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Requirements for BIM-based Thermal Comfort Analysis

ABSTRACT
When designing and creating a working or living space, the provision of thermal comfort for a building’s occupants remains a key objective. However, significant energy consumption associated with a considerable proportion of the commercial building stock is not necessarily translated into improved thermal comfort conditions. When collaborative design revolves around Building Information Models (BIMs), much of the data required for thermal comfort analysis is already defined by other project stakeholders. Furthermore and during operation, mechanical equipment such as HVAC and lighting fixtures plays a major role in functional performance, resultant thermal comfort and energy consumption. Monitoring building performance and thermal comfort requires additional representative data about indoor environmental conditions and energy consumption.

This paper presents a holistic review of the data and information needed for integration of BIM with thermal comfort modelling for commercial office spaces. For example, thermal comfort is dependent on multiple factors, such as indoor environmental conditions, user behaviour, properties of building materials etc. and this data must first be categorised in a standardised manner. The outputs of this work will contribute to a Model View Definition (MVD) for thermal comfort using the IFC standard.

Author Keywords
BIM, MVD, HVAC, IFC, BEPS, AEC, Thermal comfort Thermal comfort; Thermal environment; Predicted Mean Vote (PMV); Actual Mean Vote (AMV); Adaptive coefficient

ACM Classification Keywords
: C10, °C, Met, m/s, W/m²K, p/m², m³/s

1 INTRODUCTION
Reducing energy consumption and emissions of greenhouse gases is an important 21st century objective. The benefits of which are needed to arrest global warming and compensate for over reliance on fossil fuels. The Intergovernmental Panel on Climate Change reported that, in 2010 buildings accounted for 32% of global energy use and 19% of greenhouse gas emissions [21]. However, the amount of energy used by buildings varies between countries, for example; buildings in European countries accounted for 40% of total energy use and 36% of total CO₂ emissions [13]. There are many reasons for energy inefficient buildings: such as poor design, poor operation, lack of legislation, and strong economic, social and environmental factors just to name a few [14]. The Council of the European Union made various recommendations to improve the environmental and energy performance of the existing building stock and to make sure any new building meets the minimum performance requirements [13]. Most of the energy used in non-residential buildings occurs during the operational stage [33] and the average energy savings during this phase in the United States can reach 15% [27]. The energy performance of a building is only one aspect used to assess and determine the overall performance level. In addition, many important factors related to the indoor environment also contribute to improving building performance. These factors relate to sustainability or may affect people directly and these include: air quality, lighting quality, acoustic performance and thermal comfort.

Providing thermal comfort for a building’s occupants and decreasing energy consumption remain a key design challenge. The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) [1] and BS EN ISO 7730:2005 [22] define thermal comfort as “the condition of the mind in which satisfaction is expressed with the thermal environment”. The purpose of these global standards is to identify a method for predicting thermal satisfaction level and the degree of comfort /discomfort of people exposed to reasonable thermal environments [29]. Brager [5] suggested that “If building designers and operators can find efficient ways to allow building temperatures to float over a wider range, while affording occupants comfort, the potential for energy savings is enormous”. In this context, energy modeling and simulation tools are increasingly used to optimise and predict likely energy consumption and associated thermal comfort levels.

Most Building Energy Performance Simulation (BEPS) software can estimate thermal comfort but use concepts of traditional thermal comfort measurement to make decisions [35]. BEPS define the comfort level based on Predicted Mean Vote (PMV) which is based on a heat balance model. However, PMV can be described as a “static” model of human thermal comfort and works on input for environmental and personal factors. These kind of models fail to take personal preferences of individual users into account. Most thermal comfort simulation programs refer to ASHRAE-55-2010 or 2013 standards to determine comfort levels within each space [20]. Typically, simulation software defines the comfort zone by inputting information for the six main environmental factors indicative of thermal comfort in which the PMV is within the required limits, (-0.5 and +0.5). Human Thermal Models (HTM) have been developed over the last hundred years and can be used for evaluating thermal behaviour of the human body under both steady-state and and transient indoor environment conditions [38]. This method is based on physiology and true anatomy of the human body. The integration of PMV method and human thermal models may help to obtain accurate results for the comfort level assessment, for example the thermal models will contain surface temperatures and radiation heat transfer etc. in addition to some aspects of physiology of the human body. HTM itself has been less
Building Information Modeling (BIM) is a life-cycle collaborative technology that is gaining rapid adoption within the AEC industry. BIM can link the information used in early design stage through to operation through a common data model. In the context of this paper, BIM is a universal user interface for architectural design and building performance simulations. When coupled, BIM and sustainable building design can not only reduce energy consumption and reduce environmental effects but can also decrease costs and create a comfortable and pleasant living environment.

