the purposes of this paper, data catalogues are used to document remote data source such as datasets from sensor sets and results from simulations. This arrangement means that the server manages a reference to some dataset and does not maintain a copy of the data (reducing data duplication and management overheads) as well as ensuring that the dataset itself remains under the control of its owner.

Notifications

Software applications manipulate information or produce new information as a result of their execution. If several applications are used together to achieve some task, then they define a tool chain and implement a process where certain tasks must be completed by particular applications in a particular order. When a user is using the applications, they are in effect the coordinator of the process, and are responsible for the correct execution of the process. To automate such a process, software applications must be capable of producing notifications to indicate that they have completed some task, and also be capable of receiving and acting on relevant notifications from other applications.

A common design for a notification system uses a central coordinating server to which attached clients can publish notifications. Other clients can register interest in these by subscribing for notifications from the server. W3C's

Linked Data Notifications defines a protocol for exchange of notifications.

In this work, Linked Data Notifications (Capadisli & Guy 2017) are used to develop tool chains that can act on data exposed by the server; note this data may be accessible through a SPARQL endpoint exposed by the server itself, or one referenced by a data catalogue entry. Clients can send notification to notify the server (and its connected consumers) of a change to a data set (when a new set of sensor readings are available) or when some new artifact has been produced (when results of a simulation have been produced). Clients can trigger actions based on receipt of some notification and so a collection of clients (each an element of a tool-chain) can co-ordinate their actions.

Implementation

This section describes how the DDIS was implemented, with particular focus on how the server was developed to meet its goals. The server seeks to act as a data store which client software can submit to and retrieve information from. This information, while submitted in disparate formats, is represented on the server as a single, unified source which can be queried by other software clients. This is achieved by creating semantic bridges between formats. The store is extensible, and can include data that is remotely located from the server, and so, allows data owners to maintain control over their data. The server is implemented using mature, cost effective techniques to reduce cost, ensure maintainability and availability.

The Scenario

The DDIS grew out of a previous project⁷. While the project had several nascent versions of features described here-in, functionality was centralized, clients and server were tightly bound, meaning that repurposing would have required a significant refactoring effort. For example, in the project, modification of attributes provided by a data collection tool required reworking of both the database and code used to expose the attributes to client systems. The goals outlined for the DDIS seek to address these limitations and make the server readily applicable to a wider range of scenarios.

The scenario used to illustrate the DDIS is derived from this earlier system, and consists of three client components in addition to the server; these are a standalone data collection tool, a simulation engine and a reporting client through which end users can view results. It is assumed that each of these clients are provided by separate vendors, that their implementation is commercially sensitive and that each must act as data controller for information artifacts generated by their tools.

The data collection tool collects attributes required by the simulation tool. It is able to determine when it has collected sufficient information to allow the simulation engine run. When end users have completed data entry, the tool exposes this information and creates a data catalogue for that information on the DDIS. It also posts a notification to indicate that data collection is complete and provide details of the data catalogue entry. As an interested client, can then either alert its operator (or automatically) retrieve the collected information run a simulation on it. The simulation engine then adds a data catalogue entry for the simulation results, and posts a notification. The reporting interface, having expressed interest in such events, then retrieves the result set and displays it for the end user.

Guiding Principles

The design and development of the Dynamic District Information Server was guided by two principles; the first, ensured that the server was flexible enough to be customized for specific project requirements and, secondly, ensuring that operation of the server was affordable. Flexibility was achieved by keeping core data representations - such as bridges between various information formats - simple, and devoid of extraneous detail; this detail can be added as bespoke functionality, or accessing external data stores.

The second goal of reducing the cost of operating the server is achieved by mitigating costs around setting up and maintaining the server. Costs arise through the acquisition of hardware, which must be maintained by trained personnel, and often requires bespoke supporting infrastructure. The DDIS is deployable as a turn-key machine image that is deployed to cloud based servers such as those provided by Amazon Web Services and Microsoft Azure. This approach is advantageous as the effort of maintaining hardware and software services, such as security, are delegated to specialists in these companies. Furthermore, these virtual servers will not suffer failures resulting in extra expenses and reduced availability. In addition, hardware can be scaled to demand dynamically, ensuring that cost of operation is optimized.

The DDIS is then initialized through the use of a web based wizard; users from a civil engineering background did not have to develop specific technical skill outside of their domain to use the server. The work described in this paper was run on a medium EC2 AWS instance, and supported data collection and simulation clients.

Architecture Overview

The DDIS consists of four key functional areas (shown in Figure 2):

- A series of interfaces to allow client software to query

⁷<http://newtrend-project.eu>

Figure 2: DDIS Architecture Overview

(through RESTful or SPARQL based interfaces) and to interact with the notifications system;

- A DCAT compliant data catalogue;
- A Core Spine or RDF schema that can be used to place other information in the space and time covered by the project. This spine allows information to be associated with entities in either the urban or building information spaces, and creates a bridge to allow seamless querying across these spaces;
- Subsystems to manage the native formats of both the urban and building spaces;

The DDIS server provides a semantic context for building related data, placing it in time and space; this information can be local or remote. The resulting context can be used by clients to query the associated information. The server can be queried through either RESTful APIs or SPARQL query interfaces. The server also provides a notification service to allow attached clients to inform each other of events. In order to define a common context, a definition must be provided in terms of information available in the project. Ideally, the context is agreed between organizations participating in the project.

The server would be set up thus; both the owner of the server and any other members of the project that will manage data would meet at the project's beginning. The structure of the Core Spine would be agreed, including supported data formats (in the case of the NewTrend project, these formats included CityGML and IFC). Once this structure was agreed, individual data stakeholders can proceed to publish their data in a way that links to this spine schema. As each contribution was made available,

its location would be published in the DDIS' data catalogue. There after, when a client tried to access this data, they would first query the catalogue for the available RDF schema (Step 1, Figure 2), and using these, formulate SPARQL queries across both the Core Spine and the information sources described in the catalogue (Step 2, Figure 2). A separate process management schema based on notifications (described later) is represented by Step 3, Figure 2. The structure of the core spine, shown in Figure 3, is intentionally minimalist. Its purpose is to provide a generic context in place and time to other information artefacts. Entities - buildings, building components or groups of buildings are contained by or contain other entities. Each version of an entity is versioned using a change event which has a time and changing agent. This change event can be used both to version and inform the provenance of entities. Finally, an entity can act as a binding element between formats represented on the server. For example, in the scenario, where an entity, such as a building, is represented in both CityGML and IFC formats⁸, the identities of the entity in both formats can be associated as values in the bridging entity. The spine is managed using the Apache Jena project⁹, with particular use being made of the RDF API, ARQ, TDB and the Ontology API. This infrastructure is made available through the Fuseki project¹⁰.

The scenario called for management of data in two formats, CityGML (Gerhard Gröger 2015) and IFC. In this case the DDIS managed these formats using mature, widely adopted software systems, and interfaced with these to produce RDF on the fly. CityGML was managed on a POSTGIS database¹¹ using Virtual City Systems 3d City Database Importer/Exporter tool¹². IFC is managed using the open source BIMServer¹³; its APIs and plugins are used to interact with the buildings' representations. These are sources are accessed using Python libraries - that query POSTGIS in the case of CityGML or through the BIMServer's API for IFC (represented as green ellipses in Figure 2).

Adding Other Data

Organisations can publish data and add it to the server. This information must be expressed in the context of the core RDF schema for the project. For example, in the case of the scenario, information would be associated with some version of an entity; for example, sensor data might be expressed as being measured in a room of a particular

⁸We focus on these formats in this work, other formats can be supported

⁹<https://jena.apache.org>

¹⁰<https://jena.apache.org/documentation/fuseki2/index.html>

¹¹<https://postgis.net>

¹²<https://www.3dcitydb.org/3dcitydb/3dimpexp/>

¹³<http://bimserver.org>

Figure 3: Core RDF Schema

building. Information is expressed in RDF. Any vocabulary can be used, though, the Data Cube has been found to be particularly suitable, given its support for expressing information in several dimensions.

Once the information has been acquired, it must be made linkable. This can be achieved using varying degrees of sophistication. Simple publishing the file on a web server will expose information statically. Information can also be exposed dynamically, where a web server accesses some information source (such as a database) and transforms an information subset to a data cube. Both processes ensure that the data is controlled by its owner. This approach helps maintain compliance with data privacy best practice.

Finally, information must be made discoverable. This is done by adding a data entry to the DDIS data catalogue. This entry is in turn exposed using the DCAT vocabulary. The vocabulary is expressive, allowing details including the title, version, data of publication and modification, data use licence URL and many more attributes to be expressed. This entry is discovered by connecting clients. The structure of the data is provided, and can be used to formulate a SPARQL query.

Data access is further controlled through the DDIS by adding access control for artefacts listed in the catalogue. DDIS user accounts are grouped, and access privileges are determined by these.

Process Support

While each client of the server can interact independently with the DDIS, these tools are often used as part of defined processes, creating ordering dependencies in their use. For instance, an energy simulation engine cannot run until it can retrieve building geometry, district data and other parameters from the server. The DDIS provides a notification service that allows other tools to register custom notifications on DDIS, provides an interface to allow a tool to publish these notifications, and allows other clients to subscribe for notifications that are relevant to their operation. Available notification definitions can be retrieved from the server. These definitions describe both notification types and the cargo element of each. Both a data pull and push methodology are provided. The pull methodology is implemented by the client polling for notifications of interest; this technique was initially provided, but was found to be inefficient because of the amount of network traffic generated and the extra computational effort imposed on the DDIS. A pull service was implemented where a client provided a callback server call. In this case, on receipt of a notification, the server posts a notification to interested clients' callback. This call then invokes the clients response to the notification. This process is described in Figure 4. The schema used builds on W3C's Linked Data Notifications standard¹⁴. It was built using a server add-on called Django Notifications, though it could also be built using any cloud based notification service.

In the case of the scenario, two components needed to work with the server in sequence. The data collection tool must first complete data collection. Once this is complete, the tool posts a notification to the server. When the project was set up, the client running the simulation engine posted interest in notifications from the data collection tool; when it did this, it provided a URL that would invoke the simulation clients response. On receipt of the notification from the data collection tool, the server makes a call to the URL and the simulation client retrieves the data from the server.

Future Work

The development of the DDIS server has highlighted several future avenues of investigation, including dynamic toolchain definition and data provenance.

Other formats, such as W3C's LBD standard will be integrated. In addition, the notification system will be extended. While the server provides a mechanism through which clients can notify the server of some event. This notification can then be polled by other clients, and used to trigger events on these. Future work will include providing a semantic infrastructure through which complex processes can be defined.

¹⁴<https://www.w3.org/TR/ldn/>

Figure 4: Notification Flow

Data Provenance is concerned with providing traceability for information. While information artefacts can be versioned using many current information management system, little meta-data about the production of information is captured and maintained. Furthermore, once that information has been used in a simulation, few if any systems record details of datasets input to these. The authors consider that being able to query for, for example, which simulation results depend on a mis-calibrated measuring device, is a key extension to the current DDIS server. While several approach to this functionality exist, it remains to be determined which of these will provide the desired accuracy, while optimising computational and storage costs.

Conclusions

This paper introduced the DDIS and a scenario to which it was applied. The server contributes the following:

- Provides a semantic context to place information in time and space
- A data catalogue to make project information discoverable
- A notification service to allow clients attached to the server interact with one another

Together these features provide the tools to help stakeholders and toolchains in a project to interact with one another

in a way that is relatively cheap to run and maintain, while addressing real world commercial interests, such as allowing participants to maintain control over their data.

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OPPORTUNITIES FOR COMMUNAL PHOTOVOLTAIC-THERMAL HEATING SYSTEMS WITH STORAGE

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Abstract

With 70% of the world's population projected to live in urban areas by 2060 (ARUP, 2016) and 67% of current energy related emissions produced in urban areas (IEA, 2008), there is a compelling case to investigate the reduction of CO₂ emissions from heating in densely populated areas in the UK or other regions with heating requirements. This paper investigates how a single PVT panel system with thermal and electrical storage could reduce heating emissions for a row of terraced houses. The main findings of the study carried out in Dymola/Modelica were that there is potential for greater thermal and electrical output with larger PVT systems and shared communal electrical and thermal storage. Pre-heating the mains water which supplies the hot water tank using the PVT both increased the PVT thermal efficiency and utilisation, and the electrical efficiency. In this configuration, the PVT system was able to supply all hot water demands of a row of terraced houses and supply about 91% of electricity demands.

Introduction

As the UK works towards a target of 80% emissions reduction by 2050, relative to 1990 levels (CCC, 2018), a transformation in building energy systems and existing/new infrastructure will play an important role. With approximately 14% of the UK's emissions produced by gas for space and water heating (BEIS, 2018), and the domestic sector accounting for 53% of the UK's total energy demand (Ramos et al, 2017), this study investigates how to decarbonise the UK's residential heating systems.

There is a need to investigate the reduction of emissions in densely populated areas since 70% of the world's population are projected to live in urban areas by 2060 (ARUP, 2016). Since low-rise purpose-built flats, converted flats and terraced houses comprise about 68% of London building accommodation types (Greater London Authority, 2011), this study investigated emissions reduction amongst terraced houses. Future work could retrospectively extend the methods and findings of this study to other cities and building types.

Although in its infancy, with approximately 50 pilot installations in operation mainly in Europe, Power-to-Gas

technologies could be a promising solution to low carbon heating in the UK (Lambert, 2018). Air source heat pumps (ASHPs) could also be important in decarbonising future domestic heating, however there are some challenges presented in the ease of installing in densely populated areas. The Microgeneration Installer Standards (MIS, 2005) states that *heat pumps should not be located adjacent to sleeping areas or on floors that can transmit vibration and the location of external fans (ASHPs) should be chosen to avoid nuisance to neighbours* (Building Performance Centre, 2011).

Solar photovoltaic-thermal (PVT) collectors could be a competitive alternative or supplement to heat pumps in areas with high energy density since PVTs simultaneously produce electricity and heat, whilst increasing the PVT efficiency through cooling. With 80% of the existing housing stock forecast to still be in use in 2050; alongside low carbon heating technologies, certainly also improving insulation, air-tightness and ventilation strategies will play an important role in meeting emissions targets (UKGBC, 2019).

This study investigates multiple dwellings sharing one PVT heating system. In addition to there being a research gap for PVT district heating, several potential benefits of using a single system spread across multiple buildings as opposed to individual buildings have been identified:

- Heat demand from a group of buildings may be asynchronous, particularly if it has different functions and occupants. With this added diversity, there is the potential for a more efficient system as what would typically be wasted heat when there is low demand, could be shared across a heat network instead of being stored in a thermal storage which would incur storage losses (The Association for Decentralised Heat (2018), Olsen et al (2014)).
- There may be more space to accommodate a shared plant facility, compared to a small flat which is unlikely to have the space or desire to accommodate battery and thermal storage.
- There is an added level of flexibility in the system design. For example, if one building is partially shaded, an unshaded roof of a neighboring building

could be used instead to mount the PVT system. Buildings with less optimal mounting positions for PVT could compensate by housing the thermal and electrical storage system.

Literature review

This section reviews literature and industrial developments of PVT systems. An important aspect of PVT heating is the thermal energy storage, therefore this is also considered in the review.

PVT Studies

There have been previous studies investigating PVT systems in single dwellings with hot water tank storage or GSHPs. A modelling study found that a PVT collector (2.25kW_p) with a water storage tank met 51% of total electricity and 36% of total domestic hot water (DHW) demand for a 3-bedroom terraced house with 15m² available roof area (Herrando et al, 2014); only a closed loop PVT to storage tank configuration was modelled. This study also investigates the most common dwelling in London – a 3-bedroom terraced house, however an open loop PVT and water tank configuration was also investigated.

A study by Xia et al (2017) investigated the performance of a GSHP-PVT system supplying space and water heating to a two-storey house in Australia with 248m² floor area. It was concluded that when the PVT collector area was less than 54m² it was more effective for the PVT thermal output to be used for DHW, otherwise it was more effective to recharge the ground in non-heating seasons and to retrieve the heat via the GSHP during heating periods. Three scenarios were modelled in TRNSYS, again all with a direct closed loop heat exchanger to the 60°C tank and PVT system, there were no considerations or discussion on the electrical performance of the PVT and how different configurations could increase the PVT electrical efficiency through cooling. The study modelled how over 20 years the ground temperature was maintained at about 16°C with PVT ground charging, but without ground charging the ground temperature declined down to about 7°C meaning the heat pumps energy consumption progressively increased each year. A limitation on the 20-year analysis was that the climate conditions remained the same each year, there was uncertainty how ground temperature would vary under future climate conditions.

A comparison of a Matlab PVT and solar thermal collector model found the thermal efficiency was 58.7% and 71.5% respectively. The electrical side of the PVT had 13.69% efficiency, giving a combined PVT efficiency of 72.39%, leading to 16% greater energy savings (details of how the energy savings were calculated were not included in the paper) (Raut & Bhattarai, 2012).

PVT Installations

There are about 500 PVT installations in the UK, but few have credible monitoring methods (BEIS, 2016), the BEIS PVT report has some brief details on an installation in Leicester on a new detached house, the PVT system

contributes about 17% to the heating and DHW demands, and about 40% of electrical loads with inter-seasonal storage (BEIS, 2017). An air-cooled PVT solarwall installed in Concordia University is expected to have a total system efficiency (heat and electricity) over 60% compared to 10-15% for conventional PV modules (SolarWall 2018), it has ongoing monitoring. Although there is technically great potential for PVT the high initial costs and uncertainties caused by poor knowledge of the technology was found to be limiting market penetration and installation growth (Ramos et al, 2017).

Storage

Whilst there are several studies which have demonstrated promising potential to increase PVT efficiency and output with phase change materials (PCMs) (Atkin & Farid (2015), Park et al, (2014), Browne et al, (2016), and Das et al, (2018)), and PVT-GSHP systems (Xia et al, 2017), this study implements a hot water tank since this is the most common thermal storage in domestic heating applications which makes it an appropriate starting point for a base case study, which could be built upon in future studies.

There is also justification to explore how thermal and electrical storage could support PVT systems by storing energy and supplying on demand. A study by Uribarri et al (2017) demonstrated how larger PVT roof coverage did not necessarily equate to cost savings due to asynchronicity between high energy demands and high solar conversion hours. Therefore, thermal and electrical storage could enable solar conversion to be utilized in demand hours whilst potentially also reducing total heat generation capacity and costs (Gudmundsson, 2016).

A techno-economic comparison between lead-acid batteries, li-ion batteries and a hot water tank for PV storage for a representative UK household with 3kW_p PV array concluded that the hot water tank (100-200l) was the most economic choice, if the tank was previously heated with grid electricity. However, it was discussed that there may be a stronger economic case for battery storage in other setups, and it also enables it to connect to the grid. With larger storage tanks not necessarily equating to higher solar thermal energy utilisation due to higher tank losses (Uribarri et al, 2017), and a techno-economic potential for battery storage, this research study investigated the use of battery storage to power an auxiliary heater found in a hot water storage tank.

To the author's knowledge there have been no studies investigating the potential of using PVT systems to power larger more complex systems such as a row of terraced houses. There are also no studies investigating how PVT systems could be optimised with both thermal and electrical storage, or for district scale systems, and how PVT systems could be optimised in this scenario. Therefore, the objective of this study was to quantify what percentage of space heating and DHW could be provided by 1 PVT system with thermal and electrical storage across the roof area of a series of terraced houses whilst addressing the above research gaps.

Simulation methodology

Since the nature of this study would benefit from rapid prototyping, design optimisation and analysis of innovative energy and control systems, Modelica was selected to model the system in this study (Modelica Association, 2017).

The high-level system (Figure 1) modelled comprised of the following sub-systems: weather, solar PVT, auxiliary heater, hot water tank and terraced house heating demand. Modified components and examples from the Buildings Modelica library were used to develop the system used in this study.

Table 1 summarises the parameters of the base case scenario modelled for hot water demand. Four other scenarios were modelled by adjusting the base case parameters in Table 1 to; 15000W auxiliary heater, 80°C tank set point, 1380 litres/day hot water demand (4 people in each house) and an open loop pre-heating mains water configuration. In total five system configurations were modelled.

Table 1: Base Case Scenario Parameters (10 houses)

Parameter	Value
Storage Tank Vol (m ³)	1
Aux Heater Power (W)	9600
Tank Set Point (°C)	60
DHW (Litres/day)	1880
Configuration	Closed loop to supply DHW

The following subsections detail each of the subsystems.

Weather

An IWECC EnergyPlus weather file for London (EnergyPlus, 2018) was input to the model using the weather reader in the Modelica Buildings library (BoundaryCondition.Weather Reader.TMY3). The data contained 1 year of data starting at 1:00AM on January 1st, with hourly data ending midnight on December the 31st. IWECC weather files are compiled from up to 18 years of weather data, the files represent ‘typical’ weather data suitable for use in simulations (EnergyPlus, 2019). Uncertainty lies here in how the future weather may differ from the IWECC weather file.

Solar PVT

The typical available roof area for mounting solar panels on period and modern mid or end-terraces was assumed to be 16m² (EST, 2015). The electrical and thermal functions of the PVT system were modelled as separate components to utilise the existing PV and solar collector models in the Building Modelica libraries. Simulated separately, there was no interaction between the thermal characteristics of the panel and PV efficiency. Therefore, an estimate on the annual PV output without any temperature de-rating was outlined in the ‘Analysis and Discussion’ section.

Solar PV

The PV model was based on the TESZEUS PVT 250W collector (Teszeus, 2018), with a PV maximum efficiency of 16.83% and 1.62m² area. The direct and diffuse radiation from the weather reader were summed to get the total irradiation reaching the solar panel and mounted at 45° on south facing roofs. The temperature of the PV module was not included in the model but calculated using the results of the simulation.

Solar Thermal

The solar thermal collector used the diffuse and direct radiations together with the outdoor dry bulb temperature

Figure 1: High level system diagram in Dymola of pre-heating configuration

to calculate the solar heat gain in the collector mounted at 45° on a south facing roof with a maximum of 65% efficiency based on the Teszeus PVT 250W. The heat gain and losses were calculated based on equations used in EnergyPlus (2011).

The thermal losses to ambient of the solar thermal collector were dynamically calculated using the PVT fluid temperature in each of the 3 segments ($T_{flu[i]}$), outdoor dry bulb temperature (T_{env}), array area (A_c) and heat transfer co-efficient (-slope) (Duffie and Beckham, 2006):

$$Q_{los,i} = -slope \times \frac{A_c}{n_{seg}(T_{env} - T_{flu,i})} \quad (1)$$

The heat transfer co-efficient used was based on ratings data for a glazed flat plate thermal collector from the Solar Rating and Certification Corporation (SRCC), which was $-5.103 \text{ W/m}^2\cdot\text{K}$ (SRCC, 2012). Although it is common to approximate thermal heat loss as a linear function of the temperature differential between the environment and collector, it should be noted that the co-efficient is not a constant and would realistically vary according to the collector tilt, absorber type, air temperature, wind speed and sky temperature (Harrison and Cruickshank, 2012). Since the selected PVT specification for the study did not have all the required information to characterise the heat losses (SRCC results) an assumption was made that the thermal losses would be the same as a flat glazed solar thermal collector.

PVT pump control

The pump for the PVT collector was controlled using the PVT fluid inlet temperature, outdoor dry bulb temperature and total incident radiation to calculate the critical radiation (G_{TC}) which is defined by the *Solar Engineering of Thermal Processes* book (Duffie and Beckham, 2006).

When the incident irradiation was greater than the critical radiation, the tank could gain heat from the PVT, so the pump was turned on. This theoretical pump controller has been used in other solar water heating analysis and design studies (RETSCREEN 2005, Kulkarni et al 2017). The flow rate of the pump was set to 0.03 kg/s , the minimum required to maintain the tank set point.

Hot Water Demand

The DHW demand was calculated based on the number of occupants (N), it is defined in the BRE Domestic Energy Model (BREDEM) as (Anderson et al, 2008):

$$Hot\ water\ demand = 38 + 25N \quad (2)$$

Two different hot water scenarios were modelled, one with 4 occupants in each dwelling and another with 6 in each dwelling. The hourly profile for a typical day was based on measurements of domestic hot water consumption in study by the Energy Savings Trust (2008). Together with the average daily hot water demand (sample size =124 dwellings) and the BREDEM model formula a profile was created for the study with peaks at 8am and 7pm as shown in Figure 2. The same profile was used throughout the year as hot water demands are fairly constant throughout the year (Energy Savings Trust, 2008).

Figure 2: Average daily hot water demand of row of 10 dwelling terraced houses with 6 occupants in each house

Auxiliary Heater

An auxiliary heater was included in the model to maintain the hot water tank temperature set point. This is particularly important when the tank is directly supplying hot water demands since the water must be kept above 60°C to prevent the cultivation of legionnaire's bacteria (HSE, 2018). The operational auxiliary heater power was calculated based on the electrical demand required to heat the hourly peak hot water demand (litres/hour) from 10°C up to the tank set point with the auxiliary heater power efficiency assumed to be 1 (CSE, 2018).

Tank

The tank incoming mains water was assumed to be at a fixed temperature of 10°C, however there would be some temperature deviations throughout the year (Davies et al, 2016). The hot water tank was modelled with a high density 2" foam insulation ($R = 12.5$, equal to about $0.08 \text{ W/m}^2\cdot\text{k}$) and a sturdy steel jacket (Solar Panels Plus, 2018). Three different tank set points were modelled; 45, 60 (base case scenario) and 85°C. The new flow rate for each tank temperature set point was calculated using the following equation, where $\Delta T = 70$, instead of $\Delta T = 50$ in the base case scenario.

$$\dot{m}_{80^\circ\text{C}} = \frac{Q_{BaseCase}}{C_p \times \Delta T} \quad (3)$$

Space Heating

Low temperature (LT) heating was selected for investigations since such systems could be integrated with ground source heat pump systems which is a promising configuration for future work to investigate (Xia et al, 2017). Also, LT district heating ensure greater energy efficiency on the consumer side since typically LT heating is installed in renovated buildings with a reduced heating demand. With lower heating supply temperatures there are also lower distribution losses (Olsen et al, 2014). Typically, LT heating should be installed in well insulated homes to implement LT heating efficiently. However, due to lack of data/access to data on insulated terraced house heating demands, the theoretical space heating for an insulated house was modelled with results extended to a discussion on

insulated house heating demands in the Analysis and Discussion section.

The design heat loss for a post-1919 terraced house with uninsulated cavity walls, solid ground floors, single glazing and loft insulation for a row of 10 terraced houses was assumed to be 47058W based on calculations by Allen & Pinney (1990). An average internal temperature of 19°C, external temperature of -1°C, distribution losses assumed at 16% (GSE, 2016), and a hot water supply of 45°C were used in the model.

Analysis & Discussion

Scenario comparison

Figure 3 shows how the daily auxiliary heating power consumption varied with each scenario against the daily total solar irradiation over 16 sample days selected over the course of the year. Note that all other result calculations are calculated with the entire annual dataset. Spikes were observed on cold days ($T_{env} \approx -1^\circ\text{C}$) in the electrical consumption for 2 reasons; there were greater PVT thermal losses due to the greater ΔT between the PVT and ambient, and the mains water temperature being cooler in the pre-heating scenario since it passed through the PVT and was exposed to ambient temperature.

Below about 3780W/m²/day solar irradiance, the auxiliary heater power consumption remained quite constant for all non-pre-heating scenarios. This is because on days with lower solar irradiance, the PVT did not output enough thermal energy to add useful energy to the tank set point (60°C or 80°C) and with the solar pump control based on critical radiance, the PVT thermal output was not utilised very much in the direct closed loop configurations. Figure 3 shows how the pre-heating scenario stopped the auxiliary heater consumption flat lining on days with less solar irradiance, this demonstrated how the thermal output of the PVT was being fully utilised even at times with low solar irradiance. Note that in the UK, the pre-heating scenario would require a closed loop anti-freeze mixture so future studies could model this in a separate pre-heating exchanger or tank.

Grid Dependency and Battery Storage

The grid dependency of the auxiliary heater was investigated by implementing data processing shown in Figure 4 into the model. The grid dependency was defined as the percentage of time the auxiliary heater's ON state did not match the solar PV giving an output. The instantaneous difference in power consumption between the heater and PV was found with the output from a limiter block which removed negative values and was then integrated to find the total of the limiter output over the entire year (1). The grid dependency was then found by dividing the limiter output (1) over the total heater power (2) at the end of the year.

Figure 4: Data processing to calculate auxiliary heater grid dependency

All scenarios had a high grid dependency (71 – 87%). With a high grid dependency and an annual PVT electrical output greater than the annual auxiliary heating requirement, there was a case to investigate storing the PVT electrical output in battery storage reducing the reliance on the grid. Figure 5 shows how the total auxiliary heater power consumption was 114.5kWh on the foggy day and 21.4kWh on the sunny day. The varying environmental temperatures between the foggy and

Figure 3: Daily auxiliary heating power consumption over sample days

Figure 5: Pre-heating scenario, auxiliary heater power consumption and PV output on a foggy and sunny day

sunny day would have also affected the thermal losses and PV temperature de-rating. However, even though the foggy day analysed was a cold day in January, given that there was no thermal PVT output and minimal electrical output, the thermal losses and PV temperature de-rating do not affect the following discussion. Approximately 32% of the days in the weather file would require an auxiliary heating power consumption of about 100kWh per day, with roughly an 85% grid dependency, this means 85kWh design useable capacity. Assuming an 80% Depth of Discharge, the nominal battery capacity would be about 102kWh. To put this into perspective it was estimated that this battery bank capacity could fit into an 8ft shipping container with space for wiring and the inverters for the PVT system, based on the lithium ion specification in Table 2. Future work could investigate suitable control methods for PVT-battery systems. If the PVT system were grid tied, without careful controls the batteries could be fully charged by 11am for example, meaning the peak PV production would be exported to the grid at its maximum output which may not correspond to the peak demands of the grid. With other PV systems in the area, there could be an oversupply of PV to the local grid distribution area leading to excessive voltages above the tolerable limit (IRENA, 2015). Future work could also investigate how float charging from the grid required on consecutively foggy days may impact the cost and suitability of battery storage for PVT systems.

Table 2: Lithium-ion specification (Victron, 2018)

Energy (Wh)	3840
Efficiency	99%
Dimensions (HxWxD, mm)	347x425x274
Total Energy Capacity (28 Batteries, Wh)	107520

The hot water tank outlet temperature had periods of constant or fluctuating temperatures (57-64°C). Analysis revealed how on sunny days the hot water tank temperature outlet fluctuated (down then up) between 8-9am, this coincided with a point where the incident radiation was above critical radiation but the collector temperature was below 60°C. These findings highlighted how pumps based on critical radiance should include controls in accordance with the tank set-point so that it does not lower the tank temperature below the set point.

PV temperature de-rating

A standard PV module can reach 110 °C on a sunny day in direct sunlight, which would equate to about a 43% drop in efficiency (Renugen, 2018). The PVT electrical efficiency drop was optimised in the pre-heating scenario since the fluid entered the collector at 10°C, which actively cooled the PVT. The total annual PV output (with and without temperature de-rating) was calculated using the hourly dry bulb temperature and diffuse and direct irradiance. A de-rating factor of 0.452%/°C was applied to the PV output. The PV cell temperature was calculated with the following equation (G = total irradiance):

$$T_{cell} = T_{air} + 0.035 \times G \text{ (Migan, 2013)} \quad (4)$$

The annual PV output was increased by about 15% without temperature de-rating (61264kWh with de-rating, 71768 without de-rating). Therefore, in the pre-heating case scenario, there was an electrical output increase of up to 15% compared to standard PV.

Space Heating and Refurbished Terraced House Opportunities

From January to March, the PVT thermal output provided about 7.5% of the space heating, the PVT electrical output was about 31,800kWh, which could cover about 33% of the auxiliary heating power (with battery storage). In this configuration, the PVT system met about 41% of the total space heating for the uninsulated post 1919 terraced houses over three months.

Uninsulated terraced houses are common in the UK, about two thirds of the existing housing stock are currently band C or lower (LCEA, 2018). However, with 80% of the existing housing stock forecast to be in use in 2050, the

clean growth report stated that as many homes as possible are to be upgraded to band C by 2035 (BEIS, 2017). There has been some traction on studying/investigating suitable home upgrade roll outs, such as 20 dwellings being upgraded by East Thames Housing Group. This included a 1930s end terraced house which had loft and internal wall insulation, energy saving light bulbs, solar thermal, PV and low-flow taps, in this case the home moved from EPC band F to B (heating demands were not detailed in the report) (BRE, 2006). Upgrading from band F to B equates to approximately 50% less gas consumption (GOV, 2015). Theoretically with a 50% heating demand reduction applied to the PVT space heating scenario, the PVT system would be able to supply about 80% of the space heating, with battery storage. It should be noted that LT heating would require re-sizing of radiators/underfloor heating which carries an additional refurbishment and 'hassle cost', this was identified as the largest barrier to the UK's heat pump uptake which would pertain to PVT systems (Frontier Economics and Element Energy, 2013). However, given the requirement to upgrade existing homes to higher sustainability levels, there could be a huge opportunity to transform homes to LT space heating systems alongside the UK housing stock upgrade.

Emissions Savings

Based on a carbon intensity of 0.185kgCO₂/kWh of gas and 0.270 kgCO₂/kWh of electricity ((Carbon Trust (2008), ElectricityInfo (2019))), each terraced house could save about 3.2 tonnes CO₂/year if previously gas heated, and about 2.3 tonnes of CO₂/year if previously electrically heated. This was calculated based on the pre-heating scenario where the PVT system met all DHW and 91% of electricity demands. In perspective, the average UK household emitted 8.1 tonnes CO₂/year in 2014 (CCC, 2016), based on the findings of the study there is a great potential to reduce emissions with PVT and storage systems. However, uncertainty with emission savings lie in the future carbon intensity of the electric grid, which is expected to fall in the future (James and Edwards, 2010).

Future work & conclusions

The space heating demands were derived from empirical data in this study. Future work could implement heat zoning (Dumont et al, 2015), with a limited number of more easily identifiable parameters to setup and calibrate the model, full transparency of the model could be achieved with an engineering equation solver (Bertagnolio, 2008). To reduce complexity and solving time in larger buildings with heat zoning, co-simulation with a validated building simulation program such as EnergyPlus has potential to improve the simulation efficiency and accuracy (Nicolai & Paepcke, 2017).

Future work could also build upon studies investigating the use of ground source heat pumps (GSHPs) as a secondary heating source in winter for space heating (Xia et al, 2017). It would be interesting to investigate how GSHP-PVT systems would perform in urban scenarios and how using the PVT to pre-heat the incoming mains water could improve upon the findings from the study by

Xia et al, 2017. Phase change materials also have promising potential to increase the PVT thermal efficiency which could also be investigated in future studies.

This initial study of PVT systems and storage in urban areas has produced promising results. Coming back to the study by Herrando et al (2014) of a 3-bedroom terraced house, 15m² roof area for PVT and a hot water tank storage configuration which met 51% of total electricity and 36% of the total hot water demand. When the PVT system was scaled up to a row of 10 terraced houses with electrical storage as done so in this study; the PVT system could deliver all the hot water demands and 91% of the electricity demand. The results of this study have demonstrated how there is potential for greater thermal and electrical output with larger systems and the opportunity for shared communal electrical and thermal storage. Although the findings of this study are geographically sensitive (London based), similar modelling approaches could be applied to other locations. The main outcomes of the study are summarised in the following points:

- There is a case to implement battery storage with PVT systems due to the auxiliary heater demands and PVT electrical output only matching 13-29% of the time.
- PVT electrical efficiency and thermal output is increased when the mains water is pre-heated in the PVT (because of cooling) before entering the hot water tank. In this study, this equated up to a 15% electrical output increase in London highlighting the importance of active cooling across PVT systems.
- There is potential for meeting a higher proportion of occupant energy demands with larger PVT systems using shared communal electrical and thermal storage compared to single dwelling systems.

With the renewable heat incentive confirmed until 2021 which could help subsidise early PVT and storage system installations and help with market penetration, there is a case to further investigate PVT district heating opportunities.

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EXTENDING IFC TO SUPPORT THERMAL COMFORT PREDICTION DURING DESIGN

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Abstract

During the early design stage, designers often rely on general rules of thumb to make critical decisions about the geometry, construction systems and materials without fully evaluating their effects on indoor thermal environment requirements and constraints. Currently, reviewing a design's sustainability requires designers to spend a significant amount of time manually extracting Thermal Comfort (TC) data from BIMs because of the tedious nature of this task. This paper is motivated by the absence of a standard method and a schema for extracting the necessary data for an automated TC assessment of building designs. The aim is to generate a reusable and retrievable set of Exchange Requirement's for BIM-based BTCS to facilitate efficient data extraction and exchanges from design models using the IFC file format. Furthermore, we develop an MVD mechanism that provides a structured framework for the definition and exchange of the target data as a step towards standardisation and production of BTCS related information, the results from which contribute to a proposed MVD. The application of the MVD in building design has the potential to improve the early-stage TC assessment of design alternatives. Further, it could reduce the time required to conduct the assessment, increase the reproducibility of results, and formalises the method used.

Introduction

The EU has set out ambitious strategies to improve the built environment and develop new low-energy buildings in order to reduce greenhouse gas emissions and meet targets by 2020 (European Parliament 2010). It is widely known that the most significant design decisions regarding building sustainability are generally made in the preliminary design phases of a project by stakeholders' (Bragança et al. 2014).

Building simulation is one of the most widely used design tools employed to predict thermal performance and indoor environmental conditions during a building's life-cycle (Soares et al. 2017). At present, Building Thermal Comfort Simulation (BTCS) is often evaluated in parallel

with the energy performance assessment of buildings (Szelag 2017), i.e. by using the same Energy model. Many input parameters in these models are based on standard energy efficiency requirements and energy assumptions (Sanhudo et al. 2018), thus the thermal comfort simulation is assessed based on the input data for Building Energy Performance Simulation models (BEPS) models. As a result, the input parameters used by BEPS models do not fully represent thermal comfort performance criteria and do not consider the needs of the end-user or occupant.

In current practice, modellers use traditionally generated CAD drawings and create independent simulation models that are uncorrelated with the original architectural model (Jung et al. 2018). Separate models may be created to ensure that all needed information is correctly included and is suitable for design and simulation of thermal comfort. BIM-based methods now contribute to effective design progression and information availability and can help to increase the efficiency of building use by facilitating data input for simulation and allowing more scenarios to be investigated (Kim et al. 2015).

It is clear from a search of the literature that only weak interoperability (low-fidelity data exchange) exists between BIM and BTCS and this has hindered the development of fully verified, indoor thermal conditions prediction based design. The reasons for this problem include:

1. Massive BIM data presents problems around adoption for sustainability analysis (Kim & Yu 2016);
2. Poor data exchange between BIM tools and performance assessment tools (Tuohy & Murphy 2015) in the context of performance-based design development;
3. Well defined industry standards for green BIM do not exist (Holmström et al. 2015);
4. Low industrial acceptance of green BIM applications, even though many BIM studies have been conducted (Kassem et al. 2014) and;

- At present, there is a general lack of interoperability between BIM platforms and BTCS, which is also problematic and limits the use of BIM-based prediction models in indoor environmental analysis (Jung et al. 2018).

This paper aims to define the essential Exchange Requirements (ERs) parameters for BIM-based BTCS assessment at the early design stage of a commercial building design. No set of data currently exists to provide the required information instances to support BIM-based BTCS assessment of building designs within the Architects, Engineers, Contractors, Owners and Operators (AECOO) Industries. Designers still may not know essential Thermal Comfort parameters affecting occupants' thermal sensation or they do not know how to capture these parameters to perform the analysis. The goal of this research question is to specify the information designers need for the BTCS assessment during building designs and to provide a basis for the content of the ERs model. This research established the following objectives;

- Identify and arrange the essential Thermal Comfort parameters of building designs;
- Formulate ERs model for BTCS assessment of building designs through identify entities and their components within the set of attributes, which define the base of MVD concepts will be used in the exchange.

This paper is structured as follows: Section 2 reviews the current models for predicting thermal comfort and identifies the most common thermal comfort models and their parameters. Section 3 presents a review of the current literature on BIM for sustainable design and BIM data files exchange format, in addition, highlighted the existing related MVDs. Section 4 presents the methodology and the workflow that involved for transforming BIM to BTCS, followed by discusses the full stages of IFC MVD mapping process. Section 5 is a discussion, followed by conclusions in the last section.

Predicting Thermal Comfort

Thermal comfort is largely a state of mind, separate from equations for heat and mass transfer and energy balances. The most common approach for describing thermal comfort for the purposes of prediction and building was introduced by P.O. Fanger in 1970. The model looks at five input variables: operative temperature ($^{\circ}\text{C}$), air speed (m/s), relative humidity (%), metabolic rate (Met) and clothing insulation level (Clo).

In recent years, levels of comfort are often characterised using the ASHRAE thermal sensation scale shown in Figure 1. The average thermal sensation response of a large

number of subjects, using the ASHRAE 55 thermal sensation scale, is called the Predicted Mean Vote (PMV) or the Predicted Percentage Dissatisfied (PPD) (ASHARE 2013). EN ISO 7730 presents the PMV and PPD indices based on the well-known theory of Fanger (EN-ISO-7730 2005).

Figure 1: Calculation variables and value scale of PMV (ASHARE 2013).

Current standards such as ASHRAE 55 standard and EN ISO 7730 standard specify methods for the evaluation of the thermal environment of buildings in order to obtain a certain degree of global comfort for the occupants at a certain level of activity and clothing (Yau & Chew 2014). These standards have been implemented in most BEPS tools that are available for predicting peoples' thermal comfort in buildings.

Another innovative comfort model was developed by (de Dear & Brager 1998) and commonly known as an adaptive model of thermal comfort. The model accounts for comfort by relating the acceptable range of indoor temperatures to the outdoor climate, so it is not necessary to estimate the clothing values for the space. No humidity or air-speed limits are required when this option is used. As the operative indoor ($^{\circ}\text{C}$) and the outdoor temperatures ($^{\circ}\text{C}$) are the only inputs the use of these adaptive model procedures in simulation is straightforward.

Table 1: The most popular and applicable Thermal Comfort models and their respective input variables

Date	Model	Description
1970	P.O. Fanger	Steady-state model
1978	M. Humphreys	Steady-state model
1998	Brager & de Dear	Adaptive model
2004	ASHRAE 55	Adaptive model
2005	ISO 7730,2005	Steady-state model

The evidence-based comparisons of static and Adaptive models for predicting thermal comfort clearly indicate each model has its own pros and cons. For instance, the

static model is applied globally for different types of buildings. However, the model was developed in laboratory studies, and the effects of building type were not considered. Therefore, the static model is not applicable to free running buildings. The reason may be the static method applied globally requires very limited variables that can be easily obtained and computed quickly.

The Adaptive Model is based on three pillars: behavioural adjustment, physiological adaptation and psychological adaptation. Thus, an adaptation is more than a simple collection of observable properties in a particular individual or space. This means that the set of thermal observable characteristics in PMV should be carefully extended and specified in terms of occupancy and the thermal properties of the building to include actions in human behaviour and the properties of the building fabric.

The purpose of this short review is to identify and arrange the essential TC parameters of building designs based on the most common TC models which are mainly intended for buildings, Table 1. Table 2 then specifies and arranges the essential exchange requirements parameters required for this work.

BIM for Sustainable Design

A BIM is a digital representation and repository of building data and information. BIM simplifies the automated exchange of digital information between diverse stakeholders and significantly reduces paper-based document delivery. BIM technology enables a number of automated or semi-automated facility-related services such as cost estimates, scheduling and energy simulation analysis (Cheng & Das 2014). In addition, BIM becomes a universal user interface for architectural design and building performance simulations (Yan et al. 2013).

With BIM, assessing building sustainability becomes a key element of the design process for early-stage environmental analyses. It allows users to explore different aspects, for instance building energy use, orientation, comfort and daylight (Bethany 2017). This can be done by way of linking the BIM model to building simulation tools, which allows calculation of energy use during the early design stages (Dhillon et al. 2014).

BIM and sustainable building design not only can control energy consumption and reduce environmental effects but also can decrease costs and create a comfortable condition and pleasant living environment (Zhang et al. 2015). Brager et al. (2015) suggested that "If building designers and operators can find efficient ways to allow building temperatures to float over a wider range while affording occupants comfort, the potential for energy savings is enormous".

BIM data files and formats

Data stored in one domain area are often relevant to other domains. Due to the critical lack of information interoperability, it is quite difficult to get a complete cross-domain view of a building in terms of the interaction of data streams in a clear and structured manner. Therefore, significant progress has been made in the area of common data exchange in the building industry with the development of information technology. Today, the Industry Foundation Class (IFC) and Green Building XML (gbXML) are two wide-spread data exchange formats in the AECOO industry and are used between design applications such as BIM and BEPS programs (Kamel & Memari 2018).

Despite both gbXML and IFC formats being used by the AECOO industry, their adoption does not guarantee high-fidelity and meaningful data exchange (Arayici et al. 2018). For instance;

- The gbXML format is not mature enough and has been limited to being used in simple design solutions because of its difficulty to read complex geometries (Bahar et al. 2013). This is one of the major drawbacks in the context of generating reliable models.
- The IFC schema does not capture the ways how information is created and shared by practitioners (El Asmi et al. 2015), (Juan & Zheng 2014). In other words, without a clear procedure and shared understanding between the actors about what information should be encapsulated in the IFC schema the exchange cannot be automatically and correctly transferred by the IFC schema. For this reason, some specific information can be lost during the exchange process.

The development of specifications for BIM data formats does not guarantee a viable solution to the interoperability issue unless there is a clear specification and guidance for information sharing and the integrated use of BIM for performance-based design (Hijazi et al. 2015). To support the use of IFC, BuildingSMART presented framework for Information Delivery Manual (IDM) sometimes referred to as 29481-1 ISO (2010) methodology that captures and integrates the business process while providing detailed user-defined specifications of information that needs to be exchanged at particular points within a project. To address the need and bridge the gaps, the IFC data file is used, as the ultimate aim of this paper to formulate the exchange requirements that will underpin a MVD for BTCS assessment.

Review for the existing related MVDs

The goal of MVDs are to enable data exchange through the IFC standard including geometry and non-geometry

Table 2: End-user input data requirements needed to support BIM based BTCS. These features underpin the IFC exchange model based on the selected Thermal Comfort models that are described in Table 1. The black squares (■) represent the input data that automatically derived at runtime and black lozenges (◆) defined the input data from BIM

Mathe- matical vari- able	Parameter	Unit	Thermal Comfort models				
			P.O. Fanger	M. Hump- hreys	Brager & de Dear	ASH- RAE 55	ISO 7730, 2005
Ta	Air temperature	°C	■	■		■	■
V	Air velocity	m/s	■			■	■
Clo	Clothing insulation	Clo	◆	◆			◆
RH	Relative humidity	%	■			■	■
Tr	Mean radiant temperature	°C	■			■	■
M	Metabolic rate	met	◆				◆
Ra	Outdoor airflow rate required per unit area	l/s/m ²					◆
Ra	Outdoor airflow rate required per unit person	l/s/person					◆
Pz	Zone population	number					◆
Az	Zone floor area	m ²					◆
PA	Partial water vapour pressure	Pa					■
Trm	Mean Outdoor air temperature	°C			■	■	
Top	Operative temperature	°C		■	■	■	
Ra	Radiant asymmetry	°C				■	
Tf	Floor temperature	°C		◆		◆	
Trm	Mean monthly outdoor temperature	°C				■	

data, by creating a view of the data which is specific to the needs of those who will use the information. Defining the specification of these requirements manually is complex and burdensome. To simplify this task, there is a set of MVDs specified as legal subsets of the IFC schema that fulfill defined workflow purposes. For instance, in an MVD addressed to meet the needs of BTCS analysis, the internal spaces parameters are exported from the BIM, while in an MVD addressed to meet visualisation needs, e.g. clash detection, the full geometry is parameterised.

In IFC4 the coordination view has been replaced by two official MVDs releases aligning with the two core use cases of model exchange;

The IFC4 Reference view; is to define a standardised subset of the IFC4 schema, a MVD, that is particularly suitable for some BIM work flows that are based on reference models where the exchange is mainly one-directional. The overall goal of the IFC Reference View is to provide workflows where building information models are to be consumed by the widest array of software applications that do not require modifying geometry. Such applications enable viewing, estimating, building analysis, and other downstream analysis.

The IFC4 Design Transfer View (DTV); targets all

work flows based on models that are handed over to perform in next work flows, allowing modifications of its content.

Table 3 shows comparison between these MVDs. This work adapts the IFC4 Reference view and extends its capability to support BTCS analysis.

IFC MVD creation methodology

The first part of this paper involved the definition of a set of exchange information required to support BTCS at the early stage of the building designs. The next sections define and categorise this information using ISO16739-1:2018, or the IFC data schema representations. The result of the mapping process will be used as a basis for developing an MVD for BIM-based BTCS. In order to classify the target information and create a subset of the IFC4 Reference View, the following steps are taken;

1. specify the related IFC entities based on the categories and subcategories of elements that are required for model exchange. In addition, defining sub-elements that are necessary for establishing the relationships between building elements, for example, *IfcProject*, *IfcRoot* and *IfcSpace* etc;
2. identify the attributes associated with each entity

Table 3: Table comparing the use of IFC as a Reference View or as a Design Transfer View provided by BuildingSMART

IFC4 Reference View (RV)	IFC4 Design Transfer View (DTV)
Goals	
- support the referencing workflow, e.g. the result of the import model is read-only (not allowing modifications)	- support the handover workflow, e.g allowing import model for further modifications.
Scenario includes	
- take-off and cost estimate - clash detection - any analysis-based work flow	- transfer architecture model to engineers - import model into MEP - takeover contractors
In practical applications	
- the exporter's remain the owner - fast export and import - surly validity, no further rework expected	- the owner handed over to receiver - tolerable longer time export and import - allows for further rework

IfcProperty, for instance, property names and property values; and

- define the related objects and the relationship. In an IFC schema, building objects *IfcObject* and their properties *IfcProperty* are linked directly by *IfcRelDefinesByProperties*. The IFC4 Reference View *IfcRelDefinesByProperties* defines the relationships between property set definitions and objects. For instance, a specific property of *IfcPropertySet* can be related to a specific object of *IfcSpace* through *IfcRelDefinesByProperties*, Figure 2. This provides the assignment of an object type and is described by associating single or multiple properties.

Before going into detail on the process of mapping representation exchange requirements, it is important to explain the fundamental concepts and functional parts of the IFC components that set the scene for MVD development.

- Entities are the main nodes of the schema that include; physical elements like *IfcWall* for geometry representation and *IfcActor* for occupants;
- An attribute is basic meta-data about the entity and it where all other information about the entity can be attached;
- The property set is a container class that holds properties within a property tree;
- Properties for element-based entities use an attribute called *HasPropertySets*. This allows a property set (a group of properties) to be assigned to the entity. Within this property set are the individual properties which describe the entity further or describes its performance. The schema already contains a number of defined property sets and properties. An example for the entity *IfcSpace* is the property set

Pset_SpaceThermalRequirements with the property *SpaceTemperature*; and

- A property template defines meta-data for a property including name, description and data type. Data types may be simple such as text or floating-point numbers for particular measures.

IFC MVD mapping process

A number of information items have been identified that can be obtained from an IFC based BIM before transformation to BTCS input data. The sources of this information are:

- Project/Building information;
- Building geometry and Boundary conditions;
- HVAC System information;and
- Space related data.

Project or building entities typically include very generic information that have to be included within the IFC model before it is exported to the BTCS e.g building location, orientation and unit.

BIM geometry mainly consists of three types of information: building geometry, coordinate systems, and geometry-related semantic information. Building geometry is composed of basic building elements (walls, floors, columns, beams, windows, doors and roofs, etc.), which are usually defined as a collection of planar surfaces that enclose thermal spaces.

The geometry related semantic information refers to the geometric/topological features of each surface. They primarily include the building element that the surface represents and the space that the surface belongs to, the relationships between the surface and other surfaces and

Figure 2: The relation between *IfcObject* and their properties *IfcProperty*.

importantly, the condition (i.e. internal space, outdoor or element) of the other side of the building element providing the surface.

Within a BIM, the spaces are volumes that provide for certain functions within a building. A zone is a collection or group of spaces. IFC Zones are different from IFC Spaces insomuch that an *IfcZone* cannot exist without an *IfcSpace*. However, an *IfcSpace* does not need to be associated with a zone. In BTCS tools, e.g EnergyPlus, the zone instances contain the parameters to simulate each thermal zone of the building. Without thermal zones and surfaces, the building cant be simulated. In EnergyPlus, thermal comfort modeling is controlled primarily by the People input object. Input choices include options for selection of the type of thermal comfort model that is desired by the user as well as parameters that serve as inputs to all of the thermal comfort models. While in BIM, most of the parameters that influence thermal comfort levels inside a building can be obtained via *IfcSpace*.

Over the course of defining and extracting related data for spaces, all of the information defined in table 2 are assigned to the *IfcSpace*. The space thermal design defines most of thermal property set for all types of spaces to capture building service design values. However, the existing property sets in *IfcSpace* do not fully support the correct representation needed for BTCS analysis. Therefore, this research defines two additional property sets to overcome the lack of information: *Pset_ExtendSpaceOccupancyRequirements* and *Pset_ExtendSpaceThermalRequirements*, as demonstrated in Figure 3. Under these property sets, six additional properties are defined and added to provide relevant data. The properties e.g. Clothing insulation level (Clo) and Outdoor airflow rate required per unit area (l/s). The definition of property sets describe how sets of properties (usually defined by a name, value, unit triple) are associated to objects or object types, Figure 3. Table 4 provides a detailed description of appropriate representation of ERs mapped to the corresponding IFC4 scheme.

The model shown in Figure 4 is an excerpted version from

Figure 3: Proposed properties to add in the IFC4 Reference View to support the aimed MVD

Table 4: Mapping a set defined parameters to the corresponding IFC parameters, name and data types used for IFC MVD export during the BTCS analysis

Input exchange requirements			Corresponding IFC parameters		
Mathematical variable	Parameter	Unit	Entity	Property set	Data Type
Clo	Clothing insulation	Clo	IfcSpace	Pest_ExtendSpaceOccupancyRequirements	IfcReal
M	Metabolic rate	Met	IfcSpace	Pest_ExtendSpaceOccupancyRequirements	IfcReal
Ra	Outdoor airflow rate required per unit area	l/s/m ²	IfcSpace	Pest_ExtendSpaceThermalRequirements	IfcCountMeasure
Rp	Outdoor airflow rate required per person	l/s/p	IfcSpace	Pest_ExtendSpaceThermalRequirements	IfcCountMeasure
Pz	Zone population	number	IfcSpace	Pest_ExtendSpaceOccupancyRequirements	IfcReal
Az	Zone floor area	m ²	IfcSpace	Pest_ExtendSpaceOccupancyRequirements	IfcReal
PA	Partial water vapour pressure	Pa	IfcSpace	Pest_ExtendSpaceThermalRequirements	IfcCountMeasure
tf	Floor temperature	°C	IfcSpace	Pest_ExtendSpaceThermalRequirements	IfcCountMeasure

Figure 4: The IFC data structure to store semantic for Thermal Comfort data represents IfcSpace objects and their relations defined in an IFC's schema e.g IfcRelSpaceBoundary2nd level and IfcBuildingElement.

the full semantic information of the exchange models with a focus on the *IfcSpace* entity. There are main core elements and containers of elements that store information about building elements in general; therefore, *IfcSpace* is connected to a building coordination system and building envelope.

Discussion

The current potential of BIM for indoor environmental performance assessment is high and is based on literature analysis conducted in this study. BIM supports BTCS analysis because required information about quantities can be exported from the BIM authoring software with the help of. These can be further linked with building geometry and structural elements and building materials. According to Jung et al. (2018) the amount of environmental performance information retrieved from the model with the help of IFC is significant, both in terms of quantities and quality but it may involve further manual handling.

The indoor environmental impact should be assessed based on as-built information, and similarly specific data for the internal spaces (Kim & Yu 2016). At present, the challenge is to find a reliable and interoperable solution by combining BIM-based with BTCS tools for determining comfort levels. This absence causes thermal comfort to be assessed separately from the architects mode.

Regarding development towards performance-based design, the main challenge remains with data exchange between BIM authoring tools and performance assessment tools. To improve data exchange or more specifically the data set needed for different use cases with multiple BIM-based models, more MVDs should be defined and implemented to provide the end-user with the tools and processes they need. However, the implementation agreements such as IDM/MVDs for IFC do not necessarily allow exchanging all that information. At present, assessment and simulation tools are typically being integrated into the model authoring software either one by one or used separately. Therefore, the need for not only technical standardisation but also process standardisation to better understand who should provide each piece of information.

In this work, the application of the MVD is limited for thermal comfort assessment during buildings design phase. However, TC is very complex due to variables in the indoor environments, and the information needed to fully comply with perceived TC measures are too detailed to be captured by an IFC model on one particular dynamic calculation tool. Research efforts are needed in this direction, as TC should not be over looked to be applied only during the buildings design phase.

Based on the interviews conducted by Jung et al. (2018), Energy performance and Thermal Comfort have gained

most of the attention in the tools evaluating the quality of the building design. It remains an open question as to whether if the implementation of MVDs will become common and solve the data exchange challenges.

Conclusions and Future Work

This paper identified and arranged the essential thermal comfort parameters for building designs and formulated an ERs model for BTCS assessment during design processes of high performance buildings. This work presented a novel ERs model for a BIM-based approach to BTCS assessment. In the first task, we defined a specific data representation of the required information necessary for creating IFC ERs models for BTCS. The results of this module are being used as a first step in developing MVD, a concept binding diagrams reuse the existing IFC4 Reference View corresponding to each building entity.

The implementation of this work is expected to be a unique contribution to address the problem of manual rework and its associated knowledge by enabling the efficient and economic creation of Thermal Comfort prediction-based design. Regarding development towards performance-based design, the proposed BIM-based model and MVD provides the AECOO industry with the tools and processes required to support performance-based design along the design process and in early phases.

For future work, once creation and/or modification of MVD is completed, the validation stage can be performed to ensure that the outputs fulfill the requirements. A Ifc-Doc tool checker can be used for this validation. It should be noted that software vendors should first implement the proposed MVD in their BIM platforms so that designers do not need to spend extra time to prepare their models for BTCS assessment.

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Product and Process Modelling

AN OVERVIEW OF CONFIGURATORS FOR INDUSTRIALIZED CONSTRUCTION: TYPOLOGIES, CUSTOMER REQUIREMENTS, AND TECHNICAL APPROACHES

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Abstract

To improve productivity, the construction industry is increasingly adopting methods of industrialized construction. A key strategy to support industrialized construction is to leverage an adaptable product development platform, i.e. a configurator. Although many benefits of configurators (e.g. mass customization) have been witnessed in the manufacturing industry, the application of configurators in construction is limited and immature. This paper reviews eleven configurators in academic research and four configurators in industry practice. First, using a comparative analysis, the authors generalize three strategic typologies of configurators developed and implemented for industrialized construction. Second, stakeholder requirements are identified for each typology. Finally, the technical approaches, including related methods and theories, are reviewed using a framework of three-tier architecture decomposition. The findings contribute to practice by allowing AEC stakeholders to understand strategic typologies and customer requirements for configurators. This can assist in guiding the future development of mass-customized configurators.

Introduction

The current construction industry is filled with opportunities and challenges. According to the 2013 McKinsey Global Institute's report, the world will spend \$57 trillion on infrastructure by 2030 (Dobbs et al., 2013). With increasing demand for a new building market, the industry also faces increasing construction costs, decreasing labour supply, and long development cycles. In response to these challenges, some stakeholders within the industry are exploring the use of industrialized construction. The industrialized construction process draws from lessons of the manufacturing industry. Following a design-manufacturing-assembly approach, industrialized construction assembles buildings comprised of prefabricated components. These components range from structural elements to volumetric modules. They offer competitive pricing, quick turnaround time, and increased quality.

Some pioneering architects are leading the charge (Lubell, 2018). Traditionally, architecture has held to

the stereotype of modular buildings as dull, repetitive and unreliable. Recent architectural design using industrialized construction have been successful to avoid the negative aesthetic perception of "modular", "box-like", or "cookie-cutter" architecture. However, despite some success stories, there is still a steep learning curve that prevents new stakeholders from entering this currently niche market.

Digitalization and automation are key strategies to increase participation. New models of automation can increase efficiency by integration and optimization while enabling new human-machine collaboration and creativity (Pittman, 2018). One such form of automation to increase participation in industrialized construction is the development and use of product configurators. Product configurators, first initiated in the manufacturing industry, are widely applied in many domains, such as electronics, automobile, and aerospace. As a successful application of artificial intelligence, a configurator eases the creation of complex systems by assembling a set of components, or kit-of-parts, under certain constraints within the scope of design specifications, production capabilities and product operative performance. By decomposing the building into subsystems (e.g. floor slabs, walls, roofs, etc.) product configurators enable designers to generate and evaluate a variety of building layouts, while retaining confidence that the final design can be effectively manufactured and assembled using industrialized processes.

However, the application of configurators in construction is limited and immature. Existing configurators do not satisfy many requirements of industry practitioners (Haug, Hvam, & Mortensen, 2012; Nielsen, Brunoe, Jensen, & Andersen, 2017). Furthermore, even though application strategies of configurators have been proposed by some studies, a critical analysis comparing the similarities and differences in configurator approach has not been done. Consequently, without clear knowledge of configurator-based workflow, many construction companies are unwilling to apply configurators in projects, due to the uncertainties and potential disturbance to their original project delivery processes and technical environments. As configurators emerge in the construction industry, there is a need to understand their purpose and application. This

research conducts a comparative review of configuration development and implementation from academia and industry practice. Drawing from eleven configurators in academic research and four configurators in industry practice, we present an overview of configurators for industrialized construction. In doing so, we seek to answer three fundamental research questions:

1. What are the strategic typologies of configurators developed and implemented for industrialized construction?
2. How do these strategic typologies differ in their approach to meet stakeholders needs?
3. What are the technical approaches to develop configurators for industrialized construction?

To answer the above questions, the paper is organized as follows. At first, we presents related concepts and research gaps. Then, the research methodology is illustrated. Next, the results from the study are presented, followed with a discussion. Finally, we provide our conclusion, as well as suggested directions for future research .

Point of Departure

In the late 1980s, due to increased demand for product variety, the manufacturing industry transitioned from mass production to mass customization (Pine II, 1993). Mass customization is a widely adopted business strategy that identify and fulfill customer needs without sacrificing efficiency, effectiveness and low costs (Pine II, 1993). Mass customization maintains the main advantage of mass production, i.e. economies of scale, and meanwhile is enriched and complemented by theories of modularization, product family architecture, and reconfigurable manufacturing systems (Hu, 2013). To achieve mass customization, a crucial technical support, first proposed in the manufacturing industry, is a product configurator. Product configurators have also been referred to as design systems, co-design platforms, and toolkits (Robertson and Ulrich, 1998; Piller, 2004; Salvador and Forza, 2007). A product configurator is an intelligent information system that supports the creation of products with variations using a set of modules, as well as rules influenced by companies' marketing strategies and available resources (Haug, 2007; Aleksic, Jankovic and Rajkovic, 2017). Those modules and rules stored in a knowledge base form a product family architecture (PFA) that drives the product design in configurators (Mitchell M and Jiao, 2001; Blecker *et al.*, 2004; Wikberg, Olofsson and Ekholm, 2014).

Configurators in construction projects

In the construction industry, buildings are one typical type of product. Unlike products in the manufacturing industry, buildings combine both product-level information and project-level information (Ramaji and

Memari, 2016). The product-level information includes prefabricated modules' design dimensions, engineering attributes, and production processes. The project-level information includes site planning, site properties, site-built elements, and on-site activities. Thus, a configurator suitable for construction industry should support both product-level and project-level information management. As the information is stored in Building Information Models (BIMs), configured solutions should be represented as BIMs in different configuration views, with multiple possible design and manufacturing options, as well as construction schedules.

A vast of benefits of applying configurators in construction projects have been illustrated in three aspects: product, process, and people, as shown in Table 1.

Table 1: Benefits of Configurators applied in industrialized construction

	Benefits of Configurators
Product	Increases flexibility (Thuesen and Hvam, 2011; Jensen <i>et al.</i> , 2014; Bonev, Wörösch and Hvam, 2015; Smiding, E., Gerth, R., Jensen, 2016)
	Ensures product manufacturing and assembly of solutions is possible (Bonev, Wörösch and Hvam, 2015; Said, Chalasani and Logan, 2017; Jansson, Viklund and Olofsson, 2018; Yuan, Sun and Wang, 2018)
People	Minimizes the need for manual involvement (Frank <i>et al.</i> , 2014; Jansson, Viklund and Olofsson, 2018; Lee and Ham, 2018)
	Smooths the learning curve (Jansson, Viklund and Olofsson, 2018)
Process	Reduces time and cost for design and production (Thuesen and Hvam, 2011; Frank <i>et al.</i> , 2014; Bonev, Wörösch and Hvam, 2015; Smiding, E., Gerth, R., Jensen, 2016; Said, Chalasani and Logan, 2017; Jansson, Viklund and Olofsson, 2018)
	Enhances coordination efficiency (Malmgren, Jensen and Olofsson, 2011; Xu <i>et al.</i> , 2018; Yuan, Sun and Wang, 2018)
	Develops construction documents efficiently (Jensen, Olofsson and Johnsson, 2012; Smiding, E., Gerth, R., Jensen, 2016; Jansson, Viklund and Olofsson, 2018)
	Preserves and reuses knowledge for the next product (Frank <i>et al.</i> , 2014; Jensen <i>et al.</i> , 2014)
	Increases reliability of schedule (Wu <i>et al.</i> , 2010; Larsson <i>et al.</i> , 2015)

However, most implementation strategies of configurators in the academic study are only validated by one or two construction projects, and several are only tested within certain building systems, such as wall systems (Smiding, E., Gerth, R., Jensen, 2016; Said, Chalasani and Logan, 2017). Often, existing configurators are tailor-made for companies after a

long period of development cycle, leading to investment risk and high initial software cost. In this context, the limitations of configurators can only be partially exposed and may not be representative to support future development. This results in several unknowns regarding the implementation of configurators. It is unclear when, how, and for whom configurators should be developed. Furthermore, there is need to develop our understanding of how configurators can meet the requirements of AEC main stakeholders, including clients, designers, manufacturers and assemblers. Finally, it is necessary to understand the common technical approaches used to develop configurators.

Methodological Approach

To investigate these gaps, this paper conducts a preliminary review on the development and application of configurators in the construction industry. We first review eleven academic papers that describe the development of configurators to generate mass-customized products in the AEC sector. However, due to the nature of academic research, many of the proposed configurators are still at the conceptual or testing stage. We therefore supplement our review with four existing web-based housing configurators from industry practice. We analyze the trial or demo version of these existing commercial web-based configurators.

Source Data

The data for this comparative review comes from two main sources. First, we identify previous academic literature in which industrialized construction products are configured. The literature was gathered if it meets two criteria. Firstly, because the term “configurator” is not widely adopted in AEC literature, we widen the literature search to also include several similar concepts such as platforms and design system that are identified in the academic literature. We categorize those IT tools into configurators if they are in line with the following definition: “a software package composed of a knowledge base that stores the generic model of the product and a set of assistance tools that help the user find a solution (Aldanondo and Hadj-Hamou, 2003)”. Secondly, since our goal is to study how configurators could be used in the AEC sector, we further narrow the literature to only include configurators for construction, with a specific focus on industrialized construction (otherwise referred to as prefabrication, preassembly, modularization, and/or off-site fabrication). Eleven research studies, including nine journal papers, and two conference papers, are identified in the literature. They represent configurators of building products and services from a variety of AEC sectors (see Table 2).

Next, we identify existing cases of configurators from

industry in order to supplement early research concepts with more advanced-stage implementation cases. We identify four web-based housing configurators, which were commercially available and had demo or trial software available for testing (shown in Table 3). By configuring a simple product sample from start to finish, the authors can evaluate the configurators’ functionalities and limitations.

Table 2: Configurators in the previous academic research

AEC Sector	Configured Product
Design (Yuan, Sun and Wang, 2018)	Precast concrete buildings
Design (Taborda <i>et al.</i> , 2018)	Floor plans
Design (Farr, Piroozfar and Robinson, 2014)	Curtain wall systems
Real Estate Developer (Velooso, Celani and Scheeren, 2018)	Floor plans
Manufacturer (Bonev, Wörösch and Hvam, 2015)	Precast concrete panels
Manufacturer (Said, Chalasani and Logan, 2017)	Timber walls
Design & Construction (Jansson, Viklund and Olofsson, 2018)	Floor plans
Design & Construction (Wikberg, Olofsson and Ekholm, 2014)	Buildings
Engineering Consulting (Jensen, Olofsson and Johnsson, 2012)	Timber walls & floors
Construction (Wu <i>et al.</i> , 2010)	Construction schedules
Design & Engineering (Wee, Aurisicchio and Starzyk, 2017)	Plant rooms

Table 3: Commercial web-based configurators

Web-based Configurator	Configured Product
HiStruct	Steel structures
AGACAD	Wood & Precast concrete elements
Creatomus	Private homes and apartments
My Projectfrog	Wood panelized buildings

Comparative Analysis

From the fifteen identified cases, we conduct a comparative analysis. First, we assess the characteristics of each configurator, along the following five dimensions:

- Who are the main users of the proposed configurator? (who?)
- When are configurators used in a project? (when?)
- How is configuration performed / what are the

key activities? (how?)

