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Information Modelling for Urban Building Energy Simulation - A Taxonomic Review

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ABSTRACT

Climate change, increasing emissions and rising global temperatures have gradually affected the way we think about the future of our planet. Urban areas possess significant potential for reducing the energy consumption of the overall energy system. In recent years, there is an increasing number of research initiatives related to Urban Building Energy Modelling (UBEM) that focus on simulation processes and validation techniques. Although input data are crucial for the modelling process as well as for the validity of the results, the availability of input data and associated data formats were not analysed in detail. This paper closes the identified knowledge gap by presenting a taxonomic analysis of key UBEM components including: input data formats, simulation tools, simulation results and validation techniques. This paper concludes that over $\sim$ 95% of the studies analysed were not reproducible due to the absence of information relating to key aspects of the respective methodologies such as data sources and simulation workflows. This paper also qualifies how weak levels of interoperability, with respect to input and output data, is present in all phases of UBEM.

Acronyms

ADE Application Domain Extension

BEM Building Energy Modelling

BEPS Building Energy Performance Simulation

BIM Building Information Modelling

BPS Building Performance Simulation

CAD Computer-aided design

CIM City Information modelling

CityGML City Geographical Markup Language

EERE Energy Efficiency and Renewable Energy

Energy ADE Energy Application Domain Extension

EU European Union

FileGDB ESRI File Geodatabase

FMI Functional Mockup Interface

gbXML Green Building XML

GHG Greenhouse Gas Emissions

GIS Geographic Information Systems

GML Geographic Markup Language

HVAC Heating, Ventilation and Air Conditioning

IDA ICE EQUA IDA Indoor Climate and Energy

IFC Industry Foundation Classes

INSEL Integrated Simulation Environment Language

INSPIRE Infrastructure for Spatial Information in Europe

JSON JavaScript Object Notation

KML Keyhole Markup Language

LoD Levels of Detail

NMF Neutral Model Format

NZEB Nearly Zero Energy Building

OGC Open Geospatial Consortium

OSM Open Street Map

TRNSYS Transient System Simulation Tool

UBEM Urban Building Energy Modelling

UMI Urban modelling Interface

USEM Urban-scale Energy Modelling

XML Extensible Markup Language

1. Introduction

In 2014, the United Nations projected an increase in the number of people living in cities from 54% in 2014 to 66% in 2050 [1, 2]. Furthermore, improved living standards come at a significant economic and environmental cost [3]. Globally, urban areas and buildings account for more than two-thirds of the energy consumed and 70% of CO_2 emissions [4]. Access to clean and sustainable energy is gradually being prioritised in different countries, thus increasing the importance of developing urban energy planning tools. Meaningfully predicting future energy balances and energy flows at a urban scale requires significant resources. One key component of this urban energy mix is the buildings sector, particularly with respect to the associated energy demand and emissions.

Modelling the associated energy consumption and Greenhouse Gas Emissions (GHG) of buildings can benefit a number of use cases and stakeholders, for example design engineers, urban planners investigating renovation strategies and policy makers [5]. Western society has placed a significant emphasis on large scale renovation of the existing building stock. A comprehensive analysis of renovation activities and Nearly Zero Energy Building (NZEB) adapted in the European Union (EU) from 2012 to 2016 shows the significant impact these actions can have on building energy demands [6]. However, a reduction in energy consumption and an adjustment of peak electrical loads are only possible when supported by appropriate policies and technologies. One potential approach to quantifying sustainable and energy-efficient scenarios that integrates the perspectives of multiple stakeholder is Urban Building Energy Modelling (UBEM).

UBEM can analyse the impacts of neighbouring buildings and calculating urban-scale energy demands. Many UBEM principles are inherited from Building Energy Modelling (BEM), also called Building Energy Performance Simulation (BEPS), by using similar methodologies and techniques but at a larger scale. According to the United States Office of Energy Efficiency and Renewable Energy (EERE), BEM or BEPS is a physics-based software simulation of building energy usage [7]. Depending on the application, BEM requires various input data such as building geometry, construction details, data models, building physics data (such as U-value, density, heat capacity), Heating, Ventilation and Air Conditioning (HVAC), occupant behaviour, and occupancy profiles [8]. Using a software-based approach, thermal loads of buildings are calculated based on a numerical evaluation of a mathematically described physical model. The software-based approach can also perform calculations and simulations related to occupant comfort simulation and energy costs. Generally, building models are less detailed in UBEM when compared to a single building BEM.

UBEM has two distinct approaches: top-down or bottom-up [9]. The former tends to work at an aggregated level i.e. at the national level and uses historical time-series energy consumption data or CO_2 emission data [10]. These models express the relationship between energy and economics at a large scale and connect variables such as fuel prices, gross domestic product and income to the energy sector. The issue with these models is that they often lack details relating to current and future building technologies that could influence the energy demand of a building [11]. On the other hand, the bottom-up approach works in a disaggregated manner and requires extensive details for each component in the building [12]. A bottom-up model accounts for individual dwelling's energy consumption and results are extrapolated to represent regional or national energy demands. This approach is useful when evaluating the performance of different energy efficiency measures and technologies [13]. This review paper focuses on bottom-up UBEM approaches. The top-down UBEM approach is, therefore, beyond the scope of this paper.

In recent years, researchers published multiple studies and review articles in the field of UBEM. The publication trend illustrated in Figure 1 demonstrates the gradual increase in UBEM publications between 2011-2020. In 2018-2020, the number of published reviews articles were most significant to the field. One notable article from Hong et al. in 2020 [14] highlights the ten significant questions on UBEM. These questions streamline the main challenges, opportunities and future perspectives in the field of UBEM, the most significant of which are now discussed.

A seminal review paper by Reinhart and Davila [15] describes the domain of UBEM as *"nascent"* and focuses on: 1) input data (weather data, geometrical data and non-geometrical data), 2) thermal modelling and 3) results validation. Goy et al. [16] address the impact of input data on BEM at an urban scale using a Morris sensitivity analysis approach and shows that accessible data significantly impacts the entire modelling process. The sensitivity analysis highlighted that temperature set-point and thermal characteristics have a major impact on urban energy simulations. Chen et al. [17] discusses some of the key challenges of data integration for city buildings and provides an overview of public building data in CityGML, GeoJSON and ESRI File Geodatabase (FileGDB) for UBEM. Overall, the literature, however, omits the fact that multiple issues related to the practicalities of acquiring non-geometrical data at an urban level persist today.

Another review from Sola et al. [18] about Urban-scale Energy Modelling (USEM) classifies tools or engines used

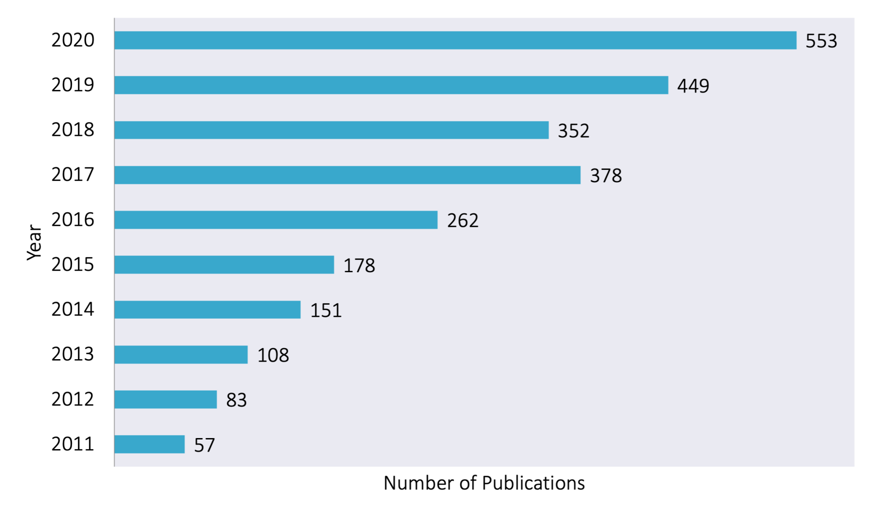

Figure 1: Publication trend in the field of UBEM between 2011-2020

in the simulation of urban-scale energy systems. USEM is further classified into UBEM that estimates the energy demand at an urban scale endogenously and considers building stock characterisation and building energy demand modelling respectively. The characterisation of building stocks focuses on the archetypes and geometrical data from Geographic Information Systems (GIS). These archetypes can be difficult to create at a national, regional or city scale basis as the segmentation parameters and number of archetypes can vary on a case by case basis [19]. The review from Sola et al. [18] on thermal modelling tools also lists a number of bottom-up physics based UBEM tools and provides an overview of relevant characteristics of the individual tools. The review lacks validation and verification methods.

Ferrando et al. [20] also presents a comprehensive assessment of existing UBEM tools along with an overview of research and development potential. The review focuses on bottom-up physics-based UBEM tools and classifies the tools according to data input, simulation outputs, workflow of the modelling process, applicability regarding scale or type of the project and finally the potential users. Other articles such as Abbassabadi et al. [21], Han et al. [22], Li et al. [23], etc. also provide an overview of the field, however, a noticeable gap emerges in terms of inconsistencies related to input data types, simulation platforms, enrichment techniques and generation of simulation results.

