Framework for automated IFC-based thermal comfort analysis based on IFC model maturity

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Abstract

Thermal comfort greatly affects the condition of occupants in buildings. Still, during building design, thermal comfort is often neglected, as the simulation of input parameters takes time and manual effort. To enable an automated IFC-based simulation set-up, we identify simulation approaches to derive the inputs required for thermal comfort analysis. A hierarchical approach selects the simulation's input parameters if input from given IFC files is unavailable. We propose a framework that maps these simulation approaches, input requirements, and comfort metrics to maturity stages from early to detailed design. Within the design process, our framework assists 1) in defining data exchange requirements and 2) selecting comfort metrics based on given IFC data.

Highlights

- Input data requirements for thermal comfort metrics over the design process are established
- Maturity levels for IFC data are defined based on the thermal comfort metrics and the design stage
- A framework enabling IFC-based simulation set-up for thermal comfort analysis is presented

Practical implications

The proposed framework enables building designers to define input requirements and to choose applicable methods for thermal comfort analysis on the basis of their design stage. Requirements for Industry Foundation Classes (IFC) data are defined and tested according to the buildingSMART Information Delivery Specification (IDS) standard.

Introduction

Thermal comfort plays an important role in building design, as it can greatly affect the well-being, work performance, and concentration of occupants (Cui et al., 2013; Rupp et al., 2015). Recent research has shown that people spend approximately 90% of their day inside built environments (Allen and Macomber, 2020), making thermal comfort analysis a valuable metric to consider in building design. In the early design stages, a simplified thermal comfort analysis could be used to support fundamental design decisions for the building's cubature and orientation. However, creating a suitable model for thermal comfort analysis can be a time-consuming and challenging task because of the complex nature of building design and operation. To meet this challenge, researchers are increasingly using the Industry Foundation Classes (IFC) as a base for automated model transformations. In IFC, the 2nd level space boundaries, defined by the *IfcRelSpaceBoundary2ndLevel* entity in the IFC4 schema, represent the heat transferring space bounding surfaces, that simplify the automatic setup of geometric and semantic information in thermal performance simulation (Fichter et al., 2021). From these simulation results, input data for thermal comfort analysis are derived.

Aim of this work is to assist 1) in defining data exchange requirements within the design process and 2) in selecting comfort metrics based on the given IFC data. This work introduces a framework to efficiently perform building simulations that achieve both energy efficiency and high thermal comfort. To this end, the proposed framework selects suitable Building Energy Performance Simulation (BEPS) and Computational Fluid Dynamics (CFD) methods by identifying IFC objects contained within a provided IFC model. This approach allows designers to inspect and optimize energy efficiency and thermal comfort on the basis of the maturity of the IFC model.

Related research

In the field of thermal comfort analysis, various metrics have been developed and applied in related research, each requiring different input parameters. The Predicted Mean Vote (PMV) and Predicted Percentage Dissatisfied (PPD) metrics derived by Fanger (1970) are among the most frequently used, and have been incorporated in national standards of thermal comfort (ISO 7730, 2005; ASHRAE Standard 55, 2017). Established on the basis of human heat balance, the calculation of PMV/PPD requires four environmental parameters (air temperature, radiation temperature, air velocity, and relative humidity) as well as two personal parameters (clothing level and metabolic activity). Although the original metrics have been modified especially regarding adaptive capabilities, Fanger's PMV/PPD model is still among the most widely used (Zhao et al., 2021).

Reviewing models and input parameters for thermal comfort, Alshehri et al. (2019) identified input requirements

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for thermal comfort analysis according to Fanger (1970), ASHRAE Standard 55 (2017), ISO 7730 (2005), displayed in Table 1. The input parameters show that all the presented approaches have the four environment parameters (air temperature, air velocity, humidity, and mean radiant temperature) as common input requirements, as well as the two personal parameters regarding clothing and metabolic information.

Table 1: Data requirements for IFC-based thermal comfort analysis, adapted from Alshehri et al. (2019).