- What are the typical targeted products suitable for each strategy? (what targets?)
- What are the expected outputs generated by configurators? (what outputs?)

The result of this comparative analysis is the identification of three strategic typologies.

Second, for each strategic typology, we assess which customer requirements each configurator in our analysis attempts to meet. The requirements include the perspective of the client/owner, the designer, the manufacturer, and the assembler for the project. Through this, we try to understand how the strategic typologies of configurators attempt to meet the customer requirements of the many fragmented stakeholders found in AEC.

Third, we consider that the development and application of configurators are likely interlinked. We next evaluate each of the fifteen configurators by their technical approach. We do so using a framework of three-tier architecture decomposition (Figure 1), widely adopted in software architecture for web applications. The three-tiers include (1) the presentation tier, (2) the application tier and (3) the data tier. The presentation tier consists of a graphical user interface (GUI), which receives input and displays the different model views to users. Through API requests, the presentation tier calls the application tier to carry out core functionalities provided by configurators. The application tier visits the data tier, which stores a single source of truth (SSOT) of information managed in configurators. This separation between data and applications enables much flexibility for development teams to upgrade, add or replace components in other tiers. The resulting comparison summarizes and analyses the technical approach for configurators from each these three tiers.

Figure 1: Three tier architecture of a configurator

Findings

This section presents the results of the above analysis. First, we demonstrate three strategic typologies of how configurators are implemented in projects. Then, we present what customer requirements each type of configurators could fulfill. In the end, we illustrate how to organize the software architecture of configurators by three tiers to satisfy those requirements.

Strategic Typologies of Configurators

From our review, three different strategic typologies emerge (Table 4).

Table 4: Typologies of configurators in the construction industry

	Typology 1	Typology 2	Typology 3
Who	Real estate developers, Landscape planners, Architects	Architects, Engineers, Fabricators	Engineers, Fabricators
When	Concept design before creating BIMs	Design stage when creating BIMs	Detailed design after creating BIMs
How	1. Codify configuration logic 2. Generate configuration by low-level representations 3. Convert the representations to BIMs in CAD applications	1. Codify configuration logic 2. Enter configuration parameters into the UI of a plugin 3. Generate BIMs, as well as documents automatically in CAD applications	1. Codify configuration logic 2. Perform component optimization on the developed BIMs 3. Cluster components with similar sizes and apply standard modules with higher performance
Target	Site plan, Floor plan	Prefab elements	Prefab elements
Output	Sales models	3D parametric models	Standard modules
Cases	MyProjectfrog, HiStruct, Creatomus	AGACAD	-
	(Wikberg, Olofsson and Ekholm, 2014; Jansson, Viklund and Olofsson, 2018; Taborda <i>et al.</i> , 2018; Veloso, Celani and Scheeren, 2018)	(Jensen, Olofsson and Johnsson, 2012; Farr, Piroozfar and Robinson, 2014; Yuan, Sun and Wang, 2018)	(Said, Chalasani and Logan, 2017; Lee and Ham, 2018)

Typology 1 represents configurators for projects at the planning stage. Stakeholders for typology 1 typically include real estate developers, architects, and landscape planners. The major objective of applying configurators is to generate diverse development plans, such as site plans and floor plans, for decision-makers to select. Because engineers typically do not participate in this step of the process, the plan representations can be graphic illustrations with low-levels of detail, such as images and wireframes. Compared with a traditional design strategy, the reviewed literature claims two advantages. First, real

estate developers allow customers to interactively design their desired houses by offering available selections based on the companies' capability and economic analysis. Second, intelligent algorithms can identify more feasible or advantageous floor plans using the embedded configuration rules. Some configurators can convert these representations to building information models, which could be exploited to build a linkage between the sales stage and the design stage.

Typology 2 represents configurators at the project design phase. This is the most widely-applied situation for configurators. In this scenario, architects, engineers, and fabricators are involved. The targeted products include prefabricated modules, assemblies, and parts. Users need to define related rules and constraints by configurators in advance. Usually, the rules and constraints can be stored and reused for future product development. The effort spent on this process depends on the complexity of products and the configurators' rule translation capabilities. Once those rules are embedded in the system, operators just need to enter the necessary design parameters via a user interface. 3D building information models can then be automatically generated, along with related data and documentation such as G-codes for NC machines, permit drawings, and a manufacturing bill of materials.

Typology 3 is less applied in commercial configurators than the other two typologies. Related research work has been done in the design for manufacturing and assembly (DfMA) domain. Engineers and fabricators usually adopt DfMA principles in the detailed design stage before the manufacturing process. To gain the scale of economy as much as possible, users perform component optimization on the prefabricated parts by configurators. The main procedures involve clustering components with similar geometric features and assigning standard modules to each cluster with higher building performance, such as structural capacity. As a result, the degree of standardization increases. However, due to a lack of M&A knowledge base, designers seldom consider DfMA in the early design stage, when decisions greatly affect the project performance, such as ease of manufacturing and assembly, project cost and duration, quality issues, etc.

Customer requirements for Configurators

To support the selection of configurators, we match the above three typologies with customers' requirements from main stakeholders, including clients, designers, manufacturers, and assemblers. In Table 5, we review which are the customer requirements for each typology. We use "●" to represent the requirements met by configurators in academic research (Table 2), and "▲" for the requirements met by commercial configurators (Table 3).

Table 5: Customer requirements for strategic typologies of configurators

Customer Requirements	Typology 1	Typology 2	Typology 3
Clients			
Visualize design options	●, ▲	●, ▲	●
Select variant types of elements	●, ▲	●, ▲	
Output time and cost estimates	▲		●
Designers			
Perform parametric design	●	●, ▲	●
Perform parts' connection		▲	
Perform structural analysis		●	●
Perform clash detection		●	
Perform component optimization			●
Input building regulations	●	●	●
Input product constraints	●, ▲	●, ▲	●
Output 3D parametric models	●, ▲	●, ▲	
Output engineering drawings		●, ▲	
Manufacturers			
Output production drawings		●, ▲	
Output bill of material		●, ▲	
Output NC operational codes		●	
Assemblers			
Output schedules			
Output assembly instructions		●	
Output site layout			

Three specific findings can be pointed out. First, typology 2 satisfies most of customer requirements. These configurators are targeted at automating AEC specialists' work, which accounts for a large portion of construction activities. Second, some functional requirements exceed the scope of configurators which are defined by manufacturing industry initially, such as shop drawing creation. The reason could be that the AEC sector is fragmented, so an integrated and multifunctional platform is sought by all stakeholders. Third, typology 3 which focus on DfMA is less

realized in existing configurators. One of identified reasons is few design metrics are defined and standardized to measure the manufacturability and ease of assembly for products.

Technical approaches to build Configurators

After addressing the customer requirements, the development process starts with the design of software architecture. Similar to other web-based application, we find that the configurators in our study can be analysed based on three-tier architecture. This includes a Presentation tier, Application tier and Data tier, as shown in Figure 1. The technical approaches to build software components on each tier are described as follows.

- **Presentation tier**

The user interface (UI) on this tier enables customers to be involved in the design process. Determined by product specification processes, the UI enables different levels of freedom for the non-expert and expert collaborative design. The main product specification strategies are select variant, configure to order, modify to order, and engineering to order. With the delaying of the customer order decoupling points, the design flexibility enabled by UI becomes more limited. There are four typical design activities, namely selecting standard elements, editing design parameters, arranging spatial layouts, and defining configuration rules. Table 6 presents the relationship between customer order decoupling points (CODP) of web configurators and corresponding available design activities.

- **Application tier**

The application tier, also called business logic tier, process main functionalities of configurators. Each of function could be programmed as a reusable component. Here, a component is a software “unit”, which could be a block of reusable code or an independent application, so as to support the customized combination of multi-functionalities required by different customers. In this research, the

rule definition component and product planning component are reviewed based on previous configurators. Other application components found (e.g. economic calculation, 3D model creation) are not included in this research.

The rule definition component takes charge of translating the knowledge from domain experts to computer operable language to guide the product configuration. Technical approaches to formalize the configuration knowledge includes the parameter-driven approach, constraint satisfaction problems (CSP), shape grammars, and genetic algorithm. Table 7 shows what types of rules embedded, as well as how those rules are represented and formalized in examined configurators. The component can be built via either API functions and general programming languages, such as Autodesk Revit API, or CAD built-in functions, such as the Boolean operators used in TactonWroks Studio.

The product planning component guides engineers in building a product architecture, which is made up of independent modules and modules interfaces (Jensen, Olofsson and Johnsson, 2012). Here, a module is a cluster of building elements which could be produced by mass production approach. Mechanisms that indicate a strategic reason that a module should be created are called module drivers (Lange and Imsdahl, 2014). Previous studies have highlighted that modularization is the foundation for product planning in the climate of mass customization, and various approaches have been proposed to tackle various module drivers. For example, Wee et al. (Wee, Aurisicchio and Starzyk, 2017) made use of three tools, including Design Structure Matrix (DSM), Modular Identification Matrix (MIM) and Generational Variance Index (GVI) to build module-based product architecture of plant rooms based on 15 module drivers, including technical specification, common unit, transportation, maintenance, etc. Said et al. (Said, Chalasani and Logan, 2017) set up a genetic algorithm to cluster timber walls with similar geometry for fabrication efficiency.

Table 6: Design activities under various CODP scenarios

Configurators	CODP	Select standard elements	Edit design parameters	Arrange spatial layouts	Define configuration rules
Creatomus	Select variant	Available	Limited	Not applicable	Not applicable
My Projectfrog	Configure to order	Available	Available	Limited	Not applicable
HiStruct	Modify to order	Available	Available	Available	Not applicable
AGACAD	Engineer to order	Available	Available	Available	Available

Table 7: Configuration rules' representation and formalization

Configurators	An example of Configuration rules	Rule representation methods	Programming tool
Floor plan configurator (Taborda <i>et al.</i> , 2018)	The kitchen must be placed either at the front of the house or next to the living room	Genetic algorithm	Java
Floor plan configurator (Velooso, Celani and Scheeren, 2018)	A spatial division rule is to divide the apartment into private, social and service areas.	Shape grammars	Rhinoceros + Grasshopper
Façade configurator (Farr, Piroozfar and Robinson, 2014)	Variations of forms, materials, openings, and relative locations of openings within the façade	Parameter-driven approach	Revit built-in functions and families
Scheduling configurator (Wu <i>et al.</i> , 2010)	The number of workers, the number of concrete pumps and the number of falsework equipment for pouring concrete	Constraint satisfaction problems	General programming language

• Data tier

The central database maintains a single source of truth (SSOT) of information managed in configurators. The rule definition component, product planning component, and other applications store and retrieve data here. However, few configurators separate their database from various applications. In that case, any updates occurring in one place - such as 3D models in Revit – cannot be reflected in other scenarios, such as bill of materials (BOM) in PDM systems. As a result, repetitive data exchange between various applications is necessary and data inconsistency is inevitable. To solve the issue, a neutral data format or schema would be needed for cloud-based cross platforms (Afsari, Eastman and Castro-Lacouture, 2017).

Discussion

Industrialized construction is gaining more share in the construction market. More stakeholders adopt this approach by delivering their products from design to manufacturing and assembly. Configurators provide a common environment to integrate data, functions and processes during the project life cycle. However, due to the lack of scalability, the examined configurators can only be fit for one generation of products from one company. This requires a better understanding of customer requirements and product upgrading knowledge.

This paper makes a contribution to practice by allowing AEC stakeholders to understand their strategic typologies and customer requirements of configurators from Table 5. This can assist in guiding the future development of customized configurators. Without further development in academia and in practice, it is unlikely that the potential benefits of configurators can be adopted by greater segments of the construction industry.

Conclusions and Future Work

Configurators are important IT systems that support mass customization. This paper presents a preliminary review of the development and application of

configurators in the construction industry. Based on fifteen configurators, we first generalize three typologies of configurators by clarifying when, how and for whom the configurators are developed for. Next, a framework of customer requirements for construction configurators is proposed to understand what customer requirements could be met by each type of configurators. Finally, to support the further development of configurators, we review the technical approaches, including related methods and theories, to build each component of configurators from three aspects, i.e. Presentation tier, Application tier and Data tier.

Future research should be done in two perspectives. First, an integrated framework of configurators should be studied. Stakeholders in the construction industry are seeking for an integrated and multi-functional platform to support design, manufacturing and assembly processes. However, examined three types of configurators could only fit for a certain phase of projects lifecycle, and lack connections between each other. Second, previous studies identify multiple module drivers, such as module connections, transportation distance and production time (Anvari, Angeloudis and Ochieng, 2016; Said, Chalasani and Logan, 2017; Salama *et al.*, 2017). However, due to the uniqueness of construction projects, module drivers should be identified, and more importantly, quantified for different building types. In the end, those drivers could be embedded into the configurators, so as to optimize the modular architecture of buildings.

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RELATING GEOMETRY DESCRIPTIONS TO ITS DERIVATIVES ON THE WEB

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Abstract

Sharing building information over the Web is becoming more popular, leading to advances in describing building models in a Semantic Web context. However, those descriptions lack unified approaches for linking geometry descriptions to building elements, derived properties and derived other geometry descriptions. To bridge this gap, we analyse the basic characteristics of geometric dependencies and propose the Ontology for Managing Geometry (OMG) based on this analysis. In this paper, we present our results and show how the OMG provides means to link geometric and non-geometric data in meaningful ways. Thus, exchanging building data, including geometry, on the Web becomes more efficient.

Introduction

The exchange of building data in a Semantic Web context is of growing interest for researches related to the construction industry. However, current results mainly focus on non-geometric or topological building data, as can be seen in Pauwels et al. (2017). The description of geometry on the Web is lagging behind compared to the developments in other fields of interest to the construction industry, hindering the exchange of complete building data using Semantic Web technologies.

To our knowledge, conducted research on the topic of geometry representation in a Semantic Web context is lacking unified and meaningful connections for geometry descriptions. This affects the relation between (building) elements and their geometry description as well as dependencies between geometry descriptions and properties derived from it (e.g. volumes, dimensions, and areas) or other derived geometric representations (e.g. a bounding box derived from a chair geometry). Nonetheless, these dependencies are needed on every-day basis to ensure data integrity during modelling, exchange and collaboration processes and have already been discussed for geometry descriptions outside of the Semantic Web domain (Mirtschin, Jon 2018) as well as inside of it (Zhang et al. 2017). This shows the need for an approach to enable the creation of such substantial connections between geometry derivatives and

their origins within a Semantic Web context.

To fulfil this requirement, this paper aims to serve as a foundation for further research to ensure the integrity of geometric data on the Web and therefore summarises different use cases that may occur in this background while also proposing an approach on how to model the observed relations. Our approach is based on an analysis of necessary relations between geometry descriptions and their derivatives to create a meaningful vocabulary to express them. Further, we investigate the publicly available Ontology for Property Management or OPM¹ (Rasmussen, Lefrançois, Bonduel, Hviid & Karlshøj 2018) regarding its applicability towards geometry descriptions, as we understand geometry description to be a specific kind of property of an object.

Next, we conduct a literature review of existing approaches for connecting different geometry representations and related fields such as property management. This is followed by an analysis of the three different types of geometric dependencies we identified: 1) between an object and its geometry, 2) between geometries that describe the same object, and 3) between non-geometric properties and geometry. With these insights in mind, we introduce the Ontology for Managing Geometry (OMG) in detail, after which we review the OMG using example data and competency questions deduced from the previously presented analysis. Finally, we conclude this paper with a discussion of our results and give a brief outlook on the next necessary steps to ensure parametric modelling on the Web.

Related Work

The conducted literature review includes four topics that align with the identified types of geometric dependencies: First, the application of multiple geometry descriptions in the built environment. Second, ensuring data integrity while handling geometry descriptions of different geometry representations. Third, modelling of parametric coherence between geometry descriptions and non-geometric data, and fourth, the representation of data that changes over time.

Beginning with the application of multiple geometry de-

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¹<https://w3id.org/opm>

scriptions, we found that this is – especially in the context of Level of Detail or Level of Geometry – a highly anticipated topic. For example, the CityGML and IFC standards already support multiple geometry descriptions to describe environments and buildings in different levels of detail (Ohori et al. (2015), IFC). The definition of the geometry representations, however, is predefined within these standards. Thus, users are limited in their choice of geometry representations. Especially for as-built BIM this can be a disadvantage, since the as-built geometry is usually captured in point clouds, that are currently not supported by the IFC standard. Therefore, Krijnen & Beetz (2017) propose a point cloud extension of the IFC schema to allow the collection of all building data within one file. While the extension of EXPRESS-based standards seems cumbersome, such an extension could easily be achieved using Semantic Web technologies.

Still, when multiple geometry descriptions are provided for the same object, the risk of data discrepancies arises unless specific routines are set up to ensure data integrity. One option to do so is presented in Pauwels et al. (2011), where the authors propose a methodology to convert geometry descriptions of different geometry formats using a Semantic Web interface. Yet, the authors suggest to create this conversion on the fly instead of storing both geometry descriptions persistently. This may be suitable if the second geometry description is rarely needed and serves for archiving or exchange purposes only. In the latter case, this would still hold the disadvantage that the link between the original geometry description and the converted one might get lost during the exchange. For these reasons, we suggest to keep all geometry descriptions attached to the object, though algorithms and methodologies as the one presented by Pauwels et al. (2011) could be applied for keeping the data consistent.

When it comes to keeping the data consistent, one must also consider the relations between non-geometric and geometric data, as those are commonly dependent from each other. Correspondingly, data integrity is already an issue for building models that only contain one geometry description, e.g. when the height of an element is also described as a non-geometric property. To ensure data integrity, these dependencies must be described in detail to update the data accordingly. In a Semantic Web context, Zhang et al. (2017) introduce BimSPARQL to automatically retrieve a selection of properties that can be derived from the object's geometry description. They propose a new vocabulary with underlying SPARQL functions to enhance querying building data. However, this approach only takes specific properties into account and must be extended for the introduction of new dependencies. Another approach was presented by Wagner et al. (2018), in which the authors present a product ontology including

parametric coherences between geometry descriptions and non-geometric properties. With this approach, any relation can be modelled using an ontology dedicated to describe equations and mathematical operations. Nonetheless, the described equations need to be translated and executed by a math kernel to generate the desired output. Both approaches allow additional relations between non-geometric and geometric data, but are lacking methods to easily identify outdated data and thus must be executed every time the data is queried. By storing the calculated results within the data and keeping it synchronised, handling (parametric) dependencies would become simpler and more effective. Apart from the efforts made in the construction industry, ontologies from different domains – such as the PROV ontology² – introduce concepts to describe such derivations persistently.

In order to keep dependent data synchronised, it must be possible to model data that evolves over time. While it has been an objective in research to create methodologies to keep track of the evolution of ontologies in general, these approaches (e.g. Pittet et al. (2014)) focus on the ontology's schema level (TBox) and can therefore not directly be applied to instance level (ABox). Within the W3C Linked Building Data Community Group (W3C LBD CG)³, efforts have been made to allow version control of properties. The basic idea of the group was to allow the modelling of properties on three levels with different options for adding metadata (Bonduel 2018). On the first level, the property is directly connected to the building object using individual datatype properties for effective querying. Additional information, e.g. the used unit, could be described using custom datatypes (Lefrançois & Zimmermann 2016). The second level introduces an intermediate node for the property which contains the property's value and can also hold additional metadata, e.g. the used unit, the author, or the timestamp of the property's creation respectively last update. This already allows the inclusion of most relevant metadata, but can still only hold one value for the property, thereby losing older value entries when updating. The third and highest level also enables a persistent recording of the property's history. Between the property node and the property's value, another node for the property state is inserted. Thus, one property can have multiple states – and with that values – while during queries only the current state would be retrieved unless the user defined otherwise. This third level for property modelling can be realised using the Ontology for Property Management (OPM, Rasmussen, Lefrançois, Bonduel, Hviid & Karlshøj (2018)).

The OPM and three levels approach of the W3C LBD CG provide methods to address some of the core features

²<http://www.w3.org/ns/prov>

³<https://w3c-lbd-cg.github.io/lbd/>

desired for relating geometry descriptions to their derivatives, namely a stable, modular and efficient way for adding metadata to properties and keeping track of their change history. Since we understand geometry to be closely related to properties, the work presented in this paper is oriented towards these approaches and will also use multiple levels for modelling geometry. At the same time, the OPM itself cannot be reused as RDF-based geometry descriptions are not just based on properties but also on concepts (e.g. box, sphere, and so forth). Even non-RDF-based geometry descriptions may depend on multiple files, i.e. OBJ geometries that can be enriched by material descriptions which must be stored in a separate file. Hence, we need to identify all relevant relations that should be depicted to create a new ontology to address all of these collected requirements.

Geometric dependencies

In our analysis, we identified three types of geometric dependencies: (1) the connection between an object and its geometric representation(s), (2) semantically meaningful dependencies between geometry representations of the same object, and (3) relations between geometries and their derived properties. Following, our findings on these dependencies will be explained in more detail.

Geometry descriptions and objects

Discussed dependencies of this paragraph occur between geometry descriptions and the objects they are portraying. For connecting geometry descriptions and objects, no restriction towards the relation's cardinality should be imposed on the user to allow multiple geometry descriptions. However, if multiple geometry representations are connected to one object, these representations should be enriched with metadata to enable meaningful differentiation of them. Ergo, a flexible and modular approach to connect geometry descriptions and objects is needed that enables the addition of different amounts of metadata in respect of the current use case. This could be realised by introducing different levels of this relation, similar as suggested by the W3C LBD CG for property modelling (Bonduel 2018).

At the same time, the connection should be generalised for RDF-based and non-RDF-based geometry descriptions to ease unified querying for geometry. In this regard, the introduction of a geometry context as metadata would further simplify the extraction of a specific kind of geometry model from the entire graph (e.g. planner models).

Moreover, it should be possible – while still optional – to add geometry states to the geometry description for version control purposes. Similar to how version control can be realised by the OPM's property states, geometry states could be introduced. But with RDF-based geometry

descriptions in mind, it does not seem feasible to create a new geometry state for every change on properties within the geometry description. Instead, the OPM could be used to describe such property changes, while changes on (object) node level (e.g. class types, deletion of nodes) must be recorded by the geometry state.

Geometry descriptions of the same object

This category covers dependencies between geometry descriptions only. Relations between geometry descriptions of the same object mainly focus on the definition of which description can be derived from another. In some cases, this relation may be bidirectional, allowing to convert the geometry descriptions back and forth. Additionally, when version control is wanted, this relation should also be manifested on geometry state level, defining the conducted derivation of the specific geometry states. Without relations on state level, unnecessary derivations or even endless loops of deriving geometry descriptions from each other may occur, as they are derived based only on timestamps. Also, geometry descriptions that cannot be used to (indirectly) derive any other geometry representation of the same object, should be classified as read-only to prevent changes that cannot be deduced back into the data pool.

Apart from relations to describe derivabilities, geometry descriptions can also be dependent on each other in different ways. For example, a geometry description could serve as a supplement for another one, as is often the case in heritage models. The underlying geometry description is stored in a simplified mesh or solid geometry, while details are represented in point clouds. It is not always feasible, wanted or even possible, to convert fine details to other geometry representations, so it should be possible to model some kind of relation where one geometry description supplements another.

Another type of relation would be the reuse of previously defined geometry descriptions. This may happen in one of two ways: Either the first geometry description is reused without changes, e.g. when multiple instances of one object type such as a particular kind of chair are placed within a model, or when the first geometry is used as a basis for further development, while the original geometry is still needed as it was modelled before. An example for this would be a bounding box created in the early planning stages to induce the idea of a chair within a room which is subsequently modelled in more detail based on the original bounding box. Since the bounding box representation may still be of relevance for simulation use cases, it should not be overwritten. In both cases, the relation is purely informative and does not contain any further details on possible derivations. If such dependencies are required, they have to be modelled separately.

Geometry descriptions and derived properties

The last category of geometric dependencies is between geometry descriptions and their derived properties. Such derivations may be implicit or explicit. As an example, the height of a wall may be explicitly defined in the wall's geometry description (e.g. if it is an extrusion), while it is commonly also described as a non-geometric property. To avoid redundant and conflicting data, the non-geometric property should be linked to the geometric property.

Implicitly derived properties, on the other hand, can not be derived from one singular geometry property, but require mathematical evaluation of the geometry (e.g. the volume of the wall, which is dependent on the base area, extrusion and possibly even voids within the wall). To emphasise this relation, the property should be connected to the geometry description itself. However, the calculation of the new property value after changing the geometry, must be calculated externally.

Ontology for Managing Geometry (OMG)

Based on the previous analysis and the concepts and methods presented in the OPM ontology, the Ontology for Geometry Management (OMG)⁴ was developed. The ontology is also publicly available on GitLab⁵.

The OMG ontology aims to provide means to connect geometry descriptions to building data and relate geometries with derived or dependent geometries and properties. To create a more concise ontology, we defined that the exact description of parametric dependencies, algorithms to derive geometry representations from each other, and the geometry description itself are out of scope of this ontology.

Within the OMG, several concepts from other ontologies were reused. Furthermore, the example data contains additional schemata, e.g. for geometry descriptions. To ease the understanding of the upcoming figures and examples, Listing 1 introduces all used ontologies and prefixes in this paper.

```
@prefix omg: <https://w3id.org/omg#> .
@prefix fog: <https://w3id.org/fog#> .
@prefix opm: <https://w3id.org/opm#> .
@prefix prov: <http://www.w3.org/ns/prov#> .
@prefix seas: <https://w3id.org/seas/> .
@prefix schema: <http://schema.org/> .
@prefix bot: <https://w3id.org/bot#> .
@prefix geom: <http://rdf.bg/geometry.ttl#> .
```

Listing 1: Used ontologies and prefixes.

The OMG enables – similar to the proposed property modelling by the W3C LBD CG (Bonduel 2018) – the modelling of relations between objects and geometry on three

levels. While the first level provides means to directly connect geometry descriptions to objects, the levels 2 and 3 introduce additional intermediate geometry and geometry state nodes to allow metadata to be attached to the geometry. Within the following figures of the OMG architecture, objects, properties and classes that are not part of the presented OMG ontology are greyed out for better understanding of the new concepts.

Figure 1 depicts how geometry can be connected to an object using the OMG level 1. The two proposed properties `omg:hasComplexGeometryDescription` and `omg:hasSimpleGeometryDescription` can be used to link to the first node of an RDF-based geometry description or to add non-RDF geometry descriptions as literals or paths to external files. Since these relations are generic and hold no information about the used geometry format, individual relations should be introduced as subproperties for used geometry formats and their versions. For this purpose, the File Ontology for Geometry formats (FOG)⁶ ontology was created (Bonduel et al. 2019) and can be further extended in its openly available GitHub repository⁷.

Figure 1: OMG level 1.

If more metadata needs to be added to the graph, the OMG level 2 includes the `omg:Geometry` and `omg:GeometryContext` classes. A geometry node can be connected to a geometry context and other geometry nodes (dependencies), and can be used to enrich the geometry description with metadata as the author or timestamp of creation using other ontologies as the PROV ontology or schema.org. The geometry description itself can then be attached to the geometry node with the same properties as those introduced for OMG level 1. A potential layout of a graph with a OMG level 2 description can be seen in Fig. 2.

Any object can be connected to one or multiple geometry nodes using the `omg:hasGeometry` relation. If multiple geometry nodes are applied, it is possible to relate them to each other to describe their dependencies. For instance, geometry nodes can be linked using `omg:isDerivedFromGeometry` to indicate that the first geometry has been derived from the second.

For cases where one geometry complements another, as is often the case with point clouds and tessellated ge-

⁴<https://w3id.org/omg>

⁵<https://gitlab.iib.tu-darmstadt.de/Wagner/omg.git>

⁶<https://w3id.org/fog>

⁷<https://github.com/mathib/fog-ontology>

Figure 2: OMG level 2.

ometries, the `opm:complementsGeometry` relation can be used. However, note that this relation does not imply any dependencies on the geometries' derivations. Additionally, the `omg:transformsGeometry` relation can connect geometries that share the same base geometry but are placed in different locations. This might be the case for geometries of the same object, where one geometry representation is placed in its local coordinate system and other geometries reuse the original geometry and place it in different global or other local coordinate systems. Another example would be multiple instances of the same geometry like doors or windows. If this relation is used, the connecting geometry node should only contain information about the transformation, e.g. a transformation matrix, while the geometry description itself should be defined in the connected, original geometry node. Finally, a geometry context can be related to a geometry node with the `omg:hasGeometryContext` property. By using a geometry context, the extraction of multiple geometry descriptions from an entire graph that are relevant for a specific use case can be simplified.

The last level also includes concepts to manage evolving geometry descriptions. An overview of OMG level 3 is shown in Fig. 3. It introduces the new class `omg:GeometryState`, which is closely related to the `opm:PropertyState` and can also be connected to a geometry context. Inspired by the idea of the `opm:CurrentPropertyState`, the OMG also introduces a subclass for the geometry state to define those states that are currently valid: `omg:CurrentGeometryState`.

A geometry state describes an object's geometry at a specific point in time, which poses the requirement of adding a timestamp to each geometry state. Using the `omg:hasGeometryState` relation, one or more geome-

Figure 3: OMG level 3 – overview.

try states can be related to a geometry node. When OMG level 3 is applied, the geometry descriptions are connected to the geometry states. As soon as the geometry description is changed, a new geometry state with the changed description should be added. However, since it is not feasible to create a new geometry node with a copy of widely unchanged RDF-based geometry descriptions when only one property of the description changes, the OMG ontology should be combined with the OPM ontology for RDF-based geometry descriptions. Thus, geometry states can be connected to any geometry object within the geometry description using the `omg:containsGeometryObject` relation. Subsequently, the chain property `omg:containsPropertyState` will infer a link between any property states of the geometry description and the geometry state itself based on the former relation and the OPM architecture (see Fig. 4).

Figure 4: OMG level 3 – geometry states.

Apart of keeping track of current changes, geometry states can also be used to enhance the definition of geometry derivations as was introduced in OMG level 2.

As shown in Fig. 5, this definition takes place on two layers: between geometry nodes and between geometry state nodes. In contrast to the application of the `omg:isDerivedFromGeometry` property for level 2, this property is now used to indicate the *possibility* to derive a geometry. Thus, one geometry node may have multiple other geometry nodes connected this way and in case of bidirectional dependencies, the property can be added twice between two nodes, pointing in different directions. To define the specific derivation of one geometry state, the `omg:isDerivedFromGeometryState` property is introduced.

Figure 5: OMG level 3 – derived geometry states.

To correctly model these dependencies, any modified (changes on property level of an RDF-based geometry description) or new geometry state (changes on object level of an RDF-based geometry description or changes in non-RDF-based geometry descriptions) should be modelled without the `omg:isDerivedFromGeometryState` property first. This means for the case of modified geometry states, that this property must be removed. Afterwards, geometry states must be connected to a description's geometry state using the `omg:isDerivedFromGeometryState` property if they were modified or created by derivation of that geometry description. With this approach, infinite loops while updating geometry descriptions can be prevented: Since newly generated geometry descriptions will be stored in a new state, this state's timestamp will be more current than the one of the initially changed geometry state. If the dependency is modelled bidirectionally, this may cause a loop. Thus, the new relation was defined to pinpoint the origin of a new geometry state and will ensure that the new state will not cause its origin's update. If the state was created because of manual changes, this relation will not be used and thereby the data discrepancy can be detected.

Independent of the OMG levels, relations dedicated to describe dependencies between geometries and properties are defined. As mentioned before, we differentiate between explicit and implicit dependencies. Figure 6

depicts the introduced relations for the first case. The `omg:isExplicitlyDerivedFrom` property connects two `seas:Property` nodes – one of the semantic description of the object and one of the geometric description. Based on this relation and the architecture of the OPM, the chain property `omg:hasInferredPropertyState` will infer the relation between the derived property and any `opm:PropertyState` of its origin property.

Figure 6: Explicit property derivation.

The relation for implicit dependencies is simpler, as no values or states can directly be inferred. Instead, the `omg:isImplicitlyDerivedFrom` property connects any property to a geometry node (see Fig. 7).

Figure 7: Implicit property derivation.

Recommendations for using OMG

When applying the OMG, we recommend to first evaluate the requirements of the considered (part of the) project before defining which level will be used to avoid unnecessary overhead or too rigid data structures. The functionalities of the different levels are also shown in Table 1.

Note that it is in principle possible to attach multiple geometries to a building element using OMG level 1. However, since it is not possible to define derivations between or geometry contexts of geometry descriptions in general,

Table 1: Functionalities of the OMG levels.

Functionality	level 1	level 2	level 3
Connecting geometry	yes	yes	yes
Multiple geometries	no*	yes	yes
Defining derivations	no	yes	yes
Defining context(s)	no	yes	yes
Version control	no	no	yes
Explicit properties	yes	yes	yes
Implicit properties	no	yes	yes

and – even worse – to describe differences between multiple geometry descriptions of the same format, we highly recommend not to do so. Additionally, when non-RDF-based geometry descriptions that require multiple literals are attached directly to the object, it might be problematic to identify which literals belong together, especially when multiple geometry representations are attached using OMG level 1.

For version control on complex, RDF-based geometry descriptions (OMG level 3), we also highly encourage the combination of the OMG with the OPM to prevent unnecessary duplicates of geometry descriptions when only one value changed.

Alignment of OMG

Since the OMG was designed as a generic ontology to attach geometry to any object, it can be used in any field of application in principle. However, as we originally designed it to support the application of linked building data, we propose alignments to mostly building specific ontologies in this section.

The biggest overlap of the OMG is with the OPM. The concepts of both ontologies are strongly related, however, since geometry cannot be classified as a subtype of properties, it did not seem feasible to extend the OPM ontology. Thus, we suggest to create an upper level management ontology to pool both OPM and OMG with their concepts – especially the property and geometry states – together. This would enable concepts of the OPM that are also applicable to the OMG, e.g. `opm:Deleted` or `opm:Assumed`, to be transferred to the upper level ontology and thus be used by both, OPM and OMG. Also, the introduced `omg:hasInferredPropertyState` property should be transferred to the OPM, since it is mainly using concepts, classes and relations of the OPM.

Another close relative of the OMG is the File Ontology for Geometry formats (FOG), that extends the OMG to create file format and ontology specific subproperties of the `omg:hasComplexGeometryDescription` and `omg:hasSimpleGeometryDescription` properties.

In the background of the built environment, another

important alignment is towards the Building Topology Ontology (BOT). The BOT already introduces properties to describe RDF- and non-RDF-based geometries to building elements or zones: `bot:hasSimple3DModel` and `bot:has3DModel` (Rasmussen, Frausing, Hviid & Karlshøj 2018). However, since these relations confine to 3D geometry, while the OMG can also be used to connect 2D geometries, we refrained in reusing those properties. Instead, we suggest to rename the properties to `bot:hasComplexModel` and `bot:hasSimpleModel` and align them with the OMG properties `omg:hasComplexGeometryDescription` and `omg:hasSimpleGeometryDescription`. While aligning these properties, one should consider the consequences of `owl:equivalentProperty` regarding the property's range and domain restrictions. Another option would be to remove these properties entirely from the BOT ontology and instead use the concepts introduced in OMG.

Furthermore, all properties that indicate (parametric) dependencies of geometries and other geometries or properties are defined as subproperties of the `prov:wasDerivedFrom` property of the PROV ontology.

Proof of concept

To prove the functionalities of the OMG ontology, an openly available *SPARQL-visualizer* demo was created to address the underlying competency questions of the ontology⁸. The demo provides example data that can be used for all of its steps. However, for the more complex steps, i.e. manipulating the database or querying with reasoning, a Stardog triplestore must be connected to the visualiser. The competency questions (CQ) that are answered by the demo are explained next.

CQ1: How can a single geometry description be connected to an object directly?

This question is used to demonstrate the simplest functionalities of OMG as might be of use for data exchange. It can be fulfilled by using OMG level 1 as shown in Fig. 1 and serves as the basis for all other competency questions and functionalities.

CQ2: How can multiple geometry descriptions with their dependencies be related to an object?

In case multiple geometry descriptions are required, they must be attached to an object in meaningful ways, allowing the expression of the descriptions' dependencies. Based on this question, OMG level 2 was developed and therefore this level can address it (see Fig. 2).

⁸<https://madsholten.github.io/sparql-visualizer/?file=https:%2F%2Fwww.dropbox.com%2Fs%2Fg1c9oclaxv118ud%2Fomg-demo.json>

CQ3: How can version control of linked geometry descriptions be realised?

Especially during the collaboration process, the version control of geometry – and any content in general – is of utmost importance. Thus, OMG level 3 addresses this topic and can be used to store information about different versions in two different ways, depending on the type of the geometry description: simple or complex (see Fig.3 and 4).

Since the question when a new geometry state should be created and when old ones should be changed is not addressed fully in this paper, this step aims to give better insights into the proposed methodology. It thus also demonstrates how OMG can be combined with OPM.

CQ4: Which are geometries of the same geometry context?

By introducing the `omg:GeometryContext` class, geometries and geometry descriptions can be put in context to ease the extraction of an entire geometric building model for specific use cases (see Fig. 2 and 3). This step demonstrates how such contexts can be added, manipulated and deleted.

CQ5: How can geometries be complemented or transformed?

The properties `omg:transformsGeometry` and `omg:complementsGeometry` allow the definition of complemented and transformed geometries (see Fig. 2). With this definition, it is easy to identify such geometries for further processing during data extraction, exchange or processing.

CQ6: What are the dependencies between properties and geometry?

With the introduced `omg:isExplicitlyDerivedFrom` and `omg:isImplicitlyDerivedFrom` properties and their concepts, meaningful connections between geometry and non-geometric properties can be created. For explicit derivations, the relation between the derived property and the origin's property states can also be inferred by the `omg:hasInferredPropertyState` property, facilitating parametric descriptions (see Fig.6 and 7). The work-flow for doing this is demonstrated in this step of the demo.

CQ7: What is the current timestamp of a geometry state?

This question can be answered in two different ways for simple, non-RDF-based and complex, RDF-based geometry descriptions. Simple geometry descriptions will require a new geometry state for each submitted change which leads to a simple SPARQL query to extract the timestamp. For complex geometry descriptions, however, this becomes more complicated: A new geometry state is

only introduced, when the description changed in its used objects, while changes in geometric properties should be handled using the OPM. Thus, all property states of a geometry state must be evaluated – as well as the geometry state itself – regarding their timestamps and the most current timestamp needs to be returned. This process is simplified by the `omg:containsPropertyState` property.

CQ8: Where are discrepancies within a graph?

Finally, it must be possible to identify data discrepancies such as outdated geometry states that are still labelled as `omg:CurrentGeometryState`. Since this is the most complex and needed functionality of the OMG, tab 8 of the *SPARQL-visualizer* demo shows step-by-step how this topic can be handled with the introduced concepts.

In this demo, it is shown how one column element can be connected to multiple, derived (simple) geometries under version control. Beginning with one STEP geometry, a derived OBJ geometry, followed by a derived COLLADA geometry are added. On geometry node level, possibilities for further derivations are modelled. Since the OBJ geometry is for visualising purposes only in this scenario, it can only be derived. Its possible origins are both, the STEP and COLLADA geometry. The STEP and COLLADA geometries can be derived from each other, as both may be used in modelling software applications. The resulting graph on geometry node level can be seen in Fig. 8.

Figure 8: Example for geometry dependencies.

At this time, each geometry also has one geometry state – classified as `omg:CurrentGeometryState` as well as `omg:GeometryState`. Each state contains information about their time of generation, their simple geometry description and their origin of derivation. An overview of the geometry states without discrepancies can be found in Fig. 9. For better visualisation, the connection towards their geometry nodes are not shown in this picture.

This far, no data discrepancies exist. However, in the next step, a new geometry state for the COLLADA geometry is inserted – this may happen when manual changes are made to the description, e.g. during the planning and modelling phases of a building. Since this state contains changes that

Figure 9: Geometry states without discrepancies.

are not part of the STEP and OBJ geometry states, data discrepancies occur. In order to locate such problems, the data must be queried for them, as is shown in Lst. 2.

```
@prefix omg: <https://w3id.org/omg#> .
@prefix prov: <http://www.w3.org/ns/prov#> .

SELECT DISTINCT ?outdatedGeometry ?originGeometry
WHERE{
  #Find all omg:CurrentGeometryState that are either derived from
  #or deriving geometry states that are not a
  #omg:CurrentGeometryState (and thus outdated)
  ?outdatedGeometryState a omg:CurrentGeometryState ;
  ^omg:isDerivedFromGeometryState|omg:
    isDerivedFromGeometryState ?anyState .
  FILTER NOT EXISTS {
    ?anyState a omg:CurrentGeometryState .
  }
  #Any geometry that either contains the previously identified
  #outdated omg:CurrentGeometryState or has a geometry state
  #that has been derived from it are also outdated.
  ?outdatedGeometry omg:hasGeometryState|omg:hasGeometryState/
    omg:isDerivedFromGeometryState ?outdatedGeometryState ;
  omg:isDerivedFromGeometry ?originGeometry .
  #To ensure that only those origins of change and outdated
  #geometries are listed that are suitable as an origin of
  #change (that are not outdated) respectively are truly
  #outdated, the timestamps are compared
  ?outdatedGeometry omg:hasGeometryState ?someOutdatedState .
  ?someOutdatedState a omg:CurrentGeometryState ;
  prov:generatedAtTime ?outTime .
  ?originGeometry omg:hasGeometryState ?originState .
  ?originState a omg:CurrentGeometryState ;
  prov:generatedAtTime ?originTime .
  FILTER (?originTime > ?outTime)
}
```

Listing 2: SPARQL query to find data discrepancies.

In the given example of the demo, this query will re-

turn the STEP and the OBJ geometry as outdated and the COLLADA geometry as possible origin for each. After the STEP geometry is updated and the same query is run again, the OBJ geometry will return two possible origins for new derivations: The COLLADA and the STEP geometry. Once all geometries are updated, this query will not yield any results. In order to have these queries working, it is essential that the `omg:isDerivedFromGeometryState` property is used properly.

Conclusions

Within the introduced OMG ontology, a unified approach for linking geometry to building objects, including the definition of dependencies between geometry and non-geometric properties, is proposed. Furthermore, the OMG allows users to decide individually in which detail this connection should be made. For more details, it is possible to define dependencies between multiple geometry representations as well as describing the changes that were made to the description. The OMG is an abstract, upper level ontology that can be extended for specific needs and requirements, while the core of the ontology should not be changed after a mutual agreement within the community on its architecture was made. This will help to ease the integration of geometric descriptions into a Semantic Web context and therefore contribute to establishing Linked Data for the built environment.

However, the schema and its concepts are rather complex, making some sort of middleware necessary. Such a middle-ware should help users to apply the concepts of OMG without having to fully understand how the methodology works. This affects the creation and comparison of geometry and geometry state nodes to identify and prevent data discrepancies, as well as the interpretation of the concepts for geometry transformation and complementation. The latter is defined in the schema, but for interpretation or extraction of the geometry, this definition must be processed to create one singular geometry description that can be used directly in software applications. In this context, it should also be mentioned that, even though it is part of the results of our requirement analysis, the OMG currently does not provide means to mark or identify geometry descriptions as read-only for cases, where potential changes cannot be transferred back to the data pool.

Furthermore, the alignment of the OMG, especially to BOT and OPM, is currently a proposal and must be discussed, e.g. within the W3C LBD CG, and finalised. Another challenge are the rather generic properties to attach the actual geometry description. Since these properties contain no information about the used geometry format and other metadata as the up-axis, the integration of the description into software applications is hindered. Because of this issue, the FOG is introduced to create subproperties

for specific geometry formats, including their versions.

In future research, the aforementioned open issues should be addressed and, most importantly, the OMG should be used in practical use cases to evaluate its applicability and validate its concepts. To further enhance the integration of geometry into the Semantic Web, parametric descriptions must be investigated in more detail. At this time, the OMG only defines whether dependencies exist, but do not give any means to describe how these dependencies can be resolved. Thus, an approach to define the exact parametric coherences should be created.

In the aspect of the OMG's character as upper level ontology, a study to evaluate its applicability in other fields, as robotics, mechanical engineering, etc., needs to be conducted. Based on the results of such a study, further alignments of the OMG towards other, upper level ontologies should be examined.

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DEVELOPMENT OF A BIM LIBRARY FOR BUILDING ENERGY RETROFITTING: CURRENT WORKFLOWS AND A PROPOSAL FOR A RECOMMENDER SYSTEM

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Abstract

Building Information Modeling (BIM) is an object-oriented design process based on the assembling of building components virtually prototyped. Both the BIM objects available in BIM authoring platforms and the ones provided by manufacturers in digital marketplaces do not include the level of information need suitable to manage each purpose and use case within a BIM environment. Considering the purpose of energy retrofitting, this study analyzes the use of a BIM library of External Thermal Insulation Composite Systems (ETICS) as provided by a global manufacturer. The set of requirements for supporting a preliminary energy analysis is evaluated. Moreover, a data spreadsheet for energy analysis, bi-directionally linked to the BIM model, has been developed as a calculation tool for the energy evaluation of design options. Finally, the outline concept of a web-based system able to support the recommended selection of the most suitable BIM object from one or more BIM libraries based on various project parameters, including the selected BIM uses, is proposed.

Introduction

Object-oriented design and BIM libraries

BIM-oriented design is an information modeling and management process based on the assembling of building components virtually prototyped (i.e., BIM objects) (Hjelseth, 2011). Building Information Modeling (BIM), in fact, could be defined as “the object-oriented modeling of the data-rich building components, incorporating 3D geometries, spatial information, thermal values, and material properties; parameters upon which data interoperability builds up” (Gourlis & Kovacic, 2017). Moreover, data interoperability could be defined as the ability of BIM authoring platforms and BIM tools to exchange data and operate on them within a BIM environment (Eastman et al., 2011) based on specific purposes, uses and related workflows.

A BIM use is a “method of applying building information modeling during the lifecycle of a facility” in order to “achieve one or more specific objectives”

(Kreider & Messner, 2013). The level of information need to be embedded within a BIM object represents the degree of reliability regarding the implementation of BIM processes and technologies suitable for specific use cases (Kreider & Messner, 2013). Relevant information content in BIM objects should be therefore managed according to specific BIM uses in order to exchange consistent, relevant, and reliable information (Hjelseth, 2011).

When dealing with parametric and object-oriented modeling, object classes (e.g., walls, doors, slabs, and so forth) define how the object instances “are structured, how they are edited and how they behave when their context changes” (Sacks et al., 2018). A library of BIM objects is, therefore, a set of object classes, which can be provided as either *predefined* by each BIM authoring platform or *user-defined* to create customized digital representation of building components. The latter option could be adopted by the users of BIM authoring platforms in order to manage some limitations of predefined BIM objects in relation, for instance, to the level of information need of each BIM object based on the relevant use cases. This capability is considered as an essential skill for “any company or organization which appears as BIM-aware” in order to use them as effective knowledge containers on a routine basis (Sacks et al., 2018).

BIM objects are also available in web-based marketplaces (e.g., BIMobject, MagiCAD Cloud, MEPcontent, etc.), where manufacturers can provide their own building components to be used in BIM-based projects. Most of the digital marketplaces allows downloading BIM objects that are compatible with Autodesk Revit. Sketch Up, ArchiCAD, Allplan and Vectorworks, for example, are other BIM authoring platforms for which BIM objects are also available in digital marketplaces, although in small numbers compared to those available for Revit. In some cases, manufacturers also allow users to download the Industry Foundation Classes (IFC) version of BIM objects (e.g., 17.100 out of 61.686 object families are available in the IFC format in BIMobject®). Some plug-ins also exist for BIM authoring platforms in order to download BIM objects

directly within the BIM authoring platforms from digital marketplaces.

The management of the BIM objects for energy-related applications

Both the BIM objects available in BIM authoring platforms and the ones provided by manufacturers in digital marketplaces do not include the level of information need suitable to manage each purpose and use case within a BIM environment. In order to narrow the scope of the study down to one possible BIM use for the design phase of a building facility, energy retrofitting has been taken into account.

In the energy modeling process, object relationships and semantics related to architectural models do not substantially affect simulation results and they are often abstracted, risking delays in the result interpretation over the design stage (Kim et al, 2016). Consistent object classifications and semantics between BIM and BEM (Building Energy Modeling) are needed to guarantee interoperable BIM-to-BEM data flows and design processes. For this reason, if the energy analysis represents a BIM use, the building components managed as BIM objects should contain the parameters that are required to enable energy analysis-oriented tools receiving values from the BIM model. Consequently, data exchanges between the building objects and their attributes between different domains could be managed more effectively and could guarantee reliable results from the analysis.

BIM libraries-based recommendation

As already said, *predefined* BIM objects could not be used for any purposes and uses; *user-defined* attributes are needed for specific applications, indeed. Moreover, within the digital marketplaces, BIM objects can be searched in by categories and file formats; no information is usually available neither about their informative content nor the specification for the BIM uses they can be implemented for. It could be useful, instead, to guide users in the selection of the most appropriate BIM object based on their needs. For that reason, this study also proposes a novel recommender system as a method to guide the users in the selection of the most appropriate BIM object based on BIM purposes and use cases.

In fact, similarly to what happens for e-commerce business models, a recommender system permits to deliver context-aware suggestions to the design teams in order to reduce their effort in manually searching the most appropriate BIM objects into one or more libraries building components virtually prototyped. Recommender systems, also known as recommendation systems, aim to suggest to the *shoppers* (i.e., the practitioners) those items that are most probably of interest for them among the ones available in a repository. As well as they can reduce the time and effort required to a user in making a

choice, for example discovering a recent movie to be watched related with the user's concerns (Ricci et al., 2015). Recommenders, in fact, are used in an integrated way as sources of knowledge in order to infer users' interests. The most common type of knowledge lies with the users' feedbacks, which can be explicit or implicit. An example of explicit feedback is the rating a user can provide for an item she/he purchased. Moreover, the simple act of buying an item or accessing to its description can be interpreted as an endorsement for the item and, therefore, implicit feedback for it. The typical problem solved by recommenders is thus the prediction of the level of interest, or rating, a user will assign to a given item. However, for the largest portion of the practical applications, it can be sufficing to identify and propose as ranked list the top-k relevant items for a specific user (Aggarwal, 2016).

Several recommendation techniques have been developed. For example, the *collaborative filtering technique* exploits choices or ratings of users that are similar to a user A, or made similar past choices, in order to establish unknown interests of A. This technique suffers from the "cold start problem", where items with no evaluations are ruled out by recommendations. In *content-based techniques*, descriptive attributes of items are considered to suggest items to a user that are similar to items rated with a high score by the same user. *Hybrid techniques* exploit the availability of different information sources to apply and combine collaborative contents, as well as social and context-aware recommendation models also in order to overcome the weaknesses of the single model techniques (Burke, 2007).

Structure of the paper and scope of the study

Based on the background described in the previous paragraphs, the paper is organized as follows. In the next paragraph, as an example, the customization of a manufacturer's BIM library for supporting energy-related analysis in energy retrofitting design processes is described. In particular, this example application is related to the energy calculations for a retrofitting project applied to three types of buildings. According to the Italian national regulation, the level of information need to consider for such a use case is identified.

Furthermore, the development of a data spreadsheet bi-directionally linked to the building information model for the preliminary energy-related analysis of design options has been developed for each type of building. Then, as a result of this example application, the concept of a recommender system, which could help the users in selecting the most appropriate BIM objects for the specific use case from one or more BIM libraries has been proposed. In this study, the focus stays with the application of the recommender system for energy retrofitting. However, this study represents

a first step into the development of web systems able to support users in the selection of the most appropriate BIM object from one or more BIM libraries based on various project parameters, related to BIM purposes and use cases.

Development of a BIM library for the BEM use case

Research method and materials

Three building typologies have been used as a test field to double check the energy performance achieved through standardized envelope components suitable for energy retrofit. The BIM models of the buildings have been realized and BIM objects have been used to develop a BIM library to test the different solution by a bi-directional link (i.e., through Visual Programming Language VPL) between the BIM model and an Excel spreadsheet, where equations to calculate the energy parameters and indicators included in the national regulation have been implemented. In this way, the energy performance deriving from each configuration could be tested and compared to support the decision-making process. From the BIM model, the geometrical information and the energy parameters associated to the materials adopted for the components' layers are transferred through VPL scripts to the Excel spreadsheet. The same parameters will be included in the recommender system to filter the BIM objects most suitable to achieve energy goals. The building performance is not only due to components performance but also to the building configuration (e.g., shape, complexity, the ratio between opaque and transparent envelope, etc.); for that reason, the test cases have been developed for the energy comparison of the baseline (i.e., existing situation) and the design case (i.e., retrofitted building).

Case studies and BIM models

The BIM models of the three case studies (i.e., buildings with different destinations and characteristics) have been realized in Autodesk Revit. They are: (a) a single family house; (b) a multi-story residential building; (c) an office building (Figure 1).

Figure 1: Typologies of buildings adopted as case studies

The building (a) is a 100 m² single family house with three bedrooms, two bathrooms and a kitchen-cum-living room. This is a commonly adopted typology, widespread throughout the national territory. Consequently, the energy retrofitting of this type of building has wide energy and economic potential considering the lifespan of the building and the age of the existing building stock. The building (b) is multi-story residential building with 16 apartments of about 80 m² each, with a kitchen-cum-living room, two bedrooms, a bathroom and a storeroom. The building (c) is an office with a very different widely glazed envelope; the vertical distribution is concentrated in the core, where stairs and elevators are located. The floor is 600 m² and the height is 35 m (i.e., 6 m for the ground floor and 3.5 m for the type floor).

The case studies have been tested with the BIM objects products and components (i.e. mainly opaque for the residential buildings a) and b) and glazing systems for the office building c). The thermal properties of the case studies replicate the characteristics of the existing residential national built environment, with no insulation layer in the opaque envelope and installing single glazed windows. The buildings have been tested in three representative Italian climate locations (Table 1).

Table 1: Information about the three locations

Info	Milan	Rome	Palermo
Latitude	45.4773 N	41.9109 N	38.1121 N
Longitude	9.1815 E	12.4818 E	13.3366 E
Cl. zone	E	D	B
DD	2404	1415	751
HDays	182	166	121

Existing envelope conditions

The existing envelope conditions are described in Table 2.

Table 2: Existing envelope in the BIM model

Vertical wall	Thickness [mm]
• lime and cement plaster	15
• hollow brick	250
• lime and cement plaster	15
Ground floor	Thickness [mm]
• expanded clay concrete for unventilated substrates	
• reinforced concrete	200
• sand and cement screed	40
• waterproofing membrane	
• ceramic tiles	10
Ceiling	Thickness [mm]
• lime and cement plaster	15
• hollow-core concrete slab	240
• sand and cement screed	40
Roof	Thickness [mm]
• lime and gypsum plaster	15
• hollow-core concrete slab	240
• sand and cement screed	40

The existing envelopes for the three buildings have been retrofitted using the selected External Thermal Insulation Composite System (ETICS) as described in the following sections. The BIM models have been equipped with the BIM objects provided by a global manufacturer and customizing the thickness of the insulation layers to accomplish the required performances in the different climates (Table 1).

Energy information modeling supported by a BIM library

The BIM libraries created by the aforementioned manufacturer provides useful datasets to characterize the transparent or opaque envelope. The BIM library of an ETICS, freely downloadable from the manufacturer's website, has been adopted in order to conceive some retrofitting measures to enhance the energy quality of the existing buildings (a), (b) and (c). Moreover, the characteristics included in the BIM objects have been analyzed in order to understand their suitability and reliability to support the energy analysis. The aim is to compare the existing situation and the retrofitted one on a performance basis (Figure 2). *Predefined* object classes and set of requirements have been used to create the BIM base case.

Figure 2: ETICS adopted as retrofit system

The system has been selected taking into account the market penetration as well as the energy and environmental performances (i.e., rock wool with 80% of recycled material).

BIM object for the energy retrofitting of the opaque vertical and horizontal envelope

The manufacturer's BIM library generates and provides a sample file with specific geometrical (Table 3; Figure 3), thermal and acoustic performances. Design flexibility is endorsed to define specified performance system's profiles. In the "type properties" (Figure 2) the main system's features have been reported; in some cases, information can be defined through the materials' attributes (e.g., total thickness: 393.5 mm, thermal transmittance (declared): 0.25 W/m²K), while for other specific parameters it has been specified by means of laboratory tests considering the thickness of the layers included in the thermal insulation system (acoustic insulation performance: R_w=60 db).

Table 3: BIM object geometrical information for wall

Layers	Thickness [mm]
Lime and cement plaster	15
Brick with pores	250
Lime and cement plaster	15
Weber.therm AP50 start	8
Isover clima34 G3	100
Weber.therm TA8	
Glass fibre reinforcement net	
Weber.therm AP50 start	8
Weber.prim RC14	
Weber.cote Action F-R-M	1.5

As far as the roof and ground slab are concerned, the following solutions have been adopted and tested in the case studies (Table 4; Table 5). The thermal and acoustic performances of the roof have been provided by the BIM object, such as:

- total thickness: 355.5 mm;
- thermal transmittance (declared): 0.2 W/m²K;
- acoustic insulation performance: R_w=42 db.

Figure 3: Type properties for the wall insulation system of the manufacturer

Regarding the ceiling system, the solution for energy retrofitting has been conceived as a rock wool insulation layer of Isover IBR K 4+:

- total thickness: 355 mm;
- thermal transmittance (declared): 0.18 W/m²K;
- acoustic insulation performance: R_w=56 db).

Table 4: BIM object of the roof

Layers	Thickness [mm]
Matchboarding	20
Isover VARIO KM DUPLEX	0.8
OSB panel	19
Wooden joists	60
Isover BAC CF N ROOFINE G3	60
Wooden joists	60
Isover BAC CF N ROOFINE G3	60
OSB panel	19
Air gap with joists	50
Bituver SYNTODEFENSE	0.8
Slats for tiles	
Tiles	6

Table 5: BIM object of the slab against ground

Layers	Thickness [mm]
Expanded clay concrete for unventilated substrates	
Reinforced concrete	200
Overlap band Akustrip 33	
Insulation Isover Ekosol N 4+	
Bituminous cardboard Bituver Bitulan C3	
Distribution screed	40
Ceramic tiles	10

BIM object for the transparent envelope

As far as the transparent envelope is concerned, the glazing systems have been defined throughout the glazed solution provided by the manufacturer's library as well as specific frames: the available BIM objects were only related to glasses, indeed. The glass-related BIM objects included the information about double and triple glazing systems without any additional details about the integration with the structural frame. The designer is then responsible for specifying the results involving the special analyses for the glazing systems (i.e., glass and frame, seals, glass stop, etc.). The manufacturer provides the object families: whenever the glass has to be included in the model, it is possible to check the possibilities given by the library and to replace the windows with the available objects (Figure 4). In the retrofitted situation, a double glazing system has been adopted due to the main market choices affected by economic reasons.

Figure 4: Manufacture's family for double glazing systems

Performance-related information that are needed in order to perform the energy analysis

The research aims at applying the BIM objects dealing with the thermal insulation system to the case studies (Figure 1) in order to evaluate how they can be used to support the energy analysis according to the energy parameters required by the national regulations (Italian Ministerial Decree, 2015). They require the calculation of specific thermal parameters needed to define the building energy performance (i.e., energy label) throughout a computational procedure. The procedure implements the standard building energy balance (UNI-TS 11300:2018). The energy calculation focused on the main parameters of thermal analysis in the static regime of the buildings as approved by the mentioned standard. A bi-directional link through VPL has been developed between the BIM models and an Excel spreadsheet, which implements the equations accomplishing the national standard calculation. The link has been developed in order to arrange and manage the computational procedure and to achieve the energy results for the case studies starting from the thermal information stored into the BIM objects

included into the building information models. Data are then visualized in a dashboard displaying three information levels:

- *climate data*, related to the location of the existing building (UNI Standard 10349) including climate zone at territorial level, Degree Days (DD), Heating Days (Hdays);
- *geometric data*, about building typology, net area, gross volume, net volume, exposed to the outdoor surfaces, S/V ratio (surface area exposed to the outdoor and gross heated volume ratio);
- *performance data*, referred to the thermal losses and gains, the acoustic performance of the evaluated building according to the parameters included in Table 6.

Table 6 summarizes the thermal information and the main acoustic parameters, which derive from the layers included in the opaque envelope introduced into the BIM models through the manufacturer's BIM objects.

Table 6: Thermal parameter for the energy evaluation.

Parameter	Unit
Thermal transmittance	W/m ² K
<ul style="list-style-type: none"> external wall roof slab windows 	
Solar contributions through windows	kWh
Solar collection area	m ²
Acoustic insulation performance	db
Stationary heat exchange	W/K
<ul style="list-style-type: none"> to outside to ground to unheated spaces 	
Energy demand	kWh
Energy performance in winter period	kWh/m ² y
	kWh/m ³ y
Energy label	A4-G

The findings and outcomes stemming from the BIM objects' analysis concerning the ETICS, as well as the predefined Revit objects, show how the information included needs an integration before starting the data transfer procedure in order to fill correctly any spreadsheet cells required for performing the energy analysis. A customized digital representation of the building components had to be developed, including user-defined properties.

For instance, the thermal transmittance, associated to the windows and related to the glass surface and the frame specific features, has been added to the "window" BIM object as well as its area, which is requested in order to calculate the heat gains given by the solar radiation through the windows; the solar collection area should be added modifying the window family, too (Figure 5).

The data enrichment procedure is a crucial step for BIM modeling in order to assure a reliable level of information need based on the relevant BIM use. It is strongly related to the final task of the data export. Some needed data for the energy calculation are related to the materials' properties, while others to the dimensions of surfaces; therefore, in some cases, it is possible to get the information as a direct output, while for other situations special equations have to be implemented in the BIM object's properties in order to obtain the combined data as, for example, the area given by the dimensions of the windows (i.e., length and width) (Figure 5).

Dimension	Parametro	Valore	Formula	Blocco
Altezza	Altezza	1200.0		
Altezza da terra	Altezza da terra	900.0		
Altezza	Altezza	1200.0		
Larghezza	Larghezza	1000.0		
Larghezza approssimativa	Larghezza approssimativa	1000.0		
Altezza approssimativa	Altezza approssimativa	1000.0		

Parametro	Valore	Formula	Blocco
Fattore solare g (1/100)	0.350000		
Peso (kg/m2)	38.000000		
Potere Fonoassorbente R _w (dB)	43		
Riflessione Luminosa Esterna R _{le} (%)	28		
Riflessione Luminosa Interna R _{li} (%)	27		
Shading Coefficient Sc	0.410000		
Trasmissione Luminosa T _L (%)	58.000000		
Trasmissione Termica Uw (W/m2K)	1.000000		
Trasmissione Termica U _g	1.3500		
Altezza	900.0		
Default Sill Height	900.0		

Figure 5: Family of windows available in the manufacturer's website modified to include the values needed for the energy evaluation

Definition of the calculation model for energy performance assessment

The calculation model has been developed in Excel organizing different sheets for each specific analysis referred to the national regulation requirements, which imply component and building energy performance levels. The spreadsheet has n. 13 sections arranged to cover thermal and acoustic requirements. The list of the calculation sections is as follows:

1. *Dashboard*: the summary of the performance data is displayed for each implemented case study (Table 6);
2. *Qh*: the energy label is calculated as heating demand of the whole building;
3. *HD*: the stationary specific thermal losses of the opaque vertical, horizontal envelope and of the transparent surfaces is calculated based on area of the component and thermal transmittance of the opaque and transparent components;
4. *Hg*: the stationary specific thermal losses to

- ground based on area of the component and thermal transmittance of the slab is calculated;
5. *HU*: the stationary specific thermal losses to unheated spaces based area of the component and thermal transmittance of the components is calculated;
6. *Qs*: solar gains through windows based on solar radiation of the climate zone, orientation of the window and size of the window are calculated;
7. *Asol*: the solar collection area is calculated
8. *D2m,nT,W*: the acoustic insulation effect of the components is calculated;
9. *Uwall*: it is possible to organize the stratification of the vertical opaque envelope components based on custom materials and on the BIM library components and a comparison with the limit of thermal transmittance provided by law is automatically performed.
10. *Uroof*: it is possible to organize the stratification of the horizontal opaque envelope (roof) components based on custom materials and on the BIM library components and a comparison with the limit of thermal transmittance provided by law is automatically performed;
11. *Uslab*: it is possible to organize the stratification of the horizontal (slabs) opaque envelope components based on custom materials and on the BIM library components and a comparison with the limit of thermal transmittance provided by law is automatically performed.;
12. *Uwindows*: the thermal transmittance calculation of the windows;
13. *Model data*: surface area and thermal transmittance of the components of the building are transferred by the BIM model.

The sections of the spreadsheet are correlated and connected to realize the calculation starting from the BIM data and visualizing the results in the *Dashboard* section.

The bi-directional data transfer link from the BIM model to the energy calculation spreadsheet

The information provided by the building information model, including BIM objects that have been enriched with *user-defined* properties, have been transferred to the Excel spreadsheet implemented with the equation for the energy balance included in the national regulation through the VPL (Visual Programming Language); the input data have been used to calculate the predefined performance parameters. In this way, it was possible to enable the efficient use of the BIM library through the application of product selection procedures and performance calculations based on a functional workflow from the information model to the Excel spreadsheet. Autodesk Dynamo has been used to link the building information model to the Excel spreadsheet where n. 13 sections have been arranged as described in the previous section. In particular, in

Autodesk Dynamo VPL can be used to transfer data from Autodesk Revit to Excel and vice versa. In this study, the thermo-physical information has been used to populate the calculation model in Excel in order to evaluate the possible energy upgrade of the case studies throughout the BIM library system adopted in the building information models. The adopted tools are shown in Figure 6.

Figure 6: Workflow of data transfer from the building information model to the calculation spreadsheet through VPL

The building information models have been conceived as data sources for the energy calculation spreadsheet, considering the main parameters needed for the geometrical and alpha-numerical data sections. The idea is that the BIM object can be used by the practitioners in their project where refurbishment envelope solutions are required. The use of the BIM object with the data enrichment provide the data to the calculation tool through the transfer link giving the feedback about the achievable performance with the BIM configuration. The bi-directional link is used to communicate to the BIM environment the energy quality of the solution and thus compare different options to reach the energy goal. The procedure requires the filtering of any object classes by categories. In this way it is possible to select all the elements of the same category within the BIM model and then to sort them by name (Elements.FilterByName) in order to obtain the list of the specific components of interest. Based on the list, it is then possible to select the specific properties that have to be exported in order to fill the relevant cells in the spreadsheet for enabling the energy analysis (Element.GetParameterValueByName).

The same procedure has been applied also to the windows using the specific category. Through the BIM object (Family Types) it is possible to write down the complete list of the family features (Get Family Parameters). For the roof and slab components the type properties have been then selected through the element name (RoofType.ByName) (Figure 7).

Figure 7: Dynamo script for wall data transfer and roof performance data transfer (as example the declared thermal transmittance)

In order to enhance the data transfer process, it is crucial to realize the correct link in the VPL understanding if the needed information is related to the type properties or to the family properties. In fact, the structure of the script has to be customized in the different situations for the data extraction and communication to the calculation model in Excel.

Results of the energy analysis

The calculation of the energy retro in the three case studies shows the following results:

- in building (a), the single-family house the vertical walls insulation assures an energy saving of about 27%. The windows' replacement (with a double glazing system) and the roof insulation lead to an average 78% of energy saving for space heating. The insulation of the slab reduces of 6% the previous results (Figure 8).
- For building (b) residential apartments, the wall insulation can improve the energy performance in Milan of 17%, in Rome of 19% and in Palermo of 23%. The higher implementation is achieved with windows' replacement and roof insulation with 67% of energy saving in Milan, 76% in Rome and 88% in Palermo. The insulation of the slab increases the performance of about 16%.
- For the office building (c) the evaluation has been defined applying all the energy retrofit measures at the same time and a whole reduction of 61% of the energy demand could be achieved in Milan, a 69% of energy saving has been registered in Rome and an 80% could be achieved in Palermo (Figure 9).