The field of UBEM has expanded over the last few years and there is now a large variety of tools, data and approaches documented in literature. To date, there is limited transfer of knowledge, insights and data between studies and the reproducibility is compromised. This paper identifies key aspects that are required to ensure reproducibility the field of UBEM. We highlight future opportunities moving towards standardisation of UBEM. This paper aims to provide a taxonomic review of the input data, simulation tools and results validation as available today in the field of UBEM. The taxonomic approach scientifically identifies and categorises research in order to clearly understand different workflows used in UBEM. None of the systematic reviews discuss the aspect of reproducibility with respect to UBEM results; therefore this paper complements the literature. The approach we take in this paper distinguishes itself from other reviews as it examines the UBEM workflow in detail rather than considering a particular element or result with respect to the other categories. Most of the available studies fail to discuss the process of geometrical and non-geometrical enrichment. This paper segregates the different enrichment techniques, for example, enrichment of building physics and occupancy data. This paper also compliments the existing studies in the field of UBEM by quantifying the usage of different data models and simulation tools. Furthermore, this paper proposes a taxonomic method to review UBEM related research studies. The proposed taxonomy based approach along with the other available articles can be used to review and quantify the use of data models, simulation tools and enrichment techniques along with identification of reproducible studies.

This paper has five sections: Section 2 describes input models and an overview of various modelling methods and simulation tools for UBEM; Section 3 explains the taxonomic approach taken by the authors in the review process; The Sections 4.1, 4.2, 4.3 and 4.4 include an analysis based on the amount of information present in individual articles; The present study discusses the output of the taxonomic approach in Section 5 and the future opportunities in Section

6.

2. Background

This section provides an introduction to input data models (Section 2.1), building data models and formats (Section 2.2 and Section 2.3), and simulation tools (Section 2.4). In addition, this review served as a basis for defining the structure of the taxonomy and selecting appropriate keywords.

2.1. Input data models for City Quarter Information Modelling

Physics-based UBEM simulations require detailed input data at the individual building level. These input data facilitate modelling of buildings' thermodynamic behaviour and their energy systems. Digital representations of buildings are a key aspect of UBEM and require structuring and organisation of raw input data. Moreover, spatial information related to the building and its orientation is necessary to simulate the building for energy related applications. Although, input data are essential to UBEM, obtaining sufficient and accurate building data at a large-scale is quite challenging [16]. The key input data categories used for UBEM are taken from noted studies by Reihnart et. al. [15] and Chen et. al. [24] (Table 1).

Table 1: Overview of key input data categories used for UBEM based on [15] and [24].

Data category	**Description**
Location and geometry	Geographic location of the building, shape and orientation of the building's exterior boundary surfaces, boundary conditions (e.g. air, ground, adjacent building) of these surfaces and building's floor area size.
Openings	Location, shape and orientation of openings (doors and windows) in exterior boundary surfaces.
Thermal Zones and Thermal Boundaries	Geometric representation of internal zones (e.g. rooms) with distinct thermal conditions, and of contact surfaces (thermal boundaries) between two zones or one zone and the outside environment.
Building physics	Energy relevant thermal and optical parameters of external and internal building elements (interior and exterior walls, roof, internal slabs and ground plate, windows and doors).
Building systems	Information on energy relevant building systems, especially concerning the building's Heating, Ventilation and Air Conditioning (HVAC) systems.
Usage	Information concerning the energy relevant behaviour of the building's occupants such as nominal heating/cooling temperatures and ventilation rates in different thermal zones.
Internal heat gains	Internal heat generation by building systems (e.g. lighting, electrical facilities, hot water production) and occupants.

In the context of UBEM and City Information modelling (CIM), the terms *data model* and *data format* are often used interchangeably, however, it is important to highlight the differences between the two. A *data model* is an abstract, conceptual model of data elements (classes), their attributes and properties. Whereas, a *data format* is an implementation of a data model for a specific application (e.g. Extensible Markup Language (XML) [25] and JavaScript Object Notation (JSON) [26]). Data formats are generally derived from a data model so that the data can be stored, retrieved and used for a specific purpose or application. Though many data formats are standardised open formats, some are proprietary[1] formats and can only be encoded and decoded using propriety software tools. As the energy analysis at a city quarter level requires a broad availability of data and since most UBEM data formats have open specifications,

[1]Data formats that are only supported by a specific software manufacturer or for a specific application (e.g. idm binary file for IDA ICE [27])

proprietary formats are not considered in context of this paper. Data formats can also be classified based on the application area for which a data format has been developed. Building data formats, specially designed for energy related use cases, can be distinguished from general formats which are originally being developed for other application domains (e.g. architecture, construction industry or mapping).

This study focuses on data models and formats that are primarily developed for energy studies and are maintained by dedicated standardisation bodies such as OGC [28] or SiG3D [29].

2.2. General Building data models and formats

Industry Foundation Classes (IFC)

IFC [30] is the only non-proprietary Building Information Modelling (BIM) format that is an open and international standard. buildingSMART develop and maintain the IFC standard [31]. The data model is based on a STEP Physical File (SPF) [2] [32] and uses the modelling language EXPRESS [33]. From this abstract data model, a number of data formats are derived, such as IFC SPF (based of STEP part 21 [34]) and the XML-based representation IFC-XML (based on STEP part 28 [35]) are considered for energy applications. As IFC models were originally developed for application areas in Architecture, Engineering and Construction, it primarily supports a volumetric representation of the building elements. Moreover, IFC models use hierarchically structured local coordinate systems, for which the root can be located in a global (geographic or geodetic) coordinate reference system. Structurally (see Figure 2), IFC supports the partition of a building (IfcBuilding) into storeys (IfcBuildingStorey), physical building elements (IfcBuildingElement) with openings, as well as rooms (IfcSpace) with space boundaries [36]. Using the property set concept, a number of physical properties can also be related with the building elements. Furthermore, IFC entities, relations and property sets also exist for representing the HVAC components of a building. These sets principally allow for the estimation of internal heat gains in buildings by software requiring such data [37].

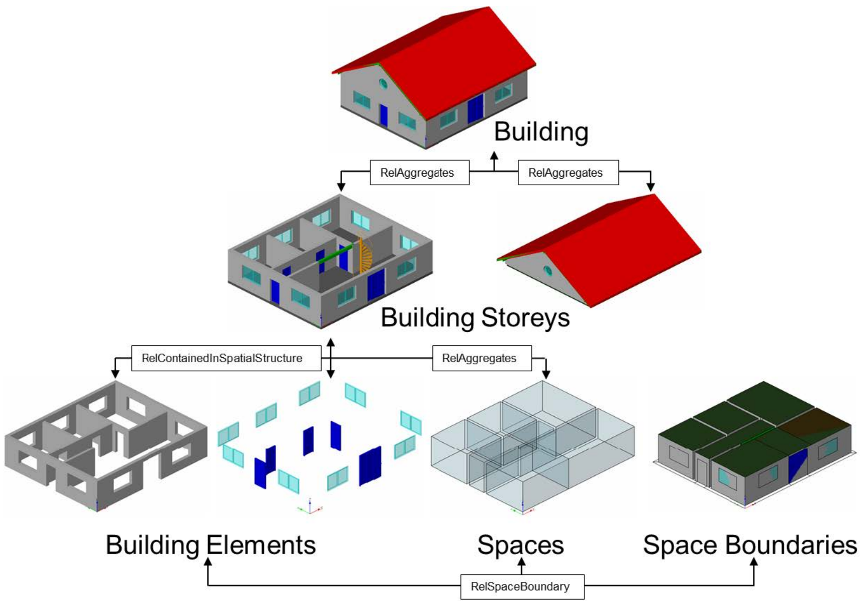

Figure 2: Basic structure of a building in the IFC data model. Image source: [38]

City Geographic Markup Language(CityGML)

CityGML of the OGC [28] is an XML-based open data format for storage and exchange of virtual 3D city models [39]. The current version CityGML 2.0 is an application schema of OGC's Geographic Markup Language (GML) version 3.1.1 [40]. GML models generally use absolute coordinates in a well-defined coordinate reference system. Moreover, CityGML is subdivided into a number of independent thematic modules. These modules are all based on the *CityGML Core* module. In the context of this paper, only the *Building Module* is considered as it contains the

[2] IFC-SPF can be read as text and is based on the ISO standard for text representation of EXPRESS data models

classes to represent a single building (*Building*), its exterior and interior structure (see Figure 3). In contrast to IFC, CityGML uses a surface geometry representation to model the different building elements.

