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Master's Degree Thesis in
"Systematic Investigation of Interoperability Issues between Building Information Modelling and Building Energy Modelling"

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Acknowledgment

"If I have seen further, it is by standing on the shoulders of giants."

_ Isaac Newton (1643-1727)

I hope that this thesis becomes a small part of the vast endeavors in addressing the BIM to BEM interoperability issues. Nevertheless, as well said by Newton, I could not have managed to finish this project without the help of many people that I had the pleasure to know them.

Abstract

Integrated building design necessitates the Architecture-Engineering-Construction-Owner-Operator (AECOO) Industry's participants to collaborate efficiently with each other through the different phases of a building. Nevertheless, to reduce the energy consumption and CO_2 emissions of a building, the emphasis is on the early design phases, since if accurate energy calculations and strategies are developed in an early design stage, the sustainable footprint of the building will be significantly reduced.

That said, Building Information Modelling (BIM) promotes collaboration among the stakeholders by allowing them to design and store and access the data related to a project into one building information model. Furthermore, this model can be used for energy analysis through Building Energy Modelling (BEM) tools in the early design stages of the project, and through the whole life-cycle.

For this, BIM and BEM tools must be able to communicate and exchange information with one another, seamlessly. This means that these tools should be interoperable. However, currently, there are some issues in the BIM to BEM exchange process, which obliges the user to check for the interoperability issues and fix them manually. Therefore, as a result of these interoperability issues, the BIM to BEM process is not automated, and creating an accurate BIM-based BEM is quite time-consuming, laborious and prone to human-made errors.

Hence, this thesis aims to systematically investigate the interoperability issues and the state of automated data exchange between BIM and BEM tools, based on the Industry Foundation Class (IFC) exchange data schema. For this, Revit and IDA-ICE are used as BIM, and BEM tools, respectively.

The outcome is the presentation of a set of interoperability issues that were found based on the investigation of 19 case studies, with some suggestions for Revit and IDA-ICE developers and future researchers in the end.

Keywords:

BIM, Building Information Modelling, Revit, BEM, Building Energy Modelling, IDA-ICE, interoperability issues

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List of abbreviations

Abbreviation	Complete name
IFC2x3	IFC2x Edition 3
BCF	BIM Collaboration Format
AEC	Architecture, Engineering, and Construction
AECOO	Architecture-Engineering-Construction-Owner-Operator
BEM	Building Energy Modelling
BIM	Building Information Modelling
BPS	Building Performance Simulation
CAD	Computer-Aided Design
FM	Facility Management
IAI	International Alliance for Interoperability
ICT	Information Communication Technology
IDA-ICE	IDA Indoor Climate and Energy
IDM	Information Delivery Manual
IDP	Integrated Design Process
IFC	Industry Foundation Class
IFD	International Framework for Dictionaries
STEP	Standard for the Exchange of Product Model Data
XML	eXtensible Marked Language

Chapter 1 Introduction

The increasing attention to improving the energy efficiency in the built-environment has brought to spotlight the Building Information Modelling (BIM) due to its potential for integration with Energy Analysis and Simulation tools. BIM is a methodology to digitally construct an architectural model that holds detailed multi-disciplinary information regarding the spatial information, thermal values, material properties, schedules, etc. through the life-cycle of the building [1-3]. The Building Information Model (we call it BIM model in this report) can be then exchanged with other software for further analysis, for instance for energy analysis, structural analysis, and so on.

In contrary to popular belief, although building information modelling has become much more straight-forward and sophisticated than the traditional 2D plans, but energy modelling software is unable to read the information coming from a BIM-based model fully, and thus are not able to analyse the energy performance of the building as it is. Hence, a manual procedure is required to either, remodel the desired building in Building Energy Modelling (BEM) tools, or to correct the wrongly-translated building information. This problem is known as interoperability issue. Indeed, "Interoperability" is the ability of two tools to communicate and exchange data that is readable for both correctly. Currently, this process is highly time and labor consuming as well as being quite error-prone, and it requires more attention [3, 4].

The BIM to BEM process consists of three parts BIM tool, model schema exchange format, and BEM tool. Interoperability issues can arise from either of these parts and are not necessarily limited to the ability of BEM tools to read the input information.

Therefore, this project was defined to investigate the potentials and difficulties of energy performance modelling and analysis using BIM to BEM methodology with having an eye on the possible solutions for the current challenges of the interoperability in BIM to BEM tools through this case study.

The first step consists of undertaking a state-of-the-art review to answer the following questions. What have other researchers suggested as main reasons behind the interoperability issue in BIM to BEM procedure? How previous case-studies have overcome interoperability challenges and are their solutions reproducible for other building types?

In the second step, BIM and BEM software will be investigated to identify the most suitable tools for results' visualization and simulation analysis. It is extremely likely for Autodesk©Revit to be used for BIM modelling due to its position as the most prevailing BIM authoring tool in the market.

Afterward, based on the preceding step, the simulation will be executed on the BIM-based model to obtain the energy performance of the building and render solutions for improving the performance through best solution packages with respect to the climatic conditions. In other words, this step will help to study several alternatives in order to choose the cost-optimal solution as recommended by the Energy Performance of Buildings Directive 2010/31/EU (EPBD Recast) [5].

The final stage of the study comprises of investigating interoperability issues found in BIM to BEM procedure and addressing it while utilizing previously suggested methods or ad-hoc solutions tailored to this specific building. Figure 5 visualizes the methodology.

1.1 Motivation, Hypothesis, Aims, and Objectives

1.1.1 Motivation

Building Information Modelling (BIM) is a methodology that creates Building Information Models which are a digital representation of physical and functional characteristics of a building. BIM models are able to store geometric, semantic and topological information for the whole life-cycle of a building. This provides an effective bed for all participants of the Architecture-Engineering-Construction-Owner-Operator (AECOO) Industry to gather their efforts and information in one model, BIM. In fact, all partners can collaborate whit each other, and access all the information only through one building information model.

This is why BIM has revolutionized the AECOO community. Because it reduces time, effort, cost, error, and confusion for individuals and companies.

Furthermore, it is possible to export the BIM model to other tools for further analysis in other domains. For instance, for energy analysis in Building Energy Modelling (BEM) tools. In order to exchange the BIM model to other tools, it should be exported to digital data structures (called data model or data schema) that are commonly accepted between other industry tools. Industry Foundation Classes (IFC) are an international open file format that is supported by various tools across many engineering disciplines. IFC is developed by BuildingSMART and has several releases. The most common release is IFC2x3 which is used in the project. The lasts release is IFC 4.

Many Building Energy Modelling (BEM) tools are capable of importing and reading the IFC file format. However, the flow of information from BIM to BEM is not automated. There are many issues that are related to either the BIM tool, the given data exchange format, and the BEM tool. Due to these issues, the tools are not able to communicate with each other seamlessly. Sometimes, after the exchange of the model to the second tool, some information is lost, objects are missing, objects are in wrong positions, and with wrong colors, elements are duplicated, or not transferred at all, and so forth. This is called interoperability issue. In fact, interoperability is the ability of two tools to exchange information or model without losing any information in between.

Despite the great potentials of BIM and BEM tools, the existing interoperability issues have made it quite difficult for experts to use BIM as the basis for their BEM model. Because finding and fixing the issues is rather time-consuming, laborious, and prone to human mistakes. That said, since the interoperability issues vary between the tools and are dependent on the type of information being exchanges, the results of one BEM modeler is not necessarily reproducible by others. This has greatly diminished the popularity of BIM-based BEM.

Therefore, to map the interoperability issues between BIM to BEM tools, we investigated 19 case-studies through a systematic approach. Our goal was to understand the Interoperability Issues that we anticipated to encounter during the cases. The building model that was used during the investigations is called BESTEST 600. The BESTEST 600 building is used in the validation of building energy simulation programs and is an internationally-recognized model. Moreover, our BIM tool was Revit which is a quite popular, and market-dominant tool for Building Information Modelling. The BEM tool used in our investigation is called IDA-ICE which is a powerful tool for energy simulation and analysis of a building, albeit it is commercial. The exchange data format between these two tools was IFC.

1.1.2 Hypothesis

This thesis hypothesizes that there exist interoperability issues between the exchange of information between BIM and BEM tools that prohibit the automated energy modelling from an architectural model.

1.1.3 Aims, Objectives

The primary aim of this thesis is to improve the computationally-aided-energy-analysis process in the building sector by investigating the interoperability issues between BIM and BEM tools and to facilitate sustainable and integrated design. This shall lead to the following objectives:

- o Review of the state-of-the-art of BIM, BEM, IFC, and related interoperability issues in the literature,
- o Review of the BIM, and BEM tools (here: Revit and IDA-ICE, respectively), and their related terminology, concepts, and definitions
- o Develop building information model of the case studies,
- o Find interoperability issues in the exchange process of the building model form BIM to BEM,
- o Propose solutions and create a framework for the interoperability issues to assist future BIM-based energy modeling and CAD companies.

1.2 Limitations

One of the limitations of this study was the lack of proper guidelines for exporting IFC from Revit, for the purpose of energy analysis. Another limitation is the software-based terminology and object hierarchy that is specific to each company. This has hugely impacted the interpretations of how different software approach one building element, e.g., a wall. In Section 3.2.1.3 we tried to compare how Revit's element hierarchy matches IDA-ICE's object hierarchy, but in the end, we noticed that such comparison might not be very valid.

1.3 Methodology

A case study approach is adopted to help understand the deficiencies and potentials of energy performance modelling and analysis using BIM to BEM methodology with particular attention to possible solutions for the existing interoperability challenges. Figure 1-1 shows the workflow of performing each case study. First, the BIM model is created in the Revit. Then, it is exported as IFC file. And finally, it is exported to IDA-ICE. At each stage, the model was explored for the interoperability issues. Figure 1-2 presents an overview of the methodology of this thesis, and Table 1-1 elaborates the case studies and the interoperability issues under investigation. The methodology and case-studies are presented in Chapter 3.
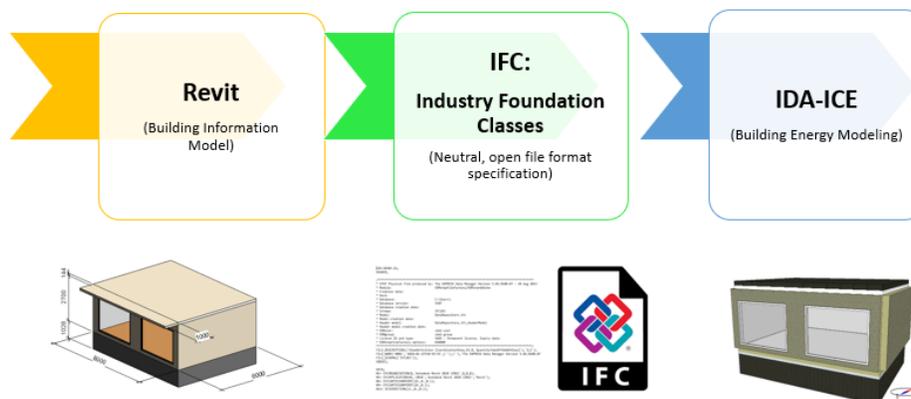
Figure 1-1 An overview of the project

Literature Review

- Building Information Modelling (BIM).
- Building Energy Modelling (BEM).
- BIM to BEM Interoprability interoprabiltiy issues in construction sector.
- Industry Foundation Classes (IFC).

Building Information Modeling

- Investigation of the BIM authoring Tool (Revit).
- Model the building base on case-study's requirement.
- Export model as IFC format.
- Investigation of how each case-study is exported to IFC classes.

Building Energy Modeling

- Investigate of the Building Energy Modelling tool (IDA-ICE).
- Import model from BIM to BEM.
- Find the missing data, redundancies, interoprability issues.
- Run Simulations.

Results and Conclusions

- present the interoperability issues found in the case-studies.
- present the suggestions for the software companies: AutoDesk (Developer of Revit) and EQUA Simulation AB(Developer of IDA-ICE)
- Present ideas for future works.

Figure 1-2 Methodology in one glance

Interoperability Issue under investigation	Task	Sub-Task	Sub-Task Description
1. Can Revit export Location line type of the walls to IFC? 2. Does the Location line type influence the imported geometry of the building inside IDA-ICE? 3.	**1** **Wall Location Line**	ST1	Wall Centerline (default)
		ST2	Core Centerline
		ST3	Finish Face: Exterior & Finish Face: Interior
		ST4	Core Face: Exterior & Core Face: Interior
4. How the placement of different 3D spatial element components (i.e., Room, Space, and Zone) in BIM affects the IFC file and the BEM model? 5.	**2** **Zone vs Space vs Room**	ST1	No Room, Space, or Zone element
		ST2	Room
		ST3	Space
		ST4	Zone
		ST5	Room + Space
		ST6	Room + Space + Zone
6. How variation of geometrical properties of Room and Space in Revit affect the BIM-based energy modelling in IDA-ICE? 7.	**3** **Space/Zone height vs. Wall height**	ST1	Space height = Room height
		ST2	Space height ≠ Room height
8. How materials' properties are exported from Revit to IDA-ICE? 9. How are they stored in the IFC data schema? 10.	**4** **Materials**	ST1	Material's thermophysical properties
11. How windows' geometry and properties are exchanged Between Revit and IDA-ICE? 12. How is a user-built window family in Revit exported to IFC? 13. Can IDA-ICE recognize a user-built window family made in Revit? 14. What are the differences between Built-in Families, and user-built families in Revit to IDA-ICE procedure? 15.	**5** **Windows**	ST1	Revit built-in windows with built-in Analytical construction
		ST2	Revit new family created from scratch window
16. Does IDA-ICE recognize the orientation of the BIM model and its components? 17. How are the changes of the orientation of building elements in Revit reflected in IDA ICE? 18.	**6** **Orientation**	ST1	Building orientation
		ST2	Change of building orientation of BM_1 from N_S direction to 30◦ NE
19. How does Revit export coordinates to IFC file? 20. How does IDA-ICE interpret the coordinates from an incoming BIM model through an IFC file?	**7** **Coordinates**	ST1	Coordinates of elements
21. How shadings and fins are created in Revit and exported to IFC? 22. How does IDA-ICE understand the shadings in the BIM model?	**8** **Shading**	ST1	Horizontal shading (South façade) BM_2
		ST2	Horizontal and vertical shading (E/W facade) BM_4

Table 1-1 Structure of Case studies, and interoperability issues

1.4   Structure of the Report

This report is organized into four chapters that are described in the following line. Additionally, Table 1-2 demonstrates an outline of the thesis structure.

Chapter 1: Introduction

> In this chapter, a general overview of the thesis is presented, along with aim, objectives, and limitations of the work.

Chapter 2: Literature Review

> In this chapter, a theoretical background to Building Information Modelling (BIM), Building Energy Modelling (BEM), Interoperability, Industry Foundation Classes (IFC), is presented.

Chapter 3: Methodology and Case-studies

> In this chapter, firstly, a brief introduction to the software of choice, i.e., Revit (for Building Information Modelling), and IDA-ICE (for Building Energy Modelling) is delivered. Afterward, case-studies are introduced and explained in detail.

Chapter 4: Conclusions and Future Works

> In this chapter, the conclusions that were made based on the case-studies' results are summarized and reported. Based on these conclusions, some ideas for future researchers are presented. Eventually, some suggestions are offered to the software companies that have developed Revit, and IDA-ICE.

Chapter	Title	Summary	Questions to be addressed
1	Introduction	Present hypothesis, aims and objectives, research questions, and the research methodology.	
2	Literature Review	Review BIM, BEM, IFC, and interoperability issues.	What is BIM? What is BEM? What is IFC, and how it stores the information? What are the interoperability issues in the BIM to BEM processes?
3	Methodology and Case-studies	A brief overview of Revit and IDA-ICE's concepts. Presentation of case-studies, and their results.	What are the interoperability issues in Revit to IDA-ICE process? What are the capabilities of Industry Foundation Classes?
4	Conclusion	Summary of findings, suggestions, and future works.	What are the possible solutions to resolve the interoperability issues found in Chapter 3? What are possible next steps for future works?

Table 1-2 The outline of the thesis structure

Chapter 2 Literature Review

This chapter begins with an overview of Building Information Modelling (BIM) in Section 2.1; it is then followed by a review of Building Energy Modelling (BEM) in Section 2.2. Afterward, the interoperability is discussed in Section 2.3, which leads to an overview of Industry Foundation Classes (IFC) in Section 2.4.

2.1 Review of Building Information Modelling (BIM)

The term "BIM" was first used by AutoDesk staff [6]. However, Jerry Laiserin is known as the first person who publicized this term in the Industry [7]. The early definition of BIM varies; Bazjanac defines BIM as a "noun" which describes " an instance of the populated data model of building" that holds multi-disciplinary "raw data" for a particular building [6]. Furthermore, Eastman [3] defines BIM as "a modeling technology and associated set of processes to produce, communicate, and analyze building models."

In other definitions, BIM "is a digital representation of physical and functional characteristics of a facility that offers potentials for life cycle modelling and management of the building or its systems" [8], and "is a methodology to manage the essential building design and project data n digital format throughout the building life-cycle" [9]. Additionally, BIM used to be referred to as Building Product Modelling, or product models, that are object-oriented. They contain data-rich building components, 3D geometrics, spatial information, thermal values, and material properties. These are the properties upon which data interoperability is built [2].

Many BIM professionals agree that BIM is an object-oriented digital representation of a building or built environment that enables the data exchange in digital form. BIM can attribute both spatial and geometrical as well as non-geometrical attributes to building elements to be implemented in the various areas of AEC, such as fire protection, safety on construction site, facility management, structural analysis, daylight simulation, construction management, cost-estimation and planning [1, 2, 10-15]. BuildingSMART considers building information model as a shared knowledge resource for information about a facility forming a reliable basis for decisions during its life-cycle (from earliest conception to demolition) [16]. Figure 2-1 shows BIM and the lifecycle of the building.
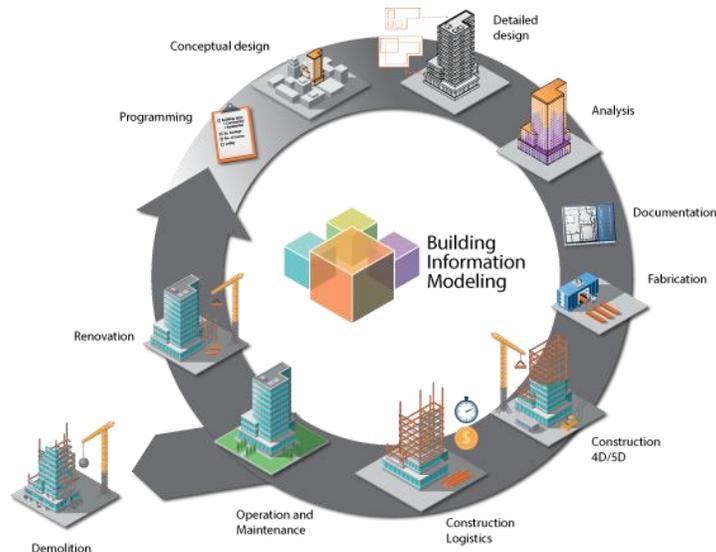
Figure 2-1 BIM through the building life-cycle [17]

Likewise, "BIM is an information-rich building model that allows the thermal, structural, or cost-analysis to be carried out, based on one building model." This definition introduces the different dimensions of a Building Information Model [2, 18] that can be seen in Figure 2-2.

3D
- **Modelling**
- An upgrade to the traditional CAD plans

4D
- **Time**
- Scheduling and construction stages simulation

5D
- **Cost**
- Planing and estimation

6D
- **Sustainability Performance**
- Thermal analysis and environmental assessment, eventually even automated building certification

7D
- **Facility Management, Maintenance and Operation**
- Fully mature and comprehensive model, ready to maintain and manage assets

8D
- **Deconstruction**
- The decommissioning, demolition, repurposing or recycling of a building or structure

Figure 2-2 The 8 Dimensions of BIM

Building Information Modeling has numerous benefits. BIM technology and associated processes are at the heart of how the building design and construction process responds to the growing pressures of higher complexity, faster development, improved sustainability while reducing the cost of the building and its subsequent use [3].

BIM is an enormous player in the future of construction sector [3]. McGraw Hill Construction reported in 2008, 45% of architects, engineers, contractors and building owners surveyed used BIM on 30% or more of their projects [19]. Although Architecture-Engineering-Construction (AEC) industry practitioners started to adopt BIM in their projects From mid-2000's, It is anticipated that BIM grows sharply in the next coming years [20, 21]. Despite that, some argue that, currently, BIM is being slowly adopted in the industry, mainly because of lack of demand, cost and interoperability issues [22].

Even now, BIM and ICT have a brought a digital tornado in Architecture-Engineering-Construction-Owner-Operator (AECOO) Industry. There are many ongoing theoretical and practical projects that are investigating the Integration of BIM and other tools [21]. There are various participants in the industry that can efficiently collaborate on one model in BIM to save time, effort, cost, and errors. Figure 2-4

demonstrates some of the significant collaborators on the BIM model. This collaboration brings many benefits for all parties, such as better interoperability capabilities, reduced conflict and project team benefits [22].
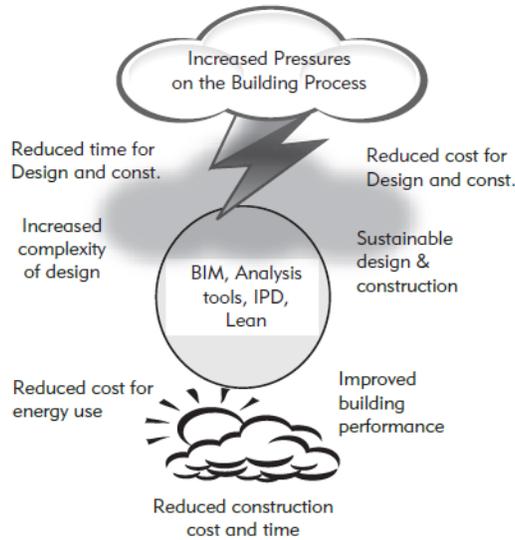
Figure 2-3 BIM technology and associated processes can help to respond to the increasing pressures on a building over its lifecycle [3].
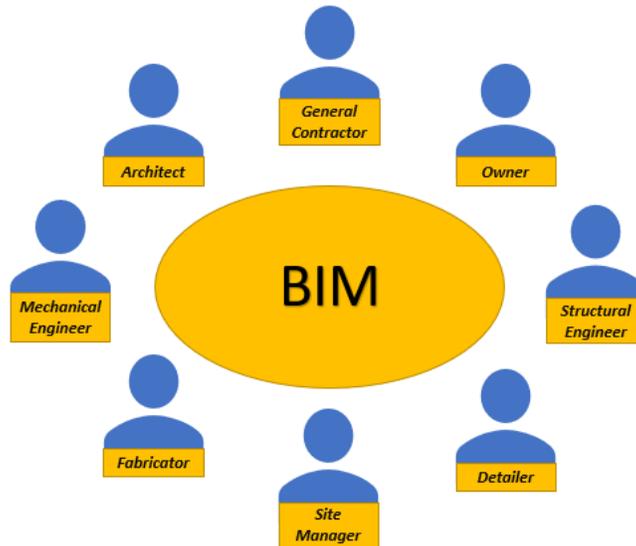
Figure 2-4 BIM promotes collaboration between various AECOO participants.

In an interesting approach, Eastman has described what is not BIM in order to clarify this term even more [3]. According to him, four types of building models are not BIM.

 I. Models that solely contain 3D data and no (or few) object attributes,
 II. Models that have no parametric intelligence,
 III. Models that are composed of several 2D CAD reference files that must be combined to define the building,
 IV. Models in which changes to dimensions in one view are not reflected in other views automatically.

One important thing to consider is that BIM is different with CAD (Computationally Architectural Design) [3]. CAD systems are becoming more intelligent day by day, which entices more users to share their data that is associated with a given design. This lead to a focus shifted from drawings and 3D images to the data itself. As a matter of fact, the key aspect that differentiates BIM from computer-aided design is the semantics A building model produced by a BIM tool includes 2D and 3D views along with the building model's contents and capabilities [3].

Furthermore, BIM can be subdivided into two levels, Big BIM and Small BIM according to [23] based on the different needs of BIM in daily practices and different situations of BIM use. Figure 2-5 elaborates more on this differentiation.
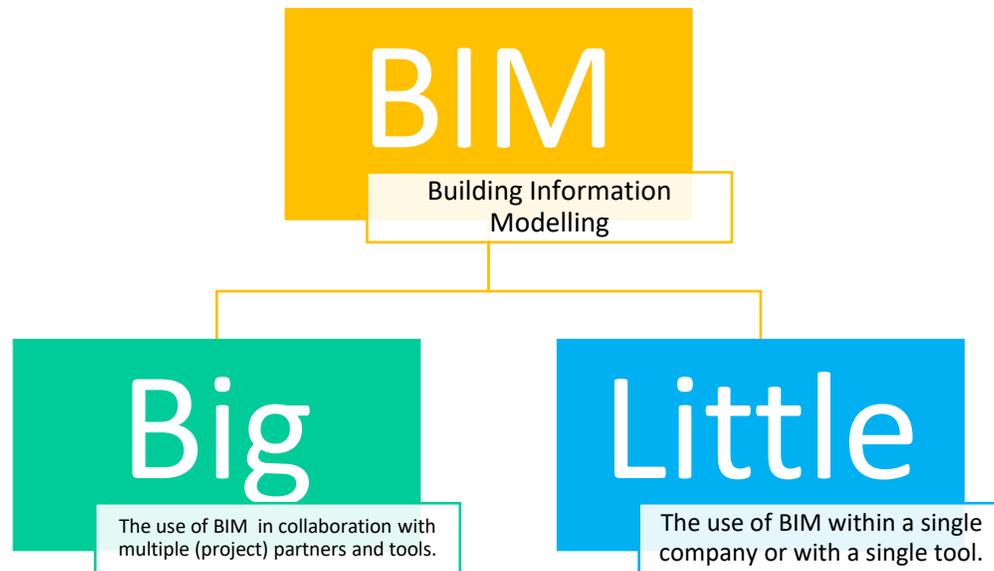
Figure 2-5 Levels of BIM [23]

BIM authoring tools allow users to make a 3D information-rich digital model of a building. Such as:

- o Revit by AutoCAD [24],
- o ArchiCAD by Graphisoft [25],
- o Tekla by Trimble [26],
- o Allplan by Nemetschek [27],
- o Microstation by Bentley [28].

Depending on the choice of BIM tool, a significant number of inputs can be inserted into the model. Some of these inputs are illustrated in Figure 2-6.

The literature review about BIM is endless; with the increased implementation of BIM in academia and industry, the number of studies that are investigating the BIM definition, and adaptation in the AECOO industry is on the rise. The different dimensions and aspects of BIM, such as sustainability, are the focus of many studies [21, 29-32].

Figure 2-6 BIM inputs

2.2 Review of Building Energy Modelling (BEM)

Building Energy simulation tools are being used by the building design professionals more and more every day, since, from an AECOO perspective, advanced analysis of building energy simulation has become a critical part of the integrated design [33]. Energy performance simulation programs are robust tools to assess the energy performance and thermal comfort of a building over its whole life-cycle. However, these simulation tools differ in many ways regarding their:

o   thermodynamic models,
o   graphical user interfaces,
o   purpose of use,
o   life-cycle applicability,
o   ability to exchange data with other software applications [34].

The term "Building Energy Simulation" tools are interchangeably used as "Building Performance Simulations" tools, and recently, they are also referred to as "Building Energy Modelling" tools, since this name resonates with Building Information Modelling tools. However, there is no significant

distinction in the literature regarding the usage of these names, and they are somewhat used by authors interchangeably. Here, in this study, we will refer to the tools that make energy simulations possible as Building Energy Modelling (BEM) tools.

In general, BEM, or BPS tools improve the understanding of how a given building operates according to certain criteria and enable comparisons of different design alternatives, with respect to its energy performance [34].
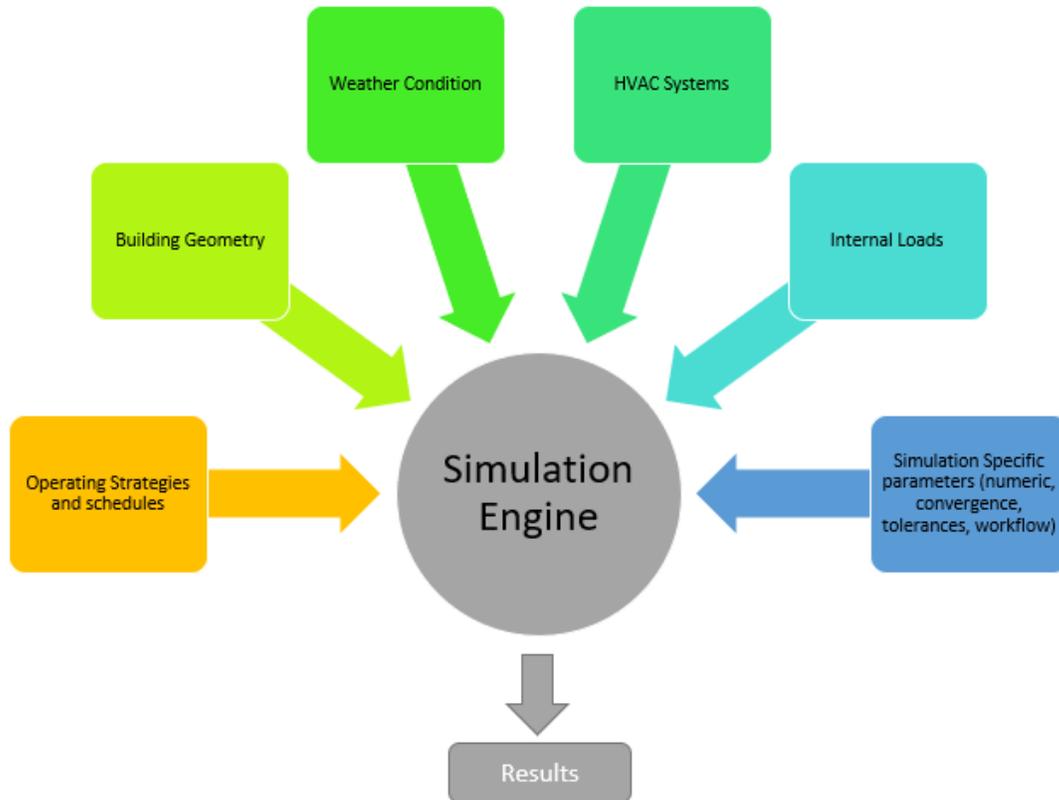
Figure 2-7 Inputs for BEM tools [33, 34]

While energy simulations could be applied in every stage of the building lifecycle, traditionally, energy performance simulation and analysis do not start until after some fundamental design decisions (such as architectural and HVAC design decisions) are made that affect the energy performance of the future building [1]. However, with the advancements of technologies in both BIM and BEM domain, there is a highlighted emphasis on the Integrated building design approaches and concepts such as Zero Energy Buildings that requires a more fluent process of energy modeling that directly leverage BIM-based thermal analyses during the design phase [35].

It can be said that today, not only in the building design phase but also in the operation phase, Building Energy Modelling tools are constantly being used by professionals. The accuracy of a thermal simulation model depends heavily on the accurate definition of building geometric characteristics, including the building envelope, the building orientation, the configuration of spaces, surfaces, and volumes [34, 36]. Figure 2-7 shows a number of necessary inputs for the Simulation Engines. The main inputs are the building

geometry, internal loads, HVAC systems and components, weather data, operating strategies and schedules, and simulation specific parameters [34].

Moreover, simulation engines contain mathematical and thermodynamic algorithms that are used to calculate the detailed energy performance according to the underlying model of the engine that can be simple text-based input and output files [34].

Building thermal simulation is the "dynamic analysis" of the energy performance of buildings using computer modeling and simulation techniques. In this simulation, a calculation of building thermal loads and thermal consumption is involved in determining the thermal characteristics of the building and its building systems. These calculations are necessary to promote sustainable built environment design and application and offers thermal comfort for the occupants. Building thermal simulation is a robust method for studying the thermal performance of buildings and to evaluate the architectural design in order to cut down the energy and carbon footprint of buildings form the design phase [33].

BEM tools, as well as many other types of simulation and analysis tools (such as acoustics and fire propagation simulation tools), have their own internal data models of building geometry. Such internal data models represent views of building geometry typically quite more straightforward than the geometry data models of CAD and BIM tools [34, 37]. Figure 2-8 illustrates this explanation clearly. Usually, architectural view of the building (the output of the CAD/BIM tools) is highly complex in terms of geometry and data, while the thermal view is quite simple in comparison.
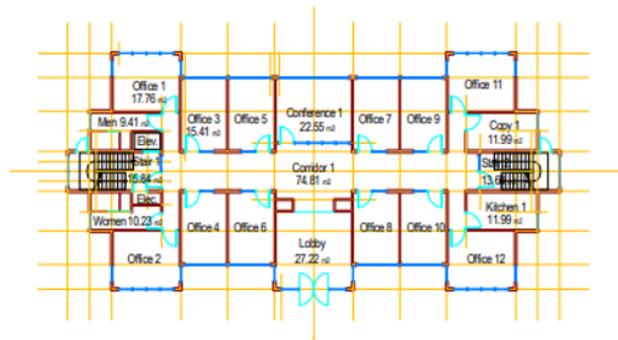
a) Geometry of a building, as depicted in a typical architectural CAD tool (architectural view)
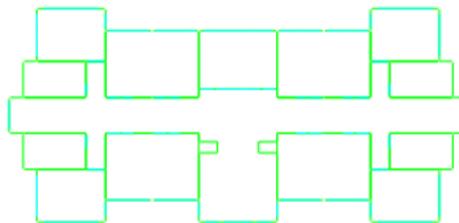
b) Geometry of the same building, as depicted by an energy performance tool, (thermal view)

Figure 2-8 Architectural view vs. Thermal view [37]

The term thermal view comes from the simplified model that is required for energy modelling, and is constructed based on the architectural model. The construction of thermal view depends of the person's understanding of the subject building, his or her knowledge and skill, experience, complexity of the building

geometry of the subject building, complexity of the building itself, available resources, etc. Eventually, the result is not necessarily reproducible and is quite arbitrary: Different people defining the thermal view of the same building generates view definitions that differ from each other [1].

Space boundaries as one of the fundamental concept of building energy models (BEMs) that are necessary for the BIM to BEM model transfer. The space boundary works as a link for building geometry definitions between the architectural and thermal view, or BIM and BEM tools.

Most simulation and analysis tools define building geometry as systems of surfaces (i.e., surfaces that delineate walls, roofs, beams, windows, and doors) which are all part of the definition of spaces and/or zones identified in the model of the building. Such surfaces are called "space boundaries" [38].

Space boundaries come in "pairs:" One pair defines the inside, while the other defines the outside of a given surface. Exterior walls, slabs, roofs, windows, and doors are an exception; they solely have one space boundary that corresponds to their interior surface because of how BEM tools handle exterior surfaces since the exterior cannot be modeled as a space or a zone [38].

Space boundaries are flat polygons with an outward or inward normal which indicates the direction of transmission or flow through the given space boundary. According to Bazjanac [38], five levels of space boundaries can be found in a building:

- o **1st level:**

    The 1st level space boundary is the whole surface of an element that bounds a space. In other words, a 1st level space boundary is the surface of a building element that is continuously visible from within a space or a zone by a person in that zone [38]. 1st level space boundary is shown in Figure 2-9.

    1st level space boundaries are implemented in visualization tools to facilitate the showing of what the eye sees in a space or a zone. These tools do not consider transmission or (energy) flow through the modeled surfaces" [38].

- o **2nd level:**

    For energy simulation purposes, space boundaries must be modeled in a more detailed manner, to take into account the different heat flows between spaces. If, for example, a wall separates one space on one side from two spaces on the other side, the 1st level boundary needs to be split up into two 2nd level boundaries [38]. If the 2nd level space boundary is interior, then it will come as "pair:" A pair is a space boundary of exactly the same shape and size, offset from the original 1st level space boundary by the thickness of the "parent" building element. This is shown by the color blue in Figure 2-10. If the viewer person stands in zone 1, the previous 1st level space boundary is subdivided into two segments which facilitate two different rates of transmission or flow. Each segment is a second (2nd) level space boundary.

    "The definition and use of 2nd level space boundaries are mandatory in the use of tools that simulate the transmission or (energy) flow through the modeled interior surfaces. Windows, skylights, and doors, as well as virtual surfaces (e.g., simulated "air walls") which constitute non-physical boundaries of zones, are also represented as 2nd level space boundary pairs in such simulation [38]".

- **3rd level:**

  Not all parts of a 1st level boundary are translated to 2nd level boundaries; some parts will be 3rd level space boundary as shown by yellow in Figure 2-10. There is no space behind these parts, but a building element on the other side, therefore, these parts are considered as 3rd level space boundaries. This means that these surfaces do not play a role in the transmission or (energy) flow through the building element because there is no other zone to receive the perpendicular transmission or flow through these unaccounted surface areas [38]. Also, exterior building elements (roofs, exterior walls, and exterior slabs) do not have 3rd level space boundaries [38].

- **4th level:**

  4th level space boundaries display same behaviors as 3rd level space boundaries. In fact, depending on the BIM tool and the placement of wall reference lines (similar to Location lines in Revit), some areas can be left unaccounted for by 3rd level boundaries. 4th level space boundaries are shown by the color purple in Figure 2-10. As exterior walls, slabs and roofs can have only one surface in simulation tools' internal data models. Thus, the exterior walls cannot include any 4th level space boundaries.

- **5th level:**

  When building elements intersect with each other at a non-right angle, another type of surfaces is formed that cannot be categorized in any other space boundaries. These areas called 5th level space boundaries have no perpendicular heat flow, shown by orange in Figure 2-11.
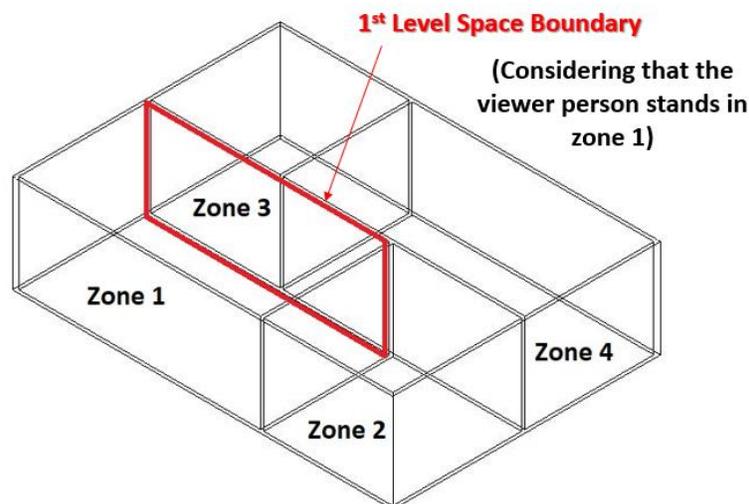
Figure 2-9 1st Spaces boundaries [38]
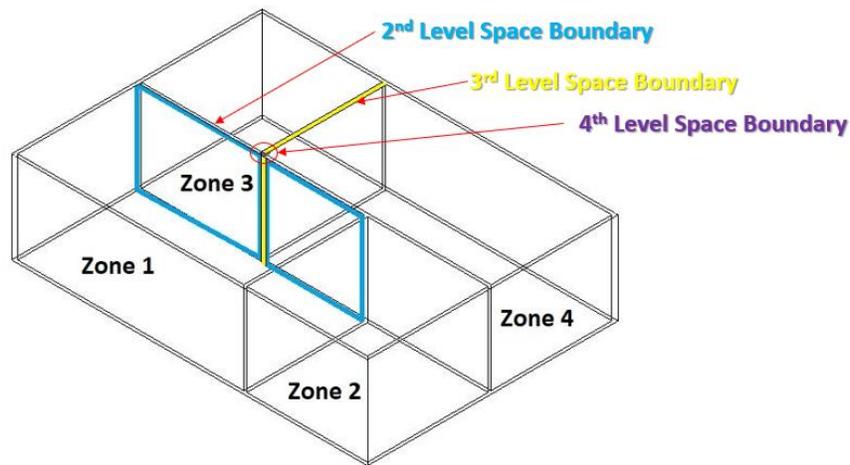
Figure 2-10 2nd, 3rd, and 4th Spaces boundaries [38]
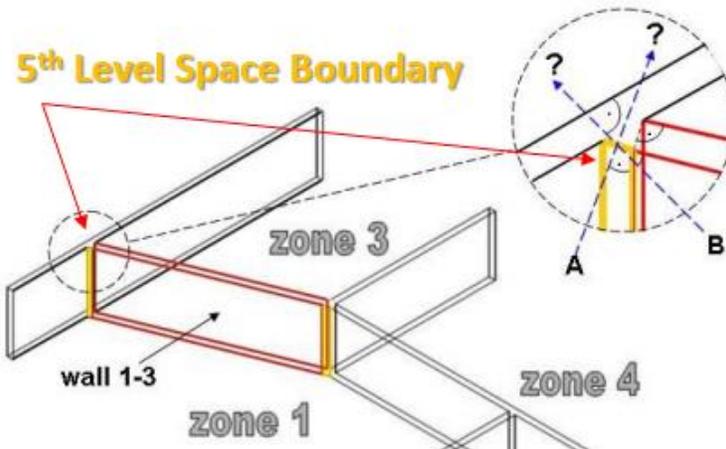
Figure 2-11 5th Spaces boundaries [38]

Therefore, there are five levels of space boundaries that are needed for the use of building geometry representations by building energy simulation tools [38]. That said, today, many BEM tools are mainly based on one-dimensional heat transfer between thermal zones. This assumption simplifies the geometric input dramatically and allows shorter simulation run-times, despite the higher accuracy of simulation results of 2 or 3-dimensional heat transfer models [34]. This means that in most cases, only 1st level and 2nd level space boundaries are considered for building energy modelling.

That said, BEM tools require the availability of geometrical and material thermal data [39]. At first, geometrical information was obtained from CAD software that necessitates a manual process to generate the proper inputs for the thermal simulation software. This process is hugely error-prone and time-consuming. The advent of BIM resulted in a paradigm shift towards an object-centric view for the representation of building information and the availability of BIM as the geometrical input of BEM tools [3, 39] That said, Consequently, since BIM model has more information that it is necessary for BEM tools, BIM-based models must be transformed (i.e. simplified, reduced, translated or interpreted) before they can be directly used by BEM tools [37].

Although there has been a surge in the energy simulation services due to market drivers such as building rating systems, e.g., LEED, BREAAM, or programs such as EU 202020 goals, there has not been significant development beyond the use of standalone simulation tools by specialized practitioners who are more comfortable with manual building data input than automated data exchange through BIM to BEM [40]. Another reason could be that dominant BIM authoring vendors prefer to implementing embedded energy analysis tools within their flagship products rather than implementing robust data exchange with third-party tools that do not contribute to their revenue stream [40].

In many cases, While based on professional expertise, the process of BIM to BEM have a tendency to be uniquely performed by each expert based upon methods and rules-of-thumb developed over time by that individual [40]. This statement was observed during the period of this research as well. It seems that there are few experts who have profound practical knowledge of exact BIM to BEM process, and this knowledge is not really openly discussed on the internet, or in the literature.

As a result, BIM to BEM process is a non-standardized process that produces energy building energy models that varies from one modeler to the next, even though the initial building design information is the same for all modelers [40]

There could be different reasons for this non-standardized process. Firstly, there has been a traditional separation between architectural, energy simulation, and mechanical engineering professional disciplines before the advent of integrated building design. This is again referring to the dichotomy between an *architectural view* of a building and energy simulation, or *thermal view* of the same building according to [41]cited in [40] which in turn has impacted the standalone nature of software tools used by each of the participating design disciplines [40].
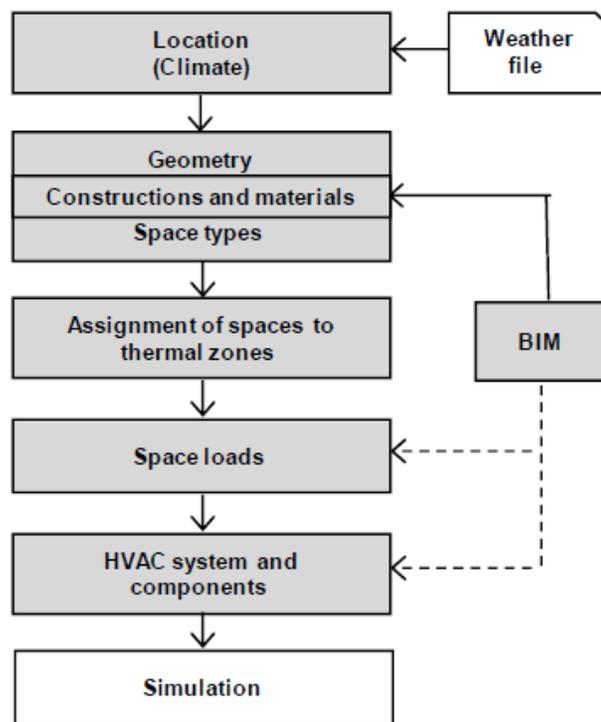
Figure 2-12 Ideal BIM-based BEM workflow [34]

There is a growing number of environmental performance building analysis programs on the market; Bahar et al. [33] have reviewed the most applicable building thermal simulation tools in the AECOO community regarding their application, input data, output data, and BIM-based geometry import. That said, since 1996, more than four hundred building energy simulation tools have been listed in the "Building Energy Software Tools Directory" provided by U.S.DOE [42, 43]. Some of these tools are open-source, and others are commercial. Nevertheless, quite a handful of them is used in industry and academia. Some of these BEM tools are listed below:

- o DesignBuilder by DesignBuilder [44],
- o Ecotect eQUEST by James J. Hirsch & Associates in collaboration with Lawrence Berkeley National Laboratory [45],
- o EnergyPlus by DOE, BOT, and NREL [46]
- o EcoDesigner by Graphisoft [47]
- o ESP-r by the University of Strathclyde [48]
- o Green Building Studio by AutoDesk [49]
- o IDA-ICE (IDA Indoor Climate and Energy) by EQUA Simulation AB [50],
- o VE (Virtual Environment) by IES (Integrated Environmental Solutions), known as IES-VE [51],
- o TRACE 700 by Trane [52],
- o TRNSYS [53],
- o Riuska by Granlund [54].

Some of these simulation tools can be plugged into BIM authoring tools as add-ins such as IESVE and Green Building Studio, which allow energy simulation within the BIM environment [43], while others require the BIM tool to provide a certain input for them, such as IDA-ICE, EnergyPlus, etc. Nevertheless, to link Building Information Modeling (BIM) tools and energy simulation tools, standard data schemas such as the Industry Foundation Classes (IFC) or Green Building XML (gbXML) are required as common data formats. While energy modeling using data schemas such as IFC and gbXML has been implemented for many simulation programs, reliable energy models can be acquired through manual model checks and modification due to many interoperability issues that arise in BIM to BEM exchange process [43].

A BIM-based BEM without any interoperability issue offers the automation of data exchange process that would bring significant time savings, error reduction, and simulation model reproducibility [40]. Figure 2-12 demonstrates the ideal workflow of energy performance in thermal simulation tools based on BIM [34]. However, due to the interoperability issue in BIM to BEM process, this workflow is obstructed.

In the next section, a detailed explanation of the essence of interoperability issues is delivered.

2.3   Review of Interoperability

According to [55], interoperability is a critical issue in the Architecture Engineering Construction Owner Operator community, especially between multiple models and tools. Eastman [3] defines "Interoperability" as the ability to exchange data between applications flawlessly, in order to have a smooth workflow in which the model transaction is automated. This seamless exchange of data eliminates data repetition, possible human error, and enables rapid reproduction of the model [3, 56].

Other researchers define interoperability as the ability to ensure that data generated by any tool can be appropriately interpreted by all other tools [57]. Any miss-communication among tools can result in interoperability issues [33]. Therefore, the interoperability issues that arise between software result in not-consistent and fragmented, that prohibits the automatic flow of information from one tool to another.

Moreover, interoperability should also allow bidirectional update of building information, meaning that any change in one of the tools engaged in the exchange process, should flow between the programs [4, 58]. Unfortunately, currently, the flow of information is one directional, regardless of the exchange format being used[3, 4, 58], Figure 2-14.

According to KISS (Knowledge Industry Survival Strategy) interoperability classification framework [20, 59], three interoperability levels can be identified that are summarized in Figure 2-13.

File and syntax levels
- *File level:* two tools successfully exchange files.
- *syntax level:* two tools to successfully parse those files without errors.

Visualization level
- the ability of two tools to faithfully visualize a model being exchanged.

Semantic level
- the ability of two tools to reach a common understanding of a model being exchangee with the same quality and consistency.

Figure 2-13 KISS (Knowledge Industry Survival Strategy) interoperability classification levels [20]

Interoperability has by tradition relied on file-based exchange formats limited to geometry, such as DXF and IGES. Later, in 1980's the need for formats that stores semantic data was satisfied by data models developments that support product and object model exchanges within different industries [3]. Appendix C contains a list of the most common exchange formats in the AECOO industry.

Since the scope of this thesis is limited to interoperability issues related to Building Information Modelling and Building Energy Modelling, we will focus on the exchange formats that corresponds to this specific exchange requirement. Presently, IFC *(Industry Foundation Class)*, and gbXML (Green Building XML, XML is an eXtensible Markup Language-based language) is the most common data schema that deals with the BIM to BEM process., each of which has their own advantages and disadvantages [4]. Both of them are developed to enable interoperability among different software environments and can be kept up to date for the duration of the building's life cycle [3, 4, 39, 40].