Of the available BIM formats, Industry Foundation Classes (IFC) is the only open life-cycle data model for buildings that is an international standard. As the IFC data model is so large, only carefully defined subsets of the model are required to support specific business processes. These subsets are called Model View Definitions (MVD) where the primary objective of MVDs is to ensure standardised import and export of specific requirements for IFC compliant software. Presently there is an absence of an MVD to support thermal comfort analysis in commercial buildings.

The future integration of BIM with simulation tools is very promising. From the early design stage, BIMs contain useful information for different project elements which can be reused to establish a BEPS and thermal comfort models. With BIM in place, monitoring of thermal comfort can continue through to and include building operation. This paper presents a holistic review of the data and information needed for integration of BIM with thermal comfort modelling for commercial office spaces. The first step in this work defines a set of necessary exchange requirements in the form of data and information for life-cycle thermal comfort analysis. This information, provided by the BIM compliant stakeholders, can be used to establish thermal comfort models during design, update during the life-cycle and evaluate against measured results during operation of commercial office spaces. This data and information requirements must be represented in a standardised manner in order to develop a Model View Definition (MVD) for thermal comfort. The outputs of this work will contribute to a Model View Definition (MVD) for thermal comfort in adherence with the IFC standard.

2 INDOOR ENVIRONMENTAL CONDITIONS
Recent quality of lifestyle increases has significantly improved certain areas of peoples’ lives. However, this advance has been accompanied by a reduction in outdoor activities and reflected in human health issues. In the 21st century “on average people spend 80-90% of their time indoors, and indoor environment has important effects on human health and work efficiency”. Creating a suitable indoor temperature is necessary for employee productivity in commercial office spaces. Furthermore, with increasing global energy costs and CO2 levels, finding methods of decreasing energy use and providing individual thermal comfort are significant goals for many industries and researchers in this field. Failing to make employees comfortable isn’t a minor consideration. About 2% of employee working hours in the UK are consumed by battles for their environment control, costing more than 13 billion each year.

Inappropriately controlled buildings not only make people unproductive, unhappy and uncomfortable, but also can cause health issues, even leading to death. For example, the excessive heatwave during the summer of 2003 killed more than 70,000 people in European countries. It also killed more than 1200 people in south India, most of them old and many in their own homes.

The heat produced by the body metabolism rate through various human activities is dependent upon a variety of factors. For example, heat is released based on the activities of the body, the higher the level of activity, the more heat produced. Heat produced is also associated with body size and age. The quantity of metabolic rate decreases as a person ages and this leads to an increase in heating demands. A large number of studies focus on various aspects of thermal comfort, well-being, and health within workplaces. The Center for the Built Environment suggested that, buildings are inefficient spaces, especially during their operation phase. Mechanical equipment such as HVAC or lighting fixtures play a major role in energy consumption and building performance. The EU Energy Efficiency Directive suggested that technical equipment for a given building has to be adjusted and adapted to occupants’ desires, which might be done by monitoring related data points. Maintaining thermal conditions during operation is one of the key tasks facing building managers. Temperature preferences are subjective thus making it difficult to satisfy thermal comfort expectations of all occupants.

The history of the studies that deal with thermal comfort suggest that there are six primary factors that have to be addressed when defining conditions for thermal comfort:

- Air temperature (°C)
- Radiant temperature (°C)
- Air speed (m/s)
- Humidity (%)
- Metabolic rate (Met)
• Clothing insulation (Clo).

2.1 THERMAL COMFORT MODELS
In 1970 Fanger introduced the first thermal comfort model; this model is still used today, with slight modifications, and is defined in ASHRAE Standard 55 [23, 1]. Fanger’s model was based on heat balance in the human body. Thermal comfort is defined as the balance of body heat gain due to metabolic rate and heat loss of the body to the surrounding environment [23]. Generally, the two main methods used for thermal comfort measurements are the predicted mean vote (PMV) and the predicted percentage dissatisfied (PPD). The PMV means the predictable mean vote of a group of people on the thermal condition, based on the 7-point comfort scale as shown in Table 1. The PPD defines the percentage of people dissatisfied with the thermal environment.