Figure 8: Performance implementation with retrofit measures in the three climate for the building (a)

Figure 9: Performance implementation with retrofit measures in the three climate for the building (b)

A recommender for BIM object-based design of buildings

According to the research perspective, BIM object libraries perform as the core components of a novel web application that has been developed in order to support design teams in using libraries in a more advanced and fruitful way. In particular, this application is meant (i) to implement energy analyses-oriented services on selected BIM objects, as described in the previous section, and (ii) recommendations for the BIM objects suitable for being integrated into a given design, as discussed in this section. The web application relies on a conceptual data model aimed to describe the relevant classes of data and associations, represented by means of a UML class diagram. The model focuses on describing the use of BIM objects in the design process. Figure 8 reports the resulting diagram in terms of classes, associations, and related multiplicities, where attributes are not detailed for the sake of compactness of the diagram. This model defines the data persistence component (i.e., the database) of the application. From an operational point of view, designers have to register to the web application by specifying their demographic data and business profiles. Then, they may describe one or more building designs in terms of, among the others, a description of the context (e.g., the building type and its location), applicable energy class, and, for each design the used BIM objects. After entering this data, designers are enabled to gain benefits from the services provided by the application. For instance, designers can ask for an energy performance analysis

to be performed on a targeted building. Moreover, they can get a recommendation consisting of a ranked list of BIM objects as alternatives to a currently selected one to be used in the target building.

In particular, recommended objects are selected according to a collaborative recommendation approach that relies on information such as features of the target building, its context, and past selections of BIM objects performed by the current and by other designers. The data model in Figure 10 can be shortly described in terms of the following requirements. Conventionally, in the following description, the authors capitalize the first letter of names of classes appearing in the diagram. A User of our web application registers to Data sources providing (libraries of) BIM objects to be used as components in Designs. A Design is associated with a Context defined by a Location, and a Type of building. Hence, an Analysis model (e.g., energy performance evaluation) can be adapted to a specific Context to keep it into account. A BIM object has a list of Performance parameters representing measures of precise technological aspects related to the object composition. A BIM object may be associated by the user with Alternative objects, which are BIM objects suitable for replacing the object thanks to, for example, having similar features even if they are produced by a different company. Moreover, an object belongs to an object Category. A User may define a BIM object variant in order to store the description of a customization she/he made to a predefined BIM object. Finally, Analysis models provide relevant evaluations applicable to both specific BIM objects and objects Categories. The authors are now going to discuss the configuration of the recommendation service for our web application, based on the presented data model. The recommender is designed to deliver a ranked, i.e., ordered by relevance, list of objects given a request expressed by a designer. From a technical point of view, the algorithm implementing the recommender combines a content-based selection of objects to be recommended with a collaboration-based ranking of them. The algorithm uses data available in a database coherent with the model in Figure 10.

Figure 10: Conceptual data model design for the application

A recommendation request is specified by the following data:

- either an object category describing the desired category of object (C), or (ii) a specific object (o) for which alternative objects are searched;
- parameters of the target design D : type of building ($D.Context.Type_of_bdng$), average cost ($D.avg_cost$), degree-days (DD) of the building location ($D.Context.Location.DD$), energy class ($D.EC$);
- intended use IU of the recommended objects.

This means the designer specifies an intended use for the BIM objects to be recommended, for example “energy retrofitting”. An intended use IU identifies a minimum set of attributes required $IU.attr$. In our proposal, for the energy retrofitting intended use, the set $IU.attr$ is consistent with the minimum set of data required as input by the energy performance calculation model described in the previous section.

Then, a recommendation request is processed in the following way (Figure 11). Firstly, all the available past designs similar to the design D are retrieved from the database at *phase 2*) according to a content-based approach. Here, an overall similarity between a pair of designs is defined and, in our proposal, this means comparing primary and contextual features of the buildings subject of designs. Formally, the overall similarity is established by four conditions based on simple similarity criteria: 2.1) the two buildings should be of the same type; 2.2) they should have close average cost per unit of surface/volume; 2.3) they should be at locations with close values of DD; 2.4) they should have close, or the same, energy classes.

Preliminarily, at *phase 1*), the maximum admitted ranges for the similarity criteria are set (e.g., the maximum difference for DD). These ranges (e.g., α , β , and γ) will be set to optimal values after performing wide experimentation with the application and users. As well as, at this phase, the category C , if not provided, is set to the one of the object o .

Then, all objects used in the designs similar to D , denoted as SD and selected by the steps at *phase 2*), are retrieved at *phase 3*). These objects are the candidates to be recommended.

In the next *phase 4*), these candidates are filtered out, firstly, by removing the ones not belonging to the category C requested by the user, as specified by the category-based filtering phase 4.1). Secondly, by removing the candidates having a set of descriptive attributes that do not include the minimum set of attributes required for the intended use of the object, as reported in phase 4.2). Finally, in the last *phase 5*) each object in the filtered candidate objects CO is ranked proportionally to the number of designs that are similar to D , and use this object. This means that most used objects are presented better than less used ones.

The ordered list of objects is shown to the user.

Figure 11: Description of the phases and steps of the recommender

In order to preliminary evaluate the proposed approach, output of the proposed recommender could be compared to the output of other approaches, i.e., (i) keyword-based search systems operating on textual descriptions associated to BIM objects, (ii) general purpose recommender systems configured to work on BIM objects, (iii) faceted search systems permitting to filter out the objects in one or more libraries based on filtering criteria expressed by designers. The authors assume all these systems, including ours, provide outputs as top-k lists, based on proposing as output of the system the best k matching objects. Based on this realistic assumption, the authors are planning to compare ours to other approaches based on both (i)

classical information retrieval measures (e.g. precision) involving a user-centered evaluation of the produced output, and (ii) specific top-k distance metrics (e.g., generalized Kendall's Tau measure).

Conclusions

The available BIM objects either as predefined in BIM authoring tools or as user-defined objects by the manufacturer usually do not include the appropriate informative content for the energy analysis purposes. The BIM-to-BEM interoperable workflow remains an open issue for effective design integration. The study represents a preliminary attempt to support the development of an energy-analysis procedure focused upon BIM objects.

This study analyses the use and customization of a manufacturers' BIM library for energy retrofitting purposes. The library is available on a digital marketplace and the users can access and download it for free. Anyway, the BIM objects developed by the manufacturers do not allow an automatic BIM-to-BEM analysis workflow and, consequently, some customization is needed. For that reason, the paper has adopted some case studies as a method to identify the information requirements needed to perform a preliminary energy analysis for retrofitting purposes during the design phase. Based on this results, the study also discusses the design of a software system for recommending the most appropriate BIM object to be used for the specific purpose and use case based on the previous experiences of other users, in order to guide the selection of the BIM object in future projects.

Such a system could support organizations and designers in the selection of the most suitable object to create their own BIM models based on previously defined purposes and use cases, acquiring knowledge from experience. Being a first step into the development of the web system, future works are needed for (1) completing its design both for energy analysis purposes and other use cases for which a recommender system could be used for; (2) developing the first prototype version of the system; (3) testing the systems on multiple projects and configurations in order to evaluate its effectiveness.

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A BIM-BASED APPROACH TO FAÇADE CLADDING OPTIMIZATION: GEOMETRICAL, ECONOMIC AND PRODUCTION CONTROL IN A DFMA PERSPECTIVE

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Abstract

The goal of this paper is providing a methodology properly supporting façade optimization in a DfMA (Design for Manufacturing and Assembly) perspective. DfMA has proven to facilitate offsite manufacturing, lowering costs and improving speed and quality of construction, especially combined with BIM strategies. A BIM-based methodology can help in setting parameters for the proper optimization of the façade, balancing production related needs and design requirements. The proposed method allows the exploration of alternatives (known as Design Optioneering) to optimize the choice of façade elements. This method is based on a mathematical algorithm and script including parameters related to geometry, production waste management and designer's needs. The proposed methodology has been tested on a newly built school in Northern Italy.

Introduction

The building envelope plays a pivotal role in building design and construction, especially when considering sustainability goals. The envelope accounts for the most part of energy consumption, and represent a major cost item in the total value of a building (Huang & Niu, 2016).

The building façade can be described as the separation layer between outside and inside, between nature and interior spaces occupied by people (Herzog, Krippner, & Lang, 2012).

Depending on the outside conditions (in terms of climatic conditions, noise, mechanical loads, local resources and context), building facades modify and influence internal conditions (including temperature, light, air, sound level, visual relationship between outside and inside). For this reason, building facades are an increasingly relevant research area (Martinez, Patterson, Carlson, & Noble, 2015). Building façade design faces a multiplicity of goals and needs. The envelope defines the architectural value of the building and in many cases, indicates the function of the building itself. Building façades are an environmental filter and play a relevant role in energy performance;

they can host building services or devices to exploit renewable energy sources (e.g. photovoltaics or hot water panels), taking an active part in the building energy balance.

In this context, early stages of design have proven to play a pivotal role for success or failure of design (Granadeiro, Duarte, Correia, & Leal, 2013); decisions taken in those stages have relevant impact on cost, time and effort of a project. Nonetheless, it is difficult to provide a complete outlook on choices and solutions in this phase, due to the limited amount of information available. In addition, a complete evaluation of design alternatives implies significant investments in terms of cost and time.

Several optimization strategies have been developed in recent years, mainly addressing energy and daylight aspects; a lack of consideration of production and installation issues can be underlined in this sense.

Optimization in building design

The concept of optimization

Complexity in architecture is a wide theme, that can regard many different aspects, from geometry and shape, to special structures and building systems (Bachman, 2008; Penttilä, 2006; Salingeros, 2016); a wide and deep analysis of this concept should involve all these fields and is beyond the scopes of the present work. Nonetheless, in this case, it is possible to define complexity as related to the high quantity of actors, goals, requirements to be fulfilled, involved in the process.

Architecture has been considered for a long time mainly an art-related activity. In the 70s, the introduction of optimization and numerical techniques allowed to keep into account structural and building services related issues in the architectural design of a building (Gero, 1975). Nowadays, the majority of existing approaches in terms of optimization are related to sustainability in building design (Evins, 2013). Optimization can be defined as the action of making the best or most effective use of a situation or a resource (Coello Coello, Lamont, & van Veldhuizen, 2007). Considering building design, even in case of a

limited number of constraints, this process is related to multiple goals and therefore multiple objective functions expressing these goals and requirements. For this reason, a multi-objective optimization is necessary to properly address this issue (Kalyanmoy, 2001) (Attia, Hamdy, O'Brien, & Carlucci, 2013). Currently, different levels and approaches of optimization are available, depending on the tools used for the development. A first distinction in this sense is that between computational or algebraic and manual methods (Evins, 2013). The use of parametric based design tools is particularly useful as it allows to simulate many design alternatives, to visualize them, and to modify parameters in real time. The parameters expressing the variety of requirements involved in building design and construction can be divided in two main groups. The first group is that of design-related aspects, including energy performance, architectural quality, and comfort of the users. The second group is mainly related to construction requirements, and includes cost, production and waste management.

Energy related optimization

One of the first fields where building design optimization took place is related to energy and environmental impact. This trend is obviously associated to the implementation of sustainability standards, such as LEED or BREEAM. These standards are particularly useful in this sense as they provide a series of indicators or parameters to be maximized or minimized, in a hierarchic structure with a scoring system based on appropriately weighted credits (Lee & Burnett, 2008; Suzer, 2015).

LEED and BREEAM, together with other major green buildings standards are mainly focusing on the use of renewable energies, energy efficiency, and indoor environmental quality. As a consequence, several optimization approaches are mainly focusing on energy efficiency, thermal performances and lighting quality. Most of these approaches address façade design, underlining the role of building envelope in the management of energy flows in buildings (Goia, Haase, & Perino, 2013).

The multidisciplinary problem of building performance optimization is particularly challenging as it requires a huge amount of data from several disciplines. Some of existing approaches are trying to face this issue focusing on the combination and trade-off between energy performance and internal comfort, considering both the building envelope and the building services, such as lighting, ventilation, heating and cooling (Andersen et al., 2008; Ascione, Bianco, De Stasio, Mauro, & Vanoli, 2015; Bouchlaghem, 2000; Chantrelle, Lahmidi, Keilholz, Mankibi, & Michel, 2011; Shaikh, Nor, Nallagownden, Elamvazuthi, & Ibrahim, 2014).

Form and structure optimization

The shape of a building represents a primary feature, that defines its identity in terms of architecture, and has a relevant impact on energy performance, integration of building services, accessibility, urban setting. Contemporary architecture is moving towards complex geometries and forms, especially in the case of non-residential buildings.

Form optimization is therefore a consistent research field: usual approaches include cost-evaluation, glazing properties, heat losses (Granadeiro et al., 2013). In this sense, many approaches are keeping into account geometry together with structural properties, in order to optimize use of materials, and to provide light structures (Beghini, Beghini, Katz, Baker, & Paulino, 2014; Rozvany, 2009; Sigmund, 2000), or considering solar radiation gain and efficiency (Fallahrafti, R., Mahdavienejad, 2015; Yi, H., Srinivasan, R.S., Braham, 2015; Yi, Y.K., Malkawi, 2012; Zhang, L., Zhang, L., Wang, 2016).

Some approaches are related to urban scale (Kämpf, J.H., Montavon, M., Bunyesc, J., Bolliger, R., Robinson, 2010; Morello, E., Gori, V., Balocco, C., Ratti, 2009), while others are addressing the building scale and its parts (Gustafsson, 2000; Nassar, Thabet, & Beliveau, 2003).

Limitations in current practices

Besides providing valuable and useful support to practice and research, the proposed methodologies have relevant limitations in terms of construction-related requirements.

RIBA's stages expressing Life Cycle of a building, for instance, include:

- Strategic definition
- Preparation and brief
- Concept Design
- Developed Design
- Technical Design
- Construction
- Handover and Close out
- In Use

Most of the proposed methods do not take into account production related optimization or waste management; these approaches are mainly addressing the operational phases of the building life cycle (Banaitiene, Banaitis, Kaklauskas, & Zavadskas, 2008).

Evaluating these aspects could be particularly challenging, as construction related requirements are strongly case-related; a one-fits-all approach is not possible.

Nonetheless, it is possible to provide a flexible methodology that could be adapted to single cases with minor changes.

Methodology

Facade design is a complex task, as it involves a variety of constraints and requirements, expressing needs and goals of several actors involved in the process. Multi-objective optimization is particularly suitable to this kind of issues, as it allows to evaluate and maximize (or minimize) various parameters simultaneously (Marler & Arora, 2004). The proposed approach is a Design Optioneering perspective, based on a multi-criteria and multi-objective optimization. This methodology allows optimizing design related aspects, and to include construction and production related constraints, towards a DfMA approach. The focus of optimization in this work is kept on design and construction related aspect rather than on production strategies.

Multi-Criteria methodologies

Multi-criteria is an effective methodology for non-linear problems (Alanne, 2004). Building facade design is a complex operation, that implies different criteria with mutual trade-offs, as previously stated. Using a multi-criteria methodology from the early stages of design could help in enhancing the effectiveness and reducing late variations, that results in cost and time increase. Current design procedures and existing tools in this context show limitations, connected to the wide variety of parameters to be taken into account: for this reason, it may be impossible to obtain complete optimality / maximization of all aspects, but compromise solutions can be found. As previously stated, lacking aspects in current practice are related to manufacturability and production issues of the solution: there have been experiences of optimization in this field, but the aim of this research is the integration of manufacturability in a multi-dimensional matrix.

Besides the multi criteria decision making (MCDM) model choice, a multi-criteria methodology unfolds through several steps, as shown in Figure 1:

- Problem definition and goal formulation
- Identification of the criteria
- Weights estimation
- Score determination
- Classification of solutions
- Feedback

The goal of this methodology is choosing the most suitable strategy for buildings facades. The setting of goals helps in identifying the macro-areas, the criteria, and the indicators that can express in a quantitative way the criteria and the requirements.

The output of a multi criteria methodology is a classification of alternatives, that allows establishing the best solution (the one with the highest score).

Figure 1: Multi-Criteria methodology scheme

A DfMA perspective

Design for Manufacturing and Assembly is a discipline stemming from the combination of DfA (Design for Assembly) and DfM (Design for Manufacturing), with the goal of simplifying the product structure to reduce the assembly cost and reducing the total parts cost. DfM provides estimation models of production cost and sensitivity analysis related to the variation of design and process parameters (Fox, Marsh, & Cockerham, 2001); DfA is based on structural models for the estimation of the efficiency of assembly processes and possible improvements (Goulding, Pour Rahimian, Arif, & Sharp, 2015). DfMA was first applied to mechanical industry, but it is nowadays spreading to other disciplines as an optimization strategy from early stages of design. DfMA's effectiveness is particularly evident as the approach provides a systematic procedure, that is quantitative and measurable. DfMA has proven to increase communication ease between the actors involved in building processes, offering simpler solutions with higher quality (Favi, Germani, & Mandolini, 2016). During construction phases, a DfMA approach allows safer labor conditions and reduction in time and costs.

A Design Optioneering approach

A Design Optioneering approach is therefore proposed, based on the setting of requirements conveying the needs of actors of the process (Gerber, Lin, Pan, & Solmaz, 2012). These requirements are expressed in a quantitative form as performance indicators. Each of them is then assigned a weight, in order to evaluate their mutual relevance, in a multi-criteria perspective.

A certain degree of flexibility is provided, as the proposed approach is methodological and can therefore be modelled on the case: the chosen parameters can be changed, and a variation in the weights assigned to the parameters is useful to express the relevance of the actors.

The evaluation of alternatives and the choice of the most suitable solution is therefore case-specific and modelled on the needs and goals of the actors.

Development and case study application

Complexity is an essential topic in AEC industry and Building Information Modelling allows an all-embracing view and control of the project. The considered parameters play a relevant role in terms of complexity of design choices, as they are not based on the best solution in absolute terms, but on the one that fits better that particular project. The strategies should therefore be defined each time, based on the European Directives 23, 24 and 25/2014 (European Union, 2014). These Directives aim to increase the freedom in the choice of the authorities, but also ask them more empowering skills.

The owner will define the criteria to be used to evaluate design choices, based on precisely defined needs. The presented case study is a school building located in Melzo (Italy), shown in Figure 2.

This case study is one of the last example of integrated tender, developed through a Most Economical Advantageous Tender (MEAT) procedure in Italian context. The construction phase lasts less than six months, without variations or controversies, thanks to a collaborative approach between designers and constructors.

Figure 2: Melzo school: South façade

The school building, designed for 500 students, was developed as a research project in collaboration with the working group led by Prof. Giuseppe M. Di Giuda from Politecnico di Milano. The building is divided into three functionally and technologically different parts. The first one is a central reinforced concrete spine that connects all rooms with administrative function, such as teaching, library and auditorium. The second part is linked to the former through a central corridor, and it is composed by three blocks with a wooden structure. These contain teaching classrooms and workshops. The third part is a double height building made of precast concrete elements, hosting gymnasium, canteen and technical rooms.

The optimization process was applied to the design of the façade of the main building, interpreting goals and needs of constructors, designers, and producers. The curved ventilated façade is composed of a metal structure, linked by fixing brackets to the concrete wall. The metal structure, composed of t-shaped steel profiles, acts as support for the cladding, made of high-pressure compact laminate panels.

The designers' choice was to create a color vibration using black, white, red, blue and yellow panels. Several issues regarding this façade were taken into account in the design and optimization phases: the curved geometry of the façade, the color variation required, the technological needs in terms of panels' sizes and shapes.

The all-embracing view of the project provided coherence thanks to a BIM approach.

The quantitative approach, reached through a multi-criteria analysis, provides the process with a traceability of decisions.

Use of extracted values to feed the algorithm

The proposed methodology allows consistency of data to make further consideration, based on the result acquired from the model (Figure 3).

The required data to feed the algorithm have to be extracted directly from the model: for this reason, Dynamo plug-in, that is perfectly integrated in BIM-based software Revit, was chosen to design and develop the algorithm. Dynamo allows to create design alternatives by means of variation in pre-set parameters. Through this methodology, the script acts directly on the model and, consequently, schedules and quantities are updated consistently with the designed model.

Figure 3: Data control

A common rule sets the basis to develop the script: a pattern composed by a black and white field and a sequence of random colored fields, in the range from one to five.

To create the pattern, the developed script requests four inputs: (i) the face of the geometry, (ii) the width

of the panels, (iii) the height of the colored central panel and (iv) RGB colors for the random pattern. Dynamo takes geometrical information from a BIM model, such as shape, allowing users to create other geometries based on a mathematical algorithm, resulting therefore in an increase in quality and time management of design processes.

The essential advantage consists in the creation of a coherent and holistic interaction among different disciplines: information be automatically evaluated and the model can be consequentially updated, establishing a bidirectional flux of data.

The arithmetical approach to the algorithm consists in the creation of a function based on the geometry. Dynamo elaborates the geometrical input, and deduces a function, from which it calculates the total length of the façade. Later on, the script divides the functions by modules' width and places points. As the nodes between panels require a list of four points in clockwise order, a complete list to place all the needed components is prepared.

Figure 4: Adaptive components

An adaptive family is created and embedded with the required parameters (i.e. material, cost and dimensions, as shown in Figure 4), set as instances so the script can modify each of them individually.

The following step regards the placement of adaptive components on located points. In order to fulfill this requirement, the elaborated list of points is split in two separated lists. The first is obtained through the node that select items at index from the list of defined points. These indexes are obtained by a random selection among the predefined range and each item is summed to the previous one. (Figure 5) This process allows to place the sequence of colored panels. The second list is obtained through a subtraction of the list of colored panels from the list of all points. Through this script, both colored and black/white panels can be placed on the façade.

Figure 5: Dynamo script

BIM Information to fulfill the algorithm

This change of mind allows a different approach: namely it is possible to base a series of consideration, that are usually based on an economical point of view, with this method are instead performance based.

Through the quantity take off (Figure 6), it is possible to evaluate the real cost of the panels of a chosen solution through simple operations, based on manufacturing procedures (number of cuts).

Waste material resulting from cutting operations is also taken into account through a simple calculation.

Data are extracted for each design solution and inserted in an Excel sheet file. Data are elaborated through a macro to fulfill the algorithm and are compared with the other solutions. In this case, the algorithm is adapted to the contractors' needs: parameters and their weights are chosen on his discriminating factors, as later on shown. Namely, in this case, selected parameters were: (i) shape, (ii) costs, (iii) number of modules and (iv) waste material. As explained in the methodology, each parameter has its own weight, as shown in Table 1.

Figure 6: Production list

Shape factor is calculated comparing the geometry of the designed solution and the optimized one, divided by the initial geometry and re-parametrized between minimum and maximum values. The second factor is costs, evaluated on production operations and re-parametrized between minimum and maximum values. The third parameter is the number of different

modules' types used in the realization of the façade, considering the color variation.

The fourth factor is the waste material to produce the façade. It is calculated as the ratio of unused material to needed material to produce all panels and re-parametrized between minimum and maximum value. Constructors' requests were considered in terms of impact on final cost. In particular, the number of modules to be used resulted as the most relevant factor in assembling period. Cutting processes to obtain the panels were set as the most relevant factor. Waste material and shape of the façade play a less relevant role, as shown in Table 1.

Table 1: Weight of parameters

Parameters	i	ii	iii	iv	tot
Weight	20	30	30	20	100

Four different solutions in terms of color variation and size were evaluated. The comparison can be carried out by applying the algorithm to different solutions, obtained through the script, with variations in panels width. As data are obtained directly from the model, all the panels, designed in the model, contain all the information needed for the evaluation. The script re-parametrized from zero to one multiplied by the weight.

Table 2: Different solution comparison

		Parameters				
Solution		i	ii	iii	iv	tot
	1	10	30	20	0	60
	2	20	30	30	15	95
	3	15	0	30	10	55
	4	0	20	20	20	60

The selected solution was the number 2, based on the final score obtained (as shown in Table 2).

Discussion and conclusions

Advantages of the provided approach

The presented approach could be applied to several stages of the design and construction process.

The possibility to adapt the chosen parameters on the needs of different actors and goals of the process results in fact in a certain degree of flexibility, that allows to apply this approach to different points of view of the process.

Considering decision related processes, it has to be noticed that currently a lack of transparency and legibility can be underlined. Some choices appear to be mainly based on previous experiences or expertise of the involved actors. This issue results in a decrease of productivity and effectiveness, as well as a lack of traceability of decisions throughout the process. It is nonetheless recognized that an efficient management of building design, together with knowledge

management and communication, results in higher quality (Knotten, Lædre, & Hansen, 2017). The proposed methodology could be helpful in this sense, as it provides a comparative evaluation on a quantitative base, enhancing control over decision processes. Furthermore, the decision process can be re-evaluated in case of change of priority (i.e. change in parameters' weights). This process results in an increase in terms of efficiency of the whole workflow.

The result is consequently a tailored solution, based on stated needs; iterations in the methodology could be applied to provide a robust decision support tool.

Current limitations and further application

This methodology has been applied and developed through a specific case study, that has helped in validating it and providing the stage for further applications. A generalization of this method could regard its application to other case study buildings, with panelized façades or modular elements. Weights used for the parameters can be adjusted depending on needs of clients. Considering that a main focus of the proposed approach is related to dimensions, this approach could also be applied to partially opaque façade, including therefore transparent elements.

Some aspects related to the algorithm are currently not automated, that means that some calculations or evaluations need to be carried out manually from the designer or the contractor. Waste related aspects were calculated manually; a promising further aspect in this sense stems from the collaboration with manufacturers, in order to develop a partially automated evaluation of production related parameters. The collaboration with the supply chain in this sense could also be useful to potentially integrate further details related to manufacturing activities and production needs.

For these reasons, the proposed methodology will be tested on several case studies, to better understand and determine advantages provided and to refine the approach.

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BLOCKCHAIN IN CONSTRUCTION LOGISTICS: STATE-OF-ART, CONSTRUCTABILITY, AND THE ADVENT OF A NEW DIGITAL BUSINESS MODEL IN SWEDEN

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Abstract

Research on blockchain technology implementation within civil engineering is quickly emerging. The use of blockchain for the integration of the material and economic flows within construction supply chain – thus creating a new digital business model for the related actors – to enhance a construction project's production, logistics management, and constructability, has been only scarcely investigated. In this paper, this shortage is documented through a comprehensive literature review. Then, the potential of Swedish independent third-party logistics consultants as a fertile ground for such a digital business model, is examined. Finally, conclusions about the pursuance of this potential paradigm shift are drawn.

Introduction

There are several approaches to define and frame the field of blockchain technology, after its first emergence in Nakamoto's (2008) seminal work (Konstantinidis et al., 2018). Among others, there has been focus on understanding it as a disruptive technology that prepares a technological ecosystem for the upcoming emergence of the Internet of Things (IoT) (Woodhead et al., 2018), and its framing as a means of performance measurement within processes containing consecutive and/or simultaneous steps (Kuhi et al., 2018). However, a generally acceptable approach underlying individual framings such as the above, defines blockchain as a peer-to-peer system of transacting values (in the form of a shared, decentralized and open ledger replicated across nodes), without the need of trusted third-party intermediaries in between to verify, secure, and settle the transactions (Dannen, 2017; O'Leary, 2017; Singhal et al., 2018). Blockchain acts as a layer on top of the Internet, which can co-exist with other Internet technologies, and its ledger databases are append-only; they cannot be altered, and every entry is permanent, with the new ones being reflected on all database copies hosted in different nodes (Singhal et al., 2018). The three major functional components of blockchain are game theory (as its mathematical basis), cryptography (as its main operational framework), and computer science (as the field of its realization) (Belle, 2017; Singhal et al., 2018).

Within the construction sector, and following earlier considerations on the transparency of information access and management in construction projects (Craig &

Sommerville, 2006), and the improvement of the contractual and procurement procedures (Eriksson & Lind, 2016), blockchain has been researched both in terms of theoretical understanding and practical implementation (Barima, 2017; Belle, 2017; Turk & Clink, 2017; Wang et al., 2017; Kamenetskii & Yas'kova, 2018; Klyukin et al., 2018; Li et al., 2018, 2019a; Navadkar et al., 2018). However, the use of blockchain for the integration of the material and economic flows within the production process of a construction project has yet to be investigated.

Such an integration could formulate a new digital business model – namely, the organizational background and processes to create, deliver and capture value (Osterwalder & Pigneur, 2010; Konstantinidis et al., 2018; Momo et al., 2018), but in a digitalized context. This is culminated through the “value proposition”, namely the creation of value for the client who is willing to pay for it, thus converting it into turnover and profit for the firm (Mangematin & Baden-Fuller, 2015; Andreini & Bettinelli, 2017). Such a new digital business model could integrate the attributes of the operational canvas by Osterwalder and Pigneur (2010): proposing and creating value for the key stakeholders and clients, monitoring key activities, key resources, stakeholder relationships and flow channels, understanding the related cost structure, and facilitating the revenue streams. In this paper, the absence of such a digital business model within the civil engineering research on blockchain technology, is highlighted; its problem-solving capabilities, uses, faced challenges, and limitations – also considering its security (Kareem et al., 2018) and its relation to constructability (Kifokeris & Xenidis, 2017) – will be noted; and the fertile ground for its implementation within the growing ecosystem of independent third-party logistics consultant firms operating in the Swedish construction sector, will be examined.

In the second section of the paper, the literature review about the state-of-art research on blockchain implementation in construction is presented, and the research and implementation gaps are showcased. In the third section of this paper, certain particularities in the Swedish construction sector are shown; then, they are tied with the proposition of the new general digital business model. Finally, in the fourth section, conclusions about the proposed paradigm shift and the advent of the new digital business model, are drawn.

Blockchain technology in the construction sector

Research on the development and implementation of blockchain technology within the construction sector is relatively new (Penzes, 2018), and with related application systems and developed solutions generally not being yet technologically and commercially mature (Gerber & Nguyen, 2019; Nguyen et al. 2019). The research efforts are mainly discretized into two categories: holistic research on the understanding and implementation of blockchain, and dedicated research on the targeted integration of blockchain with distinct fields within the lifecycle of a construction project.

The holistic approach features the following research dimensions:

- Lateral integration of blockchain within existing processes and frameworks in the construction project lifecycle, namely within procurement (Barima, 2017; Wang et al., 2017; Kamenetskii & Yas'kova, 2018; Navadkar et al., 2018), process re-engineering through digitalization (Belle, 2017; Polim et al., 2017; Coyne & Onabolu, 2018; Gausdal et al., 2018; Klyukin et al., 2018), setting the goals of strategic innovation (Graglia and Mellon, 2018), knowledge management (Piraquive et al., 2017), and logistics and supply chain management (Wang et al., 2017; Dobrovnik et al. 2018; Rubio et al. 2018). The efforts following this dimension mainly address the problem of process automation and optimization, as well as the effect of mitigating the human intervention in such processes.
- Proposal of new integrated frameworks using blockchain, regarding the technical, social and political dimensions in addressing the problem of the relative technological implementation (Li et al., 2018, 2019a)

The dedicated approach features the following research dimensions:

- Implementation of smart contracts (namely, computer protocols that facilitate, verify, or enforce the negotiation or performance of a contract, and/or obviate the need for a contractual clause) for all transactions (Cuccuru, 2017; Mason, 2017; Lamb, 2018; Mason & Escott, 2018). The efforts following this dimension mainly address the problem of process automation and optimization as well, but in dedicated fields rather than at a high-end systemic level.
- Interconnection of blockchain with IoT, to enhance construction productivity and performance (Heiskanen, 2017; Kochovski & Stankovski, 2018).
- Interconnection of blockchain with Building Information Modelling (BIM), and especially for facilitating trust among stakeholders (Mathews et al., 2017), resolving data issues like confidentiality, provenance tracking, disintermediation, non-repudiation, multiparty aggregation, traceability, inter-organizational record keeping, change tracing, and data ownership (Turk & Klinc, 2017), and using IoT as a data source for BIM (Arthur et al., 2018). There has

even been negative critique on such an interconnection, as Ghaffarianhoseini et al. (2017) state that blockchain cannot be integrated with BIM in a way that creates additional value but would rather be more useful just as a tool for document handling, auto-invoicing and automated control.

- Interconnection of blockchain with Computer Aided Design (CAD), for the optimization of the issue of digital design distribution and validation (Dounas & Lombardi, 2018).
- Interconnection of blockchain with radio frequency identification (RFID) technologies for logistics and site management (Lanko et al., 2018), to address the problem of streamlining the construction supply chain.

In all the above, and especially regarding construction logistics and supply chain management (Wang et al., 2017; Dobrovnik et al. 2018; Lanko et al., 2018; Rubio et al. 2018), there has not been an investigation on the capabilities of blockchain for the integration of the respective material and the economic flows. Considerations on pursuing this integration have been already been noted in the relative research (Love et al. 2004; Koçtaş & Tek 2013; Li et al., 2017). The consensus was that such an integration could:

- Facilitate a holistic overview of the full production of the construction project.
- Foster trust, transparency and traceability in transactions and flows.
- Enhance the quality management of the on-site deliverables (e.g. equipment or materials).
- Aid in stakeholder collaboration through the decentralization brought about by the blockchain network.
- Create monetary and qualitative value for the stakeholders.
- Assist in the optimization of a project's constructability, namely "the optimum use of construction knowledge and experience in planning, design, procurement, and field operations to achieve overall project objectives" (Construction Industry Institute, 1986). Important constructability aspects are a holistic view on logistics, supply chain integration, and close stakeholder cooperation through trusted transactions (Kifokeris & Xenidis, 2017), which pose direct interfaces with blockchain implementation.

The need for such an integration can also be addressed by the capabilities of blockchain technology itself, as has also been noted in related research efforts outside the field of construction (Chen et al., 2017; O'Leary, 2017; Risius & Spohrer, 2017; Wu et al., 2017; Francisco & Swanson, 2018; Kavassalis et al. 2018). For the conception of a new digital business model regarding the integrated blockchain implementation within the construction logistics and supply chain, the research output mentioned above (both construction-related and not) should be considered, along with:

- State-of-art developments on the understanding and implementation of blockchain technology for logistic

and supply chain management in general (Büyüközkan & Göçer, 2018; Chichoni & Webb, 2018; Hofmann & Rutschmann 2018; Hofstetter, 2018; Kim & Laskowski, 2018; Kshetri, 2018; Mukri, 2018; Verhoeven et al., 2018). Central in these research efforts is novel “value creation” through blockchain solutions for the corresponding supply chains. Such a value can be enhanced by integrating interrelated business aspects of supply chain processes with the introduced blockchain technologies, such as the material and the economic flows.

- Insights gained from the particularized blockchain-related research for supply chains within the manufacturing industry (Kayikci, 2018; Kremer, 2018; Mondragon et al., 2018). While Aloini et al. (2012) have noted certain differences between the manufacturing and construction supply chains (namely, dissimilar project complexity, configuration intensity, customer influence, process fragmentation, and stakeholder interconnection), these supply chains depict indeed a certain procedural similarity (Koçtaş & Tek, 2013). The discretization of manufacturing supply chains into discernible processes and flows (Mondragon et al., 2018) can correspond to the processes and flows of construction supply chains, and thus be extrapolated accordingly (Koçtaş & Tek, 2013). So, the advances of blockchain implementation in manufacturing, complemented by the research outcomes noted in the previous bullet, can be valuable for blockchain development within construction.
- Attention to the security issues identified for and of blockchain implementation (Khong & Escobar, 2017; Harlev et al., 2018; Kareem et al., 2018; Sklaroff, 2018; Underwood, 2018; Veuger, 2018). The “for” issues are mainly connected to the lack of trust among stakeholders in the adoption of blockchain; the disruption brought about by blockchain can be viewed with discomfort, and extreme opinions even regard it as a fad. The “of” issues are mainly derived from the abuse of those properties that make blockchain a novel disruption technology in the first place; the node-like anonymity of the distributed network can be a driver for illicit activities, the cryptocurrencies used can cause the loss of real-value grasp, any breach in the system cryptography can lead to the immediate and unrecoverable loss of virtual funds (as opposed to the potentially retrievable fiat currency funds), and the potential inflexibility of the automated processes can lead to loss rather than creation of value for the stakeholders. A new integrated digital business model for blockchain implementation in the construction supply chain and logistics should address and face those concerns.
- Emphasis on construction-specific frameworks of production and management interconnected with supply chains. Most prominent among such frameworks is constructability, which can both impact and be impacted positively by an effective supply chain with integrated flows, procedural transparency, and simultaneous early contractor involvement in the

construction project lifecycle (Love et al., 1999; O’Brien, 1999; Khalfan et al., 2001; Love et al., 2004; Karim et al., 2006; Khalfan et al., 2010; Chen, 2012; Saunders et al., 2015; Kifokeris & Xenidis, 2017). Other construction-specific aspects to be emphasized can include the implementation of lean construction principles (Koçtaş & Tek, 2013; Santorella, 2017), component prioritization (Jiang, 2016) for economic flow optimization, and the effect of the chosen contractual strategy (e.g. design-bid-build or design-and-build) (Clough et al., 2015).

- Acknowledgement of the capabilities of already developed blockchain systems – such as IBM Blockchain (Forrester Consulting, 2018) – and research on their enhancement, customization, implementation and even replacement.

Building on the above, and in considering the implementation of such a digital business model, major potential uses of blockchain in construction logistics with the aim of integrating the material and economic flows in the supply chain, can include the following:

- Deployment of a decentralized blockchain network, with the nodes corresponding to stakeholders involved in the logistics and supply chain management (e.g. clients, contractors, subcontractors, suppliers, transporters, and logistics consultants – see in the following section). This network will function as a shared, immutable ledger with historic data accessible by the stakeholders.
- Automation and direct connection of the payments to the suppliers and transporters, also with potentially using IoT. For example, data regarding the arrival and supply of materials and equipment (e.g. through sensors identifying the RFID tags of construction vehicles arriving on-site) can trigger smart contracts on the blockchain network, which will automatically support the sending of the respective payments to the relevant actors. Such payments can be realized in a form of cryptocurrency accepted by the actor, or they can be translated in fiat currencies, as per the respective crypto-system implemented in the utilized blockchain network.
- Tracking the origin of supply chain inputs (e.g. construction materials like gravel and cement) through the append-only sequences of blocks in the blockchain, and cross-checking their quality, along with the integrity and validity of the process followed by the respective subcontractors, suppliers and transporters. Any smart contract triggers related to the payment of the aforementioned actors can also include clauses considering such process-oriented cross-checks.

However, such an implementation can face significant challenges. Central among them, are the “for” and “of” security issues described above and within the respective literature (Khong & Escobar, 2017; Harlev et al., 2018; Kareem et al., 2018; Sklaroff, 2018; Underwood, 2018; Veuger, 2018); namely, the lack of trust among stakeholders in the adoption of blockchain, discomfort in the disruption brought about by blockchain, fear of

potential illicit activities rooted in the node-like anonymity of the distributed network, loss of real-value grasp due to the use of cryptocurrencies, immediate and unrecoverable loss of virtual funds in the case of breach in the system cryptography (however unlikely and/or extremely costly in computational means this may be), and potential inflexibility of the automated processes. In addition, blockchain is considered by some researchers as somewhat ambiguous in its claim on value creation – especially for construction logistics – (e.g. in Li et al., 2019b), and as difficult to implement without the simultaneous implementation and support of other types of infrastructure as well, such as BIM and IoT (Ye et al., 2019). Finally, an always present challenge is the stimulation of the respective actors and stakeholders into adopting a new digital business model utilizing such a technology. For this, the matter of understandable, monetizable, and readily available value creation is crucial.

Coupled with the challenges are the potential limitations of such an implementation. There is currently little widespread understanding of the technology underlying blockchain within the construction sector (and especially within the field of construction logistics), making the respectively dedicated and/or knowledgeable practitioners relatively rare. Due to this limitation, even in the case of an actual investment in blockchain for construction logistics, its realization may entail the outsourcing of the development process to blockchain technicians not necessarily familiar to the particularities of construction supply chains and logistics. Furthermore, cryptocurrencies may be increasingly accepted as means for transactions, but not by all, and especially not all in the construction industry; and even if a cryptocurrency is translated into fiat currency through the relative system, it cannot be avoided in the first place, since it is essential for the function of the blockchain framework.

With this background, an early concept of such a new and generic digital business model can be presented in the canvas by Osterwalder and Pigneur (2010), as in Figure 1 (see next page). It should be underlined that within this generic model, several firm-specific business models will be needed.

The case of the Swedish independent third-party logistics consultant firms

Sweden is experiencing urbanization, as is the rest of Europe. This intensified activity and its associated complex processes, may result in issues such as delayed deliveries, complicated supply chain coordination, and low productivity and efficiency (Dubois et al., 2017). To ameliorate such issues and facilitate all associated logistics services, one state-of-art business practice is the employment of independent third-party logistics consultant firms, which assist in coordinating and handling complex, recurrent and conflicting flows consisting of deliveries of materials, arrival of incoming goods, and other sub-systems. These firms are often small organizations; they embody a business model for improved construction logistics, strengthening the coordination across the supply chain by connecting the client, the material and equipment transport companies, the contractors, and the subcontractors. The most prominent among these firms are featured in Table 1 (see next page), with this list being based on the authors' targeted communication with firm representatives, the firms' websites, and related literature (Gustavsson, 2018). By configuring their business practice in the way described above, these firms are given a central role within the development of a construction project.

However, there is no established approach and level of digitalization in the coordination process they carry out – in some cases, it is facilitated by the third-party logistics firms taking a role as collaboration and process consultants, while in others it is supported by IT systems,

<u>Key partners</u>	<u>Key activities</u>	<u>Value proposition</u>	<u>Customer relationships</u>	<u>Customer segments</u>
Logistics consultants IT infrastructure specialists Clients Main contractor Subcontractors Material suppliers Retailers Transporters	Construction project production and management <u>Key resources</u> Monetary Human Technological Material	The logistics processes will be quicker, more efficient, more comprehensive, and more automated. The transactions and payments will be more secure, instant, decentralized, correct, and transparent. The optimization of the integrated flows will allow less rework, better change management, and optimized site operations. The role of economically dependent stakeholders (e.g. subcontractors) will be enhanced in a lateral manner.	Close collaboration Dynamic transactions Peer-to-peer	As created by the segmentation of the process through the implementation of disruptive blockchain technology
<u>Cost structure</u> Cost paid by the client and/or main contractor Included in the fees of the logistics consultants and/or IT specialists			<u>Channels</u> As created by the operation of the nodes Integration of material and economic streams <u>Revenue streams</u> As created by the operation of the nodes in the blockchain Decentralized, secure, transparent, and resulting through instant transactions	

Figure 1: Canvas of an integrated blockchain solution for construction supply chain and logistics

which are generally fragmented and non-integrated. These approaches do not have to be mutually exclusive, and in some cases, they are all used to some extent. They are summarily noted in the “Approach” column in Table 1, where it is hinted that some firms may still deploy a more traditional business model using established methods and tools (e.g. Prolog), while others mostly deploy a digital business model involving advanced technologies such as planning software and tracking systems (e.g. LogTrade,

Myloc). Nonetheless, all approaches involve collaboration and interaction with the on-site contributing parties and key suppliers; this is an important aspect to the “value proposition” of the respective business models (Mangematin & Baden-Fuller, 2015). In a broader perspective, other adjacent players can and will influence the collaboration on building logistics in Sweden. The equipment supplier Ramirent, for example, presents an approach to digital

Table 1: Prominent third-party logistics consultant firms within the Swedish construction sector

Name	Turnover (2017-8) €	Staff no.	Industry	Main clients	Approach	Digital solution?
LogTrade	≈ 2.328 M €	9	Construction, manufacturing, retail, transportation	Contractors, suppliers, distributors, retailers, transporters	Digitalization/automation	Yes, in-house
Myloc	≈ 1.483 M €	8	Construction, real estate, inventories, manufacturing	Contractors, suppliers, distributors, manufacturers	Digitalization/automation	Yes, in-house
Prolog Bygglogistik	≈ 1.905 M €	22	Construction, real estate	Contractors, suppliers, distributors, transporters	Facilitation/digitalization/automation	Yes, with external partner
Servistik	≈ 2.749 M €	20	Construction, manufacturing, waste management	Contractors, suppliers, distributors, manufacturers, transporters	Facilitation/digitalization/automation	Yes, in-house
Svenskt Byggdialog	≈ 100.871 M €	138	Construction, real estate	Contractors, suppliers, manufacturers	Facilitation/digitalization/automation	Yes, in-house
Svenskt Bygglogistik	≈ 4.167 M €	25	Construction, real estate, transportation	Contractors, suppliers, distributors, transporters	Facilitation/digitalization/automation	Yes, in-house
FM Management	≈ 2.337 M €	8	Construction, real estate, transportation	Contractors, suppliers, distributors, transporters	Facilitation/digitalization/automation	Yes, with external partner

logistics solutions echoing the business model implemented by other Swedish firms offering miscellaneous construction services, such as, Buildsafe, Loop Rocks, Ene Golv, and Edvirt. Moreover, the continued dominance of contractor-driven buildingLogistics is also developing and should be researched; Veidekke Sweden, for example, has acquired and uses in-house the services of a dedicated and previously autonomous logistics company. Finally, best-practices and lessons-learned from the business models of global logistics firms operating in Sweden, such as DB Schenker, DSV, and UPS, should be studied – currently not allowed in the short space of this conference paper.

In such collaborative business models, their digitalization (or the enhancement of their already digitalized solutions) with the use of blockchain can optimize their efficiency and lower their respective costs (McKinsey Global Institute, 2017). The properties of blockchain align with the need to view digital business models in an inter-organizational manner and not only as a single company effort (Vendrell-Herrero et al., 2018) – something offered when partnering with the third-party logistics consultant firms. Digital business models involve the alliance of

incumbent product-oriented firms with newcomers having digital capabilities, as a way of assuring agility and overcoming inertia in existing supply chains (Vendrell-Herrero et al., 2018).

Apart from the collaborative aspect, in developing digital business models for construction supply chains and logistics, an integrated and agile approach is needed (Thunberg & Fredriksson, 2018). In such an approach, the planning of on-site space utilization for provisional storage can be continuous, substituting the previous, more static “Area Disposition Plan” (APD) approaches. It is recurrent to mention APD as dynamic, but this rarely implies continuous integration between logistics planning and material registration, placement and installation. Such a digital approach could be integrated with the flow control system and would also involve blockchain in handling the economic flow along the physical flow (O’Leary 2017).

The employment of third-party logistics consultants can bring about all such sought collaborative, integrated and agile aspects. However, issues of delivery failure, unprecise data, delays in time, and inefficient flows and data transfers between systems, still occur, preventing the

efficiency optimization of construction supply chains and logistics – especially in large construction sites. On-site physical placement is rarely tied to any implemented digital solutions. Moreover, these firms are burdened with justifying the value-for-money for their logistics services fees – the disintegration between the material and the economic flows is evident in the decoupling between the payments for the deliveries and transportation services, and for the logistics solution.

Thus, it can be derived that the third-party logistics consultants within the Swedish construction sector both:

- Present a fertile ground for the implementation of a dedicated digital business (as a particularization of the conceptual and generic digital business model described earlier) featuring a blockchain solution that integrates the material and economic flows within the construction supply chain and logistics, since the firms display the collaborative and integrating aspects aligning with such an implementation, and
- Need such a digital business model. Even in the case of more digitally advanced firms, on-site issues of disintegration, and matters of value-for-money justification due to the decoupling of the material and economic flows, have still to be tackled.

The “value proposition” in this case, and following the early conceptual business plan in Figure 1, would be a holistic, transparent, automated and fully integrated solution for the realization of the construction supply chain and logistics processes in an unhindered way. This could facilitate the generation of additional value for the “customers” – owners, contractors and subcontractors – which could then turn to profit.

Conclusions

Blockchain is an emerging technology with disruptive potential, acting as a peer-to-peer system of transacting values (in the form of a shared, decentralized and open ledger replicated across nodes), with a reduced need of trusted third-party intermediaries in between to verify, secure, and settle the transactions.

Within the construction sector, the implementation of blockchain has been investigated both in a general and in a dedicated manner. However, there has been little research on a blockchain solution integrating the material and economic flows within the construction supply chains and logistics. Such an integration could holistically facilitate the full production of a construction project, foster trust, transparency and traceability in transactions and flows, enhance the quality management of deliverables, aid in stakeholder collaboration, and create monetary and qualitative value. This integration can ultimately be realized into a digital business model for the third-party building logistics consultants that draws from knowledge generated from the implementation of integrated blockchain solutions in other industries, and incorporates construction-specific aspects, such as constructability, lean construction and the effects of the elected contractual strategy. However, the adoption of

such a digital business model can face challenges, such as trust and security issues, and also be demarcated by limitations, such as the relatively sparse knowledge of blockchain fundamentals within the construction sector.

The Swedish independent third-party logistics consultant firms reveal, through their distinctive characteristics and operational processes, both a capability and a need for such an integrated blockchain solution. Thus, problems of on-site process disintegration, and justification of value-for-money, could be effectively mitigated.

The robust conceptualization and development of such a digital business models cannot be disintegrated from the operational processes and business models of the stakeholders collaborating with the independent third-party logistics consultant firms in Sweden. The interfaces with material and equipment rental/supplying firms, companies offering miscellaneous construction services, and global logistics firms should be investigated. Moreover, the dominant contractor-driven building logistics practice should be researched, as large contractors are currently developing their capabilities.

As future work, not only the research on the business models and processes of the aforementioned actors will follow, but also the identification, for each stakeholder, of the value creation through the implementation of an integrated blockchain solution, will take place. Moreover, the robustification and particularization of the proposed early conceptual and generic digital business model, with a central interest in creating a dedicated digital business model for the independent third-party logistics consultants in Sweden, will be pursued. In addition, the blockchain technology infrastructure itself, including the integration of flows, the distributed network, the smart contracts, the on-site triggers, and the end-user application, will be developed into a prototype. Finally, this prototype will be tested and verified in the case of a construction site, and with the attendance of the actors respectively represented by the relative nodes in the distributed network.

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INCLUDING WIDESPREAD GEOMETRY FORMATS IN SEMANTIC GRAPHS USING RDF LITERALS

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Abstract

The exchange of building data involves both geometric and non-geometric data. A promising Linked Data approach is to embed data from existing geometry formats inside Resource Description Framework (RDF) literals. Based on a study of relevant specifications and related work, this toolset-independent approach was found suitable for the exchange of geometric construction data. To implement the approach in practice, the File Ontology for Geometry formats (FOG) and accompanying modelling method is developed. In a proof-of-concept web application that uses FOG, is demonstrated how geometry descriptions of different existing formats are automatically recognised and parsed.

Introduction

Researchers in both academia and industry are actively investigating the benefits of web technologies to improve the exchange of structured building data, including geometric data (Pauwels et al., 2017). The Semantic Web technology stack is standardised by the World Wide Web Consortium (W3C) and uses Resource Description Framework (RDF) triples as an elementary building block to create graphs of linkable entities. Different methods to include RDF-based geometry descriptions in Linked Data graphs already exist. They have their own dedicated vocabularies, e.g. the [OntoBREP](#)¹ or [GEOM](#)² ontologies, and related toolsets (Perzylo et al., 2015).

Creating geometry representations in RDF according to the approach mentioned above can be achieved by using a dedicated Linked Data geometry modelling tool. Alternatively, geometry coming from regular CAD applications can be converted into RDF-based geometry descriptions. When reusing such geometry descriptions stored as an RDF graph, the geometric data has to be transformed into a readable format for geometry kernels of typical non-RDF applications used in practice. The construction industry, however, also demands a more straightforward method – not related to specific RDF-based geometry toolsets – to

easily transfer geometric data. Such data can flow bidirectionally between semantic graphs and the stakeholders' existing geometry processing tools, ideally with as little conversions as possible to minimise conversion errors.

Consequently, methods to introduce already existing and widely used geometry formats (e.g. STEP, OBJ, DWG, etc.) in RDF graphs have to be considered. Two possible alternatives for RDF-based geometry emerge: linking RDF entities of building elements to (1) external geometry files by storing their file location references in RDF literals or (2) RDF literals containing the entire content of such geometry files. This paper focuses primarily on embedding geometry descriptions in RDF literals, but also considers RDF literals referencing external geometry files.

The remainder of this paper contains four sections. The section 'RDF literals and geometric content' covers an analysis of the relevant W3C specifications, existing related implementations and practical requirements to enable the adoption of RDF literals for geometric data. The final part of this first section discusses the feasibility of using RDF literals to store geometry descriptions. Shortcomings of the existing implementations for RDF literals and geometry are addressed in the following section. A new ontology is proposed and validated together with an accompanying modelling method. Section three, 'Proof of concept application', demonstrates how the above can be implemented in applications, while the final section contains the conclusion and addresses future work.

All Uniform Resource Identifier (URI) prefixes mentioned in the remaining of this paper are assembled in Listing 1.

Listing 1: Used URI prefixes in this paper

```
@prefix rdf:
  <http://www.w3.org/1999/02/22-rdf-syntax-ns#> .
@prefix rdfs:
  <http://www.w3.org/2000/01/rdf-schema#> .
@prefix owl: <http://www.w3.org/2002/07/owl#> .
@prefix xsd: <http://www.w3.org/2001/XMLSchema#> .
@prefix bot: <https://w3id.org/bot#> .
@prefix strdf: <http://strdf.di.uoa.gr/ontology#> .
@prefix geosparql:
  <http://www.opengis.net/ont/geosparql#> .
```

¹<https://github.com/OntoBREP/ontobrep>

²<https://github.com/w3c-geom-cg/geom>


```

@prefix geom: <http://bimsparql.org/geometry#> .
@prefix cbim:
  <http://www.coinsweb.nl/cbim-2.0.RDF#> .
@prefix omg: <https://w3id.org/omg#> .
@prefix fog: <https://w3id.org/fog#> .
# namespace for example node instances
@prefix inst: <https://example.org/data#> .
# namespace for a fictive example ontology
@prefix ex: <https://example.org/onto#> .

```

RDF literals and geometric content

In this section, the potential of RDF literals for representing and exchanging geometric content is studied. The first subsection introduces how RDF literals are defined in the relevant web standards, while the second part discusses how other researchers and organisations apply RDF literals for geometric content. Based on current practice in the construction industry, five practical requirements for the use and exchange of geometric data are listed in the third subsection. Finally, the feasibility of RDF literals to store geometry descriptions is discussed.

The nature of RDF literals

The [RDF 1.1 W3C specification](https://www.w3.org/TR/rdf11-concepts/)³ determines how RDF literals should be used in Linked Data graphs and refers to other related W3C standards.

While each RDF triple consists of a subject, predicate and object, an RDF literal can only be used in the object position of a triple. Thus, a literal can have an incoming relation but no outgoing links. The three essential parts of an RDF literal are (1) the lexical form, (2) the datatype URI and (3) an optional language tag. The lexical form has to be a single collection of UNICODE characters that corresponds to a certain literal value (value space). The datatype URI refers to a datatype that in turn defines what content is valid (the lexical space), the value space and the mapping between the lexical space and the value space. Each literal has exactly one datatype.

Predefined datatype URIs in the W3C specifications have a fixed referent. The Web Ontology Language or [OWL 2 specification](https://www.w3.org/TR/2012/REC-owl2-syntax-20121211)⁴ for example contains the fixed datatypes `owl:real`, `owl:rational`, `rdfs:Literal`, `rdf:PlainLiteral`, `rdf:XMLLiteral` and a selection of XSD datatypes (XML Schema Definition Language) documented in the [W3C XSD 1.1 specification Part 2](https://www.w3.org/TR/2012/REC-xsd11-2-20120405/)⁵ (e.g. `xsd:integer`, `xsd:string`, etc.). Additionally, custom datatypes can be defined in an ontology by extending a fixed datatype or creating separate new datatypes.

Datatypes cannot be formally defined as a ‘subdatatype’ from another datatype, as each RDF literal has exactly one datatype assigned. This distinguishes them from classes

and properties in RDF, which can have respectively a ‘subclass’ or a ‘subproperty’.

Related work

The application of RDF literals for storing building geometry descriptions or references to geometry files is not new, but research documented online and in literature focuses on rather specific cases or domains. The shortcomings of six existing ontologies are analysed in this subsection. First, two frequently used geospatial ontologies are discussed, followed by three ontologies from the construction domain. Lastly, a more generic and flexible ontology, recently published by the authors of this article, is proposed.

GeoSPARQL

Two geospatial ontologies that allow to store existing geometry descriptions in RDF literals are discussed: the GeoSPARQL and the stRDF ontology.

The [OGC GeoSPARQL specification](https://www.opengeospatial.org/standards/geosparql) (Open Geospatial Consortium, 2012) describes an ontology with the same name, and a SPARQL extension for 2D spatial querying. The ontology provides terminology to connect any object via an intermediate node to a Well Known Text (WKT) or Geography Markup Language (GML) geometry description embedded in an RDF literal. The datatype property between the intermediate node and the RDF literal is specific regarding the geometry format (`geosparql:asWKT` or `geosparql:asGML`). Additionally, the literal has a custom datatype assigned (`geosparql:wktLiteral`, resp. `geosparql:gmlLiteral`). While each GML file can reference a standardised Coordination Reference System (CRS) by design, the GeoSPARQL specification allows to mention the CRS inside the lexical form of the literal in case of WKT geometry description.

stRDF

The stRDF ontology was developed together with a SPARQL extension named stSPARQL to allow 2D spatiotemporal querying (Koubarakis et al., 2012). Similar as GeoSPARQL, stRDF allows to link any object via an intermediate node to a WKT or GML geometry description stored in an RDF literal. In contrast to GeoSPARQL, only the (custom) datatypes are specific: `strdf:WKT` or `strdf:GML`. The stRDF/stSPARQL implementation also allows to include the used CRS inside the lexical form of the literal in case of WKT.

BimSPARQL

In Zhang et al. (2017), the BimSPARQL extension for SPARQL was designed to spatially query and analyse 3D WKT geometry descriptions connected to building elements from an IfcOWL-based RDF graph. Additional terminology is provided in the geometry module of the sup-

³<https://www.w3.org/TR/rdf11-concepts/>

⁴<https://www.w3.org/TR/2012/REC-owl2-syntax-20121211>

⁵<https://www.w3.org/TR/2012/REC-xsd11-2-20120405/>

porting BimSPARQL ontologies. Applying this module, the WKT geometry descriptions are stored in an RDF literal without a specific custom datatype but as an `xsd:string`. The datatype property between the intermediate node and this literal is also generic (`geom:asBody`).

Building Topology Ontology (BOT)

The Building Topology Ontology (BOT) is developed within the W3C Linked Building Data (LBD) group as a central ontology that can be extended with other modular ontologies (Rasmussen et al., 2017). The current version of BOT (v0.3.0) (W3C Linked Building Data Community Group, 2019) allows to connect any `bot:Element` or `bot:Zone` instance directly to a geometry description stored in an RDF literal using the generic datatype property `bot:hasSimple3DModel`. The BOT ontology does not define format specific datatypes or datatype properties for geometry descriptions stored in RDF literals. Besides the above datatype property, BOT also contains the object property `bot:has3DModel` to link building elements or zones to RDF-based geometry descriptions or an external geometry files. The property names and definitions suggests that they should only be used to connect to 3D geometry descriptions, thus ignoring 2D geometry.

COINS and ICDD

The COINS project (BIM-Loket, 2016) provides a methodology and vocabulary to annotate and link any group of construction related files using Linked Data technology. The result is called a COINS container, consisting of a number of files and an RDF annotation of these files and referenced files not included in the container. In the COINS approach, the separate files are linked to the RDF annotation graph using RDF literals containing the location of the file combined with the fixed datatype `xsd:anyURI`. This literal is connected with a generic property to an intermediate `cbim:UriProperty` instance node, which is again connected to a `cbim:DocumentReference` instance node. In a similar way, users can link any string literal to a `cbim:StringProperty` instance node that is connected to the `cbim:DocumentReference` instance node, to add information about the document type and the document Media type (MIME type) of the annotated file. This method allows users to define custom text descriptions at will, making it hard for software developers to query for specific files as several slightly different descriptions of the same file format might exist. Major parts of the COINS project are incorporated in the Information Container for Data Drop (ICDD) which is now under review for standardisation as ISO 21597.

Ontology for Managing Geometry (OMG)

The recently published [Ontology for Managing Geometry \(OMG\)](#) (Wagner et al., 2019) by the authors of this paper provides a datatype property named `omg:hasSimpleGeometryDescription` to link to a geometry description (2D or 3D) of any geometry format stored in an RDF literal. Similar to `bot:hasSimple3DModel`, this relation is not specific, but its scope is broadened to include both 2D and 3D geometry descriptions. OMG does not define any specific datatype properties and custom datatypes, as its scope is to arrange the management of geometry in general, independent of the actual geometry formats used. Inspired by the [Ontology for Property Management \(OPM\)](#) (Rasmussen et al., 2018), the OMG can be used to create level 1, 2 or 3 relations between a building element and its geometry descriptions (Wagner et al., 2019). This gives users the flexibility to use a more complex level 3 pattern (three relations between the building object and the geometry description) that allows version control, or a very simple level 1 pattern (direct link between an element and its geometry description) for easy querying.

Practical requirements for the use and exchange of geometry

Exchanged building geometry can be 2D or 3D, it can be a point cloud of an existing construction recorded by a laser scanner, a detailed geometry of a building product or a conceptual design of a new construction. Looking at current practice in the construction industry, it can be concluded that a wide variety of software and related geometry formats are used in different projects, during different life-cycle phases and by different actors (Pauwels et al., 2011). The following minimal practical requirements for the use and exchange of geometry descriptions using RDF literals are derived from this everyday reality:

1. Geometry descriptions stored in RDF literals can be of any existing geometry format, including text and binary files from open and proprietary formats. The RDF literals can contain 2D and/or 3D geometry descriptions. The content of text encoded geometry files can contain single and double quotation marks and is typically read line by line.
2. The actual geometry file format of the content stored in the RDF literal should be defined explicitly. As a result, software applications can query for the used geometry file formats, without having to analyse the content of each individual literal. Doing so not only helps applications to deal with the wide variety of geometry formats that can be available in an RDF graph, but also prevents the exchange of geometric data that is not supported by a certain application.

3. Some geometry schemas have multiple versions while others have multiple closely related schemas. The COLLADA format for example has a frequently used version 1.4.1, besides a newer version 1.5.0. The ASCII format Well Known Text (WKT) has a binary counterpart named Well Known Binary (WKB) that implements a similar internal data structure. Relations between both geometry schema versions and equivalent schemas should be recorded to easily retrieve geometry descriptions in similar schemas.
4. Applications should be able to unambiguously determine which RDF literals have to be treated together. Some geometry formats such as OBJ and glTF allow additional referenced files. For example the OBJ format defines a .obj file that can reference an additional .mtl file containing information about the materials and textures. Simultaneously, each building object can have multiple geometry representations from different points in time, coming from different actors and in different geometry formats.
5. It should be possible to add relevant metadata about each individual geometry description of a building object. Example metadata properties are file size, author, software that created the geometry descriptions, georeferences, the used scale / units and the up-axis. The last three properties are very relevant if the software application of a stakeholder has to use geometry from different geometry formats coming from other geometry modelling applications.

Feasibility of embedding geometry descriptions in RDF literals

The following subsection discusses the feasibility of using RDF literals to embed geometry descriptions of construction elements, according to the practical requirements and the relevant W3C specifications. Each paragraph discusses if and how each requirement can be fulfilled.

Requirement 1: allow every type of geometry format

The content of binary geometry files can be stored in RDF literals by encoding them in UNICODE characters. The base64 encoding is recommended, as its usage is widespread and encoders / decoders are available in almost every programming language. With this methodology the content of any file (text / binary and open / closed formats) can be embedded in an RDF graph. In the case of text encoded geometry files, text lines are important and the text can contain quotes. This means that each new line and quotation sign should be escaped correctly, depending on the RDF serialisation. With the OMG terminology, both two or three dimensional geometry descriptions can be included.

Requirement 2: explicit geometry formats

A natural way to denote the used geometry formats, is to define custom datatypes in an ontology as has been done in GeoSPARQL and stSPARQL for both WKT and GML literals. Other options are the definition of specific classes in combination with additional intermediate nodes or the definition of specific datatype properties. In order to be able to query for any geometry description stored in RDF literals, the generic OMG datatype property [omg:hasSimpleGeometryDescription](#) could be used to link to an RDF literal containing a geometry description.

Requirement 3: link related geometry schemas

Relations between different versions of existing geometry schemas can be established via subproperties or subclasses. However, as established earlier, it is not possible to create subdatatypes. The advantage of subproperties and subclasses is that this information can be used during a reasoning process to infer the superproperties, respectively superclasses. Alternatively, this information can also be included as metadata of the respective classes, properties or datatypes inside the ontology.

Requirement 4: bundling associated files

When a building component is connected to multiple geometry descriptions of which some have one or more associated files, at least one intermediate node between the building element and each geometry description is necessary to know which files are related to the same geometry description. The earlier mentioned OMG ontology provides vocabulary to do exactly this, which would in this case result in a level 2 (one intermediate node) or level 3 (two intermediate nodes) geometry pattern. As the referenced files (e.g. one or even multiple material files (.mtl)) are listed in the main file (e.g. the .obj file) via their file names, these names have to be stored in the graph as well.

Requirement 5: metadata for individual geometry descriptions

Relevant metadata related to the individual geometry descriptions can be added only when using at least one intermediate node between the building component and the RDF literal. The vocabulary for these metadata properties has to be documented in an ontology.

Analysis result

RDF literals – as defined in the current W3C specifications – can store the content of every kind of geometry format, making it possible to embed any geometry description directly in an RDF graph. As discussed in the related work subsection, most existing ontologies for describing such RDF literals either focus on a limited amount of specific geometry formats (e.g. GeoSPARQL, stRDF / stSPARQL

and BimSPARQL) or exclude 2D geometry descriptions (BOT). OMG on the other hand makes it possible to link to any geometry description stored in an RDF literal and is not geometry format specific. To make the approach more practical in real world situations, the following three issues have to be addressed. First, there should be a method for applications to unambiguously distinguish between RDF literals referencing external geometry files, literals embedding text-based and encoded binary geometry descriptions. Secondly, the specific geometry schema of each geometry description has to be made explicit and they should be related to other geometry schemas. Finally, content of associated files has to be connected properly to the content of its main file, including the file names as referenced in the main file. In the following section, these three issues are addressed by the new File Ontology for Geometry formats (FOG) and its related modelling patterns.

FOG: a supporting ontology for geometry descriptions in RDF graphs

This section discusses the design of the File Ontology for Geometry formats (FOG) and the accompanying Linked Data modelling patterns. FOG is designed as an OWL ontology that can be used together with the Ontology for Managing Geometry (OMG). Therefore, defining generic properties for linking building components to geometry descriptions is out of scope for FOG, as it is already covered by OMG. Additionally, terminology for properties to add metadata to individual geometry descriptions is not included in FOG. The design decisions for the FOG ontology and related ABox modelling conventions are explained via three Design Questions (DQ) derived from the feasibility analysis in the previous section.

DQ1: How to distinguish between the different applications of RDF literals?

Both text and encoded binary geometry descriptions can be embedded in an RDF literal, while a literal can also store a reference to an external geometry file.

First, the content of a literal can be a URL referring to an external geometry file that can be downloaded from a web location or is stored locally. A parser that recognises this, will know that it should look for an external file. Secondly, if a parser can recognise that the geometry description is embedded in an RDF literal and is text-based, it can be configured to unescape newline and quotation signs. Finally, if an encoded binary geometry description is embedded in an RDF literal, the type of encoding should be known – ideally without having to access the lexical form of the literal – so that the right decoder can be called by a parser. The type of encoding (e.g. base64, base122, hexadecimal, etc.) is unrelated to the binary geometry format used.

Figure 1: Datatypes used to distinguish between geometry descriptions embedded in RDF literals (a,b) (incl. encoding), and external geometry files referenced in an RDF literal (c).

Software applications can be prepared to deal with the above situations, as long as this information can be retrieved for each geometry description. As a result, stakeholders do not need to manually interpret this kind of information every time geometry is exchanged.

In the proposed modelling pattern, the datatype of each literal is used to add information about the encoding of its lexical form as depicted in Figure 1(a) and 1(b). The fixed datatype `xsd:string` can be used for a text-based geometry description while the fixed datatypes `xsd:base64Binary` and `xsd:hexBinary` can be used for encoded binary data. Alternatively, it is also possible for developers to define other binary encodings as custom datatypes in an ontology. Finally, datatypes can also be used to distinguish between embedded geometry descriptions (text or binary encoded), and references to geometry files outside the RDF graph (Figure 1(c)). In this case, the fixed datatype `xsd:anyURI` can be used when the lexical form of the literal contains the location of a file, similarly as has been proposed in COINS. Accordingly, no vocabulary has to be introduced in FOG to address this first Design Question as the fixed datatypes suffice in most cases.

DQ2: How can the used geometry format of each RDF literal be defined?

Stakeholders should be able to focus more on the content of the exchanged geometry instead of the formats. If the geometry format of a geometry description can be uniquely identified with FOG terminology, applications can unambiguously request geometry in their supported or

even preferred formats. Additionally, it should be possible for applications to retrieve the geometry format of each geometry description in an RDF graph, without having to access the lexical form of each such RDF literal.

As a consequence, FOG has to provide the necessary terminology to assert the used geometry format of each geometry description. This type of information can be modelled in several ways using custom datatypes, specific classes or specific datatype properties.