It is a known fact that the process of BIM to BEM have a tendency to be uniquely performed by each expert based upon methods and rules-of-thumb developed over time by that individual [1, 6, 40]. This statement was observed during the period of this research as well. It seems that there are few experts who have profound practical knowledge of exact BIM to BEM process, and this knowledge is not really openly discussed on the internet, or in the literature. As a result, BIM to BEM process is a non-standardized and non-reproducible process in which the resulting energy BEM models vary from one modeler to the next, even though the initial building design information is the same for all modelers [1, 33, 34, 40, 56, 60]. Abanda [61] states that there is no real time link between BIM tools and BEM tools, if problems exist in the exported BIM model to data schemas, then, the model should be fixed from the beginning in the BIM tool.
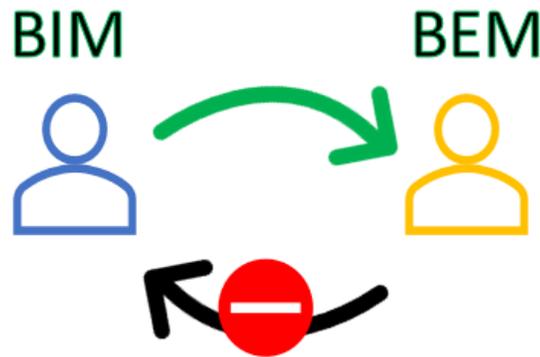
Figure 2-14 BIM to BEM process is one directional

Additionally, due to lack of seamless interoperability between BIM and BEM tools, a vast amount of information is either not transported, not interpreted, not appropriately reproduced, and etc. [2, 4, 39]. Therefore, the automation of data exchange process would bring considerable time savings, error reduction, and simulation model reproducibility [40].

In the next section, we will focus on IFC because this is the format that we have worked with throughout the project. The reason is that IDA-ICE, version 4.7.1, can accept this BIM input format. A detailed summary of BEM tools and the data formats that they support is provided by [33]

2.4   Review of Industry Foundation Classes (IFC)

NASA was one of the first companies that demanded a public domain exchange format from the CAD software companies, in order to cut down its expenses on the translators among all their CAD developers. Two NASA-funded companies, Boeing and General Electric, offered to adopt some initial efforts they had disjointedly undertaken. *IGES (Initial Graphics Exchange Specification)* is the resulting exchange standard. Using IGES reduced tremendous efforts and brought benefits for each software company, that resulted in the IGES early success throughout many designs and engineering communities [3].

As a whole, data exchanges between applications are based on two levels of definition, Schema, and Schema Language [3], Figure 2-15. *The model schema* describes the meaning of the information exchanged. The first file formats did not separate the way information was formatted from its semantic content, such as IGES. However, in 1980's, the separation of the schema from a more general language was recognized as an advantage that resulted in modern data exchange technologies with this distinction [3].
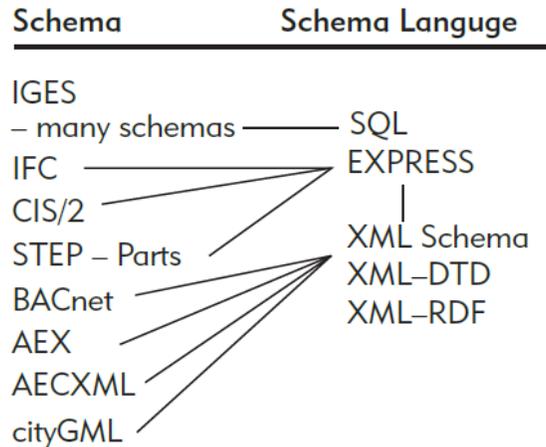
Figure 2-15 Modern Exchange formats [3].

With a rise in the demand of advanced data exchange technologies and file formats, *International Standards Organization (ISO)* in Geneva, Switzerland, initiated a Technical Committee, TC184, to initiate a subcommittee to develop a standard called *STEP (STandard for the Exchange of Product Model Data),* numbered ISO-10303, to address advance data exchange issues such as complex model, attributes and relations. *ISO-STEP* is one of their main achievements that gave birth to the *EXPRESS* language, developed by Douglas Schenck and later contributed to by Peter Wilson [3, 62]. All ISO-STEP information is in the public domain [3], and the EXPRESS language supports the modeling of products across engineering domains including mechanical and electrical systems, process plants, shipbuilding, process plans, furniture, buildings, bridges and etc.

Since EXPRESS is a machine-readable language, a graphical display version of the language was developed that is called *EXPRESS-G* for human users. following product models are related to buildings that have been developed based on the ISO-STEP through EXPRESS language:

- o AP 225
- o IFC
- o CIS/2
- o AP 241
- o ISO 15926

The explanation about all of these model schemas is beyond the scope of this report. Therefore, we will focus on *IFC (Industry Foundation Class)*, since it is the format of exchange that is used in this project.

The history of IFC starts in late 1994, when Autodesk initiated an industry consortium with twelve U.S. companies. This consortium was initially called as the Industry Alliance for Interoperability (IAI). New members were added to AIA which resulted in a name change to the International Alliance for Interoperability in 1997 that continued to work as a nonprofit industry-led international organization, with the goal of publishing the Industry Foundation Class (IFC) as a neutral data model [3]. However, IAI was renamed to BuildingSMART in 2005, and is known with this name ever since.

BuildingSMART aims to facilitate the "sharing of information throughout the lifecycle of any built environment asset, between all the participants, regardless of which software application they are using. The machine-readable, good quality data should be available for use throughout the design, procurement, construction, maintenance and operation phases" [63].

BuildingSMART has five types of open standard, with IFC being its technical core [63]. Nonetheless, each of these open standards assists the delivery and support of assets in the built environment in their unique way, as shown in Table 2-1.

Name	Abbreviation	What it does	Standard
Information Delivery Manual	IDM	Describes Processes	ISO 29481-1 ISO 29481-2
Industry Foundation Class	IFC	Transports Information / Data	ISO 16739
BIM Collaboration Format	BCF	Change Coordination	BuildingSMART BCF
International Framework for Dictionaries	IFD	Mapping of Terms	ISO 12006-3 BuildingSMART Data Dictionary
Model View Definition	MVD	Translates Processes into technical requirements	BuildingSMART MVD

Table 2-1 Five open standards of BuildingSMART [64]

2.4.1 Industry Foundation Classes (IFC)

According to BuildingSMART [63], IFC is a common data schema (model) for Building Information Modeling data that makes it possible to hold and exchange relevant data between different software applications. IFC is developed based on ISO-STEP EXPRESS language as an open standard data model to represent the entity-relationship model. Moreover, IFC has a "top-down" and relational approach that results in a large data file size with relatively complex data representation structure [39].

In other words, IFC is the data structure in which the building information can be stored in, in a manner that this data structure would be comprehensible between all tools. IFC is not controlled by a single vendor or group of software vendors, and for better interoperability between various parties it comes in three formats:

I.   IFC-SPF,
II.   IFC-XML,
III.   IFC-ZIP [3, 65].

Furthermore, Industry Foundation Classes (IFC) were developed to encompass <u>all</u> the building information, over the whole lifecycle, from feasibility and planning, through design (including analysis and simulation), construction, to occupancy and building operation [66]. In general sense, these types of information are geometric, semantic and topological information. Geometric information is related to the building form and shape in three dimensions. The semantic information defines the properties of components such as u-values of walls. Topological information captures the dependencies of components [67].

Conceptually, IFC is organized through four layers, as depicted in Figure 2-17, namely: Domain layer, Interoperability layer, Core layer, and Resource layer. The definitions of the layers are:

I. *Domain layer:*

This top layer includes schemas containing entities that are useful for defining products, processes or resources in a specific domain [56, 65]. An example of the domain is "Structural Analysis Domain."

II. *Interoperability layer:*

This layer includes schemas containing specific entity definitions that are related to a general product, process or resource which is commonly used across several domains. These definitions are typically used for inter-domain exchange and sharing of construction information. IfcSharedBuildingElements belongs to this layer and encompasses IfcWall, IfcWindows, etc. [56, 65].

III. *Core layer:*

The Core layer includes the "Kernel" schema and the "Product Extension" schemas. These schemas encompass the most general entity definitions that are related to process and control. Kernel Schema defines core concepts such as actor, group, process, relationship; and Product Extension defines abstract building components space, site, building, building element, annotations. Additionally, the entities defined at the core layer or above, hold a globally unique id and optionally owner and history information [56, 65, 68].

IV. *Resource layer:*

This is the lowest layer that includes all individual schemas containing resources that hold concepts which describe properties which are generic. Unlike core layer entities, Resource layer definitions do not include a globally unique identifier and shall not be used independently of a definition declared at a higher layer. Fundamental properties such as date and time, geometry, material, measurements belong to the Resource Layer [56, 65, 68]. This layer holds the base Express definitions [3].

Although IFC has the potential to represent an extensive range of building design, engineering, and production information, the range of possible information to be exchanged in the AECOO community is enormous. Therefore, IFC has its advantages but also has some shortcomings that are being improved by every release. Figure 2-16 shows the timeline of the release of the IFC versions since the beginning. Currently, IFC5 is under completion and is expected to have better parametric capabilities and support various infrastructure domains [69].
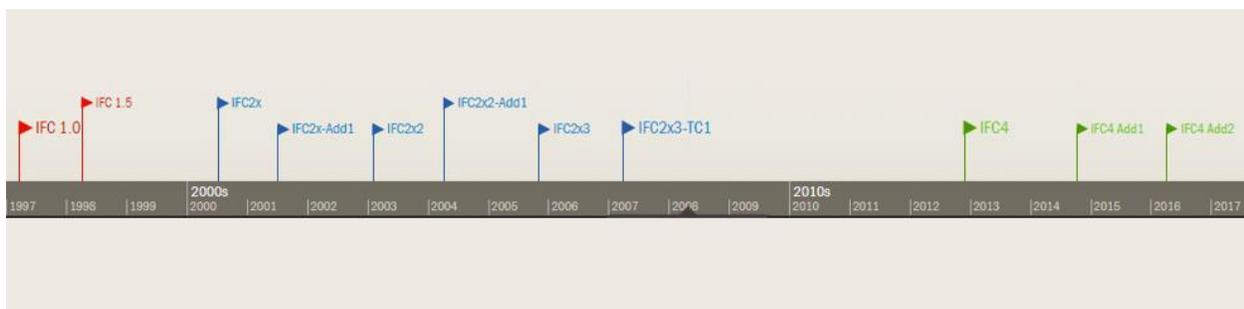
Figure 2-16 History of IFC releases [69]
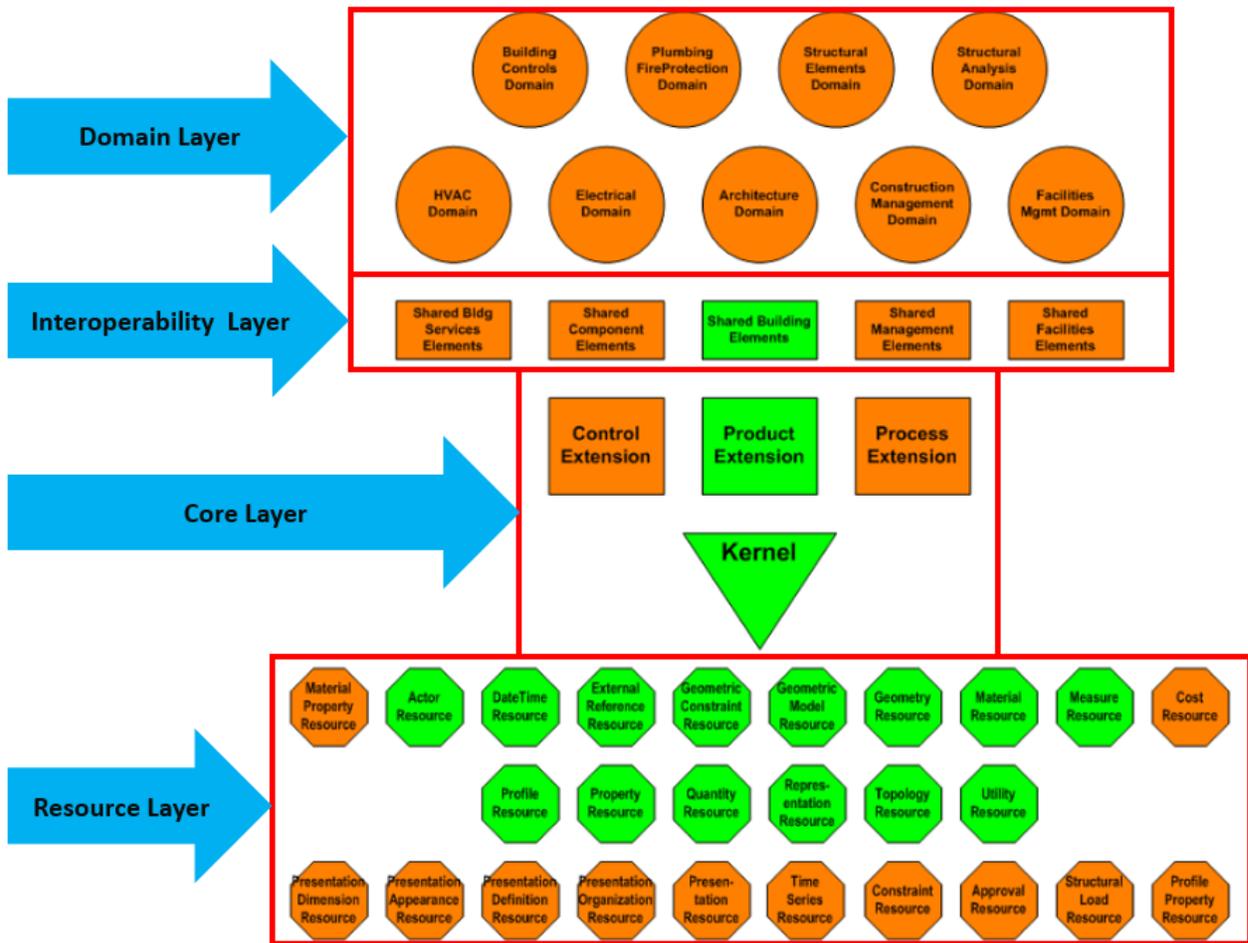
Figure 2-17 IFC2x3 Data schema architecture with conceptual layers [70, 71]

Figure 2-18 shows an example of IFC hierarchy which is quite complicated on the first take. As a matter of fact, IFC consists of entities that have attributes as well as relationships with each other. Entities are organized in an inheritance hierarchy (i.e., entities could be subtypes/supertypes of other entities).

- o **Entities** hold information about the types of objects, relations (i.e., objectified relationships), or properties.
- o **Object entities** can be physically perceptible items (e.g., wall, window), other physically existing items (e.g., space) or conceptual items (e.g., processes, work tasks).
- o **Relation entities** are used to disengage relationship semantics from the objects.
- o **Property entities** allow the assignment of characteristics (that are not described by object attributes) via relationships [3, 71, 72].

Another example is provided via Figure 2-19 that shows the Inheritance graph for IfcWallStandardCase with all the entities, relations, properties, taken from [73], BuildingSMART IFC2x3.
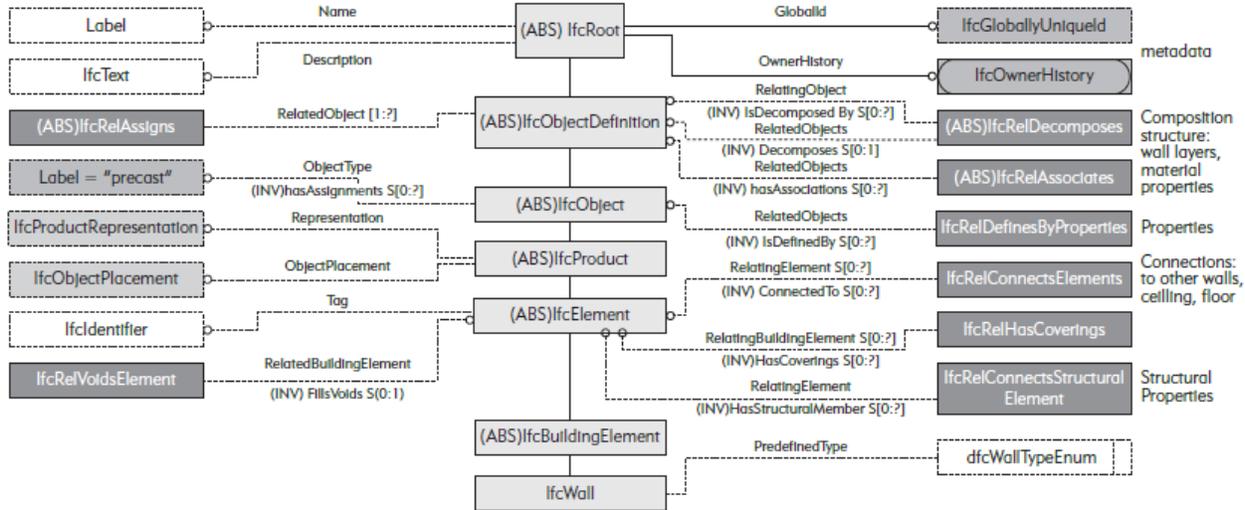
Figure 2-18 An example of the IFC structure for defining a wall [3]

```
ENTITY IfcWallStandardCase;
   ENTITY IfcRoot;
      GlobalId                      : IfcGloballyUniqueId;
      OwnerHistory                  : IfcOwnerHistory;
      Name                          : OPTIONAL IfcLabel;
      Description                   : OPTIONAL IfcText;
   ENTITY IfcObjectDefinition;
   INVERSE
      HasAssignments                : SET OF IfcRelAssigns FOR RelatedObjects;
      IsDecomposedBy                : SET OF IfcRelDecomposes FOR RelatingObject;
      Decomposes                    : SET [0:1] OF IfcRelDecomposes FOR RelatedObjects;
      HasAssociations               : SET OF IfcRelAssociates FOR RelatedObjects;
   ENTITY IfcObject;
      ObjectType                    : OPTIONAL IfcLabel;
   INVERSE
      IsDefinedBy                   : SET OF IfcRelDefines FOR RelatedObjects;
   ENTITY IfcProduct;
      ObjectPlacement               : OPTIONAL IfcObjectPlacement;
      Representation                : OPTIONAL IfcProductRepresentation;
   INVERSE
      ReferencedBy                  : SET OF IfcRelAssignsToProduct FOR RelatingProduct;
   ENTITY IfcElement;
      Tag                           : OPTIONAL IfcIdentifier;
   INVERSE
      HasStructuralMember           : SET OF IfcRelConnectsStructuralElement FOR RelatingElement;
      FillsVoids                    : SET [0:1] OF IfcRelFillsElement FOR RelatedBuildingElement;
      ConnectedTo                   : SET OF IfcRelConnectsElements FOR RelatingElement;
      HasCoverings                  : SET OF IfcRelCoversBldgElements FOR RelatingBuildingElement;
      HasProjections                : SET OF IfcRelProjectsElement FOR RelatingElement;
      ReferencedInStructures        : SET OF IfcRelReferencedInSpatialStructure FOR RelatedElements;
      HasPorts                      : SET OF IfcRelConnectsPortToElement FOR RelatedElement;
      HasOpenings                   : SET OF IfcRelVoidsElement FOR RelatingBuildingElement;
      IsConnectionRealization       : SET OF IfcRelConnectsWithRealizingElements FOR RealizingElements;
      ProvidesBoundaries            : SET OF IfcRelSpaceBoundary FOR RelatedBuildingElement;
      ConnectedFrom                 : SET OF IfcRelConnectsElements FOR RelatedElement;
      ContainedInStructure          : SET [0:1] OF IfcRelContainedInSpatialStructure FOR RelatedElements;
   ENTITY IfcBuildingElement;
   ENTITY IfcWall;
   ENTITY IfcWallStandardCase;
END_ENTITY;
```

Figure 2-19 An example of Inheritance graph for IfcWallStandardCase IFC class [73]

In the end, it is necessary to clarify what is a data model, or a data schema. In fact, a data model "specifies a dedicated grammar for a dedicated artificial language for that domain, regardless how data might be represented in a computer system. A data model is constructed of desired classes of entities (kinds of things), their attributes, and relationships among the entities and among the attributes themselves [74].

2.4.2 Information Delivery Manuals (IDM)

Information Delivery Manuals (IDM) was developed by BuildingSMART to promote efficient collaboration between AECOO participants, IDM is a methodology that captures and specifies the timing and the type of processes and information flow that should be communicated between participants during the lifecycle of a building. This methodology has been accepted as a standard called: ISO 29481-1:2010 "Building information modelling - Information delivery manual - Part 1: Methodology and format" [75].

2.4.3 BIM Collaboration Format (BCF)

BCF encodes messages to enable workflow communication between diverse BIM tools and processes. While it is initially developed by Tekla Corporation and Solibri Inc, it is now an official buildingSMART standard [64, 76]. To put this into another context, BCF facilitates the collaboration among different collaborators of the same model by allowing them to voice their issues, offer answers and make comments within an open file format that does not contain the model elements in itself. In fact, BCF's communication capability is separated from the model itself [77]. Currently, the BCF is available as:

- o *bcfXML:* an open file XML format,
- o *bcfAPI:* The RESTful webservice [76].

2.4.4 Model View Definition (MVD)

Each Model View Definition (MVD) is a subset of the IFC schema that is needed to satisfy a specific Exchange Requirements of the AECOO industry [78]. MVDs define which set of data from IFC schema based on which implementation instructions and validation rules should be used for a specific exchange between two tools [78, 79]. The reason MVD is called a subset of IFC schema is that includes a small, but specific, part of IFC concepts (classes, attributes, relationships, property sets, quantity definitions, etc.) required for a specific implementation[64]. In simple words, MVDs defines which information is needed to be exchanged for which implementation. Several official MVDs are released by BuildingSMART [80]:

I. IFC2x3 Basic FM Hand-Over view,
II. IFC2x3 Structural Analysis View,
III. IFC2x3 Coordination View (outdated as of January 2010),
IV. IFC2x3 Coordination View Version 2.0,
V. IFC4 Design Transfer View,
VI. IFC4 Reference View.

2.4.5 International Framework for Dictionaries (IFD)

Based on Eastman [3], in an early stage, the first issue was detected in the naming of objects and their properties in the IFC schema. While a "Door" is "Porta" in Italian, it is "Dør" in Norwegian and "در" in Persian. Therefore, the same object (or concept), can have different names in the different languages. This is not only true about the object but also true about the whole attributes and properties that describe that object in IFC. That said, the second issue concerns one object or property that overlaps in different standards or tools but is treated differently in each one, even though it is in the same language [3].

Hence, the need for addressing these issues was satisfied by developing the International Framework for Dictionaries (IFD). ISO 12006-3 or IFD maps the terms between different languages to facilitate interoperability [3, 64] Furthermore, IFD standard has promoted a reference library called *BuildingSmart Data Dictionary (bSDD)* that supports improved interoperability in the AECOO industry [64, 81].
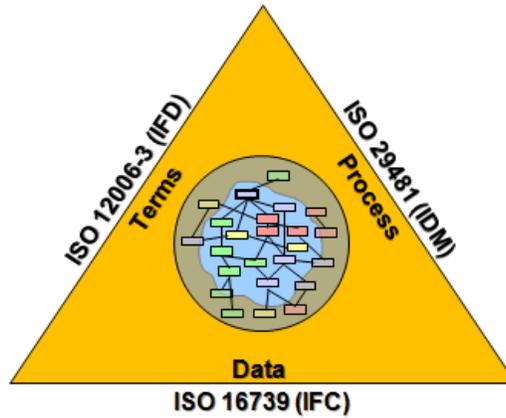
Figure 2-20 Interaction of IFC, IFD, IDM, and MVD in the middle [64, 65, 82]

2.4.6 Classification of Space Boundaries in IFC schema

According to Bazjanac [38], space boundaries can be interior, exterior and virtual. If exterior, they can be only 1st or 2nd level, as exterior building elements have only one surface in simulation tools' internal data models. He further states that IFC data model of buildings is the only data model that recognizes and classifies all levels of space boundaries as specific model entities. That said, 1st level space boundaries are classified as space boundary type 1 in IFC; 2nd level is classified as type 2a. And, 3rd, 4th and 5th level space boundaries are all classified as IFC type 2b because they all exhibit the same behavior. Table 2-2, elaborates space boundary level classification in the IFC data schema.

Space Boundary Level/ IFC type	Interior	Exterior	Virtual
1st Level	1	1	1
2nd Level	2a	2a	2a
3rd Level	2b	N/A	2b
4th Level	Incorporated in 2b	N/A	Incorporated in 2b
5th Level	Incorporated in 2b	N/A	Incorporated in 2b

Table 2-2 IFC classification type for space boundary levels

2.5 BIM-based BEM Interoperability Issues

There are a number of studies that have investigated the interoperability issues targeting BIM-based BEM process. Gourlis and Kovacic [2], Abanda and Byers [61], Ceranic et al. [83], Hyun et al. [84], and Moon et al.[4] have studied the interoperability issues in BIM to BEM process for existing case-studies, while their choice of BIM and BEM tools varies based on their criteria.

Therefore, the present project was developed as a continuation of such studies, only in a more systematic manner, and with a building model that is a worldwide standard building, with simple geometry to better track the interoperability issues.

Chapter 3 Methodology and Case-studies

This chapter is organized into three parts. The first section maneuvers over the Revit concepts, terminologies, and procedures that are necessary to know for the sake of understanding the results, while the second part discusses the IDA-ICE's concepts, terminologies, and procedures. Afterward, in the third part, the case studies are presented.

3.1 Investigation of Revit

Revit was chosen as the BIM tool in this project due to its widespread application in the construction sector [85] and in several academic researches [2, 4, 33, 61, 83, 84, 86, 87]. This section will focus on the concepts that are relevant to the BIM, or BIM-based Energy modelling.

Revit® software is a tool for actualizing BIM (Building Information Modeling). This tool compass features for architectural design, MEP (Mechanical, Electrical, Plumbing) and structural engineering, and construction. Revit supports a multidisciplinary and collaborative design process by using the "intelligent model-based" process to plan, design, construct and manage buildings and infrastructure [24].

3.1.1 Introduction

This chapter presents concepts that are interconnected between Revit, IFC data schema, and IDA-ICE. Later in Section 3.3, several references will be made to the concepts explained in this section. Notwithstanding, comparisons have been made between the similar concepts in Revit and IDA-ICE that are presented at the end of Section 3.2.

3.1.2 Element Hierarchy in Revit

Knowledge of the element hierarchy of Revit helps to understand how Revit elements are exported to IFC, and consequently, how they are imported to IDA-ICE, or any other BEM tool.

Revit is an object-oriented software. This means that each object or element follows a hierarchical order. This order is going to be described here. If we consider each element as a block, this block consists of 4 descriptive entry.

First, the definition of Element should be elucidated. In Revit terminology, everything, by default, is considered as an element. To start a project in Revit, parametric building elements must be added to the design. Revit classifies these elements by categories, families, and types. Figure 3-1 is an example [88, 89].
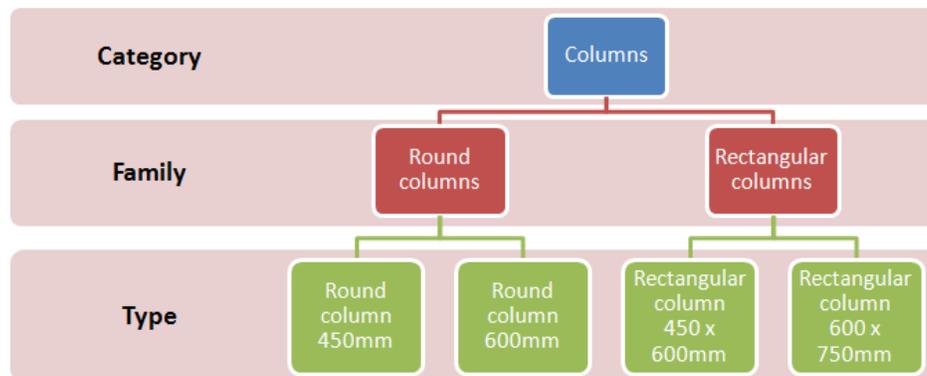
Figure 3-1 An example of Revit's element hierarchy [89]

The First entry in the Revit element Hierarchy is **Category**. Category sits on the top of the hierarchy. A Category defines the visibility and graphical representation, organization and scheduling options of Families inside the project.

The second hierarchal entry is **Family**. Each Family consists of 2D or 3D information groups that represent a discrete building or documentation element in the project. A Family outlines parametric, graphical and documentation requirements.

The third hierarchical entry is called **Type**. Type is a specific representation of a Family which serves to define distinct parametric, graphical, and documentation characteristics that make each Type distinguished from other Types inside a Family.

In the bottom of this hierarchy, lies the fourth entry which is **Instance**. An Instance is the individual depiction of a Type in a specific project which is defined by unique parametric, graphical, and documentation characteristics that makes it unique from other instances in the same project [90].
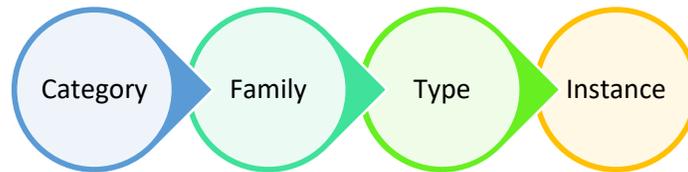
Figure 3-2 Revit's element hierarchy [90]

Figure 3-3, demonstrates another example of Element hierarchy inside the Revit interface.
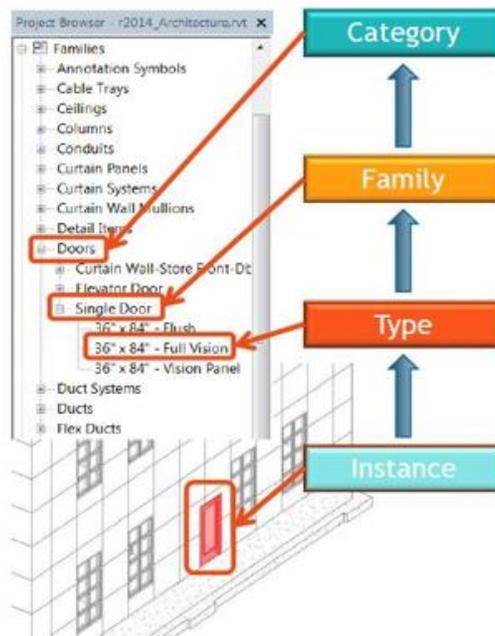
Figure 3-3 Element hierarchy inside Revit [90]

3.1.3   Element classes

According to Revit documentation, everything in Revit is called an "Element." Where Elements are then divided into three classes: Model, Datum, or view-specific class. Classes will then divide into Sub-classes. Model element class is classified as Hosts, Components; while View-Specific class is categorized as Annotations and Detail Items [90]. Figure 3-4 demonstrates this explanation.
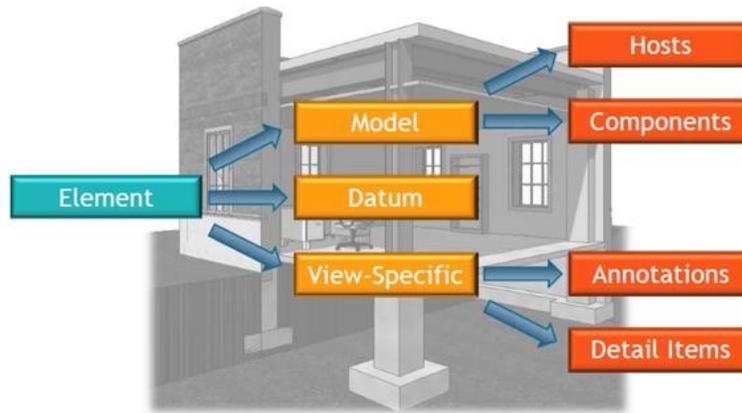
Figure 3-4 Revit's Element classes [90]

3.1.3.1   Model Elements

Model element class refers to the 3D elements in Revit that can be seen in the 3D view or the 2D views, namely plan views, section views, and elevation views.

Hosts: The first characteristics of Host elements is that they can host Component Elements. These elements are building elements that are constructed on-site. Such as Walls.

Components: These model elements are typically manufactured building elements which are installed on-site and requires Host elements to Host them. Such as Windows [90].
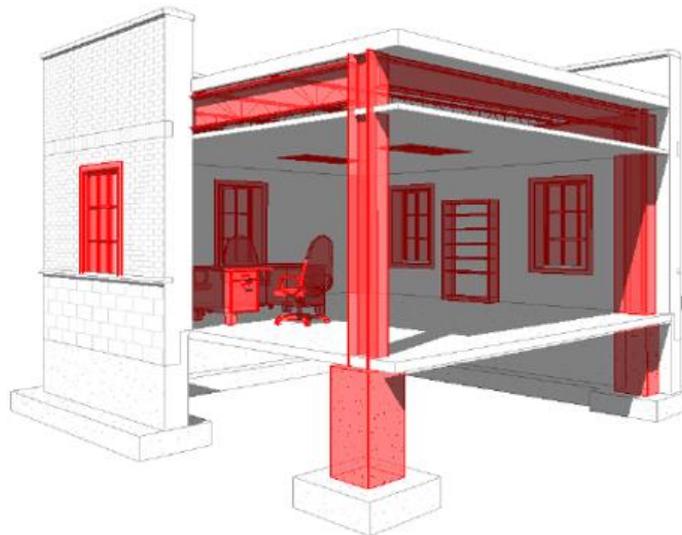
Figure 3-5 Revit's Model Element visualization [90]

Datum Elements are 3D elements in Revit that are only visible in 2D views (plan views, section views, and elevation views, etc.)

Levels/Grids: To define and show specific elevations or nodes in the model elements or the space, these contextual elements are used.

References: Similar to levels and grids, References are also contextual elements that define contextual work surface for Model elements or provide direct links to other views of the Model elements [90].
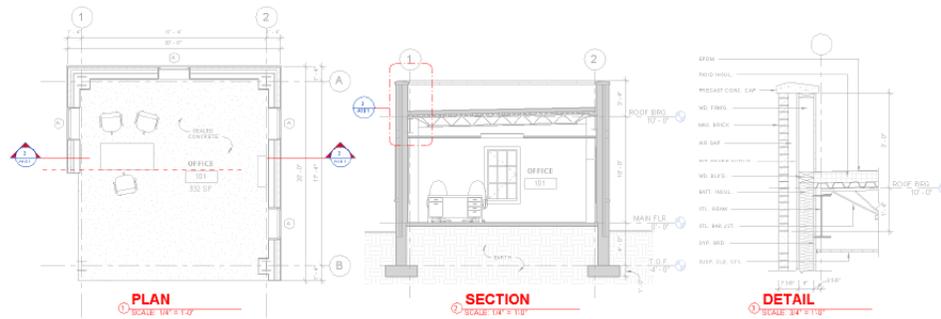
Figure 3-6 Revit's Datum Element visualization [90]

3.1.3.3 Annotation Elements

In Revit, Annotations are 2D elements that are specific to the view, meaning that if an annotation is drawn in elevation view, it is only going to be visible in that view, and other views cannot show that annotation. Therefore, it is view-specific, Figure 3-7 shows these elements.

Annotations: Annotations are documentation elements to present construction information such as measures to the user.

Detail Items: The other type of documentation elements that can overlay the model elements or stand alone to describe the finite constructions [90].
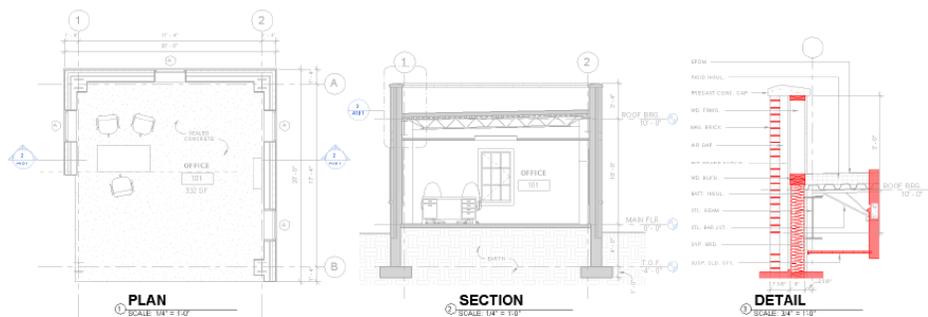
Figure 3-7 Revit's Annotation Element visualization [90]

3.1.4 Definitions of Room, Space, Zone concepts

Since this project explores the concepts that are related to both architectural design, and those related to thermal energy calculations, the definitions and differences between rooms, spaces, and zones are delivered here.

3.1.4.1 Room

A **room** is a subdivision of space within a building model, based on elements such as walls, floors, roofs, and ceilings. These elements are defined as room-bounding. Revit refers to these room-bounding elements when computing the perimeter, area, and volume of a room.

Rooms and room tags are separate but related Revit components. Rooms are model elements in Revit, like walls and doors. Room tags are annotation elements that can be added and displayed in plan views and section views. Room tags can display values for related parameters, such as room number, room name, computed area, and volume [1].

Moreover, when Rooms are placed in a bounded area, it will be momentarily shown by light blue color, Figure 3-8.
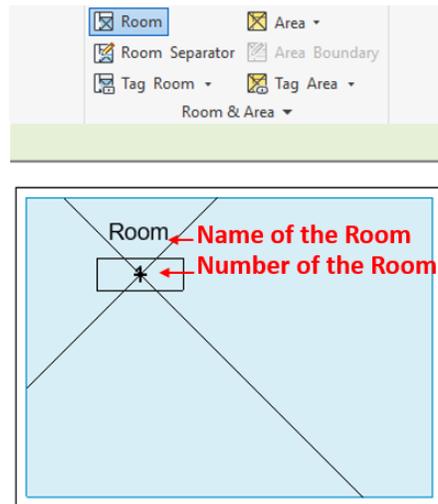
Figure 3-8 Room and Room Tag elements inside Revit

3.1.4.2 Space

Revit uses the **space** component to maintain information about the area where it is placed. Spaces store values for a variety of parameters that affect the heating and cooling load analysis for a project. Furthermore, this space information is used to calculate the volume of the area and to help determine heating and cooling loads.

Spaces can be placed (added) to a Revit model, and unplaced, and deleted. In this context, unplacing and deleting spaces are not the same. When placing the space (also Room) tag, the plane boundary is automatically detected by the software, if there are bounded. There are three types of areas: bounded, semi-bounded, or unbounded areas.

- o **Bounded areas** are areas that are bounded by room-bounding components such as walls, curtain walls, curtain systems, columns, roofs, floors, and room and space separation lines.
- o **Semi-bounded areas** are not entirely bounded by room-bounding components.
- o **Unbounded areas** are open areas without any room-bounding components [91].

After that the plane boundary situation of the area becomes clear, the vertical extent of a space should become clear as well. The vertical extent represents the space vertically from the base to the upper limit [6]. Two options should be filled: Upper Limit and Offset.

Upper Limit and Offset specify the vertical extent for the space. The upper limit selects a level above the current level that defines the upper boundary for the space. The Offset specifies a distance above or below the upper limit for the boundary. (by default, Upper Limit = current level, and Offset = 0' 0" (0.00 mm))

Finally, through the Building/Space Type Settings dialog, it is possible to create, duplicate, rename, or delete space types. Space types could be office, single-family house, and so forth. Each of these types has different thermal properties [8].

If the Space is constrained by a ceiling or other room bounding component instead of the level above, verify that the upper limit of the space is specified to the next level above, and redefine the space vertically, if necessary. [10]

A precise heating and cooling loads analysis can only be accomplished if spaces are placed (created) in all areas to account for the entire volume of the building model.

After placing an space, it is immediately assigned and added to the Default zone when they are initially added to a project. However, each space should be assigned to a zone. This removes the space from the Default zone [9]. Furthermore, after placing a space in an enclosed area, the color of that area will momentarily turn in green, Figure 3-9.
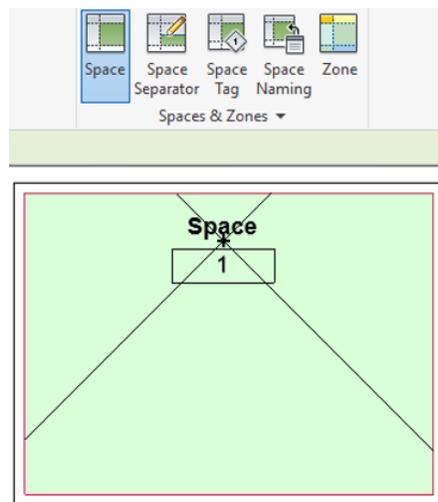
Figure 3-9 Space and Space Tag elements inside Revit

3.1.4.3   Zone
The Zone defines one or more spaces that can be controlled by environmental control systems, such as heating, cooling, and humidity control systems. In other words, zones contain spaces that have common environmental or design requirements [92]. This helps with the execution of load balancing and analysis procedures on a building model [11].

Spaces in unoccupied areas such as plenums can be added to zones. It is possible to add tags to identify spaces, rooms, and zones in a project [5]. Spaces that are on different levels can also be added to the same zone. It is possible to create zone schedules and use a zone schedule to modify zones [92].

In conclusion, zones and spaces, and rooms are independent of each other. However, zone and spaces are used together to achieve a typical result. Revit uses both zone and space information during a heating and cooling loads analysis to determine the energy demands of the building.

Rooms are architectural components that maintain information about occupied areas, while Spaces are used for the mechanical, electrical, and plumbing (MEP) disciplines to analyze volume, and for thermal energy calculations, and heating and cooling loads analysis.

When one is using Revit for mechanical and Energy purposes, projects always have at least one zone, the Default zone. When spaces are initially placed in a project, they are added to the Default zone

Zone properties collect information from spaces, such as heating and cooling temperature set points that, together with space properties, is used with a heating and cooling loads analysis to determine the energy demands of the building [92].

3.1.5   IFC export in Revit

During this research, one thing became apparent, which was the importance of Revit's setting in the IFC export window.

One of the issues that was seriously highlighted during different stages of this research was the proper export of IFC from Revit to IFC. During many trial and errors, and numerous searches on Internet, it became apparent to the author that not only the IFC export procedure is unclear, but also few professionals know how to do it properly.

This section is presented here because the IFC export window is Revit is complicated enough for the expert users, let alone the beginners. Therefore, it is very hard for those who are not used to Revit to export the information they want to IFC correctly. That said, one should be familiar not only with the export IFC window is Revit but with the structures and terminologies of IFC to correctly export IFC entities from Revit. Then, one should also be familiar with the IFC entities that Revit supports, since not all the IFC entities are automatically supported by Revit, although it is possible to enter them inside the Revit manually, or inside the IFC file, which both of them require superior knowledge of IFC data schema.

Then, another problem is also important; it is the IFC export for energy analysis purposes. While there are several default modes for IFC, few sources have explained about the proper export of IFC for energy analysis purposes. [93]

Therefore, here we decided to explain in a step by step fashion about the IFC export function in Revit. Because in the Results chapter some issues are explained that has a direct relationship with the way the user has.

This project has been done using IFC Exporter version 18.2.0.0. On 26.02.2018, a new version of IFC exporter was released that is not used here.

3.1.5.1   IFC exporter options

In this section, the options available in the IFC exporter in Revit will be explained. Figure 3-10 shows the first window that deals with IFC export. Firstly, the file name is the location where the output IFC file will be saved. Secondly, the Currently selected setup should be chosen between two options: <In-Session Setup>, and Modify setup…

The <In-Session Setup> provides the user with a set of predefined standard Model View Definitions (MVD) [94], similar to those presented in the box number 1 in Figure 3-11. Upon selecting the In-Session Setup,

no modifications can be made in the IFC export options of the predefined standard MVDs. However, The Modify setup… helps to develop a customized IFC setup.

Finally, the Revit project (with *.rvt* suffix) that the user intends to export to IFC should be chosen in the Projects to export box, in Figure 3-10. In the next sections, options and tabs that are available in the Modify setup… the button will be explained.
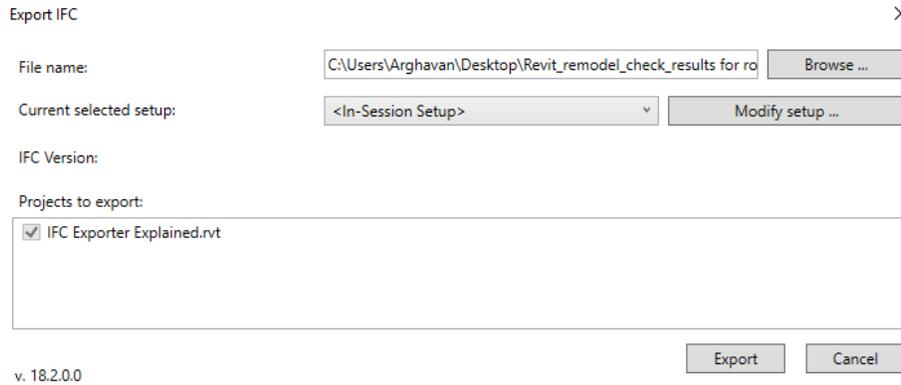
Figure 3-10 IFC explorer

3.1.5.1.1   In Session Setup

In Session Setup, number 1 in Figure 3-11refers to the preset export definitions and configurations that are readily existed in Revit. In fact, each of these configurations refers to a specific Model View Definitions (MVD). If the user selects these preset defaults, then it is not possible to change the options in any of the tabs. AutoDesk has explained each of these "In-Session Setups" in [95].

Moreover, it is possible to create a desired configuration of IFC export options and save it for future use. This is possible through the button shown as number 2, in Figure 3-11. This procedure is further explained in section 3.1.5.2, to create a desire IFC export set-up for energy analysis purposes.
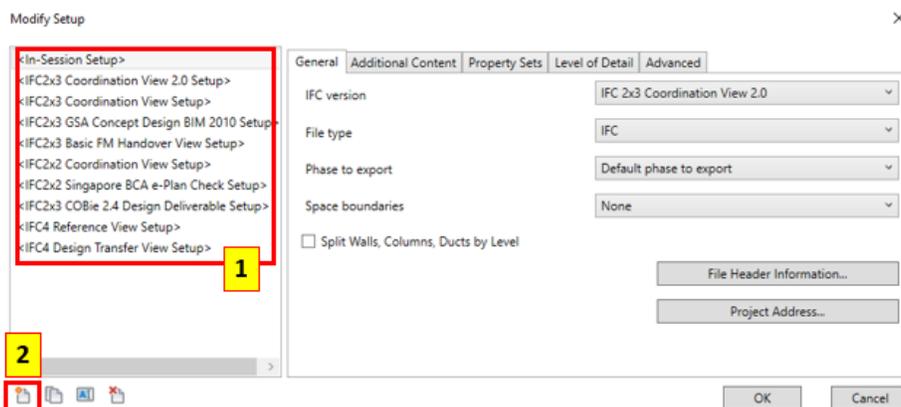
Figure 3-11 IFC exporter Modify setup window, In Session Setup (1), and Creating customized Set-up (2)

3.1.5.1.2 General tab

The first tab is the General tab, that is shown in Figure 3-12.
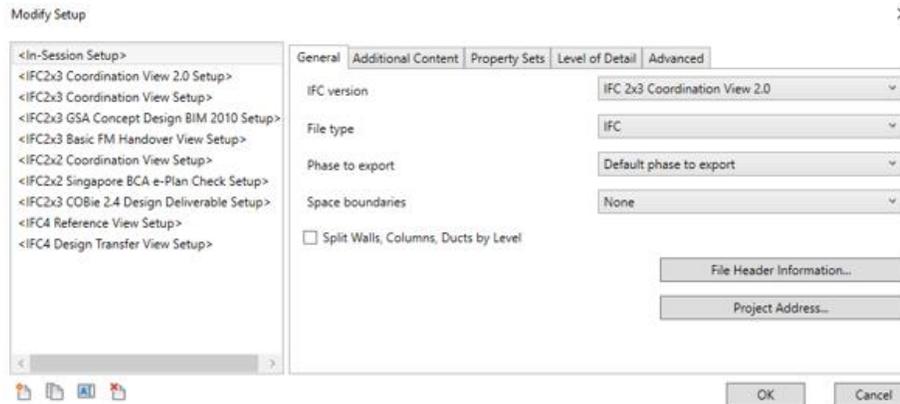
Figure 3-12 IFC exporter Modify setup window, General tab

I. IFC Version

The IFC Version should be specified among the IFC versions that were presented in <In-Session Setup>, Figure 3-13. The difference is that the user can now modify this chosen <In-Session Setup>.
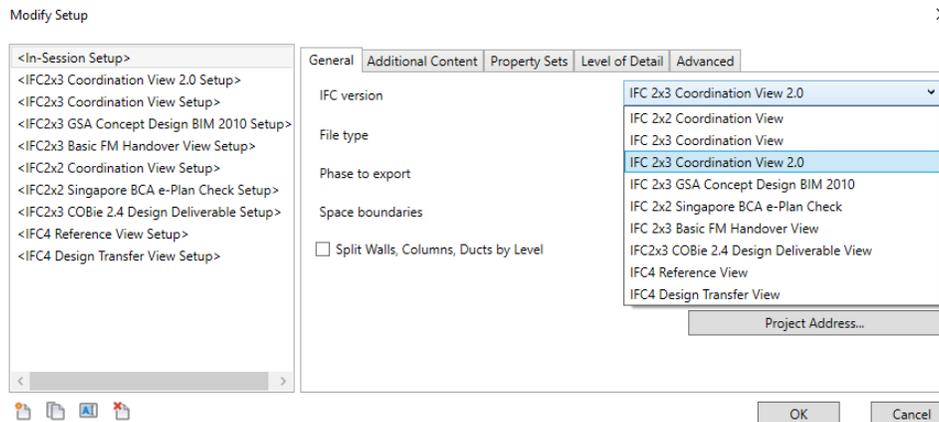
Figure 3-13 IFC exporter Modify setup window, IFC version

II. File Type

File Type refers to the different types of IFC file that user wishes to use, namely:

- o IFC
- o IFC XML
- o Zipped IFC
- o Zipped IFC XML

III. Phase to export

Then, the Phase to Export can be chosen between Existing and New Construction. If nothing is chosen, the Default phase to export will export the default phase of the elements to the IFC file.

IV. Export Space Boundaries

Space Boundaries defines the relationships between Spaces and their Boundaries (e.g., surrounding Walls, Floors, Windows, Doors and etc.) in the export. There are 3 options in Revit IFC exporter:

- o **None:** Rooms/Spaces are exported as static components without any relation to their boundaries.
- o **1st Level:** Room/Spaces are exported with basic reference of their boundaries.
- o **2nd Level:** Rooms/Spaces are exported with full relationships to their boundaries, including their properties for materials, energy transmissions and such. It should be noted that 2nd Level Room Boundaries are suitable for energy analysis.

V. Split walls and columns by level

If walls and columns have a height of multiple levels, this option will cut them into pieces by level.