Table 1. ASHRAE Thermal Satisfaction Scale

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<th>Thermal Satisfaction</th>
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<tr>
<td>3</td>
<td>Too hot</td>
</tr>
<tr>
<td>2</td>
<td>Warm</td>
</tr>
<tr>
<td>1</td>
<td>Slightly warm</td>
</tr>
<tr>
<td>0</td>
<td>Neutral</td>
</tr>
<tr>
<td>-1</td>
<td>Slightly cold</td>
</tr>
<tr>
<td>-2</td>
<td>Cold</td>
</tr>
<tr>
<td>-3</td>
<td>Too cold</td>
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Fanger’s model looks at five input variables: operative temperature (°C), air speed (m/s), relative humidity (%), metabolic rate (Met) and clothing insulation level (Clo) [28]. The operative temperature in this model is used rather than simple air temperature because it combines both air (dry-bulb) and radiant temperature. Operative temperature and relative humidity are typically available, but other variables pose problems. Even within a given room, air speeds vary [11], so localised measurements are required for each individual, a previously costly and impractical undertaking. Metabolism and clothing levels are also variable, making them hard to estimate [30]. Moreover, Fanger’s model does not account for adaptations by the user, such as acclimatisation, modification of heating controls and expectations of temperatures [28].

Adaptive models [9] try to account for behavioural adaptive measures, such as opening windows, turning on a fan or adjusting clothing. This can be accomplished by modelling the users optimal comfort temperature relative to the outside temperature. The colder or warmer it is outside, the more adaptive measures a user will take. A wide range of research has been carried out on residential and non-residential thermal comfort level. A study was conducted to validate the accuracy of the PMV model and a comparison with non-physical parameters on thermal sensation for naturally ventilated home and office environment in the UK. This study concluded that there is a real “context effect” such as gender, age, cultural and economic conditions on occupants predicted and observed thermal sensation [2]. Another study observed that, there is a relationship between job satisfaction and thermal comfort level in office buildings [9, 17]. The findings from these studies indicate that the above-mentioned non thermal parameters were not accounted in the heating balance model. Thermal comfort has a major effect on determining the energy consumption of a buildings environmental system [10].

Building simulation usually focuses on concepts of traditional thermal comfort measurement to make decisions, but we must not forget there are multiple factors and variables which can have a major effect on comfort level. These requirements should be taken into consideration and where possible included within BIM and thermal models. Consequently, this paper develops requirements based on a comprehensive understanding of both old and new concepts for thermal comfort and then categorise these requirements in a standardised manner in order to develop a MVD for thermal comfort using the IFC standard.

3 BACKGROUND ON INFORMATION EXCHANGE
Computer based information exchanges occurs in a variety of ways in the AEC industry. One mechanism is a proprietary data model tied to a particular vendor and associated software products [8]. These models generally rely on internal data to capture and store data and the user is restricted to using the tools provided by vendor. If the user needs to use another software application, a conversion of one form is needed, which is difficult and can lead to information loss and degradation. However, an open data model, conceptually provides unrestricted data exchange between applications. This approach provides an underlying data model that can retain the relevant building information [25].

3.1 INDUSTRY FOUNDATION CLASSES IFC
Industry Foundation Classes (IFC) has been under development by buildingSMART since 1994. The IFC schema is broadly known as the common data exchange format for information exchange between applications within the AEC/FM industry [6]. It gives stakeholders a comprehensive data model that enables exchange and sharing information of building geometry and building properties elements. IFC has the potential to bridge the links between stakeholders and project phases throughout its life-cycle, from early design stage to construction, operation and refurbishment or demolition [6]. IFC uses an object oriented description to assure consistent information exchange and interoperability between a number of stakeholder applications [15].

IFC4 is the latest release standard of the ISO 16739:2013, which is the only open international standard for BIM data that is shared and exchanged between software applications used by the members of a building construction or facility management project [19]. IFC4 improves the functionality of the IFC specification in its main architectural, building service and structural elements with new geometric and parametric objects along with other advantages. These additions are of significant value in the context of energy performance evaluation, environmental solutions, thermal simulations and sustainability assessments [25]. Other improvements include integration of ifcXML and mvdXML with extensively defined EXPRESS and XML schema specifications, enhanced documentation and links to buildingSMART data dictionary [31].
The key objective of this work defines a set of necessary requirements, data and information that needs to be exchanged between processes that evaluate and monitor thermal comfort level in early design and later during building operation. IFC supports activities at all project stages. However, most of the software applications focus on a specific domain only, depending on the complexity of model [19]. Therefore, the exchange requirements for software applications need to be designed according to domain specific Model View Definitions (MVD). An integrated MVD process has four phases and involves several participants as shown in (Figure 1). MVDs identify the process for exchange requirements of the AEC industry from the IFC schema. The method used is the Information Delivery Manual (IDM) [3].