Custom datatypes

An initial method could be the definition of custom datatypes in FOG (see Figure 2), similarly as has been done in stRDF/stSPARQL and GeoSPARQL. However, as stated in the W3C specifications, an RDF literal has exactly one datatype and in DQ1 it was already proposed to use the datatype to store other information. Additionally, it is not possible to create a hierarchy of custom datatypes that can be used by reasoners, as there is no such thing as a ‘subdatatype’.

Figure 2: First method: custom datatypes

Specific classes

The class of an additional intermediate node could denote the used geometry format in the content of a connected RDF literal. By defining subclasses, reasoners can be used to infer the class hierarchy of related geometry formats (see Figure 3). However, to group RDF literals that have to be treated together (see feasibility analysis of Req. 4), another additional node is needed between the building element and this node indicating the geometry format. As a consequence, this method tends to result in a relative verbose graph structure.

Figure 3: Second method: specific classes

Specific datatype properties

Alternatively, specific datatype properties that point to the RDF literal with the geometry description can be used (Figure 4). This method allows to use the datatypes for the purposes defined in DQ1 and at the same time, the graph is less verbose than the method involving specific classes. OWL allows to define subproperties, similarly as subclasses, that can be used during a reasoning process. Based on the above reasons, the method with specific datatype properties was selected to fulfil this Design Question.

Figure 4: Third method: specific datatype properties

The FOG ontology is thus populated with a taxonomy of datatype properties that refer to existing geometry formats. FOG extends OMG, as the root datatype property is [omg:hasSimpleGeometryDescription](#). The taxonomy then defines FOG subproperties per geometry format (e.g. [fog:asDwg](#)), which splits per version of the geometry format (e.g. [fog:asDwg_v2018](#)). Some geometry formats can also consist of different (related or unrelated) files, so an additional set of subproperties is defined in those cases (e.g. [fog:asGltf_v2.0-gltf](#) and [fog:asObj_v2.0-glb](#)).

FOG does not define [rdfs:range](#) restrictions on the datatype properties as the same property can be used to link to RDF literals with different datatypes depending on the situation. For example the property [fog:asGltf_v2.0-glb](#) can be used to link to a literal with a [xsd:base64Binary](#), [xsd:hexBinary](#), [xsd:anyURI](#) or even a custom datatype for other binary-to-text encodings.

Besides the FOG datatype properties, used to link to geometry descriptions stored or referenced in RDF literals, FOG also defines specific object properties (e.g. [fog:asGeomOntology](#)) as subproperties of [omg:hasComplexGeometryDescription](#) to link to RDF-based geometry descriptions that use dedicated ontologies such as GEOM, OntoBREP and OntoSTEP.

DQ3: How can associated RDF literals be grouped?

If a building object has multiple geometry descriptions of which at least one has associated files, an additional intermediate node between the building component and each

geometry description is necessary. The OMG ontology provides the necessary terminology to do so and can be used together with FOG as shown in Figure 5 for a level 2 geometry pattern (one intermediate node). The content of associated files and their original file names have to be stored in an unambiguous manner along the main geometry description. Each [omg:Geometry](#) instance node is connected via the [fog:hasReferencedContent](#) property to a corresponding [fog:ReferencedContent](#) instance node, if applicable. This node then connects to the file name via an [rdfs:label](#) and the actual content of the file via the applicable FOG datatype property as defined in DQ2. When geometry descriptions are not embedded in the graph, but links to external geometry files are defined instead, the correct referenced file name of associated files can be available in the reference string itself. An advantage of using OMG level 2 is the option to add metadata related to individual geometry descriptions as demonstrated in Figure 6. Terminology to define metadata has to be provided by an existing or a new ontology, but is covered by neither FOG nor OMG.

Figure 5: Grouping RDF literals for geometry formats with multiple files

The proposed modelling method together with the designed FOG ontology, allow users to define specific relations between building components and geometry descriptions. This makes it possible to query for geometry descriptions of specific geometry schemas, or all geometry descriptions independent of the geometry schema. The defined datatype properties from FOG can be used to connect to RDF literals containing either an embedded

Figure 6: Adding metadata to individual geometry descriptions

Metadata about each geometry schema is added to the property definition in the ontology. This includes – if applicable – the file extension, links to associated geometry schemas defined in FOG (dependencies), online specifications, IANA Media (MIME) types and links to related entries in DBpedia and/or Wikidata.

Proof of concept application

A proof of concept web application was implemented to visualise geometry stored in an RDF graph. The application, conceptually demonstrated in Figure 7, communicates via SPARQL queries with an RDF triplestore that contains the FOG ontology (TBox) and ABox RDF triples following the modelling principles defined in the previous section. The triplestore answers the query with a JSON response containing at least the three variables: (1) **value** (the lexical form of the literal), (2) **datatype** and (3) **property** (referring to the geometry schema). The decoder module of the application uses the returned **datatype** of each result to know if and how it should decode the returned **value** variable, or if it should load an external geometry file. With a switch operator each **property** variable is evalu-

⁷<https://w3id.org/fog#>

ated and the correct three.js geometry loader – if available – is called to visualise the geometry description in the 3D web viewer. This last module uses the open source three.js library to create a WebGL-based visualisation. The geometry is coloured differently per geometry schema as indicated in a user interface legend. Additionally, the switch also creates and activates a download-to-file button for each geometry description, including the ones that cannot be visualised by three.js.

Figure 7: Conceptual diagram of the demo web application

Two sample ABox datasets are published in the GitHub repository of the FOG ontology: the first only contains the graph structure and dummy content for the RDF literals, while the second contains the same graph structure with actual geometry descriptions. The first dataset is used in the publicly available [sparql-visualizer demo](https://madsholten.github.io/sparql-visualizer/)⁸ to demonstrate how it can be queried, while the second dataset is used by the demo web application. See Figure 8 for an overview of the graph structure of the first dataset. The sample datasets contain two columns (instances of `bot:Element`) consisting of three aggregated parts (capital, shaft and base, also instances of `bot:Element`). Both the columns and the aggregated parts have been connected via `omg:hasGeometry` to at least one intermediate `omg:Geometry` instance node

⁸<https://madsholten.github.io/sparql-visualizer/?file=https://raw.githubusercontent.com/mathib/fog-ontology/master/examples/fog-demo.json>

each. Each intermediate node is then connected to one geometry description using the specific properties of FOG, each related to a specific geometry schema. The second sample graph contains embedded geometry descriptions (.obj/.mtl, .glTF, .step, binary .ply and .glb), RDF-based geometry descriptions (GEOM ontology) and linked external geometry files (ASCII .ply, .dae and .e57) stored on Github. The RDF triplestore also contains the FOG ontology (TBox), to allow enhanced querying. The proof of concept application sends the query from Listing 2 to a connected RDF triplestore to get all geometry descriptions available in the default graph. To keep the query clear in this example, it ignores associated files. This query does not need reasoning as it queries the FOG ontology directly, which it assumes to be available in the named graph `<http://ontologies.org/fog/>`. Figure 9 shows the visualised geometry and the geometry descriptions that can be downloaded in the web application. Geometry descriptions using geometry schemas such as STEP, the RDF-based GEOM ontology and the E57 format, cannot be visualised by three.js as there is no loader available.

Listing 2: SPARQL query used by the demo web application

```

SELECT ?value ?property ?datatype WHERE {
  ?geometry ?property ?value ;
  a omg:Geometry .
  GRAPH <http://ontologies.org/fog/>{
    ?property rdfs:subPropertyOf* ?omgProp .
    FILTER (?omgProp IN
      (omg:hasSimpleGeometryDescription ,
       omg:hasComplexGeometryDescription)) .
  }
  BIND(DATATYPE(?value) AS ?datatype)
}

```

Conclusion

A list of five minimal, practical requirements for the use and exchange of geometry descriptions within RDF graphs was presented. It was concluded – based on the relevant W3C specifications and existing related ontologies – that RDF literals have the potential to fulfil these requirements. However, a clear and uniform modelling method and related ontology was still missing. The presented FOG ontology and related modelling patterns make it possible to embed geometry of any existing format in RDF literals. The geometry descriptions can contain 2D or 3D geometry, and the geometry schema can be open or proprietary. The suggested method can also be used to link to external geometry files and RDF-based geometry descriptions. Where RDF-based geometry descriptions demand specific applications to interpret them, the presented approach allows to reuse existing geometry formats and a wide variety of related toolsets. Thus, it is better suited for the exchange of geometry between a diverse group of stakeholders.

Figure 9: Screenshot of the demo web application

include geometry descriptions in Linked Data graphs such as linking to external geometry files and RDF-based geometries. This will help users to select the right approach for their specific use case.

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MODELLING CONSTRUCTION SCHEDULING CONSTRAINTS USING SHAPES CONSTRAINT LANGUAGE (SHACL)

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Abstract

This paper presents a new approach for modelling construction scheduling constraints using Shapes Constraint Language. Current modelling approaches focus on modelling precedence and discrete constraints at master planning or phase planning level and lacks the ability to model complex constraints at look ahead planning level. Proposed modelling approach addresses this limitation. Precedence constraints, discrete resource capacity constraints, disjunctive constraints and logical constraints are modelled using shapes constraint language for a simple lifting problem in this paper. The modelled constraints were tested, and the constraints model was able to identify the violations effectively and produce a validation report.

Introduction

Digitisation in the construction sector has led to generation of massive amounts of data from projects (Anumba et al., 2000; Whyte et al., 2016). Often these data are siloed in disconnected databases (domain or vendor specific) (Dave et al., 2016) and methods to integrate the siloed data has become highly relevant research problem in the construction sector. Incompatible data structures used during different phases of a construction project is found to be a major contributor to the existence of data silos (Čuš-Babič et al., 2014). To address this problem, researchers have proposed use of Linked-data technologies and Resource Description Framework (RDF) to represent information modelled in the construction sector (Beetz et al., 2009; Pauwels and Terkaj, 2016). Linked-data technologies offer a common environment for linking and sharing data across heterogeneous sources and domains without being limited by the scope of underlying schemas of the source data (Zhang and Beetz, 2016). Linked-data technologies are built following the principles of Description Logics (DL) which is a subset of first-order logic used extensively for representing structured knowledge (Baader et al., 2003). RDF is a standard model/format for data interchange based on the linked-data principles stated by Berners-Lee (2006). RDF enables data merging even when the underlying schemas are different and supports the evolution of schemas.

Researchers have used linked-data based approaches to address the limitations of Building Information Modelling in terms of interoperability, linking across domains and logical inferencing related to *the product information in BIM* (Liu et al., 2016; Pauwels et al., 2011; Pauwels et al., 2017; Quattriniet al., 2017; Terkaj et al., 2017; Zhang and Beetz, 2015, Zhang and Beetz, 2016) and for *facility management* (Kim et al., 2018; Lee et al., 2016; Terkaj et al., 2017). However, there has been insufficient attention to the construction stage, leaving issues of BIM during the construction stage relatively unexamined by researchers that use linked-data.

4-Dimensional Building Information Model (4D BIM) integrates the time dimension into the BIM models and researchers have used this concept and integrated it into the construction workflows to measure the performance (Huht et al., 2010; Subramanian et al., 2000). However, the data in these 4D models are not detailed to the process level information and constraints. For instance, Han and Golparvar-Fard (2017) have stated that the current methods cannot document field issues for further analysis as the 4D BIM's "Model Breakdown Structure typically does not match operational details or require creating complicated namespaces which, without visual representations, are difficult to communicate" (p. 1733). In the same context, Giretti et al. (2012) had stated that they had to decompose the tasks into sub-tasks to determine causal relationships among the involved variables so the whole progress could be estimated since there is no linear dependence between the resources employed at every hour and the work progress. The level of detail of 4D BIM is often limited to the master planning or phase planning level and lacks the level of detail and linkage required in the six weeks look ahead level. The 4D models lack the information on the relationships between the activities/ components/resources and the constraints governing them. This limits the application of automatic schedulers using artificial intelligence.

This paper tries to address this limitation, related to the lack of process level constraint codification, by modelling the process level constraint information using Shapes Constraint Language (SHACL), based on linked-data technology. The rest of this paper is divided into five sections: background, modelling constraint information

using SHACL, implementation, results and discussion, and conclusions.

Background

This section provides background knowledge on scheduling constraints and Shapes Constraint Language which are used extensively in the subsequent sections of this paper.

Scheduling constraints

Constraints are base concepts for scheduling as they inform what can or cannot happen, or in other words what can or cannot be scheduled at a point of time (Dechter and Cohen, 2003). From a functional point of view, construction schedules should ensure that the following does not happen:-

- i) Defy the laws of physics,
- ii) Assign resources (Machines, crew etc.) that are not available or suitable to activities, and
- iii) No two construction processes should happen at the same space at the same time.

These are formalized as scheduling constraints into precedence, discrete resource capacity and disjunctive constraints by researchers (Morkos, 2014; Niederliński, 2011).

Precedence constraints make sure that the principles of physics are not violated. This constraint is the basis of the Critical Path Method (Darwiche et al., 1988; Donget al., 2013). These include constraints such as roof must be cast after all the columns are cured, the third floor should be built after the second floor etc. These constraints don't validate or resolve the availability of resources.

Discrete resource capacity constraints are used to solve constraints related to the availability and assignment of resources. They are called discrete, because the resource may be available in numbers more than one, but in discrete integer values. This constraint ensures that resources are allocated according to availability. This constraint also ensures that a discrete resource is not allocated to two activities at the same time. There is abundant research on this constraint in areas such as resource levelling and resource constrained scheduling (El-Rayes and Jun, 2009; Hu and Flood, 2012).

Disjunctive constraints are constraints which states that two activities cannot happen at the same time. These can be used to model spatial constraints (Baykan and Fox, 1997), safety constraints etc. For example, there should not be any activities in the vicinity of an excavation.

In addition to the above constraints, Logical constraints are needed to govern resource assignments. Although cranes are designed to lift components, cranes have a limitation on their capacity. It can only lift up to a certain weight. These constraints should also be coded as constraints to make the schedule meaningful.

Shapes Constraint Language (SHACL)

Shapes Constraint Language (SHACL) is a data

modelling language developed by the W3C working group to model constraints against which RDF data could be validated (Knublauch et al., 2017). This addresses the limitation in linked-data technologies to define structural constraints in an RDF graph due to the inherent Open World Assumption in linked-data (Ekaputra et al., 2016).

A SHACL processor has two inputs. The first input into a SHACL processor is the data graph (data in RDF format) containing the data to be validated against constraints. The second input is the shapes graph which contains the definition of constraint against which data is to be validated. Constraints in SHACL are called shapes. There are two types of shapes, a node shape and a property shape. Node shapes declare constraints on a node (for example, a class). Property shape declares constraints on the attributes of a node through a path property. When a data graph is validated against a shapes graph, a validation result is produced. The validation report is an RDF graph describing the conformance with the constraints. It details the nodes that have passed the constraints and the ones that failed (Gayoet al., 2017).

SHACL-SPARQL is an advanced feature of SHACL which contains all the functionalities of SHACL Core and in addition the expressive power of SPARQL-based constraints and an extension mechanism to declare new constraint components. SPARQL is a semantic query language to query the information from the RDF based heterogeneous data. It features an SQL-like syntax and can be used to query RDF triples that are maintained in local files or triple stores (Harris et al., 2013).

Modelling constraint information using SHACL

This section will describe the modelling of constraints explained in the previous section in the Shapes Constraint Language. The modelling of constraints in this section is based on a simplified lifting process as shown in Figure 1. There are three classes modelled for representing this process as shown in Figure 2. The classes have attributes which are data properties and object properties. Data properties are the attributes giving the information such as start date, the weight of module etc. Object properties are the attributes which define the relationship of the object with another object.

1. Process: It is the parent class and instances of this class stores information related to the task including the start and end dates as data properties, resources, module association, precedence and disjunctive constraints as object properties.
2. Crane: Instances of this class stores the information related to the crane. For the current paper, the scope of this class is limited to one attribute crane capacity modelled as a data property, in order to demonstrate the logical constraint.
3. Module: Instances of this class stores information related to the module. Module weight is the only attribute data property used.

Even though object relationships are not explicitly defined in module and crane classes, the inherent linking in the OWL applies the relationship defined in the process class to the crane and module classes.

Logical constraint

In the current problem setting, there is a simple logical constraint which is to be satisfied while scheduling. The Lifting capacity of the crane should always be higher than the weight of the module. The constraint is modelled as shown below.

Figure 1: Lifting process

Figure 2: Class diagram for lifting process

```
OntProcess:Process
rdf:type rdfs:Class ;
rdf:type sh:NodeShape ;
rdfs:subClassOf owl:Class ;
sh:sparql [
  sh:message "Crane capacity should be greater than
module weight" ;
  sh:prefixes
<http://semanticprocess.x10host.com/Ontology/OntProc
ess> ;
  sh:select ""SELECT $this
WHERE {
  $this rdf:type OntProcess:Process.
  $this OntProcess:hasResource ?crane.
  $this OntProcess:hasAssociation ?module.
```

```
?crane OntProcess:CraneCapacity ?cc.
?module OntProcess:ModuleWeight ?mw.
FILTER (?cc <= ?mw).
}""";
]
```

The constraint is applied to the class Process as a node shape as it related to both module and the crane. Therefore, during validation, all the instances of 'OntProcess:Process' (OntProcess is the prefix defined in the ontology for the IRI), which has crane as a resource and module as an association are checked for this logical constraint. Instances of 'OntProcess:Process' which do not have crane and module assigned to it will be ignored from this check. Targeting the instances which have assignment is achieved by using SHACL-SPARQL constraint. The SELECT query is used to access the attributes of instances of Crane and Module class. From all the process instances with the module and crane assignment. The *FILTER (?cc <= ?mw).* statement filters the instances where crane capacity is less than module weight. In the case of violation of the constraint, the compiler would provide a message to the user as defined in the *sh:message* which in the current case is "Crane capacity should be higher than module weight".

Precedence constraint

Precedence constraints may be used in the current problem to define which processes have to be completed so that a new process could take place. Therefore, precedence is an object property defined on the processes. The constraint is mathematically defined as:

$$\text{Start date of current activity} \leq \text{End date of preceding activity}$$

```
OntProcess:Process
rdf:type rdfs:Class ;
rdf:type sh:NodeShape ;
rdfs:subClassOf owl:Class ;
sh:sparql [
  sh:message "Precedence condition is violated" ;
  sh:prefixes
<http://semanticprocess.x10host.com/Ontology/OntProc
ess> ;
  sh:select ""SELECT $this
WHERE {
  $this rdf:type OntProcess:Process.
  $this owl:happen_after ?process2.
  $this owl:hasStartDate ?sd1.
  ?process2 owl:hasEndDate ?ed2.
  FILTER( ?sd1 < ?ed2)
}
```

The above code defines the precedence constraint in SHACL-SPARQL. During validation, the compiler searches for all the instances of class Process with a property happen after as represented in the statement *\$this owl:happen_after ?process2*. The start dates of the current process (*\$this*) are compared with *?process2* to check whether the precedence constraint is satisfied or

violated. If it is violated, the user receives a message as defined in *sh:message*. All the instances of the class *Process* without an *owl:happen_after* property is ignored. If there are multiple precedence assignments, all the processes are checked for constraint violations.

Disjunctive constraint

Disjunctive constraints may be defined in this problem setting to make sure that one process shouldn't take place while another process is happening. There are five cases in which this might happen. Consider 2 processes, *Process1* and *Process 2*. The five cases where these two processes overlap are:-

- i. $SD1 < SD2 < ED1 < ED2$;
- ii. $SD1 < SD2 < ED2 < ED1$;
- iii. $SD2 < SD1 < ED1 < ED2$; and
- iv. $SD2 < SD1 < ED2 < ED1$.
- v. $SD1 = SD2 \ \&\& \ ED1 = ED2$

where *SD1*- start date of *Process 1*, *SD2* - start date of *Process 2*, *ED1* – end date of *Process 1* and *ED2* – end date of *Process 2*. This constraint can be represented as the following constraint.

$(SD2 < ED1 \ \&\& \ SD1 < ED2) || (SD1 = SD2 \ \&\& \ ED1 = ED2)$

This is modelled in the SHACL as follows.

```
OntProcess:Process
rdf:type rdfs:Class ;
rdf:type sh:NodeShape ;
rdfs:subClassOf owl:Class ;
sh:sparql [
  sh:message "Disjunctive constraint is violated " ;
  sh:prefixes
<http://semanticprocess.x10host.com/Ontology/OntProc
ess> ;
  sh:select ""SELECT $this
WHERE {
  $this rdf:type OntProcess:Process.
  $this owl:has_disjunctive_constraint ?process2.
  $this owl:hasEndDate ?ed1.
  $this owl:hasStartDate ?sd1.
  ?process2 owl:hasEndDate ?ed2.
  ?process2 owl:hasStartDate ?sd2.

  FILTER((?sd2<?ed1&&?sd1<?ed2)||(?sd1=?sd2    &&
?ed1=?ed2))
}""";
]
```

As given in the previous definitions, the constraint is modelled as a node shape on the *Process* class. The processes which are disjunctive to the current is assigned to the current process using the *has_disjunctive_constraint* property. All the instances of this process with this assignment are checked for the violation using the above constraint representation inside the SPARQL query as shown in $(FILTER((?sd2 < ?ed1 \ \&\& \ ?sd1 < ?ed2) || (?sd1 = ?sd2 \ \&\& \ ?ed1 = ?ed2)))$. As before, the instances without this assignment are ignored.

Discrete constraint

Discrete constraints are required in this problems setting to ensure resources (cranes) are not assigned to two processes at the same time. Since this is a constraint related to the resource, the constraint is modelled as a node shape on the class *Crane* as given below.

Pairwise comparison feature of SPARQL is used to model this constraint. As a first step, all the processes which are assigned the particular resource is shortlisted into pairs in the statements:

$?process1 \text{ OntProcess:hasResource } \$this.$

$?process2 \text{ OntProcess:hasResource } \$this.$

From this list of pairs, identical processes are removed using *FILTER* $(!(?process1=?process2))$. Then the data properties start date and end date for each process in the pair is retrieved and checked for the disjunctive constraint in the statement $FILTER((?sd2 < ?ed1 \ \&\& \ ?sd1 < ?ed2) || (?sd1 = ?sd2 \ \&\& \ ?ed1 = ?ed2))$.

The discrete constraint is necessary for all the resources. In case, the resources can have multiple assignments; this can also be defined in this constraint using SPARQL COUNT query.

```
OntProcess:Crane
rdf:type rdfs:Class ;
rdf:type sh:NodeShape ;
rdfs:subClassOf owl:Class ;
sh:sparql [
  sh:message "Discrete constraint for the resource not
satisfied" ;
  sh:prefixes
<http://semanticprocess.x10host.com/Ontology/OntProc
ess> ;
  sh:select ""SELECT $this
WHERE {
  $this rdf:type OntProcess:Crane .
  ?process1 rdf:type OntProcess:Process.
  ?process2 rdf:type OntProcess:Process.
  ?process1 OntProcess:hasResource $this.
  ?process2 OntProcess:hasResource $this.
  ?process1 owl:hasEndDate ?ed1.
  ?process1 owl:hasStartDate ?sd1.
  ?process2 owl:hasEndDate ?ed2.
  ?process2 owl:hasStartDate ?sd2.

  FILTER ( !(?process1=?process2))
  FILTER((?sd2<?ed1&&?sd1<?ed2)||(?sd1=?sd
2 && ?ed1=?ed2) )
}""";
]
```

Table 1: Instances of the process class

Process	Crane	Crane capacity (metric ton)	Module	Module Weight (metric ton)	Start date	End date	Precedence Constraint	Disjunctive constraint
Process_1	Crane_1	12	Module_1	15	01/01/2019	02/01/2019		
Process_2	Crane_2	18	Module_2	15	02/01/2019	03/01/2019	Process_1	
Process_3	Crane_2	18	Module_3	15	01/01/2019	05/01/2019	Process_1	Process_1, Process_2

Implementation

The above process was implemented using open source Python Libraries RDFLib and pySHACL in a Jupyter Notebook environment. The ontology for the process was developed using Protégé (Musen, 2015). The instances used for testing are shown in Table 1. The results of the same are presented in the next section.

Results and Discussion

The results after the validation of the data graph against shapes graph are given in Table 2. From the results in Table 2, we can identify that there are constraint violations in Process_1, Process_3 and Crane_2.

In *Process_1*, the logical constraint was violated, and the message “Crane capacity should be greater than module weight” was received as an output. This is an actual violation as *Crane_1* with a capacity of 12 metric ton was assigned to *Process_1* to lift *Module_1* which has a mass of 15 metric ton.

In *Process_3*, there are two violations which were reported in the messages “Disjunctive constraint is violated” and “Precedence condition is violated”. *Process_3* was assigned a disjunctive constraint with *Process_1* and *Process_2*. However, *Process_3* starts with *Process_1* and ends after *Process_2* which is a clear violation of the disjunctive constraint. In addition, *Process_3* was assigned a precedence constraint with *Process_1*. This is again violated as the start times of both processes are the same.

For *Crane_2*, “Discrete constraint for the resource not satisfied” was received as an output. This is true as the *Crane_1* was assigned to two processes *Process_2* and *Process_3* at the same time.

Hence from the above, we can conclude that the modelled constraints were able to detect the violations effectively. Although the model represented here is very simplistic, and the violations could be easily detected without any

modelling, the same method can be applied to more massive process datasets where it would be tedious to identify the violations. The data (RDF containing instances) and the shapes (RDF containing constraints) are different components linked through the ontology of the lifting process. More constraints can be added dynamically to the shapes file, and the validation is done for the whole data. This is an excellent advantage in construction to incorporate new constraints as they arise.

Also, as the constraints are coded in a machine-readable format (RDF), it is possible to do analytics and machine learning on this model too and derive insights for future automation of constraint modelling.

Conclusion

This paper describes a method to define construction scheduling constraints using Shapes Constraint Language. Scheduling constraints such as Precedence constraints, discrete resource capacity constraints, disjunctive constraints and logical constraints were modelled using shapes constraint language for a simple lifting problem in this paper. The modelled constraints were tested against a data set of lifting processes, and the violation constraints model was able to identify the violations effectively and produce a validation report.

This paper demonstrated the capability of linked-data approach towards constraint validation for construction scheduling problem. The described methodology could be applied to a broader set of data to produce similar results. However, that is beyond the scope of this paper. Authors are exploring methods to make the modelling of constraints user-friendly by creating an intuitive UI. Also, research is being done towards integration of this method to IFC OWL for automating look ahead planning.

Table 2: Output after constraint validation

Process	Output
Process 1	<p>Constraint Violation in SPARQLConstraintComponent (http://www.w3.org/ns/shacl#SPARQLConstraintComponent):</p> <p>Severity: sh:Violation Source Shape: OntProcess:Process Focus Node: OntProcess:Process_1 Value Node: OntProcess:Process_1 Source Constraint: [sh:message Literal("Crane capacity should be greater than module weight") ; sh:prefixes <http://semanticprocess.x10host.com/Ontology/OntProcess> ; sh:select Literal("SELECT \$this WHERE { \$this rdf:type OntProcess:Process. \$this OntProcess:hasResource ?crane. \$this OntProcess:hasAssociation ?module. ?crane OntProcess:Cranecapacity ?cc. ?module OntProcess:Moduleweight ?mw. FILTER (?cc <= ?mw).}")]</p> <p>Message: <u>Crane capacity should be greater than module weight</u></p>
Process 2	No Violation
Process 3	<p>Constraint Violation in SPARQLConstraintComponent (http://www.w3.org/ns/shacl#SPARQLConstraintComponent):</p> <p>Severity: sh:Violation Source Shape: OntProcess:Process Focus Node: OntProcess:Process_3 Value Node: OntProcess:Process_3 Source Constraint: [sh:message Literal("Precedence condition is violated") ; sh:prefixes <http://semanticprocess.x10host.com/Ontology/OntProcess> ; sh:select Literal("SELECT \$this WHERE { \$this rdf:type OntProcess:Process. \$this owl:hasAfter ?process2. \$this owl:hasEndDate ?ed1. \$this owl:hasStartDate ?sd1. ?process2 owl:hasEndDate ?ed2. ?process2 owl:hasStartDate ?sd2. FILTER(?sd1 < ?ed2) }")]</p> <p><u>Message: Precedence condition is violated</u></p> <p>Constraint Violation in SPARQLConstraintComponent (http://www.w3.org/ns/shacl#SPARQLConstraintComponent):</p> <p>Severity: sh:Violation Source Shape: OntProcess:Process Focus Node: OntProcess:Process_3 Value Node: OntProcess:Process_3 Source Constraint: [sh:message Literal("Disjunctive constraint is violated ") ; sh:prefixes <http://semanticprocess.x10host.com/Ontology/OntProcess> ; sh:select Literal("SELECT \$this WHERE { \$this rdf:type OntProcess:Process. \$this owl:has_disjunctive_constraint ?process2. \$this owl:hasEndDate ?ed1. \$this owl:hasStartDate ?sd1. ?process2 owl:hasEndDate ?ed2. ?process2 owl:hasStartDate ?sd2. FILTER((?sd2<?ed1&&?sd1<?ed2) (?sd1=?sd2 && ?ed1=?ed2)) }")]</p> <p><u>Message: Disjunctive constraint is violated</u></p>
Crane 1	No violation
Crane 2	<p>Constraint Violation in SPARQLConstraintComponent (http://www.w3.org/ns/shacl#SPARQLConstraintComponent):</p> <p>Severity: sh:Violation Source Shape: OntProcess:Crane Focus Node: OntProcess:Crane_2</p>

	Value Node: OntProcess:Crane_2 Source Constraint: [sh:message Literal("Discrete constraints for the resource not satisfied") ; sh:prefixes <http://semanticprocess.x10host.com/Ontology/OntProcess> ; sh:select Literal("SELECT \$this WHERE { \$this rdf:type OntProcess:Crane . ?process1 rdf:type OntProcess:Process. ?process2 rdf:type OntProcess:Process. ?process1 OntProcess:hasResource \$this. ?process2 OntProcess:hasResource \$this. ?process1 owl:hasEndDate ?ed1. ?process1 owl:hasStartDate ?sd1. ?process2 owl:hasEndDate ?ed2. ?process2 owl:hasStartDate ?sd2. FILTER (!(?process1=?process2)) FILTER((?sd2<?ed1&&?sd1<?ed2) (?sd1=?sd2 && ?ed1=?ed2)) }")] <u>Message: Discrete constraint for the resource not satisfied</u>
--	---

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CONTEXT CAPTURING OF MULTI INFORMATION RESOURCES FOR THE DATA EXCHANGE IN COLLABORATIVE PROJECT ENVIRONMENTS

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Abstract

This paper introduces a framework for context capturing of multi information resources and is based on the three major approaches which have been developed over the last decade. Having similar goals in mind they have come up with partially different objectives, methods and representation technologies. The three are, respectively, the Multimodel (MM) approach of the Mefisto project in Germany, the COINS approach in the Netherlands of linked documents and models and the Linked Building Data (LBD) approach of the Linked Data Group in Europe. They were developed in recent years to tackle the central problems of management and exchange of various types of data in a single package expressing a certain context and goal in an overall digital AEC environment. The differences and the commonalities of the first two approaches are addressed and the more future oriented LBD approach is compared to them. The related upcoming standard ISO 21597, pursuing a merging of the first two approaches in its Part 1, is discussed, whereas the third approach, targeting reasoning, will be a subject of Part 2 that is still under discussion.

Introduction

With the growing use of BIM in collaborative design, various questions regarding AEC communication and coordinated collaboration arise concerning the management of the continuously growing amount of data and the various data structures and formats that have come up in the last years. While BIM data finds a central data model in the Industry Foundation Classes, IFC (ISO 16739-1), there is still a need for a suitable solution for the management and exchange of distributed BIM and non-BIM data from different information sources for tasks that go beyond traditional BIM, and without preharmonizing them in one common data model. Such non-BIM data can be found in a variety of tasks from different domains such as energy-efficient design, fire safety, cost estimation, environmental engineering, construction management, facility management, etc.

Our focus is on capturing context, i.e. a context

model, which formalizes the context and makes it exchangeable and sustainable, without altering the information resources and without coming up with one harmonized big data model, as various and repeated attempts have been made over the last 4 decades of digital data exchange. Our attention is mainly focused on link information, which means maintaining the process context. The different possibilities of expressing links and their semantic expressiveness distinguish the three approaches and determine the level of the captured context.

Besides the context issue, the quality of the data is of interest. This covers not only the completeness of the data, on which quality is mainly focused, but includes also correctness and conflict free use in the context of the particularly addressed information environment. It cannot be formally achieved by IT tools but needs the active involvement of expert knowledge of engineers and architects. As it is long traditional practice, the responsible author from a certain AEC domain has to release and undersign her/his information for publishing legally, which means that this information is proven by the author as the domain expert and that s/he takes over the full responsibility for it. In former times such a legal release was done on paper, which is still common practice. However, on the paper only the domain information is communicated with some informal data from related domains indicating some basic interrelationships. For digital data an equivalent but improved procedure is needed. Each author is responsible for her/his information and for ensuring that this information is conflict free with regard to the related information of the other authors. This is necessary because, if not guaranteed, digital data may become corrupt, which may lead to severe consequences. It requires either powerful filter tools to extract from the big common data model only the domain specific data needed, e.g. based on many MVDs, or that the domain model stays separately managed by the responsible author and is only linked to other information and hence will be only accessed for common use on demand by reference or copy.

In this paper we focus specifically on the second idea. In the next sections we outline the three approaches for the management of interlinked multi information

The Three Approaches for Context Capturing of Multi Information Resources

The Elementary Models and the Link Models of a MM are stored in a MM Container (MMC) for data exchange (see Figure 1). The links themselves are simple relations, expressed by the relating objects' IDs using XML/XSD representation, i.e. links do not

In the Dutch COINS project a version of the LBD approach has been used to create a comprehensive information platform for data exchange and integration for the entire life cycle of buildings (Van Nederveen, Beheshti & Willems, 2010). The developed framework consists of a project specific BIM, the COINS Building Information Model (CBIM), and the corresponding working methods and processes summarized as the COINS Engineering Method (CEM). The CBIM model uses geometry as the central reference model, where building data is extended using ontological concepts and LBD.

The Linked Building Data Approach

The principles of LBD stem in the Semantic Web, with the goal to connect AEC data semantically and make them machine interpretable throughout the Web. Accordingly, data is stored in triples utilizing the W3C Resource Description Framework, RDF. A triple consists of subject, predicate and object. It describes a directed relation between two entities, which are defined by a Uniform Resource Identifier (URI) or a relation between an entity and a literal value (data property). The triples form a directed graph, with subjects and objects as nodes and predicates as relations. The RDF graph can then be queried using the SPARQL Protocol and RDF Query Language. Further, a more extended vocabulary and rules can be built up, utilizing the Web Ontology Language, OWL. This in turn enables the use of powerful reasoning engines to infer implicit knowledge. Thus, in its essence the LBD approach is the application of the Linked Data concept of the Semantic Web in the AEC domain. It has been intensively investigated by many researchers in the last years (Pauwels et al., 2017).

A complementary step in the direction of LBD was the development of ifcOWL, which is an OWL representation of the IFC schema (Beetz et al. 2009). It enables the development of further ontologies such as the Building Topology Ontology (BOT), an ontology for building products (PRODUCT), or for related properties (PROPS), which were all initiated by the W3C LBD Community Group (Bonduel et. al., 2018).

Comparison of the Three Approaches

Comparison of the Multimodel and the COINS Approach

At the first glance both approaches appear very similar. However, the COINS approach was first of all directed to link documents to models and hence a shallow non-intensive linking was in mind. Data overload from links had not been to be expected and therefore it was decided to represent a link as a self-standing information item defined in OWL/RDF with all related information, i.e. attributes attached. Different Link Models have not been seen necessary. In addition, in COINS there has to be a central model, which is the geometrical model, whereas in the MM approach there is no mandatory central model necessary, which gives more flexibility to align the MM to domain specific demands.

Comparison of the Multimodel and the Linked Building Data Approach

Both approaches follow the same concept, the creation of an information platform for coordinated and interoperable data exchange in projects. The goal is to unite separate information resources by linking

them. In the MM approach, ID-based links are used to link the models. Thus, a link consists of a set of IDs referencing elements from the respective models. In the LBD approach, no separate link object is required for linking the information resources. A connection can be directly created by referencing through the use of URIs, which means, link information become part of the models.

A main difference of the MM approach is to consider already existing data models, e.g. IFC, CityGML, GAEB or proprietary ones originating from established domain authoring tools. For this reason, in the MM approach there are no restrictions on data format or data structure, except that elements must show a valid ID. In contrast, applying the LBD approach requires the use of RDF or standards based on it, such as the Web Ontology Language (OWL) as data format, which in turn also requires URIs for the identification of the elements. This imposed representation format for the links has also its advantages. While different parsers have to be used to integrate the heterogeneous data into the MM context, data integration with the LBD approach can be virtually automatic. However, in LBD all information links have to be preharmonized, i.e. they have to be completely transformed from their original format in an RFD/OWL representation. In the MM approach original formats can be kept untouched and parsers or filters are needed to find the elements in the data models that should be linked via their element IDs.

There are also different principles regarding the persistence of the data. In the MM approach, the Elementary Models are static and therefore cannot be changed. In the LBD approach, on the other hand, such changes are possible. This difference is especially important when practical AEC scenarios are considered. For example, in the exchange of BIM and TAI data the unchangeability and the unambiguous assignment of responsibility to the data are mandatory in the legal sense. On the other hand, a more dynamic approach can be more useful in an open project environment where freely accessible data, e.g. weather data or building product catalogs, are important. However, even in open projects, working together in a collaborative team requires guaranteed information content as a main basis for collaboration. Information changes, from which new information may be automatically deduced without user notice and hence may remain unrecognized, can lead to wrong decisions and can reduce or even destroy the benefits of open data access.

For the automated processing of cross-model links, machine interpretable semantics are necessary. The meaning of the links is provided by definition in the LBD approach. In addition, the LBD approach also enables mechanisms for the extension of semantics and data definition. Another advantage is the appli-

cation of inference. It enables the generation of new knowledge through predicate logic, making implicitly available knowledge explicit and therefore accessible. In the MM approach, links have no directly embedded semantics that can be interpreted, but only an indirect one on the Link Model level. This semantic must first be deduced from Link Model metadata, which is a considerable technical difference.

The ICDD Standard

The upcoming ISO 21597 describes an Information Container for Data Delivery (ICDD), which mainly combines two functional approaches, i.e.: (1) the MM approach and (2) the LBD approach. The first enables structures and methods for interlinkage of heterogeneous data and their exchange between different applications as a closed solution of an engineering problem. The second enables an environment for integration of and reasoning on data on the Web, as well as dynamic semantic through ontology-based link model extensions. Both approaches have their preferred application fields in the AEC industry.

The ICDD standard was initiated by the COINS Project in 2016. In the very beginning, it was streamlined to the COINS approach and had little similarity to the MM approach. Thus, at first the goal was to develop a standard ontological platform that would enable models to be enriched with new data and to generate added value with the help of inference mechanisms, rules, etc. In the following two years both approaches developed towards a converging ICDD concept that adopted the virtues of each.

As a result, for the ICDD an ontological approach was chosen for the conception, i.e. the ICDD is described using RDF/OWL for the ICDD structure and the Link Models, but is not mandatory for the data models in part 1. The standard comprises two parts, as follows:

- Part 1 Container, in which the structure and the concepts of generic linkage are defined
- Part 2 Dynamic Semantics, in which the ontological concepts are introduced allowing extension of the basic Container structure described in Part 1.

An ICDD comprises the relevant linked models and documents in a Payload Document folder and the Linked Models in a Payload Triples folder. In addition, each container has an index file that specifies its particular content, which is a concept taken from the MM approach. The schemas for the index file as well as for the Link Models are also defined in Part 1 of the standard via the two ontologies Container.rdf and LinkSet.rdf (s. Figure 2).

The second part of the standard is mainly concerning the LBD approach. It introduces new and more

complex concepts by extending Part 1 elements. This includes the extension of classes, properties and relationships as well as an extended concept for defining metadata within the ICDD. It allows the integration of application-oriented semantic into the generic information container and thus represents a generalized meta schema for the application-oriented MM in the sense of the German DIN SPEC 91350 standard.

Figure 2: Structure of the ICDD in the official RDF/OWL representation according to ISO 21597

The ICDD XML Converter

Combining the MM and the LBD approach in ISO 21597 offers many advantages. The only restriction is that the LBD approach can only be used in RDF representation whereas the MM schemas are originally defined using XML/XSD. Therefore a converter was developed and is published via the ISO server to provide the use of both possibilities to end users and software developers in the AEC community, i.e. they are not forced to use the more complex RDF/OWL representation in case they are not interested in benefitting from the Semantic Web technologies but prefer a lean data format.

ICDD Representation in XML

The ICDD XML is based on the MMC Version 2 (github of BuildingSMART) and is slightly modified as Version 3 to meet all ICCD requirements. The main part of the Container schema is depicted in Figure 3.

Compared to the RDF/OWL representation the resulting data structure is leaner and can thus be processed faster. This is important in cases where masses of links are needed. Furthermore, XML/XSD is better supported through a variety of tools and frameworks and is more widely spread in the industry today. The price to pay is relinquishment of the reasoning abilities and the less convenient and less flexible representation of Web resources.

Figure 3: ICDD XML Container File Schema in Express G

The related ICCD structure of the Container is shown on Figure 4. The similarity to the RDF/OWL structure shown on Figure 2 is obvious. Software developers may choose ICDD XML for implementation when they do not have sufficient expertise in RDF or are not interested in the use of semantic web technologies, and would thus prefer a less complex, easier to understand and implement specification. ICDD XML may also be used in closed project environments where robustness and simplicity are preferred instead of the open Semantic Web approach where responsibility and data security can be an issue of greater concern.

On the other hand, software developers may choose ICDD RDF in project environments that require deeper semantics, dynamicity, and the reasoning capabilities offered by the RDF/OWL specification. Furthermore, ICDD RDF is of direct benefit if the required data sources are available as ontologies that can be integrated directly into the LBD approach.

Figure 4: Container Structure of the ICDD XML

Conversion Method

A converter for lossless conversion between the two representation formats of ICDD was developed and published as part of ISO 21597 Part 1. It allows selecting the appropriate representation depending on

the field of application and at the same provides for conformance with all ISO 21597 propositions.

For the transformation between the two ICDD variants it is only necessary to transform the Document Set description and the Link Models. For this purpose, the Extensible Stylesheet Language Transformation (XSLT) is used. The converter consists of the following four XSLT stylesheets:

- Document Set transformation from XML to RDF
- Document Set transformation from RDF to XML
- Link Model transformation from XML to RDF
- Link Model transformation from RDF to XML.

These stylesheets can be interpreted by a XSLT processor and create the file in the desired format from an outgoing file (see Figure 5). Subsequently, the transformed files can be replaced by their predecessor or can be stored redundantly in the ICDD Container. In the latter case, it must be ensured that both serializations are updated before each data exchange.

Figure 5: Conversion between ICDD XML and ICDD RDF/OWL through XSLT

Conversion of ICDD Containers

The developed XSLT stylesheets for transforming have been applied on several test cases, in which multiple documents and references stored in an ICDD Container have been linked via one ICDD Linkset. For convenience, a simple test case with one IFC model and one PDF document is shown here to demonstrate the transformation. The overall structure of the transformed Container and Linksets are identical, however small representational differences

exist in the resulting ICDD XML. Listing 1 shows a data snippet of the Container consisting of one IFC model and one PDF document, which are both defined as internal documents. According to ISO 21597 each document definition is started via the tag `ct:containsDocument` followed by the document type (in this case `ct:InternalDocument`).

```
<rdf:RDF
...
  <ct:ContainerDescription rdf:about="">
    <ct:containsDocument>
      <ct:InternalDocument
        rdf:ID="id99090c14-2935-4c76-9545-8345d8861861">
        <ct:pending
          rdf:datatype="http://www.w3.org/2001/XMLSchema#boolean"
        >true</ct:pending>
        <ct:filetype>ifc</ct:filetype>
        <ct:filename>48D-100.ifc</ct:filename>
        <ct:description>An IFC/BIM model</ct:description>
        <ct:name>48D-100.IFC</ct:name>
      </ct:InternalDocument>
    </ct:containsDocument>
  </ct:ContainerDescription>
...
  <ct:containsDocument>
    <ct:InternalDocument
      rdf:ID="id9b7145c0-123f-41f0-9801-82f03e96e523">
      <ct:priorVersion
        rdf:resource="#idcfd6eb56-a20f-40b4-bfbf-929bc88eea76"/>
      <ct:pending
        rdf:datatype="http://www.w3.org/2001/XMLSchema#boolean"
      >false</ct:pending>
      <ct:format>application/pdf</ct:format>
      <ct:filetype>pdf</ct:filetype>
      <ct:filename>IDSV2.pdf</ct:filename>
      <ct:description>IDS Version 2</ct:description>
      <ct:name>IDSV2.pdf</ct:name>
    </ct:InternalDocument>
  </ct:containsDocument>
...
  <ct:conformanceIndicator>part1</ct:conformanceIndicator>
  <owl:imports rdf:resource="/draft/Container.rdf"/>
...

```

Listing 1: ICDD Container defining an IFC model and a related PDF document

The first document in Listing 1 is the IFC model, named “An IFC/BIM model”, which has the status “pending”. The second document is the PDF document named “IDSV2.pdf”, which is a pending document that has a predecessor. Both documents are linked together on document level and not at element level, as it is current praxis in document management systems.

For a lossless XML conversion, the file must conform to Part 1 of ISO 21597. The Identifier (`rdf:ID`) and metadata such as filetype (`ct:filetype`), filename (`ct:filename`) or description (`ct:description`) are defined by using the corresponding data and object properties. Additionally, `ct:conformanceIndicator` shows which part of ISO 21597 is used. When converting the RDF file via a XSLT Processor using the developed XSLT Stylesheet, equivalent data in XSD representation format is generated, as shown in the following Listing 2.

```
<icdd:ICDDContainer
...
  <icdd:ContainerDescription
    ID=""
    isExternal="true" >
    <icdd:containsDocument>
      <icdd:Document
        ID="id99090c14-2935-4c76-9545-8345d8861861"
        isExternal="false"
        description="An IFC/BIM model"
        name="48D-100.IFC" pending="true">
        <icdd:InternalDocumentProperty filename="48D-100.ifc"
          filetype="ifc"/>
      </icdd:Document>
    ...
    <icdd:Document
      ID="id9b7145c0-123f-41f0-9801-82f03e96e523"
      isExternal="false"
      priorVersion="#idcfd6eb56-a20f-40b4-bfbf-929bc88eea76"
      description="IDS Version 2"
      name="IDSV2.pdf" pending="false"
      format="application/pdf">
      <icdd:InternalDocumentProperty filename="IDSV2.pdf"
        filetype="pdf"/>
    </icdd:Document>
  ...

```

Listing 2: Snippet of a converted resulting ICDD XML

The resulting ICDD XML contains all RDF properties as XML attributes in a single XML element of the type `icdd:Document`, which results in a much shorter filesize. The document type (in this case `icdd:InternalDocumentProperty`) is defined in a separate element containing attributes that define the filename and the filetype. Thereby, an additional attribute named `isExternal` is inserted for each specified Document to enable differentiation between document or model data physically contained in an ICDD (`isExternal="false"` corresponding to a local identifier `rdf:ID`) and referenced via an URI (`isExternal="true"` corresponding to a global identifier `rdf:about`). The attribute is defined as optional and defaults to "false", i.e. internally contained data in the ICDD, which is the normal case in practice.

When converting the ICDD XML back to the RDF format (see Listing 3), the test case data look similar to the original one shown in Listing 1. The small representational differences between the two listings are inessential and do not lead to data loss. They are mainly due to the more verbose document definitions in Listing 1, which are not mandatory and are therefore dropped in the translation process. Specifically, the document type is not defined by using the corresponding property, but is instead defined through `rdf:type`, which refers to the document class (in this case `InternalDocument`). Thus, despite using different ways for defining the Container, the original ICDD file as well as the converted RDF file are both valid ICDDs and no information loss occurs during the two-step conversion process.


```

<rdf:RDF
...
<ct:ContainerDescription rdf:about="">
<ct:containsDocument>
  <ct:Document
    rdf:ID="id99090c14-2935-4c76-9545-8345d8861861">
    <ct:description>An IFC/BIM model</ct:description>
    <ct:filename>48D-100.ifc</ct:filename>
    <ct:filetype>ifc</ct:filetype>
    <rdf:type rdf:resource="http://www.iso-
icdd.org/draft/Container.rdf#InternalDocument"/>
  </ct:Document>
</ct:containsDocument>
...
<ct:containsDocument>
  <ct:Document
    rdf:ID="id9b7145c0-123f-41f0-9801-82f03e96e523">
    <ct:priorVersion
      rdf:resource="#idcdf6eb56-a20f-40b4-bfbf-929bc88eea76"/>
    <ct:description>IDS Version 2</ct:description>
    <ct:filename>IDSV2.pdf</ct:filename>
    <ct:filetype>pdf</ct:filetype>
    <rdf:type rdf:resource="http://www.iso-
icdd.org/draft/Container.rdf#InternalDocument"/>
  </ct:Document>
</ct:containsDocument>

```

Listing 3 Snippet of the converted ICDD RDF back from the ICDD XML representation

Conversion of ICDD Linksets

Similar to the ICDD Container conversion, a XSLT stylesheet has been developed to map an embedded Linkset from RDF to XML. Listing 4 below shows a snippet of an original Linkset used in the test case.

```

<rdf:RDF
...
<owl:Ontology rdf:about="">
  <ct:creator
    rdf:resource="index.rdf#id08da3a34-1ad4-4cb0-aaa0-4d56e7079cf8"/>
  <owl:imports rdf:resource="index.rdf"/>
  <owl:imports rdf:resource="/draft/Linkset.rdf"/>
</owl:Ontology>
...
<ls:Link rdf:ID="19b09117a-1f9c-404f-8d0c-aac51a56149a">
  <ct:creator
    rdf:resource="index.rdf#id08da3a34-1ad4-4cb0-aaa0-4d56e7079cf8"/>
  <ls:hasLinkElement>
    <ls:LinkElement rdf:ID="1eb0b1f73c-7db9-41e9-88c4-cfc58c02316b">
      <ct:creator
        rdf:resource="index.rdf#id08da3a34-1ad4-4cb0-aaa0-4d56e7079cf8"/>
      <ls:hasDocument
        rdf:resource="index.rdf#id9b7145c0-123f-41f0-9801-82f03e96e523"/>
    </ls:LinkElement>
  </ls:hasLinkElement>
  <ls:hasLinkElement>
    <ls:LinkElement rdf:ID="1e4023c2fd-4cf3-49e1-9ff9-b6229a0b80ab">
      <ct:creator
        rdf:resource="index.rdf#id08da3a34-1ad4-4cb0-aaa0-4d56e7079cf8"/>
      <ls:hasDocument
        rdf:resource="index.rdf#id99090c14-2935-4c76-9545-8345d8861861"/>
    </ls:LinkElement>
  </ls:hasLinkElement>
</ls:Link>
...

```

Listing 4: Linkset defining a Link between an IFC model and a PDF document

The IFC Model and the PDF document defined in Listing 1 are assigned to two Link Elements (ls:LinkElement) which are linked together in one Link (ls:Link). To refer to these elements, the previously defined URIs are used.

Each Link Element refers to the corresponding document through the property ls:hasDocument, where the URI is referenced. Additionally, each Link Element and the Link itself can be referenced through an URI.

A snippet of the resulting XML data after converting the RDF file is shown in Listing 5. Similar to the XML version of the ICDD container, the ICDD Linkset uses the prefix “icdd:” for the definition of its contained elements.

```

<icdd:Linkset
...
<icdd:Link
  ID="19b09117a-1f9c-404f-8d0c-aac51a56149a"
  creator="index.rdf#id08da3a34-1ad4-4cb0-aaa0-4d56e7079cf8">
  <icdd:hasLinkElement>
    <icdd:LinkElement
      ID="1eb0b1f73c-7db9-41e9-88c4-cfc58c02316b"
      isExternal="false"
      creator="index.rdf#id08da3a34-1ad4-4cb0-aaa0-4d56e7079cf8"
      document="index.rdf#id9b7145c0-123f-41f0-9801-82f03e96e523"/>
    </icdd:hasLinkElement>
    <icdd:hasLinkElement>
      <icdd:LinkElement
        ID="1e4023c2fd-4cf3-49e1-9ff9-b6229a0b80ab"
        isExternal="false"
        creator="index.rdf#id08da3a34-1ad4-4cb0-aaa0-4d56e7079cf8"
        document="index.rdf#id99090c14-2935-4c76-9545-8345d8861861"/>
      </icdd:hasLinkElement>
    </icdd:Link>
  ...

```

Listing 5: Converted XML version of the ICDD Linkset

From Listing 5 the main difference in formalizing links can be seen. In RDF the information of a link element has to be expressed in separate entities to enable distinguishing between a RDF subject and a RDF object. This discrimination does not exist in XML and hence all link information is attached to the link element as attributes. For intensive and deeply linked models this results in valuable reduction of data which can be up to dozens of Mbytes in many everyday scenarios.

When the XML file is transformed back to RDF, the result in the test case is similar to the data shown in Listing 4. It is possible that the structure of the transformed instances is in different order than in the original RDF but this has no implication on the content and does not mean any data loss. Here, again, the inserted additional attribute isExternal helps to distinguish correctly between local (internal) and global (external) identifiers.

Current Implementations

The presented approach has been already practically verified in several scenarios. The BIM-TAI integration based on DIN SPEC 91350 is currently implemented by about 20 software vendors in Germany.

In the Mefisto project, which dealt with the collaboration of building owners and contractors, BIM (represented in IFC), bills of quantities and task schedules (represented in XML) and work specifications (represented in the German standard GAEB) have been linked and exchanged (Scherer et al. 2011). In the EU project eeEmbedded, which dealt with energy-efficient building design by examining various parametric design variants using energy simulation, a climate model, an energy system model, occupancy models and a life cycle cost model have

been used together with architectural and MEP BIM (Kadolsky & Scherer, 2016). In the German iSiGG project, which deals with the analysis of the effects of spreading fire and contagious gases and their interaction with the occupants, a numerical CFD and a crowd simulation are combined and performed as a co-simulation using dynamically changed BIM data along with various simulation-specific inputs and occupancy profiles (Scherer et al., 2018). Finally, in the German wiSIB project, which deals with the identification of the actual system performance of bridge structures subject to damages due to cracks, the BIM model of the bridge, the damage model, a monitoring model (sensor database) and a load model are combined using the developed MM framework. The available data of the container is then utilized by using an inference mechanism of the LBD approach to identify possible structural damages derived from the available data and from expert knowledge using an ontology knowledge base (Hamdan et al., 2019).

Conclusions

The forthcoming ISO 21597 standard, which describes the ICDD for data exchange of linked multiple data in one container. It combines concepts of LBD with those of the MM and the COINS approach. Although both approaches essentially follow the same ideas, i.e. (1) the definition of a model-level metadata set that allows the use of fully computer-interpretable MM containers, and (2) a linking mechanism introduced via one or more Link Models to represent inter-model relationships, they differ above all in the requirements placed on the models. Thus, the LBD approach requires the use of Semantic Web technologies such as RDF, OWL, SPARQL and pre-harmonized homogeneous data models. In contrast, the MM approach supports fully heterogeneous data models where data links are resolved with parsers and filter. An alternative formalization for immediate practical use was developed, the ICDD XML. It is conceived for pure MM application with advantages through its simplicity and robustness.

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Pauwels, P., Zhang, S. & Lee, Y. C. (2017). Semantic web technologies in AEC industry: A literature overview, *Automation in Construction*, 73, pp. 145-165.

Scherer, R. J. & Schapke, S.-E. (2011). A distributed multi-model-based management information system for simulation and decision making on construction projects, *Advanced Engineering Informatics*, 25(4), Elsevier.

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GENERATING BRIDGE GEOMETRIC DIGITAL TWINS FROM POINT CLOUDS

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Abstract

The automation of digital twinning for existing bridges from point clouds remains unresolved. Previous research yielded methods that can generate surface primitives combined with rule-based classification to create labelled cuboids and cylinders. While these methods work well in synthetic datasets or simplified cases, they encounter huge challenges when dealing with real-world point clouds. The proposed framework employs bridge engineering knowledge that mimics the intelligence of human modellers to detect and model reinforced concrete bridge objects in imperfect point clouds. Experiments on ten bridge point clouds indicate the framework can achieve high and reliable performance of geometric digital twin generation of existing bridges.

Introduction

A Digital Twin (DT) is defined as a digital replica of a real-world asset (Parrott & Lane, 2017). The asset could be a tunnel, a building, a bridge, or any other man-made asset of the built environment. A DT differs from and is much more than the traditional Computer-Aided Design. It is based on massive, cumulative, real-time, real-world data measurements across an array of dimensions, and consequent use of a digital model across the entire lifecycle of an infrastructure (Buckley & Logan, 2017). The model comprises both 3D geometry of the infrastructure components as well as a comprehensive set of semantic information, including material, functions, and relationships between the components. It could be further enriched with other information, such as sensor data (and damage information (Hüthwohl et al., 2018)). This is particularly useful for the asset inspection practice, which is currently based on on-site manual data collection and visual assessment. There is a need for at least 315,000 bridge inspections per annum across the United States and the United Kingdom (UK) given the typical two-year inspection cycle. This explains why there is a huge market demand for less labour-intensive bridge documentation techniques that can efficiently boost bridge management productivity. The greatest value of using DTs is that they are projected to save substantial costs for global infrastructure owners (unlock 15–25% savings by 2025) by automating the inspection process and enabling

accurate condition assessments and timely maintenance decisions (Barbosa et al., 2017).

The use of a DT is greatest during the design stage (as-designed), while little use is made in the closeout stage (as-built), and almost absent in the maintenance stage (as-is) (Buckley & Logan, 2017). Almost no as-is DTs are generated, so no expected value is realized (0% US, 2% UK, 1% France, and 0% Germany) (Buckley & Logan, 2017). Hereafter, the “DT” specifically refers to the “as-is DT”, generated for existing infrastructure, except as otherwise noted. Bridge owners today do not generate DTs for existing bridges, because they perceive that the cost of doing so outweighs their benefits. The following text reviews the current practice of digital twinning. This explains why the DT implementation is so limited.

The fundamental feature of DTs is the 3D geometry, without which many DT applications do not exist. We use the adjective Geometric (gDT) to highlight the DT with only geometry data, i.e. gDT. A gDT is generated using raw spatial data, such as the point clouds collected with laser scanners. The adoption of DT is very limited even though there are many capable laser scanning hardware solutions. This is mainly because the manual digital twinning from point clouds is a daunting task. We outline the end-user requirements (EURs) of DTs and then provide a brief review of existing software solutions to check their degree of automation regarding the EURs.

End-user requirements (EURs)

Developing detailed EURs of DTs is outside the scope of this study. This section summarizes the fundamental information that a DT must contain. The end-users of DTs are inspectors, engineers, and the decision makers. The EURs define the information that will be required by the end-users from both their own internal team and from suppliers. The EURs should clearly articulate the information requirements and describe the expected information deliverables. However, the nature of the EURs depends on the complexity of the project, the experience, and the requirements of the end-users. Experienced end-users may develop detailed EURs, whilst others may only set out high-level requirements, and basic rules. Broadly, a DT includes:

- EUR 1: Component-level digital representation.

A DT should contain the main structural component types of a sensed asset with a component-level resolution (Sacks et al., 2017).

- *EUR 2*: Component's explicit geometry representation and property sets. The full geometry should represent as-is conditions of the sensed asset (Borrmann & Berkahn, 2018).
- *EUR 3*: Component's taxonomy. The components should be labelled by their element types (Koch & König, 2018).
- *EUR 4*: Component's implicit information such as structural relationships, material, cost, schedule and so on. A DT should be sufficiently semantically meaningful (Sacks et al., 2018; Sacks et al., 2018).
- *EUR 5*: Component's damage information. Damage type (crack, spalling, scaling, efflorescence and others), location, and orientation should be exactly identified and embedded into the DT along with the texture data (Hüthwohl et al., 2018).
- *EUR 6*: All above-listed *EURs* should be presented in a platform neutral data format, such as Industry Foundation Classes (IFC) (Borrmann et al., 2018; Koch & König, 2018).

Major vendors such as Autodesk, Bentley, Trimble and ClearEdge3D, etc. provide the most advanced digital twinning software solutions. For example, ClearEdge3D can automatically extract pipes in a plant point cloud as well as specific standard shapes like valves and flanges from industry catalogues followed by fitting built-in models to them through a few clicks and manual adjustments. This means ClearEdge3D can realize a certain degree of automation as the *EUR 1* & *EUR 2* can be partially automated. However, the spec-driven component library of ClearEdge3D can only recognize and fit point cloud subparts with standardised shapes based on an industry specification table. For other commercial applications, none of them can automate any one of the *EURs*. Modellers must first manually segment a point cloud into subparts, and then manually fit 3D shapes to them (*EUR 1* & *EUR 2*). Fitting accurate 3D shapes to the segmented point clusters is challenging because the set of allowable primitives is limited in most software applications. Modellers need to enrich the resulting gDT with other explicit and implicit information, such as component's taxonomy (*EUR 3*), connectivity and aggregation (*EUR 4*), and defects (*EUR 5*) to meet the *EURs*. Then, all *EURs* need to be exported in IFC format (*EUR 6*).

Bridge Digital Twinning

Real world reinforced concrete (RC) bridge components usually have complicated shapes, containing complex skews, and cannot be simply fitted using idealized predefined shapes. We investigate the entire workflow of digital twinning of a typical RC bridge point cloud using CloudCompare 2.6.2 and

Autodesk Revit 2016. Revit provides excellent flexibilities that allow users to design a shape in a more freeform manner. Geometry in Revit's Family consists of solid and void forms in five varieties: Extrusion, Blend, Revolve, Sweep and Swept Blend (Figure 1). Up until the end of the manual operation, only *EURs 1, 2, 3, and 6* are satisfied. 95% of the total modelling time is spent on customizing shapes and fitting them to the point clusters. The "bottlenecks" of digital twinning using current software applications are listed as follows:

Figure 1: Forms available in Revit Family editor

- 1) Software packages can semi-automatically extract standardized shapes in point clouds but cannot automatically extract non-canonical shapes. Manual shape customization is necessary, but laborious and time-consuming.
- 2) *EUR 2* can only be manually achieved. The presence of occlusions and varying density in the data adds hours of adjustment.
- 3) *EURs 1, 3, and 6* can only be manually achieved and *EURs 4* and *5* are unavailable within existing applications.
- 4) None of existing software packages can offer a one-stop digital twinning solution. Modellers have to shuttle intermediate results in different formats, giving rise to possibility of information loss.

The following texts investigate existing automated methods in the literature related to *EURs 1, 2, 3, and 6*, i.e. *EURs* required to generate a gDT with component-level semantic labels. *EURs 4* and *5* are beyond the scope of this paper.

State of Research

We divide existing methods of digital twinning using point clouds into two groups: (1) object detection methods (*EURs 1* and *3*); and (2) 3D solid model fitting methods (*EURs 2* and *6*).

Object Detection in Point Clouds

We define "detection" in the context as the combination of *clustering* (from a point cloud to point clusters) and *classification* (labelling the point clusters). Current methods of point cloud clustering generally follow a "bottom-up" approach, which goes from points to surfaces or patches followed by semantic labelling to derive objects. Most point cloud classification methods follow a "top-down" approach, which employs human visual perception such as relationships and contexts to detect specific instances embedded in point clouds or to infer the semantics of

components in a geometric model. Real point clouds are imperfect data with many problems, such as *occlusions* and *varying point density*. We review both bottom-up and top-down detection methods and investigate how far they have solved these challenges. Specific limitations are also identified.

Bottom-up detection

The bottom-up approach pieces together low-level primitive features like points to generate higher-level features successively until a top-level system is formed. The higher-level features are surface normal, meshes, surface planes/patches, non-uniform B-Spline surfaces (NURBS) (Dimitrov et al., 2016), and voxels. Three main methods arise from the literature: Random Sample Consensus, Region Growing, and the Hough-Transform paradigm.

Random Sample Consensus (RANSAC) is especially used for detecting planar surfaces. Jung et al. (2014) used RANSAC to detect planar surfaces such as walls, floors, and ceilings in building point clouds. Whilst the RANSAC algorithm is effective in the presence of noise and outliers, it has some limitations. First, it suffers from spurious planes, which are frequently produced around the boundaries (Jung et al., 2014). Second, RANSAC requires prior knowledge about the data, meaning that the selection of a fixed number of shape hypotheses implies that a prior estimate of the inlier ratio is available. This is often not the case in practice. For example, Schnabel et al. (2007) detected plane, sphere, cylinder, cone, and tori with RANSAC using random sampling of minimal sets in a point cloud. Yet, given its computationally-expensive nature, it is unrealistic to use RANSAC to detect complex geometries. Recently, Zhang et al. (2015) presented a novel RANSAC method to detect planar patches in bridge point clouds. Although the experiments indicated this method outperforms baseline methods, it cannot detect pier patches when the point densities of those regions are low.

Region Growing (RG) is also a widely used scheme for point cloud clustering. It starts with a set of initial seeds and then adds in neighbouring points based on similarity of the surface normal, curvature and so on, until an edge is reached. Walsh et al. (2013) presented an RG algorithm to detect both planar and curved surfaces in bridge point clouds. However, the segmentation was finally achieved after manually choosing key points around the boundaries. Dimitrov & Golparvar-fard (2015) suggested an upgraded RG method which excels when the point cloud does not suffer from substantive occlusions. However, it over-segments objects when non-trivial occlusions are present. The persistent occlusion problem was addressed by Xiong et al. (2013) through a learning-paradigm that can detect occluded planar surfaces and estimate their shapes in building point clouds. However, their method cannot be directly applied to

bridge settings, whose occluded surfaces do not follow a specific pattern as in a building point cloud. In general, RG-based methods suffer from occlusion effects, and also have the boundary weakness. These limitations give rise to issues such as over-/under-segmentation, which often requires a certain amount of manual adjustment.

Hough-Transform (HT) is another commonly used clustering method. The major use of HT is in 2D and 3D, where the number of parameters is small. For example, Díaz-Vilariño et al. (2015) used HT to detect the strong horizontal and vertical lines in range image for building opening boundary detection. Adan & Huber (2011) proposed effective HT methods to detect walls in building point clouds. However, HT becomes computationally prohibitive when the number of dimension increases. For example, the HT requires a 5D Hough parameter space for cylinder detection. Rabbani (2006) suggested a two-stage approach to reduce the computational complexity as well as the number of dimension. In general, HT is powerful for detecting simple geometric objects in point clouds. However, HT is sensitive to parameter dimensions and cannot be applied in practice to shapes characterized by too many parameters. This constraint impedes its use in the detection of bridge objects, which often contain skews and imperfections, and cannot be described using generic shapes with limited parameters. The following paragraph reviews a computationally more efficient method.

Octree-Based (OB) methods have been proposed to tackle the issue of computational complexity and reduce the original point cloud size. Su et al. (2016) presented an OB segmentation method designed for piping systems. Truong-Hong et al. (2013) introduced an OB-based technique to automatically extract building façade features in point clouds. Xu et al. (2018) suggested an OB probabilistic segmentation model for construction sites. However, the segmentation accuracy of this method is quite sensitive to the voxel size. This problem was discussed by Vo et al. (2015), who proposed an octree RG-based algorithm for surface patch segmentation in urban environments. Their method can semi-automatically adjust the voxel size using an adaptive octree. However, this method faces the difficulty of patch generation for low point density regions. In general, voxel-based clustering is more computationally efficient than point-based clustering. Yet, voxel size determination remains largely a user-defined task.

Top-down detection

Bottom-up detection schemes are rarely suitable for point cloud classification. Classification through low-level primitives is insufficient since local surfaces, patches or voxels can be labelled as such, but it is difficult to determine whether they belong to the same instance. The intervention of high-level information is

required to overcome such challenges. The top-down approach usually combines a set of engineering criteria and classifies objects in point clouds that meet the criteria. Prior studies show that knowledge-based classification methods are robust, as domain-specific information such as known parameters, object instances, and topological relationships, are invariant to factors such as pose and appearance. Su et al. (2016) used a set of connectivity criteria to merge and label industrial components across voxels. Son et al. (2013) proposed a knowledge-based method for detecting industrial plant objects based on the known surface curvature and size of the pipelines. Perez-Gallardo et al. (2017) suggested a semantic model-based system to detect four object classes in an industrial scene using topological information. Laefer & Truong-Hong (2017) leveraged the steel standard library to identify and match the cross-sections of steel frames in point clouds. Recently, Riveiro et al. (2016) used specific topological constraints to segment masonry bridge point cloud through normal clustering. However, this algorithm largely depends on data quality so that it is difficult to generalize it to adapt to large-scale point clouds, which usually suffer from occlusions and non-uniformly-distributed points. Ma et al., (2017) leveraged relationship knowledge and shape features to classify bridge 3D solid objects (Figure 2). However, the input of this method needs to be a geometric bridge model (not a point cloud) without any semantic meaning. In addition, it assumes that the bridge model is developed in a grid system and the pairwise relationship between two objects is well defined. These assumptions are restrictive and make the method less feasible for real-world linear constructions, as bridges, roads, and tunnels usually possess curved horizontal/vertical alignments.