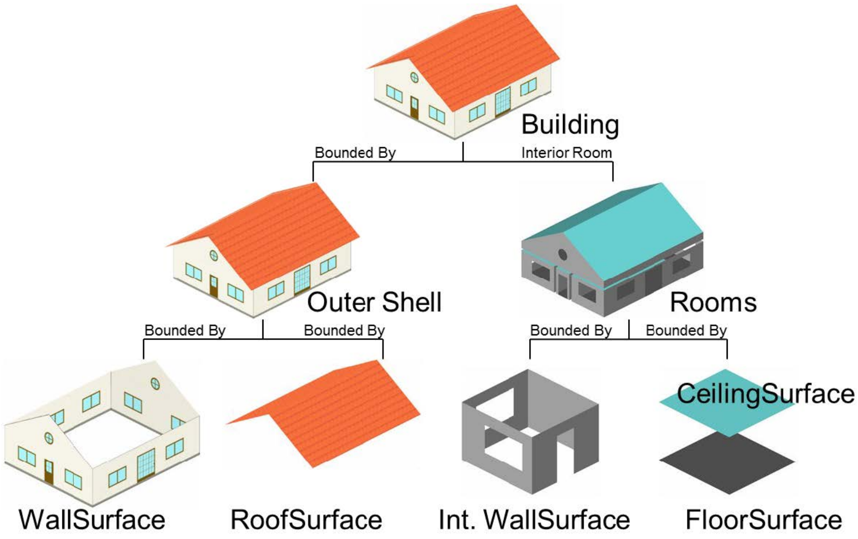

Figure 3: Basic structure of a building in the CityGML data format. Image source: [38]

An important feature of CityGML is the concept of Levels of Detail (LoD). The LoD definition supports the representation of real world objects with different geometric and semantic detailing [41]. Depending upon the information present in the model, CityGML models are defined in five LoDs. The most crude of which is LoD 0, a two and a half dimensional Digital Terrain Model over which an aerial image or a map may be draped and buildings are represented only by their footprints. In *LoD 1*, the building's exterior shell is approximated by a prismatic volume and is represented as a single geometry. *LoD 2* supports a generalised geometrical representation of the exterior shell and its subdivision into different boundary surfaces. This subdivision is made for representing the exterior parts of the walls, roofs and ground plates. In most cases, energy simulation software can directly process the generalised geometry. Moreover, in some countries, CityGML LoD 2 data sets are most commonly available as open source [42]. *LoD 3* and *LoD 4* models represent the exterior shell with more geometrical details (e.g. roof overhang), however, they mostly require geometrical pre-processing before being used for energy simulation software [43]. In LoD 3, it is additionally possible to represent the openings (doors and windows) within the boundary surfaces. LoD 4 supports the additional representations of the building's interior structure with rooms which are bounded by interior boundary surfaces (see Figure 3).

Using CityGML data for energy simulations does also have a number of challenges. Except for a purely geometric representation, building system components cannot be represented in CityGML. A means to characterise "shared walls" between adjacent buildings is also missing. The topological structure of a room model in LoD 4 is also not explicitly represented. This hinders the derivation of the energy-relevant space boundaries. The most significant drawback of using CityGML is that it lacks attributive information as there are no concepts to represent material or usage parameters. For assessing the physical behaviour of a building, only the year of construction is (sometimes) available. Furthermore, data concerning occupant's behaviour or internal energy gains must be derived from the specified building function. To overcome the lack of information in pure CityGML models, the Energy Application Domain Extension (Energy ADE) [44] can be used, which will be explained in detail in Section 2.3.

INSPIRE Building

Infrastructure for Spatial Information in Europe (INSPIRE) is an initiative of the European Parliament and Council to establish a European Spatial Data Infrastructure [45]. In the context of INSPIRE, GML-based data models are developed for different technical aspects such as the representation of individual buildings. Until 2020, the public agencies in all member states, if they are related with one of the INSPIRE technical areas, need to deliver their spatially related data in the corresponding INSPIRE data format. For buildings, INSPIRE provides two formats [46]: (i) The base model *INSPIRE Building* enables the geometrical representation of a building's exterior shell in four different CityGML LoD. The non-geometrical properties of the INSPIRE *Building* class also follow the CityGML standard. (ii) The extended model *INSPIRE Building Extended* largely corresponds to CityGML. For the *Building* class, the INSPIRE models provide a number of additional, energy relevant properties such as information about the building's connection with utility networks, its energy performance class, floor area and heating system. Concerning the ability to support energy related simulations, the model INSPIRE Building is comparable with CityGML LoD 1. Though, in the same LoD as CityGML, the INSPIRE Building Extended could have slight advantages compared to CityGML. However, the INSPIRE directive only declares the base model as mandatory. Furthermore, the extended model has, to the best knowledge of the authors, has yet to be applied by researchers and only a draft of the corresponding data format is available.

Open Street Map (OSM)

Open Street Map (OSM) is a world-wide collaboration project, aiming to develop a free, editable digital map [47]. A large number of local contributors collect 2D position and contour of real-world objects (e.g. buildings) and generate a semantic classification and attribution in form of key-value pairs. For this, the OSM organisation proposes an ontology, however, the contributors are not forced to use it. For buildings, this ontology enables to specify the type and function of a building and provide parameters to describe its 3D structure (including height, number of storeys and roof type). Due to its availability and relative ease-of-use, OSM is frequently used for projects on city quarter or city level [48, 49].

KML/Collada

The Keyhole Markup Language (KML) is an XML-based data format for visualisation and annotation of 3D geographic information. These are also referred as COLLADA models [50]. Originally developed by Google Inc. to support the GoogleEarth [51] application, the KML format (from version 2.2) is an official OGC standard [52]. In contrast to the formats mentioned previously, KML is not a semantic data format. This implies that the geometry contained in a KML data set has no well-defined meaning and except of the two text attributes, name and description, no attributive information can be related with KML objects. Furthermore, for the application context of this paper and also in the reviewed articles, KML/Collada is not considered.

2D cadastre models

In many countries, the surveying and cadastre agencies provide their data in standardised, semantic data formats such as ALKIS/NAS [53] in Germany. This standard geometrically describes a building by its footprint and several parameters for the 3D-structure. Besides important parameters such as the year of construction, building function, number of storeys, type of roof and floor area, no energy relevant building properties are recorded. The direct use of cadastre data for building energy simulations is therefore limited to spatial modelling.

2.3. Building data models specially designed for energy related applications

CityGML Energy ADE

The Energy ADE is an extension of the CityGML standard and is developed by an international working group [54] to support the application area of "energy". It uses the general CityGML ADE concept [55] supporting two different extension approaches: (i) by defining new classes, and (ii) by extension of existing CityGML classes with new attributes and relations. By using the two approaches, the actual version 1.0 of the Energy ADE ([43], [44]) principally supports all the information mentioned in Table 1. The Energy ADE data model contains four functional modules that are derived from the *Energy ADE Core* module. A couple of supporting classes for modelling time series, usage schedules and weather data are also available. The *Core* module, in particular, extends the CityGML *Building* class with energy relevant properties and relations along with the abstract base classes of the functional modules. The *Building Physics* module enables to subdivide a building into one or more thermal zones. These zones exchange energy among each other or with the outer environment via thermal boundaries and thermal openings. Moreover, the thermal and optical properties of these objects are modelled by the classes of the *Materials and Constructions* module. The module *Occupants Behaviour* supports the definition of usage zones that are related within a thermal zone. Here, the usage is primarily defined by specifying time-variant profiles for ventilation rates and heating/cooling set-point temperatures. Furthermore, specific concepts are available to model internal heat gains due to occupants, lighting, electrical appliances and domestic hot water production. Finally, the *Energy Systems* module contains several classes to represent the energy relevant building systems (energy conversion, distribution and storage systems) and its corresponding energy flows.

Green Building XML (gbXML)

gbXML [56] is an open, XML based data format supporting the data exchange between 3D BIM systems and engineering analysis tools and is supported by leading manufacturers of CAD systems such as Autodesk, Bentley and Graphisoft. Some converters, such as Open Studio Core [57], also exist to extend its application to building energy simulations. Furthermore, gbXML also contains all the information listed in Table 1.

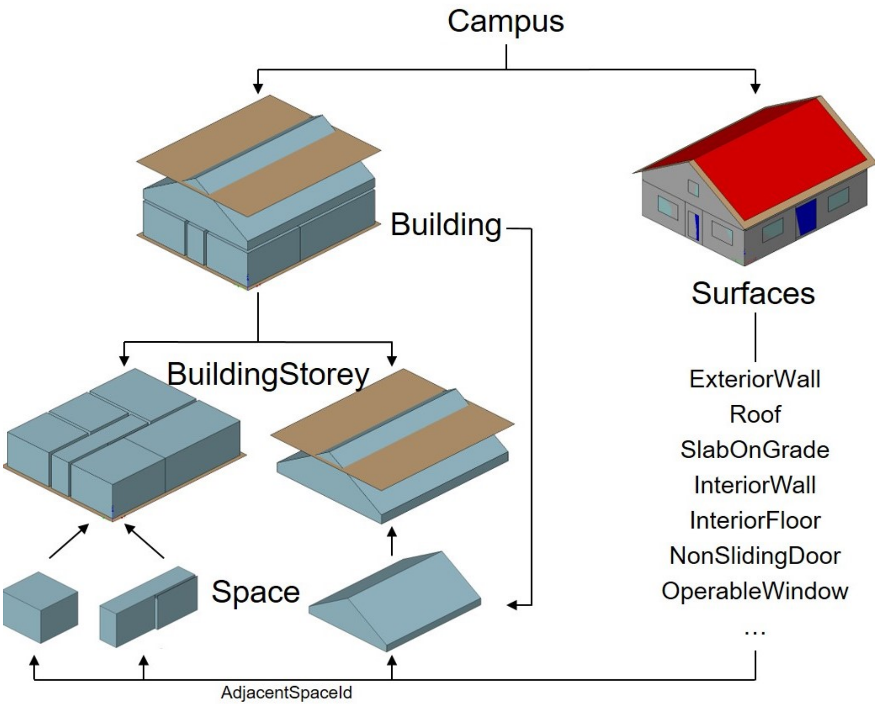

Figure 4: Basic structure of a building in the gbXML data format. Image source: [38]

Figure 4 depicts the basic structure of a gbXML model. The root element (*Campus*) may refer to one or more building objects (*Building*) that are subdivided into storeys (*BuildingStorey*) and rooms (*Space*). Internal and external thermal boundaries are modelled in parallel (*Surface*) and include material and opening information. Each *Surface* may be related with one or two *Space* objects. The *Space* class supports the representation of usage profiles, internal heat gains and building systems.