		Model		
Parameter	**Unit**	**Fanger**	**ASHRAE 55**	**ISO 7730**
Air temperature	°C	x	x	x
Air velocity	m/s	x	x	x
Clothing insulation	Clo	x	x	x
Relative humidity / Partial water vapour pressure	% / Pa	x	x	x
Mean radiant temperature	°C	x	x	x
Metabolic rate	met	x	x	x
Running mean outdoor air temperature	°C		x	
Operative temperature	°C		x	
Radiant Asymmetry	°C		x	
Floor temperature	°C		x	
Mean monthly outdoor temperature	°C		x	
Vertical Air Temperature difference	°C			x

Most of the criticism of the Fanger model gathers around its static character neglecting the outdoor temperature history and behavioral reactions of people to their thermal environment. Moreover, it allows a prediction only for a group of people, and its application to individual or personal comfort projection is limited. These predictions are only stated globally and do not support a local interpretation for individual parts of the body or asymmetric effects (e.g., caused by radiation).

The shortcomings of both the traditional Fanger/PMV and adaptive models have been addressed with the development of personal comfort models. In addition to the input parameters identified by Alshehri et al. (2019), Arakawa Martins et al. (2022) point out further input data for the computation of these personal comfort models. Data include proximate measures such as skin temperatures. This level of granularity is however not suitable for an IFC-based approach, especially during early planning stages. Ma et al. (2021) also identified variables required for thermal comfort as well as indoor air quality predictions. The authors mention that the observed focus on air temperature is too narrow, and correlated variables (such as radiant temperature) are often neglected in the reviewed studies. The authors briefly discuss that data availability is correlated to a buildings' lifecycle phases, hence occupancy data would not be available for analysis in the design phase.

The four environmental input parameters for thermal comfort models can be derived from building simulations (e.g., with an automated IFC-based model set-up (Jansen et al., 2021)), while the two personal parameters need to be stated in applicable input data. In practice, automated approaches for checking and validating IFC models for energy modeling purposes are still lacking (Di Biccari et al., 2022). To meet the input requirements for thermal comfort predictions, Alshehri et al. (2019) analyzed common thermal comfort metrics and the data available for thermal comfort simulations in the IFC standard to be applied at an early design stage. They proposed to extend the IFC property sets with additional parameters for thermal comfort analysis, but these parameters are still not included in the latest IFC data scheme[1].

Although approaches to perform an automated IFC-based BEPS exist (Jansen et al., 2021), they do not aim to improve a building's energy efficiency on the basis of occupants' thermal comfort. While previous work has used IFC in CFD simulations (Lan et al., 2021), it did not consider the space boundaries provided by the IFC schema. As a result, available data representations were neglected, leading to additional overhead by deriving geometric information that could have been defined by the use of space boundaries.

For the validation of input parameters, Tomczak et al. (2022) give an overview on methods defining information exchange requirements. Model View Definitions (MVD) as provided by Pinheiro et al. (2018), or the new buildingSMART Input Delivery Specification (IDS)[2] can be used to check the availability of required information in the model. Still, these do not validate the consistency or geometry of information (Richter et al., 2021, 2022). As the IDS format is still under development, to the best of our knowledge, no open-source IDS database is currently available. Therefore, no IDS is available specifying the input requirement of thermal comfort analysis.

Identified gaps

Integrating BEPS and CFD for thermal comfort simulations is currently challenging because of software interoperability issues across stakeholders' platforms, especially when aiming to integrate BEPS and CFD continually from the early to the later more detailed design stages. Even though related research has already identified gaps in the IFC schema (e.g., missing thermal comfort parameters), these parameters are still not included in the schema. For thermal comfort analysis during the design process, currently no information is available that supports the designers to a) choose thermal comfort metrics that support design decisions at the current design stage, b) define the IFC data requirements at a certain design stage, c) show appropriate data sources if IFC data are not available, and d) use methods to test these input data requirements at a certain design stage.

Aims and scope

To address these gaps and challenges, we propose a framework for integrating BEPS and CFD for thermal comfort simulations. The framework serves as the basis for a fully automated, open-source toolchain that follows a predefined sequence 1) to identify objects within a given IFC model, 2) to select appropriate input values from these objects for thermal comfort analysis across different design

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[1] buildingSMART, IFC4x3 schema (under ISO voting): `https://standards.buildingsmart.org/IFC/RELEASE/IFC4_3/`

[2] buildingSMART, Input Delivery Specification: `https://github.com/buildingSMART/IDS`

stages, and 3) to suggest applicable BEPS and CFD methods and prepare the automatic setup for the thermal comfort simulations. The algorithms developed as part of the framework are tested on a case study building.

Methods

The research methods constitute of two parts. In the first part, a framework is developed. In the second part of the method, the framework is applied and validated on a case study building.

