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Authors(s)	Alshehri, Fawaz, Kenny, Paul, O'Donnell, James
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Requirements specification to support BIM-based Thermal Comfort analysis

Fawaz Alshehri[1], Paul Kenny[2] and James O'Donnell[1]

1. School of Mechanical and Materials Engineering, UCD Energy Institute, University College Dublin, Ireland.

2. School of Architecture, Planning and Environmental Policy, University College Dublin, Ireland.

Abstract: Traditionally and during a building's operation, thermal comfort levels are often evaluated using equipment that is expensive to purchase and maintain. Through advanced technologies, Building Information Model (BIM) and energy simulation tools, thermal comfort and its impacts can be evaluated at the conceptual and early design stages. The development of Building Energy Performance Simulation (BEPS) tools, through the implementation of BIM, will provide design teams with rich, comprehensive data to evaluate indoor thermal conditions in order to provide acceptable comfort levels. Current energy simulation models focus on entering data manually, increasing time and cost. BIM-based energy and thermal comfort analysis provides designers with the means to explore a variety of design alternatives, as well as avoiding the time-consuming process of re-entering all of the building's geometry and HVAC specifications to perform an analysis. However, integrating BEPS with BIM-based building design tools is still limited, with one of the key obstacles being the lack of standardised methods for information exchange between the two domains. To address the needs and bridge the gaps, this paper aims to improve the information exchange process by describing data and information needed to perform thermal comfort simulation using a standardised format in order to develop a Model View Definition (MVD) for thermal comfort. This approach represents the data needed by building designers or operators to provide an acceptable level of thermal comfort in a typical small, single occupant office. Through analysis of the performance of the proposed approach, this work provides a standardised exchange of data from BIM to BEPS tools, such as EnergyPlus, using the Industry Foundation Classes (IFC) standard.

Key words: Thermal comfort, Model View Definition (MVD), Building information modeling (BIM), Building Energy Performance Simulation (BEPS), Industry Foundation Classes (IFC).

1. Introduction

Buildings are major consumers of global energy resources, using approximately 32% of total primary energy, with a potential to conserve and deliver greater performance, including occupant comfort [1]. Building design strategies and advanced construction technologies can significantly reduce energy consumption and improve indoor comfort levels. In many buildings, occupants regularly experience discomfort, directly affecting their health, well-being and performance. Approximately 80% of the energy used in commercial office spaces, for example, is for maintaining optimal comfort levels through delivery of heating, cooling, ventilating, and lighting, depending upon the energy cost and climate [2].

Energy modeling and simulation tools can be very effective tools for assessing energy consumption and comfort levels [3]. In many situations, building energy performance analyses have been conducted late in the design phase; however, investigating alternative designs and new ideas in the early design process would support the design team in choosing the best solution. One key reason is the complexity of modeling a building and its energy components is dependent on the scale of the building, as well as the cost. Creating an energy model based on a Building Information Model (BIM) as a data source provides building designers the opportunity to test and explore energy saving strategies in the early design phase, while avoiding the time-consuming process of re-entering all the building geometry and HVAC specifications to complete energy and indoor performance analysis [4].

Industry Foundation Classes (IFC) is one such BIM and is an object oriented file format with a data model developed by BuildingSMART. IFC is registered by International Organization for Standardization (ISO) as ISO 16739 and been used as the only official and open international BIM standard [5]. A number of studies have been carried out in the area of IFC data extraction in the design and construction of facilities, but BIM-based Energy Simulation has not been widely studied [6]. An IFC model of a building containing most of the essential data can store much of the information needed by different stakeholders. However, some data gaps persist, particularly around the BIM definitions required to support thermal comfort analysis.

This paper aims to define data requirements needed by building designers or operators to deliver a satisfactory level of thermal comfort in a typical small single occupant office. These requirement specifications are subsequently translated to the IFC data format This intention is support standardized exchange of the necessary information from BIM to Building Energy Performance Simulation (BEPS) tools, such as EnergyPlus, for thermal comfort modeling simulation analysis. The outputs of this ongoing research will contribute to the creation of a Model View Definition (MVD) for thermal comfort of commercial office spaces.