2.4. Simulation Tools

In the context of this paper, we introduce two different categories for simulation and modelling tools: (i) Simulation tools and (ii) Auxiliary tools. Simulation tools are self-contained simulation applications, which are used to generate building energy demands without the need for external tools. Auxiliary tools are separate applications to work with the simulation tools to extend features and improve usability. Hong et al. [14] and Ferrando et al.[20] provide a discussion of modelling approaches (physics-based, reduced-order, and data-driven approaches).

Recent literature highlights the importance of co-simulation in UBEM [14, 58]. Co-simulation involves exporting the simulation model into a neutral format and using multiple simulation tools to simulate different parts of the model [59]. A main advantage of using co-simulation within UBEM is the ability to build multi-domain models [18]. Co-simulation can be used to couple different tools for modelling buildings, HVAC systems, district heating systems, or power distribution networks. A recent study on promising standards and tools for co-simulation shows that the Functional Mockup Interface (FMI) is the most promising standard for co-simulation [60]. The Functional Mockup

Interface is a tool independent standard for co-simulation and the exchange of dynamic models which is currently supported by more than 140 tools [61].

2.4.1. Simulation tools commonly used for UBEM

CitySim is a free urban performance simulation engine that comprises a solver and a graphical user interface. Calculation functionalities include building thermal, urban radiation, occupant behaviour, plant and equipment models. CitySim has recently been further developed as CitySim+ with additional features for enhanced scalability, distributed simulation and incorporation of a data layer based on CityGML/Energy ADE [62]. *City Energy Analyst* is an open source tool for analysing and optimising energy systems at a district level. The tool enables users to investigate financial, energy and carbon benefits of different design scenarios in conjunction with schemes of distributed generation. *EnergyPlus* [63] is a whole-building simulation software to model the different energy demands of buildings. EnergyPlus is, by far, the most commonly reported tool in the reviewed literature for this paper. There are also a number of tools developed to interface with EnergyPlus as a simulation engine. The tools dependent on EnergyPlus are detailed in the section 2.4.2. *EQUA IDA Indoor Climate and Energy (IDA ICE)* is a commercial building simulation tool with libraries written in either Modelica or Neutral Model Format (NMF) [27] and can be used to model the performance of buildings including energy consumption, lighting or HVAC systems. IDA ICE can import various formats including Sketchup and IFC. *Integrated Simulation Environment Language (INSEL)* [64] is a block diagram simulation system which can be used for the simulation of photo-voltaic systems, solar thermal systems and dynamic building simulations. Ready models are available in INSEL, however, extensions to the existing models and the creation of new models is also possible [65]. The SimStadt tool developed using INSEL is briefly explained in 2.4.2. *Modelica* is an object oriented modelling language that is supported by various open source and commercial tools [66]. There are multiple open source Modelica libraries for buildings, HVAC systems, district heating systems, and energy systems [67]. The commonly used Modelica libraries in the domain of BPS are also detailed in the section 2.4.2. *Simulink* is a graphical modelling language, built on top of the programming language Matlab and is also one of the most common simulation environments [67]. *TRNSYS* is a simulation tool mainly used in the field of thermal engineering, such as buildings and HVAC systems [68].

2.4.2. Auxiliary Tools

Table 2 gives an overview of Simulation Tools and the corresponding Auxiliary Tools.

Table 2: The auxiliary tools based on the previously defined Simulation tools commonly used for UBEM

Auxiliary Tools	**Simulation Tool**	**Summary**	**Interface**	**Availability**
CESAR [69]	EnergyPlus [63]	Archetypical generation of EnergyPlus models	CMD	Closed
UMI [70]		Urban modelling plugin for Rhino 3D	GUI	Freeware
OpenStudio [71]		Various tools to support EnergyPlus	GUI	Open-Source
CityBES [72]		Web-based information exchange of urban building modelling	GUI	Freeware
TEASER [73]	Modelica [66]	Archetypical generation of Modelica models	GUI/CMD	Open-Source
SimStadt [74]	INSEL [64]	UBEM simulation platform	GUI	Closed

EnergyPlus : The tool *Combined Energy Simulation And Retrofitting (CESAR)* is used for modelling the energy performance of buildings, districts and cities in Switzerland. CESAR compiles and simulates EnergyPlus models based on statistical data of the Swiss Building Stock [69]. At the time of writing, the CESAR tool is not publicly available but reported to be under development and an open-source version is planned for release.

CityBES [72] is a web-based tool for modelling and analysing the thermal performance of a city's building stock. CityBES uses OpenStudio [71] and EnergyPlus to simulate building energy performance and CityGML to represent and exchange 3D city models.

The *Urban modelling Interface (UMI)* is an urban scale energy simulation that also includes operational energy, embodied energy and mobility. Rhinoceros 3D [75] is used as its CAD modelling platform, EnergyPlus for its building energy performance simulations, Daysim [76] for its daylight simulations and a Python module for its walkability evaluations.

Modelica : Several frameworks such as *BIM2Modelica* [77] and *TEASER* [73] automatically derive Modelica models based on IFC and CityGML respectively. The BIM2Modelica toolchain generates Modelica building models from BIM models based on the IFC format and uses a GUI with the software infrastructure of CoTeTo [78] for simplifying the code generation process for BPS. The "Tool for Energy Analysis and Simulation for Efficient Retrofit" (TEASER) on the other hand is an open framework for urban energy modelling of building stocks. TEASER provides an interface for CityGML data as input, data enrichment and the export of ready-to-simulate Modelica simulation models of a single building or at urban scale. *AixLib* [79], *Buildings* [80], *BuildingSystems* [81] and *IDEAS* [82] are the Modelica libraries that are used in TEASER for BPS at an urban scale and were brought to a common base in the IEA EBC Annex 60 Project [83].

Integrated Simulation Environment Language (INSEL) : *SimStadt* is a simulation platform that can be used for workflows related to Solar and PV potential analysis, energy demand and CO_2 emission calculations, and refurbishment scenarios generation and simulation [74]. INSEL is the simulation engine used [65].

2.5. Single building to an urban scale

The data models (Section 2.1) that represent a single building (e.g. a BIM) or city models (e.g. a GIS instance) serve very different application requirements, purposes and stakeholders. Although, both data-model types have the ability to store object geometries, surface materials, appearances, building physical characteristics and surroundings, their underlying model architectures differ considerably. This arises due to the adaptation to specific requirements of their respective originating domains [84]. Furthermore, the granularity of geometrical information stored in a BIM is typically unsuitable for transformation into the inputs required by UBEM [85], this arises due to different users, applications, developmental stages, spatial scales, coordinate systems, semantic and geometric representations along with different information storage and access methods [86]. In the context of scaling an energy model of a single building to an urban context, the availability of input data is a persistent challenge. Detailed data at the building level are only partially available in most countries [42]. Data sources include buildings' construction plans, BIM models and documentation related to physical on-site visits. For building stocks, however, accumulating the required data for BEM is much more complex. In a practical implementation of UBEM, this leads to a use of multiple available data sources, which are combined and enriched to provide all of the necessary information. Therefore, three general data sources are used: Open access, closed and commercial [42]. In an urban context, the cluster of information is provided either in form of publications (or standards) or as structured and standardised data formats (e.g. gbXML and CityGML Energy ADE).

The energy simulation tools (Section 2.4) used for modelling a single building (in BEM) or an urban area/city (in UBEM) service very different application purposes. Urban scale building energy analysis integrates the concepts of building energy use with the related HVAC systems and environmental interactions [87]. Furthermore, control strategies are being developed to computationally reduce the overall energy demands of urban areas [88]. In an urban context, simulating each building separately without considering the interaction between them can lead to inaccuracies, especially for those cities characterised by a high density or average height of buildings [89]. Building-to-building influences such as mutual shading affect the overall energy demand calculations of buildings [90]. The influence of mutual shading is also important when aiming to understand the thermal effects of the individual construction materials within buildings. Urban areas also create individual climatic conditions called the urban micro-climate [91]. GIS-based urban micro-climate models contribute to the urban energy analysis as micro-climate affects building energy consumption [92]. Different aspects of the local climate, including air temperature and wind patterns, can be modified according to geographical areas to efficiently compute the energy demands of the buildings [93]. Micro-climate and inter-building shading are highly dependent on the specific geographical context and must be meaningfully captured within appropriate UBEM tools. Defining all of the inputs and features for such simulations has been comprehensively captured by Quan & Li [94], Sanaieian *et al.* [95], Ko, Y. [96], Anderson *et al.* [97], Yang & Jiang [98]. The article by Quan & Li [94] is complementary to our work, and, therefore the inclusion of a separate classification for urban influences is currently deemed outside the scope of this paper.