VI. File Header Information

This option would add some administrative properties to the IFC, as can be observed in Figure 3-14 in Revit.

Figure 3-14 IFC exporter Modify setup window, General tab, File Header Information …

This information will be added to the beginning of the IFC file, Figure 3-15.

```
*******************************************************************************/
FILE_DESCRIPTION(('ViewDefinition [CoordinationView_V2.0]'),'2;1');
FILE_NAME('0001','2018-02-22T21:32:18',('Arghavan Akbarieh','arghavaa@stud.ntnu.no'),
('NTNU/Unibo'),'The EXPRESS Data Manager Version 5.02.0100.07 : 28 Aug 2013','20170223_1515(x64)
- Exporter 18.2.0.0 - Alternate UI 18.2.0.0','BIM Author');
FILE_SCHEMA(('IFC2X3'));
ENDSEC;

DATA;
#1= IFCORGANIZATION($,'Autodesk Revit 2018 (ENU)',$,$,$);
#5= IFCAPPLICATION(#1,'2018','Autodesk Revit 2018 (ENU)','Revit');
```

Figure 3-15 How File Header Information is exported to IFC file.

VII. Project Address

As the name suggests, this option fills the address information, Figure 3-16. The checkbox "Update Project Information" copies this data into the Project Information, Figure 3-17.

Therefore, *Project Information* in the Address tab will be copied into the *Project Address,* related to *Energy Settings*, and will end up eventually in the IFC file. Since the location of the case study is in Denver, CO, USA, we wrote the address as in Figure 3-16.

Figure 3-16 IFC exporter Modify setup window, General tab, Project Address…

Figure 3-17 How Project Address is written into other sections of Revit

This information will be written in IfcProject, IfcPostalAddress, and IfcBuilding, as can be seen in Figure 3-18.

```
#111= IFCPROJECT('38MALohzn0PQGjpTBMuHvc',#47,'0001',$,$,'Project Name','Project Status',(#103),#98);
#117= IFCPOSTALADDRESS(.USERDEFINED.,'BESTEST 600','Energy Analysis',$,('W Colfax Ave'),$,'Denver','Colorado','12345','USA');
#119= IFCBUILDING('38MALohzn0PQGjpTBMuHvd',#47,'BESTEST 600',$,$,#32,$,'BESTEST 600',.ELEMENT.,$,$,#117);
```

Figure 3-18 How Project Address is exported to IFC file

3.1.5.1.3   Additional Content tab

Figure 3-19 shows the available options in this tab.
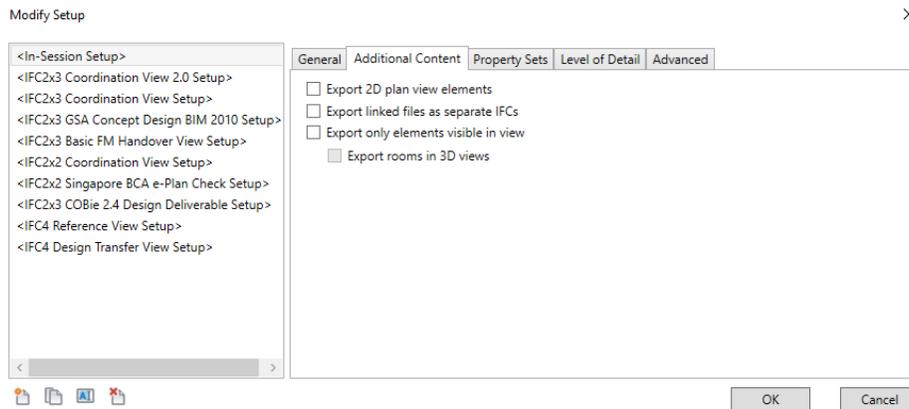
Figure 3-19 IFC exporter Modify setup window, Additional Content tab

I.   Export 2D plan view elements

This option exports 2D components from the Plan View.

II.   Export linked files as separate IFC

By selecting this option, any Revit links in the project would be exported as separate IFCs, while not selecting it, exclude Revit links [95].

III.   Export only elements visible in the view

If this option is selected, only objects visible in the current view would be exported. Otherwise, the entire model is exported to IFC.

3.1.5.1.4   Property Sets tab

Property Sets tab is shown in Figure 3-20.
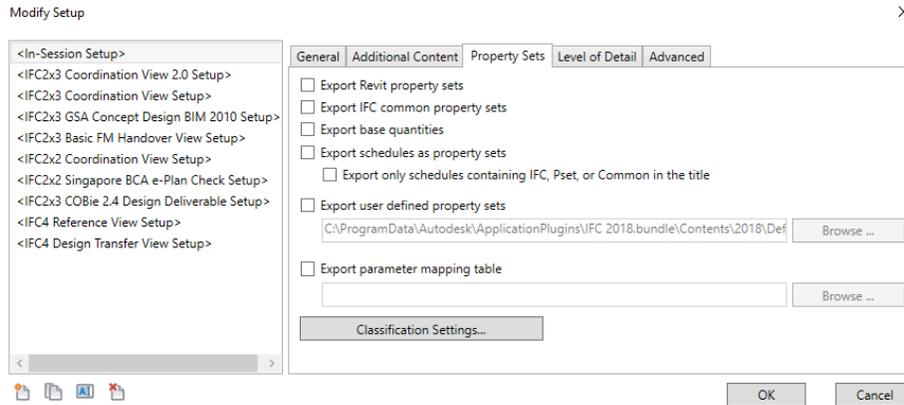
Figure 3-20 IFC exporter Modify setup window, Property Sets tab

I.   Export Revit Property Sets

This exports all Revit Parameter Groups as separate IFC Property Sets, and the parameters inside with it. Use this if you want to hand-over data that does not get mapped to a Common IFC parameter [96].

II.   Export IFC Common property sets

All IFC classes have common property sets (IFC version of a hardcoded set of parameters). Use this check box to export that and map specific hardcoded Revit parameters to them [96].

III.   Export Base Quantities

This option helps to export an IFC property set for certain categories (such as floors and walls) that contain quantity parameters such as Gross Area, volume, based on measurements of the actual objects (and not parameter values inside Revit) [96].

IV.   Export Schedules as Property Sets

Schedules would be exported as Property Sets through this option. It should be noted that this option will export all of the schedules that are present in the project, regardless of the type of parameters, be it shared parameter or project parameter, and even calculated values [96].

V.   Export user defined property sets

If selected, you can specify the name of a text file that contains the property set definitions [96].

VI.   Classification Settings

The Classification tab allows the user to specify the classification system used in the project. Following example is taken from [96], and shows how this is done. Let's say you want to name and define your Rooms through a specific classification system. And you want to export this data to the Rooms. Here's how you do this:

1.   Create Key Schedule in Revit.
2.   Add a parameter called <ClassificationCode>.
3.   Add rows as desired and fill in the data.
4.   In the Key Name, you add the description you want to use to select the parameter value in the project.

5. The parameter <ClassificationCode> should have the following syntax: [ClassificationCode]classification_description. <ClassificationCode> is the name of the Classification Code you want to be added to the IFC (the local Building Code, Naming system or such). The <Classification description> is the instance value you want a certain Object to have (e.g., Living Room) in the IFC Export.

6. Select Rooms, add the desired Key schedule.

7. Export.

Note: This option might be export correctly to IFC, or not. Therefore, Revit users should carefully examine the IFC file to make sure the desired values are exported.

3.1.5.1.5 Level of Detail tab

One tab is dedicated to Level of Detail, as can be seen in Figure 3-21.
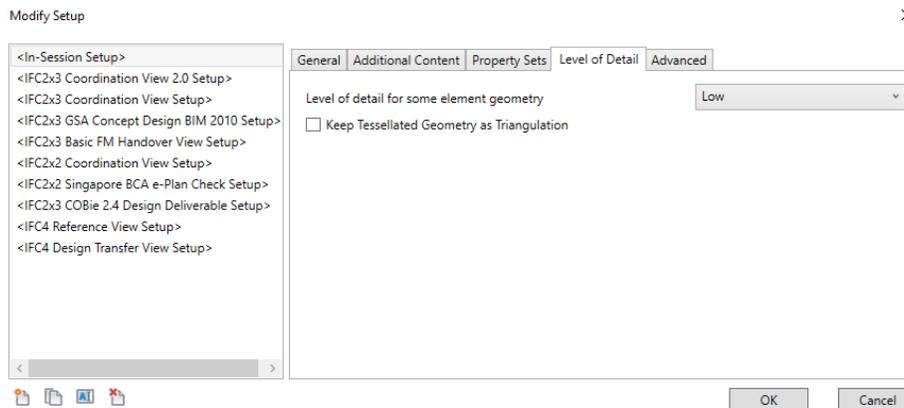
Figure 3-21 IFC exporter Modify setup window, Level of Detail tab

I. Level of detail for some element geometry

Level of detail for some element geometry has four levels that control the level of tessellation for *some* Revit elements [95]. According to AutoDesk [95], the main Revit elements that are affected by this option are elbows, floors, pipe fittings, railings, ramps, spaces, and stairs. Also, highly detailed extrusion profiles are affected for these items.

The four levels consist of:

- o Extra Low
- o Low
- o Medium
- o High

II. Keep Tessellated Geometry as Triangulation

Creating IFC file through IFC Exporter using BReps results in a massive final output. This option keeps the exported elements as triangulation rather than BReps [96].

3.1.5.1.6 Advanced tab

Several options are presented to the user in the Advanced tab as shown in
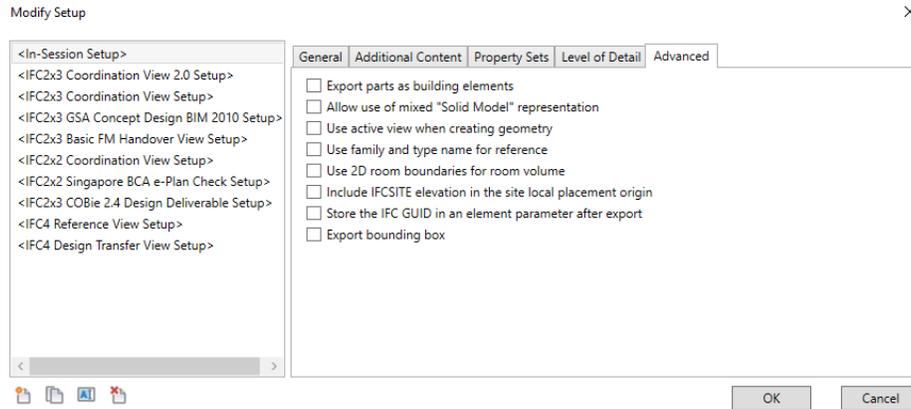
Figure 3-22 IFC exporter Modify setup window, Advanced tab

I. Export parts as building elements

If there are Parts in the model, this checkbox will export them as separate elements with no relationship to the original object. check this option off helps to export Parts as a sub-element of the encompassing object. An example is delivered here, taken from [96].

If the user has a wall split into parts, this is the right IFC:

IfcWall

IfcBuildingElementPart

IfcBuildingElementPart

IfcBuildingElementPart

However, if the Export parts as building elements are checked off, this will be the result:

IfcWall

IfcWall

IfcWall

Nevertheless, for both options, Parts should be turned on in the view (and it only works with "Export only elements visible in view") [96].

II. Allow use of mixed "Solid Model" representation

This option allows the mixing of BRep and extrusion geometries for entities [95]. This can result in smaller IFC files.

Generally, Revit exports any given geometry in two ways, firstly, Extruded solids, secondly, Boundary Representation.

    I.   Extruded solids: It means drawing the base and extruding it to a given height.
   II.   Boundary Representation: to explain this, following quote from *Angel Velez*, IFC developer for Autodesk, is presented, taken from [96]:

"The default exporter uses either one: Solids OR BReps. If the entire entity cannot be exported as a Solid, it's exported as a BRep. Which, as you can imagine, is often the case (especially with curved forms). Checking this option means the OS Exporter will always use Solids for those parts that can be defined as such. Only the parts that cannot be defined as a Solid will be exported as a BRep".

III.   Use family and type name for reference

All IFC objects have a "Reference" parameter (sort of a Type Mark and Mark in one). This lets you combine Family and Type Name into that Reference parameter.

IV.   Use 2D room boundaries for room volume

Checking this box means Revit will treat a Room Separation Line as a spatial element with a height and area when calculation the Room boundary area.

V.   Include IFCSITE elevation in the site local placement origin

To describe this option, a direct quote from Angel Velez from Autodesk, cited in [96], is presented here:

"A site has a Z offset. By IFC CV 2.0 specification, the Z offset should be included in the specification of the IFCSITE, NOT in its local placement origin. Doing both is "double counting" and will result in the site being 2x as high as it should be. However, most existing applications don't follow the CV2.0 standard, and so doing the right thing generates the wrong picture. So, check this if you want bad IFC files that behave correctly."

VI.   Store IFC GUID in the file after export

Just like all Revit components, their IFC counterparts have a unique identification code, the IFC GUID. Checking this option results in the creation of an instance parameter in all exported objects called <IfcGuid> and writing the value to it.

Select this option to store the generated IFC GUIDs in the project file after export. This will add "IFC GUID" parameters to elements and their types, and Project Information for Project, Site, and Building GUIDS.

VII.   Export Bounding Box

Export Bounding Box options, in simple words, provide the ability to export a simple geometric shape instead of more profiles [96].

3.1.5.2   IFC exporter configuration for Energy Analysis purposes
In this section, a step by step guide is presented that was followed for the customizing IFC export from Revit 2018 through IFC exporter, for the purpose of Energy Analysis.

To begin with, as can be seen in Figure 3-23 , the first step is to find the *IFC* (number 2) in the *Export* section (number 1) of the pull-down *File* tab inside Revit. It is advised to download the install the latest version of IFC exporter in order to benefit fully from latest improvements[97].

Then, a new window will pop up, Figure 3-24. First, if several Revit projects are opened simultaneously, the name of the desired project should be chosen in the *Projects to export* list. Afterward, "*Modify setup …*" button should be pushed to configure the export options for energy analysis purposes. However, if the

<In-Session Setup> button is chosen, a number of predefined standard Model View Definitions (MVD) are presented to the user [94].

For example, IFC2x3 Coordination View 2.0 gives a high fidelity of geometry [94], among these predefined setups, only "*IFC 2x3 GSA Concept Design BIM 2010*" is set to export 2nd level space boundary[98].Indeed, if the user selects *<In-Session Setup>* instead of "*Modify setup …*", the tabs will be locked for further configurations. That is why it was set earlier to choose "*Modify setup …*"!

Figure 3-23 IFC Exporter in Revit
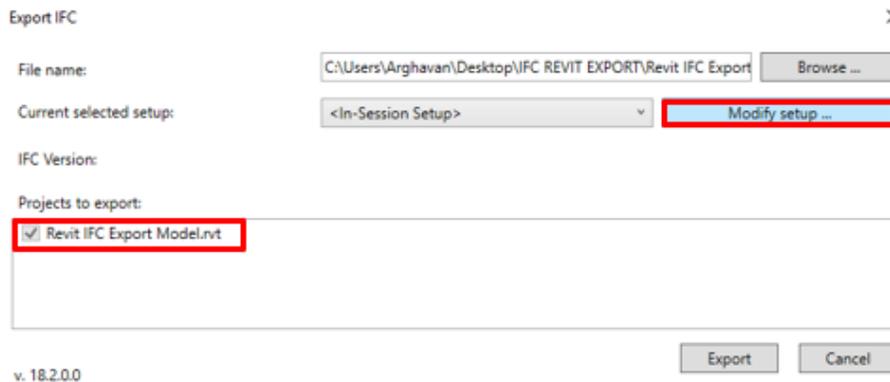
Figure 3-24 IFC Exporter in Revit, Modify Set-up

The first tab to deal with is the General tab. First, the *IFC Version* should be specified, Figure 3-25, number 1. Then, *File type* should be chosen. In this study, IFC was chosen for the export, Figure 3-25, number 2. In the next step, the *Phase to Export* can be chosen between *Existing* and *New Construction*. In this project, all the elements are New Construction, and exploring this option was beyond the scope of this study. Hence, this option was set to default.

A crucial setting that is crucial for the energy analysis is the *Space boundaries*. By default, the *Space boundaries* drop down is set to none. However, Energy Analysis software requires second level space boundary. Thus, *Space boundaries* must be set to 2nd Level as shown in Figure 3-25, number 4. The material of the building element and the adjacent spaces behind it are considered for the 2nd level space boundary since they provide thermal properties [98, 99].

It is usually recommended not to check off Split walls and columns by the story. The reasoning behind this recommendation is that this option would cut walls and columns that have a height of multiple levels into pieces by level [93, 96].

Furthermore, it is recommended to use the "Export IFC common property sets." Choosing *Revit Property sets* exports all the parameters associated with that object or file, Figure 3-26. However, on the downside, it provides no consistency. None of the information is in the property set that aligns with the IFC standard. File sizes are unnecessarily large because some data are being exported that are of no need.
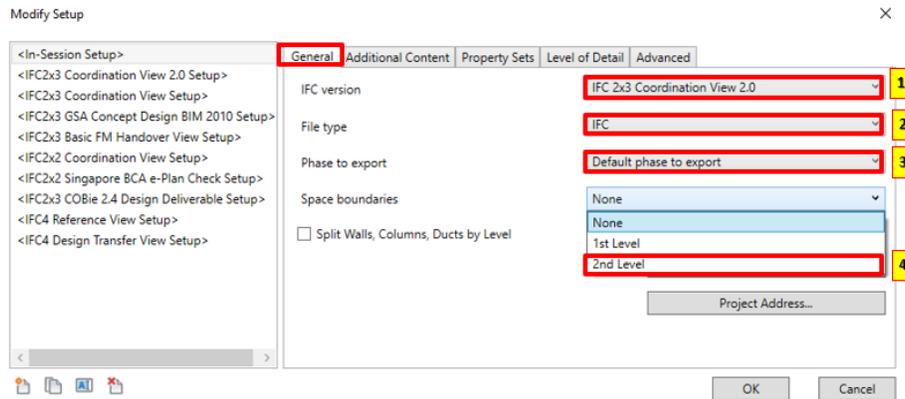
Figure 3-25 IFC Exporter, IFC general details, Space boundaries
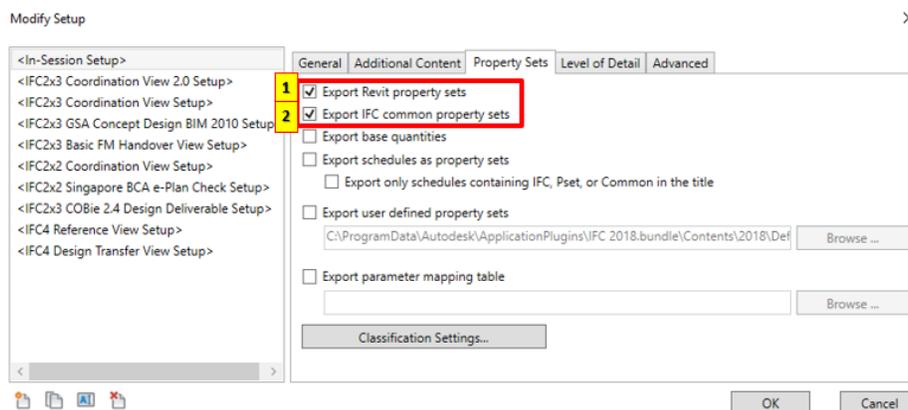
Figure 3-26 IFC Exporter, IFC Property Sets configuration for Energy Analysis Purposes

It is recommended that the left "*current view only*" remains unchecked for the entire project to be exported [99]. If this option is marked, only elements that you can see with your eyes will be exported, and for example, it is possible for the windows on the other side of the view, not to be exported.

No Changes were made, in the *Level of detail* tab, and the Advanced tab. They are left to default. Of course, due to the simple geometry of this case-study, we preferred the *Level of detail* option to be set as Lo*w* [98].

In a nutshell, all these configurations allow us to define our own customized model view definition. Also, following these guidelines can ensure a quality export.

Note One: If an option is explained in Section 3.1.5.1, and not here, it means that the default setting was used.

Note Two: There are over 100 certified companies for the IFC import and exchange of information[94].

Note Three: The reason IFC2x3 was used during this project instead of IFC4 was that, based upon [94], IFC4 is not yet certified for export and import over many platforms. Furthermore, some problems have been reported by Revit users when exporting to IFC4 in Revit, including:

  o   Walls that do not host doors or windows are included in the IFC file, as expected.
  o   Walls that host doors or windows are unexpectedly not present in the IFC file [100].

3.1.5.3   List of supported IFC classes by Revit

Following is a list of supported IFC classes in Revit provided by AutoDesk [101].

IfcActuatorType
IfcAirTerminalBoxType
IfcAirTerminalType
IfcAirToAirHeatRecoveryType
IfcAlarmType
IfcAnnotation
IfcBeam
IfcBoilerType
IfcBuildingElementPart
IfcBuildingElementProxy
IfcBuildingStorey
IfcCableCarrierFittingType
IfcCableCarrierSegmentType
IfcCableSegmentType
IfcChillerType
IfcCoilType
IfcColumnType
IfcCompressorType
IfcCondenserType
IfcControllerType
IfcCooledBeamType
IfcCoolingTowerType
IfcCovering
IfcCurtainWall
IfcDamperType
IfcDistributionChamberElementType
IfcDistributionControlElement
IfcDistributionElement
IfcDistributionFlowElement
IfcDoorType
IfcDuctFittingType
IfcDuctSegmentType
IfcDuctSilencerType
IfcElectricApplianceType
IfcElectricFlowStorageDeviceType
IfcElectricGeneratorType
IfcElectricHeaterType

IfcElectricMotorType
IfcElectricTimeControlType
IfcElementAssembly
IfcEnergyConversionDevice
IfcEvaporativeCoolerType
IfcEvaporatorType
IfcFanType
IfcFastenerType
IfcFilterType
IfcFireSuppressionTerminalType
IfcFlowController
IfcFlowFitting
IfcFlowInstrumentType
IfcFlowMeterType
IfcFlowMovingDevice
IfcFlowSegment
IfcFlowStorageDevice
IfcFlowTerminal
IfcFlowTreatmentDevice
IfcFooting
IfcFurnishingElement
IfcFurnitureType
IfcGasTerminalType
IfcHeatExchangerType
IfcHumidifierType
IfcJunctionBoxType
IfcLampType
IfcLightFixtureType
IfcMechanicalFastenerType
IfcMemberType
IfcMotorConnectionType
IfcOpeningElement
IfcOutletType
IfcPile
IfcPipeFittingType
IfcPipeSegmentType
IfcPlateType

IfcProtectiveDeviceType
IfcPumpType
IfcRailing
IfcRamp
IfcReinforcingBar
IfcReinforcingMesh
IfcRoof
IfcSanitaryTerminalType
IfcSensorType
IfcSite
IfcSlab
IfcSpace
IfcSpaceHeaterType
IfcStackTerminalType
IfcStair
IfcSwitchingDeviceType
IfcSystemFurnitureElementType
IfcTankType
IfcTransformerType
IfcTransportElementType
IfcTubeBundleType
IfcUnitaryEquipmentType
IfcValveType
IfcWall
IfcWasteTerminalType
IfcWindowType
IfcProtectiveDeviceType
IfcPumpType
IfcRailing
IfcRamp
IfcReinforcingBar
IfcReinforcingMesh
IfcRoof
IfcSanitaryTerminalType
IfcSensorType
IfcSite
IfcSlab

3.2 Investigation of IDA-ICE

IDA-ICE (IDA Indoor Climate and Energy) is a commercial energy simulation software developed by the Swedish company ***EQUA Simulation AB*** [102]. The first version (Swedish version) was released in 1998, and the first international version was released in 1999 [103]. That said, the latest version, i.e., version 4.8, was released in late 2017 [104, 105]. The current study is based on ***IDA-ICE version 4.7.1.***

IDA ICE calculates the energy usage and indoor thermal climate for buildings by using a dynamic multi-zone simulation. Each zone allows different temperature set-points, internal loads and different airflows, all with time-schedules in order to consider building's (or occupants) different demands [106].

The capabilities of IDA-ICE include calculating following items:

- o Heat balance of the zone that includes loads of sun radiation, light, occupants, furniture, heating and cooling devices, air leakages, ventilation, and surface transmission;
- o Solar radiation through windows, considering: shading devices and surrounding elements;
- o Temperatures of air and surfaces;
- o Operative temperatures;
- o Comfort indices: Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD),
- o Daylight level;
- o Air CO_2 and moisture levels;
- o Wind and buoyancy-driven airflows through openings and leaks;
- o Airflows, CO_2, pressure, and moisture at different locations of the handling and distribution systems;
- o Heating power from heating and cooling units, equipment, occupants, light, solar radiation;
- o Total energy cost using time-dependent prices [103, 107].

Furthermore, an overview of IDA-ICE's interface is presented in Appendix A.

3.2.1 Objects in IDA-ICE

This section will go over the Objects and object hierarchy in IDA-ICE.

3.2.1.1 Data Object

The Data object is the whole IDA system or an element of the IDA system with a certain name and a type. The term "**Data object**" is used to distinguish between elements of the IDA system and graphical elements. Each data object has a name. The name is unique among the components of the same parent.

3.2.1.2 Hierarchy of Data objects

The IDA System is a hierarchy of data objects (components). Every data object has a list of attributes (e.g., name, description, type, value) and components (sub-components). A component is also a data object that is a part of a greater object (parent). Every data object has a parent object which is the object containing it. In IDA ICE, all **data objects** are classified as class, entity, and type.

3.2.1.2.1 Class

All classes are built-in in IDA Modeler. The classes are defined in the IDA Simulation Environment and cannot be changed. The main classes consist of:

- o Equation Object,
- o Macro Object,
- o Variable,

- o Interface,
- o Parameter,
- o Resource.

3.2.1.2.2   Entity

Entities define the physical nature of an object. The entities are defined in the IDA applications. Typical entities are:

- o wall,
- o window,
- o radiator,
- o etc.

3.2.1.2.3   Object Type

The object type is a resource that holds the default settings for objects of that type. IDA-SE supports user-defined types.

3.2.1.2.4   Resource

A resource is a data object that stores the common parameters for other data objects. Unlike other components, the resources are not interpreted as parts of the containing object. The resources can be stored in a database. Following examples, that are taken from IDA ICE' help, are rendered for further elucidation:

- o ***Example 1:***

A building can contain the resource Concrete (of type Material). This does not mean that there is some amount of concrete in the building. This means that Concrete may be used as a material for any wall layer, for any wall in the building. If a change is made in any of the parameters of the object Concrete, it is changed in all places where the object Concrete is used [107].

- o ***Example 2:***

A building contains the resources "Big Window" and "Small Window" (both of *type* Window). When the user wishes to insert a window in some wall of the building, the "Insert new object" dialog will suggest three variants (types) of windows: "Window," "Small window" and "Big window." The parameters of the resource object "Big Window" are used as the default settings for windows of type "Big window." If some of these parameters are changed, the corresponding parameters in the real window are given new default values. This will lead to a change in the actual values for parameters that are marked as using the default value [107].

3.2.1.3   Comparison between Revit Element hierarchy and IDA-ICE Object hierarchy

In conclusion, we have to accept that IDA ICE uses only a small part of the architectural model for creating a BIM-based energy model.

Indeed, Revit and IDA ICE have born from different disciplines with developers that had separate intentions in mind. While Revit was initially created to help architects to draw their architectural ideas and plans inside this platform digitally, IDA-ICE was developed based on algorithms that calculate energy consumption in a building. Since the creation of both of these platforms goes back to the time where integrated and sustainable building design was not a common practice in the construction sector. Therefore, the anticipation that a model created in the Revit Platform is going to be used in the IDA ICE platform was not strong. Thus, it is only logical that their terminology and some basic concepts differ from each other.

This leads to the differences in the element hierarchy in Revit versus object hierarchy in IDA ICE. However, a comparison can be made between this two software with respect to their element/object hierarchy. Based on our knowledge and observations, while Revit uses the **Category> Family> Type> Instance** naming order for describing a model element such as a wall, IDA ICE has adapted to **Class>Entity>Type> Resource** for the objects in its platform.

3.2.1.4   Geometry in IDA ICE

In this section, the geometry of IDA-ICE will be explained, because there will be several references in Chapter 3: Methodologies and Case-studies, to the concepts explained here.

IDA Indoor Climate and Energy (ICE) is a program for the study of the indoor climate of individual zones within a building, as well as energy consumption for the entire building. IDA Indoor Climate and Energy is an extension of the general IDA Simulation Environment. This means that the advanced user can, in principle, simulate any system whatsoever with the aid of the general functionality in the IDA environment.

Normally, the system to be simulated consists of a building with one or more zones, a primary system and one or more air handling systems. Surrounding buildings might shade the building. The air inside the building contains both humidity and carbon dioxide. Weather data is supplied by weather data files or is artificially created by a model for a given 24-hour period. Predefined building components and other parameter objects can be loaded from a database

3.2.1.4.1   What is a Zone in IDA ICE?

"A building in IDA Indoor Climate and Energy can contain one or several zones (rooms)." In its simplest definition, a zone is "a prism with any number of flat vertical walls, a flat horizontal floor, and one ceiling." That said, the shape of the zones is limited to prisms with vertical walls, and in case of a prism intersecting with a roof, only the part under the roof is included in the zone. Each zone composed of enclosed restricted surfaces where windows, openings, and different types of heating and cooling units can exist within these surfaces [107, 108].

3.2.1.4.2   What is a building body in IDA ICE?

IDA-ICE also consists of a building body as well. The shape of building body part is limited to "prisms with flat vertical walls," however a part of such prism is limited by the roof. The roof may consist of one or more flat polygons with slope from 0° (horizontal, outer side upward) to 90° (vertical) [107, 108].

According to IDA ICE documentation [107, 108], both zone and building body could be a custom polyhedral that may be imported but not edited in ICE.

3.2.1.4.3   How is the geometry explained in IDA ICE?

IDA ICE uses three different systems for describing the positions and coordinates of the zone or building body: building system, zone system, and surface system.

3.2.1.4.4   Building System

As can be seen in Figure 3-27, the geometry of the building is defined by the corners of one or more building body parts. The corners' x and y coordinates are indicated in a local coordinate system for the building which IDA-ICE calls it the building system, that moves and rotates with the building. The origin of coordinates for the building system coincides with the lower left corner of the building. Likewise, building system is also at the origin of coordinates for the global coordinate system. This origin is marked by the origin marker in Figure 3-27.
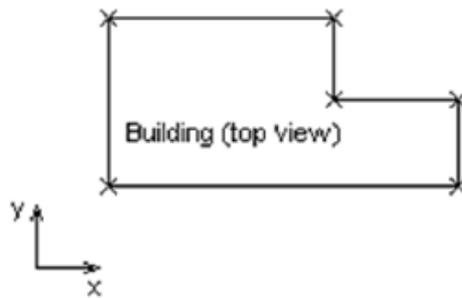
Figure 3-27 Building System in IDA-ICE

3.2.1.4.5 Zone System

The geometry of the zone in IDA ICE is defined relative to a point in the building system, where the z-coordinate gives the height of the floor above ground level. In fact, the zone is described by its height plus the corners of the floor.

The corners' x and y coordinates are indicated in a <u>local</u> coordinate system for the zone, that is named the <u>zone system</u> that moves and rotates with the zone. The zone system is defined by the origin's coordinates (in the building system) and the rotation angle around the z-axis, Figure 3-28.
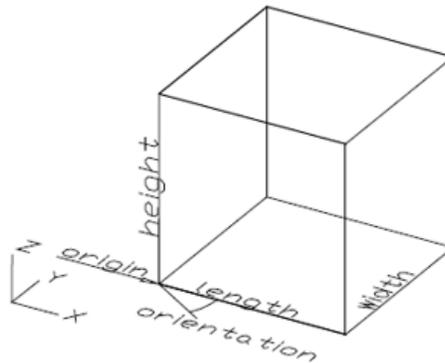
Figure 3-28 Zone System in IDA-ICE [107]

3.2.1.4.6 Surface System

Furthermore, in IDA ICE, a surface system definition exists as well. The surface system is a <u>local</u> coordinate system that is defined on every enclosing surface, Figure 3-29. The origin of the local coordinate systems varies from object to object in IDA ICE. The surface system indicates the position of features (such as openings) on the surface:

- o Vertical walls: the origin of coordinates is located in the bottom left corner of the surface (from inside the zone), Figure 3-30.
- o Floors and Horizontal ceilings: the surface system coincides with the zone system (with Z-coordinate omitted).
- o Slanted ceilings (or fragments of the ceiling): while the X-coordinate is always horizontal passes through the lowest corner of the ceiling, the Y-coordinates is located in the ceiling's plane, that is perpendicular to the x-axis and moves through the leftmost corner of the ceiling [107].
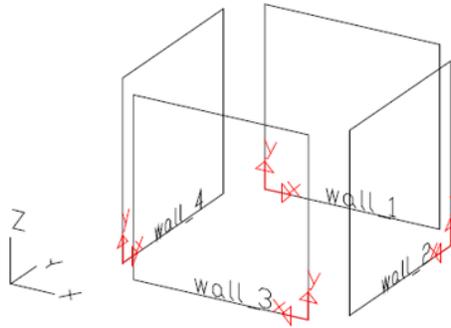
Figure 3-29 Surface System in IDA-ICE [107]
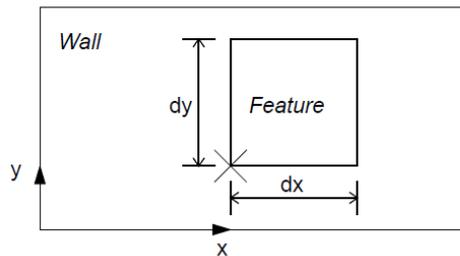
Figure 3-30 Surface System in IDA-ICE for Wall object [107]

The geometry for objects like windows and heating devices is defined by a rectangle. If the object is a rectangle, the lower left corner of the rectangle (insertion point) is given in the surface system. Otherwise, the position of an object is the intersection of the rectangle with the surface.

That all said, the coordinates of the origin are given in the site plan coordinate system. Meanwhile, orientation indicates how the building has been rotated in relation to its original position.

3.2.1.4.7 What are the IDA Resources and Database?

Database refers to the inventory of ICE's resources, while *Resource* refers to an object that stores the common parameters for other data objects.

Resource objects are frequently created from database objects, and also, can also be stored in separate resource documents that are accessed by pressing the Import button. Any change made in an IDA resource at the building level would propagate through all the instances in the building where it has been used.

The list below elaborates the types of database objects, which can be readily found in the IDA database, and are used in IDA Indoor Climate and Energy [108].

1. Wall definition
2. Material
3. Glazing System (detailed)
4. Glass pane
5. Shading material
6. Venetian blind
7. Gas properties
8. Glass definition (simplified)
9. Integrated shading
10. Location
11. Wind profile
12. Schedule
13. Profile
14. External Shading
15. Climate data
16. Occupant load
17. Equipment load
18. Lights
19. Controller setpoints
20. Surface
21. Cooling and Heating device
22. Window
23. Energy price
24. Settings for new zones

3.2.1.4.8 Walls, Roofs, Floors in IDA-ICE

To define a Construction in IDA-ICE, the Category should be defined at first. Category describes the type of category of construction, that could be an internal floor, external wall, etc. When editing the construction of some object, only the compatible categories are available. This is important in IDA-ICE, because whether a wall is internal or external impacts the thermal simulation, and the order of material layers.

The layers are shown in the list box in the Layers box, Figure 3-31. Floor layers are given in order of floor surface to floor bottom (usually ceiling below), wall layers are given in order of inside to outside, while roof constructions are described from top to bottom.

"Layer data for the selected layer is displayed in the Layer data box to the right in the dialog. Every layer has a name, a description and a thickness given in meters, and consists of a material that can be selected under the Material heading. If the desired material isn't on the list, additional material definitions can be loaded from the database. Similarly, a new material can be created by selecting New Resource, and the selected material can be stored in the database by selecting Write to database."
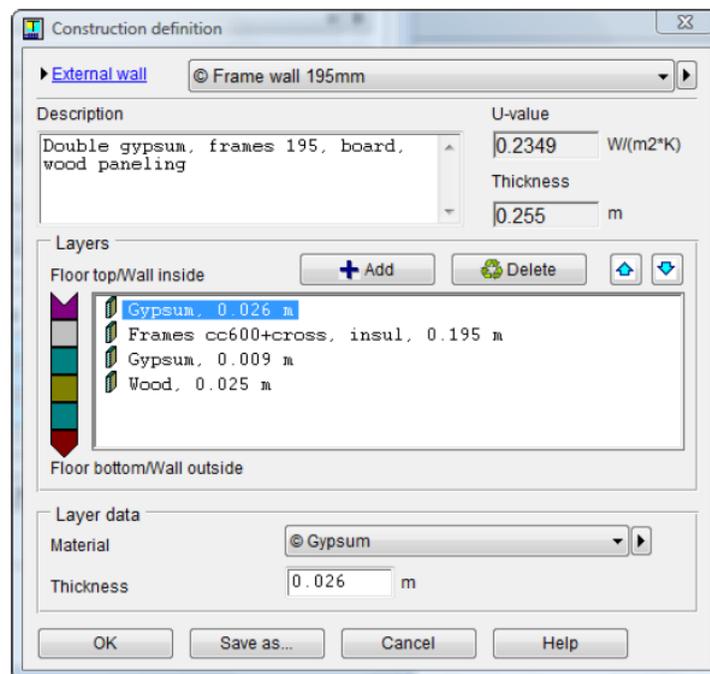
Figure 3-31 Construction definition in IDA-ICE [107]

3.2.1.4.9 Windows, Glazing, and Shading in IDA-ICE

In IDA-ICE, both the Glass construction dialog and Detailed Glazing System dialog, are used to describe optical and thermal properties of the window glazing. Glazing Choice of glass configuration, includes SHGC-, T- and U-value for the glass. Exploring these dialogs enables us to understand what is IDA-ICE's capacity to receive information regarding windows. In IDA-ICE, window consists of layers, namely pane layer (glass panes), shade layer (shading devices _optional), and cavity layer (or gaps), and each of them has their own category.

In the detailed model, the Pane parameters can be inserted. The glass pane object, its corresponding transmittance coefficient (same for both directions), reflectance coefficient, from the front side and from the back side, the thickness of the pane (in mm), and Thermal conductivity (in W/(K.m) are to be defined

here. These coefficients should be valid for radiation that is perpendicular to the pane. Coefficients for other incidence angles and for diffuse radiation will be calculated by the model.

It is also possible to define the properties of the cavity for use in a Detailed Glazing System for the Detailed window model. The Gas properties dialog is used to describe the properties of a cavity. Here, gases are considered as resource objects.

IDA ICE offers two choices for shading: Integrated Shading, and External Shading. Integrated shading refers all types of shading in the window's plane, even external blinds. This category encompasses blinds, curtains, etc.

External shading denotes permanent shading objects, on the facade, near the window, such as side fins, Balcony with sides, Simple screen, Marquee with sides, and etc. In the context of this project, we are concerned with external shading in Case 20. According to [107], It is possible to draw shading objects in the IDA ICE and save them, but, it is not possible to change shading objects to independent IDA-resources, either as resources or database objects.

3.2.1.4.10 Materials in IDA-ICE

It is also possible to create (and save) a new material or to load an object of the material type from the database. Hence, IDA-ICE material resource accepts following parameter inputs, that are necessary for building energy simulation:

- o Heat conductivity (W/mK)
- o Density (kg/m^3)
- o Specific heat (J/kg K)
- o Category The type of material (used to systematize the database)

3.2.1.4.11 Thermal Zone in IDA-ICE

The Floor Plan view shows the building body, zones, and imported CAD/BIM data at the given height which is described as level. All objects are shown in <u>building coordinates</u>. The orientation of the imported IFC building is shown through the compass on the top left, which is adjustable inside IDA-ICE.

The building body is formed of body parts which may be arranged both vertically and horizontally, but not intersecting each other at all. If the body parts are intersected, then the user will receive a warning. However, Zones can pass intersect several body parts. IDA-ICE's zone is rectangular with six surrounding surfaces, that are called main surfaces. Windows, doors, and radiators, etc. are introduced as objects on the corresponding zone surfaces.

In the context of this dissertation, zones are allocated to spaces coming from the IFC file through **IfcSpace** classes. However, it is always possible to change the position and size of a zone in Floor Plan view, manually. A color scheme describes the zones in this view. Active zones are indicated by a red border, while other existing zones in the building, both on the same floor and on other floors, are depicted by paler gray lines, which are also visible.

An important thing to note here is the floor area and the zone volume in the property page. The *floor area* is used for presentation of different parameters "per 1 m2 of floor area". IDA-ICE, by default, calculates the floor area as the area inside walls. Of course, it is possible for the user to change the default value (for example, to exclude unused parts of the zone), which in this case it will be displayed with a yellow background. Likewise, the *zone volume* is computed by the IDA ICE as the volume inside the walls, floor, and ceiling [108].
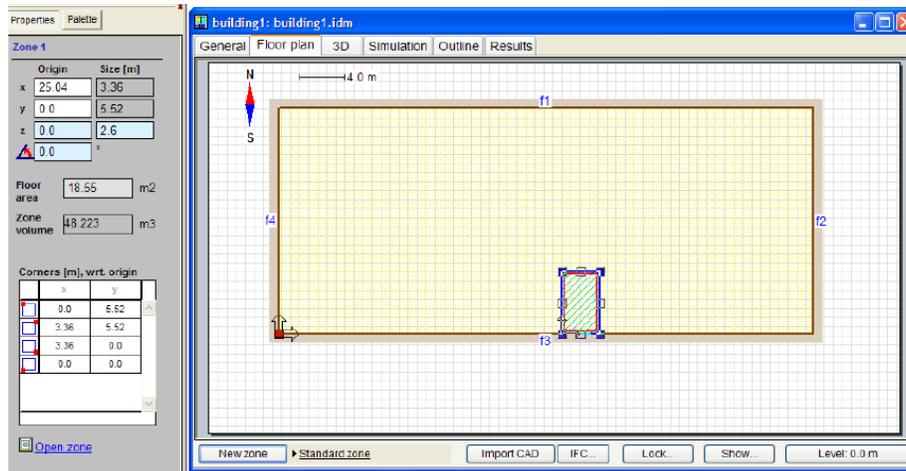
Figure 3-32 IDA-ICE Zone
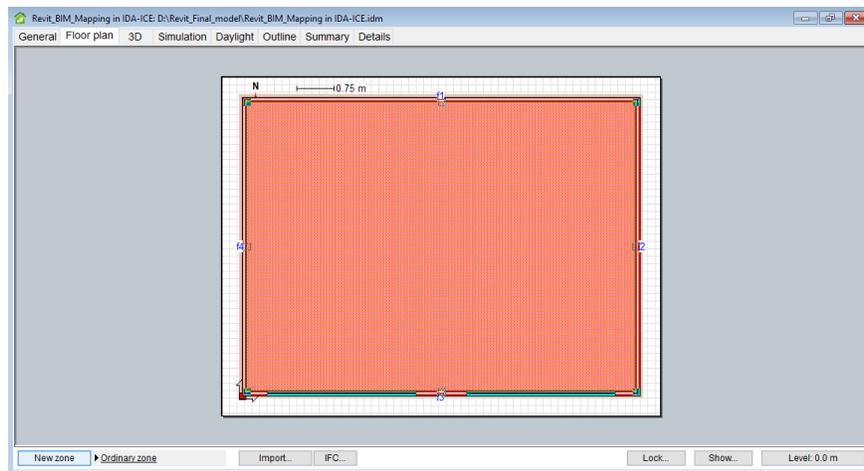
Figure 3-33 Active Zone in IDA-ICE, the zone has been assigned to IfcSpace

The changes to zone size can be made through giving numerical values for the zone's corners in the Properties page, or through selecting the corner of the zone and dragging it, manually, Figure 3-32. In IDA-ICE, if due to the changes of zone position, an external wall becomes an internal wall, the wall construction corresponding to the new position will be automatically selected.

3.2.1.4.12 Creating zones in IDA-ICE from IFC spaces

In the Level dialog, the building height from ground (Building top) and height coordinate of the floor slab with respect to ground (Building bottom) are also shown, as interpreted from the IFC file. To define which spaces in the IFC model that should constitute a (thermal) zone in the simulation model, click on (select) the adjacent spaces that should be included.

When an IFC file is imported, IDA-ICE understands the boundaries of spaces; however, IDA-ICE would not automatically assign a zone to these spaces. Therefore, to create an IDA ICE zone from the selected IFC spaces, the user should press the New zone button and choose the spaces on the plan view. This will create zones using the currently selected zone template. It is possible to create different zone templates based on the zone type, i.e., office, room, corridor, etc.

The IDA-ICE zones are created from the geometry of the corresponding IFC space(es). According to IDA-ICE documentation, if a space [in the Revit-based IFC] is taller than the typical floor to floor distance of the building, the corresponding ICE zone will also reach over more than a single floor. This argument was checked in Case 12.

After importing IFC, an important thing to note in the Floorplan view is that two models are simultaneously displayed. First one is the zones of the created ICE model, and the second one is spaces of the IFC model. Both categories of "rooms" can be individually selected and ICE zones can also be opened. This is explained in Case 01.

BIM files contain 3D geometry as well as properties for walls, windows, and materials, etc. An IDA ICE model, i.e., building bodies, zones, and windows, etc., can be automatically created from the geometrical information. Furthermore, the properties of objects in the BIM file can be mapped to the corresponding objects in the simulation model. The 3D geometry of a BIM file can also be selected to shade the simulation model.

Building bodies and zones can be automatically created from graphics files if the imported geometry consists of volumes enclosed by polygon surfaces. 3D CAD objects can be selected to shade the simulation model. In IDA-ICE it is possible to import 3D building information models (BIM) via IFC files. Most 3D CAD applications can export architectural data in the IFC format.

In the case of walls, roofs, ceilings, and floors, since they have several layers, layer thickness, and material names, once the mapping is done, corresponding ICE constructions are created automatically. This is explained in Section 3.2.2. If an object in IFC models not mapped to an IDA resource, then it will be set to a default value.

3.2.1.4.13 What file formats are supported by IDA-ICE?
IDA ICE supports many formats for direct import to the platform, including:

- IFC (*.ifc)
- CAD and vector graphic files
- AutoCAD (*.dwg, *.dxf, *.dwf)
- SketchUp (*.skp)
- 3D Studio (*.3ds)
- Image files, JPEG Interchange Format (*.jpeg,*.jpg)
- Portable Networks Graphics (*.png)
- Adobe Photoshop (*.psd)

Here, the focus is only on the .ifc suffix for the BIM-based models [108]. ICE can import CAD IFC files of IFC release 2.0, 2x, 2x2 and 2x3 generated by, e.g., ArchiCAD, Revit, Architectural Desktop, MagiCAD Room, etc. ICE imports information about wall, window and door positions.

In the case of IFC file import, IDA-ICE relies on the existence of ifcSpaces for the creation of simulated zones. Correspondingly, ICE imports styles for walls, windows, and materials that can be used to provide an appropriate property set to a group of imported objects in ICE. Using IFC, it is possible to automatically build the geometry of a building without manual editing [107, 109].

Building and zone geometry can be imported into IDA-ICE if the imported geometry only contains a volume enclosed by polygon surfaces (polyhedron) without holes between the surfaces. The geometry

should describe the inner surface of the external walls of a building, and the inner surface of the zone walls for a zone [107].

Imported building bodies and zones have protected geometry, i.e., their geometry is non-editable, only resizable. However, an imported building body is fully editable if the imported geometry only has one floor and that floor is horizontal and does not contain any holes, and the geometry does not have any outer leaning walls (surfaces with their exterior normal pointing downwards). This is the same kind of geometry that can be created in the IDA ICE roof editor [107, 108].

3.2.1.4.14 IFC Import

According to the IDA-ICE documentation [107-109], the essential information that is transferred is geometrical data, i.e., the shape and position of zones, windows, doors, building faces, etc. Zones in IDA-ICE are automatically created from so-called space objects in the IFC model. It is not sufficient that the CAD model only contains wall objects, spaces that fill the voids between walls must also have been created, a semi-automatic process in most CAD tools.

IDA-ICE can also utilize other types of information in the CAD model, such as wall constructions, that should they be present.

3.2.2   Mapping IFC data to IDA-ICE

After importing an IFC file from IFC button to the floor view tab, one can start with mapping the "named data objects" in the IFC model (if any are present) to corresponding IDA resources. "Data objects" in this context refer to any element or data that is coming from Revit information-rich model and present in IFC. Similarly, IDA resources imply the elements and information that are readily available in the software to describe the building envelope or HVAC systems, and etc.

To begin with the mapping, after pressing IFC, choose "mapping" from the tray. The Mapping dialog will be opened up. Then, for walls, windows, and other building envelope's parts, the user can select a construction in the Category combo box. However, in the case of windows, usually, the first step is to create relevant windows in the ICE database, including internal shadings, etc.

"If wall constructions have been described in the IFC model with layer thicknesses and material names, one can automatically create corresponding IDA-ICE constructions. In this case, one starts instead with binding IFC material names with IDA ICE material resources. Once the materials have been mapped, IDA ICE wall construction resources are created by pressing Import from IFC when the relevant IFC wall type has been select" [107].

If the object in the IFC model is not mapped to an IDA resource directly, it will be set to its default value. Default values can be found in the Defaults on the General tab in the building form.

3.2.2.1   Definition of Mapping

The definition of mapping is somewhat opaque; however, *Mapping* is a term used to describe the process of matching an item or entry from one group to that corresponds the most similar on the second group. In other words, mapping extracts something from the first group and associate it with the second group, so, this is called mapping from the first group to second group [110, 111].

According to IDA ICE documentation, the mapping is "The transfer of data objects from the IFC model to IDA-ICE" [109, 112].

3.2.2.2 Step by Step guide to IFC mapping ICE by example

In 3D View, zone walls (or surfaces) have a coloring scheme, according to IDA ICE documentation, that is described below:

- o grey textured: Walls or floors that are connected to an external façade,
- o dark grey striped: Ceilings that are connected to an external façade,
- o dark grey: Walls or floors that are connected to ground,
- o White: Walls, floors, and ceilings that are internal or unconnected.

