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A FINITE ELEMENT ANALYSIS APPROACH TO IMPROVE INTEROPERABILITY FOR THERMAL ENERGY SIMULATIONS

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Information exchange between architectural design models and Thermal Energy Simulation (TES) tools still suffers from interoperability problems. The main challenge is to robustly translate the geometrical information required for TES. The current practice involves a cumbersome and iterative manual correction of the model between the architect and the engineer, which is prone to human errors. Interpreting the geometry solely based on the IFC file is not a trivial process due to its complex nature, in which different attributes are cross-linked to each other. To address this issue, an approach based on the Finite Element Analysis (FEA) is proposed, which aims to provide straightforward readability of geometrical information as well as a reliable and flexible thermal simulation. To demonstrate this approach, an IFC model of a residential building was transferred to a commercial FEA software and thermal analysis was conducted. Interoperability problems regarding robust transfer of geometrical information were not encountered and the process was deemed to be efficient. FEA also revealed another strength by providing thermal analysis of individual components of the structure. This can be employed in the early design stage by rapid prototyping of different components (e.g., geometry, thermal properties) and their role on the thermal performance of the whole structure. Results are presented by comparing the proposed approach with the current practice and the potential advantages are highlighted.

Keywords: Industry Foundation Classes (IFC), Energy performance, Prototyping, Building Information Model (BIM), Building Energy Model (BEM), Information exchange.

1 INTRODUCTION

The use of building information modeling (BIM) has attracted significant attention of researchers from both the building industry and academia. Its capability to consolidate and process information from multiple domains provides a revolutionized way for building design and management, especially with regards to analysis of building performance and energy sustainability. Real BIM practices have shown advantages of improving Architect-Engineer collaboration through efficient information sharing processes which include flow of interactions between geometric design and thermal calculations. However, even with the help of various BIM authoring tools, a big challenge of interoperability is gradually observed when different categories of information are exchanged and translated among different parties: Architectural domain and Engineering domain as per this paper.

Latest approaches mainly focus on improving BIM information exchange schema or data formats to standardize the building elements. The most widespread standard in use today is the industry foundation classes (IFC), which is maintained by building SMART organization (Ma *et al*. 2013). Even though IFC files enable data transition among diverse BIM authoring software, the information exchange processes still causes numerous errors pertaining to syntactic, semantic and design programming requirements (Sacks *et al*. 2010). This problem is particularly evident when an engineer receives and evaluates BIM data (e.g., thermal zone information or space boundary conditions) from an architect in order to conduct thermal analysis (Maile *et al.* 2007). In order to overcome the incongruence and inaccuracy of information exchange, the object-oriented physical modeling approach, along with the ModelicaBIM library, is investigated to generate a robust system interface between BIM design model and energy model (Kim *et al.* 2015). Nevertheless, these IFC-based interfaces or tools remain unintuitive when modification of building data and customization of calculation modules are needed to improve energy simulation. In this regard, this paper proposes a way to load and translate design information for energy evaluation purpose without being constrained by inefficient common data schema such as IFC or gbXML. The target simulation platform chosen in this paper is the finite element analysis software ANSYS, which is able to access accurately and directly building geometry data for a wide range of thermal simulations, improving reliability and efficiency for the work of engineers.

2 INEFFICIENCY OF EXISTING BIM-BASED ENERGY SIMULATION TOOLS

According to the annual energy outlook, more than four hundred software applications for building energy simulation have been developed since 1996, including the energy simulation engines and the graphic user interfaces (GUIs) (DoE 2014). A collection of popular BIM-based energy simulation tools is listed in Table 1. Most of them rely on IFC import and export features, which are highly dependent on output files from BIM design tools in order to fit their energy simulation engines. The most discernible problem observed when using these tools is the mismatch of building components between the architectural design and the energy modeling. For example, adding a door on the exterior wall should be interpreted as adding an opening that can affect airflow and air filtration differences; however, this process is not easily interpreted accurately in energy simulation tools. There is a need to establish a rule-based building information loading mechanism for energy simulation intuitively.

Table 1. 8A collection of popular BIM-based energy simulation tools.