The modelling approaches used in BEM and UBEM differ fundamentally [99, 100], their respective simulation and validation requirements also differ [101, 102]. The definition and development of validation procedures and validation data sets for a single building, e.g. (BESTEST [103] or ASHRAE standard 140 [104]), is less complicated than validation procedures and data sets for UBEM (such as DESTEST [105]) due to the unavailability of open data sets, the lack of standardised input formats and significantly increased computational requirements for UBEM simulations [106].

The presentation of simulation results can affect a modeller's interpretation of model behaviour. This is an important aspect of simulation documentation and therefore must be included. Another noteworthy challenge for the BEM and UBEM communities is the reproducibility of studies. Reproducible studies must include a detailed description of the input data along with its availability and granularity, the simulation tool with its settings and access restrictions, and documentation of the simulation results [107]. This is important in order to compare and standardise different approaches used within different simulation workflows.

3. Method

A taxonomic review synthesises existing literature; in the context of this paper it allows (i) identification of commonly used applications for UBEM, data models, and simulation tools as well as (ii) evaluation of the reproducibility of the reviewed papers. We developed a taxonomy based on categories, sub-categories and keywords - referred to as the structure of the taxonomy in the following (see Figure 6). We defined the structure of the taxonomy based on a two stage process. In the first stage, we developed the basic structure based on existing review papers [11, 15, 108] and the energy simulation workflow defined in [109]. In the second stage, experts from the international IBPSA Project 1 (work package "City District Information Modeling" [110]) further developed the taxonomy in a workshop setting. The final taxonomy consists of the following four main categories: *input data*, *simulation tools*, *simulation results, validation and verification*.

The **input data** are further subdivided into multiple sub-categories. These include data format, building specific information regarding LoD and building physics, availability of the input data, occupancy profiles, and geometrical data analysis. **Simulation tools** is also subdivided into multiple sub-categories and keywords. These include individual tools, availability of the tools, external support of data formats, support for co-simulation, and computational details such as multiprocessing and system configuration. **Simulation results, validation and verification** include the sub-categories results (e.g. timestamps, 3D maps), validation, and verification. Reproducibility is of major importance for studies related to UBEM (see Section 2.5) . The previously mentioned categories (input data, simulation tools and simulation results, validation and verification techniques) form the basis for evaluating the reproducibility of the reviewed research. As reproducibility is a feature that is dependent on the other categories, it is evaluated as a sub-category under each of the afore mentioned categories within the taxonomy. This is due to the importance of unambiguous and consistent interpretation of literature in the field of UBEM.

The identification of relevant publications is crucial for the proposed method. Since the underlying research field is broad and diverse, not all relevant publication could be identified with a literature search using a limited number of keywords. In a first step, we identified an initial list of potentially relevant publications using a combinations of the keywords listed in Table 3 in Scopus [111] and Google Scholar [112] databases. The relevant keywords were defined in the expert workshop within IBPSA Project 1. We included journal and conference articles published after 2014. In a second step, we removed those publications that were beyond the scope of this review. We acknowledge the importance of urban influences, such as mutual shading and micro-climate, in UBEM related review processes, however, their inclusion within the keywords, taxonomy and the review is foreseen as a future work.

Table 3: Keywords used for UBEM paper classification and generation of the co-citation network diagram (Figure 5) (* is used to search singular, plural and similar forms of keywords)

Category	**Keywords**
Type of construction	dwelling, apartment*, building*, house*, national, retrofitting, neighbour*, residential, non-residential, commercial, office*, school, institution*, education*, university, industry
Scale	urban, city, district*, region*, large*, city quarter, 3D city model*, neighbourhood, building stock
Input	U-value, HVAC, Spatial, Occupancy, Building archetypes, Building typology
Data models	CityGML, gbXML, IFC, Energy ADE
Data formats	Shape File, GeoJson, CAD, GML, IDF
Simulation tools	TRNSYS, EnergyPlus, INSEL, CitySim, CityBEM, BuildSysPro/Dymola, Modelica
Enrichment	TEASER, Uncertainty
Output	energy model*, energy simulation*, energy performance, energy demand, energy consumption, time series

The identified keywords, in Table 3, are supported by a network diagram that illustrates their occurrence in research articles from 2014 to 2020 inclusive. The diagram (shown in Figure 5) is generated using the VOSviewer tool [113]. The VOSviewer categorises the keywords into five clusters based on closely related research themes in the field of UBEM. Within the network diagram, the size of each node defines the frequency of occurrence of specific keyword in research articles and the link with other keywords defines the co-occurrence of related keywords.

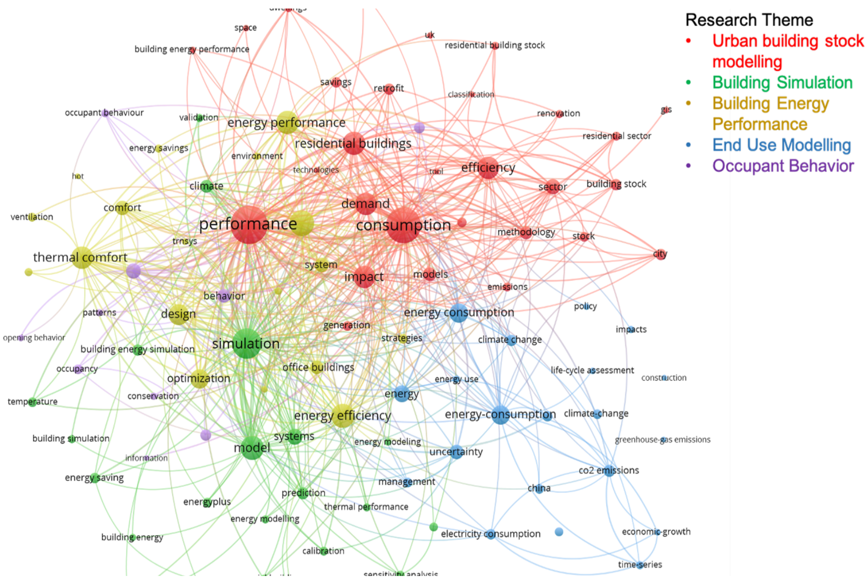

Figure 5: Occurrence of frequently used keywords in Urban Building Energy Modelling

In total 72 papers [12, 19, 48, 62, 69, 70, 72, 74, 102, 114–176] are identified and reviewed using the taxonomy and the keywords network map.