Figure 2: Bridge object classification (Ma et al., 2017)

Other detection methods

Data-driven, learning-based methods have been widely used to detect objects in point clouds. Numerous volumetric Convolutional Neural Network (CNN) and Deep Learning frameworks have been proposed by transforming points into voxel grids. Maturana & Scherer (2015) proposed a supervised 3D CNN called *VoxNet* to classify objects from the volumetric data. Likewise, Qi et al. (2016) suggested a multi-view CNN. Instead of transforming a point cloud into 3D voxel grids, Qi et al. (2017) introduced a deep neural network called *PointNet*, which can directly consume points. However, the major restrictions to applying these learning schemes to infrastructure component detection tasks include: (1) the lack of a sufficient number of labelled large-scale

real point clouds to train a good model, and (2) the high computing burden. These methods usually require a substantial down-sampling task before they can be used even in high performance computing systems (e.g. TensorFlow).

Model Fitting to Point Cluster

Model fitting techniques

Model fitting aims to use computer graphic techniques to form the 3D shape of a point cluster. There is no universal solution to describe an object. How to choose a representation totally depends on (1) the nature of the object being modelled, (2) the particular modelling technique that we choose to use, and (3) the application scenario where we bring the object to life. Existing shape representation methods can be categorized into four groups: Implicit Representation, Boundary Representation, Constructive Solid Geometry, and Swept Solid Representation. We review each of these in the following texts.

Implicit Representation. One solid modelling approach is based on the representation of 3D shapes using mathematical formulations, i.e. implicit functions. Common implicit surface definitions include, but are not limited to Plane, Sphere, Ellipsoid, Torus, Elliptic Paraboloid, and Hyperbolic Paraboloid.

Given that only a very limited number of primitives can be represented exactly by algebraic formulations, implicit functions are of limited usefulness when modelling real-world bridge objects.

Boundary Representation (B-Rep) is a method to describe shapes using their limits. The model represented using B-Rep is an explicit representation, as the object is represented by a complicated data structure giving information about each of the vertices, edges, and loops and how they are joined together to form the object. The geometry of a vertex is given by its coordinates. The edges are straight or curved lines. A face is represented by some description of its surface (algebraic or parametric forms can be used). Valero et al. (2016) developed a method to yield B-Rep models for indoor planar objects (walls, ceilings and floors).

Both Tessellated Surface Representation (TSR) and Polygon/Mesh Representation (PR/MR) can be considered as B-Rep types. A final model of TSR or PR/MR, is represented as a collection of connected surface elements. Oesau et al. (2014) leveraged a graph-cut formulation to reconstruct a synthetic building point cloud into a mesh-based model. Representing an object using polygonal facets or mesh is the most popular representation in computer graphics. However, there are some problems with polygon mesh models: 1) Level of detail. High resolution could be unduly complex. An option is to reduce the polygon resolution without degrading the rendered presentation. But by how much? 2) Missing

data, i.e. occlusions. Large occluded regions are hardly smoothed. Thus, PR/MP does not guarantee that a group of polygons facets can form a closed mesh model. 3) No sense of volume. It is difficult to extract geometric properties such as the radius of a cylindrical column on a mesh representation.

Constructive Solid Geometry (CSG) is a high-level volumetric representation that works both as a shape representation and a record of how an object was built up. The final shape can be represented as the combination of a set of elementary solid primitives, which can be cuboids, cylinders, spheres, cones, and so on. Xiao and Furukawa (2012) introduced an algorithm to reconstruct large-scale indoor environments with a CSG representation consisting of volumetric primitives. However, this method uses only cuboids as volumetric primitives, assuming that they are the most common shapes found in indoor walls. Zhang et al. (2014) (Figure 3) designed a classifier to classify infrastructure components (e.g. pier, beam, deck) and fit them with 3D shape entities (e.g. cuboid, cylinder, sheet) However, this method is tailored for simplified topology designs that do not consider the real bridge geometries. For example, a real sloped slab with varying vertical elevation cannot be simply modelled by a sheet.

Figure 3: Fitted IFC entities in synthetic bridge point clouds (Zhang et al., 2014)

Swept Solid Representation (SSR) or Extrusion is a representation of model which creates a 3D solid shape by sweeping a 2D profile that is completely enclosed by a contour line along a specific path. Ochmann et al. (2016) presented a method to reconstruct 3D building models from indoor point clouds. Laefer & Truong-Hong (2017) used a kernel-density-estimated-based method to identify and extrude the cross-sections of steel beams in point clouds. The following texts outline the principals involved in representing geometry in IFC standards.

IFC Geometric Representation

The IFC coverage increases along with the end users' needs. The fundamental feature of DTs is the 3D geometry. According to Borrmann et al. (2018), an object in a DT is initially described as a semantic identity and can then be linked with one or more geometric representations. This ability allows objects in a DT to use application-specific geometric representations. This also provides flexibility to link one or more geometric representations with a semantic

object. All geometry representations can be grouped into four classes: Bounding Boxes, Curves, Surface models, and Solid models.

Bounding Boxes are highly simplified geometric representation for 3D objects that are usually used as placeholders. They can be represented using *IfcBoundingBox*. Then, *IfcCurve* and its subclasses can be used to model line objects. Freeform curved edges (i.e. splines) and curved surfaces are required to model complex geometries. *IfcTriangulatedFaceSet* can be used to represent the tessellated surfaces, i.e. polygons with an arbitrary number of edges, or triangular mesh. Curved surface can be described using a finer mesh size, if accuracy is a concern. Specifically, *IfcBSplineSurface* can be used for representing curved surfaces, e.g. NURBS. Then, one classic way to generate 3D objects as solid models is through CSG. *IfcCsgPrimitive3D* and its subclasses can be used. However, the use of CSG is very limited. By contrast, SSR is widely. *IfcSweptAreaSolid* and its subclasses *IfcExtrudedAreaSolid*, *IfcRevolvedAreaSolid*, *IfcFixedReferenceSweptAreaSolid*, and *IfcSurfaceCurveSwptAreaSolid* can be used to present extruded solids. A closed profile *IfcArbitraryClosedProfileDef* is necessary for this representation.

Gaps in knowledge & Objectives

The problem of detecting bridge objects in the form of labelled point clusters from point clouds featuring defects has yet to be solved. Likewise, the problem of fitting 3D solid models in IFC format to real bridge point clusters has yet to be addressed. In addition, the problem of evaluating the quality of a generated gDT has yet to be studied in depth. Therefore, the objective of this research is to devise, implement, and benchmark a framework that can generate labelled geometric models of constructed bridges comprising concrete elements in IFC format.

Proposed framework

We propose a novel top-down framework which exploits bridge engineering knowledge as guidance to directly extract labelled point clusters corresponding to bridge components without generating surface primitives, and then to efficiently reconstruct these labelled point clusters into 3D IFC components. Real-world bridges are neither perfectly straight nor flat. Bridge geometries are defined by horizontal straight or curved alignments, vertical elevations, and varying cross-sections. A slicing-based algorithm is proposed to tackle these difficulties. The algorithm is repeatedly used throughout the whole framework until all the components are detected and modelled. The algorithm can deal with the skew complexity and can quickly select a set of candidate locations for target objects. The global topology of a bridge can also be well approximated using multiple slices.

We only focus on typical RC slab and beam-slab bridges, because 73% of existing highway bridges and 86% of planned future bridges are RC slab and beam-slab bridges (Kim et al., 2016). In addition, we only deal with four most important and highly detectable components of the two types of bridges, i.e. slab, pier, pier caps, and girders. The framework (Figure 4) consists of two processes: **Process 1**, detection of four bridge component types in point clouds, aiming to meet *EURs* 1 and 3, and **Process 2**, run-time model fitting to the point clusters using IFC standards, aiming to meet *EURs* 2 and 6.

Figure 4: The proposed framework of this research

The framework starts with a registered point cloud of an RC bridge. Irrelevant points such as vegetation, trees, traffic, etc. are manually removed. We then align the cropped point cloud using Principal Analysis Component (PCA) such that its centre axis, i.e. horizontal alignment, is roughly parallel to the X-axis of the global coordinate system.

Process 1 – Bridge component detection

This section (Process 1) proposes a four-step top-down object detection method through which the key components in an RC bridge point cloud are detected. The input is a roughly aligned bridge point cloud. The outputs are labelled point clusters of four component types, i.e. slab, pier cap, pier and girder. The novelty of this method lies in the fact that it directly extracts RC bridge components in point clouds without generating low-level surface primitives. We use the point cloud of the Nine Wells bridge (Figure 5) in Cambridge, UK to demonstrate the development of the method.

Figure 5: Side view of the Nine Wells bridge

The method breaks down a large bridge point cloud into sub-datasets through a recursive slicing algorithm. That is, it chops the point cloud by means of a ‘virtual parallel scalpel’ with a specified equal thickness. The first two steps are recursive. The first step segments a whole aligned bridge point cloud (D_N) into the pier assembly (denoted α_M) and deck assembly. The second and third steps detect pier areas (denoted β_{mp}) and pier caps in the pier assembly and deck assembly. The last step detects girders and slab in a merged deck assembly. Note that pier caps and girders may not exist in some bridge point clouds.

Specifically, in Step 1, we chop D_N into multiple slices along the X-axis and extract $range_{j(z)}$ which is the height of each slice j (denoted $S_{j(x)}$) (Figure 6). We classify $S_{j(x)}$ as a pier assembly slice if Eq. (1) is satisfied; otherwise, it is a deck assembly slice:

$$range_{j(z)} > \rho_1 |\max\{z_i | D_N\} - \min\{z_i | D_N\}|, \quad (1)$$

Figure 6: Slicing along X-axis - Step 1

where ρ_1 is discrimination parameter. Each extracted pier assembly α_m is considered as a miniature of D_N , so that Step 2 follows exactly the same strategy as the first step. We replace the right side of Eq. (1) with $\rho_2 |\max\{z_i | \alpha_m\} - \min\{z_i | \alpha_m\}|$, where ρ_2 is another discrimination parameter used to detect the pier area β_{mp} in α_m . Next, Step 3 detects pier caps in $\{\beta_{mp}\}$. This is achieved by removing the uninformative deck points in β_{mp} first followed by investigating the normal direction of the top part of β_{mp} . Up until now, we have detected pier, slab, and pier cap. The final Step 4 aims to detect girders. We first segment the entire deck assembly cluster into several spans according to the direction of expansion joints. We then use density histograms to detect girders in each span. We merge all over-segments and finally acquire the four labelled point clusters of bridge key

components (*EURs* 1 and 3). The details of Process 1 and the four-step object detection method can be found in (Lu et al., 2018).

Process 2 – IFC object fitting

The problem of automatic conversion from the labelled point clusters into 3D solid IFC models remains unsolved, although Process 1 can directly produce labelled point clusters of four component types. Process 2 aims to solve this problem. We propose a slicing-based object fitting method that can twinning an RC bridge into IFC format, using the four types of point cluster constituting the bridge. The inputs are the refined point clusters generated from Process 1. The outputs are two IFC files corresponding to two different levels of detail (LOD 200 and LOD 250-300). The novelty of this method lies in the fact that multiple local topological configurations derived from the slicing scheme can provide good characterization to approximate the global topology of the underlying bridge in a point cloud.

Figure 7 illustrates the workflow of the proposed method, which consists of two major steps: Step 1, geometric feature extraction of point clusters; and Step 2, *IfcObjects* fitting to the extracted features.

Figure 7: Workflow of the IFC object fitting method

LOD 200 gDT generation. In this twinning phase, the bridge is represented at a coarse level. We use TSR to generate Oriented Bounding Box (OBB) for each point cluster. TSR is an explicit way to present an OBB, whose parallelepiped geometry can be represented using the tessellated geometry model, expressing it as a triangulated tessellation using vertex coordinates. The attributes such as the length, width, and height of each OBB are given and composed into a property set.

LOD 250-300 gDT generation. In this twinning phase, the four point cluster types are represented with detailed geometries through multiple slice models. Solid extrusions are preferred wherever possible if the cross-section of each slice is deemed to be constant. Specifically, for slab point cluster, we implement similar but not identical slicing method to that proposed in Process 1 to slice the deck slab into *J* slices. The slicing does not take a parallel pattern but is rather oriented along the normal direction of the curved alignment of the slab (Figure 8). Then, the problem of modelling the entire slab is transformed

Figure 8: Slab slicing

into modelling each straight slab slice assuming each slice is straight along the tangent direction and the cross-section of each slice is constant. Similar to how the slab slice is extruded, pier cap point clusters are represented as Swept Solid using the outline of the 2D α -shape on the XY-plane. Next, for pier point clusters, we use a fuzzy-logic algorithm to first classify the cross-section into three categories: circular, quadrilateral, and others. Then, cylindrical piers are represented as Swept Solid, while quadrilateral and other shape piers are represented using multiple slice models. Finally, for girder point clusters, we use a template matching method to find the best-match girder type in existing beam catalogue, assuming that the girders are precast beams. In addition, we create a property set for each component, in which the method can flexibly add the attributes for future use.

Experiments & Results

Data collection & Research platform

We used a Faro Focus 3D X330 laser scanner to collect point clouds of ten RC highway bridges around the city of Cambridge, UK. These point clouds are available at <http://doi.org/10.5281/zenodo.1233844>. The detailed statistics of the data are given in (Lu et al., 2018). The proposed framework and all relevant algorithms were implemented on Gygax (research coding platform developed by the Construction IT group at the University of Cambridge) on a desktop computer (CPU: Intel Core i7-4790K 4.00GHz, Memory: 32GB, SSD: 500GB).

Implementation & Ground Truth Preparation

We developed a user-defined 2D clipping polygon function on Gygax using Viewport3DX in Helix Toolkit to manually delete irrelevant points. Then, the PCA alignment procedure, object detection method, and IFC object fitting method, were implemented on Gygax as different modules, respectively. We show the implementation of LOD 250-300 gDT generation of two bridges using Gygax GUI in Figure 9.

Three ground-truth (GT) datasets: *GT A*, *GT B*, and *GT C*, were created by manually conducting Step 1, Step 2, and the entire method of Process 1, respectively. The GT datasets are optimally desired outputs to compare against those generated from the proposed method. Then, two sets of models: *GT D* and *GT E* were manually created to compare against the resulting LOD 200 gDTs and LOD 250-300 gDTs, generated from the automated IFC object fitting method of Process 2, respectively. The modeling times were also

Figure 9: LOD 250-300 gDT generation. Top: Bridge 1; Bottom: Bridge 7

recorded. On average, 0.92 and 27.6 hours were spent on generating one gDT in *GT D* and *GT E*, respectively.

Experiments of Process 1 – object detection

The two parameters ρ_1 and ρ_2 were estimated by comparing against the manual detection results of *GT A* and *GT B* using point-wise performance metrics Precision (Pr), Recall (R), and F1-score (F1):

$$Pr_s = \frac{TP_s}{TP_s + FP_s} = \frac{\text{\# of correctly labelled points in cluster } s}{\text{total \# of points in cluster } s}, \quad (2)$$

$$R_s = \frac{TP_s}{TP_s + FN_s} = \frac{\text{\# of correctly labelled points in cluster } s}{\text{total \# of points in GT cluster } s}, \quad (3)$$

$$F1_s = 2 * \frac{Pr_s * R_s}{Pr_s + R_s}, \quad (4)$$

where TP refers to True Positive, FP refers to False Positive, and FN refers to False Negative. ‘s’ represents a specific point cluster in Step 1 and Step 2, respectively. We conducted a grid-search over the value space (0, 1) and computed the empirical receiver operating characteristic (ROC). The optimal values of ρ_1^* and ρ_2^* were identified when the distance to the perfect classification in the ROC was minimized. Once the other parameters were deduced based on ρ_1^* and ρ_2^* , we evaluated the entire method. For each bridge, the evaluation was conducted using bounding-box-wise metrics and using similar point-wise metrics as (2), (3), and (4). The average Pr, R and F1 of bounding-box-wise component detection for all ten bridges were 100%, 98.5%, and 99.2%. For point-wise evaluation, we also computed the micro-average scores:

$$Pr_{\text{micro}} = \frac{\sum_{s=1}^{|S|} TP_s}{\sum_{s=1}^{|S|} TP_s + \sum_{s=1}^{|S|} FP_s}, \quad (5)$$

$$R_{\text{micro}} = \frac{\sum_{s=1}^{|S|} TP_s}{\sum_{s=1}^{|S|} TP_s + \sum_{s=1}^{|S|} FN_s}, \quad (6)$$

The F1-score is simply the harmonic mean of Pr_{micro} and R_{micro} . The micro-average of P/R/F1 was 98.4% for the ten bridge data. Figure 10 only illustrates detection results of *Bridge 1* and *Bridge 7*, due to limited space. To learn how many occlusions are exactly acceptable, we re-conducted experiments using *Bridge 1* by creating arbitrary occlusions. The method achieved high detection rate (F1-score 96.6%), despite the presence of large occlusions (30-40%).

Figure 10: Detection results. Bridge 1 (L) & Bridge 7 (R)

Experiments of Process 2 – IFC object fitting

First, we used the clipping function to manually refine the results from Process 1. This is because the labelled point clusters generated from the object detection method were not perfect. FP positives retained around boundaries between adjacent point clusters. These points need to be removed before implementing the fitting method. The resulting LOD 200 and LOD 250-300 gDTs (Figure 11) were compared against the *GT D* and *GT E*, respectively. Specifically, the evaluation

Figure 11: (a) LOD 200 gDTs and (b) LOD 250-300 gDTs. Bridge 1 (L) and Bridge 7 (R)

of LOD 200 gDTs was based on point-to-point (P2P) distance metrics. We computed the volume and centroid of each GT bounding-box and the automated one. We then computed the Euclidean distance (E_{dc}) between the centroids, the false volume ratio (FVR) between the volumes, and the Euclidean distance between each corresponding vertex. The average value of FVR, E_{dc} , and P2P for ten bridges were 16.5%, 11 cm, and 23 cm, respectively. The average twinning time was 10.2 seconds. By contrast, the evaluation of LOD 250-300 gDTs was based on cloud-to-cloud (C2C) distance metrics. Specifically, the LOD 250-300 gDTs and the *GT E* were first converted into .obj

files followed by random sampling dense points from the rendered surface polygons. For each bridge, both its sampled Auto point clouds and GT point clouds were compared against the bridge's original point cloud. The estimated C2C distance between two clouds is the bigger one of the mutual $\overline{\text{dist}}$:

$$C2C = \max(\overline{\text{dist}}_{\alpha/\beta}, \overline{\text{dist}}_{\beta/\alpha}), \quad (7)$$

where α and β represent a compared point cloud and a reference point cloud, respectively. An automated gDT is deemed better modelled if its C2C (denoted $C2C_{\text{Auto}}$) is smaller than that of the manual model (denoted $C2C_{\text{GT}}$) and vice versa. Table 1 illustrates the C2C results of *Bridge 1* and *Bridge 7*. The overall $\overline{C2C}_{\text{Auto}}$ of ten bridges gDTs was 7.05 cm while the $\overline{C2C}_{\text{GT}}$ was 7.69 cm. This implies the proposed method outperforms the manual operation. In addition, the average twinning time for ten bridges was 37.8 seconds, reducing the manual time by 95.8%.

Table 1: LOD 250-300 gDTs C2C evaluation

Bridge 1	Bridge 7
$C2C_{\text{GT/Real}}$: 4.0 cm	$C2C_{\text{Auto/Real}}$: 12.5 cm

Conclusions

This paper presents a framework of gDT generation for existing RC bridges using point clouds to meet *EURs 1, 2, 3* and *6*. It follows a top-down strategy to directly generate labelled point clusters followed by fitting them with IFC objects. Experiments on ten real bridge point clouds demonstrate the efficiency and robustness of the framework. This is a huge leap over the current practice of digital twinning, which is performed manually.

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THE IFC-BRIDGE PROJECT – EXTENDING THE IFC STANDARD TO ENABLE HIGH-QUALITY EXCHANGE OF BRIDGE INFORMATION MODELS

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Abstract

The paper reports on the buildingSMART International project IFC-Bridge that developed an extension of the vendor-neutral data exchange standard Industry Foundation Classes (IFC). The paper highlights the importance of a well-defined development process and the involvement of an international expert panel. It also discusses the need to focus on "low hanging fruits" by considering only the most widespread bridge types and implementing the data exchange scenarios that provide the most benefit. The paper describes both the development process and the outcome – the actual extension of the IFC standard. In this regard, emphasis is given to the general principles of extending IFC, such as minimizing the number of new entities.

Introduction

Industry Foundation Classes (IFC) is a comprehensive data model allowing the detailed geometric and semantic description of buildings and is widely used as a software vendor-independent BIM data exchange standard. It is developed by the international non-profit organization buildingSMART and has been accepted as an ISO standard in 2013. Up to version IFC4, the IFC standard was mainly focused on buildings. However, due to increasing international demand, a substantial extension of the standard to support infrastructure facilities is being carried out.

To this end, the so-called Infra Room, a subdivision of buildingSMART International (bSI) with its own steering committee, was founded in 2013. It developed a roadmap and started a number of projects to develop the necessary extensions. The first project was IfcAlignment which defined extensions for describing the alignment of linear infrastructure assets (Liebich et al. 2017). On this basis, the IFC Infra Overall Architecture project was conducted in order to specify general principles to be followed by all Infrastructure extension projects. On top of that, the projects IfcBridge, IfcRail, IfcRoad and IfcTunnel have or will be initiated.

In this paper, we report on the IfcBridge project; its devel-

Figure 1: Overview on the IFC-Infra extensions.

opment process and the results.

The extension project

In response to the urgent demand of international infrastructure stakeholders for extending IFC for bridges, the standard development project was initiated by Infra Room as a fast-track project with a duration of 2 years. It started in January 2017 and was completed with a slight delay in April 2019. Due to the limited time and resources available, it was essential that the project focused on "low hanging" fruits; i.e. selecting use cases to be supported that bring the most value to the future users of the standard. The IfcBridge extension project followed the formal project execution guidelines of bSI that came into effect in 2015 (buildingSMART International 2015). They define two essential components to be implemented by each project:

- the organizational structure,
- the development process.

The following section will report in detail on each of the phases.

The organizational structure

For each project, a project team has to be formed. It must consist of a group of international experts, preferably a combination of domain experts and IFC specialists. In

Figure 2: Dependence of the use cases on specific geometry representations.

the case of the IfcBridge project, the project team was composed of members from Finland, Germany, France, USA and China. The project team is led by the project lead and the technical lead.

The project team met on a bi-weekly basis and reported to the Infra Room Project Steering Committee (IRPSC) on a monthly basis, which monitors project progress and funds. In addition, an international expert panel must be formed comprising experts from the domain (here: bridge engineers, contractors and operators). Expert panel meetings were held in regular intervals in order to find the scope of the project, discuss the use cases and present the final results.

The development process

As demanded by bSI guidelines, the IfcBridge project implemented the following development phases:

1. Requirements Analysis
2. Taxonomy Analysis
3. Conceptual model development
4. IFC schema extension proposal (draft)
5. Validation
6. IFC schema extension proposal (final)
7. Formal acceptance

Requirements Analysis

An important lesson learned from more than 25 years of developing the open data standard IFC (Laakso & Kiviniemi 2012) is that it is of utmost importance to first define the scope and use cases to be covered by an extension project. This becomes even more obvious when considering (1) the large extent of the existing data model

(the latest release IFC4.1 comprises 801 entities), (2) the limited time and resources available for the developing the extensions, and (3) the goal of lowering the effort for software implementation to enable a fast uptake of the standard.

The requirements analysis performed by the project team in close collaboration with the international expert panel resulted in the defining the scope as detailed in the following sub-sections (Castaing et al. 2018).

Bridge types covered

Based on discussion with the expert panel and an analysis of the most widespread bridges constructed worldwide, the following bridge types were considered in the IfcBridge project:

- Slab bridge
- Girder bridge,
- Slab-girder bridge
- Box-girder bridge
- Frame bridge
- Rigid frame bridge
- Culvert

Bridges of the following types were not directly considered, but were expected to be representable by the extension:

- Truss bridge
- Arch bridge
- Cantilever bridge
- Cable-stayed bridge
- Suspension bridge

From a material viewpoint, the following bridge types were

Figure 3: Process map developed by the IFC-Bridge project, based on prior work by the US FHWA BrIM project.

decided to be covered:

- Reinforced concrete bridges
- Prestressed concrete bridges
- Steel/Concrete composite bridges
- Steel girder bridges
- Steel bridges

Use cases covered

The project team performed an in-depth analysis of the use cases for a software vendor-independent bridge data exchange format in order to identify those that are supposed to be supported by the extension, and those that are considered out-of-scope. The analysis included specifying the sending and the receiving application, rough descriptions of the required geometry representations and the semantic data as well as an assessment of the complexity of the realization of the required data structure. In addition, the priority of individual use case support was identified through intense consulting of the expert panel.

Based on a careful analysis of the benefits of the individual use cases and the complexity and effort involved with defining the necessary data structures, the project team decided to prioritize the following use cases for explicit consideration when designing the IFC-Bridge extension:

- Initial State Modeling
- Import of major road / railway parameters
- Technical Visualization
- Coordination / Collision Detection
- 4D Construction Sequence Modeling
- Quantity Take-Off
- Progress Monitoring
- As-built vs. as-planned comparison
- Handover to asset management
- Handover to GIS for spatial analysis
- Design to design (reference model)

Due to overly high complexity, the following use cases were marked as out of scope of the fast-track project:

- Design to Design (Full model logic)
- Structural analysis
- Code Compliance Checking
- Drawing generation and exchange
- Prefabrication and manufacturing

The full design-to-design use case, which incorporates the model's design logic (Ji et al. 2013), was excluded as it would require a major effort from both BSI in defining the necessary data structures and from software vendors in correctly implementing them. It was emphasized that the exclusion from the fast-track project does not mean that these use cases will not be addressed by future IFC-Bridge extensions.

Geometry

The analysis revealed that the in-scope use cases require explicit BRep geometry and/or implicit geometry based on sweeps (Figure 2).

More specifically, many of the supported use cases demand the usage of sweeps for representing the superstructure elements (deck, shoulder, etc.), rebar and the pre-stressing elements. It was well agreed by the project team that the usage of triangulated face sets is not appropriate for these elements in many use cases, due to the loss in accuracy and the excessive increase in data size. The use of sweeps is a strong demand for realizing meaningful data exchanges.

The entity `IfcSectionedSolidHorizontal` plays an important role. It has been introduced with IFC 4.1 as a result of the development activities in the IFC-Alignment and the IFC Infra Overall Architecture projects (Liebich et al. 2017)(Borrmann et al. 2017). The entity allows to perform sweeps along an alignment where the cross-section's y-vector is kept pointing in the global z direction, in contrary to the conventional `IfcSweptAreaSolid` where the cross-section is kept perpendicular to the sweeping path at any time. `IfcSectionedSolidHorizontal` has been introduced for correctly modeling elements of infrastructure facilities (roadway layers, bridge decks) and will be applied in this sense in the IFC-Bridge extensions. It will be included in the Bridge Model View Definitions (see below).

In practice, both `IfcSweptAreaSolid` and `IfcSectionedSolidHorizontal` are needed to define alignment-based geometry, depending on how the element is built. Having in mind that the global z direction can be easily identified on site, it is commonly used for cast-in-place processes. By contrast, if the element is pre-cast in a plant in a horizontal formwork, it is required to use a profile perpendicular to the sweeping path.

Process Map

The process map depicted in Figure 3 has been developed according to the BPMN standard to clearly identify the exchange requirements and associate them with dedicated data exchange scenarios. Its purpose is to provide a general reference workflow, i.e. deviations in national or regional processes are possible.

Taxonomy Analysis

In the following phase, the bridge taxonomy was analyzed. The goal was to identify concepts specific to bridge construction and to find commonly used English terms for them. To this end, the following sources were analyzed:

- French MiND project documentation
- FHWA
- Korean IfcRoad proposal

among the project team, later by using the web-based tool BIMQ by AEC3 Germany.

Conceptual model development

In the next step, the conceptual model was developed. The conceptual model describes the IFC extensions mostly by using UML diagrams in combination with documentation text. As opposed to the approach taken by OGC, the bSI conceptual model takes the particularities of the existing IFC data model into account and describes, for example, new sub-classes as refinements to existing IFC classes. It also defines attributes and properties where appropriate. The major part of the conceptual model is depicted in UML in Figure 4.

It is very important to note that the IfcBridge project implemented the guidelines of the Infra Overall Architecture Project (Borrmann et al. 2017), which demand to keep the number of new entities to minimum and instead provide a maximum of re-usage of existing classes. A good example is the Wing Wall of an Abutment. It is not necessary to define a new class for it, instead the existing IfcWall can be used. However, it may be appropriate to extend the enumeration of the predefined types of an entity. Where necessary, the documentation was modified to include bridge concepts.

Due to the principle described above, the resulting conceptual model only adds a minimum amount of new entities. At the same time however, a large number of new predefined types for a variety of entities were introduced. Figure 5 shows these extensions.

Spatial elements

In the IFC model, spatial structure elements are applied to capture the spatial hierarchy of a project. As the prior IFC data model was limited to buildings, a significant extension was necessary. A general concept applicable also for other types of facilities was implemented by means of the entities IfcFacility and IfcFacilityPart.

The new spatial entities defined are:

- IfcFacility – subtype of IfcSpatialStructureElement
- IfcFacilityPart – subtype of IfcSpatialStructureElement
- IfcBridge – subtype of IfcFacility
- IfcBridgePart – subtype of IfcFacilityPart

Figure 6 illustrates the extensions by means of an UML model.

Physical elements

The majority of physical elements of bridges can be described by means of the existing entities. The following new entities were defined to describe bridge-specific phys-

IfcBeam: <ul style="list-style-type: none"> • GIRDER_SEGMENT • DIAPHRAGM • PIERCAP • HATSTONE • CORNICE • EDGEBEAM 	IfcColumn: <ul style="list-style-type: none"> • PIERSTEM • PIERSTEM_SEGMENT • STANDCOLUMN 	IfcCovering: <ul style="list-style-type: none"> • COPING
IfcMember: <ul style="list-style-type: none"> • STIFFENING_RIB • ARCH_SEGMENT • SUSPENSION_CABLE • SUSPENDER • STAY_CABLE 	IfcPlate: <ul style="list-style-type: none"> • FLANGE_PLATE • WEB_PLATE • STIFFENER_PLATE • GUSSET_PLATE • SPLICE_PLATE • COVER_PLATE • BASE_PLATE 	IfcSlab: <ul style="list-style-type: none"> • APPROACH_SLAB • PAVING • SIDEWALK • WEARING
IfcWall: <ul style="list-style-type: none"> • RETAININGWALL 	IfcElementAssembly: <ul style="list-style-type: none"> • ABUTMENT • PIER • PYLON • CROSS_BRACING • DECK 	IfcVibrationIsolator: <ul style="list-style-type: none"> • BASE
IfcBuildingElementPart: <ul style="list-style-type: none"> • APRON 	IfcDiscreteAccessory: <ul style="list-style-type: none"> • EXPANSION_JOINT_DEVICE 	IfcMechanicalFastener: <ul style="list-style-type: none"> • COUPLER
IfcReinforcingBar: <ul style="list-style-type: none"> • SPACEBAR 	IfcSurfaceFeature: <ul style="list-style-type: none"> • DEFECT 	IfcProjectionElement: <ul style="list-style-type: none"> • BLISTER • DEVIATOR
IfcGeographicElement: <ul style="list-style-type: none"> • SOIL_BORING_POINT 	IfcBuildingSystem: <ul style="list-style-type: none"> • REINFORCING • PRESTRESSING 	

Figure 5: The newly defined predefined types for existing entities.

ical elements:

- IfcBearing – subtype of IfcBuildingElement
- IfcDeepFoundation – subtype of IfcBuildingElement
- IfcCaissonFoundation – subtype of IfcDeepFoundation
- IfcVibrationDamper – subtype of IfcVibrationDamper
- IfcTendonConduit – subtype of IfcReinforcingElement

Figure 4 depicts an overview of the data model related to physical elements including the extensions. In addition, new predefined types were proposed for existing entities. The full list is provided in Figure 5.

Systems

New predefined types were defined for the existing entity IfcBuildingSystem in order to support a more appropriate representation of reinforcement and the prestressing system:

- REINFORCING
- PRESTRESSING

Figure 6: Extension of the spatial elements. New elements are marked in red.

Positioning

The new relationship `IfcRelPositions` (subtype of `IfcRelConnects`) may be used to relate `IfcObjects` for which placement or geometry is defined relative to alignments (or grids).

The presence of such relationship allows for modification scenarios where alignments may change and dependent objects may then have placement and geometry adjusted accordingly. Such relationship is similar in functionality as `IfcRelConnectsPathElements`, where the adjustment of a wall, beam, or column can then be propagated to connected walls, beams, or columns.

Proposed IFC schema extension (draft)

Based on the conceptual model, the actual extension of the IFC schema was realized. This was done by defining the corresponding EXPRESS schema. From the EXPRESS schema, all other data schemas supported by bSI are derived (ifcXML, ifcOWL). In addition, a comprehensive HTML documentation is generated. With respect to the latter, the project team created the documentation for new entities and updated those parts of the existing documentation where semantics were altered or extended.

The draft extension was published on bSI Forums for direct feedback from the international community.

Validation

To avoid ambiguities and identify deficiencies, the extension was validated through prototypical implementation in two IFC applications and several tests to confirm successful data exchange between these two applications. One of the employed applications is TUM Open Infra Platform (Amann et al. 2016), see Figure 8, the other one is eveBIM by CSTB.

IFC Schema extension (final)

For the publication of the final version of the schema extension, the bugs and ambiguities identified in the course of the validation phase were fixed. In addition, feedback from the international community was taken into account.

Handling of properties

Properties play an important role in IFC-based data exchange. They are not part of the schema but are defined independently by means of the `PropertySet` mechanism (Borrmann et al. 2018). This allows for a dynamic extension of the schema and enables to fulfill the data exchange needs on a national, regional or authority level without requiring international consensus (Figure 9).

According to this principle, only a limited number of properties was defined as international properties forming part of the final specification. However, there are well-defined mechanisms for handling national or authority-specific

Figure 8: TUM Open Infra Platform visualizing bridge deck geometry created by alignment-based sweep

realized in a future IFC-Bridge 2.0 project. This may involve more advanced geometric representations to capture the parametrics of bridge design and enable their exchange between different design packages (Ji et al. 2013).

Discussion

The paper presented the extension of the vendor-neutral data format IFC developed in the course of the official buildingSMART International IFC Bridge project. The extension fulfilled a pressing request of the international BIM community to better support the data exchange of bridge information models.

The project showed that it is possible to successfully develop an extension of significant extent in a limited time of only 2 years. However, a stringent process had to be implemented to reach this goal. The most important prerequisite for the success of the project was the clear definition of the bridge types to be included and the use cases to be supported by the standardization effort. In this regard, it was essential to concentrate on the "low hanging fruits", i.e. on the most widespread bridge types and the most beneficial use cases with limited complexity.

The involvement of international expert panel through frequent online workshops proved to be a very helpful resource for critical reflection of the decisions taken by the project team.

For the actual extension, the guidelines laid down by the IFC-Infra Overall Architecture project were carefully followed. Most importantly, new entities were only defined

where necessary, i.e. where existing entities did not provide the semantics required for bridge-specific concepts. In most cases, an extension of the predefined type enumerations was sufficient. This approach helps to keep the effort low for software vendors that already implemented previous versions of IFC when integrating the extensions.

With respect to properties, only a limited number were defined and became part of the official international specification.

A shortcoming of the current bSI process is the sub-optimal support by software tools. Although the project team was able to use BIM-Q to collect taxonomy items and map them to IFC entities, the synchronization with the UML tool for creating the conceptual model remained a mainly manual task. At this point, inconsistencies may easily arise. Particular challenging was the application of IfcDoc for creating the final draft schema and its documentation. Again manual work was necessary to a large extent. The authors hope for improvements at this point and better support for future extension projects.

Conclusion

The project has proven that the creation of a well-defined extension of IFC in limited time frame is possible. The formalized processes of buildingSMART International help to deliver a high quality product, ensuring both its technical validity and its applicability in the target domain.

Figure 9: The extension mechanisms of IFC allow the definition of properties on different levels.

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DIGITAL BUILT ENVIRONMENT MATURITY MODEL: DIGITAL TWINS ADVANCING SMART INFRASTRUCTURE ASSET MANAGEMENT

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Abstract

Re-definition of environmental, social, and economic outcomes is constantly pushing the infrastructure industry towards advanced digitalisation. Increasing amount of information on the use, behaviour and performance of infrastructure assets enables better decision making and asset value management. Digitalisation enables more effective utilisation of existing assets, better design, selection, and delivery of new assets. Asset data can contribute to improving the value of an asset in its life-time, a citizens' quality of life, and economic growth. Asset data is key for smart infrastructure management. Process and technology advancements enable the transformation of physical infrastructure into a smart infrastructure (digitally represented by digital twin) which may store the historical and real-time status of a physical counterpart. This paper targets methods, processes, and technologies which may be used to better capture, organise, analyse and understand the status and behaviour of infrastructure assets. Presented smart asset management maturity model will enable asset owners to introduce new methods of monitoring and decision making that may lead to the innovative smart infrastructure asset management.

Introduction

The speed of innovation is increasing. Technological advancements, which have happened in the last few decades, have enabled a comprehensive change in the way business is done. Digitalisation is changing the roles people play in their organisations. Redefined economic, environmental, and social outcomes have increased the need for the adoption of digital ways of working. Big investments in the infrastructure networks that took place in developed countries post 1950s have caused the returns on investment of new-built infrastructures to steadily fall. The infrastructure networks built in the second part of the 20th century are aging and causing huge costs, e.g. in 2014 the USA spent 57% of the budget dedicated to infrastructure on operations and maintenance (Popper and Gates, 2016). The above mentioned facts introduced several challenges within three interconnected environments:

- socio-economic
- technological (cyber-physical)
- organisational

Socio-economic environment. The financial crisis of 2007-08 and the ensuing recession, have caused shrinkage of infrastructure asset management budgets (Brumby and Verhoeven, 2010). The extreme climate changes have prodded World leaders to establish stricter laws and regulations to decrease the effect of our way of living on the natural environment. The rise in population, their standard of living, and organisational competition are increasing the need for quality and throughput of infrastructure assets that are needed to provide adequate services to end-users.

Technological (cyber-physical) environment. Digital technology and process advancements, with re-defined outcomes of the 21st century, generate the need for improvements in the way built assets are managed. One of the most important realisations has been that not all problems in infrastructure can be solved by building new infrastructure assets, but rather the efficiency of existing infrastructure assets must be improved. A comprehensive programme was started in the UK, in 2011, when the Government Construction Strategy (Cabinet office, 2011) was published.

Organisational environment. In order to improve the outcomes our infrastructure assets provide us, asset management organisations need to undergo a comprehensive change programme. The final goal of the change programme should be an agile, ever optimising – SMART organisation, capable of identifying needs and then implementing and using the latest developments which will help improve social, environmental, and economic outcomes which define their competitive advantage. Slow development of digital capabilities within infrastructure asset management organisations leaves a lot of room for improvement, and subsequently the efficiencies and improved outcomes these organisations can achieve through better, smarter management of their assets.

What is the way forward for 'smart asset management' organisations?

The increasing awareness of the benefits that new technologies bring has caused the increasing adoption of advanced digital technologies by organisations. However, these are often partial solutions and do not bring the desired benefits and potential comprehensive capability improvements that strategically aligned digital organisations are trying to achieve.

Therefore, these organisations still have a long way to go before they start reaping the significant benefits digitalisation brings. Digital alignment and constant change synchronisation can drive change and advance project performance (Bentley, 2018).

Adopting a capability maturity model approach for the gradual improvement of digital capabilities has proven to be the right way for organisations in other industries. Undergoing a comprehensive assessment allows the organisations to establish their current level of maturity. By understanding what is required to progress to the next level organisations can then plan how best to achieve it. The gradual progression through levels of maturity allows an organisation to steadily plan and mitigate any risks associated with a single, organisation – wide change.

This paper tries to unveil critical milestones that help the development of advanced methods and procedures to drive organisations to take advantage of digital twins, which are digital replicas of physical world that can drive change and new business models on one hand, increase the capacity, and introduce new sustainable development methods on the other.

This paper follows standard IMRAD structure, starting with research methodology that targets smart asset management, supported by the digital twins.

Methodology

The main problem addressed in this study is HOW to make asset management smarter? Obviously, the problem translates into digitalisation of a built environment and analysis of socio-technical systems. The problem formulation and analysis directed the research methodology (see Figure 1) that comprised: literature surveys, action research and frame-working.

Literature surveys. Literature surveys included scoping literature reviews which lead to identification of specific engineering genres along with systematic quantitative and qualitative state-of-the-art literature reviews. Special focus was given to genre research which targeted guidelines and specifications that try to classify the level of implementation of digital technologies in organisations or, in broader context, geographic regions or industries for example. Specific sub-genres that were studied in more detail are digital product and process maturity models and accompanying frameworks. The literature and genre research were facilitated by a continuous learning process resulting from action research.

Action research. Action research covered three main iterative phases which identified elements of solutions which were synthesised and tested in the context of applicable systems of systems. The focus on the development process was on key conditions that can enable “digital operations” in asset management organisations. The research methodology provided an appropriate approach for the iterative development of a maturity model, along with frame-working.

Frame-working. The goal was to identify frameworks that would frame as many possible aspects that might affect digitalisation of a built environment. For this purpose several candidate frameworks were shortlisted and tested in practical research work. Zachman’s Framework (1987) was found particularly applicable to analyse What, How, When, Who, Where, and Why specific factors are relevant. According to Zachman, it is the integration of the answers to these questions that enables a comprehensive and composite description of complex ideas. There are 6 distinctive steps of the framework: Identification, Definition, Representation, Specification, Configuration and Instantiation.

Figure 1: Research methodology: frame-worked action research

Research on digital capabilities

In this section, focus is on the background review of Capability Maturity Models (CMM) and applicable frameworks for use in smart asset management. Section 3 is the main input to section 4, which presents the core of developed smart asset management maturity model with digital twins.

Background. As the need for the development of new software began to rise due to popularisation and consumerization of computers, so did the difficulties related to the delivery of software projects. There were only a few best practices that could be used for the increasing number of software implementations.

Due to late delivery or no delivery of the software projects, the US Air Force funded a study at the Software Engineering Institute. To allow the US federal government to assess the capability of its software providers, the Software Engineering Institute produced a brief description of the process maturity framework and a maturity questionnaire (Paulk et al, 1993). With the help of this tool, the software organisation could identify the processes which needed improvement. These two later evolved into the Capability Maturity Model for Software (CMM).

Capability Maturity Models (CMM)

CMM was followed by the CMMI (Capability Maturity Model Integration) (SEI, 2010), which was looking to integrate many models into one framework. The Capability Maturity Models define five levels which represent an organisation's current capability.

The maturity model can also be used to identify processes which need improvement in order to achieve an organisation's business goals. Over the years, the CMMI has been adopted to many different industries and areas, such as regulatory compliance (O'Kane, Casserly and McCartney, 2015). Typically, a maturity model consists of a number of components (Fraser,

Moultrie and Gregory, 2002): number of levels, description of each level, and description of characteristics expected of an organisation at each level, number of dimensions, description of elements/activities at each dimension, and description of each activity as performed at each maturity level.

An overview of some relevant maturity models in the context of Zachman's framework is presented in the Table 1 below. Notably, most of the maturity models prescribe what is required and rarely elaborate methods, responsibilities and roles, and reasons why a particular maturity must be achieved.

It is also interesting that most of the maturity models do not use the concept of time, though, some well-established maturity models do define the period of validity of maturity. An interesting attempt of standardisation of BIM maturity is for example initiated by BSI Kitemark evaluation of BIM Level 2.

Asset management assessment

ISO 55000 provides a concise definition of asset management (ISO, 2014): 'a *coordinated activity of an organisation to realise value from an asset*'.

The standardisation of asset management helps the industry in adoption of asset management at a strategic level, focusing on the whole life-cycle of the system of systems of assets, within integrated management system. This offers organisations the opportunity to realise value on a much broader scale than could be achieved by focusing discreet activities on individual assets in isolated life-cycle stages (IAM, 2015).

In order to align the various asset management standards, models, principles and best practices from around the World, the GFMAM (Global Forum on Maintenance and Asset management) produced The Asset Management Landscape. It defines six Asset management subject groups, further divided into thirty-nine subjects (GFMAM, 2014).

Table 1: Overview of applicable maturity models by key concepts from Zachman's framework

	What	How	When	Who	Where	Why
CMMI	x	x		x		
UK BIM maturity levels	x	x				x
Forrester DMM 4.0	x					
Smart Cities MM	x					
Regulatory Compliance MM	x	x		x		
Plant Asset Management MM	x	x				

These represent a comprehensive view of the asset management landscape and are used as a basis for the development of various models and best practices in the field of Asset management. The document helps to compare, and align asset management knowledge and practices.

The GFMAM defines asset management maturity as the ‘...extent to which the capabilities, performance and ongoing assurance of an organisation are fit to meet the current and future needs of its stakeholders, including the ability of an organisation to foresee and respond to its operating context.’ (GFMAM, 2015). Based on this, asset management organisations would benefit greatly from not only achieving the requirements described in the ISO 55000 series, but developing their maturity beyond compliance. In order to help various asset management organisations develop their maturity models, the GFMAM’s position statement document defines the key principles for achieving this task.

The Institute of Asset management (IAM) in the UK has developed a number of maturity models over the years (IAM, 2016) based on at-the-time, latest best practice, and newest standards. The latest one is based on the ISO 5500x series of standards and the framework described in the Asset Management Landscape (IAM, 2016). It recognises the fact that the subject of asset management and the characteristics of adequacy and best practice are continually evolving and also the fact there are different operational environments, constraints, cultures and opportunities in asset management, which all affect what is considered competent or excellent.

An integrated maturity model of asset management capabilities (Mahmood et al, 2015) has researched the gaps in terms of key process areas by comparing six existing asset management maturity models against the five dimensions of engineering asset management and suggested an integrated approach. The Australian Asset Institute has built on that research by creating the Asset Management Capability Maturity Model – AMCaMM in three steps – identification of key process areas, definition of capability and maturity levels, and the definition of the capability indicators for each capability level for each process area.

Smart Asset Management Maturity (SAMM)

The definition of ‘Smart Asset Management’ (SAM) hasn’t yet been agreed, but reviewed literature suggests there are a number of characteristics which relate to SAM. These characteristics are: Being able to retrieve required information directly from the asset, be that the asset’s unique identifying name or its operational condition; and the communication between the asset and the central intelligent database thereby interacting with the organisational decision making (Nel and Jooste, 2016). The concept of SAM therefore combines the field of asset management, technology management, and organisational decision-making (see also Table 2). The mind-shift in asset management is essential: from a reactive approach to a proactive approach. The greatest feature of SAM is therefore the ability to interpret asset data in real time.

Therefore, to be able to better understand what smart asset management might look like, research on similar applications must be conducted. An area which might help in the clarification of different aspects of what is meant by “smart” in smart asset management, are smart (and digital) cities. (Cocchia, 2014) discovered digital cities are much better defined, as compared to smart cities, as all definitions focus on the key role of ICT in improving the quality of services and information supplied to citizens. The purpose of smart cities is often much broader, as they focus on outcomes, such as the improvement in the quality of urban life defined by the environmental, economic and social requirements, underpinned by the role of innovation and technology. Lately, ICTs have become a large part of smart cities and, therefore, digital cities are becoming a subset of smart cities. In the smart factory context, the term “smart” is defined as having access and making decisions based on real-time data (Shariatzadeh et al, 2016).

Four dimensions have been identified that determine digital maturity (Gill and Van Boskirk, 2016) – culture, technology, organisation, and insights. Besides the people (culture), process (organisation), and technologies, it is the information and the insights that can subsequently be gained which is one of the dimensions. Information is the lifeblood of any form of asset management.

Table 2: Review of smart asset management development concepts: derived from (ICE, 2018)

Customers	Leadership	Commercial	Capability	Asset delivery	Asset management
insight	strategy	definition	skills	availability	information management
participation	culture	recognition	suppliers	Information management	making sense
experience	innovation	digitisation investments	information security	standards and automation	decision making

It is the information that forms the basis for decisions thereby helping asset management organisations gain value from their assets. Smart asset management enables the asset management organisations to make better decisions by taking advantage of processes enabled by the latest technologies, to operate with the information which is the latest, true, and trusted information; and enriched through various procedures. BIM ensures integrity and prevents the loss of information created and collated during an asset's life-cycle. The more efficiently information about our assets is integrated, the higher may be the value extracted from those assets. At the moment, information integration is done on ad-hoc basis and is centred around individual integration opportunities (Kang, O'Brien and O'Connor, 2014).

A maturity model for information integration of capital projects has been created in order to address those issues. Similarly, at the heart of smart cities is a simple process, focused around data: improved data capture – advanced data processing & analysis – improved visualisation & display of data – targeted, automated, dynamic response – improved efficiency & better outcomes (Scottish cities alliance, 2014). Besides data, the maturity of smart cities is considered across strategic intent, technology, governance & service delivery models and stakeholder management.

Study of maturity models in relation to information systems, (Proenca and Borbinha, 2016) identified a several models, that were compared by structure, process and the support they offer. The availability, integrity and transfer of data and information during the asset's life-cycle are important factors to consider which areas BIM maturity models consider (Succar, Sher and Williams, 2013). Other digital maturity models have been created for other industries (Gill and VanBoskirk, 2016), (Aleem, Capretz and Ahmed, 2016), (Paavel, Karjust and Majak, 2017).

Digital Built Environment Maturity Model

The purpose of the Digital Built Environment Maturity Model (dbEMM) is a model that can be used to assess the level of digital capability of asset management organisations.

dbEMM is illustrated as a three-dimensional cuboid in which sides represent various criteria which need to be evaluated at each maturity stage (Figure 2):

- Areas of Digital Capability (ADC) [red]
- Supporting Organisational Environment (SOE) [green]
- Digital Twin Maturity Stages (DMS) [blue]

ADC (red), includes three main areas (data management, data analysis and decision making) which determine the digital maturity.

Note, data management covers whole data-lifecycle from data acquisition to storage and processing, while analysis prepares data for decision making.

SOE (green), represents three systems (people, process and technologies). An organisation may find its ADCs at different stages. However, the organisation can progress from one stage to the next if requirements for current stage have been successfully evaluated.

Whilst the greatest value may be created if the digital capability is standardised across the whole organisation, sometimes that is not feasible.

Consequently, the sub-organisations, as part of the bigger organisation, may be evaluated on their own, using the dbEMM. In such cases the term “organisation” used in the dbEMM, should be replaced by, and understood as, the term “Sub-organisation”.

Figure 2: Digital Built Environment Maturity Model (dbEMM) - 'Digital Twin Maturity'

At each stage, the lower level elements get evaluated to see if they are still needed and, if they are, do they need to be adjusted or changed, or kept as they are?

Some elements of the ADCs of the more mature stages may be implemented at lower levels of maturity than defined in the model. However, dbEMM can assist organisations in levelling up its maturity in a structured and comprehensive way.

The supporting organisational environment, established roles, responsibilities and procedures must be evaluated for each Area of Digital Capability that are specific to five digital twin maturity stages:

- Ad-hoc Datasets.
- Digital Twin Formation.
- Digital Twin Standard Operation.
- Digital Twin Real-Time Automation.
- Digital Twin Intelligence Contextualisation.

Stage 1: Ad-hoc Datasets.

At this stage the organisation has no standardised, organisation-wide defined digital capability. Data is collected either on paper or digital format and stored in ad-hoc repositories. The level of management of said data is, at best, local (a single person, or group).

Data is used for single-use cases, and is rarely re-used, as it usually gets lost, is not shared, becomes obsolete, or is not trusted.

Combining different pieces of data to create new uses for it, or to learn more from it, is rare and depends on the user's experience, or technology point-solutions. However, if at some point in the future, the organisation decides to carry out an organisation-wide standardisation of its digital capability it must be evaluated starting at the 1st stage of the dbEMM.

Stage 2: Digital Twin Formation.

At this stage the organisation defines and forms the first Digital Twin. The business outcomes and functions its digital capability needs to support are defined. Processes, workflows, and data flows get mapped, information requirements, inputs and outputs, information structures, standards, and roles & responsibilities get defined. The Digital Twin is defined and built.

Data gets collected, managed, and used in the same manner as in Stage 1. Data, which already exists in a digital format in various, ad-hoc repositories, gets transferred into the new, organisation-wide repository, popularly called the Single Source of Truth for the organisation.

The level of data management is organisation wide. The data collected in the Digital Twin is still in a "pre-production" state.

Stage 3: Digital Twin Standard Operation.

At this stage the organisation introduces the Digital Twin into operations. It populates their Digital Twin with all the newly created data about their assets, as defined in their information requirements. The collection of historic data, may not exist yet or may be available on paper, gets defined and the data is progressively collected, depending on the business need. New business cases get defined, based on the digital capability. The Digital Twin must be kept in-synchronisation with reality. However, this is not yet done in real-time, but at pre-defined intervals, points in time, or based on events.

Data is collected in a digital format and stored in the defined repository. The level of data management is organisation wide. Data is used for multiple-use cases and is often re-used, as it is accessible in a single place to anyone with access rights. Various types of data get combined and provide more insight, thus allowing for better decision making. 3rd party data is used to provide more insights, potentially in combination with the organisation's own data.

Stage 4: Digital Twin Real-Time Automation.

At this stage the organisation introduces the elements of the Internet of Things into operations. Some of the data about their assets gets collected, transmitted, stored, and/or used almost instantly after an event's occurrence.

Data is collected in digital format and stored in the defined repository. The level of data management is organisation wide. Data is used for multiple-use cases and is often re-used, as it is accessible in a single place to anyone with access rights. Various types of data get combined and provide more insight, and thus allow for better decision making. 3rd party data, including the end users real-time data, is used to provide more insights, potentially in combination with the organisation's own data. As some of the data is collected in real time and, potentially, continuously, some decisions can be taken much faster. The Digital Twin is more in-sync with reality using sensory reality capturing.

Stage 5: Digital Twin Intelligence Contextualisation.

At this stage the organisation introduces elements of Artificial Intelligence (AI) systems into operations. Some of the assets are capable of influencing decisions related to them.

Data is collected from various sources, across project phases - eg above the built environment (satellite LIDAR), from the built environment (temperature, stress, vibrations), mobile assets (UAV) and artificial intelligence allowing for cross-functional autonomous decision making in a given context.

Discussion and conclusions

The critique of the model could be eventual confusion about processes that are put in two dimensions. First, a process appears in the organisational triad (people, process, technology) and second, processes appear in the areas of digital capability (data management, data analysis and decision making).

In order to properly interpret the dbEMM, process in the triad should be understood as actual process in a specific organisational context - to deliver required outcomes by digital capabilities. Due to the limited scope of this paper, possible applications of dbEMM cannot be demonstrated in more detail. However, it can be claimed that the proposed maturity model could be successfully applied in many different contexts.

The initial response to maturity model shows that it may become a valuable tool to streamline the development of smart asset management and a digital (twin) - built environment. The concept of Digital Twin Maturity might be also transferred to other application areas/industries.

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Smart Structures

ROAD ASSET CLASSIFICATION SYSTEM

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Abstract

Visual inspection is the most commonly employed way of condition inspection for road networks. The process is quite labor intensive, leading to a substantive cost of inspection per lane mile and causing long inspection cycles and substantive inspection outcomes variability. Automating the process can tackle these issues. The first step to achieve automation is to understand what the assets are, what their visible condition symptoms are, what they cause and what causes them, and how to fix both their outcomes and their causes. This is the objective of this paper. Inspired by the symptoms tracker of WebMD, we conducted exploratory research that combined several guidelines into a comprehensive definition of road assets, their defects and possible maintenance techniques from the road inspector's point of view. We propose a different classification system of the road assets according to their defects and maintenance techniques driven by the computer visual monitoring approach. The result is a large map containing all the aforementioned elements.

Introduction

Highway Operational Standards 2018-2028 refer to the importance of healthy highway infrastructure as the key for a robust economy stating the need to use all the available resources (Highway Operational Standards, 2018). A publication by the United Kingdom Royal Society for the Prevention of Accidents states the importance of healthy road assets (pavement, signs, markings etc.) as they constitute a huge factor for the safety of road users (International Road Federation, 2006). Their maintenance is essential (Levik, 2001) and cost effective compared to complete road reconstruction (Medd, 2009). As a result, the identification and the measurement of the road defects (as part of maintenance policy) is quite challenging, rendering the use of suitable advanced technologies essential. There are three maintenance categories (Burningham and Stankevich, 2005):

- Routine Maintenance, which is conducted on a regular basis and entails debris removal, minor repairs etc.
- Periodic Maintenance, which is also conducted on a regular basis but is more costly than the routine maintenance, as it includes pavement reconstruction, Planning and Strategy
- Urgent Maintenance, which includes repairs that could not have been foreseen

The United Kingdom (UK) road expenditures for the year 2015-2016 were £9 bn. and 40% of them were allocated for the maintenance (£3.6 bn.). From this amount, 20% (£0.72 bn.) constituted the routine maintenance and the planning and strategy of the maintenance policy, which also represents the area of interest of this paper (Figure 1) (George and Kershaw, 2016).

The maintenance policy of the authorities in the UK is both expensive (Figure 1) and time consuming (Table 1).

Road Expenditures for ('15 – '16) = £9 bn.

Figure 1: Allocation of road expenditures for the UK (2015-2016) (George and Kershaw, 2016).

Road maintenance monitoring occurs once or twice per year for the motorways and once per two years for the minor roads (Highway Operational Standards, 2018). This inspection is mainly visual for road assets like lights, barriers and the drainage system (Royal Borough of Windsor and Maidenhead, 2017).

Currently, Fugro (Roadware, 2010) has released a dedicated vehicle: the Automatic Road Analyzer 9000 (ARAN) which is equipped with video cameras or optical sensors, lasers, ultrasonic sensors, accelerometers and automatically detects defects like longitudinal cracks, transverse cracks, potholes and rutting (Department for Transport, 2017). In the United Kingdom, Highways England and the Local Authorities (responsible for the road maintenance) use TRACS (TRAffic – speed Condition Surveys) survey vehicles and SCANNER (Surface Condition Assessment for the National Network of Roads) survey vehicles respectively, to collect data of pavement. They automatically collect geometry and condition data that can be used to manually

detect/model cracks (through image processing), bumps, potholes, gradient, crossfall, radius and curvature of road and the retro-reflectivity of road demarcation.

Table 1: Type and Inspection Frequency on the UK roads (Highway Operational Standards, 2018).

Hierarchy Description	Inspection frequency and type from City Councils
Motorway	1-2 per year (from Highways England)
Strategic Route	12 times per year (monthly)
Main Distributor	12 times per year (monthly)
Secondary Distributor	12 times per year (monthly)
Link Road	4 times a year (3 monthly)
Local Access Road	Annually (once per year)
Minor Roads	1 per two years (24 monthly) (standard is that they are passable with care)
Soft Roads (Green Lanes)	No formal inspection regime. Inspected on a reactive basis (standard is that they are passable in a 4 wheel drive vehicle)

Discussion and Analysis

The aim of this paper is to introduce a classification system of the road assets that is based on these computer vision inspection methods. For the scope of this paper road manuals from four parts of the world were used: United Kingdom, Hong Kong (Special Administrative Region of the People's Republic of China), California (United States of America) and Queensland (Commonwealth of Australia) to define the asset types. Next, the grouping of these types follows according to a) possible common defects that they might have and b) their geometrical structure and visual differences, as these characteristics affect the automated detection of these assets.

Most of the manuals specify in a first level the general road asset type and then in a second level the road furniture (asset group) that level one entails. The UK (Roads Liaison Group, 2010) follows this pattern for levels one, two and three (Table 2). The table illustrates a sample of the road manuals and the rest are part of the Appendices. The Hong Kong manual [13] is not as elaborative as the UK one and the asset types are slightly different (Table A.1). "Street lighting", "Slopes" and "Landscape Enhancement and

Vegetation" asset groups here are considered as main standalone asset types (Level 1) whereas in the UK manual they are in Level 2. The Queensland manual introduces a new category of road assets; the Intelligent Transportation System (ITS) Elements (Table A.2). ITS are deemed as advanced information and technological systems, which are

placed on the road infrastructure system [14]. The "Roads" and "Structures" types remain as main categories similar to the UK and Hong Kong manuals (Table A.3). The rest of the asset types are not extensively described. The "Intelligent Transportation System (ITS) Elements" category makes up a main asset type in the California manual as well (Table A.3) (Indicators, 2016).

The asset types defined in the manuals were classified into categories for construction and maintenance purposes. These categories are used to redefine these raw asset types in a different way aiming to introduce new asset types and asset groups that will facilitate road assets monitoring. Firstly, the asset types and groups, described in the above manuals, are gathered to gain a clear view of the number, type and groups of the road assets that are (Figure 3). The next step is to create different asset categories based on:

- 1) their possible defects
- 2) their geometrical characteristics.

In the following section, the road asset types and groups are analysed and redefined using the above criteria.

a) "Pavement" Asset Type

There are four different pavement groups: the "rigid", "rigid composite", "flexible" and "flexible composite" pavement (Roads Liaison Group, 2010) (Figure 1.2). The difference between "rigid" and "flexible" is that the road base of the first is cement whereas for the second, the road base is bitumen. Composite pavement is a pavement structure, which has flexible and rigid layers. These pavements usually have one or more asphalt concrete layer on top of a Portland cement concrete slab ("flexible composite"), although some have a typical composite structure is with the Portland cement concrete slab on top of asphalt concrete ("rigid composite") (Figure 1.2) (Highways Agency, 2006). The author suggests the merge of the four categories of these road asset groups into two: "Concrete Pavement" and "Asphalt Pavement" as the visual characteristics and defect approximation is based on the material of the pavement. The asphalt pavement is analyzed by Hadjidemetriou G.M., Masino J., Christodoulou S.E., Gauterin F, and Brilakis I. in a paper reviewed (2018) for publication by ASCE The reason of this combination is that:

- 1) The material of the pavement (asphalt or concrete) is the main factor of the pavement defects, as it is

described in the following section (defect criterion).

- 2) The surface of the flexible pavement and the flexible composite is usually black due to the asphalt material, whereas, the rigid pavement and the rigid composite is light grey (visual characteristics).

b) "Road Furniture" Asset Type

Concerning the "road furniture" asset type, the "vegetation" asset group has the same characteristics with the "hedges" as both of them are related to planting and their only defect will be the overgrowth process. This overgrowth, for example, might lead to hidden traffic signs, which constitutes a defect of the "signs" group. For this reason, "vegetation" and "hedges" will not be included in the road assets groups, for the purposes of this paper, as the only problem they might create is overgrowth and this can be included in the "Signs" defects. The "fences" category is closer to the "Barriers" and "guardrails" groups as these have similar geometrical characteristics and also similar defects (The Government of the Hong Kong Special Administrative Region, 2018). Thus, a new group named as "Barriers" is defined that includes the aforementioned road

groups. The road "Markings" group includes both mechanical markings (raised pavement markings) like cat's eyes, botts' dots etc. and the road surface markings (Highways, 2015). The "Demarcation" category as a new category that will include raised pavement markings. The road surface (coloured surface) marking should be a different asset category as they have different defect types and different visual and geometrical characteristics from the raised pavement markings.

"Shoulder / hard strip" is, in practice, an emergency lane (pavement) distinguished by either "road markings" or other "demarcation" asset groups. It has the same visual / geometrical characteristics and similar expected defects to the "Pavement" asset type, thus, it will be part of the "Pavement" asset type. The "verge" asset group usually consists of soil or grass, is placed at the edge of the road and may have the same defects as the "vegetation" group and could be included in the "vegetation" category as defined above (Heath, 1999). In this research, "earthworks" will not be considered as a road asset group since the result of earthwork distress (like landslide for example) is a visible deterioration of the road pavement (detectable stones, soils on the pavement etc.)

Figure 2: Layers of (left) flexible pavement, (right) rigid pavement and asphalt composite pavement in comparison to asphalt pavement (down) [16]

Table 2: Road assets and sub categories (UK Manual) (Roads Liaison Group, 2010)

Level 1 Asset Type	Level 2 Asset Group	Level 3: Components
Road	<ul style="list-style-type: none"> • Flexible pavements • Flexible composite pavements • Rigid concrete pavements • Rigid composite pavements 	<ul style="list-style-type: none"> • Pavement layers (formation, road base, binder course, surface course) • Other surface types e.g. paved • Hard strip/shoulder • Footway/ cycleway attached to road • Central reservation, roundabout, lay-by etc. • Markings • Kerbs • Earthworks (embankments & cuttings) • Vegetation • Drainage • Safety fences • Boundary fences and hedges • Verges
Segregated footpaths and cycle routes*	<ul style="list-style-type: none"> • Footpath (including PROW) • Bridleways (including PROW) • Off road cycle routes • Pedestrian areas 	<ul style="list-style-type: none"> • Binder course and surface course • Formation
Structures	<ul style="list-style-type: none"> • Bridges (includes subways) • Culverts (span < 1.5m) • Retaining walls • Sign/signal gantries and cantilever road signs <p>Other assets included in this group:</p> <ul style="list-style-type: none"> • Tunnels • Structural earthworks, e.g. strengthened/reinforced soils • Fords and causeways • Cattle grids 	<p>Should include all components considered in the maintenance and management of these assets.</p> <p>Smaller water carrying structures are considered as road drainage.</p>
Highway lighting and high mast lighting	<ul style="list-style-type: none"> • Lighting columns • Lighting unit attached to wall • High mast lighting 	<ul style="list-style-type: none"> • Column and foundations • Bracket • Luminaire (or other fixtures, e.g. CCTV) • Control gear, switching and internal wiring cabling

(The Local Government & Municipal Knowledge Base, no date). The “Drainage” asset group used in urban roads are: kerbs & gullies, combined kerb & drainage blocks, linear drainage channels and combined surface and ground water filter drains (Department of the Environment Heritage and Local Government, 2004). There is no reason to remove this asset group so it stays as it is.

c) “Electronic Furniture” Asset Type

The “Electronic Furniture” category includes the “Changeable Electronic Message”. Since this category is limited to this specific asset group, a new category is defined instead the general category “Electronic Signs”. This category includes LED (light – emitting diode) signs, the “changeable message signs”, and any other type of electronic sign. “Lights” (included in this asset category) are usually in the traffic signs or in the top of the poles and are used to facilitate the road users’ vision (Transport Infrastructure Ireland, 2017). The light poles are part of both of the lights and the lamps and they are considered as structures with similar defects as the ones of signs. In this case, only the lamp of the “light” or the “traffic sign” are considered as part of this group and not the support. The support (pole) could be part of the road furniture (“signs”). The “loop detector” comprises from a detector (usually a traffic signal) which is visible from the road user and a non-visible device buried under the earth. Once a vehicle passes over the loop, a magnetic field is created and the loop warns the vehicle detector, which in turn informs the light detector through the cable, and thus regulates traffic accordingly (Marszalek, Sroka and Zeglen, 2015). In a similar context, “ramp meters” also regulate traffic congestion by using a traffic light and a detector (loop buried in the road lane) that warns the traffic light if the vehicles can leave the ramp. A road inspector can understand from the traffic light if there is any defect in these two asset groups. It comprises of a support (pole) and an electronic device. Hence, the support could be part of the traffic signs since they have similar structure and defects and the device to be a separate part of the “Electronic Furniture” asset type.

“Structures” Asset Type

The structure asset category is out of the research scope of this research as there are different types of defects that are related to structural engineering and this category demands a different type of monitoring.

The new asset types, groups and the components that they might include, from the scope of the road inspector, are summarised in and shown in Figure 1.3

“Concrete Pavement” Asset Type

The defects of the second asset type, “Concrete Pavement”, are: cracking (block, corner, diagonal,

longitudinal, shrinkage and transverse cracking), deformation (joint stepping-faulting, rocking-pumping), joint sealant defects, spalling (box out spalling) and surface texture defects (ravelling, loss of surface texture-slippery surface) (Research & Development division of the Highway Department, 2013).

Figure 3: Road Assets final

The repair methods that correspond to each defect will follow.

Table A.4 in the Appendix describes the maintenance techniques for the concrete pavements defects as found in the research. Table 3 indicates the corresponding defects that these techniques cure. The defects and the cures of the “Concrete Pavement” asset group will

follow as it was analysed above (Figure 4). In Figure 1.4, each color corresponds to the defect and is linked to the corresponding maintenance technique. The defects and the cures of the “Concrete Pavement” asset group will follow as analysed (Figure 4).