Name of the tools	Receivable data formats	Major inefficiencies
Energy Plus	IDF	No GUIs
CypeThermal Eplus	IFC	Wrong geometry recognition
VABI	IFC	Inability to extend space
RUISKA	IFC	Limited thermal attributes
eQuest	gbXML	Not as generic as IFC
ClimaWin	gbXML, IFC	Limited thermal attributes
IESVE	gbXML, IFC	Not supporting HVAC items
Green Building Studio	gbXML, IFC	No 3D interface

3 THE FINITE ELEMENT ANALYSIS

The finite element method (FEM) is a numerical analysis technique that finds approximate solutions to complex partial differential equations by discretizing the domain into a finite number of elements and subsequently solving the system of equations (Moaveni 2003). The FE-industry has attained a matured status with a vast array of commercial products that can tackle a variety of problems such as structural analysis, computational fluid dynamics, thermodynamic analysis and a combination of each from microscopic to macroscopic scales. For thermal energy simulations, the heat equation of a body can be constructed in a way that provides the heat distribution of a region over time by considering various thermal properties of the materials and surrounding medium (Nikishkov 2010).

A geometry (in this case a building or a building component) that is imported into any FE-software needs initial pre-processing regarding boundary conditions, thermal loading information and material characteristics. Comparing to existing BIM-based applications, the main difference is that the direct debugging of an original IFC file could be an inefficient process due to the poor versatility among different platforms, while initial pre-processing, in terms of selecting the components in FEM, only requires a few number of settings. For example, parametric programming language of FEM can handle structural application automatically regardless of the complexity. Some of these properties are generally already defined in an architectural model, and are contained within an IFC file. The FE-software reads the geometry, thermal material parameters, boundary conditions and other information from the IFC file and, through a graphical user interface (GUI), these can be checked and validated by an engineer to ensure a compatible and successful importing process. Further steps are generally required to define the loads, e.g. the internal and external temperatures, internal heating/cooling, etc. The model needs then to be meshed, i.e. to be discretized into a finite number of elements. The mesh size is an objective metric that depends on many factors, such as the aimed temporal and spatial resolution of interest. As a rule of thumb, a finer mesh ensures convergence of results, however introduces heavy computational costs. It is thus important to keep the mesh size as big as possible while increasing the fineness of the mesh only at certain locations of complex interactions such as regions with big temperature gradients and transitional zones, such as windows, doors, or interfaces of different building components.

4 GEOMETRY-DATA CONVERSION WORKFLOW

In order to minimize the back-and-forth manual corrections of building models between the architect and engineer, a FEA based geometry-data conversion workflow is presented in Figure 1. Since the FE-software excels in loading complex and complete geometry information from 3D-CAD software, it gives significant benefits to have IFC-file first read by a 3D-CAD software and then generate imports for the FE-software for further analysis, without any loss of information. Therefore, the workflow of the geometry data conversion consists of two fundamental file formats: target IFC file and 3D-CAD software supported file format (e.g., IGES, SAT, parasolid and STEP). One advantage of using 3D-CAD software supported file is that the target geometry information carried by IFC can be customized freely when it is going to be exported from 3D-CAD software. According to the FEA based geometry-data conversion workflow, the first step is to convert the IFC file to a 3D-CAD supported file, which can then be loaded and analyzed by the FE-software in an accurate and efficient manner.

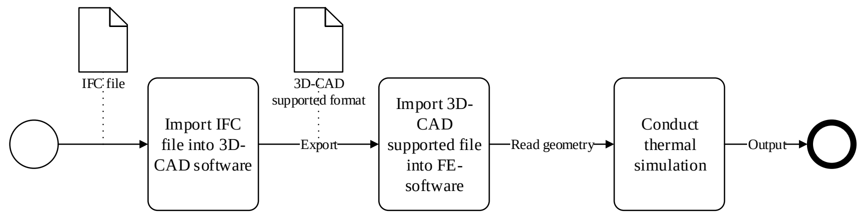
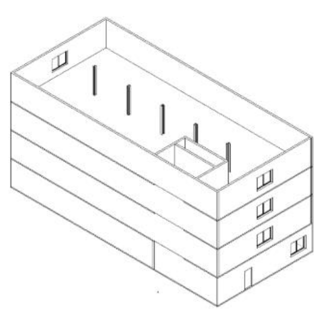


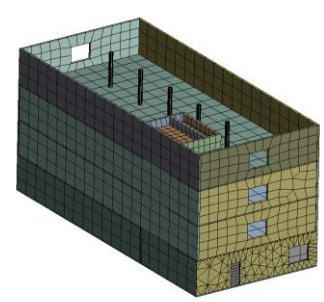
Figure 1. An FEA based geometry-data conversion workflow.