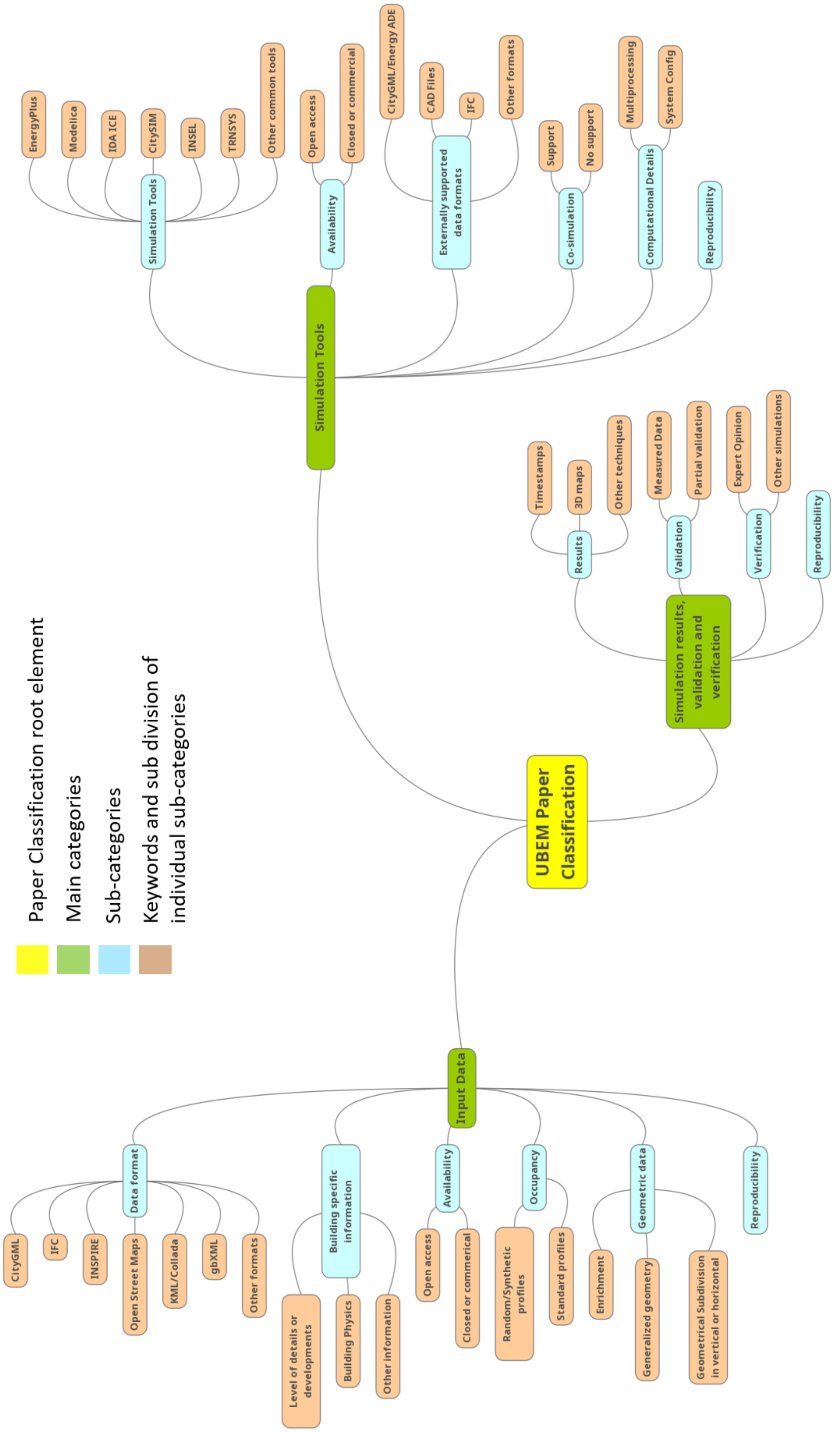

Figure 6: Overview of the taxonomy implemented for UBEM paper classification and review

3.1. Research boundaries

The taxonomy based approach in this paper is descriptive, extensive and hypothesis-driven. The keywords restrict the scope of the literature search; we defined appropriate keywords in an iterative way in workshops with experts. Although we endeavoured to keep the keyword selection process as open and objective as possible, we acknowledge that certain studies may have been unintentionally omitted.

4. Results

In this section, we present the key findings from the taxonomy based analysis; this includes an analysis of data models (Section 4.1), simulation tools (Section 4.2), simulation results and validation techniques (Section 4.3), and reproducibility (Section 4.4).

4.1. Input data models for City Quarter Information modelling

Most data models are georeferenced and contain the information related to the geographical location of the building. However, some such as CityGML LoD 1-2, INSPIRE Building and OSM lack the information about thermal openings, building physics and energy systems. A comparison of different data models highlights the strengths and weaknesses of these formats (Table 4) while a comparison of the data storage capabilities of each model is also worth noting (Table 5).

Table 4: Comparison of different data models based on the amount of information present. A detailed description of the information levels (‘+++’, ‘++’, ‘+’) is given in Table 5. The information level ‘-’ indicates that specific information is not present in the individual data model

	Geo-referencing	**Openings**	**Thermal Zones Boundaries**	**Building Physics**	**Energy systems**	**Usage**	**Internal heat gains**
IFC [177, 178]	+++	+++	+++	+++	+++	+++	+++
CityGML LoD1 [62, 177, 179]	+++	-	-	-	-	+	-
CityGML LoD2 [62, 177, 179]	+++	-	+	+	-	+	-
CityGML LoD3 [62, 177, 179]	+++	+++	+	+	-	+	-
CityGML LoD4 [62, 177, 179]	+++	+++	++	+	-	++	-
INSPIRE Building [45, 180]	+++	-	-	+	-	+	-
INSPIRE Building Extended [45, 180]	+++	+++	++	++	+	++	-
OSM [181, 182]	++	-	-	-	-	+	-
KML/Collada [183, 184]	++	-	-	-	-	-	-
National cadastre formats [42]	++	-	-	+	-	+	+
CityGML Energy ADE (LoD2) [62, 177, 179]	+++	+++	+++	+++	+++	+++	+++
gbXML [177, 185, 186]	++	+++	+++	+++	+++	+++	+++

Table 5: Comparison of different data models - Description of information levels ('+++','++','+') assigned in Table 4

	+++	++	+
Georeferencing	all coordinate systems	limited number of coordinate systems	no coordinate system, but corresponding coordinates are possible
Openings	openings supported		
Thermal Zones / Boundaries	thermal zones and thermal boundaries	thermal boundaries for buildings and spaces	thermal boundaries for buildings
Building physics	full support	partial support	weak support
Energy systems	full support	partial support	weak support
Usage	usage for buildings and rooms and extended usage properties	usage for buildings and rooms	usage for buildings
Internal heat gains	full support	partial support	weak support

The taxonomy based approach shows that 27% of the investigated studies use the CityGML data model for the location and geometry of the building. All studies using explicitly georeference CityGML, yet, 36% of the studies fail to provide information relating to the data model used and 18% of studies contain insufficient detail with respect to georeferenced geometry. Figure 7 gives a distribution of the data models that are used in the reviewed studies.

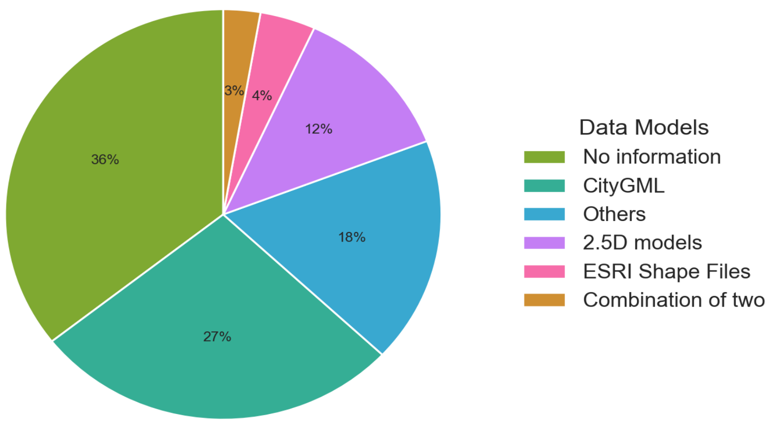

Figure 7: Distribution of data models used in the reviewed articles. Sums of percentages ≠ 100% are due to rounding errors in the annotations. Here combination of two models implies that two data models were used with respect to different simulation environments to compare the results

Out of the studies that use CityGML, only 27% provide information about the LoD used for simulations. Strikingly, only 20% of the data models are made available to be used in other research and 7% of the studies fail to mention the availability of the data models. For the geometric and spatial data used to create the digital representation of the physical aspects of the buildings, 77% of the papers provide details for the geometrical aspects used in their studies. 42% of studies mention some form of pre-processing of the geometry before simulations. This pre-processing includes approaches such as extrusion of building heights using footprints, 3D geometry transformation from one format to another, etc. For studies that consider CityGML data, 3% mention the transformation from 2D to 3D geometry while only 1% of the total articles convert LoD 2 models into LoD 3 models. Moreover, with respect to a horizontal and vertical subdivision of buildings, 72% out of the total papers fail to provide any information on this topic.

Furthermore, as occupant behaviour is acknowledged as a key source of uncertainty between predicted and actual building energy demands, many researchers attempt to model occupants presence and adaptive actions more realistically [187]. In the reviewed articles, 49% of the studies use standard occupancy profiles while 15% use individual profiles and 3% use synthetic and random profiles. For the remaining 33% of the studies, no information regarding occupancy is available.

For UBEM related simulations, "enrichment" is the process of creating attributes using inference and statistics to create a fully parameterised model of each building. Enrichment is necessary as urban scale data are often incomplete with respect to the requirements of UBEM. Of the 72 articles considered, this review found that 67% of the studies use data enrichment; 58% performed occupancy enrichment, 56% performed enrichment of the building physics; and 21% carried out HVAC enrichment. Furthermore, 67% of the studies use an archetype based enrichment approach for urban-scale simulations. This reliance on archetypal enrichment highlights an opportunity for data generators to produce more complete data sets with attributes suitable for UBEM alongside the geometric data. It is acknowledged that this would be a challenging undertaking but if additional attributes, such as building materials, age, could be attached to some of the most commonly used spatial and geometric data formats, such as CityGML with Energy ADE, the UBEM modelling process could be reproducible, automatable and transparent and, thus, lead to increased confidence in the final results. Figure 8 highlights the use of enrichment and its types in different studies.