In the following, the steps to develop the framework are described. First, the input requirements for thermal comfort metrics and parameters required to compute these are identified based on existing literature. Second, suitable BEPS simulation approaches in conjunction with thermal comfort metrics are identified for a given availability and granularity of information from early to detailed design stages. Here, the availability of input parameters for each simulation approach and metric is mapped to the maturity of an IFC file within the design process of a building. This constitutes the framework proposed in this work. Third, a hierarchical approach is defined that analyzes the availability of input data from IFC and alternative sources. For the availability to be determined, the IFC data needs to be thoroughly analyzed. In our study, we use the IFC4add2 TC1 schema (ISO 16739, 2018). Finally, all components are assembled in a workflow to illustrate the implementation of the framework proposed in this work.

For the second part, the framework is implemented and validated on a case study building. To evaluate the maturity scale proposed within the framework, the maturity stages are prototypically implemented in the buildingSMART Information Delivery Specification (IDS) format. The case study building consists of an office building. The data was developed in Autodesk Revit and exported to IFC, including space boundaries and available property sets.

Development of a framework

The following sections describe our steps of developing the framework based on related research. Figure 2 displays the completed framework. Our framework defines, in a hierarchical order, the type of thermal analysis that can be performed in design stages depending on the input parameters available. There are two use case scenarios for its application: A) the framework can be used to identify the model input requirements necessary for thermal comfort analysis at any given design stage, or B) the framework can be used to identify possible thermal comfort analysis methods for the data available in a given model.

Thermal comfort modeling and metrics

To be able to decide which thermal comfort metrics are applicable based on the given data, the input data requirements were analyzed for the thermal comfort metrics included in the standards. In our study, we focused on the input requirements from ISO 7730 (2005) shown in Table 1. The resulting extended input requirements per comfort measure are displayed in Table 2.

For the parameters required in ISO 7730 (2005), we distinguished between the thermal comfort metrics PPD, PMV, draft risk, as well as Percentage Dissatisfied (PD) for vertical floor temperature difference, PD for floor temperature, and PD for radiation asymmetry. In Table 2, we also derived the applicable data sources for these parameters, most of which are derived at runtime from a simulation or other available data sets, while met and clo values can be obtained directly from suitable property sets in IFC or added from templates based on the use condition of the space. For the local turbulence intensity, a default value could be applied. For all values with given limits, either a sensitivity analysis could be performed, or suitable values could also manually be chosen by the designer to get a rough estimate (not recommended though, due to high uncertainty in the result).

Simulation approaches from early to detailed design

The environmental parameters used for thermal comfort analysis can be derived through Building Energy Performance Simulation (BEPS). When setting up a BEPS model, simulation accuracy varies with the detail of specified input data. We therefore identified six “maturity” stages that describe the different granularity levels of input data and of simulation approaches that can be used to derive the environmental parameters for thermal comfort analysis. These stages are visualized in Figure 2. The following paragraphs describe the applicable simulation tools and methods, the applicable thermal comfort metrics, and the spatial resolution, described at the top of Figure 2.

At a very early design stage (named Stage 1 for further reference), archetypical approaches can be applied (e.g., TEASER (Remmen et al., 2018)). The Python-based TEASER (exporting simulation models based on the Modelica library AixLib) performs a BEPS based on archetypical building data sets, only requiring a minimum set of input data (e.g., building type, year of construction, construction weight, floor area). This approach can be used to estimate the environmental parameters required for simplified PMV and PPD calculations based on ISO 7730 (2005).

Once more information is available for the building design, in Stage 2, a reduced-order approach could be applied that involves more parameters of the actual building design, not only an archetypical model. An example of this simulation model is the application of TEASER, using a higher granularity of the input data than for the TEASER-based archetypical approach from Stage 1 (Jansen et al., 2021). This more granular use of TEASER enables the user to derive the environmental parameters based on the geometry of the defined spaces and available building constructions. This approach can also be used for PMV and PPD calculations like the first stage but provides a better estimate of the building using a higher granularity of input data for the actual use case.

In the third stage, a higher order BEPS can be performed to derive the environmental parameters. Here, an example is the use of EnergyPlus (Crawley et al., 2001), which requires geometric information for the individual building

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Table 2: Parameters for thermal comfort metrics according to ISO 7730 (2005), limits are stated if applicable. Clo = 0.155 m^2K/W, met = 58.2 W/m^2, PD = Percentage Dissatisfied.