Table 3: Maintenance Techniques of “Concrete” Pavement type and Defects they cure

Maintenance Techniques	Corresponding Defects that these diseases cure
PCC (Portland Cement Concrete) full depth patching	Spalling, punchouts, and corner breaks. If the slab damage is over the one-third of the slab depth, then PCC is used (Jamzad and Assadi, 2009). High severity longitudinal, diagonal, corner cracking & transverse cracks [35, 42].
Partial depth patches	Small are the ones with depth 50 – 75 mm (2 – 3”) and area less than 1 m ² (10.8 ft ²) (Jamzad and Assadi, 2009). Small ravelled areas (WSDOT, 2017).
Crack sealing	For small block cracks (<1/2 inch wide) (Officials, 1993). Low severity longitudinal, diagonal & transverse cracking (Pavement Systems, 2012).
Portland Cement Concrete (PCC) or Hot Mix Asphalt (HMA)	For large cracks (>1/2 inch or cracks with ravelled edges) (Officials, 1993). Large ravelled areas (WSDOT, 2017).
Total Reconstruction needed	High severity Surface Deformation of more than 0.5 inches (> 0.5”)
Insertion of dowel bars	Medium severity faulting of between 0.125” and 0.5” (0.125 < Surface Deformation < 0.5) in a Jointed Plain Concrete Pavement (no reinforcing steel) with no dowel bars (Concrete Reinforcing Steel Institute, 2000).
No action is needed	Low severity Surface Deformation (faulting and rocking) with a height of less than 0.125 inch (<0.125”) (Concrete Reinforcing Steel Institute, 2000).
Sealing	Medium severity Shrinkage Cracking (Concrete Reinforcing Steel Institute, 2000). Joint sealant defects (firstly cleaning of the area and of the old seal and then re-sealing) (Pavement Systems, 2012).
Reconstruction of the Slab	High severity Shrinkage cracking (Concrete Reinforcing Steel Institute, 2000).
Mechanical roughening or re-surfacing	If the concrete loses its texture (Pavement Systems, 2012)

Figure 4: Defects (top) of the “Concrete Pavement” asset group and cures (bottom) according to the intensity of the defect: low (L), medium (M), high (H)

“Road Furniture” Asset Type

The second asset type is the road furniture comprising of “Signs”, “Markings”, “Demarcation”, “Drainage” and “Barriers” asset group. For these groups, the possible defect categories are identified which affect the assets and their repair strategy. The majority of the road manuals describe extensively the first asset type (“Pavement”) and its possible defects and repair techniques; they do not refer extensively to the road furniture though. Thus, for the research on the road furniture the UK city council websites were examined as they provide an online service where the citizens can report an issue on the road. Such councils are the Essex Country Council and the Norfolk Council. There are four categories of “Sign” defects: damaged, missing, dirty and faded (Essex Country Council, 2018). For the purposes of this research, all these defects (damaged, missing, dirty, faded) have been merged into one category since they require the same cure technique. The only defect that the road

“Markings” may face is fading. If over thirty per cent of their area is faded then they should be recovered. The “Demarcation” markings need replacement if they are either missing, damaged or not over 90% reflective, (Maintenance and Programme, no date). Soil, tree material or other vegetation material usually block or flood the drainage system, so the suggested maintenance technique is to be cleaned straightaway. In case the drainage system is near a slope, then it is suggested to apply a coarse material on the entire slope or to the bottom of the slope, (Holladay, 2014). The “Barriers” asset type entails the road “barriers”, the “fences” and the “guardrails”. The main defects of this category is to be either missing or destroyed. The maintenance techniques that are used are: replacement or renewal by repainting and cleaning, (UK Highways Agency, 2006). The defects and the cures of the “Road Furniture” asset type will follow as it was analysed above. The above analysis of the “Road Furniture” asset type defects is better represented in the Figure 5.

Figure 5: Defects (top) of the “Road Furniture” asset type and cures (bottom)

“Electronic Furniture” Asset Type

The “Electronic Furniture” asset type comprises of the “Light”, “Electronic Signs”, and “Traffic Signs” asset groups. For each of these groups their plausible defects and corresponding maintenance techniques are analysed and then these defects and repair techniques are grouped. Light inspection entails electrical inspection (lightbulb) and structural inspection (pole of the light) (‘STREET LIGHTING MAINTENANCE , MANAGEMENT PLAN (Including Telematics)’, 2015). The light pole might undergo the same defects as road signs (i.e., damaged, destroyed), hence, this part of the “Light” group will form part of the “Sign” asset group. Many city councils in the UK give road users the chance to report any type of lighting problem (Workingham, 2018). One of the options given is to report either a broken lamp or a lamp that works during the day as well. As soon as the authorities receive the report, they call a technician to repair the lamp. These plausible defects are merged into one category: “Not working properly”. The “Electronic Signs” also face the same issues as they consist of an electronic sign and the structure that supports it. Following the same thought process, The structure is included in the “Sign” group category and the “Sign” in the “Light” category as they may face the same plausible defects. The inspection for the traffic lights is visual: either it is broken or does not work properly (switches on and off in a non-logical way). The maintenance techniques that are usually used are the rearrangement of loops, visual inspection every six months, replacement of the electronic units and electrical testing of the system (Adminmistartion, 2006). Figure 6 shows the previous analysis on the defects and the cures of the “Electronic Furniture” asset type.

Figure 6: Defects (top) of the “Electronic Furniture” asset type and cures (bottom)

Conclusions

The sum-up of this analysis led to the definition of the road assets from the scope of the road inspector, which is analysed in the following figures (Figures 2-6). Through this classification, the inspector who uses computer vision techniques, could potentially reduce the time that spends on the road visual inspection.

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Table A.1: Road assets and sub classes categories (Queensland Manual) (Anon., 2010)

Level 1 Asset Type	Level 2 Asset Group	Level 3: Components that Level 2 implicitly covers in valuation
Roads	• Pavement, • Surfacing, • Street Furniture, • Formation	Not Applicable in this manual
Structures	• Bridges, • Culverts, • Gantries • Jetties, Wharves, Pontoons, • Boat Ramps, • Rock Walls • Channels	
ITS & E	Not Applicable in this level	
Corridors, Ancillary Works, Encroachments, Environment	Not Applicable in this level	
Major Complex Intersection and Exchanges	Not Applicable in this level	

Table A.2: Road assets categories (California Manual) (Indicators, 2016)

Level 1 Asset Type	Level 2 Asset Group	Level 3: Components that Level 2 implicitly covers in valuation
Pavement	Not Applicable in this manual	Not Applicable in this manual
Bridges		
Culverts		
ITS Elements		

Table A.3: Maintenance techniques of “Concrete” Pavement type and their description.

Maintenance Technique	Description
PCC (Portland Cement Concrete) full depth patching	A process that proceeds as follows: extract the flawed material, insert dowel bars and slab replacements, insert a material to bond the patch with the slab material and place the PCC by ensuring that it will not extend the height of the surrounding slab (Jamzad and Assadi, 2009).
Partial depth patches	Similar repair procedure to the full depth patches. Their difference to the full depth patches is that their area is smaller and that the patch area should be extended beyond the damaged area by 75 – 100 mm (3 – 4 inches) (Jamzad and Assadi, 2009).
Crack sealing	Removal of remnants with hot air, followed by sealing (Officials, 1993)
Portland Cement Concrete (PCC) or Hot Mix Asphalt (HMA)	Remove the pavement layer and apply an overlay (either Portland Cement Concrete (PCC) or Hot Mix Asphalt (HMA) (Officials, 1993)
Insertion of dowel bars	The bars that are usually used in transverse joints to help the load transfer) (Concrete Reinforcing Steel Institute, 2000)
Mechanical roughening or re-surfacing	Using Epoxy (Pavement Systems, 2012)

SEMANTIC AND SYNTACTIC INTEROPERABILITY OF BIM AND ASSET MANAGEMENT DATA

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Abstract

Over the recent years, there has been a growing interest in how Building Information Modelling (BIM) can facilitate effective Asset Management (AM). BIM-AM data integration has come with issues related to establishing an effective process to extract, store, and distribute data to ensure interoperability. Several information exchange specifications such as COBie and SPARKie have been developed to enable effective interoperability for better building assets operation and maintenance. Due to asset heterogeneity, the exchange models cannot be generalized and applied to all assets systems. Exchange models need to be developed for particular asset systems based on their functionality and building type. In order to contribute to overcoming the BIM-AM interoperability challenge, this study aims to provide the required semantic and syntactic interoperability aspects for the data exchange of assets that consume energy from the BIM systems to the AM systems during the handover stage.

Introduction

Asset management is a term that measures the capacity and ability of an asset to achieve its objectives (Riso, 2012). An asset could be an item, equipment, space, or any other entity that generates either financial or non-financial value for the organization. Appropriate and reliable asset information, such as asset location, specifications, warranties and maintenance schedules are essential for supporting effective decision-making during asset operation lifecycles (Love et al, 2015). Due to the inadequate interoperability among the information systems utilized in the different stages of the building, excessive time and costs are spent to locate and verify the required information from previous activities for operating and maintaining the building assets (Teicholz, 2013).

Accordingly, AM requires an information system that automatically captures, stores, and integrates the data required to support better decision-making across the diverse array of requirements. An ideal information system that can store and provide the asset data during all phases of the building and can record the changes in conditions of the maintained and operated set of assets is required (Amadi-Echendu et al, 2010; Teicholz, 2013). Building Information Modelling (BIM) has been argued to provide the required information system for solving AM challenges. Despite BIM capabilities and the promises for improving AM practices, the implementation of BIM

in Facilities Management (FM) is generally, and in AM particularly, filled with obstacles (Eadie et al, 2015; Ibrahim et al, 2016). It has been argued that the interoperability challenge is the first key barrier to overcome, as the entire theoretical framework of BIM data being used for FM is predicated on the assumption that data can be exchanged between software programs (Kensek, 2015).

Most of available works concentrated on developing technology driven functions and applications to overcome the syntactic interoperability barrier rather than developing computable information requirements for better semantic interoperability (Cavka et al, 2017). The available syntactic interoperability approaches include using Industry Foundation Classes (IFC) or Construction Operation Building Information Exchange (COBie), and/or proprietary middleware (such as: Ecodocus). Even with these approaches, syntactic interoperability solutions alone cannot ensure that the integration of BIM-AM could achieve the required expected benefits and results. Pärn et al.(2017) critiqued that semantic interoperability is the single most important interoperability challenge to overcome when integrating BIM data with other systems such as AM platforms.

In spite of all of the available studies and the integration promises, there are still gaps to be filled and challenges to be solved between the integration potential and its realization in the asset management fields. Accordingly, this research aims to contribute in filling the interoperability gap by providing the required semantic and syntactic interoperability aspects for the data exchange of assets that consume energy from the BIM systems to the AM systems during the handover stage.

Research Methodology

Due to the heterogeneity of assets, the required information cannot be generalized for all assets (Cavka et al, 2017). However, the required information taxonomy can be developed for assets based on their functionality in certain building types (Farghaly et al, 2018). On the other hand, the need of providing sustainable performance during the building lifecycle has been emphasized. This study focuses on assets that consume energy. Cavka et al. (2017) stated that developing a conceptual framework which identifies the owner requirements and links them with the digital and physical products can improve the AM performance and sustainability in particular.

Figure 1: Research method framework

The considerations and recommendations above provide the foundation for the development of a new Asset Consuming Energy Information Exchange (ACEie) framework (). The framework can still be updated and adapted to cover all of the operable building assets.

The first two steps aim to identify the client requirements and related concepts to the required information in order to fulfill the semantic interoperability aspect. Therefore, qualitative data collection methods such as semi-structure interviews and focus groups would serve as appropriate tools for achieving these aims (Saunders et al, 2011). Five semi-structured interviews and two focus groups with eight experts have been conducted during the first two steps. Semi-structured interviews were conducted with two facility managers, an asset data manager, and two information managers who were involved in the decision to adopt BIM for FM in their companies. The selection criteria of the interviews includes BIM and AM experts in world-class BIM projects and construction organizations, which incorporates BIM-compliance projects throughout the UK. The focus group was conducted with eight experts in the construction and/or operation industry. The proficiency for eligibility to participate in the focus group was determined based on different criteria namely; five years' experience in BIM and/or asset management and mechanical or electrical engineer. The focus group started with high level of involvement of the interviewer, by giving an introduction to the different classifications for the building assets and brief introduction to taxonomy, LD and ontologies. The first question is then enquired, leading to an unstructured discussion about the potential answers. During discussion, the interviewer level of

involvement was low, then moved to high by concluding the discussion and then moving to the next question. Another focus group was conducted with the same participants. The second focus group has been led to evaluate and validate the developed taxonomy and the mapping developed between all the different ontologies for each individual asset that consumes energy during the development of ontologies stage. The interviewer showed the developed mapping between the different standards for each asset and consequently the participants interact to agree/disagree/refine the developed mapping and the attributes properties. The focus group's discussion was whether the abstracted concepts were precise and accurate or not.

ACEie required taxonomy

The paradigm methodology leads to taxonomies with two-way hierarchical relationships between classes and the faceted analysis leads to taxonomies, whose subject matters are classified using multiple perspectives (facets). The characteristics of the tree structure approach are the most suitable for developing the required taxonomy. After the interviews, the preliminary taxonomy based on the literature was modified and updated. Figure 2 is a diagrammatic representation of the proposed taxonomy of the required data for successful implementation of BIM in AM. The taxonomy adopts a two-level tree structure with a top-down development process. The top level is classified into six main branches/classes namely location/space, classifications, specifications, warranty, assets capex, and maintenance. At the second level, sixty subclasses are representing the required BIM data/parameters for AM at the handover stage (Farghaly et al, 2018).

Figure 2: Taxonomy for the required information for assets consuming energy (Farghaly et al, 2018).

ACEie standards ontology

Providing object-oriented cross-domain linking with the required information can provide more efficient and adequate solutions to achieve semantic interoperability between BIM and AM (Kim et al, 2018) as well as the implementation of syntactic interoperability solutions such as Model View Definitions (MVD). The information related to the design and construction stages are managed by several identified standards/vocabularies in the building information models. However, they cannot manage the asset operation and maintenance activities due to the different scopes (Kim et al, 2018).

Different ontological sources/vocabularies from the Architecture, Engineering, Construction and Operation (AECO) domain are selected in the research to achieve the required cross-domain linking, such as NRM (New Rules Measurement) 1, NRM 3, Uniclass2, SFG20, IFC, and finally Revit as a BIM Platform. NRM is a suite of documents issued by the Royal Institution of Chartered Surveyors (RICS) quantity surveying and construction professional group. NRM1 (NRM Order of cost estimating and elemental cost planning) has been published to provide

a standard and guideline on the quantification of building works for cost estimate purposes based on the UK practice, while NRM3 (Order of cost estimating and cost planning for building maintenance works) has been written to provide a standard and guideline for the quantification and description of the maintenance works for cost estimate purposes during all phases of the building. SFG20 provides the benchmark for optimum maintenance, avoiding over or under maintaining of assets and the backbone to building engineering services maintenance industry (*This is an online web-based specification, available at <http://www.sfg20.com> [last viewed 03 April 2019]*). SFG20 is a web-based online application where the different tasks of maintenance can be assigned to project assets. The SFG20 core library offers users more than 400 industry-standard maintenance specifications covering all principal types of heating, cooling and ventilation, installation, plant and electrical services, complete with regular technical updates. Although SFG20 is not specified in PAS 1192, it can be easily determined as it is aligned with NRM3. The authors accessed the SFG20 through a free trial request where the standard is provided in an online tree taxonomy.

Figure 3: An example of the linking between the different AECO vocabularies for building assets.

Once the ontological sources are selected and accessed, focus group is conducted aiming to make visible indicators that have not been previously harvested by the ontological sources and to identify relationships between concepts, such as the interconnections, incoming, and outgoing links between vocabularies/classifications. In the end of the first focus group, the links between the classes of the different classifications were documented. Figure 3 illustrates the link and mapping between the different ontological sources for a specific asset (Boiler). The hierarchical sequence for each standard is represented to reach the class to symbolize an electric boiler. The different relationships are color-coded and depicted in the bottom left of Figure 3.

Once cross-domain mapping is achieved, syntactic and semantic correctness of the developed ontologies and also the mapping between the different ontologies have to be verified. A logical based approach is adapted for syntactic evaluation. The HermiT reasoner was used to validate the consistency with the ontologies used and several other SPARQL queries are executed to observe the credibility of the obtained results. While a feature-based approach is adapted for the semantic evaluation of the developed ontologies. The feature-based approach evaluates the ontologies'

quality by engaging users and expertise.

ACEie MVD

Once the semantic interoperability aspects are covered, it is time to start the development of the MVD. This step aims to develop an MVD that meets the end-user's needs in an implementable format for sending and receiving software applications. For generating an MVD, four different approaches can be adapted; mvdXML, Generalized Model Subset Definition (GMSD), eXtended Process to Product Modelling (xPPM), and Semantic Exchange Module (SEM). Based on the comparative study by Zhang et al. (2015), it emerged that the mvdXML is the most appropriate approach on developing the proposed MVD. The mvdXML is an open standard developed by buildingSMART to define model subsets and validation rule sets. The IFC Documentation Generator (IfcDoc) is a free tool issued by buildingSMART based on MVDXML. IfcDoc reads and writes mvdXML files and also provides a graphical user interface for defining all of the different content within an mvdXML file, such as concepts, concept templates, and model views. This tool auto-generates MVD diagrams, output HTML documentation for model views, and MVD documentation.

The first step to developing an MVD, using the IfcDoc tool, is to define a new MVD in the baseline file of the selected IFC release in the overview description (IFC4 ADD2). The IFC4 Add2 is published on 15th July 2016 as a buildingSMART final standard (www.buildingsmart-tech.org/ifc/IFC4/Add2/html/). The baseline IFC file contains the full IFC schema and a set of reusable MVD concept templates and concept use definitions. A new MVD, called ACEie, is added under the scope. An MVD is assembled using exchange models, entities, concepts, property sets, and properties/attributes (Figure 4).

Figure 4: The main components of MVD

Exchange models/definitions (EMs) indicate a particular subset of information to be exchanged in a particular stage of the building lifecycle. For example, COBie V2.4 consists of 28 EMs and their related exchange requirements. ACEie MVD consists of only four EMs as it only serves the handover stage of existing buildings and their new extensions as predefined in the developed IDM. The four EMs are ACEie_Space/Location, ACEie_Classification, ACEie_Capex&Warranty, and ACEie_Maintenance.

More than 800 entities are included in the IFC4 ADD2 schema. The most abstract and root class for all IFC entities is the IfcRoot. All entities that are subtypes of IfcRoot can be used independently and they are divided into three main subtypes, which form the first level of specialization within the IFC class hierarchy, namely IfcObjectDefinition, IfcPropertyDefinition, and IfcRelationship. The required classes are selected and added to the ACEie exchange model. Although the IFC4 schema has enriched the level of detail of several assets, such as boilers, it still lacks additional classifications for some assets instead of using generic classes (Pinheiro et al,

2018). To overcome this limitation, both air-handling units and fan-cooling units were mapped to IfcAirToAirHeatRecovery and also all of the kitchen assets were mapped to IfcElectricAppliance. Once every entity is identified and added to the model view, the required information from each asset will be established using the IFC concepts.

Concepts represent a use definition for a particular entity with specific rules to be enforced (Chipman et al, 2014). The concepts generally encompass a series of specifications and implementation agreements of IFC data exchanges required for one or more entities, their relationships, and their attributes (Lee et al, 2018). The hierarchy of the building spatial elements required in the EM1 (ACEie_Space/Location EM) is defined using the predefined "Object composition" concept template. The subtype "IfcRelAggregates" is utilized to form the hierarchical structure between the different instances. Another predefined concept template is used to link between the instance and its relevant type using the subtype "IfcRefDefinesByType". IfcRelDefinesByProperties is used to add all the required property sets. Property Sets Definitions (PSD) is explicitly explained as it is used in the development of the proposed MVD.

PSD schema is an XML schema, defined as IfcPropertySet to determine all properties and property sets both inside and outside the IFC specifications. Each property set holds the required non-geometric information for specific applications. BuildingSMART developed the PSD schema to provide capabilities for the stakeholders to add the required information to achieve their purposes. Six property sets have been added to the IfcElectricDomain property sets to represent the required information for the ACEie exchange. The six property sets and their properties are based on the developed taxonomy. Overall, 60 parameters are defined and assigned to the selected objects for the exchange and the type of IfcValue has been selected for each of them separately, based on the attribute measurement. For instance, IfcElectricCurrentMeasure is selected as the primary data type for the "current" attribute, while IfcLabel is selected for all the different location attributes. In addition to the property sets, quantity sets were defined to provide the essential information related to measured attributes, such as asset dimensions.

ACEie Revit Plug-in

After the development of the MVD, it is time for implementing the solution in the software environment and apply it toward different project. The selected platform should have a dedicated building modeling section (Mechanical and Electrical section), supports object extraction, and accommodates interaction with external plug-in object-oriented interfaces. The Revit platform was found to be suitable with rich SDK

documentations and also available to researchers at the subscribing institutions.

In this research, the process of adding, connecting, and extracting the required information from the building information models for the proposed exchange is translated by the developed Revit plug-in. Revit 2019 was selected as it is the latest version released at the time of the research and it also contains several enhancements in the IFC export functions. The developed Revit plug-in consists of three primary add-ins. The first add-in implements the required information - non-graphical information - that is not predefined in the Revit elements. The second add-in function is to fill in some of the information automatically and it consists of three main functions (Figure 5).

Figure 5: Screenshot of the developed Revit plug-in

The first function reads from the linked architecture model, recognizes the room space hosts the asset, and finally fills in all the parameters related to location and spaces as defined in the architecture rooms. The second function numbers the assets of the same type in the same room to easily identify them. The third and last function of the second add-in is filling the classification parameters based on the developed cross-domain linking ontologies. The third and last add-in is developed to ensure the exportation of the properties in the correct property sets as defined in the MVD. In Revit 2019, an advanced IFC export settings tab is added and one of the added functions is the export of property sets. Several options for property sets exportation, such as export IFC common property sets, export base quantities, and export schedules as property sets. During the focus group, it has been noticed that the BIM engineers are not very familiar with IFC property sets and they would prefer

generating all of the requirements in the Revit environment. Therefore, the selected approach for exportation is using the schedules in Revit as property sets. The third add-in automatically generates six schedules named as the property sets defined in the MVD stage with the parameters hosted in each property set.

ACEie Evaluation

The completion of the study requires validation that the BIM model accurately includes the information defined in the data exchange requirements and the MVD. Several checking routines, named validation rules, are performed at this stage to guarantee that the BIM models are generated and operated correctly. In project validation, data validation tools compare between two files; the IFC file of the project (Design Data) and the reference MVD (Constrain Data) (See et al, 2012). The selected project is an extension for an educational institute (Figure 6). The architecture model includes all the different required spaces and spatial requirements such as classrooms, toilets, corridors, and the locker room. The mechanical and electrical model include all the different assets that consume energy and other assets such as sockets, switches, ducts, and mechanical equipment.

Figure 6: BIM model of the extension of the educational institute.

Each rule type was coded and identified in the ACE MVD and added through the IfcDoc tool. The logical expressions in IfcDoc, which includes several composition order of rules were used to develop the five required rule types of the developed MVD. The rule types and logic are:

- Verification of the presence of an attribute.
- Verification of the presence of an element.
- Verification of data accuracy.

- Verification of the cardinality of an element.
- Verification of the presence of property set and its required properties.

The IfcDoc tool validates the selected IFC model against the model view based on the coded and assigned rule types to the pertinent concepts. It provides two output formats for the validation results: the interactive user interface color-coded validation report and the HTML format. The color-coding differentiates the validation outcomes: Pass, Fail, No Instance, and Not Applicable. Entities and attributes that satisfy the concept rules are represented in green, while the invalid ones are represented in red. Moreover, the entities that do not have relations or attributes are not colored.

Conclusions

In spite of the BIM competencies which can facilitate managing and operating building assets effectively, the implementation of BIM in AM still faces several obstacles. One of the main obstacles is achieving interoperability between BIM and AM platforms. Several information exchange specifications such as COBie and SPARKie have been developed to achieve interoperability. However, it has been argued that these information exchange specifications alone are not sufficient as they are generalized for all assets or for specific asset system. This research proposed five aspects to enhance the interoperability between BIM and AM platforms armed with an example for assets that consume energy.

This research contributes to knowledge in two different contexts, which are theoretical and practical. Within the theoretical context, there were two main research outcomes which are related to semantic interoperability. The first outcome/finding was a conceptual taxonomy where the critical information required from BIM models for asset management practice are identified, and workflows and roles and responsibilities to fully integrate these data sets are stated. Moreover, the conceptual taxonomy is polished in the light of the case study evaluation. The second outcome was a linked data where all the different standards and classifications used in the AEC and O&M domains are linked to each other's as ontological sources to enhance the semantic interoperability among BIM and AM systems. The developed process map for the Linked Data development also contributes to the knowledge of managing and operating building assets without the authorization of BIM platforms and with exploiting Linked Data technologies.

On the other hand, within the practical context, an innovative model view definition (MVD) that would improve the integration between BIM data and other asset databases for better asset management decisions was developed. The developed MVD specifies the

appropriate entities required from the IFC schema to maintain and operate the assets in a building which consumes energy. Also, a possible application in a BIM platform to identify and extract the required data based on the proposed taxonomy was developed and demonstrated in a real-world project. The process of adding, connecting, and extracting the required information from the building information models for the proposed exchange is translated by the developed Revit plug-in. The proposed approach to enhance the interoperability challenge between BIM and AM platforms can be adapted for all assets not only the assets that consume energy. Future work includes more case studies of different building types for evaluation of the proposed framework and developed taxonomy, ontologies, and MVD.

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Systems Engineering

FROM RELATIONAL TO TECHNOLOGICAL TRUST: HOW DO THE INTERNET OF THINGS AND BLOCKCHAIN TECHNOLOGY FIT IN?

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Abstract

The construction industry is complex, fragmented and struggles to cope with an intricate and geographically diverse Supply Chain (SC) where sophisticated flows of materials, information and capital take place in a dynamic environment. In this context, building trust among partners is a necessary requirement to deliver a successful project on time and on budget. This paper investigates the main factors that build inter-firm trust in large construction projects and explores the disruptive effect that the Internet of Things (IoT) and Blockchain (BC) could have in this process. The findings are based on an in-depth analysis of the literature and ten one-to-one telephone and face-to-face interviews. The findings contribute to the literature by suggesting that a Blockchain-enabled IoT ecosystem has the potential to generate inter-firm trust at the front-end, during contract development, and throughout the construction phase. Moreover, the data denotes the need for further technological adoption in the construction industry as a means of smoothing the transition from relational trust to technological trust.

Introduction

The Supply Chain (SC) of a large construction project comprises a vast array of players – the client, consultants, designers, main contractor and sub-contractors (Donyavi & Flanagan, 2009). An intricate upstream and downstream flow of materials, information and capital takes place in a dynamic environment. Materials themselves account for 70% of the total cost of civil engineering projects (SiteSense, 2018). This denotes their contribution to project success and hence, the importance to efficiently manage them. Such a complex architecture demands real time control over every operation as well as a transparent network of players that trust each other. In addition, considering the complexity (Papadonikolaki, et al., 2017), fragmentation, and disputes (Zhang, et al., 2016) that characterise the construction industry, trust becomes a crucial ingredient for project success, which should be enabled through a transparent flow of information amongst stakeholders (Brady, 2014).

In practice however, opportunistic behaviour, mistrust and a lack of collaboration and information sharing in

projects may arise. This is particularly relevant to temporary organisations that have a limited time to build trust with a temporary partner. The current theories of inter-firm trust are extensive, yet they tend to take a relational approach to explain the formation and maintenance of trust without considering the impact of disruptive technologies. This approach places trust on a person or organization once they are considered to have the adequate profile-fit to deliver a promise or contract (Day, et al., 2013). The problem arises when a profile-fit is mis-judged due to the relationship between two parties (relational trust) and this implicates a risk for the project.

Departing from this view, this paper investigates how the trust building process may change in construction ecosystems from trusting a person or organization based on their profile-fit (relational trust), towards trusting *their* technology. The evolution of device connectivity through the Internet of Things (IoT) as well as the emergence of distributed ledger technologies like Blockchain (BC), may provide a bridge to this transition. This paper formulates and responds to the following research question:

“To what extent can the IoT and BC technology generate inter-firm trust in large-scale construction projects?”

Background

What is trust?

Trust is a multidisciplinary area of study that has received a lot of attention in psychology, sociology, philosophy and business. From the most prominent definitions of trust, such as “a willingness to be vulnerable” (Mayer, et al., 1995), a “willingness to rely” (McAllister, 1995) or “confident, positive expectations” (Lewicki & McAllister, 1998), we can note the work of (Rousseau, et al., 1998) who defined trust as “a psychological state comprising the intention to accept vulnerability based upon positive expectations of the intentions or behavior of another”. Essentially, trust is based on a feeling of vulnerability, which is assumed by the trustor, based on the expectation or confidence on the trustee’s actions. Trust has also been observed from multiple levels: interpersonal, inter-firm and intra-firm (Liu, 2015). In

the construction industry, inter-firm trust cannot exist without a level of interpersonal trust amongst the main players (Lau & Rowlinson, 2009). Interpersonal trust refers to the extent that an individual will trust another, based on the perception that they will not act opportunistically. On the other hand, inter-firm trust describes a situation where the members of an organization hold a collective perception of trust towards another entity (Gulati & Nickerson, 2008). Consequently, the members of the contracting party must build trust at an interpersonal level with their client before inter-organizational trust can be realized.

How does inter-firm trust emerge?

Scholar have analyzed trust in the context of different cultures (Zaheer & Zaheer, 2006), as a dynamic process (Lewicki, et al., 2006), as a process of continuous learning or as a network of relationships (Inkpen & Curral, 2004). In the context of construction projects, inter-firm trust co-exists with interpersonal trust (Lau & Rowlinson, 2009) and can be stimulated through a working history (Laan, et al., 2012). A much-needed synthesis of the literature was proposed by (Liu, 2015), who summarized the most notorious research on inter-firm trust in three categories: *competence*, *reliability* and *goodwill*. Table 1 below illustrates these, as well as the findings of Laan (2012).

Table 1: Main factors that build inter-firm trust

Historical trust	Working history
Competence	Skills & abilities
	Reputation & brand
	Technical capabilities
Reliability	Contract
	Mutual interest
Goodwill	Benevolence
	Integrity

In the context of the construction industry, a contractor must depict a high level of competence, reliability and goodwill for their client to trust them. Their competences are built through cognitive factors like skills, reputation, or technical capabilities. In comparison, their reliability is partially based on cognitive and institutional factors like contractual safeguards and mutual interests. Finally, the goodwill of a party is based on affective factors such as benevolence or integrity. The work of Liu (2015) emphasizes the importance of building strong tangible competences at the front-end, reliable contracts during the planning phase and developing inter-firm goodwill throughout the construction phase, in order to maintain

a healthy communication and avoid any information asymmetries along the SC.

The IoT: an end-to-end SC traceability ecosystem

The IoT is a cyber-physical system that represents the evolution of device connectivity and denotes the convergence of the physical and the digital World. This is energized by the evolution of sensing technologies, Wireless Sensor Networks (WSN), middleware and cloud computing (Ben-Daya, et al., 2017). Scholars describe it as the “extension of the Internet and the Web into the physical realm” (Miorandi, et al., 2012) or “a decentralized system to allow cooperation amongst physical digital objects augmented with sensing/actuating, processing, storing, and networking capabilities” (Fortino & Trunfio, 2014). Essentially, the IoT is “a network of physical objects that are digitally connected to sense, monitor and interact within and between a company and its SC” (Ben-Daya, et al., 2017).

In the context of a complex and dynamic environment such as the construction industry, the IoT provides a new generation of IT capabilities. Physical “things” communicate their properties in an automated manner, “providing new levels of SC visibility, agility and adaptability” (Childe, 2018). This provides a method of managing the complex flow of materials, information and capital that is ingrained in construction SC’s (O’Brien, 2008). For instance, considering the correlation between the cost of materials and a project’s total expenses, their quality and condition should always be monitored. To do so, IoT sensors can be deployed in batches of materials (e.g. rock, wood, or metal) to track their real-time geolocation, temperature, humidity, pH or stress, providing an end-to-end monitoring of the SC (Heiskanen, 2017). Such an IoT system could deliver the following improvements which are summarized in Figure 1 below:

1. An automated data transmission system: collects and sends real-time data from Radio Frequency Identification (RFID) tags to the chosen database.
2. Big Data analytics: the data gathered is cleaned, analyzed, and organized to enable interpretation.
3. An automated quality management system: the IoT-enabled RFID sensors act as “quality guarantors” as well as predicting a material’s life cycle when combined with Big Data Analytics.
4. A dispute resolution mechanism: if a damaged material arrives on-site, it can be tracked back to the point where it damaged (e.g. between tier 3 and tier 4 its humidity levels increased by 90%) hence, it is possible to allocate responsibility and liability to a specific party (e.g. tier 3).
5. Prevents information asymmetries along the SC,

providing faster responses and decision-making: all authorized stakeholders are looking at the same pieces of information.

Figure 1: IoT ecosystem in construction projects

How secure is an IoT ecosystem?

Several scholars and Information Technology (IT) research organizations have addressed the importance of data privacy and security breaches in this arena. They argue that the IoT “lacks a central control”, suffers from device heterogeneity and is vulnerable to cyber-attacks (Dorri, et al., 2016). This is particularly relevant for construction projects that demand a high level of connectivity for numerous heterogeneous IoT devices (Khajenasiria, et al., 2017). A survey conducted by the Global Digital Infrastructure Alliance identified four underlying security problems for the IoT: vulnerable network, weak application, limited authentication capabilities and unsafe endpoints (BCOT, 2017). Therefore, scholars and industry experts are increasingly looking at BC as the way to solve these vulnerabilities by securing an IoT ecosystem under a trusted, immutable, distributed ledger which results in an “Internet of Trusted Things” (Groopman & Owyang, 2018).

Blockchain (BC): securing an IoT ecosystem on a distributed ledger

Distributed ledger technologies (DLT) are revolutionizing the process of storing data and the way people, firms and governments transact (Ray, 2018). Their distributed architecture, replication method and consensus mechanisms, eliminates the need to have a central authority that governs and maintains the ledger (Mills, et al., 2016). BC is an example of a technology that has harnessed the potential of DLT’s while innovating upon them. On the one hand, it is distributed by nature and managed across a peer-to-peer network of participants that do not need to rely on a central authority. On the other hand, it has a unique structure whereby the data is stored in “blocks” that are secured and chained to each other using cryptography. Each block contains specific data regarding a transaction (monetary or non-monetary) which is used to generate a cryptographic key known

as the “hash”. This is used to chain the blocks together, and whenever a new block is added to the chain, it must contain the hash of its predecessor. This makes it essentially impossible to alter the data inside the blocks, making this technology immutable, tamper-proof and secure (Swan, 2015).

A BC can be built as a public distributed ledger or alternatively, as a private one. In both cases, the ledger has a distributed architecture that is tamper-proof, immutable and secure. Notwithstanding, they differ in who can participate, who maintains the ledger and how to reach “consensus” (the procedure to add a new block to the chain). Public BC’s use a completely decentralized management system whereby anyone has the authority to participate and become a node, either as a user (e.g. entering in a transaction) or as a “miner” (verifying transactions). In comparison, a private BC uses a semi-centralized structure to govern the distributed ledger, where participants need an invitation to take part in the BC and only those that are authorized can access the data inside the blocks, improving the privacy of participants (Chen, 2017). Public BC’s are maintained by any node that decides to mine while private BC’s by those that become miners by invitation. In a public BC, “miners” must solve complicated mathematical puzzles through a “proof-of work” (PoW) or “proof of stake” (PoS) algorithm and once “consensus” is reached, the block can be added to the chain, containing the hash of its predecessor. In comparison, the “consensus” protocols in a private BC are not usually based on the PoW or PoS algorithm for three main reasons. Firstly, this extra layer of security is unnecessary when the profile of participant is not encrypted. Secondly, the PoW reduces throughput (transactions per second) in private Blockchains. Finally, the energy cost for mining transactions is too high at low scales. In this case, a trusted team is typically allocated to manage the consensus process, which in a construction project it might be the main project manager, the architect, the engineer or the client itself.

A private BC may complement an IoT-enabled SC in the following ways (Figure 2 below illustrates this):

1. A distributed architecture: improves data security.
2. Immutability: the IoT data in BC is tamper-proof.
3. Transparency: all the data is transparent to authorized participants, reducing the room for opportunistic behavior.
4. Dispute resolution mechanism: reinforcing the traceability capabilities of the IoT and using Smart Contracts
5. Stakeholder involvement: the client is able to track the development of materials through the BC hence, it acts as a real-time traceability platform.

Together, these technologies deliver the following benefits: (a) Faster responses & decision-making, (b) Automated data transmission system, (c) Automated Quality Management, (d) SC traceability, (e) Security, (f) Dispute resolution mechanism, (g) Transparency, and (h) Stakeholder involvement.

Figure 2: How a BC complements an IoT ecosystem

The IoT may serve to improve transparency through SC visibility and monitoring, while BC technology is able to secure this ecosystem and provide a real time traceability platform. This allows to involve all stakeholders while providing an accurate quality management system and a dispute resolution mechanism. Such a system avoids the implicit risk of trusting a person or organization from a relational standpoint, where the actual level of competences, reliability or goodwill of a party might be obscured. Instead, trusting a technology might be more secure and less ambiguous than trusting people, hence helping to eliminate the “feeling of vulnerability” that Rousseau (1998) considers imperative in the trust building process of an individual.

Research gap

The process of building inter-firm trust in a construction scenario is complex, dynamic, and overlaps with the process of building interpersonal trust. Inter-firm trust theories have provided substantial evidence of the factors that stimulate trust in the construction industry. Notwithstanding, this paper aims to fill a gap in the research of Liu (2015), given the lack of consideration given to potential that disruptive technologies have in the process of building inter-firm trust. The IoT and BC fit the description of “disruptive technology” as proposed by Christensen (1995), since they have initially underperformed compared to mainstream solutions like ERP systems, given their lack of scalability, high cost and clients resistance to change. Notwithstanding, the same multinationals that offer these ERP systems (e.g.

ORACLE or SAP), have integrated some of their capabilities, to enhance their current ERP offerings, a transition known as “competence enhancing disruptive technologies” (Daneels, 2004). Eventually however, disruptive technologies can destroy the competences of those unable to commit enough resources to fuel their transition, leading to a process of creative-destruction (Schumpeter, 1942). This process energizes the transition from one sociotechnical constellation where relationships were the heart of building trust in the construction industry, towards a refined sociotechnical constellation where disruptive technologies play a role that must be acknowledged.

Methodology

This paper investigates the process of building trust with a client from a contractor’s viewpoint and how disruptive technologies can contribute to this process. Specifically, we aim to answer the following research question:

“To what extent can the IoT and BC technology generate inter-firm trust in large-scale construction projects?”

To do so, a combination of secondary and primary research has been adopted. The secondary research provides the foundation for analysis by examining previous research on inter-firm trust, IoT and BC. This serves as a lens to direct the primary research which is based on ten one-to-one, non-standardized and semi-structured telephone and face-to-face in-depth interviews. Open-ended questions allowed the interviewees to lead the discussion, delivering valuable and unexpected findings. In addition, the interviews opened with some questions regarding the size of the firm in question, and a description of a large construction project that the interviewees had dealt with. This improves the reliability and validity of responses and allows to contextualize the findings for large construction projects. Specifically, the choice has been to interview a wide spectrum of professionals working for contractors or clients involved in large construction projects, as well as experts in IoT and BC. The interviewees (IDs) that were selected from the contracting side includes a project manager, a project director, an operation director, and a Chief Financial Officer (CFO). Their expertise lies on a different phase of the projects (bidding, design, or construction) to cover the entire project lifecycle. In the client side, we interviewed a client, a consultant, an architect and an engineer who is also a Chief Executive Officer (CEO). These oversee the selection of the main contractor and the design of the project itself. In terms of technology experts, we have interviewed members of BC consortiums, researchers, a Chief Technology Officer (CTO), and the leader of the biggest IoT ecosystem in France (Objenious). Table 2 below displays the profile and experience of the interviewees and identifies them using the term (ID). It is arranged by colors to divide them in three categories; technology (light shade),

client (medium shade) and contractor (dark shade) respectively. Interviewee (4) plays a double role in the interview since it is a technology expert and a member of the client team. Similarly, interviewee (7) is a project director as well as an investor (client).

Table 2: Interviewee's identification (ID) and profiles

ID	Profile	Experience
1	Head of partnerships and indirect channels at Objenious	IoT Ecosystem in France
2	General director of notaries; Economics & technology expert; Blockchain researcher	BC security researcher
3	CTO at Beikei; Co-founder at NotaBlock; Stanford Postgraduate	BC start-up in the legal spectrum
4	Senior Project Manager at Mace bidding phase; Construction Blockchain Consortium (CBC) member	10+ years of experience in construction bidding
5	CEO and technical director of TBI focused on engineering design and construction	30+ years of experience in engineering
6	Architect and project director at Metalocus	20+ years of experience in architecture
7	Project Director and investor at Cobra Group focused on the construction phase	15+ years of experience in EPC projects
8	Commercial Operations Director at Cobra Group	35+ years of experience in EPC projects
9	Project Manager focused on the tendering phase at Vinci	4+ years of experience in tendering
10	CFO of Bouygues Construction	35+ years in project finance

Data collection and findings

According to Lau and Rowlinson (2009), the competences of a contractor – skills & abilities, reputation & brand, and professional capabilities are important contributors to inter-firm trust at an early stage in a project. These cognitive factors are important when selecting a partner at the front-end. Having experience in large construction projects was found to be crucial. According to interviewee (10) – “trust is most probably coming from the historical record of the company, and the fact that we have got

significant similar projects already built”. Moreover, from the contracting side, interviewee (7) and (8) consider that having good references is key to build trust during the bidding phase since they portray the competences that a company holds. From the client side, interviewees (4) and (5) agree that references are important, and as interviewee (5) described – “I always say you need references, because that means that other companies made this selection before”. Moreover, interviewees (5), (6), (7), (8), (9) agree that innovation is another winning factor during bidding, especially if the project is technological – “innovation is critical” (ID-7). Having a working history with a client was found to improve the chances to be invited to bid. However, as interviewee (6) explained: “If you had a previous experience, you are more likely to be invited but once invited, other factors like technical capacity or innovation play a bigger role in their decision”. Interestingly, interviewee (4) added that: “I tend to challenge every contractor that I’ve worked with more, to be more collaborative that they were before” and that “I may be harder on them”.

An important part of the reliability of a contractor is assessed during the contract development, in terms of its “consistency, the clarification of responsibility, duration and mutual interests of contract” (Liu, 2015). Given the fact that contracts for large construction projects are characterized by being based on incomplete information (Walker & Pryke, 2011), interviewee (5) argues that “with the private client, contracts need to be more flexible and adaptable to all changes, so in some way this demands to have a continuous contact with the client”. All interviewees (100%) agree that conflicts tend to be expensive, and some argue that negotiation or mediation (ID-4, 7, 8) are good strategies to avoid expensive litigation. Contracts must hence include a dispute resolution mechanism to handle litigation or conflict, add reliability, and increase the client’s trustworthiness.

The reliability that a contractor builds through the contract development evolves during the construction phase in multiple ways. Firstly, through the degree that general contractual requirements have been met (100% of the interviewees considered this crucial). According to interviewee (9): “the client needs to be sure that all the requirements that we have signed in our contract are being delivered in accordance with the contract”. Secondly, by maintaining the quality standards that were stipulated in the contract, where all the contractors interviewed (100%) view it as a necessary thing to build reliability and earn the trust of the client. Thirdly, through goodwill, being the positive intentions and relationship with another party. This is an essential element for inter-firm trust to evolve beyond the bidding and contractual phases and

is highly influenced by:

(a) *The degree of information shared.*

Contractors consider that communicating and sharing information with their clients is at the heart of building trust beyond contract development. Interviewee (6) holds that *“during the construction phase, the key to generate trust is the information”* and interviewee (10) believes that *“trust in construction comes from human communication and assurance of good information with regards to the progress”*. During the construction phase, they regard information as a fundamental factor to generate trust. Similarly, clients view this information as an asset to improve decision-making. Notwithstanding, as interviewee (7) clarified: *“I don’t need just data, I need conclusions based on this information, and this is the key point”*.

(b) *The collaboration demonstrated.*

To improve trust and maintain a smooth flow of information with the client, interviewee (8) and (9) stressed the importance of integrating their SC. For interviewee (9), *“a project necessarily needs to be built on trust between the partners, otherwise it cannot go any further.”* They claim that clients value a private firm that is doing well with their partners, since having many stakeholders that do not work collaboratively can lead to mistrust.

(c) *The involvement of the parties.*

The client’s design and engineering team considers important to implicate the client with the main stakeholders involved in the project. As interviewee (5) explained: *“we always present to the client the main people in charge of the different areas in the project to build this trust”*. This way, they can generate interpersonal trust to enable inter-firm trust to flourish as proposed by Lau & Rowlinson (2009). In addition, involving the client by maintaining them updated with the development of the project is crucial. Today, this tends to be done through a combination of progress reports (weekly, monthly or quarterly), meetings, online platforms or BIM.

How can the IoT and BC generate inter-firm trust?

In terms of its applications, the sensors can be used to track the geolocation, temperature or humidity of materials. Interviewee (1) claims they can optimize the route of trucks to *“avoid making traffic jams”*, perform *“predictive maintenance of tools”*, *“monitor the worksite”*, *“monitor the employees themselves”*, *“provide safety on-site”*, or *“saving energy during the building process”*. Additionally, the information is secured and encrypted, and the client can access it in

real time using an online platform. Furthermore, *“the data is made very understandable”* (through analytics), so the client can track the geolocation and properties of everything without a technical background. Interviewee (1) emphasized that *“trust is the good aspect of IoT because the data through IoT couldn’t lie”*.

During the bidding phase, interviewee (1) claims that *“the IoT is the answer to differentiation through innovation”* and, *“it could help to win the projects”*. In terms of its application as a dispute resolution mechanism, *“as data does not lie, it will certainly help to eradicate any conflict on the project”*. Moreover, the IoT was found to act as a quality management tool, while saving time and increasing productivity on the job-site. As interviewee (1) explained – *“we built the platform for that”*. The integration of a fully functional IoT ecosystem can take between 9-15 months if the client’s familiarity with the technology is high, otherwise it can extend more than 15 months and its price can be *“as low as 50 000 euros to more than 1 million euros”*. Interviewee (4) reinforced these views adding that: *“you can prevent the amount of time wasted just looking for things and it increases productivity on the job-site”*.

According to interviewee (4) *“BC itself is an immutable distributed ledger that tracks all of the different steps and verifies and approves the processes”*. In addition, *“it can help to solve conflicts because it can “improve auditability, therefore providing much more information to do dispute resolution”*. In the context of a construction SC, interviewee (3) claims that *“blockchain provides us with an opportunity to monitor the history of all these components and to have easier access to this information”*. He also assures that – *“this way it’s easier to hold someone accountable for the failure of a project or a specific component”*. In addition, interviewee (2) holds that *“Blockchain is a very useful technology because it’s able to give us security about the data that has been recorded in any kind of technological application”*. In terms of cost effectiveness, interviewee (3) argues that private BC’s are cheaper to run and *“it’s easier to maintain, that’s why most enterprises use it as the solution instead of using a public Blockchain”*. Moreover interviewee (2) argues that with the “proof of work” algorithm, energy costs are high because a lot of computation power is needed. Notwithstanding he argues that *“you achieve the same result if you use a proof of stake”* and *“you only need a very simple personal computer and with that is enough for each miner”*. In addition, interviewee (4) added that *“you can use a private BC”* and emphasized the importance of using that information after, in order to learn from it – *“You*

know, how owners can use this information for its further maintenance and operation schedule?”.

Discussion and analysis

At the front-end: trust evaluation

Several studies have claimed that having a working history with a client has an influence on inter-firm trust and increases the chances of being selected for a project – these claims were confirmed by Laan, et al. (2012). Our findings suggest a similar pattern, as the members of the contracting party that were interviewed (ID-8, 9, 10) agreed that having worked with a client in the past is helpful to get invited to a bidding process however, once invited, other factors like competences, price and innovation play a role. Interestingly, the existence of a working history may create a challenge for the contractor when the client's team decides to further improve their work standards through intensive investigations (ID-4).

The process of building trust with a client starts at the front-end, where the accumulated professional experience, references and reputation of contractors is crucial to win a bid for a large construction project. These are defined as competences by Liu (2015) and they englobe a wide spectrum of features such as skills, abilities, experiences, qualifications, reputation or brand value. These constitute the cognitive factors affecting the perceived trustworthiness of the contractor in the eyes of the client and are portrayed through their professional skills and references. Having strong competences conveys a feeling of security and confidence that leads to a positive evaluation of the trustworthiness of a contractor at the front-end (Laan, et al., 2012). Consequently, this increases their likelihood of being awarded a project.

In the current digital age, the findings suggest that it is increasingly important for contractors to acquire innovative technologies that secure and guarantee a high level of competences. In this context, the IoT was found to provide this level of innovativeness deriving in a method of differentiation in the bidding stage (ID-1). This technology provides the client with a new level of SC visibility while supporting the integration of a contractor's SC which improves a client's reliability. In addition, BC professionals (ID-2, 3) consider that a private BC can be used to improve the security and transparency of an IoT ecosystem.

At the front-end of a project we can conclude that the main factors affecting the level of trust with a client are the competences of a contractor. According to Liu (2015), these are their professional experience, skills, abilities and reputation, with no consideration of disruptive technologies. This paper fills this gap and suggests that technological capabilities arising from

disruptive technologies such as the IoT and BC also enhance the competences of a contractor. In turn, they become a helpful criterion during the bidding phase.

Contract development phase: trust development

During the contract development, certain cognitive and affective factors come into play, and the development of trust begins, based on the perceived reliability of the contractor. A contract assigns risks and responsibilities to the parties involved, however, these are based on incomplete information and are subject to change throughout the project (Walker & Pryke, 2011). Flexible and open contracts were found to be essential, given the uncertain nature of the industry and the inherent complexity of large construction projects (Papadonikolaki, et al., 2017). Moreover, given that disputes are common in the construction industry (Zhang, et al., 2016), and since contracts may not cover future hidden risks, having a powerful dispute resolution mechanism between both parties is a crucial asset. The findings suggest that it adds reliability to a contractor, and trust to a client. This is especially important to avoid entering into expensive litigation, where the findings suggest that both the contractor and the client team prefer to solve them through negotiation or mediation (ID-4, 7, 8).

This paper agrees with the work of Childe (2018) and Ben-Daya et al. (2017) on how the IoT improves SC visibility, agility and adaptability. In addition, it proposes that the capabilities of the IoT can also serve as a new way of resolving conflicts related to material quality management, on-site worker performance or variable cost handling (ID-1). The data can be gathered wherever a sensor is integrated (e.g. materials, trucks, people or tools). It can be argued that this data is vulnerable to cyber-attacks and is not tamper-proof (BCOT, 2017). Notwithstanding, findings suggest that BC may serve as a method of avoiding this whilst improving auditability, therefore *“providing much more information in order to do dispute resolution”* (ID-4). As such, being able to track these variables along the SC, applying data analytics and finally safely storing them in a private BC, allows both parties to precisely allocate responsibility for: (i) any damaged materials or unexpected circumstance (e.g. lost materials), (ii) a lack of on-site performance (e.g. workers effort analysis), or (iii) a sudden increase in costs (e.g. energy bills).

During the construction phase: trust evolution

During the construction phase, the trust that has been developed at the front-end and during contract development evolves in different directions depending on the performance of the contractor (Liu, 2015). This paper suggests that performance is measured by the degree that contractual requirements are being met, the

level of quality standards being offered, and the level of goodwill demonstrated. The competences of a contractor deliver a specific standard of quality and a degree of compliance with contractual requirements, both being considered by all interviewees as crucial elements for inter-firm trust to evolve. To keep up with contractual requirements, the contractors maintained their clients informed of the development of the project while keeping up with Key Performance Indicators (KPI). In this sense, the capabilities of the IoT and BC, in terms of traceability, monitoring of quality properties, and security of data, were found to act as quality guarantors. This allows to monitor what contractual requirements have been met, and what level of quality standards has been delivered. In terms of goodwill, this is determined by the level of information shared, collaboration demonstrated and involvement of the parties.

Sharing information is becoming increasingly important for contractors since efficient communication system are increasingly valued by clients (Papadonikolaki & Wamelink, 2017). All the contractors interviewed used a combination of weekly, monthly or quarterly reports, BIM or online platforms to keep their clients informed of the development of the project. From the client's point of view, the information being delivered must be understandable and useful for decision-making, not just raw data (ID-7). As such, the data gathered from the IoT sensors is cleaned, organized, secured through a private BC and presented to the client through a user-friendly interface where no technical knowledge is needed. This enables a client to efficiently monitor a project online, providing a new source of sharing information and an efficient method of portraying a contractor's competences, reliability and goodwill, all under one trusted platform. In addition, this also provides the opportunity to anticipate any changes in transportation times, delays or quality variations that have important implications for the project time and cost, which ultimately affects the client's perceived trustworthiness of the contractor.

In terms of collaboration and involvement, it was found that integrating a SC is an important contributor to inter-firm trust. By maintaining a smooth flow of information and a healthy collaboration between partners, contractors can avoid information asymmetries while improving performance, which ultimately leads to a perception of reliability for the client. To do so, the contractors either shared a database with their partners, e.g. access to a web-based platform, where the client had limited access, or more traditional electronic document management systems, e.g. google drive, or more sophisticated software's like BIM. This allowed the partners to share information,

collaborate, and then involve the client through progress reports. Notwithstanding, the client was not offered the possibility of tracking the development of the project in real time and they had to wait for these progress reports to be written. The IoT allows to improve collaboration between partners by allowing sensors to communicate to different tiers in the SC simultaneously, as well as keeping all the information under the same database (BC). This means that every partner is looking at the same information and better decision-making can be enacted. From the client's side, an online platform where they can track anything related to their project in real time and without technical knowledge is a method of involving them and was found to contribute to the evolvement of trust.

Conclusions and suggestions

This paper has investigated the main factors that contribute to the evaluation, development and evolution of inter-firm trust at the front-end, during contract development, and throughout the construction phase of large construction projects. It offers an empirical investigation of the extent to which these factors can be achieved using the IoT and BC, tackling its main research question and contributing to the work of Liu (2015) in the following ways:

1. At the front-end, the competences of a contractor are built through their professional experience (skills and project experience), their technological capabilities (fostered by disruptive technologies), and their reputation (portrayed through references), all having an influence on the likelihood of being awarded a project. Having a working history improves the chances of being invited to bid without giving a guarantee of being selected.
2. During contract development, the main factors affecting trust lie in the degree of openness and flexibility of the contract, and the degree to which it includes a robust dispute resolution mechanism that avoids expensive litigation.
3. During the construction phase, the main factors affecting inter-firm trust are the degree that contractual requirements are being met, the level of quality standards being offered, and the level of goodwill demonstrated (in terms of information shared, collaboration demonstrated and involvement of the parties).

These findings were complemented with the unveiled potential that can be derived from the IoT and BC and how it may contribute to the development of inter-firm trust, hence answering the main research question of this study. While the IoT can sense an environment and collect data from it in an automated manner, a private BC can secure this ecosystem using a

distributed architecture secured through cryptography. Together, a Blockchain-enabled IoT ecosystem offers an automated data transmission system that allows efficient quality management, dispute resolution, SC traceability, transparency, security, reduction of information asymmetries, stakeholder involvement, faster responses and efficient decision-making. These attributes were found to promote a client's reliance and trust towards a contractor. Moreover, the technology provides a method of monitoring the development of large construction projects from end-to-end. This derives in the next generation of SC visibility, auditability, transparency, and a method of sharing information, collaborating with partners and involving the client.

During the lifecycle of a project, the IoT and BC was found to have the potential to contribute to inter-firm trust in the following ways:

1. At the front end, they stimulate the formation of trust by enhancing the competences of a contractor from different angles. Firstly, by enhancing their skills and capabilities. Secondly, by enhancing their technological capabilities and finally, by improving their reputation.
2. During contract development, they provide a new method for dispute resolution by keeping a detailed, digital and immutable record of a project so both parties avoid expensive litigation. This was found to improve the reliability of a client while stimulating the development of trust.
3. During the construction phase, this ecosystem delivers value through a digital platform that enables information to be shared in a transparent, secure and immutable manner. In turn, the client benefits from an integrated SC where contractual requirements and quality standards can be accurately monitored. This enhances the perceived goodwill of a contractor.

As a final remark, we cannot neglect that these are still novel technologies that need some time to flourish so that their full potential can be embraced at an industry level. Nevertheless, in this dynamic environment, it is imperative for construction firms to embrace this transition by updating their technological capabilities and while fostering their supply chain relations.

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SYSTEMS-THEORETIC PROCESS ANALYSIS (STPA) IN BUILDING ENERGY RISK MANAGEMENT

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Abstract

As building energy management becomes a complicated process, traditional risk analysis is not adequate to address the management needs and advanced complex modelling techniques are required to handle the multi-dimensional synthesis of risks in the electricity systems. STPA (System-Theoretic Process Analysis) is a new hazard analysis technique using concepts of system and control theory. In this paper, the development of a risk management structure in the field of building energy management is presented. The hazard analysis process based on SafetyHAT information tool is applied for building operation 'accident' prevention, by illustrating the usage of the proposed tool. For this purpose, a case study considering a holistic energy management system in the tertiary building sector is examined.

Introduction

Risk management in the energy sector tends to become indispensable in energy applications nowadays. The inclusion of additional variables into the energy ecosystem makes it imperative to consider a reliable risk management framework. The aim of this study is to develop a general risk management methodology to the energy environment as a holistic approach to tackle risks associated with building energy management.

Within the scope of the study, potential "accidents" are analysed in a building energy ecosystem. An accident is defined as an undesired and unplanned event that results in a loss (including loss of human life or injury, property damage, environmental pollution, and so on) (Leveson, 2004). There are several available research methods in the bibliography, each one being distinguished by its own features and tools and applied in different fields. A typical model classification, considering also their evolution in time, results into three major groups, namely Linear or Sequential Models, Epidemiological Models and Systemic Models (Wienen et al. 2017).

On the way to define a fully-fledged methodology for modelling risks & hazards in a dynamic system, research shows that Traditional Hazard Analysis Methods work well for losses caused by failures in simple systems but are limited in their capability to

explain accident causation in the more complex systems. They cannot handle with:

- Component interaction accidents
- Systemic factors (affecting all components and barriers)
- Software and software requirements errors
- System design errors
- Indirect or non-linear interactions and complexity
- The application of risk management methodologies in the building energy sector is limited and incomplete.

Towards an approach for complex systems safe operation, system theory basics are defined. According to system theory the system is treated as a whole, not as the sum of its parts. Also, relations and interactions among system components are considered and a primary concern is emergent properties, which are properties that are not in the summation of the individual components but "emerge" when the components interact, considering overall safety as an emergent property. In this direction, the relatively new Leveson's Systems-Theoretic Accident Model and Processes (STAMP) and Systems Theoretic Process Analysis (STPA) model, endeavor to model the dynamics of complex sociotechnical systems.

From STAMP to STPA

Systems-Theoretic Accident Model and Processes

Systems-Theoretic Accident Model and Processes (STAMP) is a relatively new methodological risk management framework which is considered in this study. The STAMP model (Leveson, 2002, 2004 & 2011) gives emphasis to the security restrictions and considers an accident in a complex system not just as the case of failure of some individual system component but rather the result of either an external factor or a malfunction within the system which has not been effectively addressed by the control system (Leveson, 2011). The model differentiates from the traditional approach in considering an accident as a sequence of events and as the result of insufficient control and ineffective application of constraints on the development, design and operation of the system (Ouyang et al., 2010). The new accident model is based on system and control theory rather than

reliability theory and safety is viewed as a control problem rather than a component reliability problem. A hierarchical safety control structure is used in STAMP to represent the system and control loops in it, showing how constraints are enforced. A typical control loop is presented in Figure 1.

Instead of addressing accidents as the results of event-chain, they are considered to result from a lack of constraints on behaviour at each level of a socio-technical system. The initial system design needs to impose appropriate behavioural constraints to ensure safe operation.

Systems Theoretic Process Analysis

System-Theoretic Process Analysis (STPA) is a hazard analysis method based on the STAMP accident model. STPA is based on system control theory and not on reliability theory established in most existing risk analysis techniques. The basic principles and characteristics of STPA are (Leveson, 2013; Friedberg et al., 2017; Horney, 2017):

- The best way to detect accident chances in complex systems is to omit causal factors that are not stochastic or for which no information is available. Probabilistic analysis results may not accurately reflect the actual risks and can be riskily misleading.
- Unlike traditional risk analysis techniques, STPA is stronger in identifying risk causes and hazardous scenarios, especially those related to system design and human behaviour.
- Because STPA is a top-down approach, system security engineering can be used early in the system development process to create high-level security requirements and constraints. If risk analysis is applied promptly and in accordance with planning decisions, the number and the cost of operating failures become negligible.
- STPA, supporting hierarchical safety control structures, can be used for both technical design and organizational planning.

STPA process can be divided into four phases with interconnected activities and can be considered as a repetitive process constantly backed up as the system design evolves. The individual procedures are:

1. Determination of the base system (system foundation).
2. Identification of potential Unsafe Control Actions (UCAs).
3. Development of constraints and limitations based on UCAs.
4. Determination of Causal Factors that may lead to UCAs.

STPA can be applied to any emergent system property in the system engineering and product lifecycle, not just safety. Also STPA system safety analysis can be integrated into the entire system engineering process resulting in a significant decrease in the cost of engineering for safety as well as in effectiveness and fewer losses. It can also reduce rework, which reduces cost and schedule. Figure 2 shows a simplified version of the standard system engineering V-model. This figure is used to illustrate how to integrate STPA into the standard system engineering process. The potential roles for STPA are shown in red. STPA can be used throughout the standard system engineering process, starting in the earliest concept development stage and contribute to all the activities in system engineering.

Information tool for the STPA methodology

In this section, an information tool is presented which models and records the STPA activities in a standardized way. There are various software tools that support risk analysis based on the STPA model, e.g., A - STPA (Krauss et al., 2015), XSTAMPP (Abdulkhaleq & Wagner, 2015) and SAHRA (www.sahra.ch).

In the present study, the SafetyHAT modelling tool, developed by the US National Transportation Systems Center (SafetyHAT User Guide, Becker & Van Eikema Hommes, 2014) is applied due to its simplicity and maturity in modelling and mapping the risk management diagrams as defined in the STPA methodology. The basic features for the SafetyHAT tool are the following:

- The SafetyHAT directs analysts based on preparatory and analytical steps of STPA to provide an improved data input process, standardize information input to the system and adapt to multiple application fields.
- The SafetyHAT exploits the dynamics of a relational database for organizing and managing large amounts of data. It can support storage of big analysis data (a control system can generate more than 10,000 entries) and enhance data integrity while modifying or deleting data.
- SafetyHAT can facilitate the documentation of risk analysis through detailed presentation of STPA analysis results, documented final results and data sharing and reuse.
- System analysis capability can be extended based on previous models and analysis results.

Figure 1: Typical control loop

Figure 2: STPA and System Engineering Process

Although SafetyHAT tool supports STPA methodology, it presents two main differences in the standardized methodology:

1. While STPA methodology consists of two preparatory and two analysis steps, SafetyHAT defines an eight-stage structure.
2. SafetyHAT provides 6 Unsafe Control Action (UCA) types and 26 Causal models Factor Guides (CFG) compared to 4 UCA types and 16 CFGs used traditionally in STPA methodology.

STPA in building risk energy management

The general framework of STPA analysis is applied

on a case study within the building energy management sector. A building is considered as an autonomous operating installation and the aim is to reduce the building energy management risks. Based on the scope of the study, potential "accidents" in the building energy ecosystem are analysed. The different levels and corresponding steps for STPA analysis are described.

Level A: System dynamics definition

Step 1: System component import

To identify system-level hazards, the system and its boundaries are initially identified and defined. A system is an abstraction conceived by the analyst; therefore, a decision need to be made about what is included in the system and what the system boundary

is. From the engineering perspective, the most suitable way to define the system boundary for analysis purposes is to include the parts of it within which the system designers have some control.

First, the system foundation is described, by determining individual subsystems. The core subsystem that is examined in this research is the Building Energy Management System.

Building Energy Management Subsystem (BEMS)

The specific subsystem, taken as a reference for the case study, is part of a new holistic methodology under development by the authors for buildings energy efficiency and risk management.

The proposed building energy management model aims to enable the alignment of fine-grain building energy use data to the organizational operational activities (incorporating state of the art business process modelling and annotation techniques). By linking core operational aspects (equipment usage) and environmental conditions (temperature, humidity and luminance) to occupant behaviour underlying business processes and organizational structures, allows for systemic and holistic view over the organizational energy performance. Based on this proposed model, the Building Energy Management System include a number of controllers (e.g., Energy Management System, Presence and Process Module, Comfort Module), actuators (e.g., Smart Home Controller) and sensors (e.g., Temperature/Humidity Sensor, Luminance Sensor, Presence Sensor, Building Meter, Device Status, BPM Tool) to control the basic process of Building Energy Management with the aim of energy demand reduction considering both Business Process hosted in the building and end Users preferences.

External subsystems

As there are cases in which shared control comes from the communication with external subsystems, there is the possibility of conflicting commands by different controllers. Some confusion may result from inconsistencies between the controllers from the external subsystems which may lead to system safety constraints violation and contribute to generation of accident. For the presented case study, the other (external) subsystems (Figure 3) undertake control actions regarding:

- Energy demand reduction in peak periods by load consumption control (Demand Side Management).
- Balance between local building production and consumption to maximize local self-consumption (Local RES)
- Energy storage device operational status optimization (Battery Management)
- Optimized Power charge management

combined with local power consumption (Electric Vehicles).

The system components are presented in Table 1.

Step 2: System connection input

System connections represent information or resource flows or other interactions between subsystems and are indicatively presented in Table2. The interactions between system components are further presented in Table 3. From the analysis, it becomes apparent that energy management modelling at a building level results in a rather complex schema of interconnections.

Step 3: Control action input

A control action is the command issued by a controller that changes the state of the system. Control actions are necessary to ensure the proper system operation and safety. The control actions of the case study are shown in Table 4.

Based on the previous steps and in order to proceed to accident identification, the analytical control structure for BEMS is developed (Figure 4) which is a system model comprising of feedback control loops.

Figure 3: BEMS subsystems

Table 1: System components

Controllers:	EMS, EV_MS, RES_MS, Battery_MS, Presence & Process Module, Comfort Module, DMS_MS
Actuators	Battery Inverter, RES Inverter, EV Charge Point, Smart Home Devices (HVAC, Lighting, Plug Devices)
Sensors	Temperature/Humidity Sensor, Luminance Sensor, Presence Sensor, Building Meter, Device Status, EV Meter, Battery State, RES Meter/SCADA, Weather Meter, BPM Tool, Aggregate Demand Level
Controlled Process	Building Management

Figure 4: BEMS control structure

Level B: Accidents and Hazard Identification

Step 4: Accident identification

In STPA, an accident is defined as an "unwanted or unplanned event causing loss". Examples of accidents in the context of the building energy management are shown in (Table 5). These are the most common accidents appeared in related bibliography, without being an exhausted list.

Table 2: System connections

Battery Inverter → Battery Management → Battery State → Battery_MS
EV Charge Point → EV Management → EV Meter → EV_MS
RES Inverter → RES Management → RES Meter/SCADA, Weather Meter → RES_MS

Table 3: Component connections

Temperature/Humidity, Luminance, Device Status, Presence Sensor/ Weather Meter → EMS → DER Controller → Building Management
Building Meter → EMS → DER Controller → Building Management
3rd Party Demand Level/ Battery_MS /EV_MS/RES_MS → EMS → DER Controller → Building Management
Presence Sensor, Device Status → Presence & Process Module → EMS
Presence, Temperature, Luminance Sensor, Device Status → Comfort Sensing Module → EMS

Table 4: Record of control actions

EV_MS → Deploy EV Charge Mode → EV Charge Point
Battery_MS → Deploy Battery Control → Battery Inverter
RES_MS → Deploy RES Control → RES Inverter
Presence & Process Module → Deploy Presence Status → EMS, Comfort Module
Comfort Module → Deploy Comfort Status → EMS
EMS → Deploy Building Control (HVAC, Lights) → Smart Home (DER) Controller

Table 5: Building energy management accidents

1. High energy costs due to energy prices
2. Environmental impact: high CO2 emissions
3. End user dissatisfaction due to comfort and operational conditions
3.1 Excess of non-renewable RES generation)
3.2 High energy cost due to Electric Vehicle Load
3.3 High Battery Management cost

Step 5: Hazards identification

Hazards are defined as system states or conditions that lead to a system accident under a particular set of worst-case environmental conditions. Possible hazards are presented in Table 6. It should be emphasized that the analysis in Level B focuses on risk assessment in the building environment without examining the operational hazards of individual

components (e.g., malfunction of a battery or RES unit as a stand-alone system) which are not being addressed in this section.