At present, it is seldom to find programs that can verify if data and information are fulfilling the specifications from the Exchange Requirements in a given IDM. Currently, there is no official mechanism that will allow an automatic translation of an Exchange Requirement into rules within a computer program, as Exchange Requirements are not readable by computer [6]. Therefore, a MVD is needed to satisfy one or many Exchange Requirements between the AEC industry. The first MVD developed by buildingSMART is known as Coordination View. The main purpose of this view is to allow sharing of building models between different disciplines of the AEC industry [6]. However, a number of other MVDs are presently under development by groups of developers outside of buildingSMART. They may be submitted to buildingSMART and once accepted, buildingSMART will publish each as an official MVD.

4 REQUIREMENTS FOR BIM-BASED THERMAL COMFORT ANALYSIS

Thermal comfort analysis requires detailed specification of the analysis processes and the data and information that needs to be exchanged to support these processes. The target of this research is to describe this data and information in a standardised format. The scope of the Exchange Requirement is to support thermal comfort modelling of occupants in commercial buildings during early design, update the model during the building life-cycle and monitor thermal comfort during building operation.

When used properly, BIM can facilitate an improvement in communication between project stakeholders and throughout the building life-cycle. BIM supports early collaboration between stakeholders and can be of particular benefit for participants of the design team. Exchanging building information and models between the process can be challenging the AEC industry. Most of the applications have interests in a limited area, depending on the complexity of model. Currently, there is a lack of common Exchange Requirement for thermal comfort analysis. IFC uses an object focused on description to ensure consistent data exchange and interoperability between several applications. The exchange of information between applications must be made according to a specific MVD. The MVD defines an exchange of IFC data that would meet the end users need and implement methods of exchanging data between software applications for specific analysis, in this case CFD simulation for thermal comfort evaluation and monitor.

Human comfort is a significant consideration when designing a work space. Simulating CFD models can be used to provide insight on human comfort level. Through the use of CFD, decision makers have the ability to evaluate the thermal comfort level, identify opportunities for improvement and control this level with any modification needed during building operation. The AEC industry requires identification of what data and information is important to integrate within BIM model when exporting a select zone or zones CFD analysis. Therefore, the main purpose of MVD is to support this exchange process in order to achieve optimum a reliable results of thermal comfort analysis. Once the BIM model is complete, the MVD extracts data needed for CFD analysis from the BIM. For example, if a BIM software has already implemented a MVD to support a CFD model, the output of IFC file will include only the exchange requirements defined for that specific analysis, thus filtering unrelated information. This allows for easier, quicker data transfer and reduces the loss of information when exchanging BIM files between different applications and analysis tools.

As discussed earlier, thermal comfort is dependent on many aspects, not only environmental or personal factors. BEPS tools usually focus on concepts of traditional thermal comfort measurement to make decisions, but we must not forget there are multiple factors and variables which can have a major effect on comfort level. For example, building orientation, window opening strategy, window to wall ratio, shading strategy, lighting fixture, building wall therm-physical properties and thickness etc. In addition to the psychosocial parameters. To date this work has identified 22 objects with over 800 properties relevant for thermal comfort analysis, the objects include: Actor, Air Terminal, Air Terminal Box, Building, Building Storey, Damper, Door, Element, Element Type, Fan, Material, Opening Element, Project, Slab, Space, Space Heater, Spatial Element, Spatial Zone, Unitary Equipment,
Wall, Window and Zone. The importance of each object and property can be denoted by a mandatory or optional tag for each entry.

The thermal comfort model is required to include the mandatory parameters to achieve optimum a reliable results of thermal comfort analysis. It is important to categorise these requirements in a standardised manner first, in order to develop a MVD for thermal comfort using the IFC standard. The proposed MVD for assessment defines the exchange requirements required by designers and building managers to assess thermal comfort level. It represents the data and information to be exchanged between two or more stakeholders in support of a specific business process at a particular stage of the building life-cycle, as shown in Fig. 2. It is necessary to understand that these requirements come from the end users need and the primary role of the IFC model view is to ensure IFC implementation supports these requirements.