3.2.2.2.1 Zone assignment

Zone assignment in IDA-ICE can be performed after, of before mapping IFC data. However, first, the IFC file should be imported inside the tool, Figure 3-34.
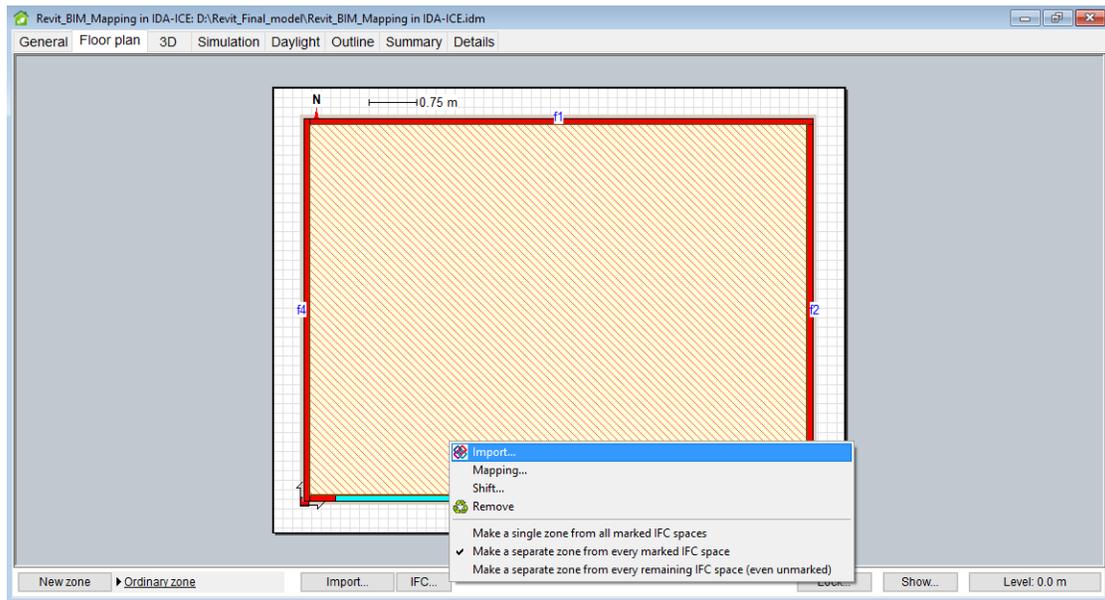
Figure 3-34 Importing IFC into IDA-ICE

3.2.2.2.2 Initial mapping step

After the import of IFC to IDA-ICE in the Floor Plan tab, using the same *IFC...* button, it is possible to start mapping, Figure 3-35. Table 3-1 explains the drop-down box in Figure 3-35 Mapping in IDA-ICE more details.

Option	Description
IFC…	Opens the IFC menu.
Import…	Import of an IFC model, or CAD drawing, or Windows graphics as background.
Mapping…	The transfer of data objects from the IFC model to IDA is described here.
Remove	Remove the imported IFC model
Make a single zone from all marked IFC spaces	When adding zone, create a single zone from all marked IFC spaces.
Make a separate zone from every marked IFC space	When adding zone, create a zone from each marked IFC spaces
Lock	Disable moving and resizing of objects of given types.

Table 3-1 Explanations about IFC Mapping Drop-down window [108]
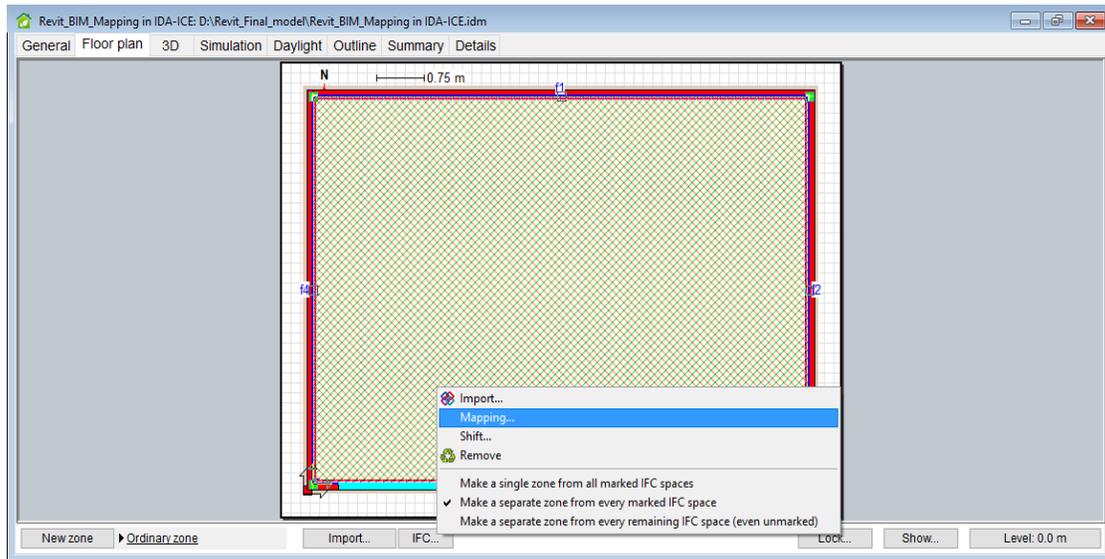
Figure 3-35 Mapping in IDA-ICE

3.2.2.2.3   Material Category

A new window will pop up. This window is called "Mapping IFC data to IDA resources," shown in. In the first step, Materials Category should be chosen from the drop-down list. Because first, materials are mapped, and then Constructions are mapped. The buttons in the Mapping IFC data to IDA resources are explained below, taken from [108]:

Name of the button	Operation or description
Category	Select an IFC category for mapping
IFC data	Available IFC data of the selected category
ICE resources	Available IDA resources of the selected category
Map to selected	Map the selected IFC objects to the selected IDA resource (First, select one or more IFC objects and one IDA resource)
Unmap selected	Disconnect selected IFC objects from their IDA resources
Import from IFC	Make a new IDA resource from IFC object. Only import of walls is implemented. Import not possible if the materials used in the wall are not already mapped to ICE.
View	Show the selected IDA resource
Load from Db	Load resource from ICE database
Create new	Create a new IDA resource

Table 3-2 Explanations about Mapping IFC data to IDA resources [108]

If the model creation in IDA-ICE has been initiated by choosing "Start new empty building," then, there is no ICE resources in the box on the left-hand side. Otherwise, if the model creation is through "new building with a single zone," then, there are some default materials in the ICE resources box, Figure 3-39.

Since we have started our model as a *new building*, there are no ICE resources available. This means that we should Load some resources from the *Load from Db* button. Now, based on the name of the materials that have been imported through IFC, that are shown in the *IFC data* box in the right-hand-side of Figure 3-38, we can choose similar resources from IDA database and load them into ICE resources.

For example, we have IFC data name of "Revit_Rigid_Rigid Insulation," therefore, it is possible to choose Heavy Insulation from the list of IDA resources on the list. The right pointing arrow indicates that the mapping has been performed, Figure 3-38.
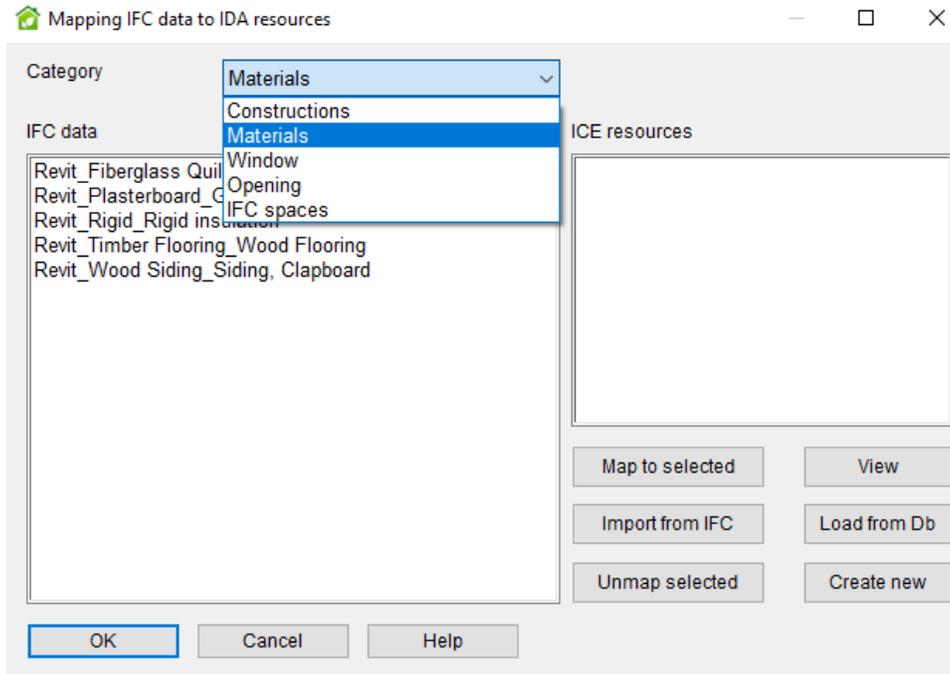
Figure 3-36 Mapping IFC data to IDA resources, Category: Materials (step one)
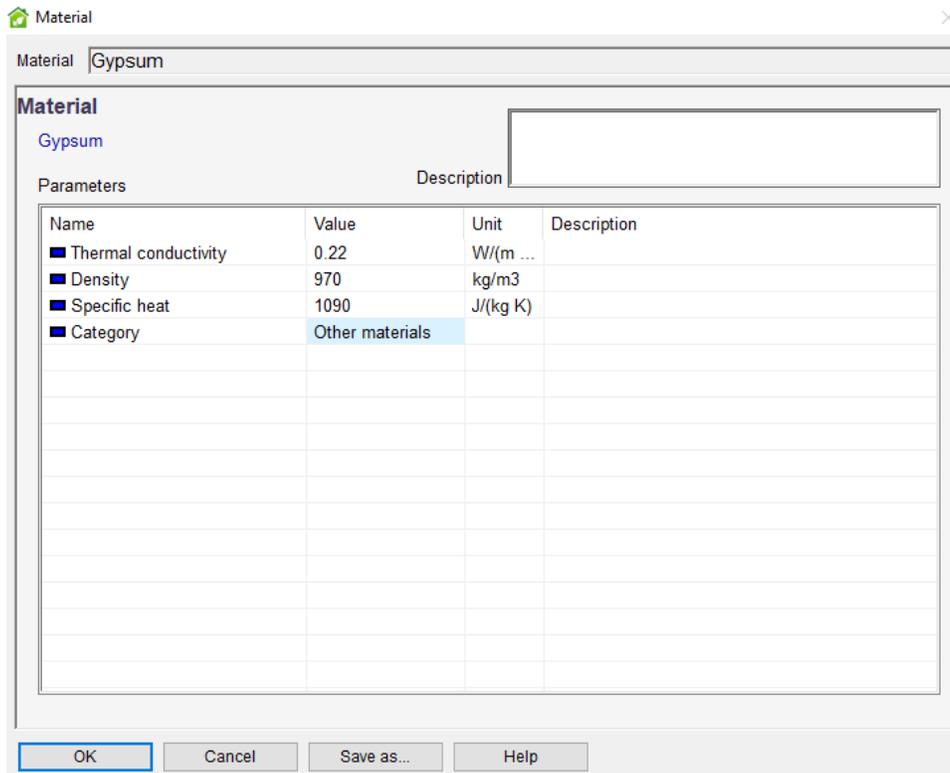
Figure 3-37 Material properties in IDA-ICE, to create or modify new materials
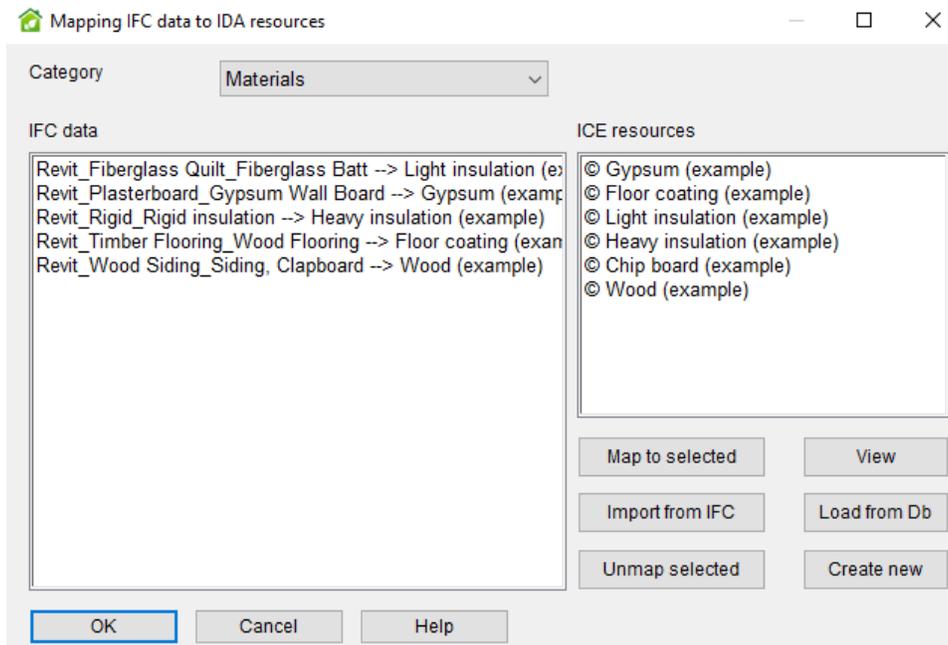
Figure 3-38 Mapping IFC data to IDA resources, Category: Materials (step three)
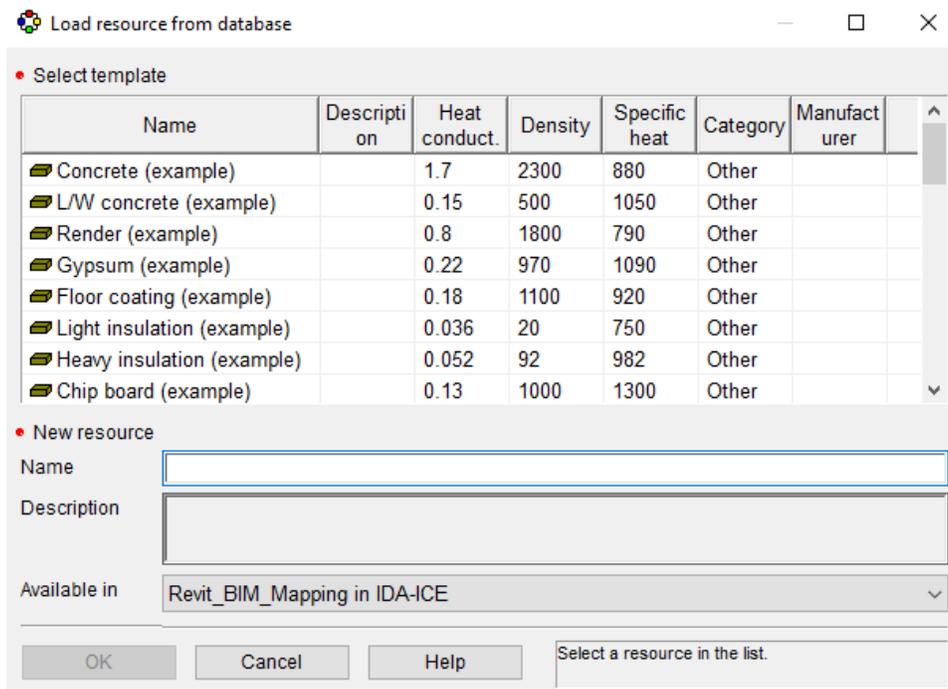
Figure 3-39 Material resources available in IDA database, IDA-ICE

3.2.2.2.4 Construction Category

After every material is correctly mapped to the similar IDA resource, then it is now possible to go to the Constructions Category and proceed with Constructions, Figure 3-40. The constructions should be selected

in the IFC data box on the left and be sent to ICE resources through the *Import From IFC* button. Some predefined constructions in the database of IDA are shown in Figure 3-41.

Therefore, the constructions with the proper material layer order (the same order as what it is in BIM), is now inserted into ICE resources.
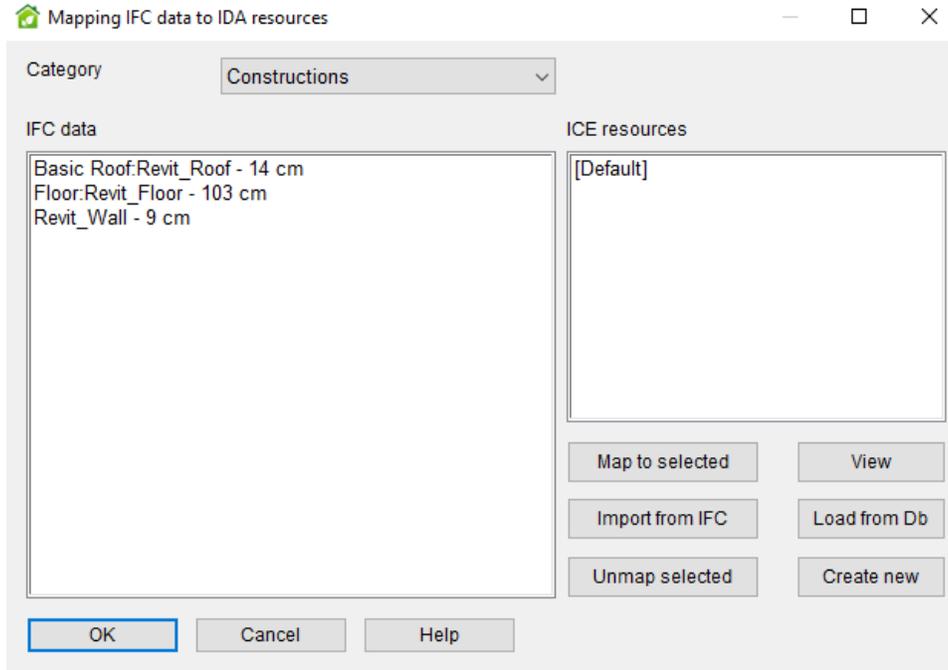
Figure 3-40 Mapping IFC data to IDA resources, Category: Constructions
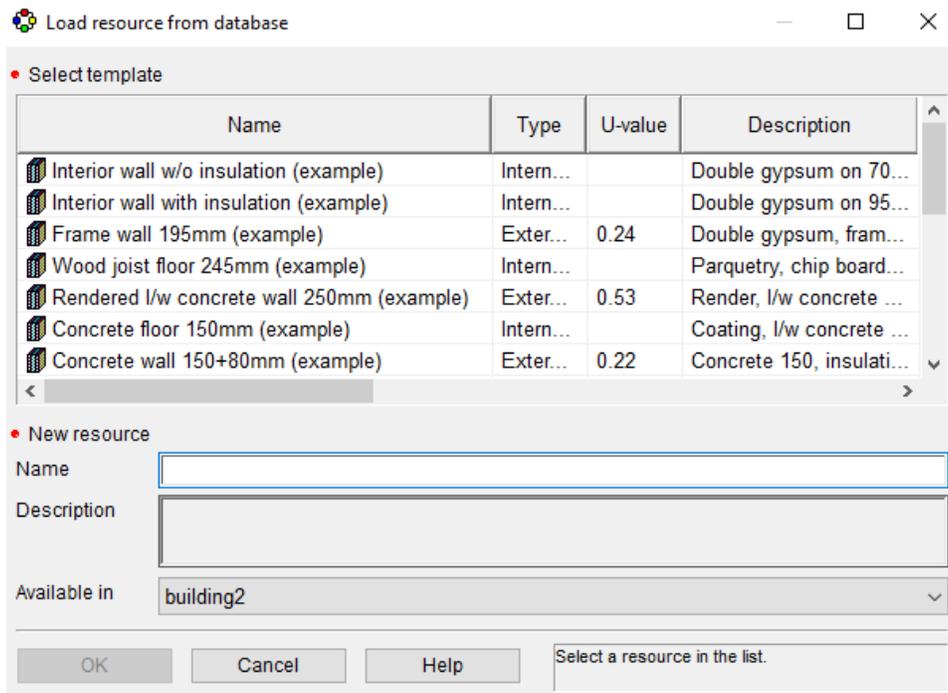
Figure 3-41 Construction resources available in IDA database, IDA-ICE

3.2.2.2.5 Window Category

In the next step, windows must be mapped as well. As can be seen, the IFC data on the right side of the contains the name of the windows that have been imported from the IFC file. The ICE resources are on the right. However, we are going to create a new ICE resource through "Create new" button, Figure 3-42, and would choose the detailed window modelling option in IDA-ICE.
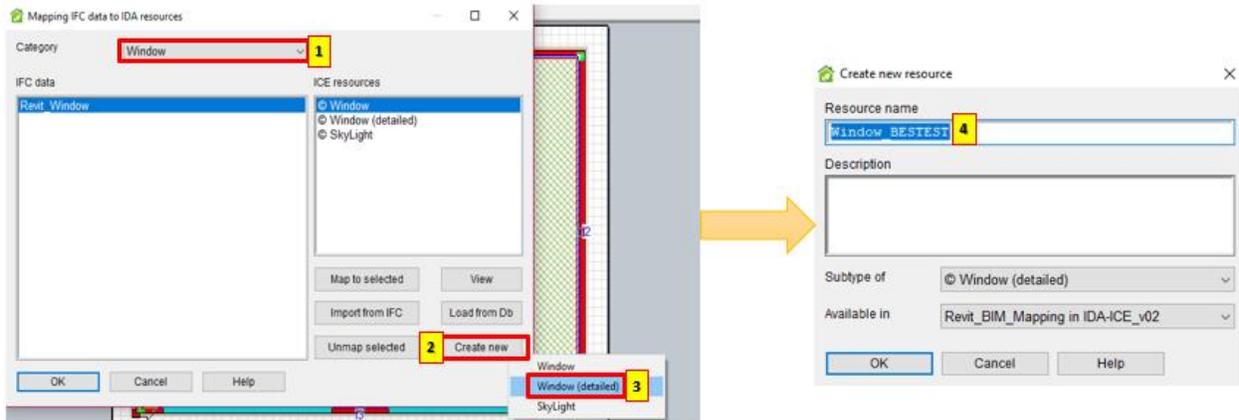
Figure 3-42 Window Mapping in IDA-ICE, creating a new detailed window

Firstly, the name of the new resource is specified. We call it "window_BESTEST" here, in order to be easily distinguishable from Revit_Window. Afterward, the dimensions of this window should be defined, Figure 3-43. Secondly, the glazing type should be chosen from resources. For this example, "2 pane, clear, 4-12-4" glass is chosen, with the thermal properties that are shown in Figure 3-43, down Right.
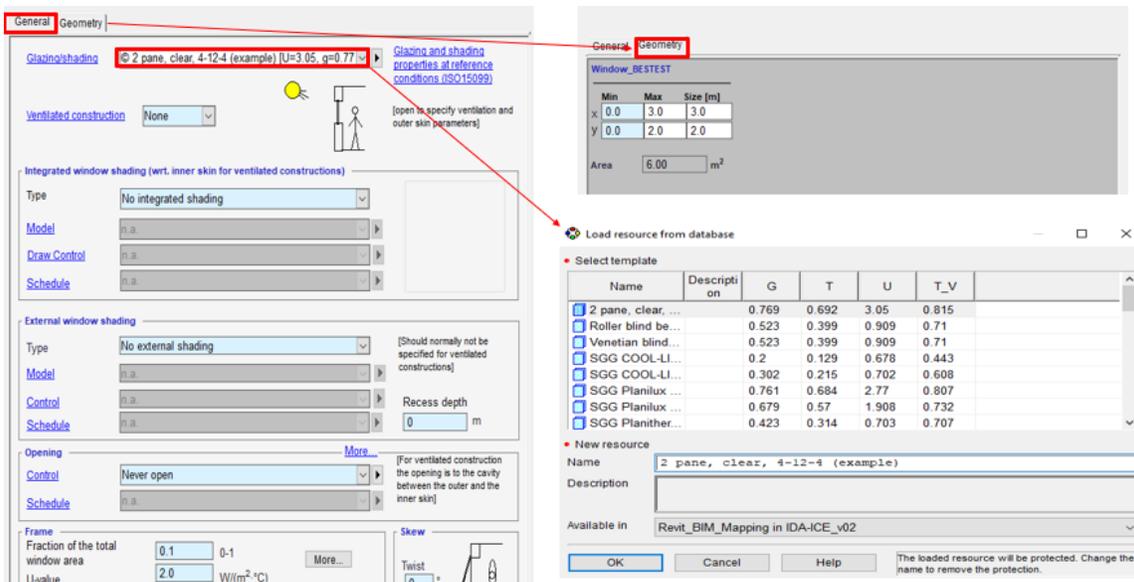
Figure 3-43 Detailed Window General tab(Left), Detailed Window Geometry (Upper Right), Glazing resources in IDA-ICE (Down Right)

Now, we can close the "Mapping IFC data to IDA resources," and move to the General tab, Figure 3-43, Left.

3.2.2.2.6 Final mapping step

In the final step, the constructions should be chosen for the surfaces, Figure 3-44. The constructions can be chosen from what we mapped earlier in the Construction category. When this procedure is done for every surface and also for windows, the mapping is complete.
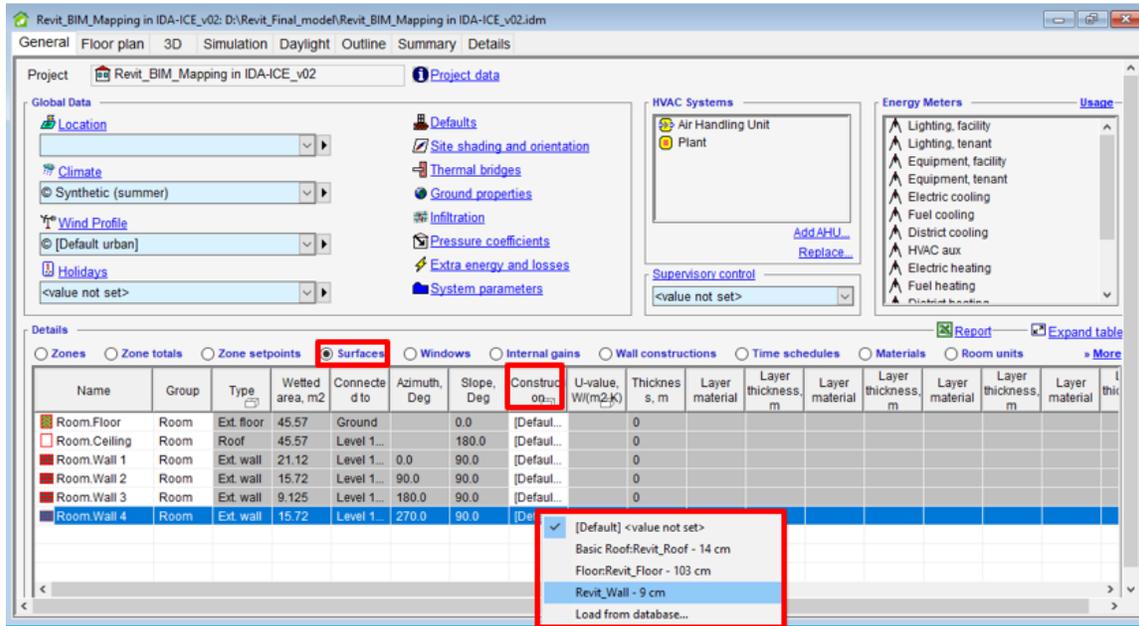
Figure 3-44 Assigning constructions to surfaces

All that said, one problem is that even though the windows are mapped in previous steps, and new windows are constructed in the detailed window section when you check the windows in the General tab, they are not mapped! In addition to that, the same IDA-ICE resources that were present in the mapping section is not present in the General tab, and the glazings have different properties.

Additionally, during the course of this research, we found that mapping sometimes does not require the last step. This means that sometimes after the mapping of the Material and Construction Category is done, they will be instantly updated in the IDA-ICE general tabs and will be visible on the surfaces. Therefore, this is a proof that the results of BIM to BEM processes are not easily reproducible, and the results of one modeler are not comparable with the results of other modelers.

3.3 Case-Studies

In order to examine the interoperability issues between Revit and IDA-ICE, a number of case studies were developed. Each case study explores a different issue. The reasoning behind the case-studies is threefold: firstly, their relevance to the energy analysis, secondly, their existence in the building model that was chosen (i.e., BESTEST 600), and finally, the method with which they should be created in Revit.

This section is organized into four sub-sections. First sub-section presents an overview of the of the case-studies in general. Second sub-section describes the buildings that were modeled in Revit. In this chapter, all the important information about the building is presented. Third sub-section maneuvers over the tasks and sub-tasks and introduce them briefly the Finally, in sub-section 4, cases are introduced, and the results are delivered and discussed.

3.3.1 Structure of Cases

In this section, a general outlook to the structure of the models and cases are presented. Due to the high number of case-studies, a systematic reference was developed that includes: Tasks, Sub-Tasks, and Building Models. Next few sections elaborate these terms in more details.

3.3.1.1 Guide to the naming system of the Cases

Briefly, following Table 3-3 explains the manner of referencing each case study. An Example could be Case01: T1_ST1_BM1. This refers to the Sub-Task1 of the Task1 in the Building Model 1.

Name	Abbreviation	Description
Building Model	**BM**	Indicates the BESTEST case under investigation
Task	**T**	Describes the general issue to investigate
Sub-Task	**S**	Describes the variations and different options to investigate in the desired class

Table 3-3 Abbreviations used for systematic reference naming

3.3.1.2 Building Model

Building Model describes the BESTEST case that is going to be investigated; Table 3-4 elaborates the abbreviations while Figure 3-45 demonstrates each building model.

Building Model	Building Model abbreviation	Building Model Description
Building Model 1	BM1	BESTEST 600
Building Model 2	BM2	BESTEST 610
Building Model 3	BM3	BESTEST 620
Building Model 4	BM4	BESTEST 630

Table 3-4 Building models' abbreviations and descriptions
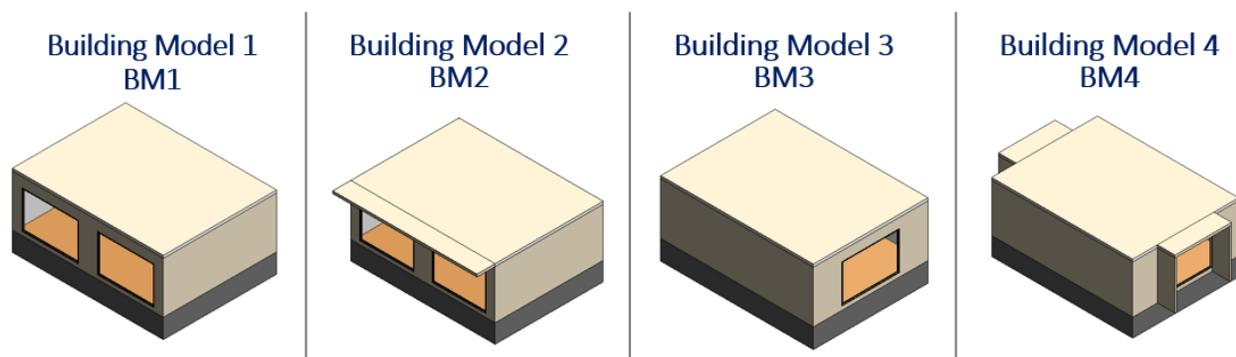
Figure 3-45 Building Models' in one view

3.3.1.3 Task

Table 3-5 summarizes the Tasks that have been investigated in this thesis.

Task	Task abbreviation	Task Description
Task 1	T1	Wall Location Line
Task 2	T2	Zone vs. Space vs. Room
Task 3	T3	Space height vs. Room height
Task 4	T4	Materials
Task 5	T5	Windows
Task 6	T6	Orientation
Task 7	T7	Coordinates
Task 8	T8	Shading

Table 3-5 Task's abbreviations and descriptions

3.3.1.4 Sub-Task

For each Task, several Sub-Tasks has been defined that are tabulated in Table 3-6.

Cases	Task	Task Description	Sub-Task	Sub-Task Description
01	T_1	Wall Location Line	ST1	Wall Centerline (default)
02			ST2	Core Centerline
03			ST3	Finish Face: Exterior & Finish Face: Interior
04			ST4	Core Face: Exterior & Core Face: Interior
05	T_2	Zone vs. Space vs. Room	ST1	No Room, Space, or Zone element
06			ST2	Room
07			ST3	Space
08			ST4	Zone
09			ST5	Room + Space
10			ST6	Room + Space + Zone
11	T_3	Space height vs. Wall height vs. Room height	ST1	Space height vs. wall height
12			ST2	Space height vs. Room height
13	T_4	Materials	ST1	Material's thermophysical properties
14	T_5	Windows	ST1	Revit built-in windows with built-in Analytical construction
15			S_2	Revit new family created from scratch window
16	T_6	Orientation	ST1	Change of building orientation of BM1 from N_S direction to 30◦ NE
17	T-7	Coordinates	ST1	Coordinates of elements
18	T_8	Shading	ST1	Horizontal shading (South façade) BM2
19			ST2	Horizontal and vertical shading (E/W facade) BM4

Table 3-6 Overview of case-studies and Sub-Tasks' abbreviations and descriptions

3.3.2 Description of the Building model

This section describes the building models, their geometry, materials types and properties, and any information pertinent to the modeling of the building inside Revit, or IDA-ICE.

3.3.2.1 Building Model 1 (BESTEST Case 600)
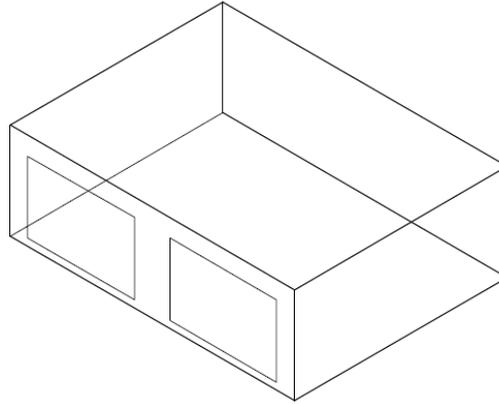
Figure 3-46 BESTEST Case 600 geometrical view [113]

The building chosen for testing the interoperability issues is the BESTEST Case 600 The model is a 6 m by 8 m by 2.7 m rectangular single zone. There is no internal walls or partitions, and 12 m² of glazing on the southern wall [113].

The Case 600, is lightweight construction and is a low-mass building; it is shown in Figure 3-46. Walls are 0.0 87 meters thick, with the following materials elaborated in Table 3-7.

Element	K	Thickness	U	R	Density	Cρ
	W/m K	m	W/m² K	M² K/W	Kg/m³	J/kg K
Plasterboard	0.160	0.012	13.333	0.075	950	840
Fiberglass Quilt	0.040	0.066	0.606	1.650	12	840
Wood Siding	0.140	0.009	15.556	0.064	530	900

Table 3-7 BESTEST Case 600's wall material description [113]

The thickness of the floor is 1.028 meter and is composed of the materials shown below in Table 3-8.

Element	K	Thickness	U	R	Density	Cρ
	W/m K	m	W/m² K	M² K/W	Kg/m³	J/kg K
Timber Flooring	0.140	0.025	5.600	0.179	650	1200
Insulation	0.040	1.003	0.040	25.075	Not-given	Not-given

Table 3-8 BESTEST Case 600's floor material description [113]

Likewise, the roof is 0.1408 meters thick. The materials are elaborated in Table 3-9.

Element	K	Thickness	U	R	Density	Cρ
	W/m K	m	W/m² K	M² K/W	Kg/m³	J/kg K
Plasterboard	0.160	0.010	16.000	0.063	950	840
Fiberglass Quilt	0.040	0.1118	0.358	2.794	12	840
Roof Deck	0.140	0.019	7.368	0.136	530	900

Table 3-9 BESTEST Case 600's roof material description [113]

The information about the BESTEST model's window is summarized in the following Table 3-10:

WINDOW PROPERTIES	VALUE	UNIT
Extinction coefficient	0.0196	/mm
Number of panes	2	-
Pane thickness	3.175	mm
Air-gap thickness	13	mm
Index of refraction	1.526	-
Normal direct-beam transmittance through one pane	0.86156	-
Thermal Conductivity of glass	1.06	W/mK
The conductance of each glass pane	333	W/m2K
Combined radiative and convective coefficient of the air gap	6.297	W/m2K
The exterior combined surface coefficient	21	W/m2K
The interior combined surface coefficient	8.29	W/m2K
U-value from interior air to ambient air	3	W/m2K
Hemispherical infrared emittance of ordinary uncoated glass	0.9	-
Density of glass	2500	kg/m3
Specific heat of the glass	750	J/kgK
Interior shade devices	-	-
Double-pane shading coefficient at normal incidence	0.907	-
Double-pane solar heat gain coefficient at normal incidence	0.789	-

Table 3-10 BESTEST Case 600's window description [113]

Also, there is 0.2 m of the wall below the window and 0.5 m of the wall above the window [113].

Some additional information is provided below that are required for energy analysis, some of them can be inserted in Revit, while others are more appropriate for EnergyPlus. As it was earlier said, the BESTEST cases are tailored for energy analysis tools.

I. Infiltration rate is 0.5 air change/hour.
II. The Internal Loads are 200 W continuous, 60% radiative, 40% convective, 100% sensible.
III. The information about mechanical Systems are as follows: 100% convective air system, 100% efficient with no duct losses and no capacity limitation, no latent heat extraction, non-proportional-type dual setpoint thermostat with a dead band, heating <20°C, cooling >27°C.
IV. The Soil Temperature is 10°C continuous [113].

Moreover, following information is applied to all building models regarding the opaque surfaces' radiative properties:
I. Thermal Emissivity: 0.90
II. Solar Absorptance: 0.60
III. Visible Absorptance: 0.60 [113]

3.3.2.2 Building Model 2 (BESTEST CASE 610)

Building Model 2 is called BESTEST Case 610, shown in Figure 3-47. It uses the exact same construction of the building Model 1 or BESTEST Case 600, except that it has a 1-meter horizontal overhang across the entire length of the south wall over the south facing windows at the roof level [113]. There is no information provided about the materials and thickness of the overhang.
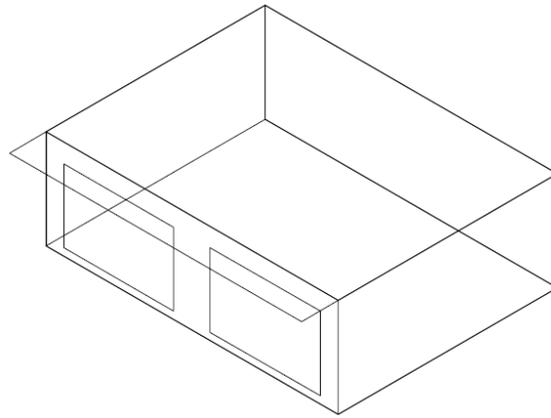
Figure 3-47 BESTEST Case 610 geometrical view [113]

3.3.2.3 Building Model 3 (BESTEST Case 620)

Building Model 3 is the BESTEST Case 620, Figure 3-48. The same construction of the building Model 1 or BESTEST Case 600 is also used for this case. The difference is the location of the windows. In this case, windows are situated on both sides of the building in West and East Façade. 6 m^2 of glazing is allocated to each wall, i.e., one window on each side. Windows, too, is similar to the windows in Case 600 [113].
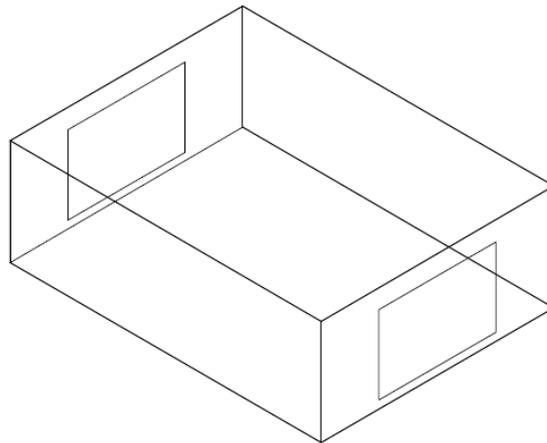
Figure 3-48 BESTEST Case 620 geometrical view [113]

3.3.2.4 Building Model 4 (BESTEST Case 630)

Building Model 4, shown in Figure 3-49, is similar to BESTEST Case 620, but it also includes shade overhangs and shade fins around the east and west windows. To further elucidate, it should be mentioned that the horizontal overhang has 1-meter wide and is situated at the roof level and extends across the 3 m width of each window. The vertical shade fins are located at the edge of each window and extend all the way from the roof down to the ground and are 1 meter wide on both left and right of the windows. Furthermore, windows and material construction are similar to that of building Model 1 or BESTEST Case 600 [113].
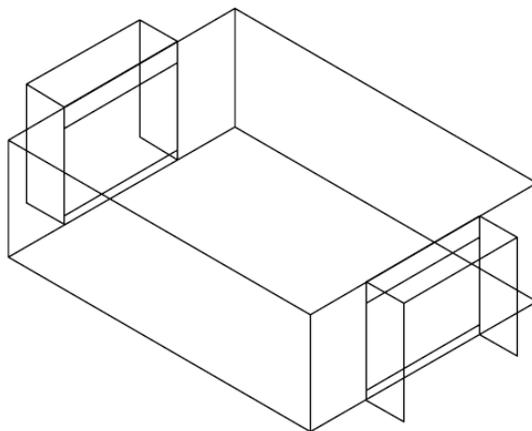
Figure 3-49 BESTEST Case 630 geometrical view [113]

The reason BESTEST cases are used is due to their widespread use in the Energy Simulations. There are a huge number of researchers in Europe [86, 114], and over the globe [43, 115-118], that have used the cases of BESTEST for their studies [119].

3.3.3 Descriptions of Tasks and Sub-Task

Since Sub-tasks are dependent on the Tasks, they are going to be explained together in this section.

To systematically investigate the interoperability issues, eight general tasks were identified as can be seen in Table 3-11. The reasoning behind determining these tasks was to identify what major areas that could have given rise to some interoperability issues. Then, Sub-Tasks were developed to go into more details on these possible issues.

Task	Task abbreviation	Task Description
Task 1	T_1	Wall Location Line
Task 2	T_2	Zone vs. Space vs. Room
Task 3	T_3	Space height vs. Room height
Task 4	T_4	Materials
Task 5	T_5	Windows
Task 6	T_6	Orientation
Task 7	T_7	Coordinates
Task 8	T_8	Shading

Table 3-11 Overview of all the Tasks

3.3.3.1   Task 1

Task 1 is related to the "Wall Location Line" in the Revit software. The interoperability questions are:

- o ***Can Revit export Location line type of the walls to IFC?***
- o ***Does the Location line type influence the imported geometry of the building inside IDA-ICE?***

4 Sub-Tasks were generated since Revit has several options for Location Line. Although the details are going to be explored later, following Table 3-12 elaborates the Sub-Tasks of Task 1.

Task	Sub-Task	Sub-Task Description
1 **Wall Location Line**	ST1	Wall Centerline (default)
	ST2	Core Centerline
	ST3	Finish Face: Exterior & Finish Face: Interior
	ST4	Core Face: Exterior & Core Face: Interior

Table 3-12 Overview of the Sub-Tasks of Task 1

3.3.3.2   Task 2

Task 2 is related to the placement of Room, Space, and Zone elements in Revit and IDA-ICE. The Sub-Tasks are presented in Table 3-13.

In contrast to IDA-ICE, which is an Energy Analysis tool, Revit was first developed as an architectural software. Later, other features, properties, and domains were added to the Revit software. Therefore, there could be slight differences between how Revit and IDA-ICE accept or assign an enclosed building body as a thermal space. Revit, as the BIM authoring tool, provides three different properties that can be assigned to an enclosed surface, namely: Room, Space, and Zone. The definitions of these concepts are presented in Section 3.1.3. The interoperability question is:

> o *How the placement of different 3D spatial element components (i.e., Room, Space, and Zone) in BIM affects the IFC file and the BEM model?*

Based on this question, six Sub-Task were developed.

Task	Sub-Task	Sub-Task Description
2 **Zone vs Space vs Room**	ST1	No Room, Space, or Zone element
	ST2	Room
	ST3	Space
	ST4	Zone
	ST5	Room + Space
	ST6	Room + Space + Zone

Table 3-13 Overview of the Sub-Tasks of Task 2

3.3.3.3   Task 3

Task 3 is a continuation of Task 2. After the investigation of the relationships between Room, Space, and Zone, in Task 2, this task investigates the geometrical relationship between space and room and building elements. Height of the wall (or height of the space and room) is chosen because, in the plan view (X-Y plane), Revit automatically assigns the Room/Space element in the indoor area of an enclosed plan, therefore, in almost every case, there is no error and the Room/Space X-Y dimensions are the same as the area dimensions. However, if the height of the Room/Space and wall are not manually checked before placing the Room/Space, some problems will occur. Hence, the interoperability question is:

> o *How variation of geometrical properties of Room and Space in Revit affect the BIM-based energy modelling in IDA-ICE?*

Table 3-14 represents the two Sub-Tasks of Task 3.

Task	Sub-Task	Sub-Task Description
3 **Space/Zone height vs. Wall height**	ST1	Space height = Room height
	ST2	Space height ≠ Room height

Table 3-14 Overview of the Sub-Tasks of Task 3

3.3.3.4 Task 4

Materials play a vital role in the energy balance of the envelope, and thus, it is paramount to investigate the exchange of materials' properties between a BIM-authoring tool and BEM tool. Task 4 has only 1 Sub-Task shown in Table 3-15. The interoperability question is:

- o *How materials' properties are exported from Revit to IDA-ICE?*
- o *How are they stored in the IFC data schema?*

Task	Sub-Task	Sub-Task Description
4 **Materials**	ST1	Material's thermophysical properties

Table 3-15 Overview of the Sub-Tasks of Task 4

3.3.3.5 Task 5

Task 5 tackles the interoperability issues that are related to windows based on two Sub-Tasks shown in Table 3-16. The interoperability questions are:

- o *How windows' geometry and properties are exchanged Between Revit and IDA-ICE?*
- o *How is a user-built window family in Revit exported to IFC?*
- o *Can IDA-ICE recognize a user-built window family made in Revit?*
- o *What are the differences between Built-in Families, and user-built families in Revit to IDA-ICE procedure?*

Task	Sub-Task	Sub-Task Description
5 **Windows**	ST1	Revit built-in windows with <u>built-in</u> Analytical construction
	ST2	Revit new family created from scratch window

Table 3-16 Overview of the Sub-Tasks of Task 5

3.3.3.6 Task 6

Due to the relocation of windows to east and west façades in <u>Building Model 3</u>, from south facade in <u>Building Model 1,</u> the changes in orientation of building was investigated. The interoperability question is:

o **Does IDA-ICE recognize the orientation of the BIM model and its components?**
o **How are the changes of the orientation of building elements in Revit reflected in IDA ICE?**

Task 6 includes two Sub-Tasks as can be seen in Table 3-17.

Task	Sub-Task	Sub-Task Description
6 **Orientation**	ST1	Building orientation
	ST2	Change of building orientation of BM_1 from N_S direction to 30◦ NE

Table 3-17 Overview of the Sub-Tasks of Task 6

3.3.3.7   Task 7

Task seven has only one Sub-Tasks, shown in Table 3-18, as it explores the following interoperability questions:

o *How does Revit export coordinates to IFC file?*
o *How does IDA-ICE interpret the coordinates from an incoming BIM model through an IFC file?*

Task	Sub-Task	Sub-Task Description
7 **Coordinates**	ST1	Coordinates of elements

Table 3-18 Overview of the Sub-Tasks of Task 7

3.3.3.8   Task 8

Task 8 explores shadings due to the addition of a horizontal shading in Building Model 2, and the addition of horizontal shadings and vertical fins in Building Model 4. two Sub-Tasks are defined, as can be observed in Table 3-19, to answer following interoperability questions:

o *How shadings and fins are created in Revit and exported to IFC?*
o *How does IDA-ICE understand the shadings in the BIM model?*

Task	Sub-Task	Sub-Task Description
8 **Shading**	ST1	Horizontal shading (South façade) BM_2
	ST2	Horizontal and vertical shading (E/W facade) BM_4

Table 3-19 Overview of the Sub-Tasks of Task 8

3.3.4   Case-Studies

In this section, a systematic overview of the cases and the results are provided. The organization of this section is based on the Tasks, Sub-Tasks, and the Building Models under the investigation. Firstly, the name of the case under investigation is presented through a Systematic reference that is summarized in Table 3-20. As an instance, Case01: T1_ST1_BM1 denotes the Sub-Task1 of the Task1 in the Building Model 1.

Then, *Interoperability issue* is introduced with some brief descriptions about the case under investigation. Subsequently, the *Methodology and Results* are presented. All cases follow this exact protocol to explore and explain the interoperability issues.

Cases	Task	Sub-Task	Building Model	Systematic Reference
1	T1	ST1	BM1	T1_ST1_BM1
2	T1	ST2	BM1	T1_ST2_BM1
3	T1	ST3	BM1	T1_ST3_BM1
4	T1	ST4	BM1	T1_ST4_BM1
5	T2	ST1	BM1	T2_ST1_BM1
6	T2	ST2	BM1	T2_ST2_BM1
7	T2	ST3	BM1	T2_ST3_BM1
8	T2	ST4	BM1	T2_ST4_BM1
9	T2	ST5	BM1	T2_ST5_BM1
10	T2	ST6	BM1	T2_ST6_BM1
11	T3	ST1	BM1	T3_ST1_BM1
12	T3	ST2	BM1	T3_ST2_BM1
13	T4	ST1	BM1	T4_ST1_BM1
14	T5	ST1	BM1	T5_ST1_BM1
15	T5	ST2	BM1	T5_ST2_BM1
16	T6	ST1	BM3	T6_ST1_BM3
17	T6	ST2	BM3	T6_ST2_BM3
18	T7	ST3	BM1	T7_ST3_BM1
19	T8	ST1	BM2	T8_ST1_BM2
20	T8	ST2	BM4	T8_ST2_BM4

Table 3-20 Overview of cases and the Systematic Reference naming

3.3.4.1   Case 01

3.3.4.1.1   Systematic reference

T1_ST1_BM1

3.3.4.1.2   Interoperability issue

The interoperability issue of this case is whether the differences of Location Line placement in Revit affects the walls in IDA-ICE's building body and zone.