2. Problem statement on BIM based thermal comfort modeling approach

The science of comfort developed in the early 20th century for the needs of the heating, ventilation and air-conditioning (HVAC) industry. Therefore, the HVAC industry needed to define ‘comfort’ in terms of the physical variables that could be controlled using HVAC systems [7]. The factors used by building thermal comfort researchers and engineers are temperature (C°), humidity (%) and air speed (m/s), clothing insulation (Clo) and metabolic rate (met). In doing so, the factors answer the needs of the engineering teams in a way that allows them to size their plant.

The best known conventional method used for thermal comfort measurements is based on the PMV (Predicted Mean Vote) or PPD (Predicted Percentage Dissatisfied). Most common BEPS software can estimate thermal comfort level based on these two scales [8]. However, because data was only collected in climate chambers, PMV does not recognize that comfort has psychological and social dimensions. A wide range of research has been carried out on residential and non-residential thermal comfort levels. One such study [9] attempted to validate the accuracy of the PMV model and compare it with non-physical parameters of thermal sensation for naturally ventilated homes and office environments in the UK. It concluded that there is a real “context effect”, such as gender, age, cultural and economic conditions, on occupants predicted and observed thermal sensation. Another study observed that there is a direct relationship between illumination intensity and an individual’s thermal stability in workplace [10]. These findings indicate that the above-mentioned non-thermal parameters were not accounted for in the heat balance model. Therefore, it’s important to specify a more comprehensive data about space conditions in order to improve the accuracy of simulation results of thermal comfort for decisions makers.

The data included in BIM can be reused to establish thermal simulation models. Traditionally, the geometries of a building are imported using 2D-DXF/DWG files to create an energy model. More 3D object-oriented building geometry models are becoming available, so major BIM software has the capability to generate IFC files of the building geometry automatically [6]. However, there are problems reported in BIM-based energy simulations resulting in missing information, misplaced or distorted building elements in BIM data exchange [6]. Therefore, eliminating or minimizing the above mentioned barriers will have a significant impact on time-saving, cost analysis and reduced hours of labor, as well as increasing the accuracy of the output.

IFC is an open and freely available data model which can be used to exchange and share BIM data for building elements. However, one major barrier to using IFC is its complexity, which requires a considerable investment of time and effort to understand the areas of the schema that can best meet the case data requirements. To support the use of IFC, buildingSMART has developed methodology using the Information Delivery Manual (IDM/MVD) to define a subset of the schema's exchange requirements. Based on this methodology, over the past a few years buildingSMART released a number of MVDs, including Coordination View, Reference View and Design Transfer View. These MVDs are suitable for a variety of workflows such as Coordination planning, Clash detection and Quantity take-off.

Concept Design BIM (CDB) developed MVD that focused on a general definition of energy analysis to support the coordination of energy analysis requirements[11]. Another effort is the Holistic Energy Efficiency Simulation and Management of Public Use Facilities (HESMOS). This project did not define an MVD but instead, the project focused on the definition of exchange requirements for energy analysis representing the last step before being able to develop an MVD. [12]. However, the above mentioned MVDs are based on large, complex data structures, whereas only a small part is needed for specific use cases, such as thermal comfort performance analysis.

Consequently, the information needed to perform thermal comfort first needs to be filtered and categorised in a standardised manner to provide relevant information and eliminate unwanted data. This paper defines the necessary data requirements and information that needs to be exchanged from BIM to typical BEPS tools (e.g. EnergyPlus). This presents an MVD for thermal comfort that represents the data needed by building designers or operators to deliver a satisfactory level of thermal comfort in a typical small, single occupant office.

3. Research methods

Thermal comfort analysis requires detailed specification of the analysis processes combined with data and information that needs to be exchanged to support these processes. The target of this paper is to describe this data and information in a standardised format. As the IFC data model is so large, only carefully defined subsets of the model are required to support specific business processes, in this case thermal comfort analysis. These subsets are called MVDs, with the primary objective being to ensure standardized import and export functions of specific requirements for IFC compliant software.

The scope of this work focuses on producing a technical version of specifications for the exchange requirements needed to develop the MVD. Usually tabular or spread sheet formats are used to document information exchange identified in an overarching process map. The process is mainly based on the

Information Delivery Manual (IDM), which is a standardized methodology developed by BuildingSMART that defines the information for existing or new processes in order to assist the various stakeholders in their tasks.