5 AN APPLICATION EXAMPLE

To illustrate the application of finite element analysis in energy simulation, a four-story office building was employed from an open IFC file repository (University of Auckland 2016). The first version of this building does not comprise a roof, yet this file was still kept since the purpose of this paper is to evaluate the transfer of information to be used in simulation software by using the proposed geometry-data conversion workflow, and not to comment on the performance of the structure itself. The IFC file was imported into the 3D-CAD software SolidWorks (SolidWorks 2014) and saved as SAT format. Subsequently, the SAT file was imported into the FE-software ANSYS (ANSYS Workbench 15.0) and a thermal analysis was performed with an outside surface temperature of -15 OC and inside temperature of 25 OC by air-conditioning. The original and imported geometry visualization after meshing is given in Figure 2. From the visual representation, it is apparent that the geometry information has been transferred without any losses. After meshing was completed, material thermal properties, which were obtained from the initial IFC file, were assigned to the different building components. An advantage of this approach was observed when checking the geometry information of both the IFC file and the ANSYS input file. It was found that the ANSYS Parametric Design Language (APDL) gives more readable information, i.e. 3D coordinates of nodes in contrast to the "encrypted" information of an IFC file. Analysis results visualizing temperature distribution and heat flux are given in Figure 3.

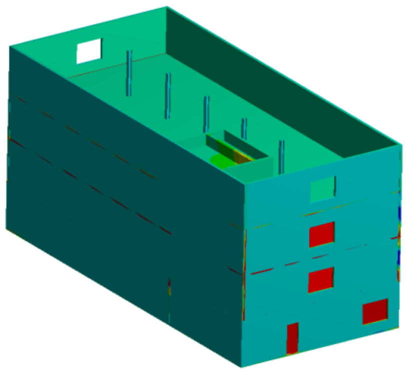


a) Original geometry of the employed IFC file, visualized by Revit

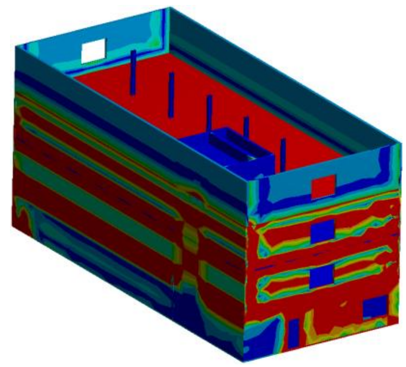


b) Imported geometry after meshing in ANSYS

Figure 2. The original and imported geometry visualization after meshing.



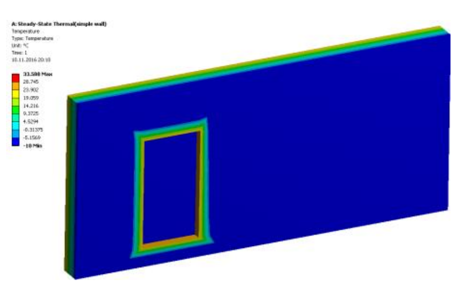
a) Temperature distribution visualization



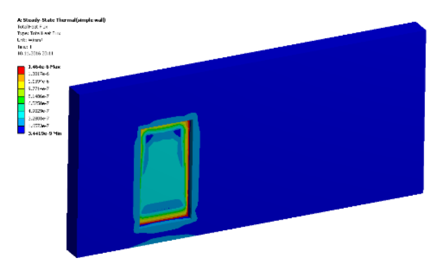
b) Heat flux visualization

Figure 3. Analysis results visualizing temperature distribution and heat flux.

Another benefit of this approach is that it allows for the analysis of individual components of the building. This enables rapid prototyping of geometry and materials to be used in the final design. This advantageous capability can be used in the early design phases in order to determine an optimized geometry and material selection for energy performance. To show this, an individual wall was simulated with the same thermal conditions as the whole building, and its resulting temperature distribution and heat flux is presented in Figure 4.



a) Temperature distribution



b) Heat flux of an individual wall with an opening(window)

Figure 4. The simulation results of the individual wall.

6 CONCLUSION AND OUTLOOK

Robust information exchange and interoperability between architectural design models and energy simulation software remains an issue to this day. To address this problem, a geometry-data conversion workflow is proposed that is based on the finite element analysis. To demonstrate the robustness and efficiency of the proposed method, an IFC-file of a four-story building was tested by employing the commercial FEM software ANSYS. An accurate transfer of geometric information was observed and a simple thermal analysis was successfully conducted. An additional benefit of the FEA was presented, namely the ability to isolate and simulate individual building components for rapid prototyping. In summary, the finite element analysis is a robust approach to accurately read geometrical information from IFC-file format, conduct thermal analysis and further customize building components to optimize the energy performance. Based on the findings, further work will focus on:

(i) Validating the approach with a comprehensive energy simulation.

(ii) Exploiting model updating schemes with FEA for automatic optimization of energy performance based on geometry and materials in the early design stage.

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