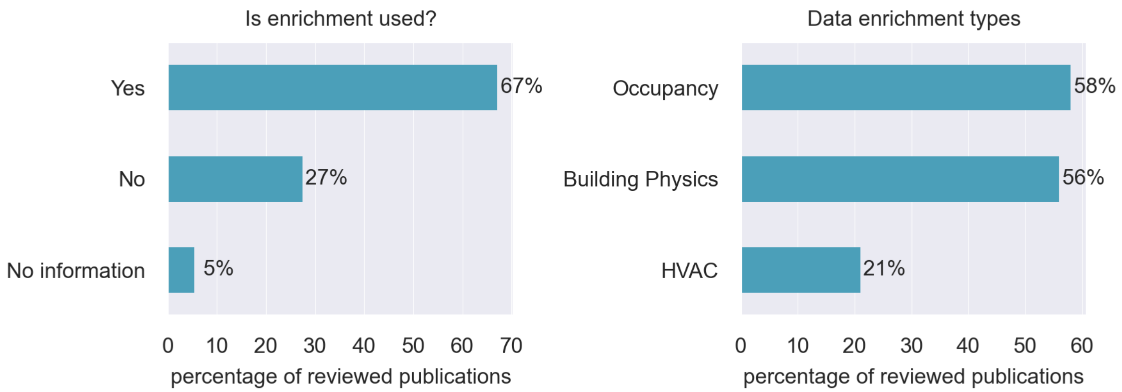

Figure 8: (Left) An overview of the usage of enrichment in the reviewed articles. Sums of percentages $\neq$ 100% are due to rounding errors in the annotations (Right) An overview of the data enrichment types considered in different studies

In the previous sections, the various data formats and models used in UBEM are discussed. However, when analysing the literature, the authors often found it difficult to determine which data model is being used in a given study. In many papers the data model is not explicitly stated. This can distort the results in Figure 7. For example, a community that is actively involved in the further development of a particular data model may be more likely to state the data model used (e.g. IBPSA Project 1 and CityGML). It was also found that a majority of studies (63%) are not reproducible as the data are not shared alongside the publication. Although data security and privacy issues prevent authors from openly sharing data, these observations highlight an issue with the communication of the data used in such studies across scientific literature. Scientific transparency and continued improvement of the UBEM process relies on clear explanations about the data used so those interested can replicate and verify the work. As a result, the field of UBEM reported in scientific literature is fragmented and non-reproducible. In future, it is vital that authors provide readers with the necessary details to understand and replicate the study with their own data. The next section details an evaluation of simulations tools and their usage in urban energy simulations.

4.2. Simulation tools

The scientific community has developed multiple simulation tools and workflows for UBEM in recent years. Table 6 provides an overview of simulation tools regarding: (i) availability (commercial, open source, freeware), (ii) externally supported UBEM data formats, and (iii) compatibility with FMI co-simulation.

Table 6: The tools for UBEM demand modelling identified in the taxonomic review. *Internal configuration files that are defined entirely in the software but uses Open Street Map data. **No known inbuilt support for data formats/models identified in the input data section.

Simulation Tools	**Externally supported UBEM data formats**	**Availability**	**Support FMI for Co-Simulation**
CitySIM Pro [62]	CityGML Energy ADE, common CAD files	Available by request	No
City Energy Analyst [134]	Internal config*	Open source	No
EnergyPlus [63]	None**	Open source	Yes
IDA ICE [27]	IFC, common CAD files	Commercial	No
INSEL [64]	None**	Freeware	Unknown
Matlab/Simulink [188]	None**	Commercial	Yes
Modelica Libraries [79–81]	None**	Open Source / Commercial	Yes
TRNSYS [68]	None**	Commercial	Yes

The taxonomic approach focuses on the individual elements of the published studies and enables a consistent assessment of the reported studies in order to establish opportunities in both the data generation and the development of simulation tools for UBEM. In total, 25 different simulation approaches are identified. These range from simplified steady-state models to dynamic models. This diversity highlights the difficulty of cross-comparing the results generated

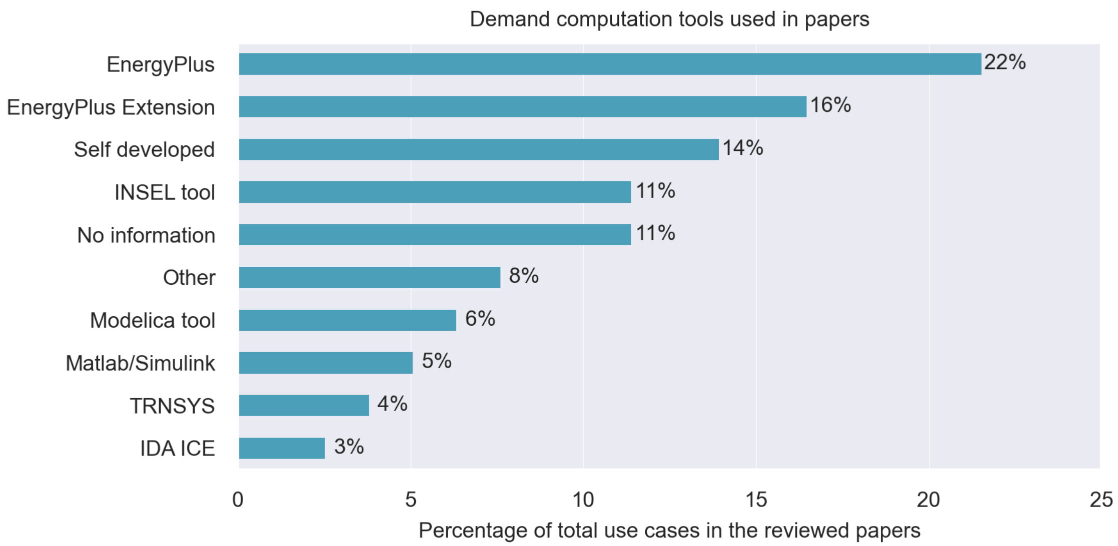

Figure 9: Simulation tools used in the reviewed papers. 100% is the total number of simulation cases in all papers (e.g. if a paper compares SimStadt and EnergyPlus, it is treated as two separate cases, one using SimStadt and one using EnergyPlus). Category 'Other' combines all tools that are used in only one of the reviewed papers, including: City Energy Analyst, Energy Carbon and Cost Assessment for Building Stocks (ECCABS), CitySim+, DeST, SwissRes, GIS/ArcView

by UBEM studies. No information is provided on the simulation approach used in 11% of the studies. By far, the most common simulation tool is EnergyPlus and its extensions that are used in 38% of the reviewed studies. The second most common is INSEL which is specified in 11% of the reviewed papers whereas Modelica is used in 6% and Matlab is used in 5% of the studies. The authors often found it challenging to consistently assign simulation kernels to the respective study. Several cases made reference to their own quasi-static energy balance calculations based on standards such as ISO 52016-1 [189]. Please note that several of the studies that mention their own tools incorporate similarly self-developed algorithms and these may make up a larger percentage of the total than the authors have recorded. It is interesting to note, that while EnergyPlus makes up the largest portion of simulation, it is not possible to directly simulate the most common geometry data input - CityGML files. Active research is being done to extend the data models, using application domain extensions (Energy ADE). This is done to provide sufficient additional attributes to enable building energy performance simulation [190]; however challenges with geometry processing still need to be overcome and this highlights an area for future research efforts. The importance of both self-contained simulation environments and their auxiliary applications are important for UBEM studies.

4.3. Simulations Results and Validation

Research in the domain of urban building energy modelling and simulation has been developing at a fast pace in recent years. This is mostly due to urgent demand for energy efficient solutions in the building sector, as explained in Section 1. The surge of new computational methods applied in UBEM requires coherent analysis, presentation and validation to give confidence in the results.

In the studies reviewed, 54% focus on the simulation of heating energy demands as their main objective. The other 46% provide additional or different results, such as electric energy demand or predictions of CO_2 emissions. Time resolutions of demand simulations range include yearly (26%), monthly (27%), daily (1%), hourly (36%) and subhourly (5%). The taxonomy recorded the finest time resolution reported in each study (Figure 10).

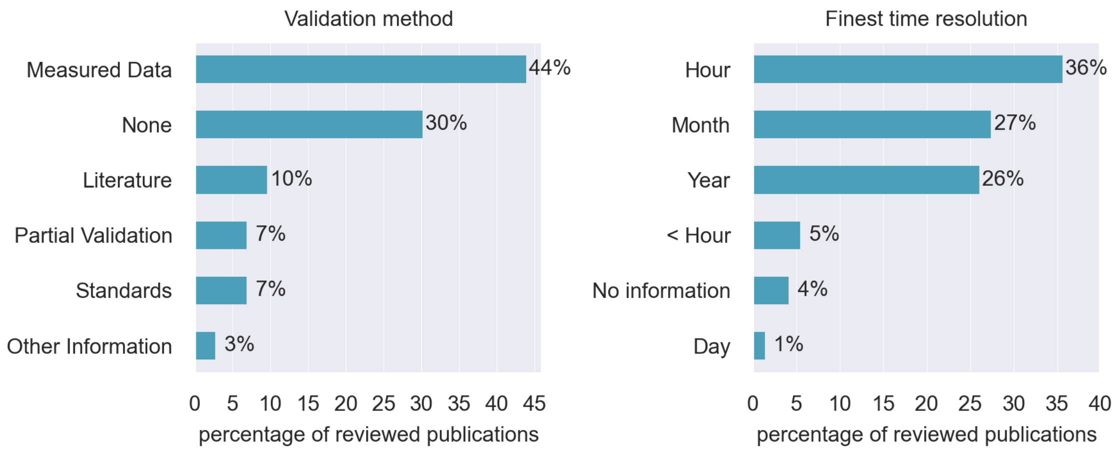

Figure 10: Relative distribution of validation methods (left) and smallest time resolution units (right) in the reviewed literature. Sums of percentages $\neq$ 100% are due to rounding errors in the annotations

Some data models also allow for the storage of simulation results. This offers the possibility to link demand data - obtained either from simulations or measurements - directly with the building data model. It also serves as an important step for demand based analysis. Furthermore, the storage of simulation results facilitates the sharing of data and expedites the creation of comprehensible visualisations of energy demand predictions at an urban scale. This is especially important as the UBEM based research results are not only relevant for the scientific community, but also for practitioners, decision-makers and local stakeholders. In total, only 16% of all reviewed papers store the results in the original data model. From the 27% of works that use CityGML (see Figure 7 on page 17), 40% use this functionality.