The first step in developing MVD using IMD is to identify the scope of the intended implementation by each stakeholder and the associated information requirements. This step includes a description of the analysis process needed to support a business requirement at a particular stage of a project. The second step of the IDM schema identifies the entities involved in the exchange. This identification is accomplished by mapping the IDM requirements using graphic process maps or tables. The requirements are mapped to or from the representation of the entities needing to be exchanged between processes. Subsequently, MVD using IMD provides a detailed description of a set of information to be exchanged supporting a business case in this situation, thermal comfort analyses. The information provided includes general statements of requirements not specific to an IFC release. Finally, information is translated into a technical version of the full standard of an exchange requirement for thermal comfort analysis. The exchange requirement is then mapped to a corresponding BIM format, typically IFC for a detailed MVD definition, Figure 1. The following sections describe each step individually.

Including IFC in IDMs reduces the risk of error at the detailed level of content of an IDM. However, very detailed and technical specifications in IDM requires that the IDM process will need domain expertise and business modeling skills and will also require very thorough technical knowledge. In this case, IDM includes information sets that are related to end users and to technicians. The IDM defines the exchange requirements needed for the development of the MVD for thermal comfort, which will bind these requirements in an IFC sub-schema.

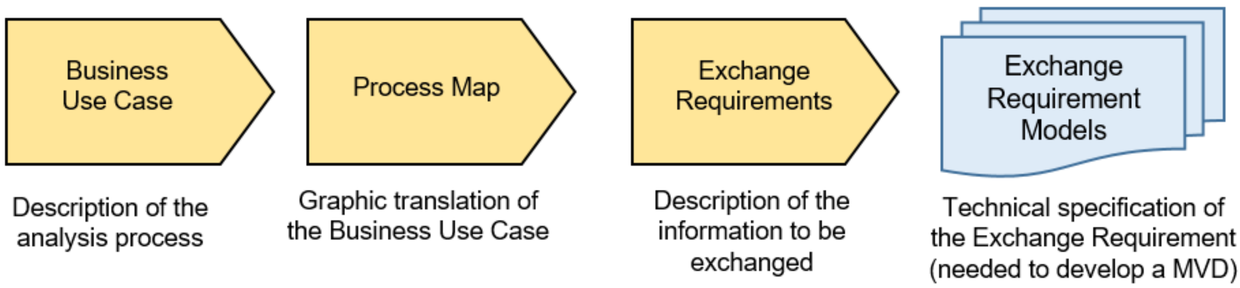

Fig 1 The process to define the sub schema for the MVD, based on the base schema of IFC.

After the mapping process, the MVD itself is created. This step currently is still under development. IfcDoc is a tool published by BuildingSMART that can be used to generate an Exchange Requirement document. If BIM software has already implemented a MVD, the output IFC file will contain the necessary exchange requirements for that particular analysis.

3.1 Description of the business use case

Typically, use case definitions are the first step of model specifications [5]. In order to define the exchange requirements, it is necessary to first establish a model based BIM IFC. This use case is a typical 7 meters squared single occupant office, Room 311 in the School of Mechanical & Materials Engineering, at University College Dublin. The room is modeled by GRAPHISOFT ArchiCAD, which is one of the prominently used BIM-based CAD tools. ArchiCAD allows the user to model both the architectural design and the Mechanical Electrical and Plumbing (MEP) systems in the same work environment. The use case consists of

a single thermal zone with HVAC system. The construction details of models, including uninsulated components, is modeled with single-glazed aluminum frame. The construction material for the use case envelope includes concrete block wall, curtain wall, concrete floor and roof (Figure 2).
Other factors which can influence thermal comfort level, such as radiators, artificial lights, occupants, office furniture and equipment, were considered in the model.