4.1 IDM Methodology for Thermal Comfort
The Information Delivery Manual (IDM) is a standardised methodology that has been developed by buildingSMART. This methodology can be used to document and describe the information that has to be exchanged between relevant stakeholders. The first step in this methodology is to identify and describe the detailed functions performed by each stakeholder and then associated information requirements. This information is subsequently translated into an exchange requirement for thermal comfort using the IDM process. The exchange requirement is then mapped to a corresponding BIM format, typically IFC for a detailed MVD definition. The advantage of including IFC in IDM is that it reduces the risk of error at detailed level of the content of an IDM. An additional advantage is that IFC makes it possible to deliver specific business rules and data validation at a detailed level and make the output from the IDM process readable by computers. However, having very detailed and technical specifications in IDM requires that the IDM process will not only need domain expertise and business modelling skills but also require very detailed technical knowledge.

In this case, IDM includes both information sets that are related to end users as well as for technicians. The IDM defines the exchange requirements needed for the development of the MVD for thermal comfort and the MVD will bind these requirements in an IFC sub-schema. The mapping process of IDM is represented by the group of concepts used and the relationship between those concepts. IFC capabilities must be supported for each functional part in terms of the entities, concepts, property sets, and property type and property value. These exchange requirements characterise the necessary data exchange between stakeholders.

The next step after the mapping process is to create the MVD itself, this step currently is still under development. IfcDoc is a tool published by buildingSMART which can be used to generate an Exchange Requirement document. This document is created in HyperText Markup Language (HTML) format and acts as the basis for software developers to implement export and import functions in their programs. If a BIM software has already implemented a MVD, the output IFC file will contain just the necessary exchange requirements for that particular analysis. In order to make this work clear and reduce the level of complexity, an illustrated example representative a part of one subset Exchange Requirements, IfcSpace of the creation of a MVD is presented in the next section.

4.2 Illustrated Example
Overall, this work encapsulates both old and new concepts of thermal comfort and then categorise these requirements in a standardised manner. The example presented in this section details a small subset of zone data requirements for thermal comfort and provides underlying data for only one subset of exchange requirements IfcSpace. The value of internal gains from heat generated by people determines the demand for energy required to keep occupants within a comfortable range.
There are a set of properties under space occupancy requirement that need to be clearly defined before exporting a BIM to thermal comfort analysis tools. For instance, maximum number of people assigned to this space over time, the temporal variation in occupant load during a regular workday, area per occupant for this type of use and the activity type assigned to this space etc. This information and others must be clearly defined per occupied space instance in order to provide suitable environmental conditions and also directly contributes to the overall energy demands for HVAC equipment. In this case, the exchange requirement space to IFC specification is IfcSpace. The IDM process of exchange requirement table is used as shown in Table 2 and then this table is used to create a corresponding graphical representation of the MVD, as shown in Fig 3.

The IFC schema encompasses several hundred entities, including building element-type entities such as IfcRoof and IfcDoor. In this case the entity IfcSpace is defined in the first column (Table 2). Each element has many property sets which must also be defined. In this case Space Occupancy Requirement and Space Thermal Load as shown in the second column form the left. For each MVD a set of concepts are applied according to the exchange requirement of a particular process as shown in the third column from the left. The fourth column contains a property description field, such as number of people required, maximal number of people and the amount of time during the day that the activity is required within this space. Subsequent columns detail whether a property is mandatory or optional. The final columns indicate the data type, which is either single, Boolean or bounded, and the unit for the property in question.

This example describes only small part of one IfcSpace entity and the final MVD for thermal comfort analyses will include all the exchange requirements and their relationships.
The main purpose of this MVD is to support building designers and managers to assess the thermal comfort level during building design and operation stages.

5 CONCLUSION AND FUTURE WORK

BIM-based Thermal Comfort analysis has been proposed in this paper to improve indoor thermal comfort conditions and building performance. This work presents an overview of the data and information needed for integration of BIM with thermal comfort modelling for commercial office spaces. In this research, a standardised method of information exchange between BIM and BEPS tools was presented. The primary objective of this work is to define a standardised set of information requirements on which software vendors can align their import and export functions. The exchange of information between applications must be designed according to a domain specific (MVD). This process is based on the MVD methodology, which defines and documents the information exchange requirements for a specific exchange scenario, in this case thermal comfort analysis. The deliverable from this paper is a small subset of an IFC compliant MVD to support BIM based thermal comfort evaluation. Some requirements for creating MVD for thermal comfort are not available in IFC schema. Consequently, necessary additions will be documented within the MVD and requested within future IFC releases.

The next stage in this research will include the development of more rigorous extension of the work presented in this paper. In order to examine and validate the proposed BIM exchange requirement, the concept will be applied in a case study, the commercial office space. After completion, the MVD will be submitted to a buildingSMART group for acceptance and publication as an official Model View Definition (MVD) for thermal comfort using the IFC standard.

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