		Data source				ISO 7730					
Parameter	Unit	derived (runtime)	IFC	Template (average)	default	PMV	PPD: f(PMV)	DR	PD Vertical Temperature	PD Floor temperature	PD radiation asymmetry
Air temperature	°C	x				10…30	10…30	20…26			
Air velocity	m/s	x				0…1	0…1	0.05…0.5			
Clothing insulation	Clo		x	x		0…2	0…2				
Mean radiant temperature	°C	x				10…40	10…40				
Metabolic rate	met		x	x		0.8…4	0.8…4				
Partial water vapour pressure	Pa	x				0…2700	0…2700				
Radiant Asymmetry	°C	x									-15…+23/35
Floor temperature	°C	x								x	
Local Turbulence intensity	%	x			x			10…60 (default = 40)			
Vertical Air Temperature difference (head and feet)	°C	x							<8		

surfaces and fenestration. To simplify the input requirements for data, in this stage, HVAC is only considered using ideal loads. Here, an IFC-based EnergyPlus approach (cf. Jansen et al. (2021)) could be used. During this stage, the set of the four environmental parameters can be extended by simulated surface temperatures. These derived temperatures can be used to calculate additional thermal comfort metrics to PMV/PPD, such as draft risk and percentage of dissatisfied people regarding vertical temperature differences, floor/wall/ceiling temperature, and radiation asymmetry.

In the fourth stage, the ideal loads of the previous stage are replaced by the actual planned HVAC design. To derive the input parameters for thermal comfort, the BEPS could be coupled with an HVAC simulation (e.g., Spawn of EnergyPlus (SOEP) (Wetter et al., 2020), i.e., EnergyPlus coupled with Modelica), resulting in an even more accurate representation of the building. Still, since the EnergyPlus results only compute all parameters per space (single-node computation), the distribution of comfort parameters within the space cannot be evaluated directly.

In the fifth stage, a detailed geometric description of the individual spaces is required, including the geometry, positions, and parameters of HVAC elements. This allows the users to derive the environmental parameters with a high spatial resolution inside the space performing a CFD, e.g., using OpenFoam. If simplified information on the building interior is available, it could be included in the simulation as lumped capacities. All available comfort metrics (e.g., ISO 7730 (2005), ASHRAE Standard 55 (2017)) can be evaluated for individual positions within the space.

The sixth and final stage requires additional information on the furniture and the estimated position of the occupants within the room. Thermal comfort (e.g., ISO 7730 for a specific office workspace) can be evaluated in detail. The CFD results could be mapped onto detailed comfort models, determining whether specific parts of the occupant's body are comfortable. This results in the highest available level of spatial resolution for thermal comfort analysis within the design stage of a building.

Maturity of IFC-data in the design process

To address this variation of available data, we further extended our six-stage framework (see Figure 2) for the building's design process, considering the maturity of the IFC from early design to a detailed model. In the bottom part of the figure, we describe the requirements for the availability of IFC entities, their geometric representations, and property sets (Psets). For each maturity stage, we distinguish between required (green) and optional (yellow) parameters for each entity and property set.

The first stage represents an early design stage, at which most likely no or only sparse IFC data are available. For this archetypical approach, the floor area and space height could be either obtained from IFC quantities (Qto) or even geometric representations of storey or space in the IFC. If these geometric data are not available from IFC, they could be obtained from information defined for the space along with the VDI 6070 ("room book"). For the evaluation of the comfort metrics, information on the personal comfort parameters (clothing and metabolic activity) are required. These could be given included in a user-defined Pset (cf. Alshehri et al. (2019)) or be selected along with the hierarchical approach (which is also applicable for all following stages).

The second stage provides space or thermal zone geometry, but still does not necessarily provide space boundary information in the IFC file. If IFC data is available, the space geometry can be obtained from Qto or the space representation in IFC. IFC data on thermal load design criteria can also be used as an input for the reduced order simulation. For a more advanced simulation set-up within this stage, thermal requirements could be obtained from the respective IFC Pset. In this stage, simplified environmental parameters can be simulated on the basis of simplified schedules with VDI 6070 (VDI 6070, 2023) compliant data as a base for the thermal comfort metrics. If no IFC data are available, the models must be set up manually. Different material setups can be tested on aggregated thermal zones. The impact of the building's fenestration, cubature, and orientation on thermal comfort can be analyzed and support fundamental design decisions at this early design stage.