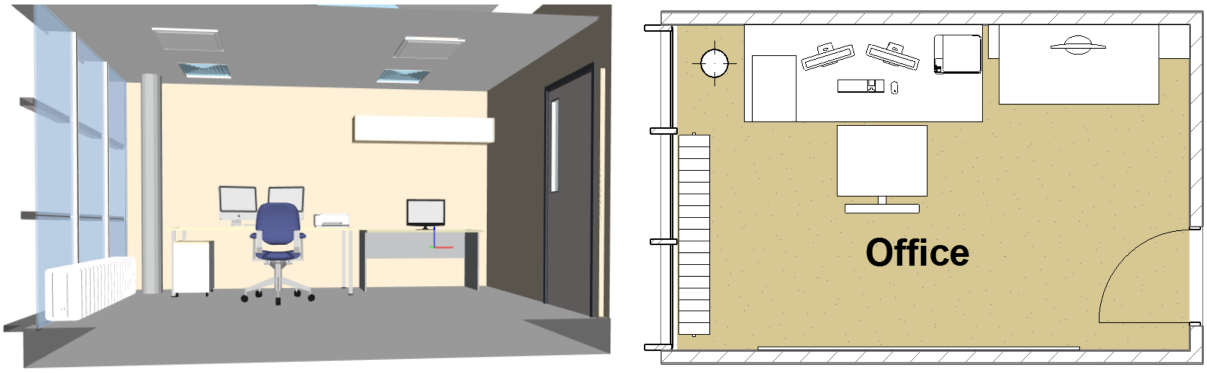

Fig 2: BIM for the use case, a single occupant office.

To enable control over the export to IFC, the authors specified the necessary content for the exchange between BIM and BEPS. For the walls, roof and floor, each material layer was defined, including physical characteristics like density (kg/m^3), thermal conductivity (W/(m. K)), thickness (mm) and surface finishing as well as specific details for the door and window. For the occupants we defined two main personal factors which have a great effect on the comfort zone, activity level (heat production in the body, Met value) and clothing level (thermal resistance of clothing, Col value). Other factors influencing the wellbeing of the inhabitants also needed to be defined. Examples of these factors are psychosocial condition, age, gender, skin color and air quality [13]. Although these factors are not affected by climatically adapted construction, they should not be forgotten. The properties of design of the HVAC system were defined for example Air Flow rate Range (m^3/s), and Temperature Range (°C) as illustrated in result section Table 2.

3.2 Process Maps

Process Maps (PM) define the processes, responsible actors and the data flow that shall be supported by the BIM approach. They allow an understanding of the arrangement of activities that are required, the users involve and the information required, consumed and produced [5]. In fig 3 example of Space design where most exchange requirements are for thermal comfort analysis. The example shown in the diagram workflow applies to all the disciplines, but extends its activities to architects and building services engineers involved in the collaborative process of information exchange. The exchange requirements include space layout (e.g. Length (mm), height (mm), gross area (m^2), etc.) and for HVAC system (e.g. Air exchange rate (ACH) and dry bulb temperature (°C), etc.).

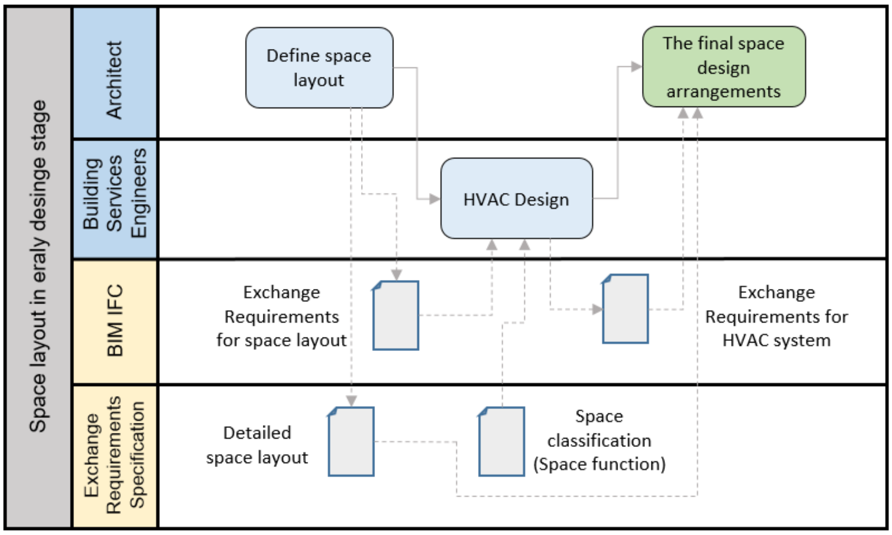

Fig 3: An example of multidisciplinary collaboration workflow process map for space design.

3.3 Exchange requirements description

The Exchange Requirements are specified in terms of the information items relevant in the exchanges. They identify which objects, property sets, properties, relations and classifications are relevant to the use case. For example, special data need to be taken for building geometry, which is typical project data in most exchanges (e.g. a Wall). The geometry of the wall includes a number of pieces (An outer leaf, an inner leaf, air gap between these leaves which usually contains insulation and a vapor layer in addition to wall renders). Properties and relations between parts may also need to be specified. Therefore, this level of details needs to be identified as possible requirements for exchange. This is done by determining a set of entities, properties and parameters for individual elements using IFC format, Table 1 and Fig 3. When used in practice, the data is stored in the IFC model. Then the necessary data to be exchanged between relevant stakeholders (geometry, HVAC system and materials properties) is extracted from the IFC-based BIM. Finally, the retrieved information is stored within the proposed IFC model. This process will successfully convert the IFC model to be ready for export to simulation software EnergyPlus, in order to perform a thermal comfort analysis.