Case 01 is the first case in the series of Sub-Tasks of Task 1 that explores the "Wall Location Line" in Revit. To clarify how the wall location lines' options inside the Revit affects the export of element to IFC, and how they are interpreted by the IDA-ICE software, Case 01 was investigated.

A "Wall" element has several properties in Revit, including Location Line, base, and top constraints, height, and etc. For the purpose of studying this Task, wall's Location Line property was chosen. According to

Autodesk [120], wall's Location Line identifies which of its vertical planes is used to position the wall in relation to the path that user sketches or otherwise specifies in the drawing area. Wall Location Line should be chosen before placing the wall in Revit, and by default, it is "Centerline." There are six options for choosing wall's location line:

I. Wall Centerline (default)

II. Core Centerline

III. Finish Face: Exterior

IV. Finish Face: Interior

V. Core Face: Exterior

VI. Core Face: Interior

Figure 3-50, visualizes the differences between the location lines in a wall element in Revit. As can be observed, a wall's center-line is the geometric centerline of the wall, while, the Finish Face Exterior, is the exterior side of the wall, and Finish Face Interior is the interior side of the wall. Likewise, Core is highlighted here in orange color. Thus, the core can have its interior face, an exterior face, and centerline, too. In this context, the core of a wall refers to the primary structural layer or layers of the wall defined by Revit. That said, in a simple brick wall, the Wall Centerline and Core Centerline planes would coincide, whereas they could be different in a compound wall [120, 121].
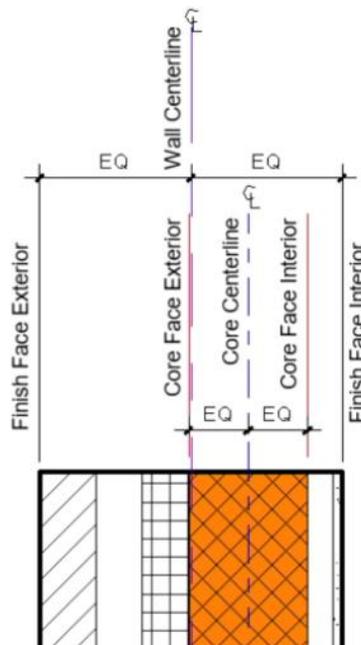
Figure 3-50 Visualization of the six different wall Location Lines in Revit [121].

3.3.4.1.3 Methodology and Results

Figure 3-51 is the plan view of the Building Model 1 developed in Revit for the Case 01. In Case 01, the walls are drawn based on the centerline. This is shown in Figure 3-52, wherein the *Constraints section* of the *Properties palette*, the Location Line is set to Wall Centerline; and the blue dot on the wall shows the centerline's position on the wall.
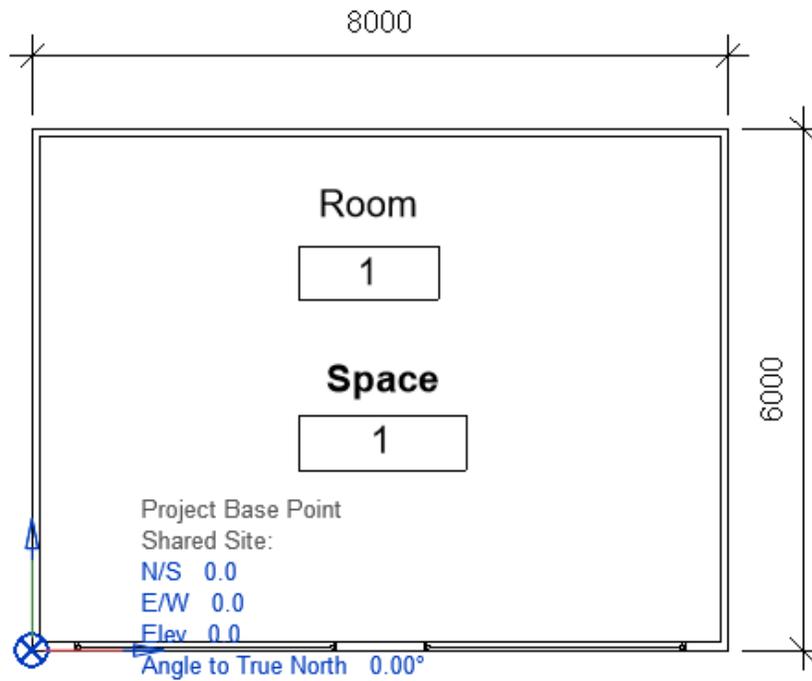
Figure 3-51 plan view of the Building Model 1 (Case 01)
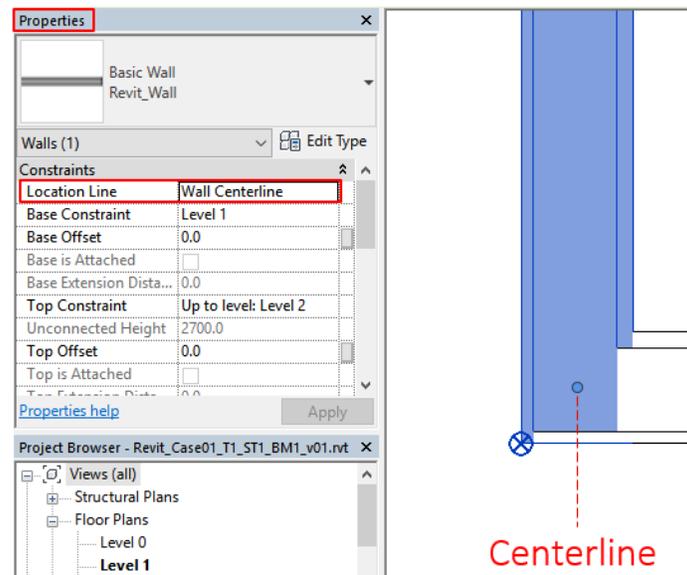
Figure 3-52 Location Line, Properties palette, and wall centerline (Case 01)

A snapshot of the Revit's interface showing the total thickness of the wall, 87.9 mm, is presented in Figure 3-53. This is the wall's face to face dimension.

	Function	Material	
1	Finish 1 [4]	Revit_Wood Siding_Siding, Clapboard	9.3
2	Thermal/Air Layer [3]	Revit_Fiberglass Quilt_Fiberglass Batt	66.3
3	**Core Boundary**	**Layers Above Wrap**	**0.0**
4	Structure [1]	Revit_Plasterboard_Gypsum Wall Board	12.3
5	**Core Boundary**	**Layers Below Wrap**	**0.0**

Figure 3-53 Thickness of the wall in Revit

After the development of the model in Revit, it was exported to IFC as explained in Section 3.1.4.3. Subsequently, the IFC file was imported to IDA-ICE as elaborated in Section 3.2.2.1.

When the model was imported to IDA-ICE, two initial observations were made that requires an explanation of Figure 3-54 and Figure 3-55.

As previously described, IDA ICE has a building body and a zone. By looking at the green arrow in Figure 3-54, it can be seen that this window shows the *Level1*. This is the level in which the current building model is constructed. Therefore, "*Level 1*" points out that the "building body" has been selected in the Floor plan Tab. On the contrary, the zone has been selected in the Floor Plan Tab in Figure 3-55, and by looking at the green arrow, it can be seen that IDA ICE considers this as a "Space".

The building body in Figure 3-54, red box number 1, shows the *size* of the wall (in meter) that is imported through IFC. In other words, this *size* is the length of the wall. With simple calculation for the larger wall length (8 meters wall in South and North Facade), it can be understood that:

$8000 - 2 * (87.9) = 782.4$ millimeters

In this calculation, 8000 refers to the face to face length of the wall on the North/South Façade, and 87.9 is the thickness of the wall as previously shown in Table 3-7, and Figure 3-53.

Furthermore, the x and y coordinates in red box number 1, in Figure 3-54, have Max and Min values. The Min value of x is 0.88, that is the whole thickness of the wall. This means that the geometry of the building was imported correctly.

In contrast, the red box number 1 in Figure 3-55, has only *Origin*, and *Size*. It seems that only this information is necessary for the zone and thermal energy calculations in IDA-ICE.

Moreover, the red box number 2 in the lower left corner of Figure 3-54, demonstrates the four corners of the building body that is reconstructed in IDA-ICE based on IFC input file. This complies with the same coordinates that were inserted in Revit. On the contrary, the red box number 2 in Figure 3-55, that reports the zone in IDA-ICE, has a corner that starts from (0,0) coordinates. This means that IDA-ICE uses its own coordinates for the zone and thermal calculations of the model.
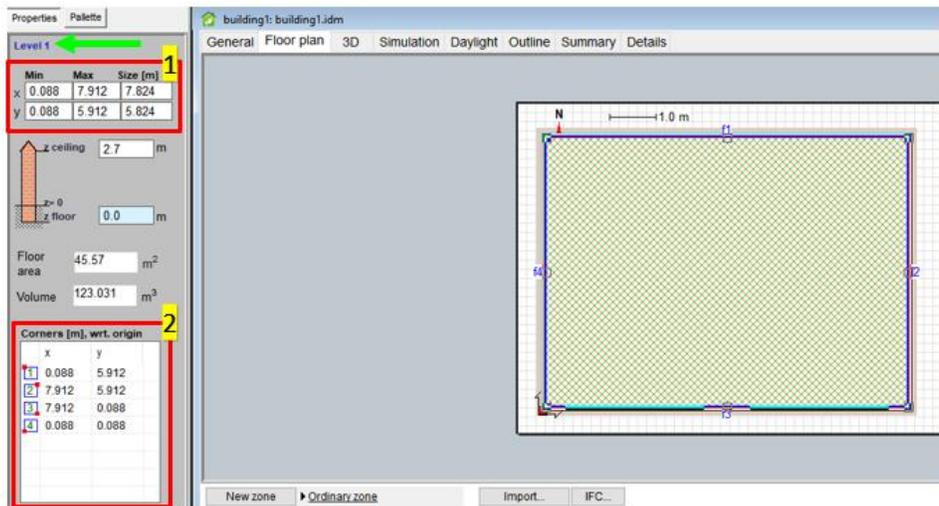
Figure 3-54 Building body in IDA-ICE (Case 01)
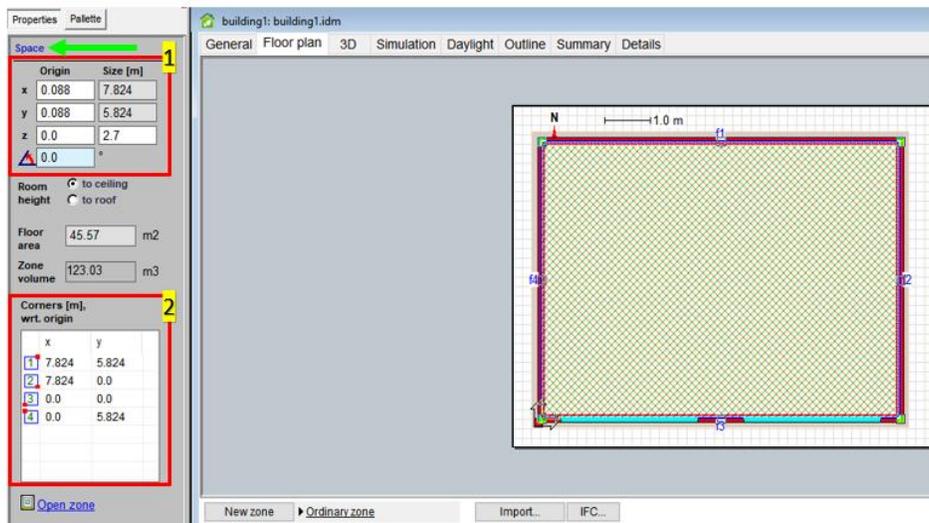
Figure 3-55 Zone in IDA-ICE (Case 01)

Finally, it should be mentioned that the corner of the building body and the zone can also be accessed through Outline tab in IDA-ICE, as shown in Figure 3-56 and Figure 3-57.
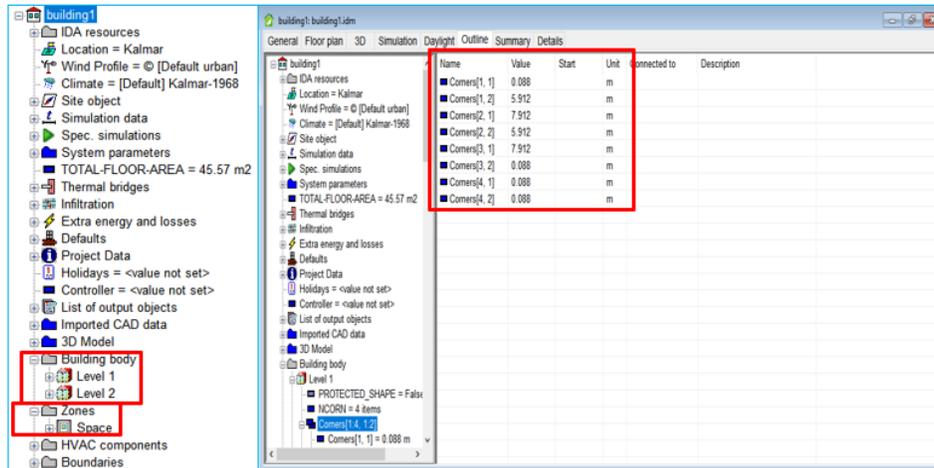
Figure 3-56 Corners of building model in IDA-ICE (Case 01)
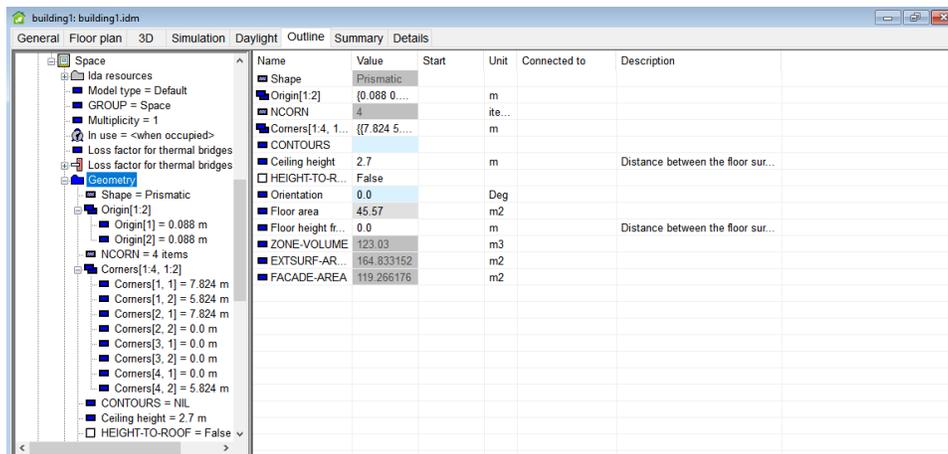
Figure 3-57 Corners of the zone in IDA-ICE (Case 01)

Furthermore, to answer one of the questions of <u>Task 1</u> that was "*Can Revit export Location line type of the walls to IFC*"? As can be seen in Figure 3-58, since Location Line is a property of Revit's wall elements (Figure 3-52), it is exported precisely to the IFC file. It is possible to open IFC-STEP files in notepad.

The information about the wall is first exported to IfcWallStandardCase, Figure 3-58.

According to BuildingSMART [73], "the standard wall (IfcWallStandardCase) defines a wall with certain constraints for the provision of parameters and with certain constraints for the geometric representation. The IfcWallStandardCase handles all cases of walls that is extruded vertically."

- o along the positive z-axis of the wall local placement coordinate system, and
- o along the positive z-axis of the global (world) coordinate system

and have a single thickness along the path, i.e.:

- o parallel sides for straight walls
- o co-centric sides for curved walls.

The following parameter shall be given:

- o Wall height, taken from the depth of extrusion, provided by the geometric representation.
- o Wall thickness, taken from the material layer set usage, attached to the wall
- o Wall offset from the axis, taken from the material layer set usage, attached to the wall

The material of the wall is defined by the IfcMaterialLayerSetUsage and is attached by the IfcRelAssociatesMaterial objectified relationship. It is accessible by the inverse HasAssociationsrelationship. The material layer set usage has to be given (enforced by where rule)."

```
#526= IFCWALLSTANDARDCASE('3cFIX6YNjFHAPmSUEb8dgl',#41,'Basic Wall:Revit Wall:326633',$,'Basic Wall:Revit Wall:326961',#499,#524,'326633');
#535= IFCMATERIAL('Revit_Wood Siding_Siding, Clapboard');
#538= IFCPRESENTATIONSTYLEASSIGNMENT((#515));
#540= IFCSTYLEDITEM($,(#538),$);
#542= IFCSTYLEDREPRESENTATION(#97,'Style','Material',(#540));
#545= IFCMATERIALDEFINITIONREPRESENTATION($,$,(#542),#535);
#548= IFCMATERIAL('Revit_Fiberglass Quilt_Fiberglass Batt');
#549= IFCCOLOURRGB($,0.407843137254902,0.407843137254902,0.407843137254902);
#550= IFCSURFACESTYLERENDERING(#549,0.,$,$,$,$,IFCNORMALISEDRATIOMEASURE(0.5),IFCSPECULAREXPONENT(64.),.NOTDEFINED.);
#551= IFCSURFACESTYLE('Revit_Fiberglass Quilt_Fiberglass Batt',.BOTH.,(#550));
#553= IFCPRESENTATIONSTYLEASSIGNMENT((#551));
#555= IFCSTYLEDITEM($,(#553),$);
#557= IFCSTYLEDREPRESENTATION(#97,'Style','Material',(#555));
#559= IFCMATERIALDEFINITIONREPRESENTATION($,$,(#557),#548);
#562= IFCMATERIAL('Revit_Plasterboard_Gypsum Wall Board');
#563= IFCCOLOURRGB($,0.894117647058824,0.894117647058824,0.894117647058824);
#564= IFCSURFACESTYLERENDERING(#563,0.,$,$,$,$,IFCNORMALISEDRATIOMEASURE(0.5),IFCSPECULAREXPONENT(64.),.NOTDEFINED.);
#565= IFCSURFACESTYLE('Revit_Plasterboard_Gypsum Wall Board',.BOTH.,(#564));
#567= IFCPRESENTATIONSTYLEASSIGNMENT((#565));
#569= IFCSTYLEDITEM($,(#567),$);
#571= IFCSTYLEDREPRESENTATION(#97,'Style','Material',(#569));
#573= IFCMATERIALDEFINITIONREPRESENTATION($,$,(#571),#562);
#576= IFCMATERIALLAYER(#535,9.3,$);
#578= IFCMATERIALLAYER(#548,66.3,$);
#579= IFCMATERIALLAYER(#562,12.3,$);
#580= IFCMATERIALLAYERSET((#576,#578,#579),'Basic Wall:Revit_Wall');
#585= IFCMATERIALLAYERSETUSAGE(#580,.AXIS2.,.NEGATIVE.,43.95);
#586= IFCWALLTYPE('3cFIX6YNjFHAPmSUEb8dnt',#41,'Basic Wall:Revit_Wall',$,$,(#652,#654,#656,#658,#660,#662),$,'326961',$,.STANDARD.);
#588= IFCPROPERTYSINGLEVALUE('Base Constraint',$,IFCLABEL('Level: Level 1'),$);
#589= IFCPROPERTYSINGLEVALUE('Base Extension Distance',$,IFCLENGTHMEASURE(0.),$);
#590= IFCPROPERTYSINGLEVALUE('Base is Attached',$,IFCBOOLEAN(.F.),$);
#591= IFCPROPERTYSINGLEVALUE('Location Line',$,IFCIDENTIFIER('Wall Centerline'),$);
#592= IFCPROPERTYSINGLEVALUE('Related to Mass',$,IFCBOOLEAN(.F.),$);
#593= IFCPROPERTYSINGLEVALUE('Room Bounding',$,IFCBOOLEAN(.T.),$);
#594= IFCPROPERTYSINGLEVALUE('Top Constraint',$,IFCLABEL('Level: Level 2'),$);
```

Figure 3-58 Location Line in IFC

If the *Export base quantities* option, as shown in Figure 3-59, is checked when the model was exported from Revit to IDA-ICE, then, a set of properties such as length, area, volume, etc. is transferred to the output IFC file as shown inFigure 3-60. In the following paragraphs, some of these quantities are explained based on IFC2x3 definitions provided by Building SMART.
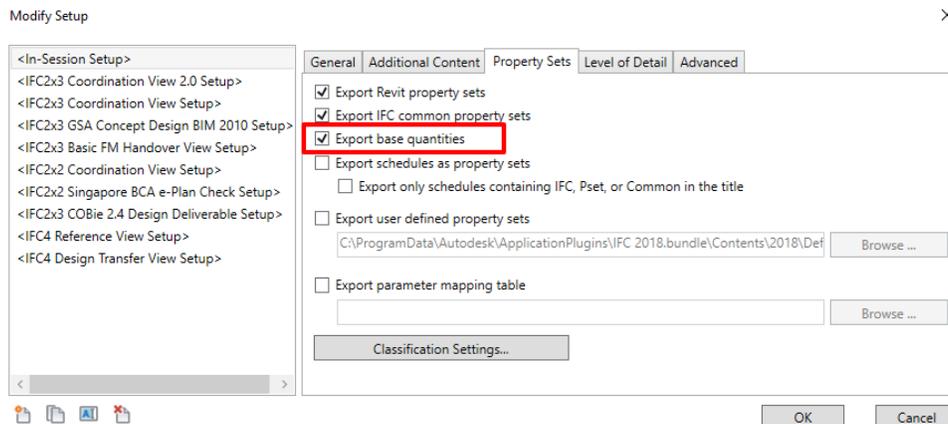
Figure 3-59 IFC Exporter setting, Export base quantities option

```
#546= IFCWALLSTANDARDCASE('3cFIX6YNjFHAPmSUEb8dgl',#41,'Basic Wall:Revit_Wall:326633',$,'Basic Wall:Revit_Wall:326961',#519,#544,'326633');
#555= IFCQUANTITYLENGTH('Height',$,$,2700.);
#556= IFCQUANTITYLENGTH('Length',$,$,6000.);
#557= IFCQUANTITYLENGTH('Width',$,$,87.9);
#558= IFCQUANTITYAREA('GrossFootprintArea',$,$,0.5274);
#559= IFCQUANTITYAREA('GrossSideArea',$,$,16.2);
#560= IFCQUANTITYVOLUME('GrossVolume',$,$,1.42398);
#561= IFCELEMENTQUANTITY('1hLBjo7jbAYxlfpWIWB1_K',#41,'BaseQuantities',$,$,(#555,#556,#557,#558,#559,#560));
#563= IFCRELDEFINESBYPROPERTIES('3LDxnDqzn99go2T653d8Ah',#41,$,$,(#546),#561);
#567= IFCMATERIAL('Revit_Wood Siding_Siding, Clapboard');
#570= IFCPRESENTATIONSTYLEASSIGNMENT((#535));
#572= IFCSTYLEDITEM($,(#570),$);
```

Figure 3-60 Quantities exported to IFC via "Export base quantities."

IfcQuantityLength is a physical quantity that defines a derived length measure to provide an element's physical property. It is normally derived from the physical properties of the element under the specific measure rules given by a method of measurement [122].

A physical quantity, IfcQuantityArea, that defines a derived area measure to provide an element's physical property. It is normally derived from the physical properties of the element under the specific measure rules given by a method of measurement [123].

IfcQuantityVolume describes a physical quantity that defines a derived volume measure to provide an element's physical property. It is normally derived from the physical properties of the element under the specific measure rules given by a method of measurement [124].

3.3.4.1.4   Conclusion
No interoperability issue was found in this case.

While the origin of the zone and building body coincides in IDA-ICE, both start from the interior face of the wall, ignoring the location line of the wall in Revit. However, to prove this result, further cases should be explored.

The Location Line is exported to IFC and has no influence on the wall in IDA-ICE BEM model.

The geometry of wall including length, thickness, and height is correctly exported to IFC and imported to IDA ICE.

3.3.4.2   Case 02

3.3.4.2.1   Systematic Reference
T1_ST2_BM1

3.3.4.2.2   Interoperability issue
The interoperability issue is whether the differences of Location Line placement in BIM-authoring tool, Revit 2018, affects the walls in IDA-ICE's building body and zone.

Case 02 is the continuation of Case 01 and is the second case in the series of Sub-Tasks of Task 1 that explores the "Wall Location Line" in Revit. The Location line that was chosen for this model is *Core Centerline*, and a new model was constructed in Revit with this property, as shown in Figure 3-61.

The core of the wall is the Plasterboard layer with the thickness of 12 millimeters (Figure 3-53). This explains the location of the blue dot in Figure 3-61.
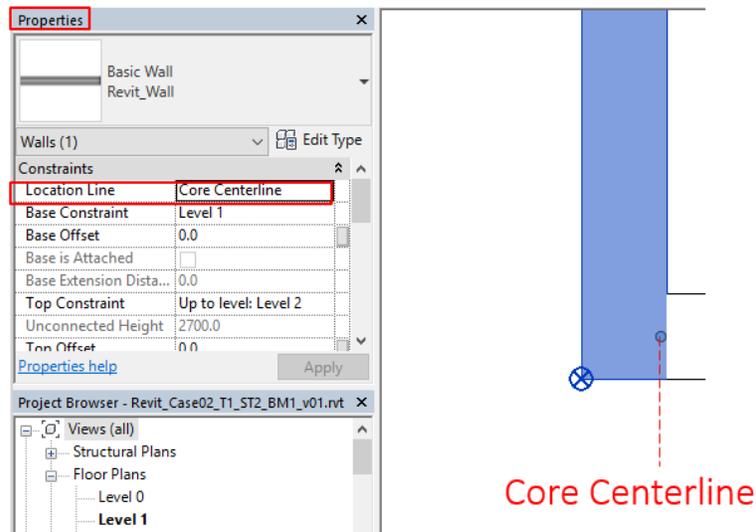
Figure 3-61 Location Line, Properties palette, and wall Core centerline (Case 02)

3.3.4.2.3 Methodology and Results

The same methodology as Case 01 was followed for the Case 02.

In Case 02, the same wall coordinates were reported by IDA-ICE (Figure 3-62, and Figure 3-63), that was reported in Case 01. Indeed, the building body has been reconstructed on the exam same coordinates that came from the Revit model.
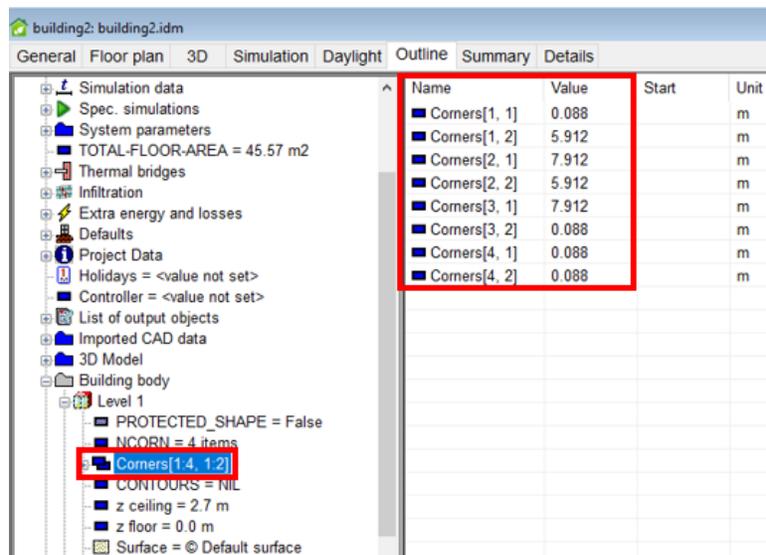
Figure 3-62 corners of the walls (coordinates) in IDA-ICE's Outline tab

3.3.4.2.4 Conclusion

No interoperability issue was found in this case.

Based on this case observations, it can be concluded that Location Line does not affect the wall geometry of the BIM-based energy model in IDA-ICE.
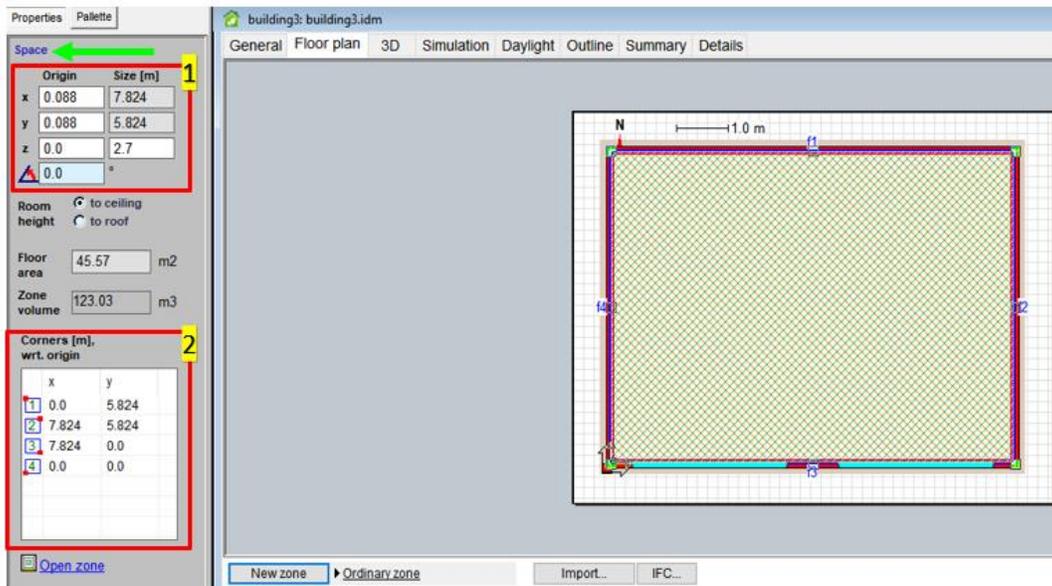
Figure 3-63 Zone in IDA-ICE (Case 02)

3.3.4.3   Case 03

3.3.4.3.1   Systematic Reference

T1_ST3_BM1

3.3.4.3.2   Interoperability issue

The interoperability issue is whether the differences of Location Line placement in BIM-authoring tool, Revit 2018, affects the walls in IDA-ICE's building body and zone.

To ensure the validity of the results achieved by Case 01 and Case 02, regarding the possible interoperability issues between the Location line of Revit's wall element and the imported wall geometry in IDA-ICE, Case 03 was examined.

3.3.4.3.3   Methodology and Results

The methodology is similar to Case 01, except that the Location line, in this case, is set to Finish Face: Exterior, Figure 3-64.

3.3.4.3.4   Conclusion

No interoperability issue was found in this case. Since "Finish Face: Exterior" acts similar o "Finish Face: Interior," we avoided examining that Location line.
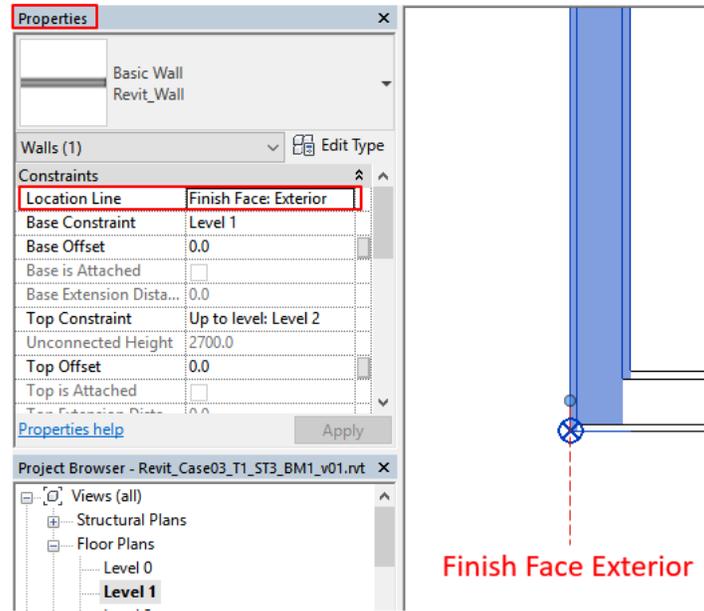
Figure 3-64 Location Line, Properties palette, and wall Finish Face: Exterior (Case 03)

3.3.4.4   Case 04

3.3.4.4.1   Systematic Reference
T1_ST4_BM1

3.3.4.4.2   Interoperability issue
The interoperability issue is whether the differences of Location Line placement in BIM-authoring tool, Revit 2018, affects the walls in IDA-ICE's building body and zone.

This case is the last case in the series of Sub-Tasks of Task 1 that explores the "Wall Location Line" in Revit. In the Case 04, Wall's "Core Face: Interior" is explored

To ensure the validity of the results achieved by Case 01 and Case 02, regarding the possible interoperability issues between the Location line of Revit's wall element and the imported wall geometry in IDA-ICE, Case 03 was examined.

3.3.4.4.3   Methodology and Results
Wall's "Core Face: Interior" is explored in Case 04, through the similar methodology as Case 01. That said, examining Wall's "Core Face: Exterior" type of wall location line was avoided due to its similar behavior to Wall's "Core Face: Interior."

3.3.4.4.4   Conclusion
Indeed, no interoperability issue was found in Case 04 as the wall's geometrical information has been exchanged between BIM and BEM tools seamlessly.
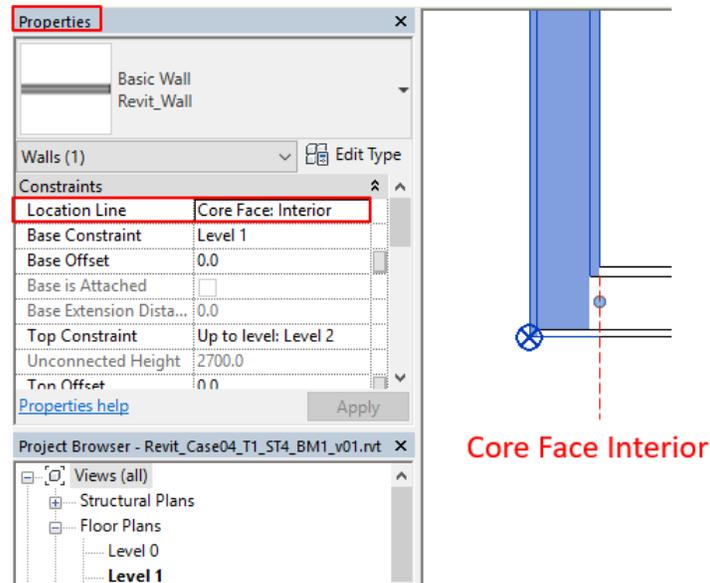
Figure 3-65 Location Line, Properties palette, and wall Core Face: Interior (Case 04)

We can safely conclude that Revit wall's location line in the BIM model, has no influence in the geometry of walls in building body, and in the zone, in IDA-ICE interface.

Although the type of "location line" is exported from Revit to IFC, IDA-ICE reconstructs the walls coming from an IFC building models based on the interior face to face length of the wall or the zone and based on the thickness of the wall.

3.3.4.5   Case 05
3.3.4.5.1   Systematic Reference
T2_ST1_BM1

3.3.4.5.2   Interoperability issue
The interoperability issue is how does IDA-ICE react to a Revit-based BIM model that has no Room, Space, or Zone element in the Revit model?

Case 05 is the first case in series of Sub-Tasks of Task 2 that check how the building model information about Room, Space, and Zone are exported to IFC. Also, Case 05 helps to understand the impacts of presence or absence of Revit's Room, and Space components on IDA-ICE's perception of the space and zone. In other words, we want to see if upon importing an IFC file of a model without Revit's Room, and Space components, IDA-ICE automatically assign a zone to the areas or not?

3.3.4.5.3   Methodology and Results
The base model is the same as Case 01. However, there is no Room, Space, or Zone element present in the Revit model. The model is exported from Revit to IFC as explained in Section 31.4.3. Then, the IFC file is imported to IDA-ICE as explained Section 3.2.2.1.

Since no Room, Space, or Zone was placed inside the building geometry, no information about Room or Space is exported to IFC. As a result, after importing IFC to IDA-ICE, no semi-automatic zone assignment happened. The user must draw the zone by hand, by clicking on the outlines of the room.

In case 05, the Revit model held only the geometrical information. No semantic information about whether the area is a Room or Space, existed in the model as shown in Figure 3-66. This led to IDA-ICE treating the IFC model in the same way. IDA-ICE did not assign any zone to the imported geometry automatically.

3.3.4.5.4   Conclusion

It cannot be concluded that an interoperability issue was found, because the aim of this case was to show that if no Room or Space is placed in the Revit, then IDA-ICE will treat this BIM model as a "geometry only" input.
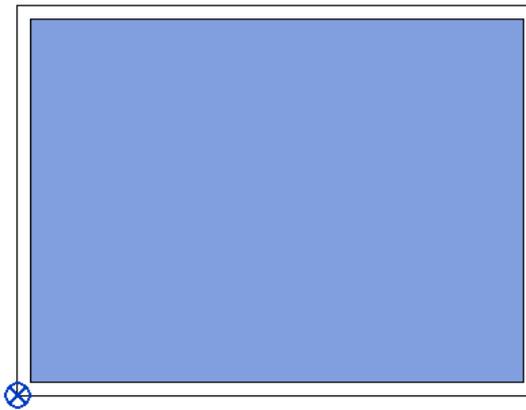
Figure 3-66 Plan view of the Building Model 1 <u>without Room or Space elements</u> (Case 05)

3.3.4.6   Case 06

3.3.4.6.1   Systematic Reference
T2_ST2_BM1

3.3.4.6.2   Interoperability issue
In this case, we want to explore how the placement of only Room element components in BIM, affects the IFC file and the BEM model?

For this purpose, Case 06 has only Room element inside the enclosed building area in Revit. Room element is explained in <u>Section 3.1.3.1</u>. In other words, Case 06's interoperability issue is the interaction of a BIM-based building model having a room element, which is an architectural component, with the zone assignment inside IDA-ICE interface. This case was proposed because It is unclear whether IDA-ICE can automatically understand that an enclosed building body is actually a thermal space if only Room element is present in the Revit-based IFC input.

3.3.4.6.3   Methodology and Results
The methodology consists of following steps:

    I.   Room element (and subsequently room tag element) was placed on the area, inside the enclosed geometry of the BESTEST600 or Building Model 1.
    II.   The model was exported to IFC.

III.   The IFC was imported to IDA-ICE.

The Room element should be carefully placed, and considerable attention should be directed towards the "Upper Limit" and "Limit Offset" properties. Because both of these properties define the upper boundary of the room [125]. It should be noted that *Upper Limit* defines the level from which the upper boundary of the room is measured [126]. Correspondingly, *Limit Offset* describes the distance at which the upper boundary of the room occurs [126]. Filling in this information inside Revit could be tricky. There are two ways to create a Revit Room inside an enclosed building body appropriately.

In Figure 3-67, A and B, the Level we are working in, i.e., Level 1, is dimmed and unchangeable. The first option is to choose the Upper Limit as Level 2 and assign 0 value to the Limit Offset (Figure 3-67, A). In this way, the building height goes from level 1 to level 2 and has 0 offset from level 2. The outcome is a room height of 2700mm or 2.7 meters. The second option (Figure 3-67, B) is to choose the Level 1 as the Upper Limit, and define the Limit Offset as 2700 millimeters. This would create a room with a height of 2700 millimeter (2700 offsets from Level 1). In a nutshell, the result of these two methods is the same.
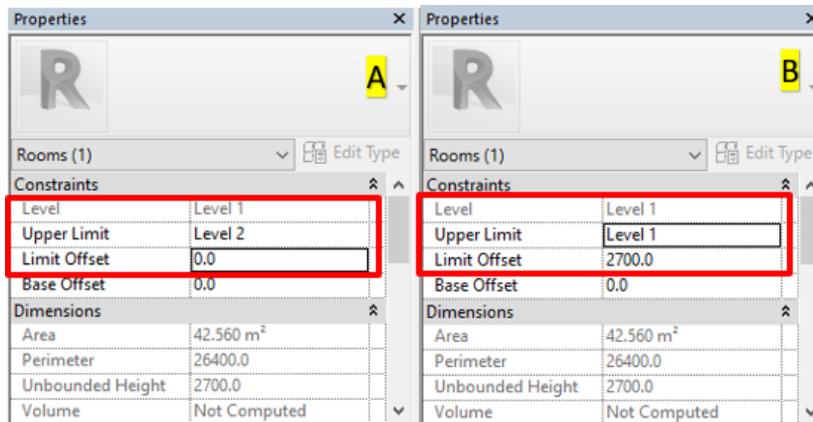
Figure 3-67 Room Properties, Defining Upper Limit, and Limit Offset

After adjusting the height of the room element with the height of the wall, the Revit model was exported to IFC, and further imported to IDA-ICE. Despite the enclosed building having a Room element and Room tag in Revit, IDA-ICE could not automatically detect any spaces in the Floor view tab. Just like the case of building with no Revit room/space element, Case 05, "Zones" should be manually drawn in IDA-ICE by the users.
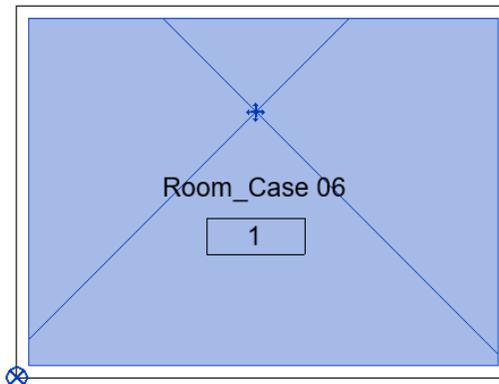
Figure 3-68 Plan view of the Building Model 1 with Room element (Case 06)

It should be mentioned that the room information is saved in *IfcSpace class*, #153, highlighted in Figure 3-69. However, upon exporting the Revit property sets to IFC, the *Name* of the room, and its *Category* is stored in *IfcPropertySingleValue* rule, #242, and #243 in Figure 3-70.

```
#150= IFCSPACE('1B1hkdxbr0Y9E4$22idFzH',#41,'1',$,$,#133,#146,'Room_Case 06',.ELEMENT.,.INTERNAL.,$)
#155= IFCCARTESIANPOINT((2700.,0.));
#157= IFCCARTESIANPOINT((2700.,5800.));
#159= IFCCARTESIANPOINT((0.,5800.));
#161= IFCPOLYLINE((#9,#155,#157,#159,#9));
#163= IFCCARTESIANPOINT((100.,100.,0.));
#165= IFCAXIS2PLACEMENT3D(#163,#13,#19);
#166= IFCPLANE(#165);
```

Figure 3-69 IFC file, IfcSpace, Revit's Room element

```
#239= IFCPROPERTYSINGLEVALUE('Reference',$,IFCIDENTIFIER('Room Case 06 1'),$);
#240= IFCPROPERTYSINGLEVALUE('Category',$,IFCLABEL('Rooms'),$);
#241= IFCPROPERTYSET('2VEt4F5kb4vu13vKGFfJ1d',#41,'Pset_SpaceCommon',$,(#239,#240));
#246= IFCRELDEFINESBYPROPERTIES('1T4gqO_Mz0eQ4c8mIsFgYj',#41,$,$,(#150),#241);
```

Figure 3-70 IFC file, IfcPropertySingleValue

IfcPropertySingleValue class is "a property with a single value that defines a property object which has a single (numeric or descriptive) value assigned. It defines a property - single value combination for which the property name, the value with measure type (and optionally the unit) is given" [127].

3.3.4.6.4   Conclusion
The interoperability issue found here was that IDA-ICE could not automatically detect a thermal zone if only Room element is available in the model.

The importance of this finding is because many Revit-based BIMs that are developed by architects has only Room elements to assign occupancy information and the usability of the room. Therefore, this case proved that for a BIM-based energy simulation in IDA-ICE, Room element is not enough.

Therefore, we have a suggestion for IDA-ICE to improve their algorithm in order for Room elements to be treated as zones for the semi-automatic assignment of the zone in IDA-ICE.

3.3.4.7   Case 07
3.3.4.7.1   Systematic Reference
T2_ST3_BM1

3.3.4.7.2   Interoperability issue
In Case 07, the interoperability issue is how does the placement of only Space element in Revit (BIM), affect the IFC file and the BEM model?

It this section, the Space element will be added to the building information model in Revit. There are no other elements present, namely: no room, or no zone.

We want to see how The Space element is written into IFC through Revit's IFC exporter. And, how does IDA-ICE read and react to The Space element coming from a Revit project?

3.3.4.7.3 Methodology and Results

Case 07 investigates the Space element in Revit. Space element is explained in <u>Section 3.1.3.2.</u> Space can be placed on the enclosed building body in the presence and absence of Room element inside the Revit software. Case 07 only explores Space element placement in the absence of Room element in the model,

Room and Space are different elements by nature, since each of them, stores specific information (explained in <u>Appendix B</u>). However, the same discussion about the height of the Room element in <u>Case 06</u> applies also to the height of the Space element. Eventually, following the same methodology as Case 06, after placing the space element in Revit, the model was exported to IFC, and then imported to IDA-ICE.

In Figure 3-72 below, it can be seen that the *Space element* is stored in IfcSpace class. The name of the Space element was intentionally changed to "Space_Case 07" to track it inside the IFC file.
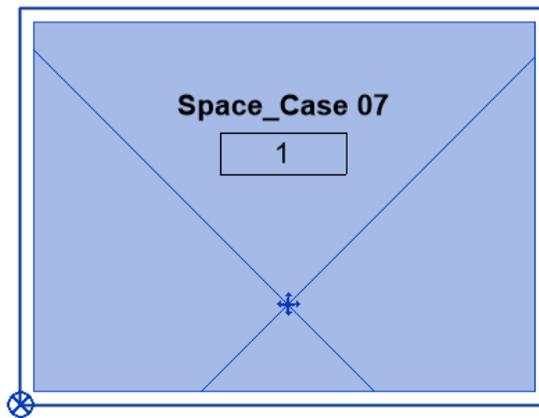
Figure 3-71 Plan view of the Building Model 1 <u>with Space element</u> (Case 07)

```
#150= IFCSPACE('2dqkysQgPB5OijcqPWnnhb',#41,'1',$,$,#133,#146,'Space_Case 07',.ELEMENT.,.INTERNAL.,$);
#155= IFCPROPERTYSINGLEVALUE('Reference',$,IFCIDENTIFIER('Space_Case 07 1'),$);
#156= IFCPROPERTYSINGLEVALUE('Category',$,IFCLABEL('Spaces'),$);
#157= IFCPROPERTYSET('0nsaPUTVr8Rhxa6brLp05G',#41,'Pset_SpaceCommon',$,(#155,#156));
#162= IFCRELDEFINESBYPROPERTIES('2dW68jNCHBpAkBTvKO1ak7',#41,$,$,(#150),#157);
```

Figure 3-72 IFC file, IfcSpace, Revit's Space element

After importing the BIM-based IFC file into IDA-ICE, we observed that no automatic zone detection and assignment occurred inside IDA-ICE. Therefore, the user must manually draw the zones.

The result was as unpredicted as it could be. Again, the zone should be drawn by hand in this case, as just like the Case 09, no automatic space detection has occurred during the import of IFC to IDA-ICE. This was an unpredicted result. Because Space element in Revit stores information about heating and cooling loads and is specifically used for energy analysis purposes. Therefore, the assumption before exploring this case was that the presence of Space element inside Revit would lead to the automatic detection of Zones, or Spaces inside IDA-ICE. This assumption proofed to be not true.

3.3.4.7.4 Conclusion

The interoperability issue is that IDA-ICE cannot automatically detect thermal zone, even though the BIM model has Space element inside it.

3.3.4.8   Case 08

3.3.4.8.1   Systematic Reference

T2_ST4_BM1

3.3.4.8.2   Interoperability issue

In Case 08, the interoperability issue is how does the placement of only Zone element in Revit (BIM), affect the IFC file and the BEM model?

The logic dictates that the next case after placing a Room element, and then Space element, should be placing a Zone element. However, two technical issues exist here that make it impossible to develop and create Case 10 inside Revit. Firstly, as explained in Section 3.1.3.2 and Section 3.1.3.3, when a Space is added inside Revit, it is automatically assigned to a default zone. Therefore, a Zone already exists in the model.

Secondly, the Zone element can only be placed if a Space element already exists in the model. Therefore, it is not feasible to develop Case 10 with only Zone element, and it is not possible to explore the interoperability issues due to the presence of the only Zone in the model.

The reason Case 08 was not omitted from the list of cases, and also it is being explained here is to answer the curiosity of other Revit users and BIM modelers that are reading this section.

3.3.4.9   Case 09

3.3.4.9.1   Systematic Reference

T2_ST5_BM1

3.3.4.9.2   Interoperability issue

In Case 09, the interoperability issue is how does the placement of both Room and Space element in Revit (BIM), affect the IFC file and the BEM model?

After exploring the possibility and conditions of adding Room and Space elements in Revit separately, Case 09 is developed to examine the exchange of information between Revit and IDA-ICE when both Room and Space elements are placed in the model in one enclosed building body.

Through cases 07 and 08, it became clear that IDA-ICE does not, not necessary cannot, read the information about space from only Room element or only Space element. Therefore, the combination of these two semantic elements is explored here to see if the interoperability issue still insists.

3.3.4.9.3   Methodology and Results

As depicted in Figure 3-73, both Room and Space elements are placed in the enclosed geometry in the building model. Then, the model was exported to IFC, and IFC was imported to IDA-ICE.

After the IFC import in IDA-ICE, there was no need to draw a zone manually. In fact, zones were easily detected by IDA-ICE, shown in Figure 3-74.

As a result of exploring Case 09, it is safe to say that IDA-ICE can automatically detect a space coming from the imported IFC file of a Revit-based BIM model if both Space and Room elements are present in the enclosed area, Figure 3-74.