The third stage requires IFC information on space boundaries, heating and cooling schedules and occupancy data. If this information is unavailable from IFC, standard schedules from literature can be used and selected on the basis of the individual zone usage.

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In the fourth stage, the IFC data should provide additional information on the air exchange rate and heating and cooling capacity of the HVAC design, which gives a better estimate of the draft risk and potential issues with radiation asymmetry than the previous stage.

The fifth stage of IFC model maturity requires additional IFC data on the type and position of the air handling unit (AHU), as well as the type, position and geometry of the heating device.

In the final stage, furniture data (type and position) can be obtained from the IFC. Based on the furniture data, estimates of the occupants' positions can be evaluated for thermal comfort.

Availability of input data

Different input sources can deliver the input data required for thermal comfort analysis. In order to check the availability of data in a given model, we propose the hierarchical approach illustrated in Figure 1.

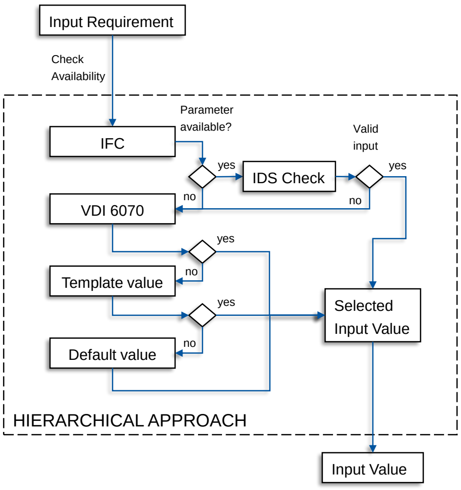

Figure 1: Hierarchical approach to select input parameters from suitable input source.

If the required input is available in IFC, the input value obtained from IFC should be validated. For this IFC input validation, the new buildingSMART Input Delivery Specification (IDS) format can be applied. If the IFC input is invalid or not available, data defined according to the German guideline VDI 6070 ("room book") (VDI 6070, 2023) should be selected, if available. This guideline defines the fundamentals for machine-readable data documentation within a building's life cycle. If no VDI 6070 data is available, but the space usage is known, the parameter can be selected according to the space usage based on usage templates. If even the space usage is unavailable, a default value could be chosen, but rather new IFC data should be requested from the architect or designer. Otherwise, archetypical approaches can be used to estimate the building's environmental parameters for thermal comfort analysis.

Application of the developed framework

In the following, we propose a workflow for the application of our framework in the design process. Supporting the automated input requirement verification based on our framework, we prototypically implemented the requirements derived from our proposed framework in the new Information Delivery Specification (IDS) standard. Then, we tested the IDS on a case study building.

Validate maturity of IFC data

For the integration of our framework within the design process, the workflow presented in Figure 3 is suggested.

First, the targeted maturity stages within the design process need to be defined to ensure that building models can be enriched with the input data required for the comfort metrics. Second, to automatically check whether IFC models contain the input requirements, these requirements can be defined within an IDS. Once defined, the IDS can be used to evaluate if the IFC maturity requirements are fulfilled in a given model. If the requirements are met, the thermal comfort analysis can be performed to support design decisions. If the IFC requirements are not met, input parameters can be selected using our hierarchical approach (see Figure 1) to perform the comfort simulation. If the hierarchical approach is not applicable, a new IFC (or other applicable data within the hierarchical approach) should be requested from the responsible IFC author.

Information Delivery Specification (IDS)

In the presented study, an IDS file (IDS version 0.9) was prototypically implemented a) to evaluate the maturity of the IFC file, as well as b) to evaluate the applicability of the IDS file and standard for our requirements. We set up an IDS to evaluate existing data within an IFC file. Our IDS validated the availability of the requested IFC entities and their geometric representation within the file. However, the IDS format does not seem to be applicable to check the occurrence of property sets. Instead, the occurrence of property sets were evaluated by requesting specific attributes from the property sets.