Table 6: Building energy management hazards

1. Unacceptable environmental conditions in the building
2. Load misalignment in relation to business processes
3. Peak demand in the local ecosystem (building layout)
4. Local production mismatch with consumption
4.1 Production not available from RES units
4.2 Power not available from a battery pack
4.3 Battery Power Mismatch vs. Consumption
4.4 Non-Controllable Charging Procedure for Electric Vehicles

Level C: Identifying Unsafe Control Actions

After defining the fundamental risk analysis parameters, the next analysis level refers to the 'Unsafe Control Action' (UCA) identification.

Step 6: Identifying UCAs

UCAs assess the evaluation of the potential scenarios that may lead to accidents as those mentioned in the previous step. UCAs are identified by using pre-loaded phrases for control actions, such as:

1. 'Not Provided When Needed'
2. 'Provided When Not Needed'.
3. 'Provided Too Early'
4. 'Provided Too Late'
5. 'Stopped Too Soon'
6. 'Applied Too Long'

For a full analysis, each UCA guidance phrase should be evaluated in each control action. As part of the detailed UCAs analysis, an indicative example is described.

1. A system controller with the corresponding possible control actions is selected, e.g., EMS → Deploy Control HVAC (set point / status / mode).
2. One of the six guidance phrases is selected e.g., NOT PROVIDED WHEN NEEDED
3. One or more system hazards are linked with the UCA description by selecting the risks at the last stage of the process e.g., Deploy Control → NOT PROVIDED WHEN NEEDED →

a. Unacceptable environmental conditions (temperature and humidity) in the building
 b. Load misalignment in relation to business processes
 c. Peak Demand in the building

Following UCA determining and recording, the next step is to analyse the causal factors.

Step 7: Causal factors analysis

The process of analysing causal factors guides the analysis in identifying how data and connections in the system may lead to unsafe control states. STPA methodology provides guidance for conducting causal factor analysis through the use of guidance factors that provide generic description of how systems or links could lead to unsafe control activities.

Within the methodological framework, the identification of causal factors consists of recording of unsafe control actions by the controller and detecting causes of inadequate feedback from monitors, external systems and / or other controllers. Indicatively, some basic causal factors for Unsafe Control Actions are:

- Decision making inability by controllers
- Incorrect decision-making by controllers
- No control by actuators
- Incorrect control by actuators

The modeling process is described for the test case:

1. Select a controller and the corresponding UCA e.g., EMS → Deploy Control HVAC → NOT PROVIDED WHEN NEEDED → Cannot be controlled by the Activators.
2. Select a component defined as the causal system e.g., Building Energy Meter.
3. Selection of a causal factor sentence e.g. Sensor INADEQUATE OPERATION with a sample of the details for irregular behaviour.
4. The same process is followed for all connections.

Once the addition of causal parameters for an unsafe description of the control action is done, the modelling process is completed based on the STPA methodology. The relationship 'many to many' captures all possible connections between causes and accidents based on the information we provide in the analysis.

Step 8: Data Export and Safety Recommendations

The result of the analysis is the extensive list of all the individual system components with the recording of unsafe control actions and causal factors. The extracted file from the analysis is a formatted spreadsheet presenting all the individual model co and the final list of individual UCAs (Table 7) and CFs (Table 8) in an overall risk management layout. The number of CFs is evolving on the basis of the UCAs defined in the project. In this context, risk & safety recommendations are developed as suggestions for dealing with hazardous control operations, on the basis of causal factors (those that can lead to an "unsafe state"), and represent possible actions to avoid or reduce the impact of potentially unsafe conditions. Indicative relationships between causal factors and recommendations are depicted in Table 9.

Table 7: Unsafe Control Actions list

COMPONENT_NAME	CONTROL_ACTION	UNSAFE_CONTROL_ACTION	UCA_DESC	HAZARD
Business Module	Deploy Business Constrains	Not provided when needed	Medium Risk - User Preferences violation	Non preference in environmental and operational conditions
Business Module	Deploy Business Constrains	Provided, but the intensity is incorrect (too much or too little)	Low Risk - User Preferences violation	Non preference in environmental and operational conditions
Context Module	Deploy Comfort Constrains	Not provided when needed	Medium Risk - User Preferences violation	Non preference in environmental and operational conditions
Context Module	Deploy Comfort Constrains	Provided when control action is not needed and unsafe	Low Risk - User Preferences violation	Non preference in environmental and operational conditions
DSM_MS	Deploy Building Control (HVAC, Lights)	Provided, but duration is too long or too short	High Risk -Non balance with local RES	Imbalance of local RES with demand
DSM_MS	Deploy Building Control (HVAC, Lights)	Provided, but duration is too long or too short	Low Risk -Peak in Demand	Peak Demand in local network
DSM_MS	Deploy Building Control (HVAC, Lights)	Provided, but executed incorrectly (not executed)	High Risk -Non balance with local RES	Imbalance of local RES with demand
DSM_MS	Deploy Building Control (HVAC, Lights)	Provided, but the starting time is too soon or too late	Low Risk -Peak in Demand	Peak Demand in local network
DSM_MS	Deploy Building Control (HVAC, Lights)	Provided when control action is not needed and unsafe	Low Risk - Imbalance local demand	Non preference in environmental and operational conditions

Table 8: Causal Factors Analysis

CAUSAL_FACT_NO	CF_DESC	FROM_COMPONENT	TO_COMPONENT
1	Hazardous interaction with other components in the rest of the network	PRESENCE_SENSOR	Business Module
2	Sensor to controller signal inadequate, missing, or delayed: Hardware open, short, missing, intermittent faulty	AGGREGATE DEMAND	DSM_MS
3	Sensor to controller signal inadequate, missing, or delayed: Hardware open, short, missing, intermittent faulty	BATTERY_MS	DSM_MS
4	Sensor to controller signal inadequate, missing, or delayed: Hardware open, short, missing, intermittent faulty	RES_MS	DSM_MS
5	Sensor to controller signal inadequate, missing, or delayed: Hardware open, short, missing, intermittent faulty	WEATHER_METER	DSM_MS
6	Sensor to controller signal inadequate, missing, or delayed: Communication bus error	AGGREGATE DEMAND	DSM_MS
7	Sensor to controller signal inadequate, missing, or delayed: Communication bus error	BATTERY_MS	DSM_MS
8	External disturbances	DSM_MS	BUILDING_CONTROLLER
9	External disturbances	PRESENCE_SENSOR	Business Module
10	External disturbances	WEATHER_METER	Comfort Module

Table 9: UCAs and associated Recommendations

Controllers	Unsafe Control Actions	Risk Safety Recommendations
DER (HVAC & Light) Command	DSM_Controller does not provide control command when required (Grid constrain, RES/Battery imbalance)	<ul style="list-style-type: none"> ▪ Ensure reliable & uninterrupted DSM software operation ▪ Ensure reliable communication with building actuators and external components (SCADA/ Batteries etc...)
	DSM_Controller provide inefficient control command	<ul style="list-style-type: none"> ▪ Ensure functional reliability of the software: accurate DER model parameters incorporation ▪ Enable training period for definition of model parameters
	DSM_Controller provide inaccurate control command	<ul style="list-style-type: none"> ▪ Ensure functional reliability of interfaces with sensors: energy & environmental sensors reporting accurate contextual conditions ▪ Avoid triggering conflicting actions for load management
Context Module	Context Module does not provide profiles when required	<ul style="list-style-type: none"> ▪ Ensure reliable & uninterrupted Context Profile software operation ▪ Ensure reliable communication of Context Profile module with DSMController
	Context Module provide inefficient command to DSM_Controller	<ul style="list-style-type: none"> ▪ Ensure functional reliability of the software: accurate user preference profiles incorporating contextual parameters ▪ Enable training period for definition of contextual model parameters
	Context Module provide inaccurate results to DSM_Controller	<ul style="list-style-type: none"> ▪ Ensure functional reliability of interfaces with sensors: environmental sensors reporting accurate contextual conditions required for the extraction of contextual profiles ▪ Enable users to adapt their preferences when significant outliers and inaccuracies in the model

Discussion of results

The development and application of the proposed methodology through the corresponding information systems in the screening scenario (energy management in the building sector) has enabled the robustness evaluation of STPA and the reliability of results it provides. The emphasis in this work is to ensure the proper implementation of individual steps of the modelling process and to evaluate the novelty of the proposed approach in comparison to previous methods reported in the literature. The main advancements in this regard are the following:

- Although risk analysis models are being examined in the energy sector, they focus on grid production and operation and not on the consumption segment.
- Risk modelling, in line with demand flexibility, has not been reported in a standardized way in the literature. Demand management is a new mechanism in the energy field with great application opportunity in the framework of smart grids.
- The analysis here is not limited to a single system but it is considered in the context of complex systems and processes. In fact, the emphasis is on the interconnection of individual controllers being independent yet interconnected modules in a building environment.

- STPA provides a direct and clear description of all problem parameters and a thorough analysis of the interactions between them during the design and assessment of the alternative screening scenarios.

Conclusions

This paper presents the adaptation of a new accident analysis technique called STPA (System-Theoretic Process Analysis) and the application of a corresponding computer tool, namely SafetyHAT, to formally develop potential unsafe control situations that may lead to significant hazards in a building energy management system and recommendations for their confrontation.

Considering the complexity of the problem, an attempt to analyse all potential system flaws within a system and check whether they can result in unsafe control actions (UCAs) with traditional risk management models, seems rather unattainable. Instead, it is suggested to start with the hazards, the UCAs and their contextual factors and work backward to identify potential causes. There may still be a large number of causes, but significantly fewer than trying to identify everything that can go wrong and then see if it will lead to a UCA.

Besides the proposed modelling architecture, results from a case study are presented as part of the evaluation of the model feasibility and usefulness for

safety analysis, especially at the early design phase. Results of the evaluation reveal that managing unsafe situations in complex dynamic systems which include a large number of components (controllers, actuators, sensors and controlled processes), could be supported efficiently by the proposed standardized approach.

Our plans for future work consist in deep evaluation of STPA as a hazards identification and analysis methodology with focus on energy applications. Next steps involve a) comparison of the results from STPA with traditional hazard analysis methodologies and further evaluation of results b) further expansion of the methodology to address additional risk and hazards with focus also on smart building environment and smart grids.

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Nomenclature

CF: Causal Factors

DER: Distributed Energy Resources

DSM: Demand Side Management

EMS: Energy Management System

EV: Electric Vehicles

RES: Renewable Energy Sources

STAMP: Systems-Theoretic Accident Model and Processes

STPA: Systems-Theoretic Process Analysis

UCA: Unsafe Control Action

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Virtual and Augmented Reality

USING AUGMENTED REALITY AND MIXED REALITY TO INTERPRET DESIGN CHOICES OF HIGH-PERFORMANCE BUILDINGS

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Abstract

Evaluating building performances, such as the indoor daylight, is usually based on numerical simulation and 2D image illustration. It does not take advantage of emerging Augmented Reality (AR) or Mixed Reality (MR) techniques to intuitively aid the building design. The current study probes into the topic bringing building geometry information together with simulation results into AR/MR environments. After introducing some precedent work in the literature, authors recap the typical workflow and report its application on two case studies. The first case study displays the structural simulation of a high-rise building in AR, while the second case study shows the daylight simulation of a two-story house within MR. At last, reflections are conducted and future possibilities are identified. Authors deem that, in the aim of this study, only retrofitting projects are suitable for MR. The present work can help practitioners better understand this new approach, offering the added value of using AR/MR for building design.

Introduction

Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR) are advanced technologies in interactions among people, computer, and reality. By allowing digital and physical objects coexist and providing an intuitive sense of how it might feel like to live in the animated environment, they become powerful tools for building designers. There are no unanimous and clear taxonomies of these virtual environments in the literature or in the industry (Flavián et al. 2018). For the present study, AR refers to technique overlaying virtual objects on the real-world environment while MR refers to techniques not just overlaying but anchoring virtual objects to the real world. The AR can be used indoor or outdoor while the MR seldom can be utilized outside a building.

Actually, it is not novel to aid the building design process with these virtual environments. As early as the 1990s, Donath & Regenbrecht (1995) have started integrating VR with the architecture design. Afterwards, Broll et al. (2004) and Postema (2005) explored AR usages during the conceptual design stage. Following them, scholars integrated Building Information Modelling (BIM) with AR for interactive visualization (Belcher & Johnson, 2008b; J. Wang, Wang, Shou, & Xu, 2014; L. Wang, 2017). Moreover,

educators found that AR also can improve the teaching quality of building design (Ayer et al., 2016; X. Wang, 2007; Milovanovic et al., 2017).

Although there have been considerable interests in interpreting building design in virtual environments, investigations on visualizing the performance simulation together in AR/MR are still insufficient. Interrogatively visualizing these data in the AR/MR can decrease misinterpretations and help designers make correct decisions (Li et al. 2017). This topic was firstly coined by Belcher & Johnson (2008a) who superimposed the virtual model with light simulation data obtained from software Radiance and Ecotect. Lakaemper & Malkawi (2009) integrated the robot mapping, computational fluid dynamics (CFD), and AR to visualize the indoor thermal performance. Similarly, CFD and AR were integrated to efficiently diagnose the energy performance deviation in existing buildings (Golparvar-Fard & Ham 2014). However, due to the fast development of AR/MR hardware and software, these studies in references may not reflect the up-to-date situation.

In the following part of this paper, the latest methodology and workflow of integrating building performance simulation within AR/MR will be introduced. Due to the scope of this work, specific simulation techniques and how simulation influences the decision-making in designs will not be expanded. Afterwards, two case studies dealing with different performance disciplines are reported. In the end, potentials and possibilities of this kind of AR/MR usage will be explored.

The present work offers the latest knowledge to practitioners and inspires them to envisage other similar utilisations. Meanwhile, in the discussion section, authors point out appropriate applying scenarios of AR and MR respectively.

Methodology

Apparatus

It is exceptionally available and simple to practice AR because it requires no other equipment besides a regular tablet or smartphone. The device screen is the tangible interface to exhibit, add, size, and rotate 3D models. MR is higher demanding on the equipment than the AR. Windows 10 based HoloLens, developed by Microsoft, is the most advanced equipment in the

current market (Kress & Cummings 2017). It is the first self-contained holographic computer which does not need a PC or phone connection, nor external cameras (Microsoft 2018). HoloLens 2 is the latest version, which was issued on February 2019. Besides the HoloLens, Magic Leap One which was issued in the August 2018 is the only equipment has similar functions. One AR equipment can easily support several users observing the design together while multi-devices are required to hold up multi-users' simultaneous observation.

Software

Software used during the implementation process can be categorised into geometry modelling tools (Rhino, Revit, Sketchup, etc.), simulation tools (for different disciplines), format-conversion tools, and AR/MR Apps. The building geometry modelling and the simulation are not going to be discussed herein due to they are mature topics with affluent research papers. The mid-process software is similar between AR and MR.

Exporting building models into immersive virtual environments used to be time-consuming, let alone integrating simulation results together. However, it turns out to be much easier with the gaming engine Unity and others like Blender XR. For the final AR/MR Apps, ARki, Pair, and SmartReality are the best AR Apps elected by the architects' favourite website Archidaily (Grozdanic 2017). There are also many commercial MR Apps, like ARchitect and

SketchUp Viewer, etc. Utilizing Unity and Visual Studio is the sweeping workflow for making holographic Apps for the HoloLens (Hockett & Ingleby 2016). At the same time, MR Apps also can be built up just by using the HoloLens emulator, without a HoloLens.

Dataflow

The present study will not deeply introduce functions or characteristics of individual software but focusing on the general dataflow and the data format conversion (Figure 1). Geometry modelling tools play two primary roles in the whole process. On one side, the geometry information is saved as a file in the MotionBuilder format (FBX) which enable all software to share these 3D data for the final presentation. On the other side, they also need to export the geometry information to simulators for simulation, via formats of IDF/IFC/gbXML. With the help of software like Blender, Paraview, and Unity, simulation results can be transformed into vector graphic formats, which can be integrated with building geometry and imported into the AR Apps. The last step is visualizing these data by Apps for AR/MR equipment. Once the file is carried into these Apps, designers can scan in the paper or physical model version of building layouts and then interpret the design in AR/MR. Detailed dataflow is shown in Figure 1 and practical work is outlined in the following section with two case studies for AR and MR respectively.

Figure 1: Dataflow of the whole process

Case studies

The AR case

Located in the Central Business District of Beijing, the 528-meter-tall skyscraper China Zun (Figure 2a) is the

world's tallest building in a high seismic risk zone. Therefore, its structural design is deliberately based on a multi-objective optimization, aiming to obtain the max lateral stiffness, the least material cost, the minimum distance between mega columns and curtain

walls. Moreover, there are aesthetical requirements from architects as well as various constraints demanded by Chinese building design codes, such as minimum member thickness, vertical and lateral load related column axial compression ratio. Therefore, good visualization of such performance-based results (Figure 2b) would be necessary for people to understand and improve their design work.

The structural performance is analysed by the software GSA, developed by the design company Arup. The GSA outputs structure members vs strain energy density, under a specified lateral force load case. The higher the strain energy density of a structural member, the more this structural member contribute to the lateral stiffness of the whole building structure. Overall lateral stiffness efficiency is significantly influenced by sizes and strain energy densities of structural members. The detailed building design process will not be discussed herein but more introductions on this design can be found in the previous publication (Cheng et al. 2016).

The workflow of visualizing strain energy density in 3D structural members are as following (Figure 2C):

1. Simulation results of strain energy density are obtained from the GSA, and then imported them

into Rhino/Grasshopper as table arrays via the CSV format.

2. In the Grasshopper, values of strain energy density are designated with colours based on a colour contour range, and the colour information is assigned to each structure member of the original colourless geometry model.
3. The colour-assigned structural model is exported as a file in the FBX format.
4. The FBX file is imported to a pre-defined Unity file. In the Unity, the colour assigned model is rescaled and positioned in relation to the 2D plan of China Zun, which will act as the signature marker for the AR App to recognise and to position the model in the AR environment.
5. By using the XCode, designers export the Unity file as an IPA file which could be installed to iPhone or iPad via iTunes. The IPA file is opened by the Arup Real, an in-house AR App developed by Arup and based on the Vuforia engine. This App is only for the IOS system so that designers can see the design on an iPhone or iPad.
6. Designers capture the printed floor plan in the camera view by using Arup Real on an iPhone or iPad. After that, the building model with the colour contour of strain energy density could be visualized in AR.

Figure 2: AR visualization of China Zun (a, China Zun in AR and in the physical reality; b, a screenshot of Strain Energy Density colour contour; c, dataflow of the process)

The MR case

The second case is using MR to visualize a simple house design with illuminance simulation results. The house is located in the city of Cairo which has a climate with extreme solar heat. Radiation is too intense to be ignored when seeking for the interior daylight illuminance in Cairo. Therefore, this project has a focal point balancing the indoor visual comfort and the thermal radiation from daylight. The initial building geometry is built in the Autodesk Formit and roughly analysed with the cloud-based simulation software Insight 360. Then the sketchy geometry is imported in the Autodesk Revit for a deeper design, during which more shading devices are put on facades. The detailed design process will not be introduced herein because it is not the focal point. After the model is completely built, the daylight is simulated by the Green building studio, cloud-based simulation software embedded in the Autodesk Revit. The analysis plane height is set at 80 cm while the June 22nd (summer solstice) and December 22nd (winter

solstice) are selected for the simulation because they are two extreme dates. The brighter colour in simulation results (Figure 3a) represents the higher illuminance reached inside the house.

Afterwards, it is the data processing stage which already has been introduced in chapter 2.2. Building geometry information is exported as an Autodesk MotionBuilder format (FBX) file, BIM data (such as window size) and simulation results are exported as excel files. Simulation result at each point is represented as a 3D box with colour (Figure 3d) rather than a 2D textured representation. In the end, the geometrical model, the model element data (BIM data), and illuminance simulation results are combined in the program Unity 3D and exported to an App for visualizing the data in the HoloLens. The final interactive App herein is developed by Middle East Technical University. It provides interactions with the model in different scales. Users can navigate freely inside the building, and they can rotate, scale, and move objects, by gesturing and pointing (Figure 3b).

Figure 3: The second study (a, geometry model with the simulation result in Revit; b, the working site and monitoring screen; c, operating the model with gestures; d, a snapshot of simulation results viewed in HoloLens)

Discussions

Reflections

Visualizing building geometries together with simulation results in both AR and MR helps designers make better-informed decisions. The core of the

present topic is AR/MR enabling visualization of invisible concepts or events by superimposing virtual objects or information onto physical objects or environments (Mekni & Lemieux 2014). Therefore, the current topic can be discussed from three aspects: invisible concepts (which category of building performance evaluation), virtual objects or

information (how to visualize invisible concepts), physical objects or environments (physical bases to integrate virtual objects).

Firstly, invisible concepts (building performance objectives) aimed for both AR and MR should be spatially based and place-varying, otherwise there is no necessity exhibiting them in virtual environments whose goodness is to improve the spatial perception. For example, a building's total energy consumption is easy to be understood in a 2D chart. However, if we transform the indicator into energy consumption intensity (thermal zone varied), it would be more suitable for the current topic.

The second issue is to transform the invisible simulation information into perceivable objects, such as 3D charts and heat maps, etc. Appropriate selection can make people less confused when facing the complex data. For example, in the second case study, interpreting the simulation results by 3D boxes can let people easily understand the overall condition in a room. Another advantage of visualization in AR/MR is the ability to identify performance variations on the time dimension, which is especially useful for non-instantaneous simulations, such as the wind movement.

At last, for the physical objects and environments holding the virtual model, using a printed floor plan or a physical model by 3D printing are two main ways for the AR. Interpreting new designs in MR, as the second case in the present paper, actually does not fully utilize MR's advancements because virtual objects do not have any practical correlations with the real physical surroundings. The same intention can be easily achieved by just using the VR or AR. From another perspective, only retrofitting projects which has the original construction framework to impose virtual objects may be more suitable to use the MR.

Future possibilities

There are four future opportunities deserve to be mentioned herein. First of all, the current performance simulation and AR/MR visualization are not linked. Both case studies need manually inputting rather than automatically updating simulation results after design modifications. Future platforms under the present topic should also enable people to stream data in real time or designing high-performance buildings in the immersive virtual world (Sgambelluri 2017), such as the App vSpline allowing users to intuitively create, manipulate, analyze, and 3D print physical prototypes all within VR (vSpline 2018). After designers modifying building models in virtual environments directly, simulation results can be demonstrated on the virtual model in immediately.

The second development orientation is combining AR/MR with the performance-based generative design. By integrating parametric modelling, simulation, and optimization, there will be hundreds

of design solutions automatically generated. Detailed information of this design method can be found in another literature review (Zhao & Angelis n.d.). Together with their respective performance simulation results, all of them can be exhibited and navigated in web-based applications like DesignExplorer (Thornton 2017) or Project Fractal (Autodesk 2017). With the technique WebXR (W3C 2018), these applications can be straightforwardly realized in virtual environments. It is more easily than the previous idea modifying design solutions in AR/MR directly.

The third opportunity is to develop an integrated platform incorporating fragmental information from different disciplines, allowing users to seamlessly switch among them. For example, one layer of daylight simulation result and another layer of thermal comfort simulation (of different thermal zones) shown on the same building floor. When people switch between them, one of them can be visible while the other becomes hidden. Such kind of integrative and interactive representation offers a comprehensive understanding of building performance. However, the reaction speed of that model may slow down when it carries too much information.

The last possibility is using the tangible media techniques to bring the design and simulation information back into the real world. By representing them in the form of pixels on bit-mapped displays, tangible media techniques can bring information from the virtual environments to the reality (Ishii 2008). So, it can be integrated into the design workflow in the present study if a more intuitive feeling is required by architects or building designers (Figure 4). A related experiment can be found in the study conducted by Fitzgerald & Ishill (2018).

Figure 4: Tangible Media Techniques (a, geometry and colour information in a tablet; b, these information was represented in the real world. (Leithinger et al. 2013))

Conclusions

The present study recaps the general process of visualizing building geometries together with performance simulation results in AR/MR environments. Demonstrating the spatiotemporal building performance more intuitively, this type of design interpretation can help people avoid error-prone decision makings. Two practical case studies are reported, representing AR and MR respectively. In the end, these AR/MR usages are provokingly reflected on and future research opportunities are also discussed. Authors pointed out that projects designing new buildings, other than building retrofitting, may have limited meaning showing simulation results together in the MR. In that case, using MR has no apparent advantage than AR or VR. Their respective suitability for various applying scenarios will be deeply distinguished in future work.

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A FRAMEWORK OF PROCEDURAL CONSIDERATIONS FOR IMPLEMENTING VIRTUAL REALITY IN DESIGN REVIEWS

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Abstract

The implementation of immersive virtual reality in the construction sector is experiencing a period of renewed interest since the research efforts of the early 2000s. VR-related applications are increasing in number and scopes, with a focus on communication and analysis of design intents. On the other hand, procedural challenges still obstacle their effective adoption for such purposes. The paper proposes a preliminary set of procedural considerations to take into account when immersive VR is used for feedback collection in design reviews. It is the result of an inductive approach associated with qualitative research methods based on seven semi-structured interviews with representative design stakeholders (i.e., twenty-four), including clients, designers, end-users and an accessibility expert. They were asked to evaluate VR adoption for the usability-focused analysis of a new school building. The framework represents a first step to address in a systematic way the practical implications related to VR-aided design reviews, especially when clients and end-users are involved.

Introduction

Research and applications related to Virtual Reality (VR) in the Architecture, Engineering, Construction and Facility Management (AEC/FM) industry are steadily increasing in number and scopes. This growing interest in VR systems, which are currently considered as one of the next trends of digital innovation (Mansouri & Akhavian, 2018), is closely linked to the ever-increasing adoption of Building Information Modelling (BIM) processes, procedures and technologies that characterises the on-going digital transition of the industry.

A building information model, in fact, could be the starting point for the development of a virtual facility prototype. In product design, virtual prototypes of design proposals are known as the anticipation of a product that does not exist in reality yet (Bordegoni & Rizzi, 2011). Virtual facility prototypes can be also effectively explored, tested and evaluated before being physically realised (Tutt & Harty, 2013). Often, the use of virtual prototypes implies the adoption of

virtual reality systems as visualisation and interaction platform. In particular, immersive virtual environments allow stakeholders to experience the full-scale representation of a virtual facility prototype in an intuitive and engaging manner through immersion and sense of presence (Paes et al., 2017). Based on those characteristics, immersive VR could be classified as *semi-immersive* VR and *fully-immersive* VR. The former is an experience where a portion of the field of view of the user is covered by the system; the latter is an experience where the entire field of view of the user is covered by the system thus increasing the sense of presence within the virtual prototype (Whyte & Nikolić, 2018; Castronovo et al. 2013; Shiratuddin et al. 2004).

Previous studies discussed a range of purposes and use cases for VR implementation in the building process. Communication of design intents and design review have resulted to be the main purposes for implementing virtual reality in BIM-based design processes (Lather et al., 2018). Previous researches in product design as well as perspectives from both academia and industry in the construction domain show how virtual reality systems could support collaboration through improved communication and access to information for all the stakeholders, regardless of their technical background. It has been demonstrated, for example, how VR systems could support the demand-side of the building process, such as clients and end-users, who may lack technical expertise, to participate in the decision-making process more effectively than using only traditional representations (e.g., 2D drawings, renderings, video-renderings) to access information (Van den Berg et al., 2017; Paes et al., 2017; Castronovo et al., 2013; Bullinger et al., 2010).

Immersive Virtual Reality in usability-focused design reviews

Within the multiple purposes and use cases VR systems could be applied for, the scope of this study has been narrowed down to the convergence that is currently on-going between BIM, VR and soft landings principles, which highlight the need for a smooth transition from design to operation through

the early involvement of clients and end-users (BS 8536-1:2015). Virtual reality, in fact, has been also applied in previous researches as an occupancy evaluation tool to support clients, end-users and facility managers in the collaboratively evaluation of functionality and usability of building spaces in order to feed back into the design stage the experience of the built environment in operation (Whyte, 2002; Hilfert & König, 2016; Tseng et al., 2017; Liu, 2017). For example, Liu et al. (2014) showed how virtual facility prototypes allow reviewers to deeper understand the implications of design decisions. Van den Berg et al. (2017) reviewed the literature to explore how design reviews can be supported by immersive virtual environments to communicate design intents as well as to ask for design feedback, allowing designers and clients to navigate through and comment on a design in progress. Exploration from a user perspective, participation in solution-finding and feedback on a design proposal are the patterns they identified in relation to VR implementation in usability-focused design reviews.

Research gap and scope of the paper

Within this research background, virtual reality is being used “to feed back the knowledge that clients, and end-users have about inhabitation into the design stage” (Whyte, 2002). Virtual reality, in fact, could be used as part of a strategy of obtaining feedback adopting a participatory approach as an attempt to bridge the gap in understanding between designers and the demand-side (Van den Berg et al., 2017). On the other hand, while research in the application of virtual reality systems is growing, both technological and procedural challenges to its effective implementation still exist. The latter are within the scope of this study.

They are illustrated, for example, by the need to implement VR in a structured manner and as part of a larger narrative during design reviews (Whyte, 2002; Lather et al., 2018). Moreover, other practical implications should be considered such as the need to guide the navigation of the stakeholders through the virtual facility prototype, the need to consider contractual constraints preparing VR representations as well as the need for setting the most appropriate level of detail or realism that could greatly affect the quality of the feedback and the overall effectiveness of the design meeting (Whyte & Nikolić, 2018; Liu et al. 2014; Whyte, 2002). Moreover, motion sickness, novelty effect and previous user experience with VR systems also affect the result of the design review (Ferdig, 2013; Khashe et al., 2018).

The need for addressing practical implications in a more systematic way as a guide for the design teams when planning to use VR with other stakeholders is within the scope of this study, which proposes a preliminary set of procedural considerations to adopt

when clients and end-users are involved in VR-aided usability-focused design review meetings. This represents a first step into the development of solid and systematic procedural guidelines for implementing immersive VR in usability-focused design reviews effectively.

Methodology

Data collection

Practical experience is “the best guide” to “understand implementation of virtual reality” (Whyte, 2002). An inductive research approach based on qualitative methods for data collection and data analysis has been applied (Maftei et al., 2018; Liu et al., 2018; Van den Berg et al., 2017; Liu et al., 2014; Tutt and Harty, 2013). Seven semi-structured group interviews have been organised involving a representative panel of design stakeholders (i.e., twenty-four participants including clients, designers, end-users and an accessibility expert) in the evaluation of immersive VR as a medium to support the usability-focused analysis of a new school building (Table 1). The aim of the interviews was to investigate process-related aspects and practical implications for adopting virtual reality in design review meetings from the perspective of design stakeholders. Designers and clients were selected based on their previous experience with BIM implementation and involvement with design and procurement of school buildings. Moreover, an accessibility expert, who is both a designer and a wheelchair user, was involved to discuss usability-related aspects, as well as a representative panel of end-users (i.e., school directors, students, teachers, parents) of a similar building.

Table 1: Organisation of the interviews

Session	Stakeholders involved	Participants (n.)
1.	BIM manager (architecture)	1
2.	Accessibility expert	1
3.	BIM manager (architecture)	2
4.	Public client	3
5.	BIM manager (architecture, structure, MEP)	3
6.	End-users (school director, teachers, students, parents)	11
7.	Public client	3
Total number of participants		24

Before starting the interviews, participants were first (1) briefed on the objective of the research and then (2) introduced to the VR environment, learning how to use it to move and interact within the virtual facility prototype. During the (3) navigation within the virtual facility prototype, stakeholders were asked to review operational requirements related to the functionality and effectiveness of internal spaces based on their use and destination (Table 2). Finally, semi-structured group interviews have been adopted

as a method to further explore VR implementation from the perspective of each category of stakeholders.

A semi-immersive VR environment was used (Figure 1; Figure 2). It featured a stereoscopic projector and a single portable rear-projected wall with a user-tracking system, while a 3D mouse, a flystick and a keyboard were used as VR controllers. The Virtualis Visionary Render visualisation package was used to import the Industry Foundation Classes (IFC) version of the building information model into the immersive virtual environment and to prepare the VR representation. Though the use of this specific type of VR system was determined by its availability, the focus was not on the system but on the user experience (Paes et al., 2017).

Table 2: Design requirements taken into account

Operational requirements of functionality and effectiveness for internal spaces of innovative schools
1. Functionality of building spaces in relation to their use and destination
2. Effectiveness of building spaces to ensure innovative learning methods
3. Accessibility and safety of circulation paths
4. Interchangeability of building spaces to adapt to current needs (e.g., classroom/laboratory)
5. Flexible aggregation of contiguous spaces
6. Upgrading of circulation paths for teaching or aggregative use

Figure 1: Interaction with the virtual facility prototype

Figure 2: Review of the design proposal

The semi-structured interviews consisted of open-ended questions organised into four topics (Table 3). Team members had unique roles during data

collection: one of the researchers, acting both as a facilitator during the design review and interviewer had a more personal interaction with the interviewees. Other three members of the research team were responsible for supporting the VR experience and, then, for audio recording the interview. Data were then collected and stored to be subsequently analysed.

Table 3: Preliminary coding schema based on the interview plan

Primary codes	Focus
Contractual aspects	to evaluate if the implementation of VR systems might be correlated to contractual constraints
Level of geometrical detail	to understand how to manage the VR representation at different design phases and purposes of VR adoption
Communication with clients end-users in VR	to consider the value of VR in supporting communication among the demand- and supply-sides of the design process
Stakeholder engagement in usability-focused design reviews	to evaluate if VR improves the understanding of usability issues in a design proposal compared to traditional representations

Data analysis

An inductive grounded theory approach was applied to the analysis of qualitative data, which have been first coded, identifying key points of the data to be gathered, and then grouped into concepts and categories of concepts that have been finally used for generating the proposed contribution (Suwal & Singh, 2018; Aksenova et al., 2018; Liu, 2017; Kumar, 2013).

Interviews have been taped and transcribed (Whyte, 2003). In order to code the interviews, the transcripts were imported in NVivo 12 software (Aksenova et al., 2018) as text files (i.e., *.docx format), organised in cases, which represent the units of observation of the analysis, and then classified by the profile of relevant stakeholders (i.e., designers, accessibility expert, clients, end-users) (Table 4).

Table 4: Interview transcripts

Case classification	Files (n.)*	Participants (n.)	Interview duration
Designers	3	6	1h40min
Public clients	2	6	1h
End-users	1	11	40min
Accessibility expert	1	1	30min
Total:	7	24	3h50min

*One file corresponds to one group interview

During the interview analysis, sentences or group of sentences were assigned to primary codes. Primary codes, in their first version, reflected the interview

plan and the related topics (Table 3). In a second round of coding, some sentences or groups of sentences have been re-assigned to new codes (Suwal & Singh, 2018), which have been then grouped as secondary-level codes and, in some cases, as third-level codes. Decision of code assignment was carried out by the authors based on “personal judgement and interpretation of what the sentences conveyed” (Suwal & Singh, 2018). The assigned codes were rechecked iteratively in order to validate that the various sentences and groups of sentences were assigned to the right codes so to ensure that the assigned codes were accurately mapped to interpret the answers (Suwal & Singh, 2018) (Table 5).

Table 5: Final coding schema

Primary codes and related sub-codes	Files	Ref.
1_Contractual aspects		39
1.1_Public procurement routes	7	27
1.1.1_Transparency	3	4
1.2_Costs for VR implementation	5	6
1.3_EIR – Exchange Information Requirements	2	4
1.4_Process management	1	2
2_Level of geometrical detail		106
2.1_Materials	4	10
2.2_Lighting	1	1
2.3_Furniture	7	26
2.4_Stages of the building process	3	5
2.5_Type of stakeholder	7	20
2.5.1_Management of expectations	7	15
3_Communication with clients and end-users		153
3.1_Design visualisation using VR systems	7	107
3.1.2_Rendering	4	14
3.1.3_BIM Model	4	40
3.1.4_2D drawings	7	25
4_Stakeholder engagement in design review		141
4.1_Clients	6	33
4.2_End-users	7	37
4.2.1_Needs of end-users	3	11
4.3_Collaboration	3	7
4.3.1_Preparation of VR experience	2	2

The final coding schema reflects themes and patterns that emerged from data analysis and discovers issues of importance that were raised by participants (Kumar, 2013). Their role in VR implementation based on the interviews with the representative panel of design stakeholders is discussed in the next paragraph adopting a narrative approach.

Research findings

Contractual aspects for VR implementation

Clients and designers were those who discussed the contractual aspects of VR implementation the most, focusing on related procedural considerations (Table 6). According to them, the adoption of VR in the process should be managed as a BIM use (Kreider

2013) and aligned with project objectives and information requirements as defined by the client in the Exchange Information Requirements (EIR) (Quote_S1, S3, S5). Moreover, in their opinion, VR implementation should be considered as a rewarding factor during the tender evaluation in public procurements (Quote_S1, S3, S5). One of the designers stated to be ready to submit VR-compatible versions of a BIM model, considering it as:

“A further tool the client has to evaluate the design proposal in a more transparent way and to support the selection of the most valuable design proposal.” (Quote_S1)

The majority of the designers, however, declared to be available to propose the use of VR in their pre-contract BIM Execution Plan (BEP) and to invest in the adoption of the necessary technology only once their tender offer is selected, emphasising a more project-level approach rather than an organisational one to the implementation of virtual reality (Quote_S3, S5).

According to the clients, VR implementation is not a priority of their digitalisation process (Quote_S7); however, they have recognised VR as an effective support for the analysis and communication of design intents (Quote_S4, S7). According to them, in fact, the use of VR potentially supports (1) collaborative practices as participatory design, (2) the multidisciplinary design coordination and (3) the review of a design intent, going behind normative texts and rather taking into account how the building will be effectively used by the occupants (Quote_S4, S7). On the other hand, they highlighted how:

“VR does not change the nature of public contracts. What has to be investigated is rather when to implement VR to involve end-users in order to effectively manage the design changes, for example the ones related to the functionality of the internal spaces, that this tool will inevitably stimulate the need for”. (Quote_S7)

Table 6: Contractual-related consideration for VR adoption*

Consideration	Description
VR adoption as a BIM use	The implementation of VR should be planned in the BEP and structured as a BIM use, defining its related facility elements, design phase, discipline and level of detail/information based on the objectives previously defined by the client in the EIR

* other contractual-related considerations are discussed in the relevant following paragraphs

Level of detail considerations

The level of geometrical detail and the level of information embedded within a BIM object represents the degree of reliability to which a BIM

use is implemented (Kreider, 2013). The participants were asked to express their opinion about the necessary geometrical detail to evaluate the functionality of the internal spaces of the design proposal and to suggest what procedural considerations should be taken into account in relation to that specific aspect of VR implementation (Table 7). In particular, the presence of furniture, the use of textures and the lighting settings have been the aspects the participants considered the most (Figure 3, Figure 4).

According to the designers, the level of geometrical detail for the representation of a design proposal within the virtual environment depends on (1) the purpose of the VR implementation, (2) the design phase when VR is implemented and (3) the stakeholders involved in the design review session (e.g., their level of technical expertise) (Quote_S1, S3, S5).

In relation to the purpose of VR implementation, the level of detail should be enough to allow stakeholders to evaluate the functionality of internal spaces. According to the accessibility expert, for example:

“If the accessibility of the internal spaces is considered and it is within the scope of the analysis, it means that elements that are strongly related to how a wheelchair user interacts with the space, such as, for example, the height of edges and handles of doors, as well as the height of sockets should be included in the virtual facility prototype”. (Quote_S2)

Moreover, the interaction with pieces of furniture is needed to evaluate the flexibility and accessibility of internal spaces and they have to be included within the virtual facility prototype even if they are just placeholders to simulate how the end-user interacts with them within the designed space. In fact:

“The problem of accessible spaces is that, when furnished, they can become inaccessible. With virtual reality, I perceive the space and its relationship with furnishing going behind normative requirements: it is necessary”. (Quote_S2)

On the other hand, other interviewees highlighted how the level of detail should also be considered from a contractual point of view because of the possibility that end-users may expect to see in the final building what they have experienced in the simulation (S3, S5). The presence of furniture is considered as an example: the building information model explored in VR contains pieces of furniture, which strongly characterise the design of the internal spaces. They are an essential part of the design of innovative schools and are needed to effectively evaluate the functionality and flexibility of learning environments. For example, one of the public clients said:

Table 7: Level of detail of the VR representation

Consideration	Description
Level of detail of the virtual prototype	Set the level of detail of the VR representation considering (1) the purpose why VR is used; (2) the design phase; (3) the stakeholders engaged in the meeting and their needs (avoid realism if not necessary)
Level of information need of the virtual prototype	Align the level of information need of the virtual prototype with what is required for the specific stage of the design process for taking decisions
VR preparation	Schedule a preliminary VR preparation phase, investing time in delivering an appropriate virtual prototype based on what previously specified
Management of expectations	Declare the level of detail during the meeting through visual cues to discern the decisions already made and those to be made about the design aspects (neutral for non-decided)

Figure 3: The corridor of the primary school with furniture and flexible walls becomes an educational space

Figure 4: The corridor of the secondary school furnished for individual study

“The furniture defines the multifunctional spaces where teaching is done in an innovative way. I perceive the ennobling of the corridor as learning

space much better than on 2D drawings. To date (to represent the same design aspect) they use renderings and text descriptions, while with immersive VR the communication of the design intent would be more effective.” (Quote_S7)

On the other hand, according to the different types of public procurements, it may be possible that the furniture is not actually included within the design phase but demanded at a later stage of the building process and to the responsibility of other stakeholders (Quote_S4, S7). For that reason, the understanding of what should be included in the VR representation based on the stakeholders involved and the objectives of the design review session is essential and should be well discussed during the preparation of the meeting and the related development of the VR scenario (Quote_S7).

Regarding the target audience for using VR, managing the expectations of end-users in design review meetings has been the most discussed topic. For example, according to clients and designers, members of the design team understand that example furniture might be just a placeholder. On the other hand, end-users need more information in relation to how the building will be actually used in order to better understand the design and provide their feedback. When preparing a VR representation, the risk exists for too much realism, such as in textures and furniture that could create an expectation in end-users and clients. One of the architects involved in the VR sessions said:

“Users expect what they see, while designers know it may be just a placeholder. Not using textures would make the representation less misleading and avoid creating an expectation. The risk is that a strong characterisation of the space will become deceptive. The risk of creating false expectations already exists in renderings and in traditional representations.” (Quote_S3)

Public clients agree with the need to calibrate the level of detail based on the stakeholders involved in the VR-aided design reviews. One of them said:

“The detail becomes an obstacle and not a help in participatory planning and stakeholder engagement because it confuses and creates expectations. What really counts is the functional, distributive and organisational aspect of the spaces”. (Quote_S7)

Moreover, the need to declare the level of detail of the VR representation at the beginning of the VR-aided design review session emerged. One of the clients said:

“It is necessary to declare at the beginning (of the immersive session) what is decided and what is only a suggestion and a symbol. As a school director, I would have difficulty understanding what

is contractual and what is not in this representation and to provide my feedback. For that reason, I would not show this representation to an end-user unless the elements in that are decided. In design phases in which decisions have not yet been taken, it is preferable to use neutral textures”. (Quote_S7)

The end-users involved in the research confirmed those statements, further highlighting the need to consider the use of characterising elements such as furniture and textures within the virtual environment in order to avoid disappointment.

The level of detail of the virtual facility prototype should also be compliant with what is required for each design phase in the public procurement code (Quote_S4, S7). In relation to the design phases, one of the designers suggested that:

“During the concept design the graphical representation of the building information model within the virtual environment should include volumes and masses in order to allow stakeholders to evaluate overall dimensions of functional units and the interface between the building and the external context. During the detail design phase, instead, the level of detail should increase in order to allow users to evaluate internal spaces and circulation paths during the immersive sessions”. (Quote_S1)

Communication with clients and end-users

Participants were asked what they believe to be the communicative potential of the VR system they tested before the interview (Figure 1) and how this could support, in their opinion, the effective communication of design intent to clients and end-users (Table 8). All the stakeholders expressed a positive opinion, highlighting the differences with traditional 2D drawings and renders; which were also available in the room to support design understanding. For example, one of the designers commented that the communication of the design proposal in a design review meeting typically starts with the floor plans followed by non-interactive rendering and video-rendering (S1). In this process:

“VR systems are useful for an immediate perception of the spaces that only technical experts can otherwise understand based on traditional representations.” (Quote_S3)

At the same time the type of representation used will depend on the skill and background of the participant:

“As a designer I need to start from 2D drawings; it may be different for clients and for digital natives as the students. It would be interesting to evaluate it”. (Quote_S3)

On the other hand, the school director as one of the end-users argues:

“This [VR] type of representation allows us to better understand the design proposal and formulate an idea of the spaces stronger than looking at 2D drawings. We actually do not know how to read 2D drawings.” (Quote_S6)

Thus, even if using virtual reality, multiple modes of representation would be needed to support the communication of the design proposal, including more conventional representations (Quote_S1, S3, S4). This has been also previously confirmed through the need for multimodal and interactive spaces, rather than VR alone (Lather et al., 2018, Balakrishnan et al., 2006; Whyte, 2002).

Table 8: Procedural considerations to support the communication of design intents using immersive VR

Consideration	Description
VR as a medium in an interactive workspace	Provide stakeholders with multiple media to access design information based on their needs and technical expertise. An interactive workspace should be set
Risk for novelty effect and motion sickness	Manage the risk for a dispersive and unfocused session, considering that a novelty effect could influence stakeholders as well as motion sickness could reduce their performance because of discomfort and nausea

Stakeholder engagement in design review

Whereas communication here means “to present information about a facility in a method in which it can be shared or exchanged” (Kreider, 2013); to engage users, means to allow them to “express their views in an environment that is conducive to obtaining an honest and accurate understanding of their needs” (BS 8536-1:2015).

Interviewees also discussed how virtual environments could be used to engage stakeholders in design review meetings, effectively involving clients and end-users (Table 9). All the participants expressed a positive opinion, highlighting the differences between a VR-aided design review meeting and traditional processes. According to the accessibility expert, for example:

“Immersive reality has the potential to become an important tool for soft landings, as a communication bridge between the design and the occupancy of the building.” (Quote_S2)

Moreover, in another meeting, three designers with different backgrounds all agreed in saying that:

“The immersive virtual environment should be used in order to engage end-users in the design process so that they can express an opinion and provide feedback”. (Quote_S5)

The participants discussed the potential benefits VR

systems could provide to collaboration, as well as to the demand-side (i.e., clients, end-users) of the building process. At the same time, they also stated how planning stakeholder engagement in the process management is an important task. For example, one of the public clients said:

“When using immersive virtual environments in a participatory design process, I could acquire from my interlocutor information, design requirements and needs that I had not planned and considered and, in the process, I can adjust the design proposal.” (Quote_S4)

Moreover:

“If the end-user is not the client, it is more difficult to involve him/her; however, clients and end-users are the stakeholders to be engaged because they will live and operate in the designed space and the communication of the design proposal has a greater impact for them” (Quote_S3)

However, if according end-users, navigating the model in VR may help them find answers more easily (S6), both designers and clients, as well as the accessibility expert, said that this process of communication of the design intent should be guided, confirming one of the consideration that already emerged discussing the contractual aspects of VR implementation. One of the clients, for example, highlighted how:

“Visualisation in virtual reality must be prepared according to the audience; for the same project and for the same project phase, different sessions and different views are expected”. (Quote_S7)

Moreover, an agenda for the meeting should be organised in order to obtain the necessary feedback based on the objectives of the meeting. Liu et al. (2018) developed a process model describing the activities that characterise a usability-focused design review meeting. In relation to that, one of the interviewees said:

“Design review meetings involving end-users should be organised in three steps: (1) understanding of the design proposal from a functional point of view through 2D static views; (2) description of the intended use and operation of the building; (3) guided navigation within the immersive VR”. (Quote_S1)

Both clients and designers agree in saying that leaving freedom of navigation to clients and end-users would entail the risk of a dispersive and unfocused session, which (a) does not consider the key aspects on which to make decisions and, not of minor importance, (b) would go beyond the maximum time for which it was proved that a session can be conducted without causing discomfort and

nausea in the people involved due to virtual reality sickness. A third-person driver, expert in VR systems, should guide the stakeholders within the virtual facility prototype and they should not move by themselves without following pre-defined paths, viewpoints and activities that have to be preliminarily scheduled based on the objective of the meeting (Quote_S1, S2, S3, S5, S7).

Table 9: Procedural considerations to support stakeholder engagement using immersive VR

Consideration	Description
Pre-defined paths and viewpoint to navigate the model	Prepare pre-defined paths and viewpoints to guide the immersion based on the objectives of the meeting and the stakeholders involved
Third-person VR driver to guide the immersion	Avoid training participants in using VR systems and option for a third-person VR driver to guide the immersion based on the agenda set by the facilitator. This helps in managing time, meetings objectives, reducing risk for novelty effect and motion sickness
Design review agenda identifying decision gates	The facilitator (e.g., project manager) should schedule phases and decision gates of the design review meeting in order to guide VR preparation and stakeholder engagement

Discussion and conclusions

Discussion of findings and their contribution

This study proposes a framework of procedural considerations (Figure 5) for implementing virtual reality systems in usability-focused design review meetings. The results confirm findings from previous studies (Whyte, 2002; Liu et al., 2014; Van den Berg., 2017; Hilfert & König, 2016; Whyte & Nikolic, 2018; Lather et al., 2018, Ferdig, 2013) and integrate them identifying the relevant categories of procedural considerations and practical implications that have to be taken into account when VR systems are used as media to access information in design reviews. The preliminary set that has been developed in this study represents a first step into the development of a systematic and comprehensive framework to guide designers in implementing VR systems. It may be refined and changed by future experience and research activities.

Results have revealed how some aspects related to the implementation of virtual reality in design reviews still need to be further investigated and, eventually, disseminated (e.g., contractual aspects). The perceived use of VR systems for reviewing design intents confirm that analysis and communication are the most adopted purposes for VR implementation in the AEC/FM industry (Lather et

al., 2018). The topic of stakeholder engagement also emerged in close relation to the previous ones, highlighting the role of virtual reality as collaborative tool that can effectively converge with BIM procedures and soft landings strategies. Another topic that was widely discussed is the necessary level of geometrical detail to effectively visualise and navigate within a virtual prototype when designers, clients and end-users are involved in design reviews. In particular, the risk for providing expectations in clients and end-users was discussed. At the same time, the need for an intensive investment in time and cost for creating effective VR representations has been considered as one of the limits for the smooth adoption of VR technologies in the design review process, confirming also in this case aspects already emerged in previous research (Khesha et al., 2018).

Literature review	Semi-structured interviews with a representative panel of design stakeholders			
Purpose of the design review meeting (e.g., Liu et al., 2014)	Prepare the VR representation according to the objectives of the design review			
Level of detail of the VR representation (e.g., Whyte 2002; Liu et al., 2014, Van den Berg et al., 2017)	Set the level of detail of the virtual facility prototype			
	Set the informative content of the virtual facility prototype			
	Management of expectations of the stakeholders involved in relation to the VR representation			
Contractual constraints (e.g., Whyte, 2002; Whyte and Nikolic, 2018)	Structure VR adoption as a BIM use			
Pre-defined navigation paths and viewpoints to navigate the model (e.g., Whyte, 2002, Liu et al., 2014)	Prepare pre-defined paths and viewpoints to guide the navigation through the model			
Previous experience with VR systems (e.g., Liu et al., 2014; Paes et al., 2017; Khashe et al., 2018)	Avoid training people in using VR systems. Prefer a VR driver and a facilitator to guide the navigation			
Collaboration (e.g., Whyte, 2002; Bullinger et al., 2010 ; Van den Berg et al., 2017, Liu et al., 2018)	Organise the design review agenda identifying decision gates and steps for stakeholder engagement			
Need for multiple media and use of VR system in a wider narrative (e.g., Whyte, 2002; Lather et al., 2018)	Organise an interactive workspace including VR among multiple media to access information			
	Annotations should be linked to the building information model (e.g., BCF format)			
Novelty effect (e.g., Ferdig, 2013)	Manage the risk for the novelty effect			
Motion sickness (e.g., Hilfert and König, 2016)	Manage the risk for motion sickness			

Concepts are mapped and colour-coded based on the relevant categories ([red]: stakeholder engagement; [blue]: communication; [green]: level of detail; [orange]: contractual considerations)

Figure 5: Preliminary framework of procedural considerations for VR implementation in usability-focused design reviews.

Limitation of the research

As far as the research limitations concerned, they are related to both applications of findings and generalisations based on the methods used. This study dealt with an individual case (i.e., a school building design review with relevant stakeholders) and findings cannot be generalised if not compared with a wider set of building design reviews, specific design processes and particular type of design review meetings and related objectives. This research is thus limited to the generation of a preliminary framework of procedural considerations and practical implications for implementing VR in design reviews when clients and end-users are involved. On the one hand, findings provide evidence to results from previous researches; on the other hand, additional research is needed to test, refine and extend the theory that has been built here (Van den Berg et al., 2017). Moreover, the data set could be extended in additional research activities and findings need to be generalised in additional projects.

Future works

In order to validate the results of this study, the authors will evaluate the comprehensiveness of the framework of procedural considerations and, eventually, the need to extend and integrate it. For that reason, the authors have planned a next step of the research, which will be based on a series of talks with VR experts from both the academia and the industry. The talks will be managed in the form of semi-structured interviews and they will allow the authors to sharpen research generalisability and raise the theoretical level of the contribution providing further evidence on the need for a systematic and solid framework of procedural considerations to guide VR implementation from the practical experience of lead VR users. In future works the framework of procedural considerations could be matched to the phases of a VR-aided usability-focused design review session protocol in order to develop solid guidelines for VR implementation.

The growing interest of the construction sector towards virtual reality systems and interactive workspaces requires further research in order to effectively address technology investments and integration of those systems into design processes. In particular, a lack of understanding in relation to the added value, if any, generated by VR adoption exists. For that reason, comparative and quantitative research could be adopted to measure the added value of VR systems in design review (Khashe et al, 2018; Paes et al, 2017). Moreover, no guidelines are available to lead users to the selection of the most appropriate VR system based on their needs and expected user performance and interaction with the virtual facility prototype according to VR purposes and related uses. Furthermore, future research works

should investigate how cognitive processes in collaborative activities, such as design review meetings when multiple stakeholders are involved, change because of the adoption of virtual reality systems. Finally, additional research should be related to the contractual aspects of VR adoption in design review meetings; the different types of design processes (e.g., user-centred design, participatory design) should be also taken into account.

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VIRTUAL REALITY USE FOR EVALUATION AND IMPROVEMENT OF BUILDING EMERGENCY SIGNAGE

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Abstract

Immersive Virtual Reality (VR) is often used to visualise architecture, interior design and building use. This study looks into the use of VR in evaluation of emergency signage with respect to fire evacuation. In a single case study experiment using Serious Gaming (SG), test persons were immersed into VR using a head mounted display (HMD) and asked to evacuate a test building in a fire evacuation scenario. The case study experiment provided a keen understanding into people's reaction to emergency signage and how detection of such signage during evacuation can be improved.

Introduction

In fire evacuation, certain design requirements must be fulfilled, securing the ability to evacuate a building rapidly, easily and safely, before being impacted by the fire (Trafik- og Byggestyrelsen, 2016) (Kobes *et al.*, 2010). The evacuation time for building users can vary a lot, depending on pre-movement time and the actual movement speed during evacuation. How familiar a person is with a building is another factor to consider regarding evacuation time (Purser and Bensilum, 2001). Evacuation speed/ time is important, as research shows a correlation between delayed evacuation and number of fire deaths (Wang *et al.*, 2014) (Purser and Bensilum, 2001). In this study evacuation time is understood as the time from evacuation is announced to a person is evacuated.

During evacuation, people are likely to prefer leaving a building through the same route as they entered (Trafik- og Byggestyrelsen, 2016) (Purser and Bensilum, 2001) (Sime, 1985), which can prolong the evacuation speed and expose people to harm. To reduce evacuation time to protected escape routes, emergency signage must be placed in a manner that makes them noticeable and they must be designed in a way that makes people follow them (Sime, 1985).

Even when emergency signage complies with legislation and standards regarding evacuation of buildings, issues can nevertheless be found and improvements made.

To test the function and visibility of exit signs, the emergency signage of a university building was tested using Serious Gaming (SG), in Immersive Virtual Reality (VR). The VR was viewed using head mounted display (HMD). HMD viewed VR makes it easier to evaluate building design based on 3D models (Petrova *et al.*, 2017). It makes room for increased user involvement (Rasmussen, Gade and Jensen, 2017) (Kuliga *et al.*, 2015) (Svidt and Sørensen, 2012) (Christiansson and Svidt, 2011), and allows simulating dangerous situations without putting the users in harm (Wang *et al.*, 2014). Use of VR additionally supports shared perception and communication leading to better decision making (Niu, Pan and Zhao, 2016) (Roupé, Johansson and Tallgren, 2016).

In VR it is possible to observe human behaviour and track their movements. VR has the potential to act as a simplified mean of communication between users and designers, deepening the understanding of people's needs and wishes with respect to the design (Sørensen and Svidt, 2017). VR use additionally allows changing of the virtual environment (VE) test persons are exposed to, in a more cost- effective way than real life mock- ups (Andrée, Nilsson and Eriksson, 2016; Zou, Li and Cao, 2017) granting a maximum control over the presented scenarios (Kinatader *et al.*, 2014) (Wiederhold and Wiederhold, 2010).

Earlier studies have addressed the use of VR for attaining knowledge of human behaviour during evacuation (Kobes *et al.*, 2010; Gwynne *et al.*, 2016, 2017) the psychological aspects of evacuation (Gamberini *et al.*, 2015), selection of emergency exits (Andrée, Nilsson and Eriksson, 2016), decision-making during extreme situations, (Rüppel and Schatz, 2011) and the difference between VR evacuation training compared to traditional training approaches, such as: video, posters, seminars, courses and evacuation drills (Feng *et al.*, 2018).

VR has additionally been concluded as an efficient tool for providing understanding of the evacuation process to building designers and end users (Rüppel and Schatz, 2011; Zhang and Wang, 2012) and make people accustomed to a building environment and

prepare them for an evacuation (Wang *et al.*, 2014).

Use of VR in evaluation of exit sign placement and escape route design, is nevertheless a novel approach in the building industry (Kobes *et al.*, 2010; Kinateder *et al.*, 2014; Andrée, Nilsson and Eriksson, 2016).

In the past twenty years, Serious Gaming (SG) has become an increasingly used tool for training and behavioural analysis (Feng *et al.*, 2018) (Connolly *et al.*, 2012) (Kobes *et al.*, 2010). A transverse characterization of SG has however still not emerged in the industry (Connolly *et al.*, 2012) (Susi, Johannesson and Backlund, 2007). In this paper we use the definition of SG as formulated by (Susi, Johannesson and Backlund, 2007), also used by (Feng *et al.*, 2018): *“The application of gaming technology, process, and design to the solution of problems faced by businesses and other organizations. SGs promote the transfer and cross-fertilization of game development knowledge and techniques in traditionally non-game markets such as training, product design, sales, marketing, etc.”*

Nudging refers to purposefully changing the architectural elements that influence people’s behaviour. This is done by making changes to the environment guiding and enabling individuals to make desired choices almost automatically (Lehner, Mont and Heiskanen, 2016). In this study, we used nudging principles to find improved solutions to the emergency signage design.

This paper focuses on design and improvement of emergency signage, answering the research question: How can emergency signage design and placement be improved using VR based on a Serious Game scenario?

Methodology

The research design of the study is in the following described through 5 subsections as shown in Figure 1.

Figure 1 The 5 subsections of the research design.

Empirical data collection

The research question was answered through a design

driven co-creation methodology, involving both expert interview persons and building user testing through VR.

Interviews were conducted using the Contextual Design Inquiry methodology (Beyer and Holtzblatt, 1997) Both experts and building users were interviewed immediately after having been immersed into VR. Written questionnaires were also used in collecting empirical data.

Selection of expert interview persons was based on a stakeholder analysis, revealing which stakeholders held the highest interest and influence over the test building’s escape route design. In this paper a District Surveyor can be both building technical surveyors and fire safety officers (principal surveyor). Two persons with many years of experience in fire safety issues and hazards were therefore chosen as interviewees, acting as District Surveyors during the experiment.

Test persons were selected, considering the potential users of the building such as students, teachers, researchers and visiting professors. It was stressed involving people both with and without knowledge of the escape route design of the building as recommended by (Trafik- og Byggestyrelsen, 2016).

Experimental conditions

The experiment involving the building users, was conducted during an exploration event in Northern Jutland, Denmark, called The Digital Days 2018, where experiment participants living up to the experimental conditions were found.

The experiment was divided into three test phases.

- A) Expert involvement: Experts explored the existing exit signage guiding towards the protected escape routes in the architectural and engineering building model as well as the VR, using both HMD and monitor display.
- B) Improvement of the VR: Experts proposed four changes to the escape route design, in order to improve the exit signage and the guiding to protected escape routes as shown in Table 1.
- C) User involvement: A user group of 20 people explored the original escape route design of the test building through VR, by reacting to the SG scenario. Another group of 20 people then tested the escape route design after improvements were made, based on expert proposals.

Improvement of the escape route design was additionally based on nudging principles. Nudging works through four types of tools: 1) simplification and framing of information, 2) changes to the physical environment, 3) changes to the default policy, and 4) the use of social norms (Lehner, Mont and Heiskanen, 2016).

Table 1 The four improvements made to the VR

1.	Pictograms on escape route doors
2.	Lowering of exit signs
3.	Light arrows showing direction to doors
4.	Permanent indication of perimeters

Simplification was used in the SG by making the scenario more straight forward. Improvements of the escape route signage in the VE was made by changing the placement, the lighting and colouring of the emergency signage.

Experimental Design

The experiment was designed as a SG, allowing test persons to do a playthrough of a scenario by entering and navigating around the test building in VR with the purpose of assembling in a meeting room. Upon arriving in the building, the text: “Please assemble on the 3rd floor of the building, in room 1.308 for a meeting” was displayed. Upon arriving in the meeting room, the building’s warning system announced: “Please follow the emergency signage of the building towards the protected escape route in order to exit the building. Please do not use the elevator”.

A provocative scenario of a fire, as shown in Figure 2 was inserted into the same route the test persons followed to the meeting room, intending to force test persons to use the nearest emergency exit. The provocation was furthermore inserted to force a mental and behavioural response of the test persons similar to

Figure 2 Visual fire presented to the test persons in the VR Serious Game scenario.

real stressful situations, as described by (Cao, Lin and Li, 2019) (Zou, Li and Cao, 2017).

After completing the SG in VR, each test person gave feedback on the questions shown in table 2.

Table 2 Feedback questions

Questions
How hard was it to identify the escape routes of the building?
Did the scenario make you aware of missing exit signage?

The VR model was then updated based on expert evaluation and change proposals, before being presented to the user group. The users were then asked to evaluate different improvement solutions based on the expert proposals (Table 1). Nudging principles were also used in selection of improved solutions.

One of the design changes was inserting pictograms on emergency exits, as shown in Figure 3.

Figure 3 Left door: Before update of the VR. Right door: After the update of the VR.

Technological development

The building used for placement and design testing of the emergency signage, was the Department of Civil Engineering at Aalborg University, Denmark. Initial analysis of the actual building revealed some unsuitable design choices and placements of the existing emergency signage, making the building relevant for user involved VR evaluation.

The building’s emergency signage and protected escape routes were designed based on Danish Building Regulations 2015 and the Danish Sample Collection of Fire Protection of Construction (Trafik- og Byggestyrelsen, 2016).

Figure 4 The upper floorplan shows the test person's evacuation route, on the 3rd floor before changes were made to the VR. The lower floorplan illustrates the evacuation route test persons took on the 3rd floor after changes were made to the VR.

Emergency signage in the SG VR was modelled based on the existing 3D models of the building and the documentation used by the owner to attain the building permit.

The VR was built using a 3D model of the test building in the .IFC format and the Unreal 4 game engine.

Only rooms relevant to the test scenario were furnished, and technical equipment e.g. elevators were not functioning in VR, as elevators are not approved for use during fire evacuation in the real building.

The Oculus Rift CV1 head mounted display (HMD) was used in all test sessions. The HMD was connected to the PC via cable. Oculus Touch controllers were used to manoeuvre in VR.

Variables of the study

The test persons were in the age between: 20 and 29. 95 per cent were male, 75 per cent students, 10 per cent employed in engineering companies whilst the remaining 15 per cent were working in construction, architecture or education.

Results and discussion

Multiple conclusions were derived from the data collected after the test person's completion of the SG and the follow-up interviews.

As shown in Figure 4, the test persons (illustrated as red lines) were struggling finding the closest emergency exit to a protected escape route from the starting point in room 1.308 in the test building. Some

test persons were even running to the far end of the building before finding a protected escape route. 80 per cent of the test persons failed to use the nearest emergency exit. After the VR was improved, 13 of 20 persons used the nearest emergency exit, equivalent to 65 per cent.

In the VR based on the test building's existing emergency signage only 40 per cent of test persons used protected escape routes to evacuate the building. In the improved version 80 per cent did.

Even though the fire scenario playthrough on the 2nd floor was supposed to hinder test persons from evacuating through the same route they had entered the building, 25 per cent of the test persons ignored the flames in the SG before changes were made to the VR. In the improved model however, 20 per cent still used the route they entered the building at, despite of the visible flames.

Based on the interviews conducted after completion of the unimproved SG VR, 40 per cent of the test persons rated the escape routes easy to identify, whilst 25 per cent rated them hard or very hard to identify.

Only 10 per cent of the test persons rated the identification of the escape routes to be very easy in the unimproved VR. In the improved VR however, 45 per cent rated the escape routes to be very easy to identify.

With respect to evacuation times, the test persons were timed during their SG playthrough. The evacuation times of the unimproved VR ranged from fastest to

slowest: 2.36 min to 1.00 min. In the improved VR it ranged from fastest to slowest: 3.07 min. to 50 sec. The spread of the evacuation times was in the unimproved VR: 31 seconds whilst the improved VR had a spread of evacuation times of: 37 seconds.

The data showed that the evacuation time went from an average of 1.32 min. in the unimproved VR to 1.15 min. in the improved VR, thus a 19 per cent improvement, making it possible to conclude the use of VR for evaluation of emergency signage an efficient tool for improving evacuation times.

Improvement rating

As earlier described (Table 1) four different improvements were made to the VR to heighten the salience and intuitiveness of the emergency exit signage. These improvements were rated on a scale from 1 to 5 by the test persons based on four criterion, where 1 was equivalent to the test person strongly disagreeing and 5 equivalent to strongly agreeing. The data was collected using a written questionnaire based on:

- 1) Visibility
- 2) Obvious functionality
- 3) Helpfulness during evacuation
- 4) Aesthetic impact on architecture

Figure 5 shows the average scores of the solutions.

Pictograms on escape route doors

Pictograms on emergency exits were inserted in the VR. This improvement was rated to be very visible with an average score of 4.65. The test persons furthermore rated the obvious functionality of the change 4.40 and the helpfulness during evacuation 4.20. Regarding the aesthetic impact on the architecture the rating was only 2.05. This could

indicate that the test persons primarily focusses on the practicality of the pictograms. The limited participation of architects in the experiment, could also be a factor in this regard.

As the pictograms are a permanent part of the architecture, it can be argued that the solution will lose its salient function over time, as building users might stop noticing them. This argument also applies to lowering of exit signs.

Lowering of exit signs

Another improvement of the VR was lowering of the exit signs. In the unimproved model the exit signs were placed just below the ceiling in the test building. After improvements were made, the signs were lowered with approximately 500 mm. creating higher visibility and functionality. The experts noted that people have a tendency to look down during evacuation, clarifying why the average rating of visibility of the lowered signs was only 3.80. The helpfulness of the lowered signs during evacuation was rated 3.52 and defacing of architecture 2.25, making this improvement less useful and more defacing to the architecture, making it a less feasible solution to aid the evacuation of people.

Light arrows showing direction to doors

As mentioned earlier, experts noted that people usually look down during evacuation. Light arrows were therefore inserted into VR to direct people toward the emergency exits. This improvement was rated with an average of 4.40 with respect to visibility, which is the same as the pictogram solution mentioned previously. The solution was additionally the highest scoring improvement with respect to helpfulness during evacuation with an average score of 4.35. It furthermore had a score of 2.15 regarding defacing of architecture.

Figure 5 Average scores of the solutions implemented in VR.

In contrast to the two previously mentioned solutions, the light arrows are not a permanent part of the building's architecture, as they only turn on during evacuation. This means the light arrows will attract attention because they are not noticed on a daily basis by the building users, making this a more salient solution.