Figure 3-75 shows the Case 09's IFC output file. As can be observed, both Room and Space elements are exported to IfcSpace class.
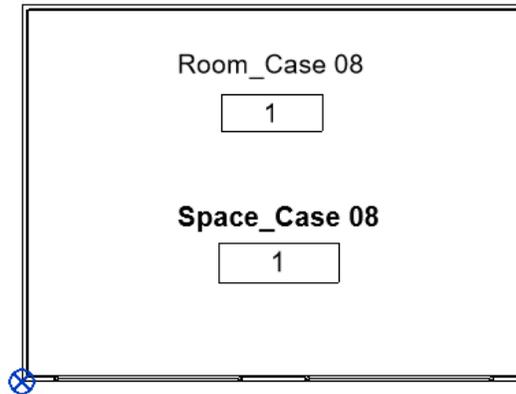
Figure 3-73 plan view of the Building Model 1 <u>with both Revit's Room and Space elements</u> (Case 08)

The reason we say Revit-based BIM model is that we cannot generalize this result to other BIM authoring tools since their semantic information might be different.

Based on AQUA documentation[128], "ICE relies on the existence of ifcSpaces for the creation of simulated zones." However, these case studies show that a successful BIM or IFC import to IDA-ICE requires more than IfcSpace classes. Because although IfcSpace class existed in Case 07, and Case 08, the *semi-automatic thermal zone assignment* could not be executed when only Room or only Space element existed in Revit model.
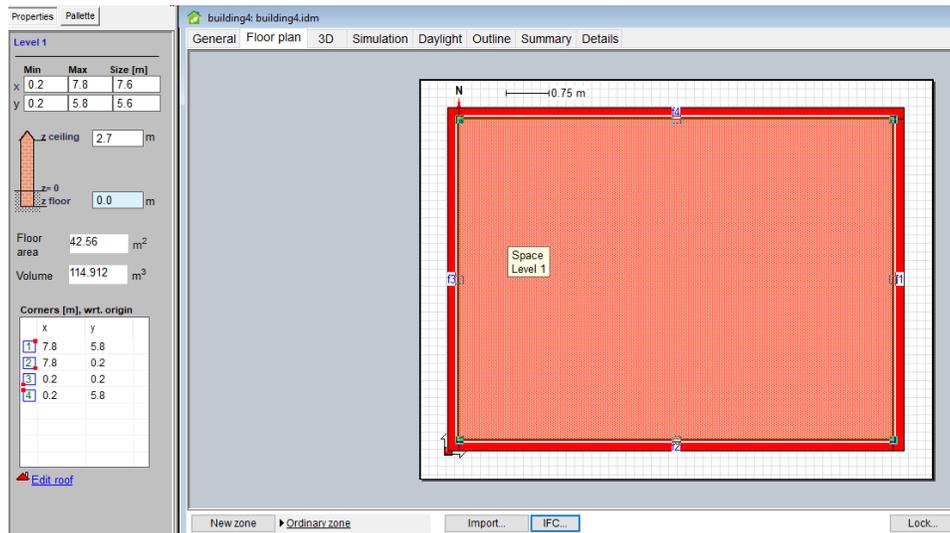
Figure 3-74 IDA-ICE interface, Automatic Zone assignment to the enclosed geometry (Case 09)

3.3.4.9.4 Conclusion

No interoperability issue was found in Case 09.

In conclusion, if the Revit project designed by the architects lacks both Room and Space elements in an enclosed building body, then, IDA-ICE is unable to detect and execute the *semi-automatic thermal zone assignment*. In other words, if both Room and Space elements are placed in Revit, then, IDA-ICE can

perform the *semi-automatic thermal zone assignment*, and there is no need for manual zone assignment by users.

```
#151= IFCCARTESIANPOINT((4000.,3000.,0.));
#153= IFCAXIS2PLACEMENT3D(#151,$,$);
#154= IFCEXTRUDEDAREASOLID(#150,#153,#19,2700.);
#155= IFCSHAPEREPRESENTATION(#102,'Body','SweptSolid',(#154));
#158= IFCPRODUCTDEFINITIONSHAPE($,$,(#155));
#162= IFCSPACE('24FR83Mbj7DA6iJ84W6rXY',#41,'1',$,$,#145,#158,'Room_Case 08',.ELEMENT.,.INTERNAL.,$);
#167= IFCCARTESIANPOINT((2843.9,0.));
#169= IFCCARTESIANPOINT((2843.9,5912.1));
#171= IFCCARTESIANPOINT((0.,5912.1));
    ⋮
#384= IFCSHAPEREPRESENTATION(#102,'Body','SweptSolid',(#383));
#386= IFCPRODUCTDEFINITIONSHAPE($,$,(#384));
#388= IFCSPACE('24FR83Mbj7DA6iJ84W6rXf',#41,'1',$,$,#375,#386,'Space_Case 08',.ELEMENT.,.INTERNAL.,$);
#391= IFCPROPERTYSINGLEVALUE('Reference',$,IFCIDENTIFIER('Space_Case 08 1'),$);
#392= IFCPROPERTYSINGLEVALUE('Category',$,IFCLABEL('Spaces'),$);
#393= IFCPROPERTYSET('1qhSFJwtX499Ni0MES0Uap',#41,'Pset_SpaceCommon',$,(#391,#392));
#395= IFCRELDEFINESBYPROPERTIES('3s3VH8tFTD1g17wocJHspI',#41,$,$,(#388),#393);
```

Figure 3-75 IFC file, IfcSpace, Revit's Room and Space elements are written into separate IfcSpace records

3.3.4.10 Case 10

3.3.4.10.1 Systematic Reference

T2_ST6_BM1

3.3.4.10.2 Interoperability issue

The interoperability issue that Case 10 investigates is how does the placement of Zone element in a BIM model that already has Room and Space elements, affect the IFC file and the BEM model?

This case in the continuation of the Case 08 (BIM model with only Zone element), and Case09 (BIM model with both Space and Room elements). This case helps to understand what happens if we have a Zone element in the Revit model, how it will be exported to IFC, and how does IDA-ICE read such information in the IFC file?

3.3.4.10.3 Methodology and Results

A Zone element was added to the model that already has Space, and Room elements. In contrary to the Case 06, Case 07, and Case 09, when a Zone element is added to the Revit model, there will be no explicit Zone tag on the model. A hint to see if the Zone is placed on the model is that there will be an extra line in between the wall thickness, Figure 3-77.

According to AutoDesk [92], "when spaces are initially placed in a project, they are added to the Default zone. When you assign a Space to a zone that you create, the Space is removed from the Default zone". Therefore, in the current case, we have a Zone that is not the default zone.

The model was then exported to IFC file, and imported to IDA-ICE. There seems to be no significant difference between the results this case (BIM model with Zone, Space, and Room elements) and those of Case 09 (BIM model with both Space and Room elements). IDA-ICE was able to detect the space in the imported IFC model and assign zones in the semi-automatic manner that was previously explained.

After investigating the IFC file, we found that a new IFC record was added to the file in this case-study, which is IfcZone, Figure 3-76.

```
#1080= IFCZONE('1H4QNC2Wz6Rh1RkfW7fEIc',#41,'1:327489',$,'');
#1082= IFCRELASSIGNSTOGROUP('1H4QNC2Wz6Rh1Rkfa7fEIc',#41,$,$,(#338),$,#1080);
#1085= IFCPROPERTYSINGLEVALUE('Reference',$,IFCIDENTIFIER('1'),$);
#1086= IFCPROPERTYSINGLEVALUE('Category',$,IFCLABEL('HVAC Zones'),$);
#1087= IFCPROPERTYSET('19XyowZT55phoKy1D0iArW',#41,'Pset_ZoneCommon',$,(#1085,#1086));
#1089= IFCRELDEFINESBYPROPERTIES('1Lf4qPFNH6ef2zSmmWulIH',#41,$,$,(#1080),#1087);
#1093= IFCPROPERTYSINGLEVALUE('Coil Bypass',$,IFCREAL(0.),$);
#1094= IFCPROPERTYSINGLEVALUE('Cooling Air Temperature',$,IFCTHERMALTRANSMITTANCEMEASURE(12.2222222222223),$);
#1095= IFCPROPERTYSINGLEVALUE('Cooling Set Point',$,IFCTHERMALTRANSMITTANCEMEASURE(23.3333333333334),$);
#1096= IFCPROPERTYSINGLEVALUE('Dehumidification Set Point',$,IFCREAL(0.7),$);
```

Figure 3-76 IFC file, IfcZone (Case 10)

According to BuildingSmart, with respect to IFC2x3 [129], "a zone (**IfcZone**) is an aggregation of spaces, partial spaces or other zones. Zone structures may not be hierarchical, i.e., one individual IfcSpace may be associated with zero, one, or several IfcZone's. IfcSpace's are aggregated into an IfcZone by using the objectified relationship IfcRelAssignsToGroup as specified at the supertype IfcGroup".
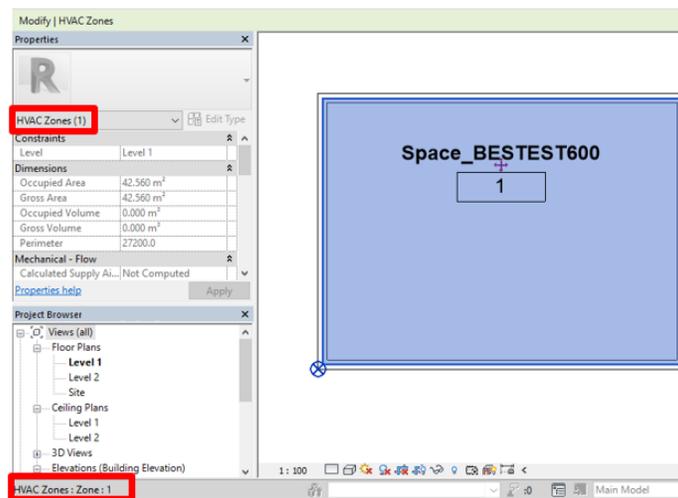
Figure 3-77 Revit Interface, Zone

The result of this case-study has given birth to some new research questions. Since this building model in Case 10, has only one Space and one Zone, future studies will need to be undertaken to investigate:

- o   A building model with several Spaces, and one Zone,
- o   A building model with several spaces and several zones,

in order to clarify how IDA-ICE reads information about space and zones from IFC. This might help to understand the ability of IDA-ICE in reading IfcZone, while IfcSpace class is also present.

Furthermore, to develop a full picture of how Spaces and Zones interact with each other in one BIM model, additional studies can focus on the possibilities of the Zone properties and Space properties in Revit. Indeed, each of these elements in Revit can store numerous energy-related values as their properties. Therefore, there are a lot of inputs regarding Spaces or Zones that Revit can readily accept, however, it is unclear whether they are adequately exported to IFC, and whether IDA-ICE can read them.

3.3.4.10.4 Conclusion
No interoperability issue was found in this case.

This case demonstrated that with one Zone and one Space (in addition to Room element) in BIM model, the result remains the same as the case 09, where only Space and Room elements were present.

3.3.4.11 Case 11

3.3.4.11.1 Systematic Reference

T3_ST1_BM1

3.3.4.11.2 Interoperability issue

The interoperability issue that this case investigates is how variation of geometrical properties of the building body (here: height of the wall), and geometrical properties of Room or Space (here: height of the Room or Space elements) in Revit affect the BIM-based energy modelling in IDA-ICE?

This case study investigates the interoperability issues that might arise due to the different height of the Space element with respect to the height of the wall.

3.3.4.11.3 Methodology and Results

While the wall height in the Revit model is set to 2.7 meters, the height of both Room and Space is intentionally set to 4 meters. The Room/Space height was previously explained in Case 06.

After importing the model to IDA-ICE, the immediate warning we received was "For each pair of intersecting spaces the bigger one is removed. In total removed 1 spaces: (Space)". While this is a quite simple model, if the model had many spaces, it would have been very hard to detect which spaces were removed by IDA-ICE. Therefore, it is our suggestion to IDA-ICE to improve their features by informing the user not only of the overlapping issues, but of the objects name, or maybe IFC classes that are physically overlapping in the software.

At first glance, after *semi-automatically zone assignment* was executed in IDA-ICE, the final thermal zone model in 3D tab had the same length as the wall height (equal to 2.7 meters) as shown in Figure 3-78. But, after we ran a simulation, we receive an error saying that "The ceiling of Room is located above the roof." Therefore, by a deep search into the model, we found that zone height that was taken into account for the simulation was 4 meters as shown in Figure 3-79. This is a clear interoperability issue.

Therefore, the first finding is that IDA-ICE has understood that the length of the zone is not matching the length of building body, but when it came to simulation, it had taken into account the height of the zone coming from the IfcSpace class, not the height of the building body.

Another interesting finding is that Revit produced no error about this overlapping issue when exporting the model to IFC. Therefore, Revit users who intend to use their BIM models for energy analysis purposes should be careful about the Space and Room elements' height in their models.

3.3.4.11.4 Conclusion

Interoperability issue was found.

Revit easily allows creation and storage of a model where Space/Room elements volume does not match the volume of the 3D building body. Likewise, Revit also easily export such model to IFC. However, this is problematic if such IFC output is to be used for energy modelling, because, for the purpose of calculations, Space volume should match the volume of the enclosed building.

Furthermore, IDA-ICE accepts the information of the IfcSpace class when it comes to performing simulation, and neglects the information of the building body, even though the zone in 3D view of IDA-ICE reflects the building body geometry.

Therefore, based on observations, it can be concluded that the 3D shaped of Room and Space elements should match with the 3D shape of the enclosed building body because both Space and Room elements are required for automatic detection of spaces in IDA ICE, thus, their geometry (i.e., height, length, and width) should match.
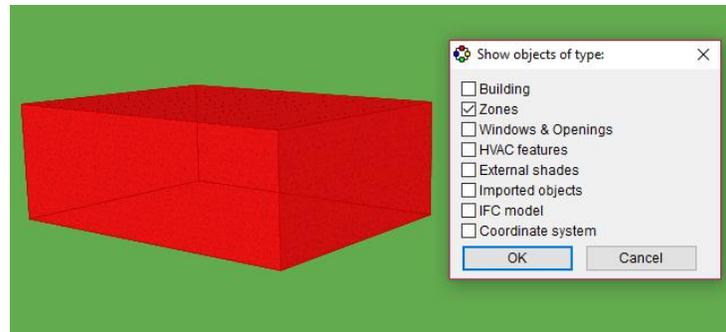
Figure 3-78 Space height is higher than wall height, IDA-ICE (Case 11)
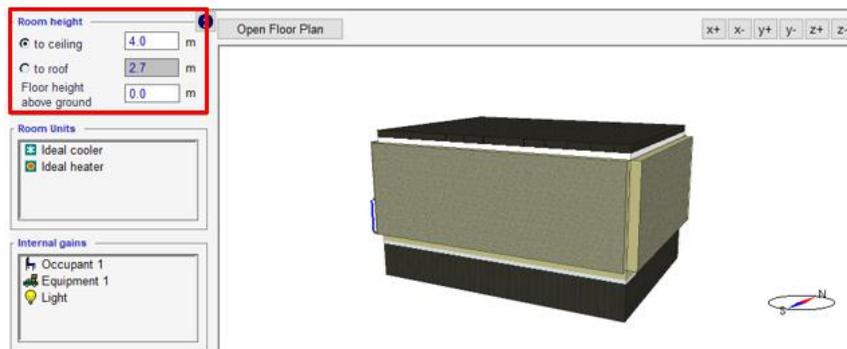
Figure 3-79 zone height in IDA-ICE, Space/Room height is considered as to ceiling height (Case 11)

3.3.4.12 Case 12

3.3.4.12.1 Systematic Reference
T3_ST2_BM1

3.3.4.12.2 Interoperability issue
The interoperability issue that this case investigates is how variation of geometrical properties of Space element, and geometrical properties of Room element in Revit affect the BIM-based energy modelling in IDA-ICE?

3.3.4.12.3 Methodology and Results
This case is the continuation of the previous case. The reason height of the Space and Room elements in Revit is chosen explained in Task 3.

In the first trial in Case 12, the height of Space element is 2.7 meters, that is equal to the height of the model's wall, while the height of the Room in 4 meters. The model is then exported from Revit to IFC without any problem. In the next step, the IFC file was imported to IDA-ICE. The first observation was the error we received about the overlapping of some objects. Again, we received the following error: "For each pair of intersecting spaces the bigger one is removed. In total removed 1 spaces: (Space)". After performing simulation, we also received this error: "The ceiling of Room is located above the roof." In this case, similar to Case 11, the thermal zone's height was considered as 4 meters, by IDA-ICE!

Therefore, in another trial, we decided to change the height of Space element to 4 meters, and the height of the Room to 2.7 meters (equal to the height of the model's wall). We, again, received the error: "For each pair of intersecting spaces the bigger one is removed. In total removed 1 spaces: (Space)" also for this trial. However, in this case, the height of the zone was considered as 2.7 meters for the simulation, by IDA-ICE.

This showed two things, firstly, IDA-ICE is sensitive to Space and Room elements 3D geometry in the Revit model. Secondly, in this case, and within the aforementioned two trials, it was proved that IDA-ICE receives the information about the height of the zone, from IfcSpace that holds the information about Room element! This is an unusual finding, because Room element in Revit is an architectural element, and usually, for the purpose of energy analysis, the Space element is used in Revit.

Nevertheless, this was a simple model and detecting whether Space element's height was higher than Room element's, or the reverse was easy. In models with a large number of spaces in the building plan, the unmatched space and room elements can be quite troublesome, especially because the user does not receive any information from IDA-ICE regarding which elements are mismatched. Therefore, this case was slightly more problematic than the previous Case 11. Because both Room and Space properties are associated with the IfcSpace class, and even if we can detect it in IDA-ICE, it is not possible to say if the height of the Space is higher than the height of the Room, or it is the opposite.

In this case, a solution is to use Solibri Model Viewer [130], to check the elements easily and quickly. The rationale behind this decision is that with Solibri Model Viewer it is possible to check the IfcSpace classes and their details. So, it is easier to detect the difference in the height of these elements. Another advantage is that by choosing each IFC class, the model inside Solibri Model Viewer will be highlighted and the user can easily see what element of the BIM model is chosen, Figure 3-80.
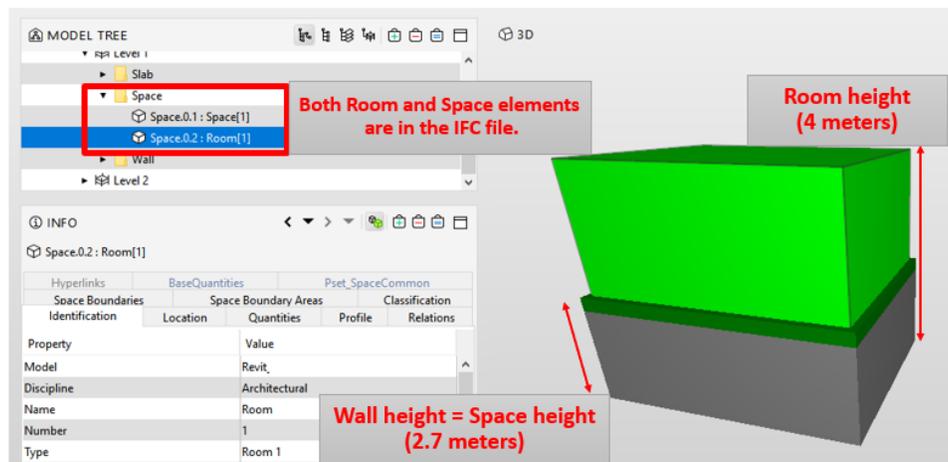
Figure 3-80 Room height is higher than Space height, Solibri Model Viewer (Case 12)

IfcSpace is "a Space represents an area or volume bounded actually or theoretically. Spaces are areas or volumes that provide for certain functions within a building" [131].

3.3.4.12.4 Conclusion
Interoperability issue was found.

It was concluded that IDA-ICE receives the zone height information from the IfcSpace that holds Room element information. The reasoning behind this is unknown to us.

In addition to that, it can be concluded that inside Revit model, due to its architectural nature, a difference in the Room and Space height is not a big problem and probably would be just ignored by BIM modelers who are not concerned with using BIM for energy analysis. However, it is necessary to check and keep track of these elements to have a clean IFC file, and for re-usability of the BIM model in future.

Considering that this is a simple building model, with only one enclosed building, it is easy to inspect it and check the Space, and Room height (i.e., Upper Limit, and Limit Offset in Revit). Should the building model have several rooms and floors, it will be troublesome, time-consuming effort to check which Room, Space elements are mistakenly populated with different spatial element data. Additionally, by using Solibri Model Checker, this problem can be addressed.

The final conclusion is that Room and Space elements' 3D properties should match for a proper BIM-based BEM analysis.

3.3.4.13 Case 13
3.3.4.13.1 Systematic Reference
T5_ST1_BM1

3.3.4.13.2 Interoperability issue
The interoperability issue, in this case, is how material's thermo-physical properties are exchanged between platforms, and how does Revit export this information to IFC?

Since materials are crucial players in the energy balance of a building, this case examines how are materials' properties (especially the thermal properties) are exported from Revit to IFC? And how are they imported from IFC to IDA-ICE?

3.3.4.13.3 Methodology and Results
The materials used for the construction of the model in Revit is explained in section 3.2. For this case, the wall's materials were targeted to be investigated. Then, the materials were created inside Revit according to the BESTEST Case 600 instructions [113]. In fact, thermal properties are inserted inside Revit, as shown in Figure 3-82. This procedure was repeated for walls, roof, and floor. Afterward, the model was Exported to IDA-ICE.

One issue that came up during this case was the modality of the IFC export setting inside Revit. In this case, the IFC export configuration impacts the output IFC file greatly. The IFC export settings of Revit are explained in Section 3.1.4.

At the first trial, the IFC export configuration was set to only "Export IFC common property sets," Figure 3-83. The IFC file exported by this configuration _lacks_ the thermal properties of each material layers that

were inserted into Revit. By these thermal properties, we mean the thermal properties that are shown in Figure 3-81, and Table 3-7.

In fact, since the IFC file is a text file, with the *.txt* format, the IFC file was opened by Notepad. Then, we chose a target value. This target value was 0.1430 which is the thermal conductivity of the wood siding material used in the wall, described in Table 3-7. Not only this value but none of the other values of the Thermal tab in the Revit's Material Browser, Figure 3-81, was found in this IFC text file.

That said, the thermal properties of the whole wall, Figure 3-82, was not exported to IFC either. The target value for this investigation was 1.682 which is the thermal resistance of the wall. Figure 3-85 shows that the target value was not found in the IFC file.
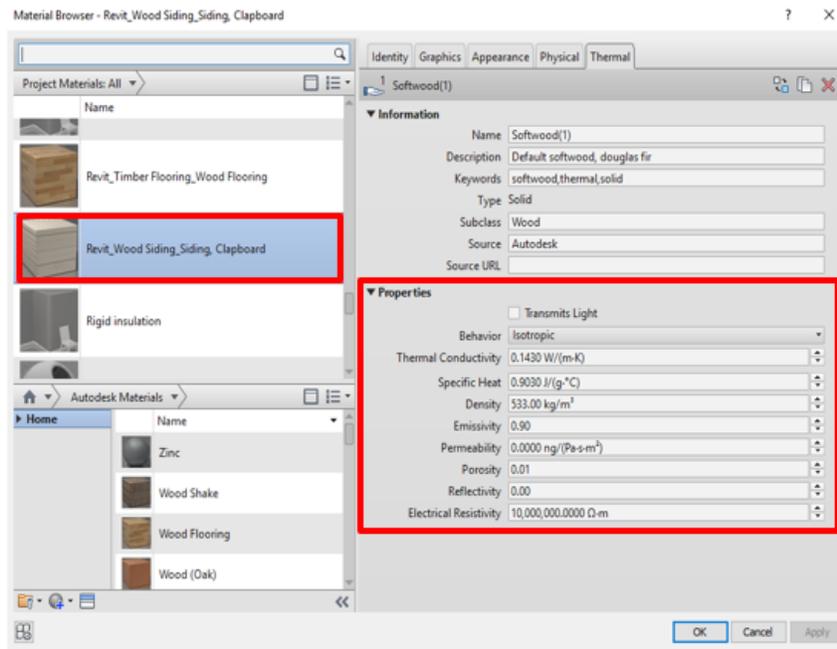
Figure 3-81 Thermal properties of the material Wood in the wall, BESTEST 600, Building Model 1
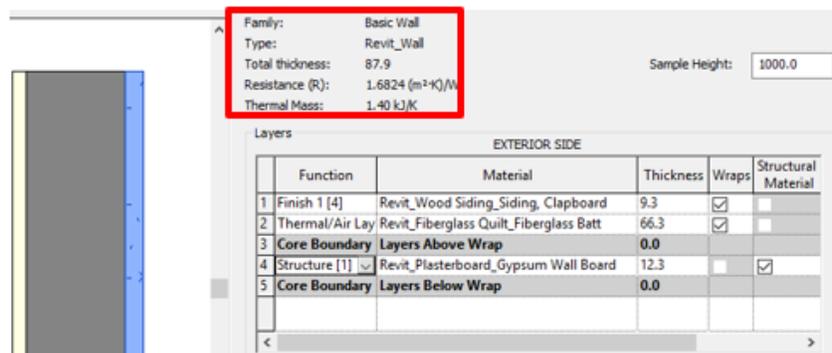
Figure 3-82 Thermal properties of the whole wall, BESTEST 600, Building Model 1
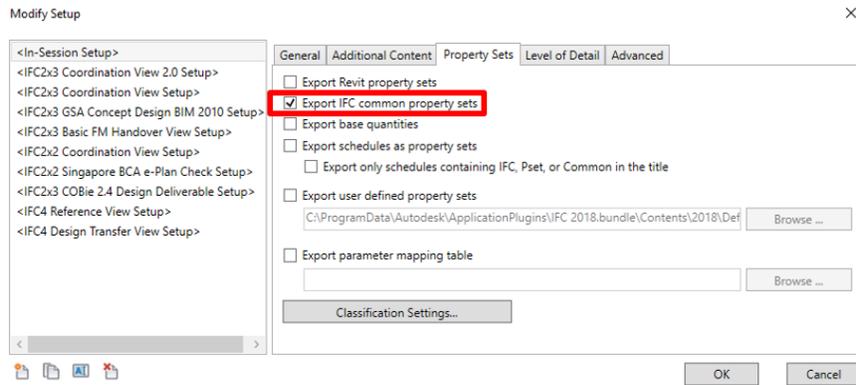
Figure 3-83 IFC Exporter, Export IFC common property sets

Therefore, we changed the configuration of IFC Exporter in the second trial. In this trial, "Export Revit property sets" was checked plus the "Export IFC common property sets," Figure 3-84. Hence, we again explored to see if the thermal properties of each material are exported or not, but the answer was no. Therefore, we moved on to next step, to explore whether thermal properties of the whole wall are exported from Revit to IFC, or not. Using the target value of Wall's thermal resistance: 1.628, we found that the Wall's thermal properties have been exported to IFC as IfcPropertySingleValue, Figure 3-86.

Additionally, other thermo-physical properties that are exported to IFC are those that are mentioned in the Analytical Properties of the Type Properties of the Wall in Revit, Figure 3-87.
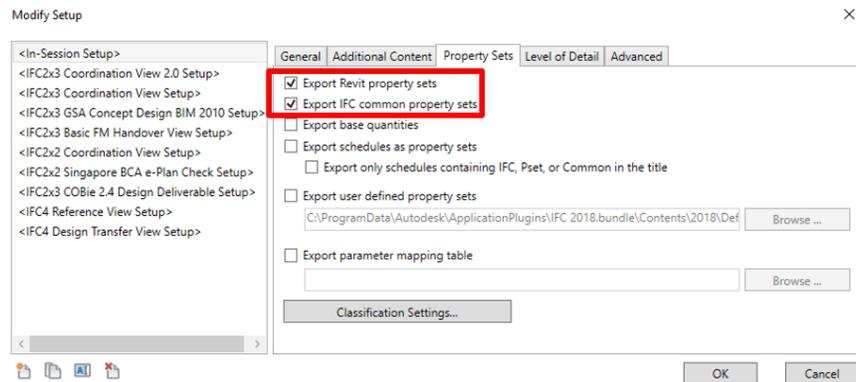
Figure 3-84 IFC Exporter, Export IFC common property sets, and Export Revit Property sets

IfcPropertySingleValue class describes "a property with a single value (IfcPropertySingleValue) that defines a property object which has a single (numeric or descriptive) value assigned. It defines a property - single value combination for which the property name, the value with measure type (and optionally the unit) is given" [127]. Therefore, we can conclude at this step that the thermal properties of the wall element were exported to IFC, but not the thermal properties of each layer of material that construct the wall.

```
#1= IFCORGANIZATION($,'Autodesk Revit 2018 (ENU)',$,$,$);
#5= IFCAPPLICATION(#1,'2018','Autodesk Revit 2018 (ENU)','Revit');
#6= IFCCARTESIANPOINT((0.,0.,0.));
#9= IFCCARTESIANPOINT((0.,0.));
#11= IFCDIRECTION((1.,0.,0.));
#13= IFCDIRECTION((-1.,0.,0.));
#15= IFCDIRECTION((0.,1.,0.));
#17= IFCDIRECTION((0.,-1.,0.));
#19= IFCDIRECTION((0.,0.,1.));
#21= IFCDIRECTION((0.,0.,-1.));
#23= IFCDIRECTION((1.,0.));
#25= IFCDIRECTION((-1.,0.));
#27= IFCDIRECTION((0.,1.));
#29= IFCDIRECTION((0.,-1.));
#31= IFCAXIS2PLACEMENT3D(#6,$,$);
#32= IFCLOCALPLACEMENT(#972,#31);
#35= IFCPERSON($,'Akbarieh','Arghavan',$,$,$,$,$);
#37= IFCORGANIZATION($,'NTNU','',$,$);
#38= IFCPERSONANDORGANIZATION(#35,#37,$);
#41= IFCOWNERHISTORY(#38,#5,$,.NOCHANGE.,$,$,$,1513075385);
#42= IFCSIUNIT(*,.LENGTHUNIT.,.MILLI.,.METRE.);
#43= IFCSIUNIT(*,.LENGTHUNIT.,$,.METRE.);
#44= IFCSIUNIT(*,.AREAUNIT.,$,.SQUARE_METRE.);
#45= IFCSIUNIT(*,.VOLUMEUNIT.,$,.CUBIC_METRE.);
#46= IFCSIUNIT(*,.PLANEANGLEUNIT.,$,.RADIAN.);
#47= IFCDIMENSIONALEXPONENTS(0,0,0,0,0,0,0);
```
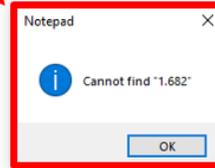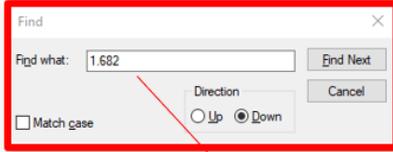
Figure 3-85 IFC file, no thermal properties related to the wall was found in the IFC file, trial 1

```
#632= IFCPROPERTYSINGLEVALUE('Top Offset',$,IFCLENGTHMEASURE(0.),$);
#633= IFCPROPERTYSINGLEVALUE('Unconnected Height',$,IFCLENGTHMEASURE(2700.),$);
#634= IFCPROPERTYSINGLEVALUE('Phase Created',$,IFCLABEL('New Construction'),$);
#635= IFCPROPERTYSINGLEVALUE('Enable Analytical Model',$,IFCBOOLEAN(.F.),$);
#636= IFCPROPERTYSINGLEVALUE('Structural',$,IFCBOOLEAN(.F.),$);
#637= IFCPROPERTYSINGLEVALUE('Structural Usage',$,IFCIDENTIFIER('Non-bearing'),$);
#638= IFCPROPERTYSINGLEVALUE('Area',$,IFCAREAMEASURE(16.2),$);
#639= IFCPROPERTYSINGLEVALUE('Length',$,IFCLENGTHMEASURE(5912.10000000001),$);
#640= IFCPROPERTYSINGLEVALUE('Volume',$,IFCVOLUMEMEASURE(1.42398),$);
#641= IFCPROPERTYSINGLEVALUE('Category',$,IFCLABEL('Walls'),$);
#642= IFCPROPERTYSINGLEVALUE('Family',$,IFCLABEL('Basic Wall: Revit_Wall'),$);
#643= IFCPROPERTYSINGLEVALUE('Family and Type',$,IFCLABEL('Basic Wall: Revit_Wall'),$);
#644= IFCPROPERTYSINGLEVALUE('Type',$,IFCLABEL('Basic Wall: Revit_Wall'),$);
#645= IFCPROPERTYSINGLEVALUE('Type Id',$,IFCLABEL('Basic Wall: Revit_Wall'),$);
#646= IFCPROPERTYSINGLEVALUE('Absorptance',$,IFCREAL(0.6),$);
#647= IFCPROPERTYSINGLEVALUE('Heat Transfer Coefficient (U)',$,IFCREAL(0.594404671655508),$);
#648= IFCPROPERTYSINGLEVALUE('Roughness',$,IFCINTEGER(3),$);
#649= IFCPROPERTYSINGLEVALUE('Thermal mass',$,IFCREAL(15084.2241),$);
#650= IFCPROPERTYSINGLEVALUE('Thermal Resistance (R)',$,IFCREAL(1.68235555285063),$);
#651= IFCPROPERTYSINGLEVALUE('Structural Material',$,IFCLABEL('Revit_Plasterboard_Gypsum Wall Board'),$);
#652= IFCPROPERTYSINGLEVALUE('Coarse Scale Fill Color',$,IFCINTEGER(0),$);
#653= IFCPROPERTYSINGLEVALUE('Function',$,IFCIDENTIFIER('Exterior'),$);
#654= IFCPROPERTYSINGLEVALUE('Width',$,IFCLENGTHMEASURE(87.9),$);
```
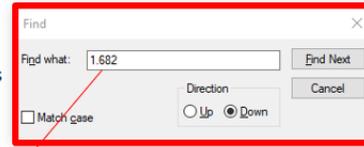
Figure 3-86 IFC file, some thermal properties related to the wall was found in the IFC file, trial 2

Figure 3-87 Analytical Properties of wall element, Revit

Furthermore, understanding how Revit elements are exported as IFC records in the IFC text file helps to propose solutions for interoperability issues. Therefore, we further examined the IFC file to scrutinize which IFC classes have hosted information about materials. As can be observed in Figure 3-88, the name of the material layer is written in the IfcSurfaceStyle class (Record #538), while the same name is again written in IfcMaterial class as well (Record #570).

```
#537= IFCSURFACESTYLERENDERING(#536,0.,$,$,$,$,IFCNORMALISEDRATIOMEASURE(0.5),IFCSPECULAREXPONENT(64.),.NOTDEFINED.);
#538= IFCSURFACESTYLE('Revit Wood Siding Siding, Clapboard',.BOTH.,(#537));
#540= IFCPRESENTATIONSTYLEASSIGNMENT((#538));
#542= IFCSTYLEDITEM(#535,(#540),$);
#545= IFCSHAPEREPRESENTATION(#102,'Body','SweptSolid',(#535));
#547= IFCPRODUCTDEFINITIONSHAPE($,$,(#527,#545));
#549= IFCWALLSTANDARDCASE('3cFIX6YNjFHAPmSUEb8dgl',#41,'Basic Wall:Revit_Wall:326633',$,'Basic Wall:Revit_Wall:326961',#522,#547,'326633');
#558= IFCQUANTITYLENGTH('Height',$,$,2700.);
#559= IFCQUANTITYLENGTH('Length',$,$,6000.);
#560= IFCQUANTITYLENGTH('Width',$,$,87.9);
#561= IFCQUANTITYAREA('GrossFootprintArea',$,$,0.5274);
#562= IFCQUANTITYAREA('GrossSideArea',$,$,16.2);
#563= IFCQUANTITYVOLUME('GrossVolume',$,$,1.42398);
#564= IFCELEMENTQUANTITY('3A8pP6bhX08uARzxANNXRx',#41,'BaseQuantities',$,$,(#558,#559,#560,#561,#562,#563));
#566= IFCRELDEFINESBYPROPERTIES('0Xo$9Rd1DB7RVy4AkPiz5i',#41,$,$,(#549),#564);
#570= IFCMATERIAL('Revit Wood Siding Siding, Clapboard');
#573= IFCPRESENTATIONSTYLEASSIGNMENT((#538));
#575= IFCSTYLEDITEM($,(#573),$);
#577= IFCSTYLEDREPRESENTATION(#97,'Style','Material',(#575));
#580= IFCMATERIALDEFINITIONREPRESENTATION($,$,(#577),#570);
```

Figure 3-88 IFC file, IfcSurfaceStyle, and IfcMaterial

It is explained by IDA-ICE documentation [107-109], that ICE can import **styles** for walls, windows, and materials to provide an appropriate property set to a group of imported objects in the platform. Indeed, these style names are used for attaching the same set of simulation properties to all objects with the same name [109]. That said, *styles* are also used in IDA-ICE to facilitate the mapping procedure; mapping is explained in . The user can map each *style name* imported from IFC to an appropriate *construction* or *property* in an IDA-ICE database. If a style name is not mapped, then a default construction or property set will be used [109]. In this context, styles refer to *IfcSurfaceStyle* that was described earlier.

The definition of IfcSurfaceStyle according to BuildingSMART [132] is an assignment of one or many surface style elements to a surface, defined by subtypes of IfcSurface, IfcFaceBasedSurfaceModel, or IfcShellBasedSurfaceModel, or by subtypes of IfcSolidModel. The positive direction of the surface normal relates to the positive side. In case of solids, the outside of the solid is to be taken as the positive side.

Moreover, IfcMaterial is defined as a homogeneous substance that can be used to form elements [133]. Meanwhile, the thickness of each material layer of the wall is also exported to IFC through *IfcMaterialLayer*. A comparison can be made between records #611, #613, #614 in Figure 3-89 and the thicknesses in Figure 3-82.

```
#608= IFCMATERIALDEFINITIONREPRESENTATION($,$,(#606),#597);
#611= IFCMATERIALLAYER(#570,9.3,$);
#613= IFCMATERIALLAYER(#583,66.3,$);
#614= IFCMATERIALLAYER(#597,12.3,$);
#615= IFCMATERIALLAYERSET((#611,#613,#614),'Basic Wall:Revit_Wall');
#620= IFCMATERIALLAYERSETUSAGE(#615,.AXIS2.,.NEGATIVE.,43.95);
```

Figure 3-89 IFC file, IfcMaterialLayer

BuildingSMART defines IfcMaterialLaye in version IFC2x3 [134], as a single and identifiable part of an element which is constructed of a number of layers (one or more).Each IfcMaterialLayer is located relative to the referencing IfcMaterialLayerSet,

Additionally, the thickness of the whole wall, which is 87.9 mm, is also exported to IDA-ICE. But this information is exported to a different IFC class than the thickness of each material, Figure 3-90.

IfcQuantityLength is "a physical quantity that defines a derived length measure to provide an element's physical property. It is normally derived from the physical properties of the element under the specific measure rules given by a method of measurement" [122].

```
#558= IFCQUANTITYLENGTH('Height',$,$,2700.);
#559= IFCQUANTITYLENGTH('Length',$,$,6000.);
#560= IFCQUANTITYLENGTH('Width',$,$,87.9);
#561= IFCQUANTITYAREA('GrossFootprintArea',$,$,0.5274);
#562= IFCQUANTITYAREA('GrossSideArea',$,$,16.2);
#563= IFCQUANTITYVOLUME('GrossVolume',$,$,1.42398);
#564= IFCELEMENTQUANTITY('3A8pP6bhX08uARzxANNXRx',#41,'BaseQuantities',$,$,(#558,#559,#560,#561,#562,#563));
#566= IFCRELDEFINESBYPROPERTIES('0Xo$9Rd1DB7RVy4AkPiz5i',#41,$,$,(#549),#564);
```

Figure 3-90 IFC file, IfcQuantityLength

In the next step, the IFC file was imported to IDA-ICE. While it seems that IDA-ICE has understood the thickness of the wall as can be observed in Figure 3-91; but it has not understood or used the thickness of each materials layer that also existed in the imported IFC file, Figure 3-92.

Additionally, it should be mentioned that there are two options to start a new project in IDA-ICE. One is to "Start new empty building," and the other is "Start new building with a single zone." For the purpose of this case-study, both of them are used and elaborated here:

- o **Option "Start new building with a single zone":** some default suggestions in the ICE resources will appear on the right-hand side.
- o **Option "Start new empty building":** no suggestions for ICE resources exist in the model. All resources must be loaded from the database.

In either of these two options, the wall information was not correctly read by the IDA-ICE. There was no problem with roof and floor, and they had been imported with correct thicknesses.
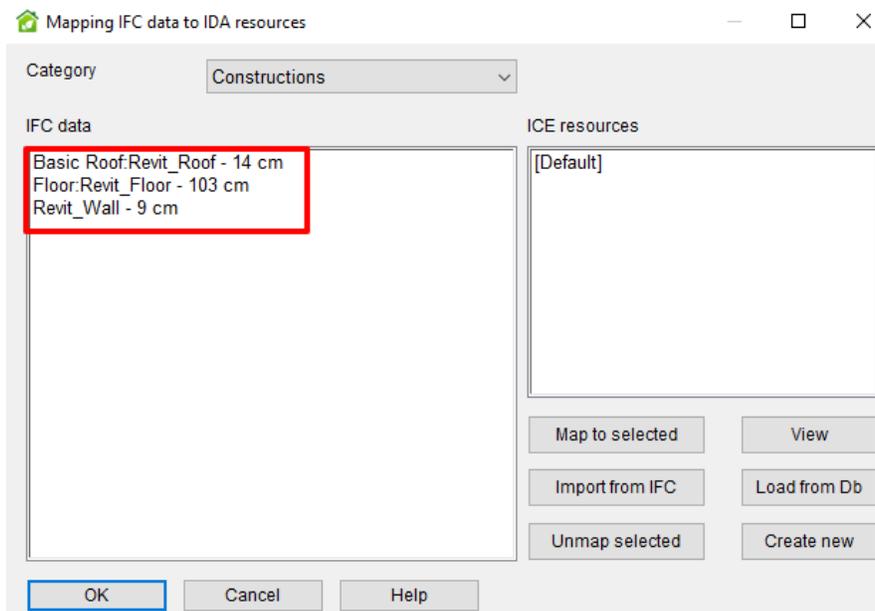
Figure 3-91 IDA-ICE Mapping IFC data to IDA resources window, Thickness of elements are derived from IFC data
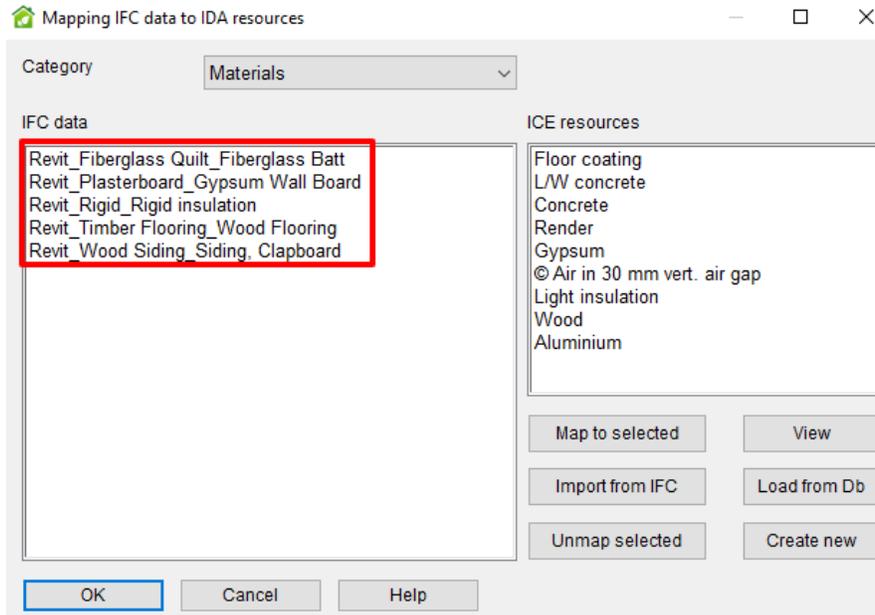
*Figure 3-92 IDA-ICE Mapping IFC data to IDA resources window, Thickness of materials are **not** derived from IFC data*

This is the end of the results of this case because now materials and construction should be mapped in order to proceed with the simulation.

3.3.4.13.4 Conclusion

Interoperability issues were found in this case.

The interoperability issue investigated here has enormous impacts on the energy analysis of a building. The process of inserting proper thermal properties of materials into IDA-ICE is not automated, which is time-consuming and laborious. Also, there is the possibility of miss-mapping the data in case of a large building with numerous material layers.

It is possible to re-create the desired materials in IDA-ICE, and just map it to the imported building material style. Also, companies using IDA-ICE's regularly can have their own database of materials.

That said, the BIM tool (Revit) also lacks potentials to export the materials thermal properties to IFC. Furthermore, the categories thermal properties, e.g., walls, are exported to IFC from Revit, since IDA-ICE cannot understand this information. Therefore this exchanged information is useless. This leads to a strong interoperability issue in this case.

While discussing with experts and in the online forum many solutions were rendered on how to solve this issue and export each layer's material to IFC, they are ad-hoc solutions [135], solutions that are developed by BIM-BEM experts over the year, and only they know how to do those procedures precisely. In the following paragraphs, we shortly describe these solutions without going into details. That said, these solutions have not been tested in this study since it was out of the scope of this project. Future researchers are welcome to examine the possibility of using these methods in order to automate information exchange between Revit and IFC.

In the end, after finding that Revit does not export these properties to IFC, a question rose up. If the IFC file contains these precise thermal properties, is IDA-ICE able to import them, read them, and reproduce the same material in its interface? Based on our experience and observations with IDA-ICE through this

project, the answer is No. Because in the current version, 4.7.1, regardless of the amount of information related to materials inside an IFC file, IDA-ICE still obliges the user to go through the mapping process, meaning that the basic algorithm of the software is not able to read any information about the materials, except name and thickness.

Thus, we suggest that IDA-ICE improve this feature and provide new features that read the materials properties, besides name and thickness, should such information exists in the IFC.

A possible solution to populate an IFC file with new information is to manually write IFC records into the text file to enrich it with thermal properties information. However, this is a complicated task due to the complexity of the IFC data structure. The person doing this task must be completely aware of the hierarchy of IFC classes. Several methods can be undertaken for this task. Firstly, Dynamo can be a viable option, since it already has a plugin in Revit. It is a powerful tool, and also easy to use. Secondly, other programming platforms can also be helpful for manually or semi-manually writing IFC records. Thirdly, online open source platforms such as Ifcopenshell.org are another option that would help to write IFC records. Therefore, there is plenty of room for future researchers to improve and facilitate the export of thermal properties of the materials to IFC.

Nonetheless, it is also our suggestion to AutoDesk to improve the IFC settings and enables Revit to export material's properties to IFC. This would hugely benefit the construction industry and dramatically reduces the interoperability issues, while automates the flow of information from BIM to BEM.

We also propose IDA-ICE to add a feature that automatically accepts the thermal properties of the whole element since this data can be already found in the IFC file. This means that instead of mapping the materials from IFC to IDA resources, and then adding the constructions from IFC to IDA resources, as explained in [put the link], a new category of constructions is read from IFC that is associated with the thermal properties. This would hugely reduce the time and effort for BIM to BEM process using IDA-ICE.

3.3.4.14 Case 14

3.3.4.14.1 Systematic Reference
T5_ST1_BM2

3.3.4.14.2 Interoperability issue
The interoperability issue, in this case, is how do windows, their geometry, and type of materials, are exported from Revit to IFC and read by IDA-ICE? This case investigates Revit's window families that are built by the user.

3.3.4.14.3 Methodology and Results
Windows has huge impacts on the energy gain and loss of a building; therefore, as a necessary component of the building, it was investigated in this case study that how Revit exports Windows geometry, and thermophysical properties into IFC, and how this information is read by IDA-ICE.