Table 1 An example of Exchange Requirement necessary from BIM to perform thermal analysis, for a wall entity.

Entity	Property Set	Property	Data Type	Unit
IfcWall	Pset_WallCommon	ThermalTransmittance	ThermalTransmittanceMeasure	W/m².K

In figure 3, an example of a BIM model is shown with a Block_ Plastered _2_Sides_Wall. Of the geometric, thermal properties (Value, W/m².K), and other physical characteristics for the wall such as density (kg/m³), thermal conductivity (W/m. K), thickness (mm) and surface finishing were included.

After defining the exchange requirements necessary in BIM to perform analysis, an IFC file stores the building information in IFC format, which consists of the parameters required for a specific analysis case, e.g. thermal comfort evaluation. Therefore, the output of IFC file from this case study only includes the exchange requirements defined for that specific analysis, thus filtering unrelated information. This approach allows for easier and quicker data transfer and reduces the loss of information when exchanging BIM files between different applications and analysis tools.

3.4 Exchange requirements using IFC building data model

This step provides technical specification of the data and information needed to develop a MVD for thermal comfort simulation. In this use case, grouping is achieved through assignment of entity types and relating these entities with common IFC properties (Fig 3). This use case model encompasses 11 objects with over 109 properties for thermal comfort analysis. These objects included Curtain wall, Column, Door, Light fixture, Material, Roof, Slab, Space, Space Boundary, Space heater, Wall and Window. The results from this case study describe sets of essential properties needed for the integration of BIM with thermal comfort modeling before exporting the model into the simulation tool EnergyPlus. Table 2 presents a technical version of the basic requirements by entity types and also presents overall definitions and properties descriptions for each entity.