Case Study

For testing our framework, we selected the case study building DigitalHub[3] (Figure 4, displayed in BIMVision[4]), a set of open-source IFC4 models that provides architectural, heating, air conditioning, and sanitary equipment in an individual IFC file each. The maturity level of data within the IFC files were evaluated for the combination of the three IFC files for architecture, heating, and air conditioning. The application of the IDS has shown that all required IFC entities up to IFC maturity Stage 5 were available in the IFC, such that only *IfcFurniture* data was missing. For all of these entities but the *IfcBuildingStorey*, a geometric representation was provided. Despite the high maturity level of IFC entities, only few of the property sets required for thermal comfort analysis were available (i.e., Pset *AirSideSystemInformation*, *SpaceHeaterTypeCommon*, *AirTerminalTypeCommon*). Therefore, most of the input parameters

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[3] RWTH Aachen University, DigitalHub: `https://github.com/RWTH-E3D/DigitalHub`

[4] BIM Viewer BimVision: `https://bimvision.eu/`

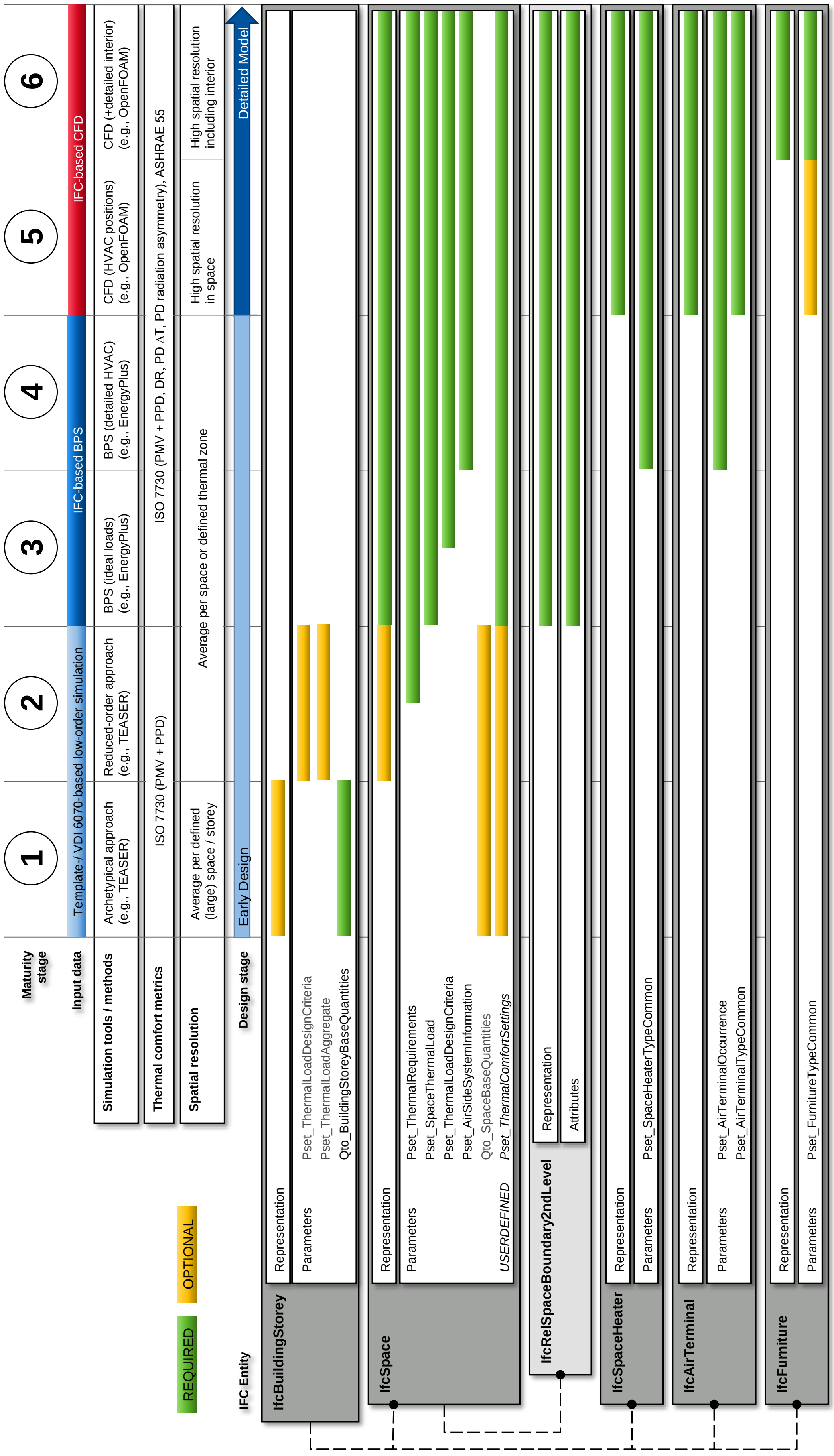

Figure 2: IFC entities and property sets mapped to maturity stages for thermal comfort analysis using BEPS and CFD