The windows are on the south façade; Figure 3-93 shows a 3D view of the windows while, Figure 3-94 shows the dimensions of the windows , as explained in Table 3-10, more clearly inside Revit. The glass properties are inserted into the glass material section, according to the thermal, and geometrical properties of the window of BESTEST 600, or Building Model 1 that was explained earlier, Figure 3-96. The next task was to choose an analytical construction in Revit that closely resembles the thermal properties of BESTEST cases, Figure 3-95. After some investigations, "Double glazing – domestic" was chosen because

its thermal characteristics were quite close to our needs. Then, the model was exported to IFC, and imported in IDA-ICE.
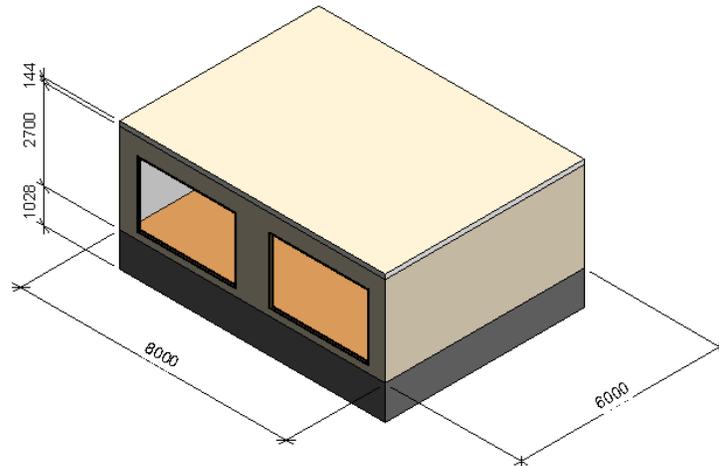
Figure 3-93 Building Model 1 in Revit, Windows on the south Façade, 3D view
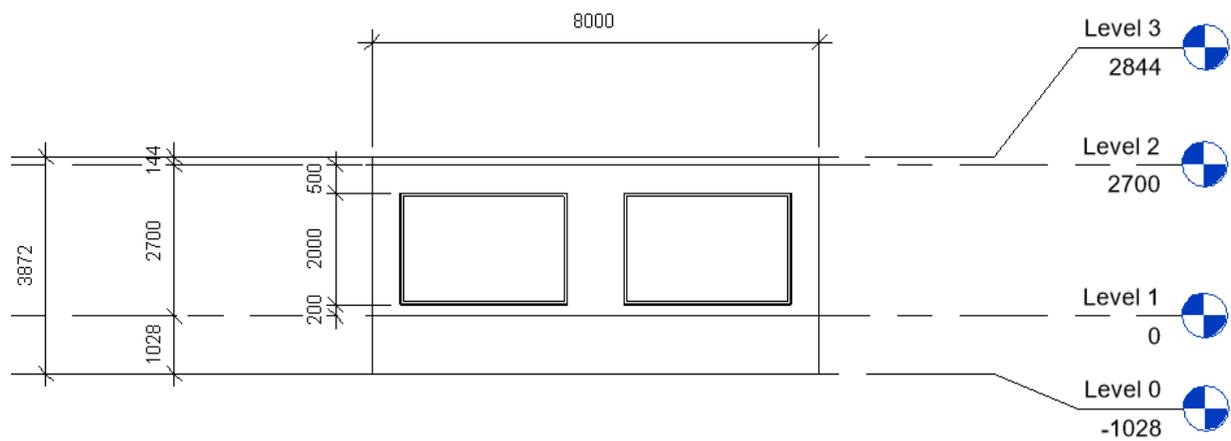
Figure 3-94 Building Model 1 in Revit, Windows on the south Façade, South Elevation view
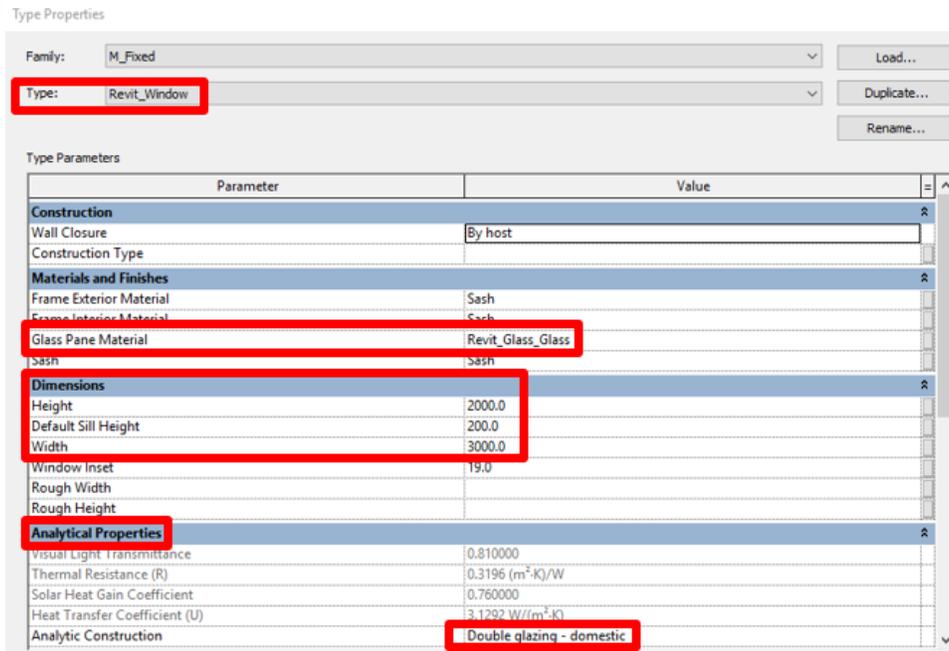
Figure 3-95 Window properties inside Revit, Dimensions, and Analytical Properties of the Windows (Case 14)
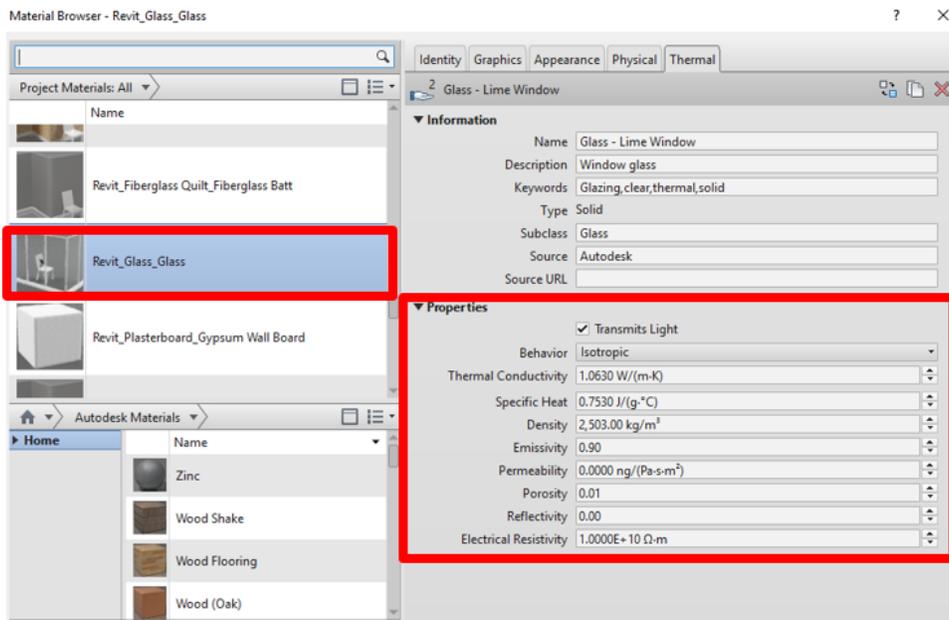
Figure 3-96 Glass thermal properties inside Revit

Even though the geometry of the windows is perfectly imported to IDA-ICE, no information related to the glazing and frame is exported to IDA-ICE. As can be seen in Figure 3-98, the General tab's values are set to none, or to default, meaning that IDA-ICE has not read this information from the imported IFC file. This is why window mapping is required to add information about the windows. This would be the end of the investigation of this case in IDA-ICE. We can conclude that only geometry is exported, and no information about the analytical properties of the windows, or the glazing type is read by IDA-ICE.
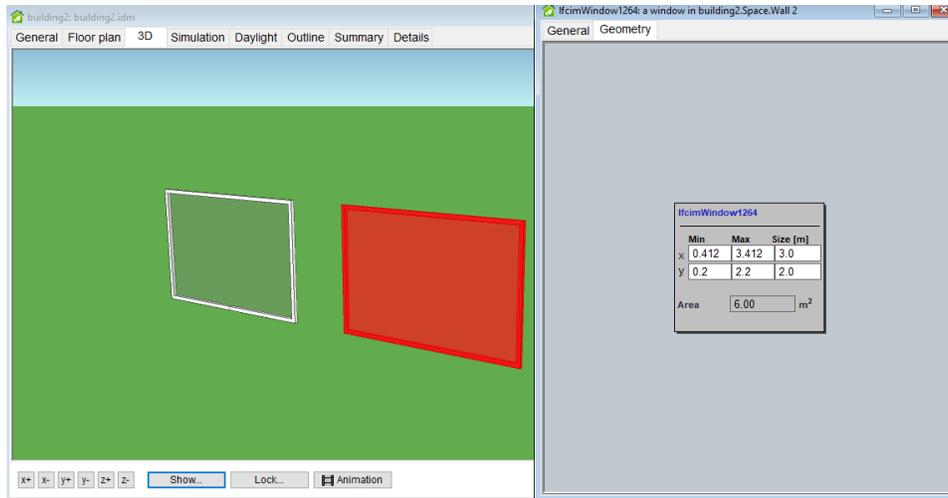
Figure 3-97 IDA-ICE, windows geometry
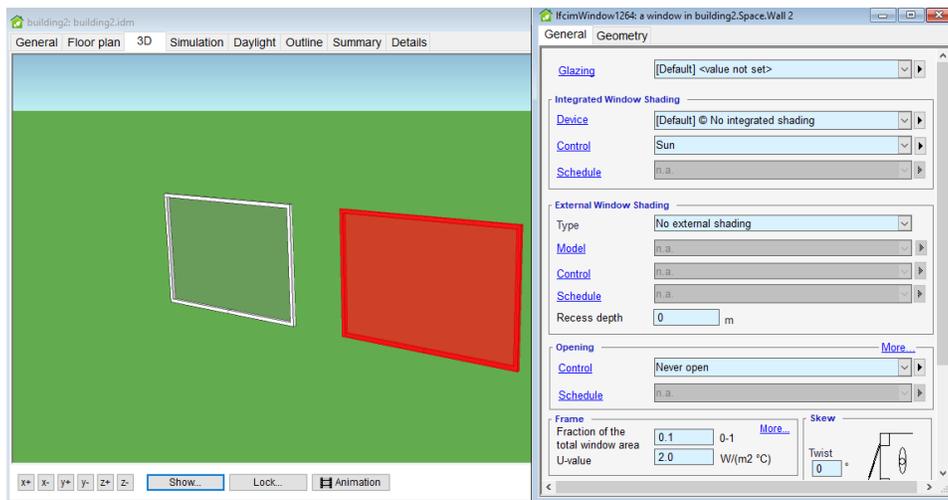
Figure 3-98 IDA-ICE, windows properties, glass, and frame properties

To control how window information is exported from Revit to IFC, the IFC file was investigated. The information about the dimension of the window is exported to IfcWindow.

Following Figure 3-99 shows the IFC file that has been generated with Revit exporter. As can be seen, information about the dimension of the window is primarily exported to IfcWindow.

It should be noted that this IFC was generated by choosing the "Export Revit property sets" option in IFC exported as explained in [put link]. Therefore, many of the values and properties are exported into the IFC file as IfcPropertySingleValue classes. That said, the dimensions of the window are again written to IfcPropertySingleValue classes in record #1300 and #1301 in Figure 3-100. Likewise, Analytic Construction, and all its properties are also written to IfcPropertySingleValue classes, records #1289, #1290, #1291, #1292, #1293. However, the material of window and frame (and also sill), are exported to record #1267, into the IfcMaterialList class.

Consequently, the information about the glass type and sash material are reported in IfcSurfaceStyle, Figure 3-99. Despite this, no thermal properties were imported about these materials.

```
#1198= IFCSURFACESTYLERENDERING(#1197,0.85,$,$,$,$,IFCNORMALISEDRATIOMEASURE(0.5),IFCSPECULAREXPONENT(64.),.NOTDEFINED.);
#1199= IFCSURFACESTYLE('Revit_Glass_Glass',.BOTH.,(#1198));
#1201= IFCPRESENTATIONSTYLEASSIGNMENT((#1199));
#1203= IFCSTYLEDITEM(#1118,(#1201),$);
#1206= IFCCOLOURRGB($,0.87843137254902,0.698039215686274,0.494117647058824);
#1207= IFCSURFACESTYLERENDERING(#1206,0.,$,$,$,$,IFCNORMALISEDRATIOMEASURE(0.5),IFCSPECULAREXPONENT(128.),.NOTDEFINED.);
#1208= IFCSURFACESTYLE('Sash',.BOTH.,(#1207));
#1210= IFCPRESENTATIONSTYLEASSIGNMENT((#1208));
#1212= IFCSTYLEDITEM(#1144,(#1210),$);
#1215= IFCSTYLEDITEM(#1170,(#1210),$);
#1218= IFCSTYLEDITEM(#1196,(#1210),$);
```

Figure 3-99 IFC file, IfcSurfaceStyle storing information about glass type and sash material

Since the information about glass was already inserted as a material, just like the case 13, none of them was imported to IFC.

```
#1264= IFCWINDOW('3a4ELEJnfAVuzkIf_3lcw1',#41,'M_Fixed:Revit_Window:329028',$,'Revit_Window',#1769,#1258,'329028',2000.,3000.);
#1267= IFCMATERIALLIST((#1231,#1241));
#1269= IFCPROPERTYSINGLEVALUE('Reference',$,IFCIDENTIFIER('Revit_Window'),$);
#1270= IFCPROPERTYSINGLEVALUE('ThermalTransmittance',$,IFCTHERMALTRANSMITTANCEMEASURE(3.1292),$);
#1271= IFCPROPERTYSET('3a4ELEJnfAVuzkGM63lcw1',#41,'Pset_WindowCommon',$,(#672,#1269,#1270));
#1273= IFCRELDEFINESBYPROPERTIES('3jxnuQAnP9MRV12DRuGcBH',#41,$,$,(#1264),#1271);
#1277= IFCPROPERTYSINGLEVALUE('Level',$,IFCLABEL('Level: Level 1'),$);
#1278= IFCPROPERTYSINGLEVALUE('Sill Height',$,IFCLENGTHMEASURE(200.),$);
#1279= IFCPROPERTYSINGLEVALUE('Area',$,IFCAREAMEASURE(7.66947280000021),$);
#1280= IFCPROPERTYSINGLEVALUE('Volume',$,IFCVOLUMEMEASURE(0.103100541600005),$);
#1281= IFCPROPERTYSINGLEVALUE('Mark',$,IFCTEXT('4'),$);
#1282= IFCPROPERTYSINGLEVALUE('Category',$,IFCLABEL('Windows'),$);
#1283= IFCPROPERTYSINGLEVALUE('Family',$,IFCLABEL('M_Fixed: Revit_Window'),$);
#1284= IFCPROPERTYSINGLEVALUE('Family and Type',$,IFCLABEL('M_Fixed: Revit_Window'),$);
#1285= IFCPROPERTYSINGLEVALUE('Head Height',$,IFCLENGTHMEASURE(2200.),$);
#1286= IFCPROPERTYSINGLEVALUE('Host Id',$,IFCLABEL('Basic Wall: Revit_Wall'),$);
#1287= IFCPROPERTYSINGLEVALUE('Type',$,IFCLABEL('M_Fixed: Revit_Window'),$);
#1288= IFCPROPERTYSINGLEVALUE('Type Id',$,IFCLABEL('M_Fixed: Revit_Window'),$);
#1289= IFCPROPERTYSINGLEVALUE('Analytic Construction',$,IFCTEXT('Double glazing - domestic'),$);
#1290= IFCPROPERTYSINGLEVALUE('Heat Transfer Coefficient (U)',$,IFCREAL(3.1292),$);
#1291= IFCPROPERTYSINGLEVALUE('Solar Heat Gain Coefficient',$,IFCREAL(0.76),$);
#1292= IFCPROPERTYSINGLEVALUE('Thermal Resistance (R)',$,IFCREAL(0.319570497251694),$);
#1293= IFCPROPERTYSINGLEVALUE('Visual Light Transmittance',$,IFCREAL(0.81),$);
#1294= IFCPROPERTYSINGLEVALUE('Frame Exterior Material',$,IFCLABEL('Sash'),$);
#1295= IFCPROPERTYSINGLEVALUE('Frame Interior Material',$,IFCLABEL('Sash'),$);
#1296= IFCPROPERTYSINGLEVALUE('Glass Pane Material',$,IFCLABEL('Revit_Glass_Glass'),$);
#1297= IFCPROPERTYSINGLEVALUE('Sash',$,IFCLABEL('Sash'),$);
#1298= IFCPROPERTYSINGLEVALUE('Wall Closure',$,IFCIDENTIFIER('By host'),$);
#1299= IFCPROPERTYSINGLEVALUE('Default Sill Height',$,IFCLENGTHMEASURE(200.),$);
#1300= IFCPROPERTYSINGLEVALUE('Height',$,IFCLENGTHMEASURE(2000.),$);
#1301= IFCPROPERTYSINGLEVALUE('Width',$,IFCLENGTHMEASURE(3000.),$);
#1302= IFCPROPERTYSINGLEVALUE('Window Inset',$,IFCLENGTHMEASURE(19.),$);
#1303= IFCPROPERTYSINGLEVALUE('Code Name',$,IFCTEXT(''),$);
#1304= IFCPROPERTYSINGLEVALUE('OmniClass Number',$,IFCTEXT('23.30.20.17.11'),$);
#1305= IFCPROPERTYSINGLEVALUE('OmniClass Title',$,IFCTEXT('Fixed Windows'),$);
#1306= IFCPROPERTYSINGLEVALUE('Type Mark',$,IFCTEXT('19'),$);
#1307= IFCPROPERTYSINGLEVALUE('Type Name',$,IFCTEXT('Revit_Window'),$);
```

Figure 3-100 IFC file, IfcWindow, IfcMaterialList, IfcProprtySingleValue

An interesting observation was made based on this case study. IDA-ICE has not considered the glass material, that is described in Figure 3-96, as a material in the Mapping window, even though the glass material is inside the Revit file. This could mean that either IDA-ICE does not read IfcSurfaceStyle class, or, read it but does not consider it as a material. Instead, IDA-ICE has a separate Category in the Mapping, which is dedicated to Windows. In this Category, it is possible to see the windows that are present in the BIM-based IFC file. However, no information about the materials constructing the window is present in this mapping box.

3.3.4.14.4 Conclusion

Interoperability issue was found.

The interoperability issue of Case 14, is in many ways similar to the interoperability issues in Case 13. Firstly, the material properties of window's glass and frame are not exported from Revit to IFC at all. Then, the analytical constructions, i.e., "Double glazing – domestic" and its properties are exported to IFC as IfcPropertySingleValue classes which are of little use in the Revit to IDA-ICE exchange process. Because in any case, IDA-ICE obliges the user to map materials that are present in the IFC data to IDA resources!

3.3.4.15 Case 15

3.3.4.15.1 Introduction

The interoperability issue, in this case, is how do windows, their geometry, and type of materials, are exported from Revit to IFC and read by IDA-ICE? This case investigates Revit's built-in window families.

Windows significantly influence the energy gain and loss of a building; therefore, as a necessary component of the building, it was investigated in this case study that how Revit export Windows geometry, and thermophysical properties into IFC.

3.3.4.15.2 Methodology and Results

It should be noted that this case was proposed before importing Case 14 into the IDA-ICE, which means by that time, we did not know the outcome of this case study. However, since the conclusion of Case 14 is that windows should be mapped in IDA-ICE because not many information are exchanged between BIM and IDA-ICE, this conclusion can be generalized to any window family, built-in or user-created. Despite this, we decided to test this case-study regardless of the previous results.

The first challenge of creating a new window family with the properties explained in the BESTEST documentation [113] was that there is available no information in the documentation, or in the literature, about the materials used for the frame of the BESTEST window. Although several researchers have created BESTEST models, they have not specified that materials for the frame models are well [10, 43, 86, 115-117, 136-138]. This is understandable because the BESTEST cases were initially developed for EnergyPlus. Therefore, frame's material was of less importance for this tool. However, with the new releases of other Building Performance Simulation tools, even frame's thermal properties are being considered as a part of building energy modelling effort.

The second challenge was whether the window should have two glass panes, as explained in the BESTEST documentation [113], or the window should have one pane in the new family, but stores the information that resembles a double glazed window?

After some discussions, we decided that for this research project, it is better to model a window with one pane but with the information related to a double-pane window. The rationale behind this decision is due to the space boundaries. BPS tools are now able to understand the second level space boundary. This means that each side of a surface (here: glass pane) will be considered as a surface, and might create confusion for the BPS tool regarding the thermal energy calculations [1]

As unpredicted as it could be, the windows in Revit has some limitations when it comes to export their data to IFC; but even more, it is also difficult to enter the right materials for the window construction is Revit. We chose "Double glazing – domestic" similar to the previous case in the end. Figure 3-102 shows the final window model that we created in Revit. After the model was exported to IFC, and the imported to IDA-

ICE, we saw that the windows are flawlessly exchanged in this BIM to BEM model, geometrically-wise, Figure 3-103.

To set-up, this new window to be exported to IFC file properly, IfcExportAs, and IfcExportType classes were used. The procedure of IfcExportAs and IfcExportType is better explained in Case 18 in more detail.
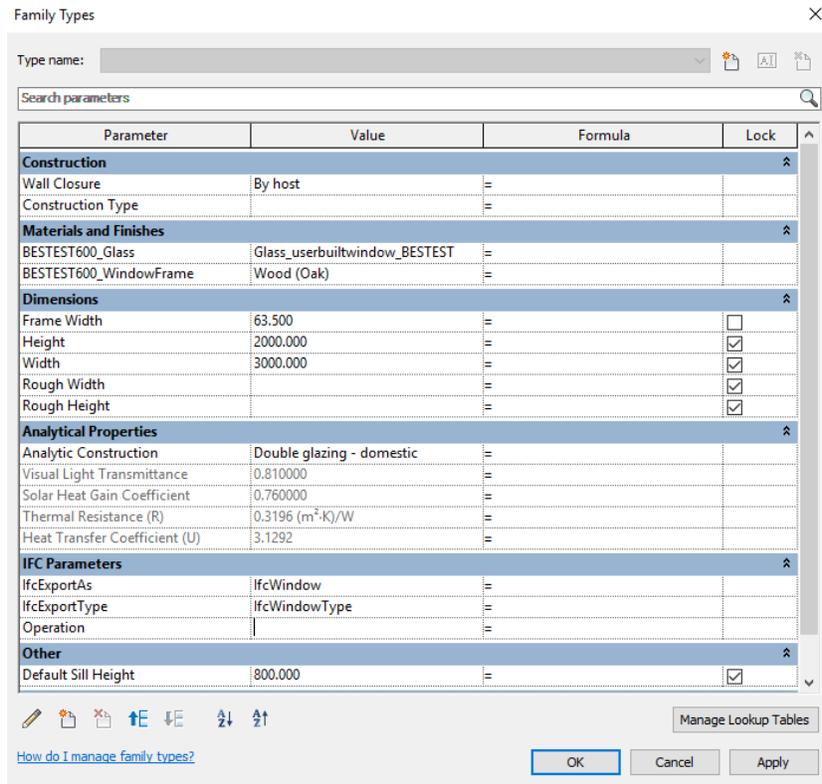
Figure 3-101 Window properties inserted into the new window family in Revit (Case 15)
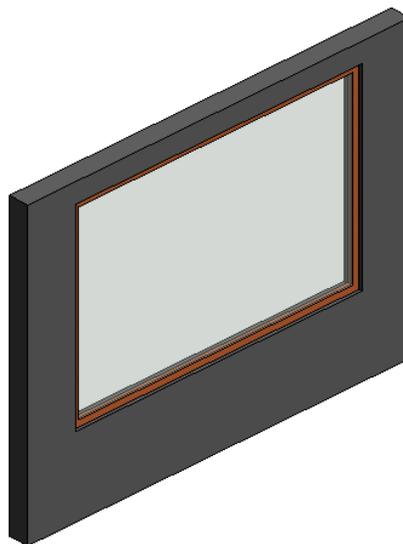
Figure 3-102 Revit's user-built window in 3D view (Case 15)
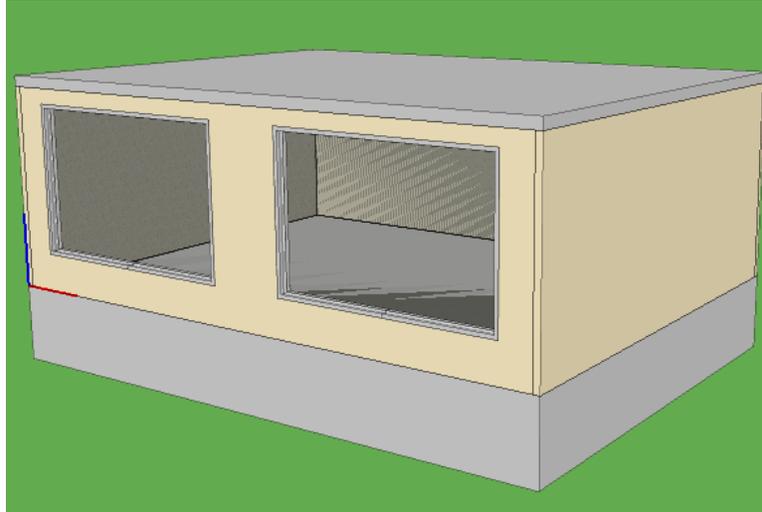
Figure 3-103 Revit's user-built windows are visualized in IDA-ICE through IFC file.
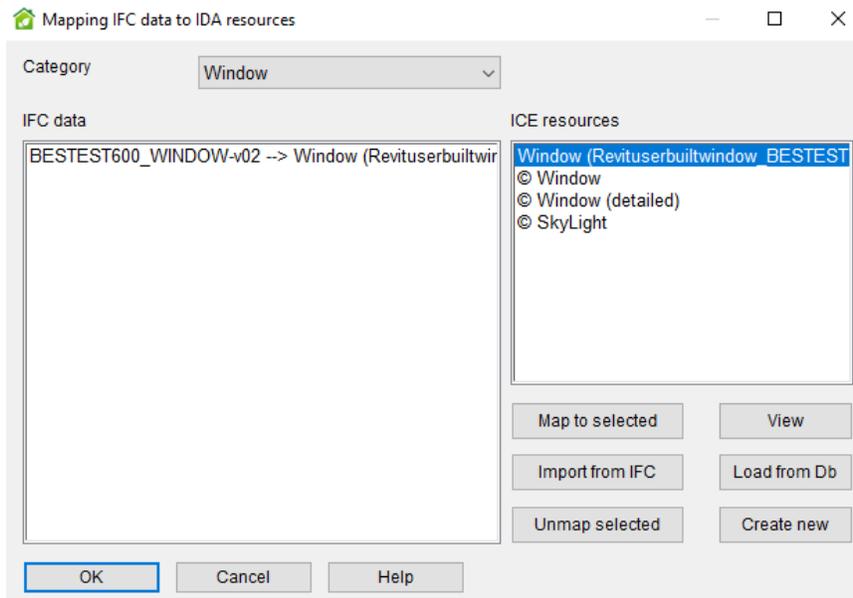
Figure 3-104 Window mapping inside IDA-ICE (Case 15)

The result is that window mapping is required for this case study as well, Figure 3-104. This means that IDA-ICE has read these newly-created family, but since all the windows that are coming through an IFC file into this tool require window mapping, the windows of this case are of no exception.

We ran two simulations, along with Case 14 in which the windows where Revit Built-in families, and the second one, with the current Case 15 in which the Revit user builds the windows. Our purpose was to see if there is a difference between the results of two windows.

The result of the Simulation using the built-in window family (Case 14) is presented in Figure 3-105, and The result of the Simulation using the built-in window family (Case 15) is presented in Figure 3-106. By looking at the red boxes, it can be observed that the results differ quite insignificantly. This translated into two things. Firstly, IDA-ICE has successfully read IFC file regarding the user-built window family and understood that it is a window, meaning that IfcExportAs and IfcExportType were successfully

implemented. Secondly, it has treated the user-built window similarly to the built-in window, since the simulations results are almost the same.
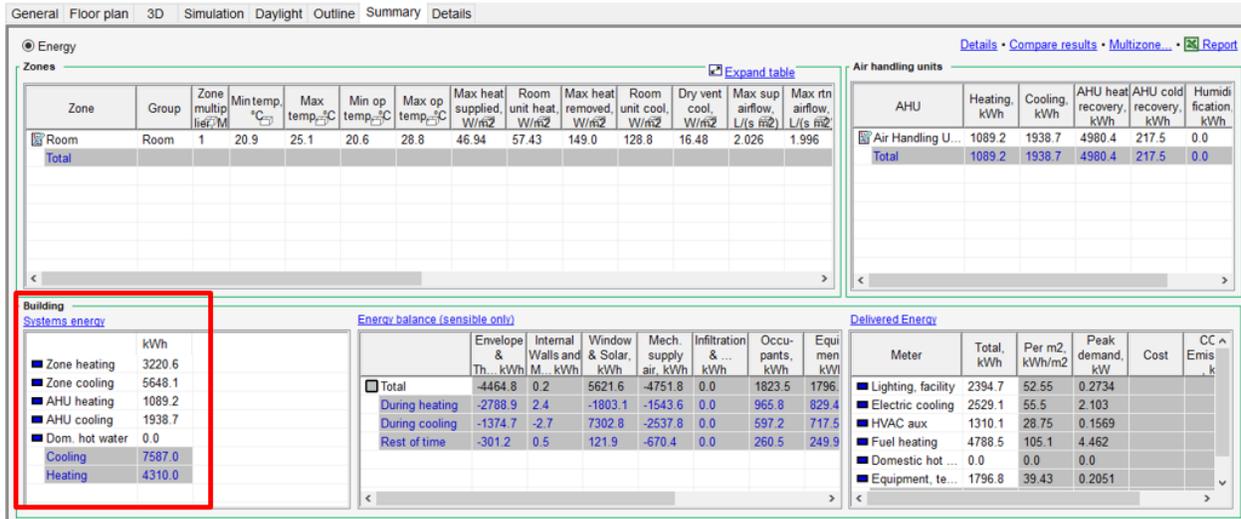
Figure 3-105 Simulation results of the Case 14, Building Model with built-in window family (Case 14)
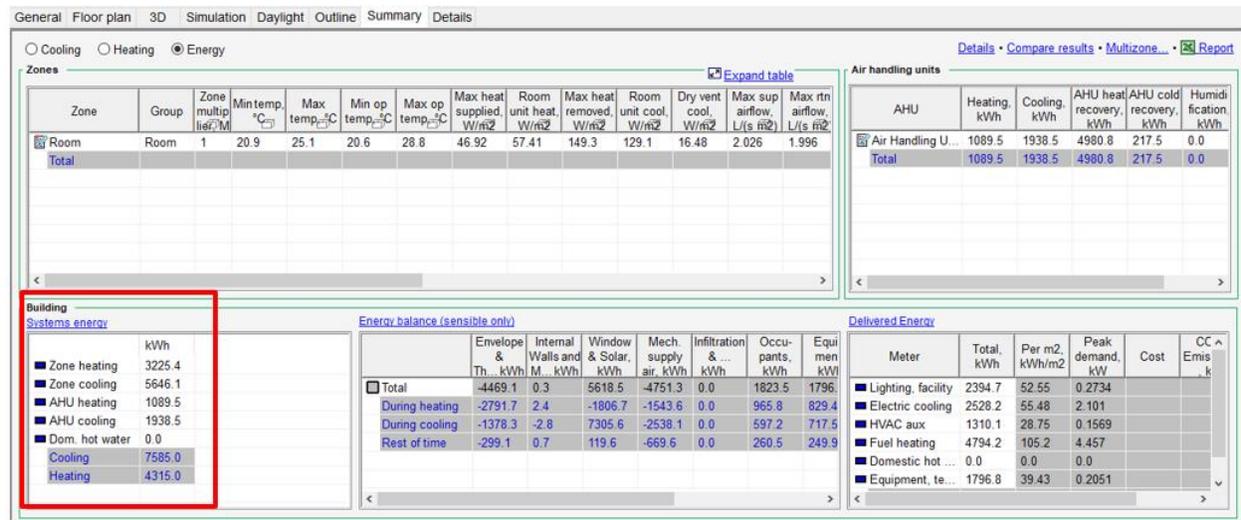
Figure 3-106 Simulation results of the Case 15, Building Model with user-built window family (Case 15)

3.3.4.15.3 Conclusion

Any new interoperability issue was not found in Case 15. The same interoperability issue as Case 14 persists which is that windows' thermal characteristics are not exported from Revit to IDA-ICE at one hand. On the other hand, IDA-ICE is not able to read information about windows' thermal characteristics. Therefore, it requires an internal process called Window mapping that helps to reproduce the windows' thermal properties inside its platform.

The first conclusion is that IDA-ICE can communicate with BIM models that have new user-built families and BIM modelers are not limited to the families that are readily existed in the Revit package.

The second conclusion is that Revit's IfcExportAs and IfcExportType works fine, and can compensate for IFC classes that are not in the model.

3.3.4.16 Case 16

3.3.4.16.1 Systematic Reference

T6_ST1_BM3

3.3.4.16.2 Interoperability issue

The interoperability issue in Case 17 is regarding the building orientation and objects orientation. The question is: how do changes in the orientation of the building from the True North in the model for 30 degrees towards North-East in BIM, affect the IFC file, and IDA-ICE?

Indeed, we are interested to see how the orientation of the building and objects are recorded in IFC file, and if IDA-ICE is able to translate orientation changes in its platform seamlessly.

3.3.4.16.3 Methodology and Results

To prepare the Revit model of this case study, the Building Model 3 was used that was also tilted by 30 degrees in North-East direction, Figure 3-107. After exporting the model to IFC, and importing it into IDA-ICE, the first observation was that the titled building model was correctly shown in IDA-ICE.

Through the properties and palettes of IDA-ICE interface, it was explored whether the coordinates of the elements were exported as they were placed in Revit or not.
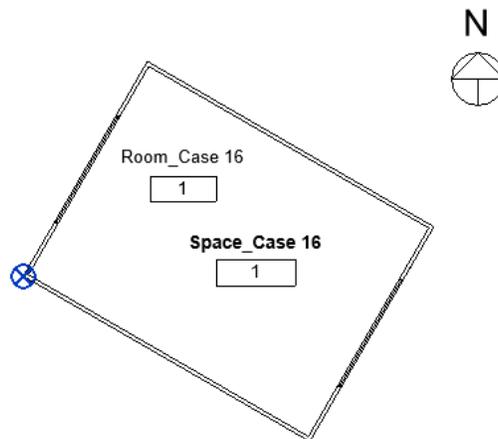
Figure 3-107 Orientation in Case 16 in Revit
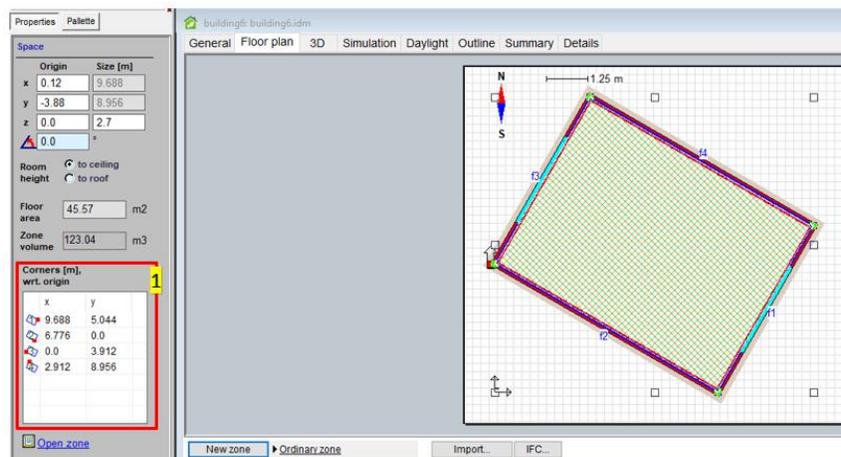
Figure 3-108 Orientation in Case 16 in IDA-ICE

It was found that during the IFC export phase inside Revit, if the "Export Revit Property Sets" is not checked off, then the rotation from the True-North inside Revit is not exported to IfCDirection. Yet, if the IFC file is imported to IDA-ICE, the geometry and zone will be perfectly shown as it was modeled in Revit. It is our conclusion that, when the building or the building elements are rotated, they take new coordinates, so the new coordinates will be written in IFC export file. Thus, even without having the rotation angle, IDA-ICE can reconstruct a rotated geometry from coordinates. This can be seen in Figure 3-108, box number 1.

IfcDirection is an entity that defines a general direction vector in two or three-dimensional space. The actual magnitudes of the components have no effect upon the direction being defined, only the ratios X:Y:Z or X:Y is significant [139].

Furthermore, If the orientation of the building inside Revit is not set to True North, the rotation will be exported to IfcDirection. In Figure 3-109 below, the line highlighted with yellow shows a rotation of 30 degrees.

```
#220= IFCCARTESIANPOINT((3016.08681649643,5136.11560621024,0.));
#222= IFCDIRECTION((0.500000000000017,0.866025403784429,0.));
#224= IFCAXIS2PLACEMENT3D(#220,#222,#19);
#225= IFCPLANE(#224);
```

Figure 3-109 IFC file, IfcDirection

3.3.4.16.4   Conclusion
No interoperability was found.

IDA-ICE can correctly deal with the orientation and has no problem with reading the orientation of the BIM model. In the same vein, Revit has exported orientation of building and objects with any issue.

3.3.4.17   Case 17

3.3.4.17.1 Systematic Reference
T7_ST1_BM1

3.3.4.17.2 Interoperability issue
The interoperability issues that this case investigates are twofold. Firstly, how does Revit export coordinates to IFC file? And how does IDA-ICE interpret the coordinates from an incoming BIM model through an IFC file?

The exchange of information between Revit and IDA-ICE, regarding the cartesian coordinates, and the origin of the 2D plane was investigated in this case.

3.3.4.17.3 Methodology and Results
When we open the Revit new project, unlike AutoCAD, there is no point in the interface that shows the (0,0,0) coordinates. However, based on Revit terminology, the Project Base Point [140], can be made visible at the center of the Revit's plan view by turning on the *Project Base Point* box in the *Visibility/Graphic* box, shown in Figure 3-98. The project base point defines the origin (0,0,0) of the project coordinate system [140] in Revit.

After importing the Revit model to IDA-ICE (Building Model 1), it became clear that IDA-ICE perfectly reads the information about the coordinates of the objects and reflect them in its own platform. Figure 3-111 is the evidence of this statement; on the left, the X-Y-Z arrows in IDA-ICE are located on the outer face of

the wall, and the walls are transparent, showing the zone inside. Likewise, on the right, the Base Point is shown on the outer face of the wall in Revit.
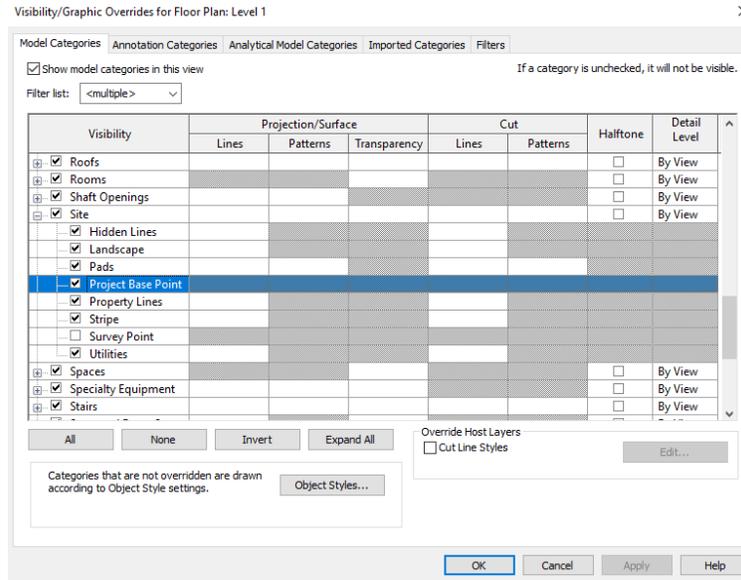
Figure 3-110 Visibility/Graphic window in Revit, Project Base Point
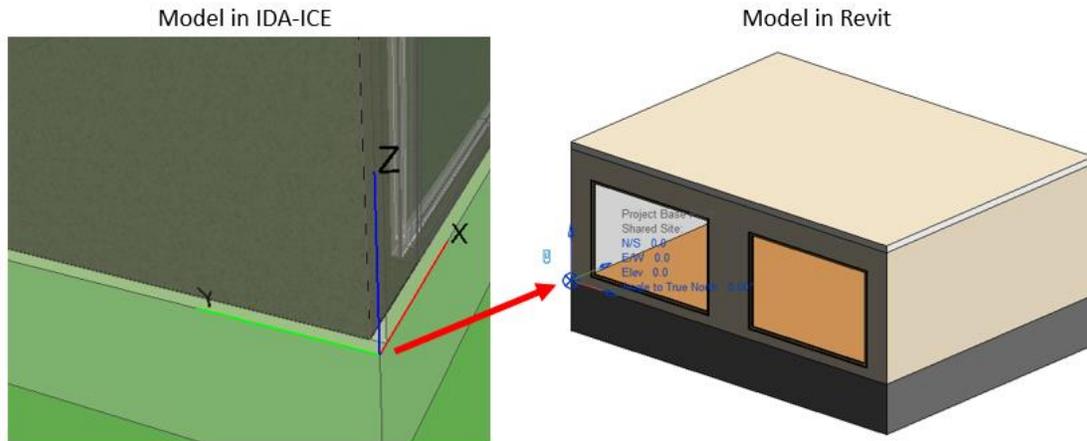
Figure 3-111 Coordinates of (0,0,0) point in IDA-ICE (left), and in Revit (right)

The Base point is shown in Figure 3-113, and the Base Point is the (0,0,0) origin. This data is stored in IfcSite [141], and as can be seen in Figure 3-112, there are several IFC records that finally refers to the line #6 in the IFC file, which stores the origin point of Revit.

```
#6= IFCCARTESIANPOINT((0.,0.,0.));
#9= IFCCARTESIANPOINT((0.,0.));
#1570= IFCAXIS2PLACEMENT3D(#6,$,$);
#1571= IFCLOCALPLACEMENT($,#1570);
#1572= IFCSITE('1S12QwbqDDdgU4gnce8FaW',#41,'Default',$,'',#1571,$,$,.ELEMENT.,(39,44,24,33508),(-104,-59,-31,-270751),0.,$,$);
```

Figure 3-112 IFC file, How coordinates are exported to IFC?
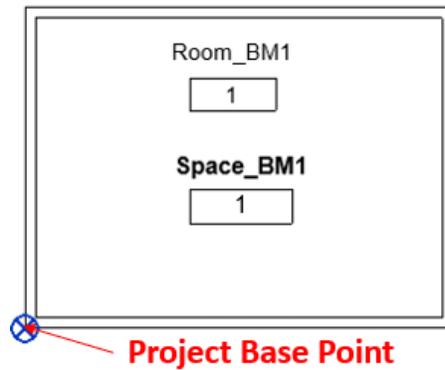
Figure 3-113 Except Case 19, all the cases have a corner that is on the Project Base Point and (0,0,0,) coordinates.

Despite all these, the Zone is IDA ICE always start at (0,0). By looking at Figure 3-115, you can see that on the red box number 2, one of the coordinates is (0,0). The zone in IDA ICE always has one corner with coordinates (0,0). The reason for this is because IDA-ICE is an energy analysis tools, and zones are crucial to the calculations. Therefore, the zone always has a (0,0) coordinates to facilitate calculation. Meanwhile, the actual coordinates of the building in Revit are of no importance to IDA-ICE.
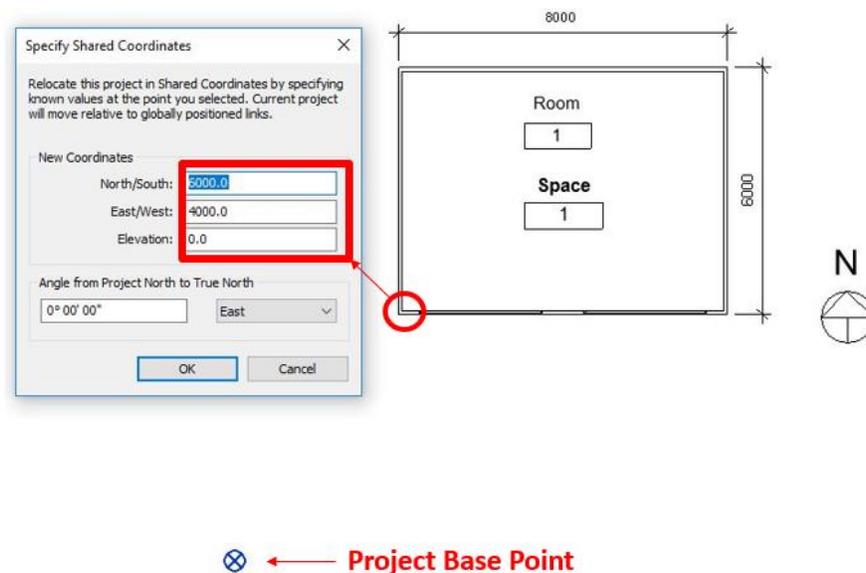
Figure 3-114 change of coordinates of the Revit model (Case 19)

To better explain the coordinates in Revit and IDA-ICE and their relationship, the building model was moved from the (0,0,0) coordinates in Revit, to new coordinates shown in the box in Figure 3-114.

After importing the new model to IDA-ICE, the new BIM model coordinates were reported in the red box number 2 in Figure 3-116. Again, as explained earlier, the zone coordinates of the same BIM model in IDA-ICE has a corner that starts at (0,0), Figure 3-115, box number 2. It should be noted that the size of the wall in X and Y directions has remained unchanged in box 1 in both Figure 3-115, and Figure 3-116.
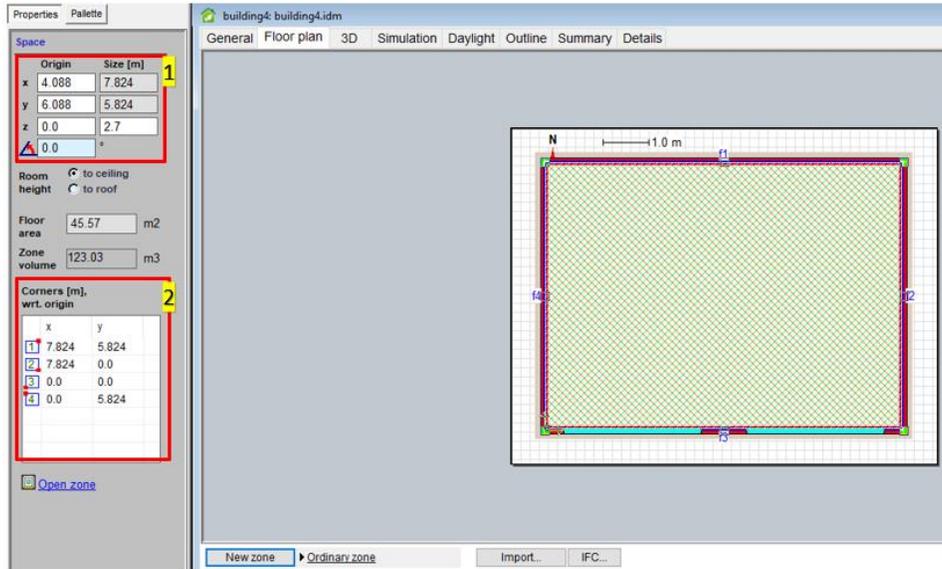
Figure 3-115 Zone in IDA-ICE (Case 18)
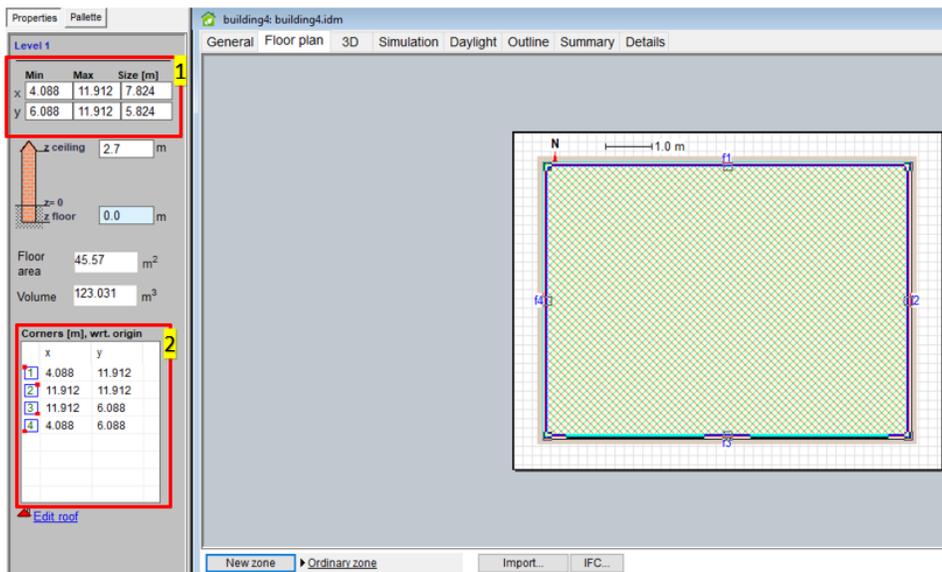
Figure 3-116 Building body in IDA-ICE (Case 18)

3.3.4.17.4 Conclusion

No interoperability was found in this case.

However, Revit user should be conscious about the choice of the starting point of the Revit architectural model. Therefore, in order to avoid any confusion between architects and energy engineers, it is our suggestion that BIM model has a known Project Base Point coordinate, to reproduce it precisely in IDA-ICE, or any other software that can read coordinates from an IFC file.

3.3.4.18.1 Interoperability issue

The interoperability issues are how shadings and fins are created in Revit and exported to IFC? And how does IDA-ICE understand the shadings in the BIM model?

Case 18 and 19 are presented together because their interoperability issues are similar.

3.3.4.18.2 Methodology and Results

To test the shading, the first challenge was how to draw it. Unlike IDA-ICE, there is no element or object such as shading device in Revit to draw a shading. Therefore, it is possible to draw a surface with a desired thickness in many ways and consider it as a shading device in the architectural model. During the design of shadings, we asked many experts on their idea about how to design this shading surface. The solutions were numerous. On one hand, due to many capabilities of Revit, some proposed to draw a shading with "Face-based" families [142], and "In-place" families[143]. On the other hand, some proposed to use Wall object to create this shading, but we had to reject this solution because if we draw anything with wall object inside Revit, then it will be automatically mapped to IfcWall! While this is efficient for architectural modelling, it could pose a massive problem for energy modelling. The reason in that shadings are a crucial component in the energy balance of a room. Therefore, their role is crucial in energy analysis models. But in BIM architectural models, they act as an object that can be omitted from the original plan and are of second importance level with respect to windows.

The reason this is brought up here is that it shows that the perspective of architects is different with the perspective of those who want to use the building information model as the basis of their model in other tools and/or for energy analysis purposes. Since, from the very beginning, we knew that we need to draw a shading in a way that it could be exported appropriately to IFC, that can also be recognized by the BEM tool, we were cautious with our method of designing a shading in Revit.