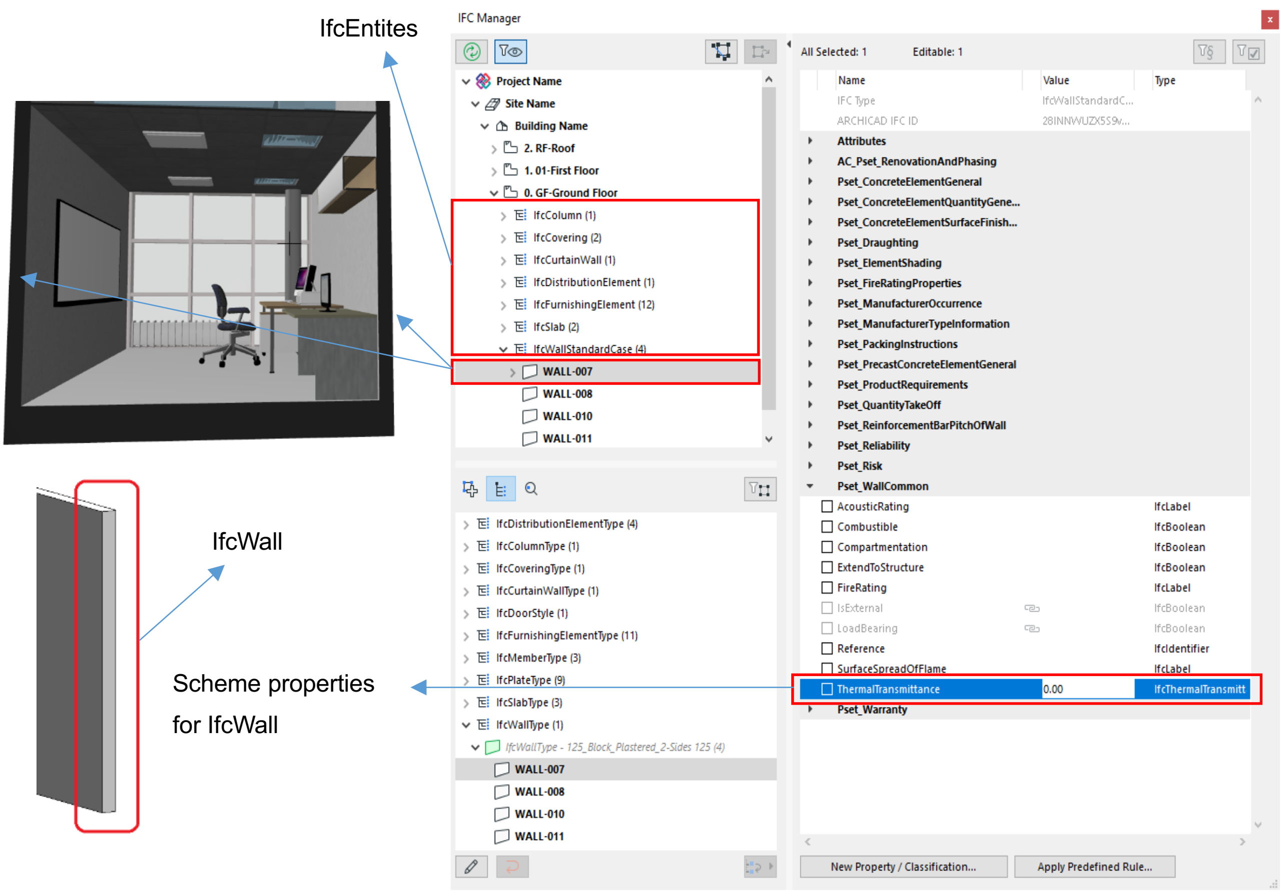

Fig 3 An example of defining properties for one entity of the use case, IfcWall.

Table 2: Exchange Requirements necessary from BIM to perform thermal analysis.

Entity	Property Set	Property	Data Type	Unit
IfcLightFixture	Pset_LightFixtureTypeCommon	NumberOfSources	IfcInteger	--
		TotalWattage	IfcPowerMeasure	W
	Pset_LightFixtureTypeThermal	MaximumSpaceSensibleLoad	IfcPowerMeasure	W
		SensibleLoadToRadiant	IfcPositiveRatioMeasure	W
IfcDoor IfcWindow	Qto_DoorBaseQuantities Qto_WindowBaseQuantities	OverallHeight	IfcPositiveLengthMeasure	mm
		OverallWidth	IfcPositiveLengthMeasure	mm
	Pset_DoorCommon Pset_WindowCommon	Reference	IfcIdentifier	--
		Infiltration	IfcVolumetricFlowRateMeasure	m³/s
		IsExternal	IfcBoolean	--
		ThermalTransmittance	IfcThermalTransmittanceMeasure	W/m².K
	Pset_DoorWindowGlazingType	Reflectivity	IfcPositiveRatioMeasure	--
		SolarHeatGainTransmittance	IfcPositiveRatioMeasure	W/m².K
IfcMaterial	Pset_MaterialEnergy	ViscosityTemperatureDerivative	IfcReal	Pa·s
		MoistureCapacityThermalGradient	IfcReal	--
		ThermalConductivityTemperatureDerivative	IfcReal	W/m.K
		SpecificHeatTemperatureDerivative	IfcReal	J/kg.K
	Pset_MaterialThermal	SpecificHeatCapacity	IfcSpecificHeatCapacityMeasure	J/kg.K
		ThermalConductivity	IfcThermalConductivityMeasure	W/m.K
	Pstc_MaterialThermal	SolarRefraction	IfcReal	--
		CoefficientOfHeatTransfer	IfcCoefficientOfHeatTransfer	W/m².K
		AbsorptionCoefficient	IfcAbsorptionCoefficient	--
IfcSlab IfcRoof	Pset_SlabCommon Pset_RoofCommon	Reference	IfcIdentifier	--
		ThermalTransmittance	IfcThermalTransmittanceMeasure	W/m².K
		IsExternal	IfcBoolean	--
		PitchAngle	IfcPlaneAngleMeasure	radian
	Qto_SlabBaseQuantities Qto_RoofBaseQuantities	Width	IfcLengthMeasure	mm
		Length	IfcLengthMeasure	mm
		Depth	IfcLengthMeasure	mm
		GrossArea	IfcAreaMeasure	m²
		NetArea	IfcAreaMeasure	m²
		GrossVolume	IfcVolumeMeasure	m³
		NetVolume	IfcVolumeMeasure	m³
IFCSpaceheater	Pset_SpaceHeaterTypeCommon	TemperatureClassification	IfcSpaceHeaterTemperature	--
		ThermalMassHeatCapacity	IfcReal	J/K
		NumberOfPanels	IfcInteger	--
	Pset_SpaceHeaterTypeRadiator	RadiatorType	IfcLabel	--
	Qto_SpaceHeaterBaseQuantities	Length	IfcQuantityLength	mm
IfcSpace	Pset_ SpaceOccupancyRequirements	OccupancyType	IfcLabel	--
		OccupancyNumber	IfcCountMeasure	--
		OccupancyNumberPeak	IfcCountMeasure	--
		OccupancyTimePerDay	IfcTimeMeasure	--
		AreaPerOccupant	IfcAreaMeasure	m²
		MinimumHeadroom	IfcLengthMeasure	mm
	Pset_ SpaceThermalLoad	People	IfcPowerMeasure	W
		EquipmentSensible	IfcPowerMeasure	W
		Lighting	IfcPowerMeasure	W
		AirExchangeRate	IfcPowerMeasure	W
		DryBulbTemperature	IfcPowerMeasure	W
		RelativeHumidity	IfcPowerMeasure	W
		TotalSensibleLoad	IfcPowerMeasure	W
		InfiltrationSensible	IfcPowerMeasure	W
IfcWall IfcCurtainwall IfcColum	Pset_WallCommon Pset_CurtainWallCommon	Reference	IfcIdentifier	--
		ThermalTransmittance	IfcThermalTransmittanceMeasure	W/m².K
	Qto_WallBaseQuantities Qto_ColumBaseQuantites	Length	IfcLengthMeasure	mm
		Width	IfcLengthMeasure	mm
		Height	IfcLengthMeasure	mm
		GrossSideArea	IfcAreaMeasure	m²
		NetSideArea	IfcAreaMeasure	m²
		GrossVolume	IfcVolumeMeasure	m³
		NetVolume	IfcVolumeMeasure	m³