Permanent indication of escape routes

The final solution implemented in VR was a permanent indication of the escape route perimeter on the building's floors. This solution was rated 3.45 in visibility, 2.70 in obvious functionality and 2.40 in helpfulness during evacuation. This means the solution was the least feasible improvement solution in the experiment. With respect to architectural defacing the solution scored 2.40 making the solution the most defacing option.

As the solution would be a permanent visual feature of

the building it is likely to become less salient to the building users during evacuation, and might attain more aesthetic value than practical. The permanent indication must furthermore be supported with one of the previously described solutions, as it only indicates the perimeter outline of the escape route with no direct guidance towards protected escape routes.

Nudging the solutions

The solution options shown in Figure 6, were all analysed based on comments from experts and nudging principles, before being implemented in VR. After the final experiment was conducted, the test persons were asked to rate the solutions.

The response from the test persons indicated that the pictogram and the lowered exit sign solutions would be a better solution than the existing emergency signage. The "arrow on the floor" solution could according to the test persons be improved by supplying

Figure 6 Different solution options. The boxes in yellow frame shows the solutions used in the VR scenario presented to the test persons.

the arrow with a “FIRE EXIT” caption, to make the meaning of it explicit. 50 per cent of the test persons rated the solution in VR, highlighted in Figure 6, to be good or very good. By supplying the arrow with a caption, its rate however increased to 95 per cent.

With respect to the permanent indication on the floor, 45 per cent rated the green and the white perimeter line to be equally good for guidance towards the protected escape route. However, 65 per cent rated the green coloured full marking the best solution.

The experiment was not conducted again after this evaluation. However, iteration of the experiment could have provided an even better understanding of the function of the emergency signage. In future research additional iterations must therefore be conducted.

Limitations

One of the primary limitations of the study was the lack of smoke and heat radiation from the simulated fire, allowing people to run through it in VR unaffected.

The human view of 210° (Traquair, 1938) is in VR limited horizontally to 110°, whilst the vertical view is reduced from 150° to 110° (Digital Trends, 2019). This reduction in view might have prevented test persons in discovering signage during the serious game, influencing the documented evacuation times.

As the test experiment of the emergency exit signage in VR only took 5 - 10 min., full building overview was not possible to acquire for the test persons, as it would be the case for people using the building on a daily basis. This might have influenced the evacuation times.

Conclusion

Emergency signage is an important factor to consider with respect to ease and speed of fire evacuation. Through a Serious Game presented in Immersive Virtual Reality experts and test persons evaluated the design and placement of the emergency signage of a test building. 40 test persons, divided into two groups, completed the Serious Game playthrough whilst their evacuation movement and time was captured. Based on the results from the test of the existing emergency signage, a new Virtual Environment with improved signage was developed and tested with another group of potential building users.

The improvements made based on the initial evaluation resulted in a 19 per cent decrease in evacuation time, and 65 per cent of the test persons using the nearest emergency exit to a protected escape route and out of the test building. This result makes it possible to conclude use of VR for evaluation of emergency signage an efficient tool for improving evacuation times.

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EVALUATION OF VIRTUAL SAFETY TRAINING TOOL APPLICATION WITH CONSTRUCTION WORKERS

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Abstract

Construction sites can be categorized as one of the most high-risk workplaces in terms of occupational safety. Previous studies indicate that highly engaging safety training tools mitigate on-site accidents. In this regard, virtual technologies are encouraged to be used in the development of the safety training tools in the construction industry since they provide visualization, multiuser interactions and task compatibility. In this study, we utilized a virtual safety training tool entitled V-SAFE.v2 which includes only scaffolding task sequence and framework installation processes. V-SAFE.v2 is a highly engaging safety training tool which enable workers to collaborate with each other and gain safety knowledge in an interactive way. In this study, the applicability and efficiency of this training tool were examined at a real construction site. The experiments were conducted with seven construction workers. The effectiveness of V-SAFE.v2 training on their safety knowledge was examined by a comparative analysis. According to the results, V-SAFE.v2 has a potential to increase awareness of the construction workers on the occupational safety issues.

Introduction

The construction industry is considered as one of the most dangerous industries due to its temporary and dynamic nature (Al-Humaidi and Tan, 2010; Fang and Wu, 2013). Statistics have shown that the number of accidents occurs in the construction industry is higher than any other industry (Eurostat). Mohammadi et al (2018) mentioned that even though the workers in the construction industry account for only 6% of total workers in other industries, the percentage of construction industry fatalities is 20%. Although, the percentage of fatalities is considered to be very high, this figure cannot be held against the fact that the construction industry is growing rapidly. Therefore, in order for the construction companies to show growth and progress in the industry, health and safety management should be given special attention.

According to the occupational safety and health administration (OSHA) in the United States, there are about 65% of the construction industry workers work on scaffolds, and about 72% of the workers injured in

scaffold accidents. Therefore, trying to protect these workers may prevent about 4500 injuries and about 60 deaths every year (Bureau of Labor Statistics (BLS). High fatal and non-fatal accident rates of the construction industry are also a serious problem in European Union countries. According to Eurostat 2016 database, a total of 3546 fatal accidents occurred in 28 European Union countries and around 21% of these accidents appear in the construction sector.

Rubio-Romero et al. (2013) mentioned that 40% of construction site accidents in Spain caused by falling from heights, and about 30% of these accidents are caused by the falls from temporary construction devices such as scaffolds. There are many studies regarding the safety level of scaffolding equipment since it is considered as the major cause of falls from height accidents in the industry (Rubio-Romero et al. 2013). Some studies show the risk involved when handling more loads on “suspended scaffolds” (Saurin and Guimarães, 2006) while another study ensures about the ergonomically unsuitable techniques when disassembling scaffolding (Cutlip et al., 2000). Another study conducted in Poland by Hola et al. (2017), includes a set of 177 on-site scaffolding accidents. The study shows that 43.5% of accidents resulting severe body injuries, while about 35.6% of accidents cause light body injuries (Hola et al., 2017).

Therefore, falls from height accidents should have a high level of attention and proper training techniques should be implemented in order to improve the safety level in the construction industry. In this regard, the virtual environment is becoming one of the leading tools in the safety management field. It provides the workers a safe and easy way of learning. For this reason, the advantage of using virtual environments in the construction industry has fair attention and it should be implemented properly to reduce the number of fatalities and accidents occurring in construction sites. The purpose of this study is to test a virtual safety training tool with real construction workers in order to present the effectiveness and suitability of virtual environments.

Background

In recent years, virtual technologies are frequently used in many research areas related to occupational

safety, such as construction, aviation and medicine. Virtual environments enable users to experience real world components in a computer simulated environment (Lovreglio 2018). It is also widely accepted that 3D games encourage the participants for difficult and risky activity training and provide recalling knowledge for a long period of time (Chittaro and Buttussi 2015). For all these reasons, there are various virtual technology-based safety training tools that have been developed and used in the construction industry over the last decade.

For example, Sacks and his colleagues (2013) developed a tool to identify workplace risks in the virtual construction environment. They conducted a study with 66 participants to test the efficiency of the simulation tool. The subjects were divided into two groups; one of them received traditional safety training by using 2D materials and the others were trained by the 3D immersive virtual environment to recognize the construction site hazards. According to the results, the second group trained in the 3D environment performed better in terms of identifying the workplace hazards. Guo et al. (2012) conducted another study on safety training using virtual reality. In this study, the authors introduced and tested a multi-user safety training tool for dismantling a tower crane. In this study, project managers and crane operators used the game-based training tool and answered a survey related to both traditional and VR-based innovative training methods. The findings of the survey show that the crane operations will be safer and more efficient with the support of game-based training tools compared to traditional methods. Another study (Albert et al., 2014) focused on the virtual reality technology to improve the hazard recognition skills of construction workers. The researchers developed a high fidelity augmented virtual environment and tested its feasibility with 6 workers. After defining the initial knowledge level of all participants by conducting a paper-based test, they walked in the virtual environment to identify the workplace hazards. Then, the same written test was applied to the participants again. The empirical test results indicated the participants increased their performance by 27% after experiencing the virtual environment. Guo et al., (2016) compared the effectiveness of on-site training and off-site training. They concluded that on-site training is inactive and may have clashes with other construction activities, consequently, overall construction productivity can be reduced by the application of on-site safety training. On the other side, off-site safety training is poor in terms of hands-on-practice opportunity for construction workers. Virtual environment applications can ameliorate off-site hands-on-practice by mimicking real construction site therefore it can provide visualized information to trainees. Bhide et al., (2015) emphasize that virtual environment-based training is a bridge that closes the

gap between learning by practice and learning in traditional classrooms. The same study also underlines that tracking the position and orientation of character according to reality is one of the main features of the virtual environment.

Hallowell et al., (2016) confirms that virtual environment applications increased the ability of trainees to reconnoiter buildings and infrastructure prior to site implementation, thereby increasing the recognition of hazards through design. Researchers approve that initial training is one of the most important aspects of competence on a construction site (Cameron et al., 2011; Hatala et al., 2014). Training can be improved further by providing feedback which allows the modification or control of a process using its anticipated results or effects. Therefore, integrating feedback feature into virtual environment applications will increase the effectiveness of safety-training (Lawani et al., 2018).

Even though many studies emphasize the advantage of using virtual environments in safety training, a limited number of studies clarify the role of virtual environments in scaffolding activities. Nadhim et al., (2016) mentioned that scaffolding activities are one of the major causes of falling-from-heights incidents. The study indicates that 23% of falling-from-height accidents occur during the assembling, disassembling or post-assembling activities of scaffolding. The same study points out that the second most serious cause of falling-from-height accidents depends on the learners' experience, lack of education or knowledge level. Moreover, Sawacha et al. (1998) show that scaffolding activities are one of the main causes of construction risks. Therefore, proper safety training is crucial in reducing the risks associated with scaffolding activities (Sawacha et al., 1998).

Research Methodology

In this study, our main objective is to train the site workers against construction hazards during scaffolding activities by using a virtual environment-based safety training tool. For this purpose, we utilized the second version of V-SAFE.v2 which involves only scaffolding activities. V-SAFE.v2 provides a realistic working space to its users and ensures that they are exposed to potential construction accidents in a risk-free environment (Figure 1). Furthermore, V-SAFE.v2 is very user-friendly with its point-and-click design; particular attention was paid to the ease of use, as it was developed for construction workers.

Figure 1: V-SAFE.v2

V-SAFE.v2

First of all, V-SAFE.v2 is supported by a cloud-based learning management system (Cloud LMS). By using Cloud LMS, the necessary information is stored and analyzed in the system. V-SAFE.v2 enables workers to be trained collaboratively through its multi-user feature. In real construction sites, workers communicate and interact with each other, therefore, in order for the tool to be efficient, workers should interact simultaneously during the training session.

There are three different modules in V-SAFE.v2; i) Training Module, ii) Test 1 Module, ii) Test 2 Module. In each module, up to three participants can be trained simultaneously. In the Training Module, V-SAFE.v2 guides the participants and provides necessary information through written assistance and flashing objects. In other words, workers learn how to safely perform the scaffolding activities. In Test 1 Module, participants perform the construction tasks without any guidance and the performance of each trainee is recorded automatically for providing feedbacks. The training tool can also be utilized by a single user, where the other two roles are controlled by an autonomous agent. The autonomous agents follow the right sequence of steps so that the software would be able to evaluate the individual worker performance.

Moreover, the Test 2 Module is also supported by autonomous agents which can perform the task incorrectly. Therefore, if the autonomous agent is selected in a way to act incorrectly, there will be an accident in Test 2 Module. Accordingly, all trainees could experience an accident that raises awareness of the consequences of catastrophic cases.

Experiment Setting

In this study, 7 construction workers participated in the experiments (Figure 2). The subjects were working in the roof installation team of a large-scale infrastructure project in Istanbul. The workers who built the roof assembly on the scaffold were experienced in the

installation and dismantling of scaffolding.

The experiment is divided into 3 major steps. In the first step, workers were asked to fill a questionnaire that contains questions regarding their background, age, ability to use computers, experience on computer games, and their expertise in the construction industry. They also responded to a paper-based exam containing 10 multiple choice questions on scaffolding safety. Accordingly, the pre-training knowledge of workers on scaffolding safety is determined. In the second step, workers used the Training and Test 1 Modules of V-SAFE.v2, so the individual training performance of each worker is evaluated.

Figure 2: Experiment Participant

After completing the testing part, workers received a performance-based feedback report (Figure 3). Once they successfully finish the V-SAFE.v2 training, they were again asked to respond to the same exam questions. Hence, their pre-training and post-training answers are compared.

Figure 3: V-SAFE.v2 Feedback.

Results and Discussion

A wide variety of construction activities incur site workers to hazards and scaffolding activities are one of the most dangerous construction activities. Therefore, ensuring safety on site is essential to keep workers away from hazard sources. In this respect, we aimed to develop an effective safety training method to simulate the scaffolding activities, which is an essential and common activity of almost all construction projects. For this purpose, we utilized the second version of V-SAFE, which involves only scaffolding activities.

In order to validate the effectiveness of V-SAFE.v2, we conducted an experiment with real construction workers who perform construction activities on scaffolds. Using construction workers in such experiments is not a common practice, a great percentage of scientific experiments were conducted using students or engineers who are well educated. Yet, most of the construction workers are uneducated, therefore it is extremely important directly using workers to collect their feedback on the tool rather than using engineers or students. Fang et al., (2015) mentioned that lack of education and training are the major reasons behind the worker's shortage of hazard recognition. Therefore, our research study is essential since we train workers and present their safety performance.

As shown in Table 1, 7 construction workers were selected to perform the experiment, they have different ages, site experience, and duties. As shown in the same table, only two of them have not played a computer game before, while the other five workers have played computer games. We also gathered information about the computer games they played. Only three of them have played 3D games, while the other 4 workers had never experienced a virtual environment before.

Table 1: Pre-test Questionnaire Results

Participants	Age	Duty	Experience (years)	Computer Games	3D Computer Games
CW1	31	Unskilled Worker	1	Yes	No
CW2	34	Assembler	12	Yes	Yes
CW3	49	Assembler	6	No	No
CW4	40	Foreman	20	Yes	Yes
CW5	27	Assembler	5	Yes	Yes
CW6	30	Foreman	10	Yes	No
CW7	39	Assembler	20	No	No

In the first stage of the experiment, a paper based multiple choice exam was conducted to measure the occupational safety and scaffolding knowledge of the

field workers before the training. We prepared the exam questions based on the scaffolding safety guideline published by The Ministry of Labor and Social Security in Turkey. In this test, the construction workers made an average of 5 mistakes in 10 questions. Following the written test, field workers received a highly engaging safety training on scaffolding activities through V-SAFE.v2. After completing the V-SAFE.v2 training phase, participants proceeded to the Test 1 Module, where they performed tasks without any guidance or assistance from the system. Participants who completed the V-SAFE.v2 test module responded to the same 10 questions. According to the written test results, participants made an average of 2.86 mistakes in 10 questions after receiving a highly engaging safety training through V-SAFE.v2. We then compared the pre-training and post-training exam scores using paired t test. According to the analysis results, a significant increase was observed in the test scores. In other words, participants performed better in the written exam after the training. This corresponds to the outcome of a study (Guo et al., 2016) that claims virtual reality safety training leads to better results than conventional way of training.

Table 2: Test Results (Pre-V-SAFE.v2 & Post V-SAFE.v2)

Participant	Paper-based Exam	
	#of Mistakes	
	Pre-V-Safe.v2	Post-V-Safe.v2
CW1	5	3
CW2	5	3
CW3	5	3
CW4	5	2
CW5	5	3
CW6	5	4
CW7	5	2
Average	5	2.86

Cameron et al., (2011) discusses that training has a positive impact on trainees in terms of transforming theoretical information into reality. The experimental results also affirm that experiential learning is substantial in terms of scaffolding activities in V-SAFE.v2. While participants could only answer half of the questions correctly, after training in a virtual environment, their safety knowledge is enhanced and the number of mistakes they made significantly reduced. Similarly, Hollowell et al. (2016) also showed that trainees are able to distinguish construction process sequences more clearly in the virtual environment. Therefore, one can conclude that enhanced spatial knowledge representation through

virtual environment, enables greater opportunities for experiential learning.

Conclusion

To sum up, virtual technologies have been exceedingly used in the construction industry, however, a limited number of research has concentrated on using virtual environments for simulating scaffolding activities. These activities are common, complicated and expose workers to hazards, therefore, providing safety during scaffolding activities is essential. In the construction industry, virtual technology applications have been used in occupational safety in recent years. It is difficult for untrained construction workers without computer literacy to use complex safety tools based on virtual environments. However, V-SAFE.v2 is highly user-friendly, therefore the workers can perform the tasks without having any difficulty. The results show that the simplicity of application is required to achieve the desired results. The development of workers' safety knowledge is the most important indicator of the functionality of having a simple interface in the training tool. Many studies pointed out the importance of hands-on-practice during safety training, however, construction companies still prioritize the traditional safety training methods, such as presentations, and lectures, in which it fails to provide hands-on-practice. In this sense, V-SAFE.v2 provides a great opportunity of repetitive practice in a risk free environment. An important limitation of this study is about the number of participants, which is quite essential in such experiments, more than seven participants are required to truly conclude that the findings are significant. Furthermore, the study does not compare conventional ways of training with virtual training methods, future studies are planned to include the comparison of both methods. Furthermore, due to the small number of participants, the multiuser capabilities of V-SAFE.v2 were not utilized, however, the multiuser property has a high potential to increase the effectiveness of the tool in safety training. In a nutshell, in this study, we aim to train workers on scaffolding activities without any exposure to risk by using virtual environments. In this regard initial findings indicate that V-SAFE.v2 has a high potential in effective occupational safety training.

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BIM-BASED AUGMENTED REALITY TOOL FOR THE MONITORING OF CONSTRUCTION PERFORMANCE AND PROGRESS

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Abstract

The construction industry is still lagging behind other industries in adopting new technologies for monitoring of performance and progress of construction works. In other industries like production or automotive such processes are already partly or fully automated. To improve effectiveness of construction scheduling and quality of works, this research proposes a BIM-based augmented reality application for site managers so-called AR4C. This application is combining Location-Based Management System and Building Information Modeling (BIM) to visualize in Augmented Reality key information related to progress and performance of construction works superimposed on the real world. This paper describes methodologies and technologies implemented in the AR4C application to control effectively construction works.

Introduction

The construction industry is a project-based industry characterized by heterogeneity, extreme complexity, fragmented supply chain and variability of trade performance. Construction projects are subjected to high risk in terms of schedule deviation due to inefficient processes and poor communication, which generate up to 30% of construction costs (The Economist, 15/01/2000). In addition, some unpredictable factors like weather conditions can extend the duration of certain construction tasks. Olawale & Sun (2010) found that in UK, 60% of construction project organizations struggle with time and cost overruns on more than 10% of their projects. According to statistics published by KPMG in 2015 on the global construction industry, only 25% of projects came within 10% of their original deadlines in the past three years. This occurs, because inadequate and inaccurate monitoring and control processes are practiced on worksites (Memon et al., 2012). An effective monitoring of construction performance and progress is crucial to deliver project on time within the established budget (Nassar, 2009). Continuous verification of project status allows site manager to identify problems early and make conscious decisions on time to prevent scheduling deviations (Maalek & Sadehpour, 2012). In conventional processes,

monitoring and controlling of construction works is mostly done by manual and paper-based methods (Navon, 2007). It is time-consuming process, which requires that site managers analyze and calculate huge amount of data and fill paper forms. In addition, site managers often do not have at their disposal tools to visualize and represent the information in a simple and user-friendly manner (Lee, S., Pena-Mora, 2006).

To provide site managers with meaningful data on project performance and progress, it is important to introduce efficient monitoring methods. It is possible to reduce execution schedule deviations up to 15% (IBC, 2000), project cost up to 10% (IBC, 1999) as well as cost of reworks, claims and disputes (Yates & Epstein, 2006), if successful progress monitoring is applied. It is important to identify a management system that enables an efficient method to collect data on project progress and performance. A promising management system is a Location-based Management System (LBMS). Seppänen (2009) found that it is possible to achieve a duration compression of 10% with schedule optimization. Seppänen et al. (2014) evaluated that LBMS is able to increase production rate on average 37% and prevents production problems by 50%. LBMS supports the effective allocation of resources and the reduction of waste, which are related to some lean construction principles (Andersson & Christensen, 2007). LBMS requires a constant monitoring of productivity rates and resource distribution, since these factors are recognized as waste, if managed inefficiently (Kenley and Seppänen, 2010). Beyond scheduling monitoring, an important aspect of performance is the quality control of performed works. According to Mills et al. (2009) omissions in quality controls may cause construction errors and quality degradation, which negatively affect both costs and project schedule. Therefore, insufficient management and low quality control affects delays, project profitability, cost increase (Zavadskas et al., 2014) and it has relevant impacts on productivity (Yi & Chan, 2014).

Once site managers dispose of information on project performance and progress, it is important to visualize and highlight the most important data. The representation of project status data can be done through a dashboard, which displays information on

key performance indicators (KPIs). It can save time of site managers in reviewing reports and calculating data. Dashboard provides KPIs values according to predefined goals and shows at a glance the current project status. It provides a better understanding of the project, allows site managers to make fast decisions and corrective actions (Lamprey & Fayek, 2012). Augmented Reality (AR) is promising technology to improve visualization of such information directly on the construction site. Kopsida & Brilakis (2013) investigated the use of AR for project progress monitoring as a way to compare it to the as-planned schedule.

Background on systems for performance and progress monitoring

The Information and Communication Technologies (ICT) utilization ratio in the construction industry is still relatively low (Dehlin & Olofsson, 2008). McKinsey Global Institute Industry Digitization Index from 2015 (McKinsey Global Institute, 2016) classified the construction industry at the end of the list. It does not mean that the construction industry does not attempt to adopt new solution and technologies. Construction companies are willing to test new ICT solutions that can improve design and construction processes. Nevertheless, there are several barriers (organizational, technical, lack of skilled employees, social and habitual resistance to change, etc.) to fully implement ICT solutions and automate conventional processes. In recent years, the effort put in the adoption of ICT in the construction industry has had a significant impact on both productivity and economic growth of construction companies (Kenley & Seppänen, 2010). Along with the development of technologies like Building Information Modeling (BIM), Augmented Reality (AR), Virtual Reality (VR) and Internet of Things (e.g. near-field communication (NFC) and radio-frequency identification (RFID) sensors), new hardware and software tools have been introduced to the construction industry, especially in the design and construction phase. These technologies allow the automation of construction processes and have potentiality to improve monitoring of construction works and manage information flow as well as reduce construction errors. Leading commercial software companies are proposing solutions for automating construction project control. BIM-based construction management platforms and mobile filed applications enable users to automate planning and monitoring of construction works, management of documents as well as information sharing on project status. Autodesk® BIM360 Docs™, Oracle Aconex Connected BIM, Oracle Latista, Tekla BIMsight, Dalux TwinBIM are some examples of them. These solutions use BIM model of the project to facilitate controlling process and integrate often Augmented Reality/Virtual Reality technology to

access the most current project information through the 3D model. The 3D model is overlaid into the real perspective. Increasing automation of controlling processes on site, due to BIM and AR technology, can improve decision-making process, provide real-time access to information and report issues. Nevertheless, these applications do not support the monitoring of construction process and performance and do not manage construction process according to lean management practices. If consider applications that manage projects according to lean construction methods, such as Autodesk® BIM 360 Plan™, Trimble Vico Office, VisiLean, the use of AR technology to display 3D building model superimposed on the real world with all task related information and with construction progress and performance KPIs has not been integrated yet. VTT Technical Research Centre has been developing an AR implementation VisiLean to display 3D models in AR, but it is an external applications. So, it emerges that the integration of AR to provide context-aware project and progress information related to construction works could be investigated for BIM and Lean Construction application.

Moreover, literature review shows that research projects have been carried out to provide visual information on project performance and progress. KanBIM is BIM-based system to support production planning and day-to-day production control on construction sites based on the Last Planner System. It provides visual information reported on building model (Sacks et al., 2013). D4 AR - a new image-based modeling technique for visualizing progress discrepancies between as-planned and as-built is using daily progress photographs and superimposition of the reconstructed scene over as-planned 4D models (Golparvar-Fard et al., 2009). Golparvar-Fard et al. (2009) and Roh et al. (2009) have developed an augmented reality model that enables user to walk through the construction site and display progress status. Kopsida and Brilakis (2016) proposed a solution for markerless mobile-based augmented reality solution to assist inspection and progress monitoring for interior activities by displaying 3D as-planned BIM model and detecting differences with actual construction. In the ACCEPT project (Ratajczak et al., 2017), a system for construction management was developed, which uses smart glasses and smartphone to display in AR overlaid digital model and information onto real construction environment. However, in these research projects, the monitoring and controlling of project performance and progress according to lean construction method through AR has not be proposed.

Proposed solution

This research paper describes a BIM, AR and Lean-based mobile application, so-called AR4C, to support

construction processes on site according to lean construction methods. AR4C aims to improve performance of the construction process by monitoring of construction works on a daily basis in a specific location of the project. The AR4C application is envisioned to enhance the project control by rapidly identification of deviations from project schedule, variation in performance and progress using AR combined with BIM and LBMS. The project controlling methodology applied to AR4C has initiated within the European project - ACCEPT (www.accept-project.com) funded by the Horizon 2020 Framework Programme and has been continued by Fraunhofer Italia and Free University of Bozen-Bolzano in the Ph.D. research project, presented in this paper. In this research, the identified problem is related to the lack of field tools for site managers that use LBMS to monitor construction progress and performance.

The AR4C application addresses this problem and it is envisioned as a field tool mainly for site managers and workers to provide them with context-aware information at anytime and anywhere on the construction site. In this paper, the authors focus on performance and progress controlling that could be potentially done by using the AR4C application. More information on other functionalities of this application can be read in the previous research paper (Ratajczak et al., 2018). The AR4C application is a prototype version and it is developed for the Android smartphone Lenovo Phab 2 Pro, since it integrates Google Project Tango technology like motion tracking and depth perception. This technology gives the ability to detect the device position relative to the world around it with high precision and accuracy. These two features - accuracy and precision are mandatory for displaying 3D model in AR, which is superimposed on the real world location. It is also important to underline that the authors established this research project to investigate benefits that could be reached by using BIM, AR and Lean application on site, but also define obstacles in implementing these technologies and lean methods in construction companies. Human factor plays an essential role in adopting new technologies/methods, so the user experience and acceptance will be evaluated as well.

Methodologies and enabling technologies

The AR4C application supports site managers in the controlling process of construction performance and progress. The main contribution of this research work was focused on the practical and theoretical integration of different technologies and methodologies into one system. The novelty of this integration consists in creating a unique field application that is able to detect easily scheduling deviation by visualizing construction progress in AR, to provide daily progress and performance data of construction work as well as

to provide context-aware information/documents on scheduled tasks. To enable these functionalities several methodologies and technologies have been implemented in AR4C. Their description and implementation is reported below.

Building Information Modeling (BIM)

BIM is a 3D model-based process of generating and managing building data (e.g. geometry, spatial relationships, quantities, properties of building components, etc.) during its life cycle. BIM is also a tool that facilitates more integrated design and construction process, which results in increased productivity and accuracy during the design and construction phase, better quality of buildings at lower cost and reduced project duration (Eastman et al. 2008). In AR4C, BIM is used to provide 3D interactive model that can provide geometrical and technical data on components and materials, and locations associated to each component/material by using specific codes. This information forms a reliable basis for monitoring of construction works and it is imported to AR4C using exchange file formats like .fbx and .xml.

Lean construction methods

Lean construction is a management approach based on principles of the Toyota Production System, which has been adopted to the construction context. It focuses on removing waste, creating value for the customer, and continuous improvement (Sacks et al., 2010). According to Kenley & Seppänen (2010), LBMS can be considered as a lean technique, since it focuses on production control based on pull controlling. In LBMS, construction activities and their controlling refer always to locations. Organization of activities by locations provides more comprehensive information, avoids interruption between different trades, and enhances constancy of the workflow (Kenley & Seppänen, 2010). It can also increase productivity and prevent production problems, which cause cascading delays and impact project durations by 10% (Seppänen, 2009).

In AR4C, task scheduling is defined according to location hierarchy level with respective codes, so-called LBS codes (Location Breakdown Structure). Codes can be defined based on three-level hierarchy (Figure 1). Each of the location hierarchy has a different scope. The highest level (level 1) refers to locations, where structure can be built independently (e.g. individual buildings or parts of large building). The middle level (level 2) should be defined to plan production flow of structures, so it refers always to floors. The lowest level (level 3) is used to plan effectively construction tasks at detailed level. It is important to define locations in a way to carry out accurate monitoring of task progress. In AR4C, LBS codes are composed by combining abbreviation of location nomenclature at each level, e.g.

BLDG1.F1.U1: Building 1 - Floor 1 - Unit 1. Moreover, task hierarchy has been introduced in LMBS. Each construction task is defined by WBS code (Work breakdown Structure) and aforementioned LBS code. The combination of both codes provides a unique nomenclature for each task, so-called WBS/LBS code, which is used in the AR4C to identify a specific task in a specific location. By embedding these codes in 3D building model in properties and parameters of its elements/materials (as shown in Figure 1), the application is able to display information on performance and progress related to a specific location for selected tasks or group of tasks and highlight progress status of objects, which contain these codes.

Figure 1 Codification of tasks and locations in BIM

Tiered methodology

The Tiered Structure (TS) methodology has been adopted to provide tailored KPIs on construction performance and progress to different stakeholders of the construction project. A message communicated by KPIs should yield information that is meaningful, timely, and reliable for a specific group of stakeholders in order to make conscious and rapid decisions. For this reason, TS methodology introduces four levels (tiers) of information granularity, which refer to project work breakdown structure and business owners of each level. This methodology is comprised of four tiers (Tier 0-3):

- **Tier 0** represents high-level of project information - building level, where tailored information are delivered to the client and to the project manager.
- **Tier 1** refers to construction work package level (e.g. structures) and are delivered to the project manager and site manager.

- **Tier 2** is related to construction task level (e.g. concrete slab). The owner of this level is a site manager.
- **Tier 3** represents the lowest level of the project information – workflow, which defines a sequence of construction activities (e.g. formworks, steel bar reinforcements, etc.) that should be performed by a crew to complete a task on tier 2. This tier creates a foundation for the monitoring of the entire construction process of the project.

Monitoring of construction performance and progress

The concept of “pitching” (Dallasega et al., 2013) is used to apply LBMS and thus entails the opportunity to schedule and monitor location-based tasks on a daily basis. One “Pitch” is defined as the maximum daily job content that can be done by a composed crew of workers within a certain location. LBMS considers that the project is broken down to physical location, to which different activities can be assigned. The construction production is defined according to TS methodology, which offers the possibility to granulate information and measure construction performance and process at different levels (tiers). To plan and schedule the construction production according to LBMS and TS, site manager creates workflows (a sequence of activities that are needed to complete a task) for a specific location and assign crews/workers to those activities. Workflows refer to tier 3. The workflow is attached to a task (tier 2) that has to be performed in a given period. Once scheduling is done, the monitoring of activities of running task can start. Monitoring is done by foreman on a daily basis by reporting the percentage or absolute value of completed activities (input data). If a daily goal has not been met, the remained work content will be considered during the following days. Through the daily monitoring of activities, the collected input data are used for calculations of construction performance and progress KPIs, which are afterwards displayed on 3D model in AR. The monitoring at the lowest measureable level (activities-tier 3) is applied, because it allows the projection and aggregation of information to deliver the overall process status on superior tiers.

Performance and progress indicators

Construction industry does not have standardized measurement of performance indicators. Indicators should be in line with business goals and conform to company benchmark. The construction project is considered successful, if reaches desirable performance in terms of cost (within the budget), safety (accident free project), schedule (on-time project) and quality (conformance with specifications and standards) (Forbes & Ahmed, 2011).

In the AR4C project, KPIs focus on areas of productivity, project schedule, quality and costs.

Table 1 summarizes main KPIs considered. The definition of each KPIs refers to the activity level (tier 3). The most of these KPIs are reported to superior tiers by doing data aggregation from lower tiers.

Table 1: KPIs considered in the AR4C application

KPIs	Definition
Current Progress – CP	CP [%] is a relation of the pitch content of a single activity to the overall pitch content of the whole workflow.
Performance Ability Ratio – PAR	PAR-value [-] is the ratio of the defined content of 1 Pitch to the actual measured progress on-site. Value >1 indicates a lack of performance with respect to the expected performance. Value = 1 means that the foreseen goal has been met. Value < 1 refers to a more powerful performance than expected. Ranking activities regarding this criterion provides perception towards improvement potentials of single activities.
Reason for non-completion - RNC	RNC [-] states a root cause for non-completed activities on time. It allows the analysis of poorly running task.
Percent Plan Completed – PPC	PPC [%] is the ratio of fulfilled assignments (achieved goals) to the total number of assignments scheduled for a particular day. If the goal is achieved PPC value is 100%, if not it is 0%. The PPC-value provides information regarding the reliability of the scheduling and the smoothness of the workflow.
Delay Indicator - DI	DI [days] is a difference between planned working days and remaining days (calculated only for tier 3)
Extra Effort - EE	EE [days] is a sum of Delay Indicator of each activity in a task or tasks of a work package (calculated only for tier 0-2)
Quality gate - QG	QG [-] is a number of fulfilled quality checklists out of total number of checks assigned to a tasks
Construction errors - CE	CE [-] is a number of construction errors detected during inspections by site manager
Extra costs - EC	EC [€] is an additional cost calculated as a multiplication of extra effort expressed in days per cost rates for men-hours in terms of labor costs.

Augmented Reality (AR)

AR is a technology that overlays on a real world environment a computer-generated content like images, videos, animations, text, etc. In the construction industry, AR is recognized as a promising technology to improve monitoring of construction works and project communication. It is possible to show as-planned and as-built project and visualize the construction progress (Zollmann, 2014). In addition, AR can facilitate the understanding of project documentation, construction progress through 3D visualization of models on site (Meža et al., 2015). In the AR4C application, AR technology enables users to interact with 3D building model and embedded information in the model. Moreover, it displays in AR progress of construction task according to user's location by coloring elements of the 3D model that are superimposed on the real world. So, the deviation from the master schedule can be easily detected. Moreover, this AR visualization will be accompanied by performance and progress KPIs.

Dashboard

Dashboard is a visual interface to report most significant information at a glance through KPIs that are relevant to meet predefined objectives of the project. Dashboard helps keeping the project within the schedule and budget. It also reduces labor effort put in manual intensive reporting process. In this research project, aforementioned methodologies has been implemented and tested in a dashboard, which was developed as a web based application during the European project – ACCEPT, funded within the Horizon 2020 Framework Program. In the AR4C application, it is planned to integrate a dashboard view in order to provide users with the possibility to choose information at different levels of the project and not only focus on KPIs at task level.

AR4C and Dashboard prototype

The AR4C application is under development and currently has reached the maturity at the level 4 according to TRL scale (Technology Readiness Level). The dashboard is a prototype with TRL4 as well. It means that the main contribution was done in design, development and lab testing of single components and processes of both applications.

System Architecture

To create the AR4C prototype, Unity was chosen as a main development environment. The application is composed of several components such as: a) **3D model Management**; b) **Data Management**; and c) **GUI Management**. It is necessary to import external assets to component a) and b) like 3D BIM model using .fbx file and its metadata via .xml file, respectively. Component c) allows the visualization of 3D model in AR and related information within the Graphical User Interface (GUI). External APIs are integrated with

Unity: a) **Tango SDK**, which provides different features to gather information on the device position and orientation and to interact with it; b) **Firestore SDK**, which stores digital assets like, images, video, checklist, drawings and allows the AR4C application to access them whenever needed. It acts as a centralized database of the application. Scheduling data are prepared in an external software – Ms Project according to LBMS requirements and are imported to the Unity via xml. file. Master schedule contains the same WBS and LBS codes as in BIM model, task and work packages names as well as benchmark project data (e.g. durations).

Regarding the dashboard, it is an interactive web based-platform, which provides users with KPIs referred to a specific location of the construction project. The Dashboard home page is divided into 3 sections: a) **3D BIM Viewer** of the current project status (Figure 2); b) **panel for displaying the information** relevant to the selected level (tier) of the project (Figure 3), and c) **graphs** to illustrate trends of several KPIs (Figure 4). Currently it is out-standing

application and it has not been integrated in AR4C yet. Dashboard is a tool, which is fed with data collected from the construction site. Data are actually collected using Excel sheet and are imported manually to the dashboard.

Figure 2 3D Viewer in the Dashboard.

Figure 3 Information panel with construction progress and performance data for the workflow level.

Figure 4 Graphical representation of PAR value trend.

Functionalities

Table 2 lists functionalities that have been implemented in the AR4C application so far. More information on implemented functionalities can be also found in Ratajczak et al. (2018).

Table 2: Implemented functionalities in AR4C

Functionality	Description
Navigate 3D Model	The user navigates the 3D model in the application by walking in the real environment (Figure 5)
Visualize Element Information	The user can touch every element in the 3D model, and extract information from it (Figure 6).
Read Geometry Information	The user can visualize technical data of a given component.
Filter 3D Model	The user can enable and disable different layers of the 3D model (Figure 5).
Consult Task List	The user can consult a list of tasks currently available.
Upload/Read Note	The user can: <ul style="list-style-type: none">• type/read a note related to a selected component• upload/download the note to/from the shared database by touching a button.

building. The difference was variable and approximately varied between 0,4 and 1 meters. This test provided indications to improve the accuracy of the visualization of the 3D building model in AR. In these testing users were involved to provide their feedback on the usability of the application. It was done through focus groups, where users could use the application and fill out a questionnaire. Almost all respondents considered that it is very likely that the information provided by the AR4C prototype will allow a faster access to relevant information on site and will improve the productivity of the construction process, if the monitoring of construction works will be implemented.

Figure 5 Test of 3D model alignment on the real building.

Further research

System integration

The AR4C application requires further integration. To visualize data as it is currently done in 3D BIM Viewer in the dashboard and to enhance the project controlling by site manager during the inspection, it is necessary to develop components, which read construction progress and process KPIs for running construction tasks and correlate them with elements of the 3D model by means of WBS and LBS codes. Users should be able to access data in AR4C and see the construction performance and progress of tasks in their current location. These data should be displayed in AR by highlighting building components in different colors (red – behind schedule, green – on time, blue – ahead schedule) with KPIs values. To each KPIs a color bullets are also displayed to approximately indicate a criticality level for detected deviations that can have an impact on the overall project performance (green= no impact on the project; yellow = deviations are tolerable and do not impact on the project); orange = heightened criticality of the project performance), red = very critical to the project). A mock-up of this implementation is shown in Figure 8.

Another planned aspect in this research is the integration of the automatic recognition of locations in the construction site according to LBS codes. It is required to provide information on scheduled tasks, checklist, progress and performance KPIs, while site manager is walking through the construction site.

For that reason, the use of Bluetooth low energy beacons will be investigated in order to offer contextualized information. By applying beacons and naming them with LBS codes, the AR4C will be able to recognize, which beacon is approaching and in consequence will display scheduled task as well as visualize information on task progress and performance. Schweigkofler et al. (2018) have in part investigated this approach.

Figure 8 Visualization of construction progress in AR with performance KPIs for a specific task

Validation

As further activities in the AR4C project, it is planned to conduct testing in a construction site to evaluate benefits and obstacles that can be generated by introducing the AR4C application in real world environment. It will be important to determine, if the proposed monitoring method can improve the project control and anticipate corrective decisions. In addition, it will be attempt to evaluate how this method can improve the productivity of the construction process. Since the research project is performed in the collaboration with the construction company - Budimex in Poland, the application will be tested in one of its construction projects. The user acceptance and experience will be also fundamental during the validation phase. For this reason, people from the construction site will be asked to evaluate the AR4C application by using it in predefined scenarios, which will simulate a real situation on site. Beyond the end-user test, the authors will focus also on: a) defining with site manager KPIs that are relevant for Budimex, b) defining benchmark and ranges for these KPIs, c) and measuring KPIs.

Conclusion

This paper describes methodologies, technologies as well as implemented and planned functionalities in a mobile AR application for the construction site, so-called AR4C, which runs on the Android smartphone - Lenovo Phab 2 Pro. It provides users with context-aware information related to the construction project like 3D model, technical features of building components and materials, list of construction tasks, installation procedures as well as quality and

construction checklists. The application integrates lean construction techniques like Location-based Management System (LBMS) with Building Information Modeling (BIM) in order to support the efficient management of construction works on site. So far, preliminary tests of AR4C were carried out in two buildings at Fraunhofer Italia. A group of specialists tested the application and provided a good feedback regarding the usability and utility of the application on the construction site. They agreed that the AR4C application could improve the communication by providing a faster access to relevant information on site. It is also likely that it will improve building quality by avoiding construction error and will enhance the productivity of construction processes, when the monitoring of construction works will be implemented. For this reason, the authors plan to implement new features related to the controlling process of construction works through performance and progress KPIs displayed in AR and dashboard view. As a further step, the testing of all methodologies and technologies implemented in AR4C will be carried out on a real construction site.

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Late Breaking Abstracts

USING VIRTUAL REALITY TO MODEL WAYFINDING BEHAVIOUR

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1 BACKGROUND AND IDENTIFICATION OF PROBLEM / KNOWLEDGE GAP

It is widely reported that Virtual Reality Environments (VRE) hold potential in the architecture, engineering and construction sectors (AEC) for providing the experience of a building at various stages prior to completion (Whyte and Nikolić, 2018). Most commonly, this includes the design phase especially as a tool for collaboration, and during construction especially as a tool to increase efficiency and identify potential mistakes. There is an implicit assumption in accepting these ideas that the representation produced and experienced in the VRE is in some way analogous to the environment that will be experienced in the Real world. Furthermore, especially in its use in the design phase and with the recognition of the importance of participatory design and stakeholder involvement, VR is seen as a tool for testing and predicting occupant behaviours. However, it is not clear to what extent the Virtual experience is representative of the Real experience, and how we should embrace and accommodate any differences. There is an acknowledged “lack of appropriate validation studies” that may be leading to the rapid uptake of VR for potentially unsuitable purposes (Nilsson and Kinatader, 2015:13). Hence the work reported here, although it focusses on wayfinding and navigation as one part of the building experience, has wider implications for the use of VR in AEC, and more specifically the use of VR data as the basis for design decisions.

2 RESEARCH AIM AND METHODOLOGY

This project sought to answer the question: Can a VRE assist in wayfinding and navigation around an unfamiliar Real building? To do this we produced a realistic building model (see Figs.1a,b) in an Oculus Rift head mounted display, and set up in the entrance area of the same Real building. Volunteers completed a wayfinding task, to navigate from the entrance to a specific room, and made the journey in both the VRE and the Real building. The target room (Room 109) was chosen as it provided a limited choice of directions, with distinct signage cues (See Figure 2). Room 109 was reached from the entrance by going up the stairs and then either turning left (the shorter route) or right (the longer route). The room numbering system suggested turning right, increasing from 102 directly in front, 103 to the right, then 104 etc. although 109 is actually more than halfway around. Participants were divided into two groups – GROUP 1 carried out the task in the VRE first, then the Real building; GROUP 2 carried out the task in the Real building first, then the VRE. A total of 60 journeys were recorded, including the time and route taken (see Figs.3a -d below).

Figures 1a, 1b: Stairs as seen in the Real Environment (RE) left, and Virtual Environment (VRE) right.
Participants had to decide whether to turn left or right at the top of the stairs

3 RESEARCH FINDINGS

Figures 3a-d summarise the results, and show that both Groups made similar choices in their route selection, with a far greater proportion taking the shorter route second time around, whether this was in the VRE or Real building, with a consequently similar reduction in average time taken. Taken at face value, this suggests that an immersive Virtual Reality Environment can be used to model and predict the behaviour of occupants in wayfinding and becoming familiar with the layout of a building. However, we also noted subtle but important differences in the way the two environments were experienced, including greater risk taking in the VRE (e.g. jumps), and more head movement in

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the Real environment. Therefore, we need to adopt a cautious approach when designing by VR, and recognise that the results of behaviour tests in a VRE should complement design decisions, rather than act as their sole justification.

Figure 2: Isometric view of the Case Study building, showing Wayfinding Task 'Start' and 'Finish', and individual routes taken. Note the choice of two primary routes: turning left or right at the top of the stairs.

Fig. 4a: GROUP1 VR first (average time: 43.9secs)

Fig. 4b: GROUP1 Real second (average time 39.9secs)

Fig. 4c: GROUP2 Real first (average time: 46.6secs)

Fig. 4b: GROUP2 VR second (average time 35.0secs)

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THE LOGIC OF KNOWLEDGE

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1 BACKGROUND AND IDENTIFICATION OF PROBLEM / KNOWLEDGE GAP

Construction and the built environment sector has often be represented as being functionally unsustainable and inherently inefficient. External judgements are made on its poor financial stability, poor environmental performance and social failure. Internal assessments focus on poor satisfaction of client requirements, regulatory compliance and a failure to learn from recommendations and advisory material. This paper is intended to address the problem of failure to accumulate and apply knowledge systematically, leaving the sector dependant on tacit knowledge, experience and habits. There are plenty of research publication outlining compliance checking solutions based on labour-intensive programming of relatively specific problems, their accumulation into desktop tools (Solibri 1998 onwards) and one example of an integrated solution. The Singapore Governments ePlanCheck (1998-2004) system demonstrated that by bringing together regulatory domain experts, BIM schema experts and procedural coding skills, a solution was developed that accurately checked design proposals against the then current zoning, spatial and architectural building compliance regulations. The apparent success of this implementation led to optimism that other regulations regime could be addressed in the USA, Norway and UK. Successful proof-of-concepts were made for Scottish apartment-noise performance regulations, and of delivering prioritised advice on mitigating the risk of falls for the UK Health and Safety Executive. The reality was that the solution failed to address two key success criteria: efficiency and acceptability. Requirements are specific to an individual project, and regulations are revised on a 2-5 yearly cycle. It would never be feasible to apply the three-party resources used in the Singapore project continuously to maintain, let-alone extend, the scope. In the USA building code compliance is specified and administered at the level of 3000 independent counties. The acceptability of the results was also challenged in that there was no demonstrable connection between the authoritative text of the regulations and the results. Whilst other sectors, such a finance and medicine, are able to apply considerable resources to individual sub-problems, construction needs a generic approach so as to exploit the limited investment in process improvement and R&D effectively. Operable knowledge is the knowledge that can be used systematically to drive design and engineering development and to the verify compliance systematically. The knowledge gap is how to render knowledge operable.

2 RESEARCH AIM AND METHODOLOGY

AEC3 recognised that the problem could not be solved incrementally for example by gradual improvements in the style of source normative material, the adoption of different coding languages nor the simplification of the information models being presented. Regulatory experts were attempting to place key phrases into a regular spreadsheet structure. The structure of these spreadsheets seemed constantly expanding. Section, paragraph and sentence structures seemed to offer unlimited levels of complexity. Some authors had attempted to enumerate the number of requirement structures found but there was no reason to expect that there could be an upper limit, given the often-convoluted language constructs arising from committee and consensus authoring. It was necessary to separate the logical structure of normative documents from the interpretation of terms and exploit existing robust rule engines

The paradigm shift (Nisbet, 2008) came in recognising that the recursive structure of language and the roles of individual adjectives and nouns fell into four distinct categories. Operable knowledge occurs as words and sections applying, narrowing, broadening, and excluding scope. The application to the scope can be normative, definitive or descriptive.

The four categories transcend language, grammar and style. The skill to recognise the categories in the source text can be found in the regulatory experts who are most familiar with the text. The identified terms can be catalogued in a dictionary (strictly a thesaurus), along with explanatory plain language expressions to support any extended dialogue

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with applicants. Technical objects and query strings applicable to the descriptive resources such as reports or BIM models can be added.

3 RESEARCH FINDINGS

The novelty of this conceptualisation of knowledge represents a challenge to the current assumptions in this sector and beyond. The challenge has been met in two ways: firstly, by indicating a theoretical basis, and secondly by showing its application in practice.

The four-fold analysis can be analogised with the Aristotelian square-of-opposition terms used for predicate logic (Hjelseth, 2011). It can be associated to the four operators found in computer logic ('AND', 'OR', 'NOTAND' and 'NOTOR'). Taken together these create an assurance the conceptualisation is complete and effective. Other logical operators that are included in the literature of logic such as 'exclusive-or' and 'if-and-only-if' can be represented using the four categories when written out in full plain text and marked-up.

The methodology has been exploited in a number of demonstrations and trials. A clause of the US ICC IECC was captured and delivered as a resource for three distinct checking engines within a few weeks of the conceptualisation being announced. Large tables of requirements for the US NIBS WBDG hospital design guide were captured and checked against a reference hospital design. Suggested room-swaps were checked as a design support tool. In 2016 the UK 'InnovateUK RegBIM' project (Beach, 2013) showed that parts of UK Building regulations and the BREEAM environmental guidance scheme could be captured and checked against a BIM model. The mark-up was used to automatically generate intermediate representations, such as the IFC constraint schema and the Java Drools rule representation. Subsequently, SPARQL, DMN and Java/C++procedural-code representations have been generated automatically for use by other applications. In 2017 AEC3 began development of a workbench using the source marked-up text directly. This is now operational and offers the opportunity for inclusion of features not always available through other rule-engines such as heuristics, tracking of unknowns, and the introduction of uncertainty.

A third response showing that this work can 'move-the-dial' of the perception of automated code compliance amongst UK construction experts began last year with the authoring and collation of an industry-wide questionnaire under the UK CDBB DCOM initiative. These results will form the baseline for specific trials next year.

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TOWARDS AUTOMATED QUALITY ASSESSMENT OF CONSTRUCTION ELEMENTS

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1 BACKGROUND AND IDENTIFICATION OF PROBLEM / KNOWLEDGE GAP

Construction progress monitoring has gained increasing interest in the recent decade due to the implementation of Building Information Modeling and affordable and efficient Reality Capture technologies. The latter include Laser scanning (Bosché and Haas, 2008) as well as photogrammetric methods (Golparvar-Fard *et al.*, 2009). Scan-vs-BIM methods allow an as-planned vs. as-built comparison to make inferences on the presence of individual construction elements. With the incorporation of 4D data, statements on the construction progress are possible (Turkan *et al.*, 2012). However, point clouds do not always provide sufficient or adequate information for quality assessment. Thus, recent research has been focussing on image-based methods and deep learning to solve this problem. For example, several researchers effectively detect cracks in asphalt or concrete elements using images instead of 3D point clouds (Nhat-Duc, Nguyen and Tran, 2018).

The authors propose to incorporate photogrammetry-based Scan-vs-BIM workflows with image-based processing enhancements to make detailed inferences on construction quality as well as providing continuous and semantically-classified image data for QA personnel.

2 RESEARCH AIM AND METHODOLOGY

The presented research aims at the extension of currently established, point cloud-based construction progress monitoring workflows to facilitate quality control during construction. For this purpose, photogrammetric point clouds and the underlying images are used as a basis. The Structure from Motion (SfM) process estimates the initial camera positions for all points of view. The point cloud is then aligned with the corresponding digital building model using well-established site (geo)referencing surveying techniques. With the knowledge of each element and the position of the cameras, the 3D elements can be back-projected into the 2D plane of all images (Braun and Borrmann, 2019). For example, Figure 1 shows a sample of a back-projected column.

Figure 1: Projected 3D geometry of a column into the

It is crucial to mention that not all elements should be back-projected into the image plane. Instead, only those elements that were detected as built in a previous point cloud as-planned vs. as-built detection are back-projected.

After completing the back-projection for all detected elements at all times of observation, a list of all images that contain visual data about any given construction element is obtained automatically (see Figure 2). Additionally, the as-planned vs. as-built comparison returns all 3D points that were matched to this given object, and these points can also be back-projected to the image that they were reconstructed from. This allows identifying the image, that reconstructed most points, which can be seen as the image that shows an element from the best point of view.

In the next step, the 'as-built' textures from the pictures can be projected onto the geometry of the digital model and these textures can be analysed to further assess quality.

Figure 2: directed graph for an element and all images that it is visible on

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3 RESEARCH FINDINGS

The proposed methods were tested on real-world construction sites. Figure 3 shows the resulting relations between all detected elements and the images taken during observation. With the help of this graph, all photos that show a specific element can be quickly identified. This provides an effective means to organise semantically the acquired pictures, which is of value to construction professional when they seek to retrieve visual information about any construction element.

Quality Assessment can be either done manually on these provided pictures, but also in automated ways, e.g., by detecting cracks on the surface of these elements using now increasingly popular (and powerful) deep learning techniques.

Figure 3: Construction elements (top row) and the corresponding pictures they are visible in (bottom row)

In the next step of this research, the gathered textures of construction elements will be prepared for detailed quality checks. This includes already established methods such as crack detection but also other forms of verification that material and surface match the material and geometric specifications contained in the digital model. An interest angle of analysis of this problem is that, in the context of photogrammetric reconstructions, surfaces of construction elements are typically viewed from multiple angles. This means that vision-based quality assessment can leverage results from multiple viewpoints that may be given different levels of reliability.

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GEOMETRIC OPTIMIZATION OF MECHANICAL ELECTRICAL AND PLUMBING (MEP) INFORMATION MODELS

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1 BACKGROUND AND IDENTIFICATION OF PROBLEM / KNOWLEDGE GAP

Building information models of Mechanical, Electrical and Plumbing (MEP) systems are generally characterized by redundant information and a high density of components with irregular shapes. MEP information models, compared with those of other disciplines such as architectural and structural, have (i) an extremely larger number of components, (ii) more complex and significant interrelations with other engineering domains, and (iii) more spatial constraints in general, especially when addressing design changes due to restrictions by other systems. Consequently, they require large storage spaces and are not conducive for exchange and interchange purposes. The geometric optimization of MEP information models can play a significant role in facilitating model exchange and handover by increasing the efficiency of their storage, transmission and display. To date, the body of knowledge on geometric optimization of MEP information models is still very limited. This paper aims to address this knowledge and technical gap as follows.

2 RESEARCH AIM AND METHODOLOGY

This paper presents an approach for the geometric optimization of MEP information models, develop and test a corresponding prototype in real world projects. The approach comprises of:

- **IFC-based model description:** Data models such as IFC are not optimized for storage and their highly structured geometry is demanding in terms of computing cost, making it unsuitable for operations involving a large number of objects in a query (Beetz et al., 2010). The IFC schema, however, defines Boundary Representations (BREP), primitive geometry (e.g. profile sweeping), and Constructive Solid Geometry (CSG) methods. Since each of these methods has unique indispensable characteristics, a multi-form storage mode was adopted in this research: primitive geometry and CSG hold essential abstract information such as lengths, surface areas and profile shapes that are required for collaboration. BREP, a richer form that uses restored topological faces that are reverse engineered from the triangulated, is necessary to obtain the geometries of arbitrary shapes. Hence, model information is stored in two forms, namely IFC files and BIM databases, the former is intended for information sharing purposes with other relevant information systems and actors, while the latter is used to structure model information for storage purpose.
- **Storage optimisation:** it employs a mapping-based model description method and a novel Quadric-Error-Metric (QEM) mesh simplification algorithm, reducing the required storage for such models while maintaining the contour of components. The similarity mapping compares two triangles meshes and the result is compared with a threshold, δ . If the result does not exceed δ , then the two components are similar and the model data will therefore be mapped. The value of the pre-set threshold δ could be adapted according to actual conditions, where a larger value stands for a lower tolerance for matching errors, and vice versa. Quadric Error Metrics (QEM)-based edge-collapsing algorithm simplifies the geometry while controlling the level of simplification to avoid severe distortion of the original model. An edge collapsing cost considering historical errors and overall accumulated error were developed to achieve this goal.
- **Transmission and display optimisation:** to enable efficient compression of data and fulfil the need for cross-platform exchange, the transmission of models employs spherical compression algorithms, fixed-dictionary and GZIP compression. Display optimisation employs a clustering-based normal vector regeneration algorithm for triangle meshes. A multi-step iterative process is used for the normal vector regeneration.

3 RESEARCH FINDINGS

Tested on a complex geometry such as that of fire pump, the simplification algorithm achieved a compression ratio of 80% while maintaining the geometry visually intact (Figure 1). The solution proposed in this study was also

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applied to a large-scale MEP project, the Hedong Station of Guangzhou Metro in Liwan District, Guangzhou, China. The components in the MEP systems are in large numbers and complex shapes, with the number of triangles reaching up to about 10 million and occupying a storage space of around 2 GB of space. Figure 2 shows that the proposed techniques reduced the transmission volume by more than 80% which is considered a significant contribution in terms of time and costs associated with transmission and display of models. Some limitations related to specific algorithms i.e. the similarity-matching algorithm considers coincidences and similarities between meshes after translation, but not after any other geometric transformations such as rotation or scaling) were identified and some issues regarding the selection of certain algorithms (i.e. K-means clustering algorithm requiring as input the number of clusters which is not known in advance) are still open for debate. Moreover, the algorithms proposed are also not easily parallelized. The similarity matching algorithm involves iterating through all the meshes in the model and tests the similarity between each pair; and the mesh simplification algorithm seeks to identify the vertex with the least collapsing error globally, which rules out the potential for the two algorithms to benefit from parallelization. Therefore, this limitation is inherent in the problem addressed itself, instead of in the proposed implementation. The rendering of the models are parallelized and calculated on the GPU, which is implicitly implemented by the graphics facility. The practical use of the proposed solution is in all engineering and construction applications requiring the storage, transmission and display of large volumes of model data, or in the operation stage where the adoption of 3D models is still embryonic.

Figure 1: Different levels of Mesh Simplification for a Fire Pump

Figure 2: Storage optimization and compression of MEP models

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MANAGE THE COMPLEXITY OF ARCHITECTURAL DESIGN THROUGH THE PROACTIVE DESIGN PARADIGM

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1 BACKGROUND AND IDENTIFICATION OF PROBLEM / KNOWLEDGE GAP

Nowadays, the building process shows a low success rate in terms of reliance of imposed time and cost forecasting. The causes are multiple: the lack of collaboration between the actors, the use of tools not suitable for managing the complexity of the contemporary building, the fragmentation of the market and an overall technological delay in production techniques, still linked to a "craft" vision of the building or anchored to a vision of the industrial system of the second or third industrial revolution. These are just some of the lacks affecting the construction chain which, since 2008, has been experiencing a continuous haemorrhage of revenues and personnel (Marchesini, 2016). In order to solve the numerous practical problems of design, architects, like all the process actors, iteratively seek appropriate solutions, which can be implemented according to the available resources (Roewe, 1987). In these conditions, it is essential to systematize information and knowledge about the building organization in a consistent manner, considering that, in the advancement of the various design phases, there may be different types, some due to its own peculiarities that lead to problems such as:

- those due to further design constraints may emerge during the design and construction phases;
- design problems that change because and their temporary solutions (partial or total) interact with the design objectives that change from the initial ones;
- those caused by the long duration of the useful life of the building organization, if compared to other manufacturing sectors, which lead to change the intended use, which are due to adaptation to changing regulations, emergency situations not predictable a priori, etc.;

Therefore, in order to stem the complexity and multiplicity of architectural design, since the earliest times the actors have created canons, styles and repeatable solutions (e.g.: the capitals of temples and the ashlar of Gothic cathedrals) to arrive, in the 20th century, at often ideological strategies (e.g. "form follows function") aimed at reducing such uncertainties and standardizing the approach to problem solving. Now, in the 'Post Industrial Digital Era' an attempt to bind architectural design into solutions where financial risks and technological uncertainties could be predictable (Wang and Crolla, 2018) is currently underway. However, these approaches have demonstrated over time all their limitations until, through the refinement of ICT techniques, digital tools and techniques have revealed the inconsistencies and limitations of this approach given the logical and methodological rigor, applied through algorithms, which did not allow any ambiguity. Subsequently, the construction sector was progressively enriched by new methodologies (e.g. CAD/CAM, BIM, etc.) capable of increasing the collaboration of processes, simplifying the verification cycles by all actors and, for the production of components, connecting the project directly to the machine (digital fabrication). But this transformation did not take place in parallel in the design and construction methodologies and in the process chain. The goal of the research is therefore the definition of a new collaborative design methodology, based on advanced digital modeling tools capable of supporting designers according to the simulative approach. In this way, it is possible to analyse in advance problems and results of design and construction in a virtual environment, avoiding the need to make up for design shortcomings with expensive variations during the work. To achieve this goal, the BIM modeling environment was linked to a simulation environment based on the Agents paradigm. These Agents, governed by their rules, behaviours and objectives, define their actions based on the ability to predict, thanks to the simulation, the results of their choices and, therefore, establish an overall rate of satisfaction of all due requirements.

2 RESEARCH AIM AND METHODOLOGY

The aim of the System under development is to be a design assistant able to interface with the designer, putting to system - through the modeling of these aspects as autonomous interconnected agents - the current practice (eg: data

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from data sheets), cognitive psychology (standard solutions, designer's preferences, conventions, etc..) and computational intelligence, understood in this case as the ability to have such computing power as to be able to launch many simulations on the same phenomenon, analyse and infer on a wider spectrum of cases and increase the accuracy of the final result. In concrete terms, the system is based on the concept of an 'Autonomous Agent', that is an entity capable of carrying out operations according to internal and external conditions, attributes, topology, behavioural rules and set objectives, without direct human control (Wooldridge, 2009). This independence can be declined according to different levels of complexity: In fact, an agent can have very simple behaviours, purely reactive with respect to the application of conditional rules of 'if-then' (PR Predicate Rules), or present ever greater levels of intelligence such as, for example, the behaviour based on the application of rules in an 'event based' relation or from the history of the process (data driven, narrative), until reaching complete autonomy (Castelfranchi and Falcone, 1998) which, also thanks to systems of statistical inference, lead to pro-active behaviour, that is, the condition in which the machine - in addition to prefiguring the outcome of the choices - suggests one or more solutions capable of achieving the best result in relation to the needs to be satisfied. Moreover, the agent has a purely relational nature, aimed at creating multi-agent systems, which are better suited to modeling complex reality and its dynamic interconnections. The prototype was developed to link the results of the iterations that took place in the high intelligence simulative environment (Novembri et al., 2017) Agent-based with the BIM world, using the connection made available by the API (Application Programming Interface), thus creating a continuous, reciprocal, updating of the data of the two levels. Therefore, each BIM object (both instance and prototype) will be replicated in the higher intelligence abstraction level through an "agent system" according to its own rules, objectives and behaviours. Taking as an example a building, this will be modeled in the system through an agent who must achieve objectives, to the extent that the other agents will also have to satisfy theirs. This process works in parallel on BIM objects. It ends when each BIM object has found, satisfying the requirements imposed, its size and characteristics in relation to others.

3 RESEARCH FINDINGS

The results, limited to the example elaborated for the purpose, is the automatic generation of a building detail (building component, procedure, work area, etc.) such as to satisfy all the macro and micro frameworks of the agents involved in where, among other properties, the workers to be employed and the areas to be occupied are inserted, in such a way as to be able to verify also the aspects related to the constructability of the building. The result of this interaction takes place through a graphic interface called 'canvas' that describes, given the executive design of the elements contained in that area, the timing and the actual work area, also taking into account the propaedeutic sequence between the various activities. This Agent System prototype aims to be a design partner, able to dialogue with the actor-designer, first of all imitating the approach modes such as, for example, the ability to think according to different levels of abstraction of intelligence and taking into account the different design solutions, albeit partial. Moreover, the usefulness of this approach is given by the dynamic behaviour of multi-agent systems which, when stimulated, activate the entire respective network of interdependencies in order to elaborate as many solutions as possible necessary to define the "satisfying" state to be reached (Simon, 1996). Moreover, in addition to the possibilities given by the combination of statistical intelligence and computer science of inferential logic, there are also the techniques of artificial neural networks, genetic algorithms and Fuzzy simulations to be deeply tested. The perspectives of this research are in the interconnection of systems with agents with advanced sensors, according to the paradigm IoT - Internet of Things). In this way, the Agent will be put in constant communication with the real environment, opening up new paths such as: the constant collection of data on existing structures, the optimization of frequency and maintenance interventions, the micro-robotics of the site.

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OPERATION AND MAINTENANCE OF BUILT ASSETS: A PATHWAY TOWARDS INDIVIDUALISED TRAINING EXPERIENCES

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1 BACKGROUND AND IDENTIFICATION OF PROBLEM / KNOWLEDGE GAP

Workforce health and safety (H&S) in the construction sector is a global concern. The construction sector has one of the highest fatal injury rates in both the developed and the developing world (Kassem et al., 2017). Efforts to improve the H&S performance in the construction sector are plentiful. However, until recently studies have mainly focused on H&S issues on the construction site. Facilities management and in particular the operation and maintenance of built assets has a much higher rate of injury and illness when compared to all other fields of employment (Wetzel and Thabet, 2018). More effort should be dedicated to address H&S risks at this stage. Safety learning and training, as a proactive strategy to improve the H&S performance of the construction sector, has received significant attention in recent years.

Studies proposing new approaches for H&S learning and training have proposed a number of approaches that are characterized by a varying degree of 'virtualisation' ranging from pure reality, through augmented and mixed reality, to full virtual reality. While the degree of 'virtualisation' of the proposed approaches is an important variable to consider, the extent of 'personalisation' enabled by such approaches is key. Personalisation in learning and training refer to experiences which are tailored to the specific needs of the individual according to the job role and to the specific characteristics of the context (company or otherwise) in which the individual is required to complete his/her tasks. This emerging trend is being driven by innovators on both the demand side (e.g. forward-looking clients and operators innovating in health H&S learning and training to meet ambitious H&S performance) and on the supply side (e.g. specialised learning and training providers, and technology providers). This paper presents the outcome from the first stage of a study aiming to develop an individualised training solution for the construction and facilities management (FM) domain.

2 RESEARCH AIM AND METHODOLOGY

This research aims to establish an individualised solution for H&S compliance training management and delivery for the construction and facilities management domains. This includes the development of the framework, the corresponding software prototype, and its testing.

The research starts off by adopting a technology-agnostic approach and concentrates on addressing preliminary concepts such as: understanding the importance of individualised training; what makes training individualised; and what are the interplays between personalisation of training and enabling technologies. Following this initial stage, the next step is to develop the conceptual framework for individualised training, the technical specific, the prototype platform, and its testing.

To date, three key knowledge gaps were identified: i) the lack of a framework road-mapping the levels of learning and training experiences and recognising the need for individualised experiences; ii) a consensus as to what makes a learning and training experience individualised and the role of technology in enabling the varying degrees of personalisation; ; and iii) limited availability of digitally-enabled solutions providing individualised learning and training experiences and evidence of their impact on safety performance and productivity.

This paper addresses the first gap by focussing on the H&S compliance training management and delivery as a specific area of application. Case building (also referred to as 'case writing') was used to solicit knowledge about current practice and methods of compliance training management and delivery through interviews of five experts from the construction and facilities management (FM) who are involved in compliance training delivery and management. The knowledge from the interviews was assimilated into a pathway showing the trajectory of H&S training perspectives including the different levels of personalisation and their interplay with data and interoperability of the enabling technologies. To help the knowledge assimilation exercise, use cases covering different FM perspectives including multiple scenarios (e.g. Trainee Environmental Surveyor responsible for undertaking surveys in the built environment

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undertaking surveys in the built environment to test for the presence of asbestos with/without credentials to access site, etc.) were explored. The pathway is presented in the next section.

3 RESEARCH FINDINGS

The pathway towards individualised training is included in Figure 1. It shows the trajectory from a generalised training towards a fully individualised training offer. The generalised training offer represents arrangements which are common in the UK for facilities management site operatives. For example, prior to accessing the site (and as a condition of the Service Level Agreement between client and contractor) the operative is required to have undertaken regulatory and industry standard training in order to be deemed suitably qualified (and as such insured) to undertake the task in hand.

Beyond the generalised domain, training has the potential to become individualised at three main levels: i) Baseline individualised represents training related to general client arrangements such as client process and procedures around a specific risk; ii) Semi-individualised: addresses training which is specific to the site on which the job is being carried out; and iii) fully individualised: covers site (e.g. specific location/condition of the site), type of job/task (e.g. asbestos removal) and individual (e.g. credential of the specific individuals undertaking the job) specific training.

The fundamental challenge when moving to higher levels of individualisation is in the interoperability of systems which currently are commonly existing in silo (e.g. systems for scheduling, HR, job sheets, training plans).

The pathway proposes that the more interoperable are the systems holding data regarding job scheduling, built asset data (including risk classification) and training plans (including outcomes), the more likely are the possibilities for realising a progressive individualised training offer. Other important aspects that change when moving towards individualised training are 'data' and 'interoperability'. Data type and data requirements change and increase for higher level of individualisations. Data type change from static to dynamic type which bring challenges to its change management to ensure that the right and most up-to-date information is used in the individualised training. Also the volume of the required data from across disparate systems increases when moving towards higher level of personalisation. This pathway is put forward in the context of the H&S compliance training delivery and management but it can be applied to other areas of training. The next step in this research is to establish and validate a framework and a technical specification for fully individualised training approach, and develop and test the platform prototype.

Figure 1: Towards Individualised Training: A Health and Safety Training Perspective in the FM Domain

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