The results presented in 95% of the scientific papers considered in this review are not reproducible (see Section 4.4). In addition, approximately 30% of all papers do not validate the presented results based on measured data or other methods whereas 7% provide only partial validations (Figure 10). In the context of this paper, partial validation is labelled if, in an article, either the data models or the simulation results are validated. Contrary to this, in 44% of the studies, comparisons of simulation results against measured data are performed. Articles such as Meha et al. [146], which use bottom-up and top-down heat demand mapping methods for small municipalities, compare the simulation results of the two approaches with measured data. Other studies such as Österbring et al. [154], Mastrucci et al. [155], Nageler et al. [114], Li et al. [131] also compare their simulation results to measured values. Although the number of articles that compare their results to measured data is high, however, due to a consistent lack in availability of open measured data [16, 191, 192] it is often difficult for simulation scientists and research communities to compare their models and calculation in the field of UBEM. Once openly available, the measured data can be used to validate different approaches, workflows and simulation environments. Within the 44% of the (previously mentioned) studies, none openly allows the usage of their individual measured data to the simulation community and thereby making the approach/simulation irreproducible. Furthermore, 10% of the studies (such as Streicher et al. [135], Turcsanyi, P. [149], Eikermeier et al. [150]), perform the comparison against results from other scientific contributions, energy performance certificates and national standards. Zirak et al. [121], Monien et al. [141], Murshed et al. [164] also verify their simulations with other environments and platforms.

Another important aspect is the way in which authors chose to visualise the results of the energy modelling. For the taxonomy, three main visualisation categories are defined: time series plots, illustration of results with 2D maps, and visualisations using 3D spatial models. Other plots such as error plots or flow charts, etc. are not considered in this paper. It was found that 62% of all papers use one of the three aforementioned visualisation methods, with the relative distribution depicted in Figure 11. Used in almost equal measure are time series plots, with 34% of the papers and 2D maps with 36%. Less common, but nevertheless present in every fifth paper (22%), is the use of 3D spatial models. An important observation is that, in total, 44% of all papers use either one of spatial illustrations methods, indicating that either the energy modelling results are somehow stored in the data model or the studies use an additional file for visualisation purposes and overlay the files with the simulation results.

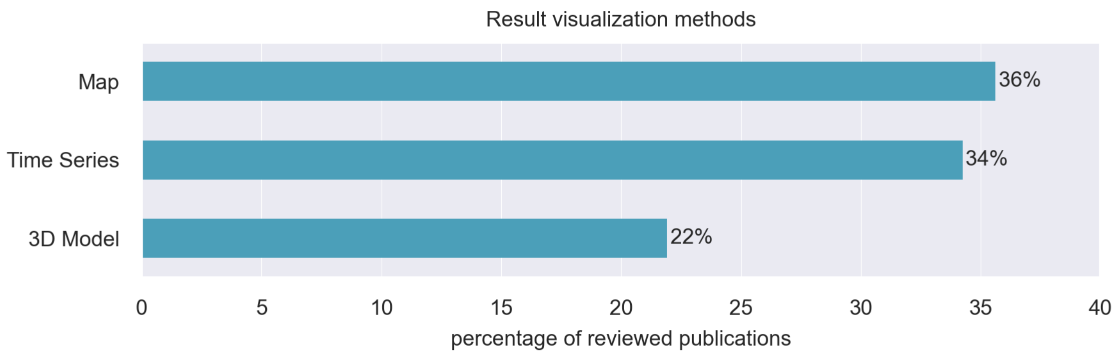

Figure 11: Types of result visualisation methods in reviewed proceedings and their relative distribution. Sums of percentages $\neq$ 100% are due to rounding errors in the annotations

4.4. Reproducibility

We categorise studies as reproducible if the simulation results can be reproduced by others. An overwhelming majority of reviewed publications ($\sim$ 95%) can not be reproduced. This is either due to the unavailability of input data and/or the impossibility to reproduce the simulation workflow. In terms of input data, we identified three common reasons why studies cannot be replicated: (i) the spatial and/or energy thematic models used are not available as open-source and/or open-data; (ii) data sources are not mentioned; (iii) pre-processing steps are not described in detail. For the simulation workflow, either the software tool is not available and/or the simulation method used or developed in the paper is not described thoroughly.

5. Discussion

The taxonomy based approach in this paper highly depends on the (i) selection of keywords (ii) classification of categories, and (iii) selection of appropriate articles. Although the keyword selection process is transparent, the authors are aware that this is a threat to validity; nevertheless, to the authors' knowledge, this is the most transparent selection process. This review selects articles that use bottom-up UBEM approaches. Although the classification and review is based on the selected keywords, however, in future, we would like to widen the domain of our approach, extend the keyword list and review papers focusing on urban influences and other simulation tools.

This taxonomic review identified CityGML to be the most commonly used input data format for UBEM. Although CityGML provides the geometrical and geographical information of a building, the format omits energy relevant features and properties. CityGML can be extended (e.g. resulting in the Energy ADE) with energy-specific semantic information by subsequent enrichment processes. The results show that data models such as gbXML and CityGML Energy ADE, which can represent energy relevant information, are seldom used. Harmonising the two models with comparable capabilities would combine the advantage of CityGML's availability with gbXML's implementations. Currently, IFC, an extensive standardised and open building information model, plays no role in UBEM. Even though several data models exist and are used for UBEM-based approaches, we presume that their acceptance is restricted due to limited availability. As not many detailed data sets are available in standardised formats, broader usage of such formats is further limited. Therefore, we argue that research should focus on generation of representative data sets (e.g. standard archetypes) that can be combined with georeferenced data. This would also require geodata to contain the correct allocation variables such as building age, use and refurbishment status.

We found that EnergyPlus is the most frequently used simulation kernel for UBEM; a significant number of simulation kernels are also self-developed. Different kernels depend on different input data, simulation settings, predefined parameters, and model assumptions. In general, not all simulation settings are transparent to the community. Many of the identified simulation tools are complex (e.g. EnergyPlus) and require a large number of input variables to compute the energy demand. This conflicts with the scarcity of available building stock data, leading to the necessity of data enrichment and, consequently, propagates high input variable uncertainties into the simulations.

The most common output of the simulation process is yearly heating energy demand in an hourly time resolution. Usually, these time series are stored without any meta data. This hinders data interoperability and collaboration between researchers further. For validation, a substantial share of 44% of the reviewed articles validate the results based on measured data, whereas, 30% do no validation at all. The authors consider several possible reasons, e.g. that there is no access to the required data or the required data may not be available. Furthermore, we observe that the challenge of validation is primarily a problem of data availability rather than a methodological problem. Therefore, it would be beneficial for UBEM validation if there were open standardised validation data sets that provide complete input data along with measured energy consumption for a representative building stock.

Reproducibility is a key part of any scientific process. However, the results show that for the majority of papers analysed in this review, it is not possible to reproduce the results. Although, lower reproducibility is a problem across peer-reviewed literature in general [193, 194], wherever possible, open data sets should be used as this helps the scientific community to efficiently develop, validate and maintain energy simulation tools and workflows.

6. Conclusion and Future Work

This paper analyses different aspects of UBEM through a taxonomic analysis. This includes various data types, simulation environments, results and visualisation, and the reproducibility of research studies. 27% of the authors use CityGML input data for UBEM approaches. As CityGML data sets are often openly available, future developments should focus on the enrichment of open data sets and on storing the information as common data formats such as gbXML and CityGML Energy ADE. There is a mismatch between the most commonly utilised input data format (CityGML) and the most prominently used simulation environment (EnergyPlus (22%)). Since EnergyPlus does not support the input functionality of CityGML format, further research addressing the direct use of this format is an important step towards standardising UBEM approaches. Further research should define metrics that allow for a transparent comparison of different simulation kernels. 44% of the studies validate the outputs using measured data. As validation is one of the key aspects of research studies, development of UBEM-benchmark validation data set should be an objective of future research. Future research should also address the validity and uncertainties of enrichment variables (e.g. U-Values) and the generation of standard enrichment data sets. A large number of the articles (34%) focus on outputs as time series. Future work should provide sufficient meta data to describe the simulation results. Since only a limited number of the identified studies are reproducible, future work should thoroughly describe the granularity and quality of input data, the data models, the simulation parameters and settings, and details of the validation procedure. In addition, sample data sets should be published alongside the results in order to compare different approaches. In future, articles based on top-down UBEM approaches shall be systematically reviewed as this will complement the results presented in this paper. Quantification of environmental and inter-building influences such as micro-climate and mutual shading should be included in the future research using different case studies and implementations. An integration of the present taxonomy with the classifications, related to urban context influences, made in previous studies is planned in the future. A main task for the future will be a committed support of open data, software and processes in the field of UBEM.

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