4. Discussion

The Information Delivery Manual (IDM) is a standardized methodology that has been developed by BuildingSMART. This methodology is used in the case study to document and describe the information to be exchanged between BIM and BEPS in order to develop a MVD for thermal comfort.

BIM simplifies updating and sharing of digital design data for buildings. However, by utilising BIM as data source for establishing thermal simulation model can be complex and challenges for the design team. These issues are due to the large amount of data contained with the BIM. The proposed MVD will assist in resolving these complexities and improving automated or semi-automated information flow.

Energy transfer, airflow and comfort are interrelated in many buildings. Conventional energy modeling software, including EnergyPlus, is mainly used to examine two aspects of building efficiency. Firstly, it assesses the efficiency of the building envelope, including fabric, structure, and lighting. Secondly, it examines the efficiency of various solutions for the HVAC system [14]. The relationship between the efficiency of the building envelope and HVAC efficiency defines the total energy consumption of the building and also has an impact on indoor thermal comfort levels. However, the benefits of these software packages are limited, so finding an appropriate match is an important part of indoor thermal comfort simulation.

Computational Fluid Dynamics (CFD) is a more detailed approach to comfort analysis where airflow patterns and temperature distributions are determined for individual zones or a group of zones [15]. CFD models can be used to accurately predict thermal comfort and test alternative HVAC systems at the spatial resolution achievable. When it comes to investigative occupant comfort, CFD can provide a more reliable image of conditions than energy simulation software, while energy models assume level temperatures within the model domain [16]. The integration of BIM and CFD models can provide more accurate predictions about building energy use and the indoor environment due to the complementary information provided by the two models.

5 Conclusions

The current systems focus on manually entering data. This is waste of time, money effort as well as errors can possibly occur. Moreover, a limitation with BIM based conventional software for thermal comfort analysis has been identified. Therefore, this paper presents an approach to develop a BIM based BEPS tools using the IDM/MVD methodology for implementation and documents the data exchange requirements for thermal comfort analysis using IFC. In order to validate the proposed approach, a case study has been presented, which identified the existing and missing objects in the latest release of the IFC schema that are relevant for thermal comfort analysis.

The outcome of this work can have significant contributions for BIM based data exchange through significant time-saving, consistently high quality BIM instances and reduced hours of modeling effort.

The next part of this research will focus on using the IfcDoc tool which was developed by BuildingSMART to generate MVDs and corresponding IFC documentation.

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