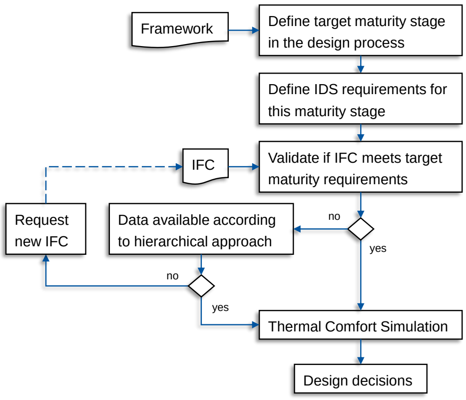

Figure 3: IFC maturity analysis workflow for thermal comfort analysis

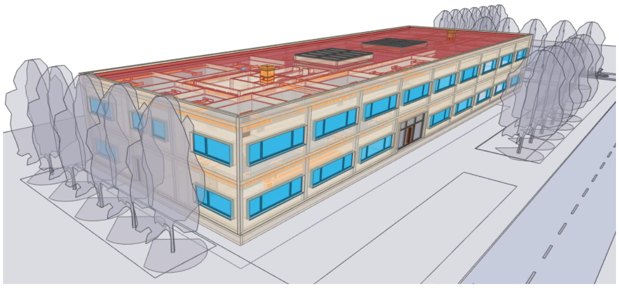

Figure 4: Use Case: DigitalHub.

besides the geometry require a template-based enrichment. As the required IFC entities were available, requesting a new IFC file with more Pset information could enable the thermal comfort analysis. It was therefore concluded that the requirements for the IFC data should be communicated according to the proposed framework at the start of the design process (or at least before the IFC data exchange).

Discussion

We presented a framework that assists in the definition of input requirements for thermal comfort analysis over the design process of buildings. Even though we defined the stages to be treated independently, information from the BEPS-based Stages 3 and 4 could also be used as a criterion to identify the need for a more detailed CFD-Analysis (Stage 5 and 6) in critical spaces. An in-depth testing of this combination of approaches should be addressed in further research to use the computational capacities for CFD analysis consciously. Mapping CFD results to a manikin of the human body could support a local thermal comfort analysis.

A Sensitivity Analysis (SA) on the input parameters presented in Table 2 is subject of further research. The SA gives insights on the effect of uncertainties for individual parameters on the simulation results and assists in evaluating the quality of input parameters in the IFC.

The limiting factor to our proposed framework is the availability of property sets in given IFC data. buildingSMART should extend the schema by personal comfort parameters (clothing and metabolic activity), so that these parameters can be provided in a standardized way. Until the IFC authoring tools provide these personal parameters, there is still a long way to go before fully automated thermal comfort analysis can become possible. A comfort certification for BIM authoring tools could assist IFC standardization, such that the input requirements for thermal comfort analysis could be provided in the IFC files. This certification should verify that the software includes the export of space boundaries and personal comfort parameters.

The implementation of the IDS was quite cumbersome. Once more attributes from property sets are available and requirements for individual parameters are defined in further research, the IDS could assist in validating the specific parameters. For the state of our framework (Figure 2), the definition of an MVD could have been sufficient.

The latest official IFC Standard IFC4add2 TC1 was used in this study. However, at the time of this study, a newer IFC-Standard IFC4x3 is being voted on by the ISO committee. Thus, IFC files in IFC4x3 format are still not yet available in proprietary authoring tools. With the transition to IFC4x3 however, some property sets in IFC would change their names, and new parameters would be added, which should be included in further research.

Conclusion

The current study addressed gaps and challenges in integrating BEPS and CFD simulations for thermal comfort analysis based on provided IFC models. A novel framework was proposed that defines input requirements and assists in identifying objects within a given IFC model for automated IFC-based thermal comfort analysis. For six maturity levels, the framework suggests appropriate thermal comfort methods on the basis of BEPS or CFD from early to detailed design stages. The IFC schema was analyzed to determine requirements for thermal comfort analysis, and potential areas for schema extensions were identified. We proposed a hierarchical approach to select the input data from other resources for cases where the provided IFC file does not meet the input requirements. Our framework was applied to a case study building, illustrating the application of the framework for thermal comfort analysis on IFC models.

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