In this case study, the shading is drawn by "Model In-Place" option from the component. Then, in the Family Category and Parameters pop-up window, since there is no category as shading or even any other category that is close to shading, the "Generic Model" was chosen. Then, with "Sweep" function, the shading was developed inside Revit.
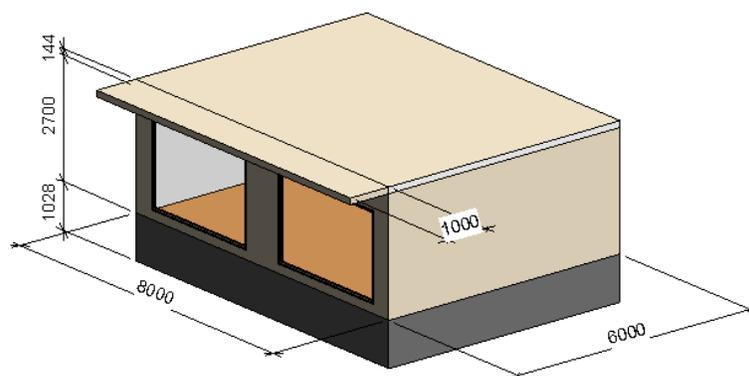
Figure 3-117 Building Model 2, horizontal shading (Case 18)

As elaborated in Building Model 2, the length of the shading is 1 meter (1000 millimeter, Figure 3-117). While there is no material defined for it. In this case study material, wood was chosen for it in order to match the other materials that were already used during in the model; this model is going to be called **Case 18.a** from now on. Likewise, Figure 3-118 shows the Case 19 that corresponds to Building Model 4.
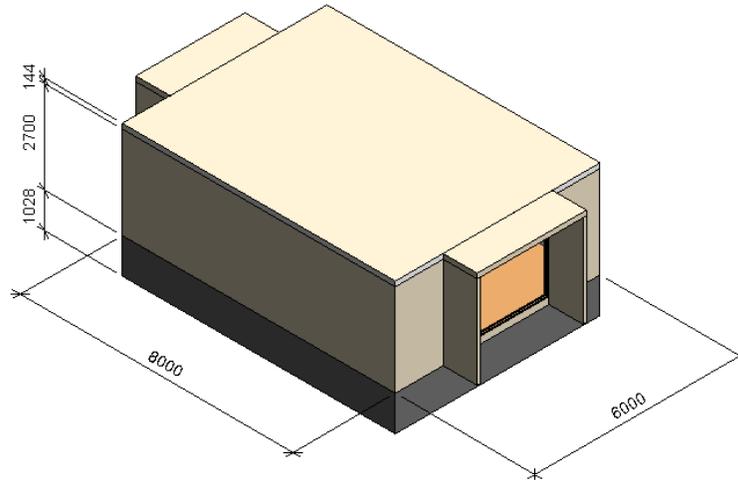
Figure 3-118 Building Model 4, horizontal shading, and vertical fins (Case 19)

All that said, since there is no object as shading in the object-oriented BIM authoring tool of this study (i.e., Revit 2018), we created a shading surface by "Component" objects [144]. Then, after this step, it became clear that since there is not shading element defined for Revit by default, so, Revit cannot automatically map our shading object to proper IFC class. Therefore, we investigated and understood that BuildingSmart has a class called IfcShadingDevices that is for shading, but it is not supported by Revit. Section 3.1.4.4 there is a list of supported IFC classes by Revit.

After this step, the critical task was to find how we can insert IfcShadingDevices inside the Revit and how to export it from Revit to IFC. This was investigated by two methods.

The first method is to assign a subcategory (called Horizontal Shading) to the mass object we created, i.e., shading surface. Then, this category will be visible in the IFC export options in Figure 3-120, number 3. From there, it is possible to manually write the IFC class that this category should be written to.Figure 3-119 Shows this procedure. It can be seen that we have manually chosen IfcShadingDevice for the Shading category. Following procedure is followed to make a subcategory.
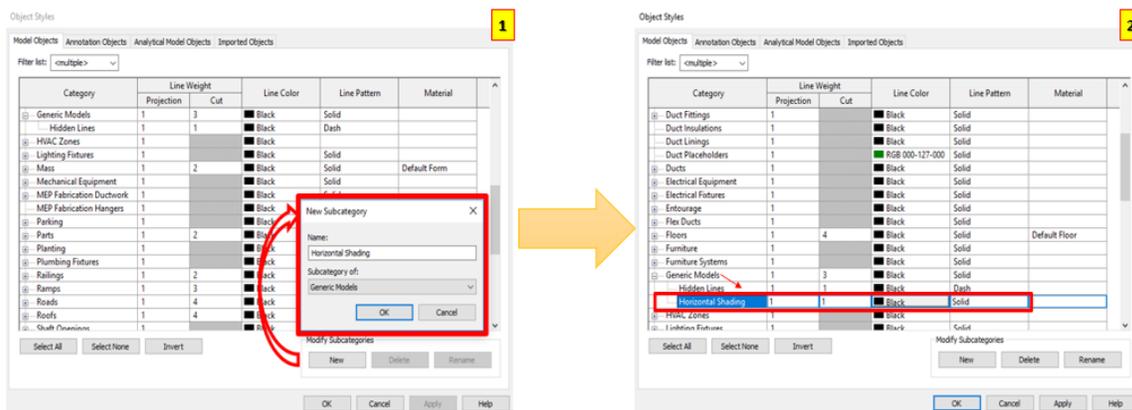
Figure 3-119 Creating new subcategory (1), overwriting the subcategory's IFC with the desire IFC class (2) in Revit
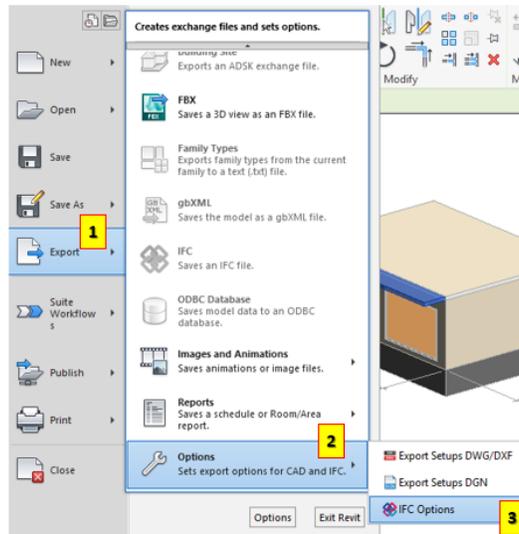
Figure 3-120 IFC options in Revit

It can be observed that this new subcategory is visible in the list of IFC Export Classes. However, it is by default set as IfcBuildingElementProxy. We can override this by IfcShadingDevice. In this way, the generic model that we created will be considered as a shading device by other platforms.

While this seems like a viable option, the surface was not recognized by IDA ICE as a shading element! The geometry of the surface was correctly exported from Revit to IFC, and correctly imported from IFC to IDA-ICE, but the desired functionality was not.

The second method is to use IfcExportAs and IfcExportType. These are some shared parameters that can be added to the model [145]. While the procedure is explained in [145], we explain it here step by step as we did this case study.

First, the shading mass that we designed should be selected. Then, in the modify mode, Family Types must be selected, Figure 3-121. In this window, first, a new parameter should be added. For this, upon pushing the add new parameter button, a new window will pop up. The name of this window is "Parameter Properties." In this window, Shared Parameter should be chosen (red box number 2), and then the select button should be chosen.
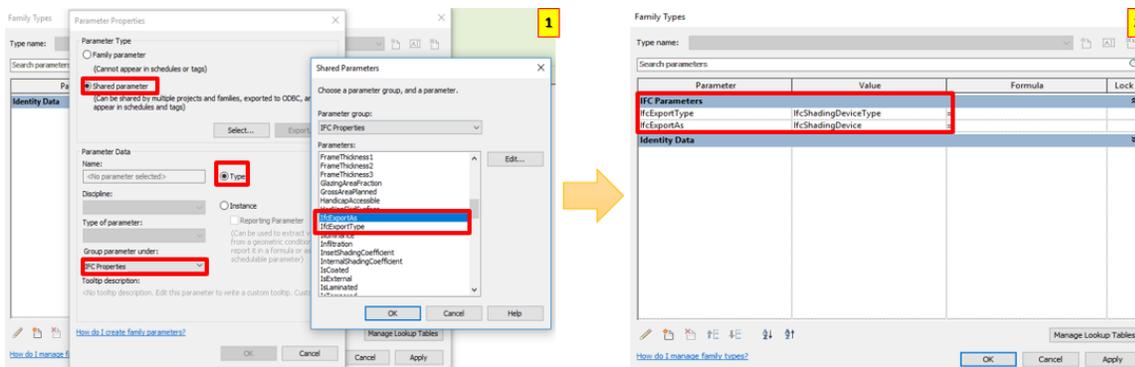
Figure 3-121 Creating IfcExportAs and IfcExportType in Revit

Afterward, the "Shared Parameters" will be opened up. In this window, IfcExportAs is chosen. Then, from the "Group Parameter under:" drop-down list, IFC Parameters should be chosen, Figure 3-121. Additionally, Type should be checked off as shown in Figure 3-121.

The same procedure must be followed to add and describe IfcExportType. As a result, these shared parameters will be added under IFC Parameters as shown in Figure 3-121. Now, we can add our desired IFC entities to the object.

In Case 18, where Shadings are being investigated, IfcExportAs is set to IfcShadingDevice, and IfcExportType is set to IfcShadingDeviceType.

After both options were exercised to populate the Revit's shading object with IfcShadingDevice class, we export it and import it to IDA-ICE. Figure 3-122 shows how BIM-based IFC is read and visualized by IDA-ICE. Although the shading is visible in the model, it is not because of the IfcShadingDevice, but because of the geometry of a mass-object that it was initially created from. The reason we say this is because when we filter the incoming IFC model, as shown in Figure 3-123, no shading is present in the thermal model.
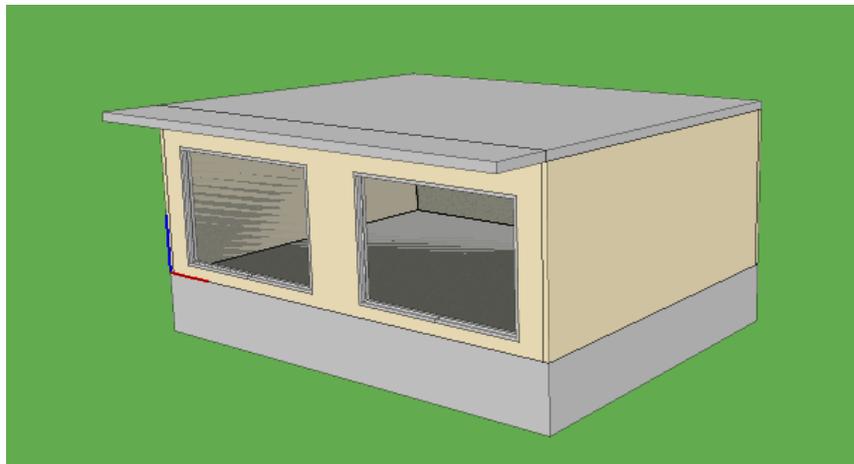
Figure 3-122 Building Model 2, Shading object geometry in IDA-ICE (Case 18.a)
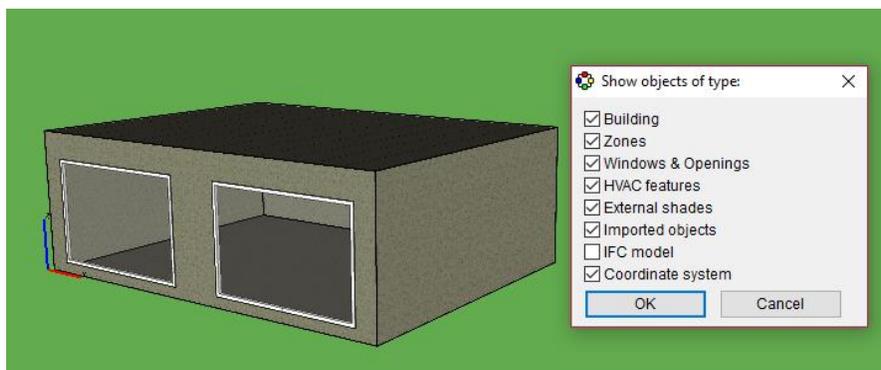
Figure 3-123 Building Model 2, Shading object is not present in the thermal zone in IDA-ICE (Case 18.a)

To check whether IDA-ICE reads the IfcShadingDevice, we decided to create shading in IDA-ICE. This case is going to be referred to as Case 18.b henceforth. Horizontal shading was created by inserting the dimension in the box in Figure 3-124. Accessing this mode for creating a shading in IDA-ICE is possible through "Site shading and Orientation" in the General tab. The shading can be seen in Figure 3-125.
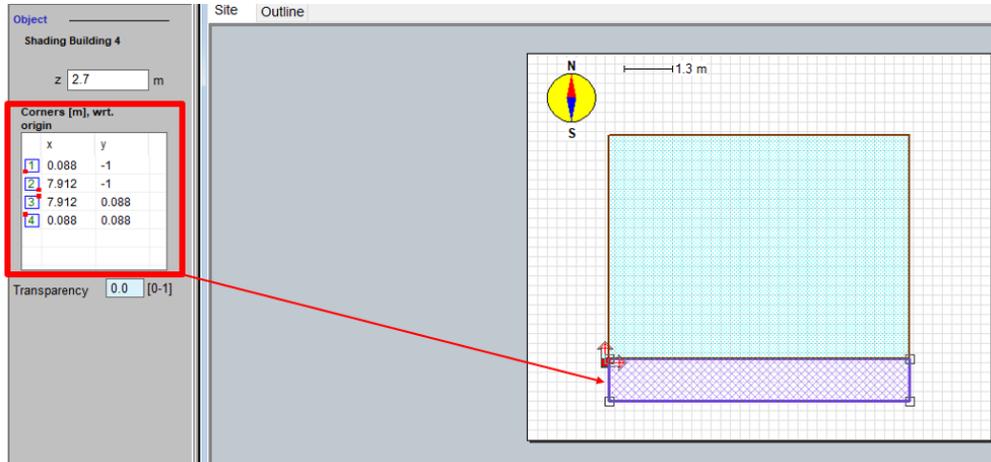
Figure 3-124 Creating External Horizontal Shading in IDA-ICE (Case 18.b)
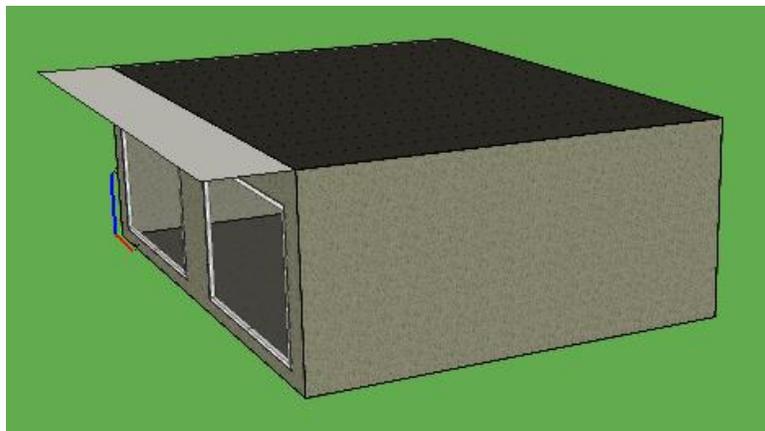
Figure 3-125 External Horizontal Shading, created inside IDA-ICE (Case 18.b)

Therefore, three simulations were performed:

A. Simulation A: Building Model 1 (Case 14), Figure 3-126,
B. Simulation B: Building Model 2 with IfcShadingDevice (Case 18.a), Figure 3-117 and Figure 3-122,
C. Simulation C: Building Model 2 with shading created inside IDA-ICE (Case 18.b), Figure 3-125.

The location of these simulations is Denver, CO, in united states. This is in accordance with the BESTEST cases' location as stated in [113]. The weather file in IDA-ICE is Denver (Int. Airport).

Indeed, there is no big difference between the simulation results of Simulation A (Case 14 or Building Model 1) and Simulation B (Case 18 or Building Model 1 with IfcShadingDevice and shading). This finding confirms that IDA-ICE did not read IfcShadingDevice. Had IDA-ICE read the IfcShadingDevice class, the results would have been significantly different.

However, the Zone Cooling Loads of Case 18.b in Figure 3-129, is 4126.1 kWh which is considerably less than 5648.4 kWh as of Case 18.a in Figure 3-128. This is directly related to the presence of horizontal shading in the model. Therefore, this comparison confirms that IDA-ICE does not recognize the Shading in case 18.a, and even though the IFC model had IfcShadingDevice class, it was not helpful for BIM to BEM procedure in this case-study.

In addition to that, according to EQUA Simulation AB [146], the roof overhangs and balconies (Such as the mass-object shading in Case 18.a) are considered for shadow calculations and animation in IDA-ICE. This means that Case 18.a and Case 18.b are similar in this regard.

Since the result clearly show that Shadings should be manually created in IDA-ICE, regardless of the shadings in BIM model, Case 19 was not further investigated. We believe that the results of Case 28 are similar to Case 19.
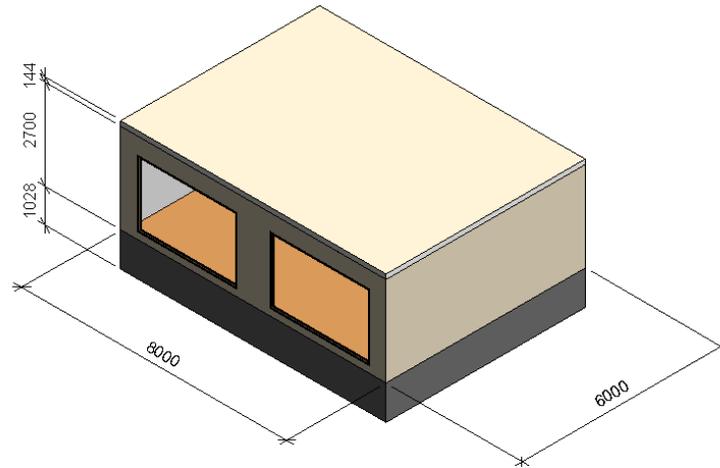
Figure 3-126 Building Model 1 (Case 14)

3.3.4.18.3 Conclusion

An interoperability issue was found.

The primary issue is that Revit does not have model element class that is specific for shadings and/or fins, therefore, there Revit does not support IfcShadingDevices class. That said, one limitation of this case-study is that IfcShadingDevice belongs to IFC 2x4 (e.i. IFC4), not IFC2x3!

The other issue was found with IDA-ICE. Even though the BIM model was populated with IfcShadingDevice class in the IFC file, IDA-ICE could not accept this IFC class to automatically create shading which requires users to draw a shading in the IDA-ICE platform manually.

There are several other sub conclusions including that IfcExportAs and IfcExportType work perfectly in exporting IFC classes from Revit to IFC. A side-conclusion of this model is that the geometry of the mass objects (Place-in mass) in Revit is entirely transferred to IDA-ICE.

In the end, it is our first suggestion to Revit to try to add the IfcShadingDevice class or any other appropriate class to their supported IFC classes. Our second suggestion is for them to make separate model elements that function as Shading. This would hugely influence the BIM to BEM process since as a result, a shading will be automatically created in the BEM model instead of manual efforts.

Figure 3-127 Simulation A (Building Model 1, Case 14)

Systems energy (Building):

	kWh
Zone heating	3220.6
Zone cooling	5648.1
AHU heating	1089.2
AHU cooling	1938.7
Dom. hot water	0.0
Cooling	7587.0
Heating	4310.0

Figure 3-127 Simulation A (Building Model 1, Case 14)

Figure 3-128:

Systems energy (Building):

	kWh
Zone heating	3220.2
Zone cooling	5648.4
AHU heating	1089.1
AHU cooling	1938.6
Dom. hot water	0.0
Cooling	7587.0
Heating	4309.0
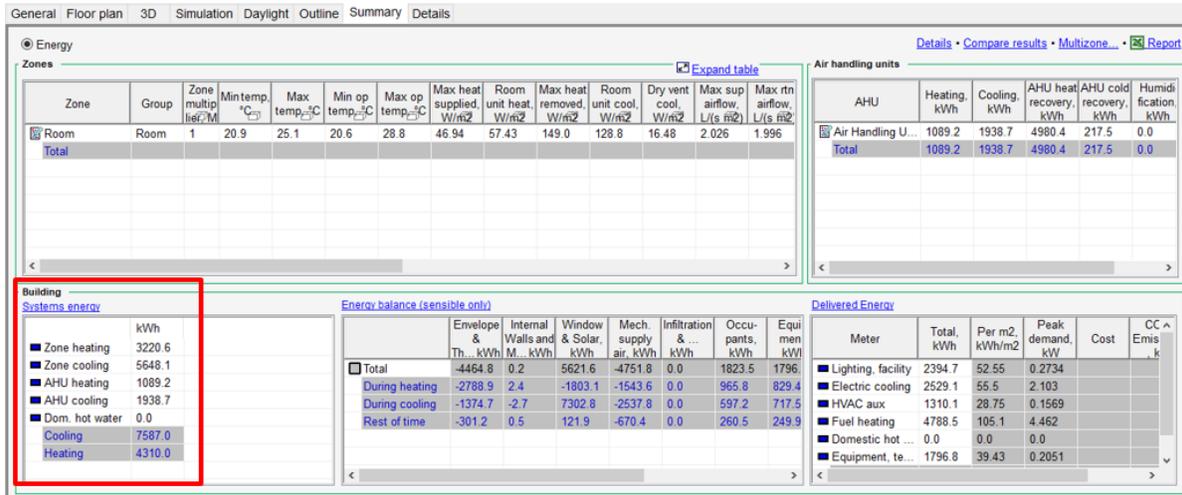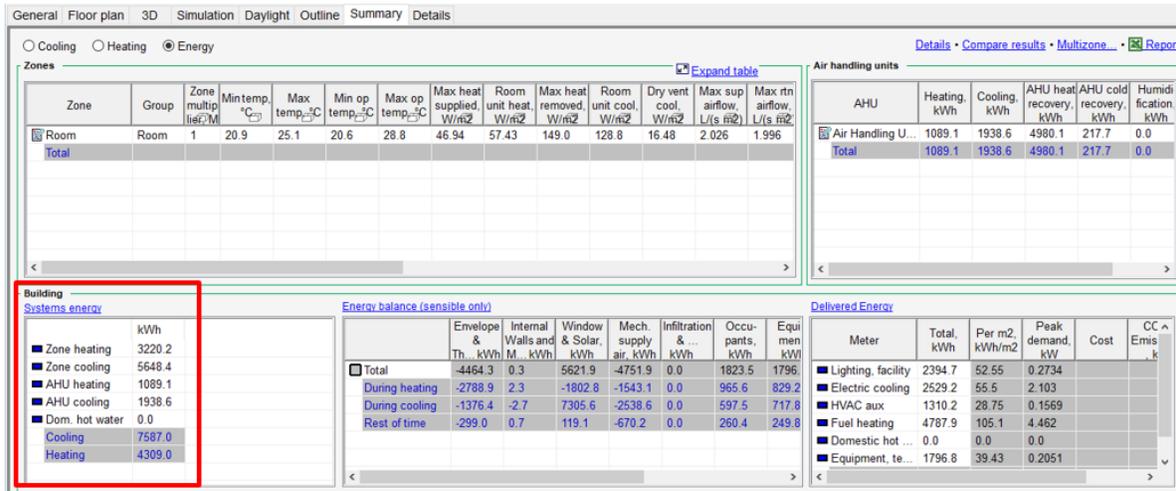
Figure 3-128 Simulation B (Building Model 2 with IfcShadingDevice, Case 18.a)

Figure 3-129:

Systems energy (Building):

	kWh
Zone heating	3304.4
Zone cooling	4126.1
AHU heating	1096.4
AHU cooling	1937.7
Dom. hot water	0.0
Cooling	6064.0
Heating	4401.0
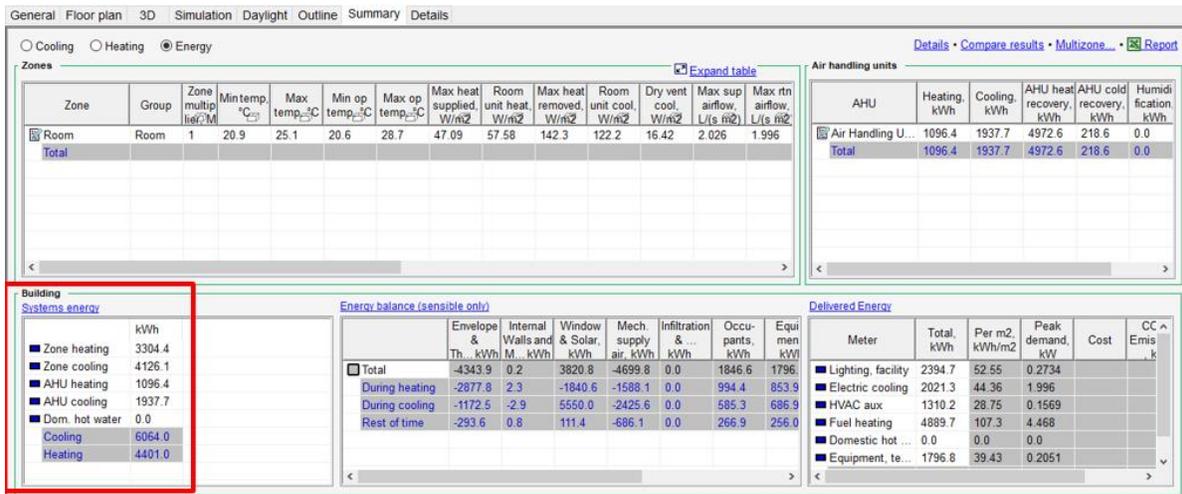
Figure 3-129 Simulation C (Building Model 2 with shading created in IDA-ICE tool, Case 18.b)

Chapter 4   Conclusions and Future Works

This thesis aims to improve the energy simulation processes by focusing on the interoperability issues between BIM and BEM tools, in order to promote sustainable and integrated design. This was fulfilled by the attainment of the objectives expressed in Chapter 1, and by addressing the interoperability questions. Therefore, Chapter 4 starts with a summary of the research steps taken to accomplish the research objectives stated in Section 1.1.2. Concluding remarks are then presented in Section 4.2, and future work is suggested in Section 4.3.

4.1   Summary

The present study began with an introduction to aim and objectives, followed by a literature review on Building Information Modelling (BIM), Building Energy Modelling (BEM), Interoperability, Industry Foundation Classes (IFC), in Chapter 2. Afterward, an overview of the chosen BIM tool, i.e., Revit, and BEM tool, i.e., IDA-ICE was presented to introduce some of the necessary concepts and terminologies in Chapter 3. Consequently, case-studies and their interoperability issues were discussed in Chapter 3.

4.2   Conclusion Remarks and Suggestions

After investigating BIM to BEM interoperability issues through 19 case-study, by using Revit 2018, and IDA-ICE 4.7.1, several concluding remarks have been derived out.

Cases 1 to 4 showed that the Location Line of the walls that is a property of the wall element has no influence on the walls of the BIM-based energy model inside IDA-ICE. In fact, IDA-ICE reconstructs the walls coming from an IFC file, based on the interior face to face length of the wall or the zone and based on the thickness of the wall, even though the type of "location line" exists in the IFC. That said, it was investigated that Revit, correctly export wall Location Line property to the IFC file format.

Furthermore, through these 4 cases, it was confirmed that the 3D geometry of the BIM model is exchanged between BIM and BEM tool, without any problem. This compass both Revit model elements (such as walls, floors, windows) and mass object (such as mass families).

Through cases 05, 06, and 07, it became clear that concerning Spatial Intelligence elements such as Room, Space, Zone elements inside Revit, some interoperability issues can come up. Firstly, a Building Information Model without any such spatial intelligence elements is merely treated by a BEM tool as a "geometry only," or a 3D model, input file.

In case 05, IDA-ICE received the 3D geometry data, but no *semi-automatic thermal zone assignment* was executed by the tool because the input file had only geometrical information. It should be noted here that *fully automatic zone assignment* is not yet possible in IDA-ICE.

Cases 06, and 07 resulted in an interoperability issue concerning Spatial Intelligence elements. The results of these cases demonstrated that IDA-ICE only executes *semi-automatic thermal zone assignment* when the Revit model has both Space and Room elements inside an enclosed building body. In other words, if the model has only Room elements or only Space elements, IDA-ICE cannot detect a thermal zone and does not execute the *semi-automatic thermal zone assignment*. Hence, the user should manually draw all the zones in IDA-ICE.

Additionally, according to IDA-ICE, after the import of IFC into the tool, the *semi-automatic thermal zone assignment* is dependent on the IfcSpace class inside the input IFC file. However, our investigations in cases 06 and 07 demonstrated that even though IfcSpace exists in the IFC file, IDA-ICE cannot execute *automatic thermal zone assignment*. It should be noted here that Revit exports both of these spatial intelligence elements, i.e., Room and Space, to IfcSpace classes. Therefore, the interoperability issue that

was found is that IDA-ICE cannot automatically detect thermal zone, even though the BIM model has either Space element or Room element, and when IfcSpace exists in the imported IFC file.

It was revealed, in Case 08, that only when <u>both</u> Room and Space elements cohabit in one IFC file, *semi-automatic thermal zone assignment* is executed by IDA-ICE. However, an issue exists here because Revit exports both of these spatial intelligence elements, i.e., Room and Space, to IfcSpace classes. This requires EQUA Simulation AB, the developer company of IDA-ICE, to clarify how IDA-ICE reads IfcSpace, in order for building designers to develop BIM models that work seamlessly with IDA-ICE.

Based on the findings and conclusion of Case 05, 06, 07, and 09, it is our suggestion to EQUA Simulation AB to improve the IDA-ICE features regarding the *semi-automatic zone assignment* in order for IDA-ICE to detect thermal zones when either Space or Room exists in a BIM file. This feature can reduce the time and efforts necessary for producing BIM-base BEM models.

Case 10 showed no interoperability issues concerning a building model with one Zone and one Space element (in addition to Room element). IDA-ICE was able to detect the zone semi-automatically.

Case 11 and 12 demonstrate an interoperability issue that is related to the different origin of Revit and IDA-ICE, as architectural, and energy simulation tools, respectively. Revit easily allows creation and storage of a model where the Space and Room elements volumes do not match the volume of the building body. Equally, Revit also easily exports such model to IFC without producing any error. However, such building model is problematic for the energy model, because, for the purpose of thermal load calculations, Space volume should match the volume of the enclosed building body.

Therefore, based on observations, it can be concluded that the 3D shape of Room and Space should match with the 3D shape of the enclosed building body. By 3D, we mean the length of building elements in X, Y, and Z directions. Having a BIM model with the building geometry that corresponds to Room and Space (spatial intelligence) elements' geometry is required for the semi-automatic detection of zones in IDA-ICE, their geometry (i.e., height, length, and width) should match. It is necessary to check and keep track of these elements to have a clean IFC file, and for re-usability of the BIM model in future.

Additionally, through Case 11 and Case 12, it became clear that IDA-ICE accepts the Zone height information from the Room element, and form the IfcSpace record that holds the information about Room elements. The reason is unknown to us and requires future investigations.

Considering that the Building Model 1 was a simple building model, with only one enclosed building body, it was easy to inspect it and check the Space, and Room heights (i.e., Upper Limit, and Limit Offset in Revit). Should the building model have several rooms and floors, it will be a troublesome, and time-consuming effort to check which Room, Space elements are mistakenly populated with different spatial element data. Additionally, it can be said that third-party software such as Solibri Model Viewer can be helpful with problem detection in the IFC file.

Case 13 scrutinized the interoperability issues related to Materials from the perspective of Revit and IDA-ICE, separately. This is explained in the following paragraphs.

The first issue is that Revit lacks the ability to export the materials' thermal properties to IFC properly. At best, Revit can export thermal characteristics of elements as a whole (e.g., wall) to IFC, in the form of IfcPropertySingleValue class which means that even though these characteristics are exported to IFC, they are not exported to the right IFC classes. To further elucidate, Revit can export thermal characteristics of the whole wall, not the thermal characteristics of each material layer of the wall, to IFC.

The second issue concerns IDA-ICE. Regardless of the amount of information in the IFC file, IDA-ICE can only comprehend Style (i.e., name) of materials from the imported IFC file. This obliges the user to map every material from IFC data to IDA resources. Therefore, the flow of information from BIM to BEM is not automatic at all, because inserting thermal properties of materials into IDA-ICE is not automatic. The mapping process in IDA-ICE, explained in Section 3.2.2, is quite time-consuming and laborious which can lead to possible human-made errors when the building model is huge.

Furthermore, the third issue is that, even though the thermal characteristics of elements as a whole (e.g., wall) exist inside the IFC file, IDA-ICE cannot read all of them, but only name and thickness of the elements.

Therefore, concerning the exchange of information about materials, it can be concluded that Revit and IDA-ICE are barely able to communicate with each. Solving this type of interoperability issue requires both software vendors to improve their products since BIM to BEM process will be hugely uplifted if the BEM tool can read the materials' properties automatically, should such information exist in the IFC.

That said, based on the findings of Case 13, we suggest AutoDesk Revit to improve the IFC exporter and settings, for Revit to be able to export material's properties to IFC. Solving this issue from the BIM vendors seriously benefit the AECOO industry and reduces the interoperability issues which leverage BEM vendors to improve their products in return.

Additionally, we also propose that IDA-ICE add a new feature to automatically accept the thermal properties of the *whole element* from the IFC file. This suggestion is because this information can already be readily found in the IFC file. This means that a new category can be added to the "Mapping IFC data to IDA resources," that can read the constructions with their thermal-characteristics (that are in IfcPropertySingleValue) from the IFC file. If IDA-ICE reads the properties of a whole element, and subsequently, implement it in its platforms without considering each single material layer, then the flow of information can be automatic when it comes to materials' properties. This would immensely reduce the time and effort for BIM to BEM process using IDA-ICE and will promote using this tool for projects where detailed information about materials is not necessary.

The findings in Case 14 demonstrated that when windows are concerned, both Revit and IDA-ICE have some software limitations that introduces interoperability issues. These issues are rather similar to the issues regarding materials' thermal properties. Firstly, the material properties of window's glass and frame are not exported from Revit to IFC, only the analytical constructions, i.e., "Double glazing – domestic" and its properties are exported to IFC as IfcPropertySingleValue classes which are of little use in the Revit to IDA-ICE exchange process, because in any case, IDA-ICE obliges the user to map windows from IFC data to IDA resources. Therefore, the exchange of window's information from BIM to BEM is not automated.

The results of Case 15 were similar to Case 14. However, a new conclusion was drawn in this case regarding the *User-built families* in Revit. A window family was created in Revit from scratch in this case, and after the import to IDA-ICE, it was observed that IDA-ICE is able to read this user-built family, and understand that it is a window, even though we had to eventually map the window in IDA-ICE, similar to Case 14. Hence, IDA-ICE can communicate with building models that have new user-built families. This finding means that BIM modelers are not limited to the families that are readily existed in the Revit package.

Furthermore, Cases 16 and 17, that dealt with orientation, and coordinates, respectively, had no interoperability issues. In fact, in both cases, the data was seamlessly transferred between Revit and IDA-ICE. Nevertheless, it is our suggestion to Revit users to start their project from a known point from the Project Base Point, to avoid future conflicts.

Finally, some interoperability issues were found in Cases 18 and 19. These cases investigated the shadings in the BIM and BEM tools.

The primary issue was related to Revit's shortcomings, since this BIM-authoring tool do not have any model element family that act individually as shading and/or fin. Subsequently, Revit cannot export any information that shows the model has shadings, into the IFC file. This also means that Revit does not support IfcShadingDevices class that is dedicated to shadings in IFC 2x4. The fact that Revit has no shading object is a significant hindrance to developing BIM-based BEM models.

The second interoperability issue concerns IDA-ICE. Firstly, IDA-ICE did not detect any shading in the IFC file that was populated with IfcShadingDevices. Secondly, it was proved that for considering shading in the energy simulation calculations, IDA-ICE requires the user to draw a shading inside the IDA-ICE platform manually. Therefore, there is no automatic process in which IDA-ICE detects a shading in an input BIM model.

To solve this interoperability issue, a dual effort should be undertaken by both Autodesk company and EQUA Simulation AB company. On the one hand, Autodesk Revit can add a new object family that functions as s shading device, and also empower it with proper IFC classes that stores and exchange shading properties. As a consequence, this would prevent ad-hoc or case-based solutions for creating a shading device in building information models via Revit, that result in interoperability issues.

On the other hand, IDA-ICE can facilitate accepting IfcShadingDevices or any other proper IFC class related to shading, to automate the process of shading design. Currently, it is only possible to draw the horizontal and vertical shading manually and to assign the integrated shading during the process of window mapping. As previously stated, IDA-ICE mapping process is quite a time-consuming and error-prone and requires EQUA Simulation AB company's attention.

Notwithstanding, Case 18 also proved that the geometry of Revit Mass-objects is transferred seamlessly to IDA-ICE.

In some cases, the validity of using Revit's IfcExportAs, and IfcExportType for exporting to desired IFC classes in the BIM to BEM process was successfully approved.

Finally, it has been observed in many cases throughout this project, that changing one option in IFC Exporter has prevented certain information to be written into IFC file. Therefore, Revit user must be aware of the IFC export options that affect the output IFC file and the quality of BIM to IFC to BEM process.

4.3   Future works

During this work, a number of ideas have emerged that could be used as continuous studies. All of them are related to our work and have arisen due to discussions regarding the subject of this thesis.

I.   Since the IDA-ICE version 4.8 has been released, it is our suggestion to check whether the interoperability issues found in this project are also persistent in BIM to BEM process by using IDA-ICE Version 4.8.

II.   Revit Zones are an interesting subject that we, unfortunately, did not have enough time to look further into. In our model, we only had one Zone and one Space element, but there are two other possibilities that can be further explored:

  o   Several Spaces and one Zone,
  o   Several Spaces and several Zones,

These cases will help to better clarify how IDA-ICE interacts with theses Revit elements in IFC file, while more insights will be received about how IfcSpace and IfcZone work simultaneously in the IFC file.

I.   To develop a full picture of how Spaces and Zones interact with each other in one BIM model, additional studies can focus on the possibilities of the:
- Zone properties in Revit,
- Space properties in Revit.

Indeed, each of these elements in Revit can store numerous energy-related values as their properties. Therefore, there are a lot of inputs regarding Spaces or Zones that Revit can readily accept. However, it is unclear whether they are exported adequately to IFC, and whether IDA-ICE can read them. Thus, future researchers can focus on the Space, Zone properties as well.

II.   Moreover, it is possible to populate an IFC file with new information. A possible solution is to manually write IFC records into the text file to enrich it with thermal properties information. In practice, this solution demands a highly knowledgeable person that is thoroughly familiar with the complex IFC hierarchy. The same solution is possible through programming. Several methods can be undertaken for this task:
- Firstly, *Dynamo* [147] can be a viable option, since it already has a plugin in Revit. It is a powerful, easy-to-use tool.
- Secondly, programming platforms such as *MATLAB* [148] can be helpful for realizing this task.
- Thirdly, online open source platforms such as *Ifcopenshell.org* [149] are another option that would help to write IFC records.

These are some directions that future researchers can follow in order improve and facilitate the export of thermal properties of the materials to IFC.

III.   Another subject that needs to be further investigated is to extend the capabilities of Revit with respect to the IFC export, by using Dynamo. While ad-hoc solutions can be developed by this graphical programming interface, it is possible to create a plug-in that helps sedbuilding designers to better export BIM to IFC in future works.

IV.   Finally, this research proposed and investigated a systematic approach to Revit (BIM tool) to IFC (Data schema) to IDA-ICE (BEM tool) process. Future researchers can follow the same approach with different BIM tool and/or with different BEM tool. This provides a way to compare the BEM software in terms of their interoperability with BIM.

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A. Appendix A.

For the purpose of further clarification of the case-studies, a short overview of IDA-ICE and its capabilities and interface is presented here. The figures and descriptions are taken from [108].

A.1 Introduction to IDA ICE interface:

In this section, the described objects, properties, and etc. are directly within the context of this project and the case studies. Any other object available in IDA ICE that was not related to the goals of this study is omitted in explanation.

IDA ICE is the abbreviated name of "Indoor Climate and Energy (IDA ICE)" which is a dynamic multi-zone simulation application for the precise study of an entire building with respect to its indoor climate of individual zones, and its energy consumption.

To provide both efficiency and flexibility, IDA ICE provides three user levels: Wizard, Standard and Advanced. This is while, IDA ICE, itself, is delivered in two editions: Standard and Expert. This project has used expert edition.

A.2 An overview of Standard Level

For starting a project in IDA ICE, there are wo possibilities. First, to start with an empty building, and second, to start with a building with a single zone. In the latter case, unlike the former, an already ready-to-simulate project will be opened up. The building in this project has the geometry of a single zone with a "southerly orientation". The default settings of this building contain wall constructions, glazing, shadings, location, synthetic weather, mechanical zone ventilation, controller setpoints and all other inputs required for a simulation.
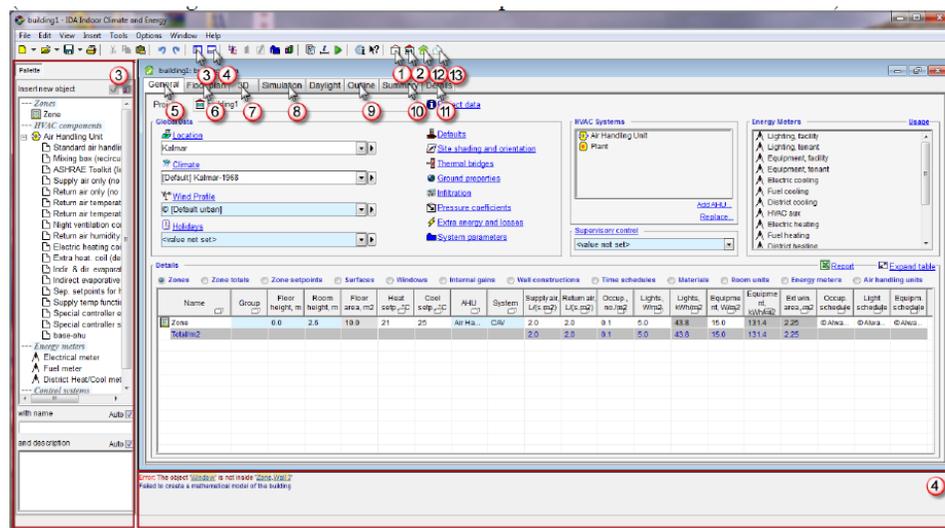

Figure A-1 IDA-ICE interface, Standard level, General tab [108]

An important part of IDA ICE is the **General** tab, Figure A-1, where the main information about the project is presented, including: Global Data, HVAC Systems, Energy Meters and tables with model details.

The next important tab that is being regularly used is the **Floor plan** tab that illustrates a 2D view of the building geometry. In this tab, a building body, zones, windows and doors are depicted. And, the opening of the IFC file is possible through this tab.

Moreover, the **3D** tab is a useful visualization option in IDA ICE, since both the model and the results can be visualized and animated here. In this tab, upon selecting an object, the property page in the side bar will open up. Also, double clicking on an object will open up the object form.

Finally, the simulation options are given in the **Simulation** tab and all different kinds of simulation-runs are started here. Later, statistics from finished simulations are shown, as well as links to key results.

In the Expert edition of IDA ICE, there is the **Outline** tab that gives the outline view of the project. That said, an overview of the simulation results could be shown in **Summary** tab, depending on which edition of IDA ICE is being used. The same is true, about **Details** tab, which delivers details of the simulation.

In the standard view, there is ESBO Wizard and VELUX Wizard. ESBO Wizard is a special simpler user interface for setting up a multi-zone simulation model. While, VELUX Wizard is a special simpler user interface for setting up a single zone simulation model with singular emphasis on natural ventilation by windows.

A.3 An overview of General Tab

In the General Tab, it is possible to start the project with a new building with a single zone and, modifying the project data, and location data that includes geographical position, and weather data.

In this Tab, different parameters that are valid for the whole building are presented to be adjusted. Also, the access to the structure and parameters of the air handling unit and the building plant, is provided, along with the meters for keeping track of energy and CO_2 emissions.

Change the table view: Individual tables can be viewed and edited by clicking on the corresponding radio button. Many parameters (data related to zones, surfaces, windows, loads, constructions, etc.) can be changed directly in these tables. Tables can be sorted, and data can be visualized in 3D. Make sure you understand how these tables work. In this tab, it is also possible to export the input tables to Excel.

A.4 An overview of Floor plan tab

In the plan view it is possible to Select an object (e.g. the building body, zone, …) to edit its properties in the side bar (It is advised by IDA ICE documentation to ensure that the Properties and not the Palette view of the side bar is active).

It is possible to rename, cut, copy, delete, replace or edit objects and zones in this view. Through the import button, it is possible to import IFC, or other CAD files. Nonetheless, IFC export can be done independently through IFC button. IFC button also enables the user to map IFC objects which are going to be explained later. This is possible in Expert edition only. In this tab, the vertical level in the building from where the floor plan is being shown and in the show button, it is possible to set a view filter to exclude object types from being shown.
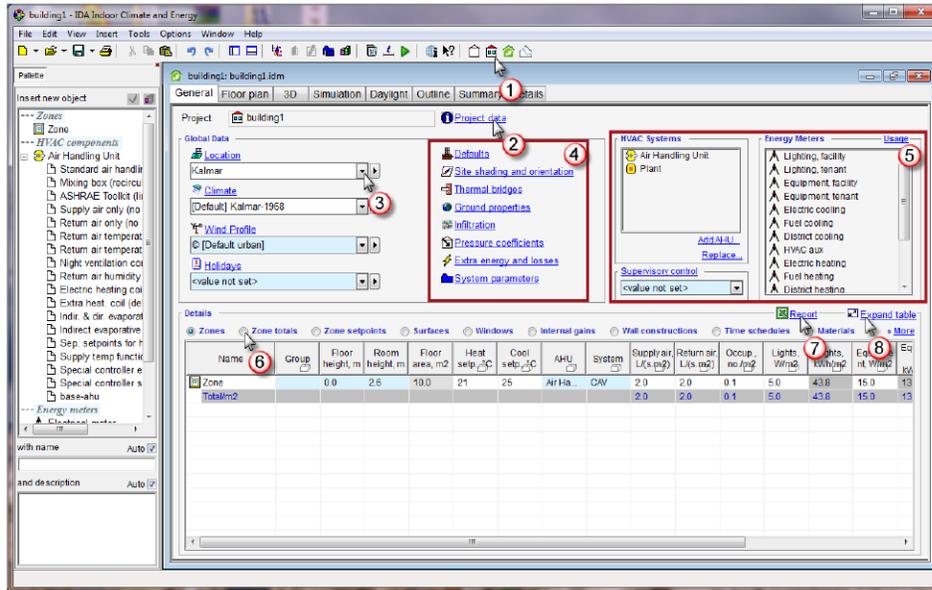
Figure A-2 IDA-ICE interface, General tab [108]
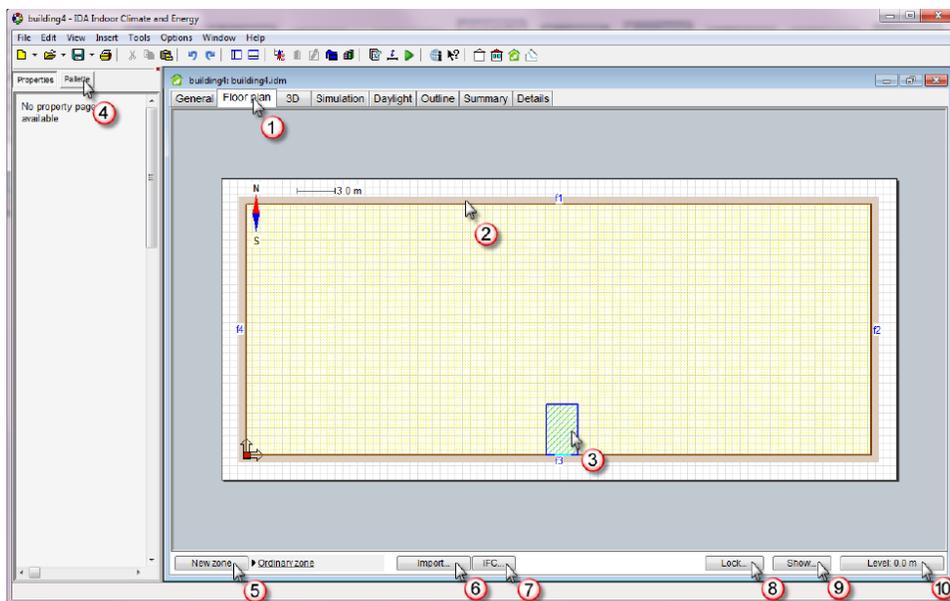
Figure A-3 IDA-ICE interface, Standard level, General tab [108]

A.5 An overview of 3D view

In this tab, the 3D model of the building and its zones are visualized. The x+, x-, y+, y-, z+, z- buttons on the bottom left part of the window, create a section through the building.

If the simulations are done, the Animate button will animate the results. Additionally, it is possible to show the shadows during the animation.
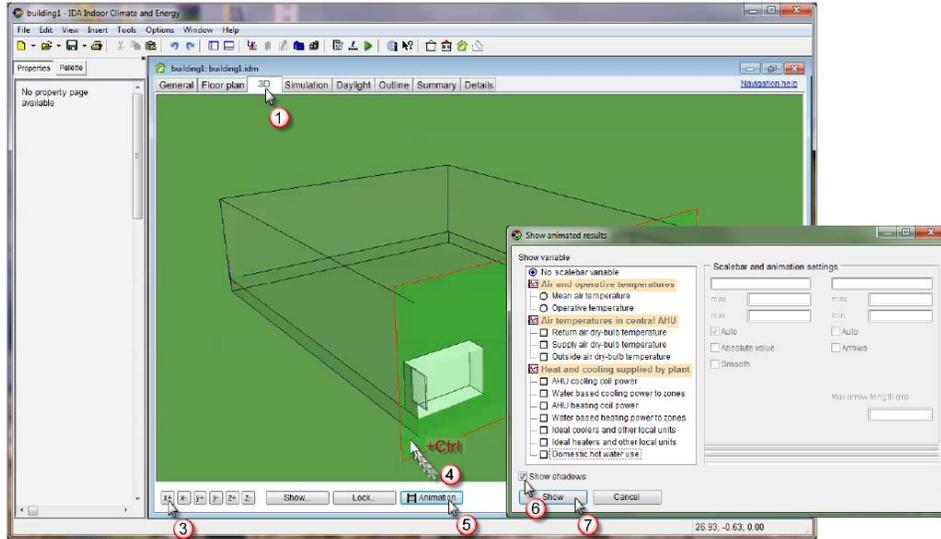
Figure A-4 IDA-ICE interface, Standard level, 3D tab [108]

A.6 An overview of Simulation tab, Summary tab, and Details tab

In the Simulation tab, it is possible to start a simulation. And the results would be shown on the Summary tab. In this Simulation tab, there are 4 different types of simulations: Heating load calculation, cooling load calculation, energy calculation or even customized calculation.
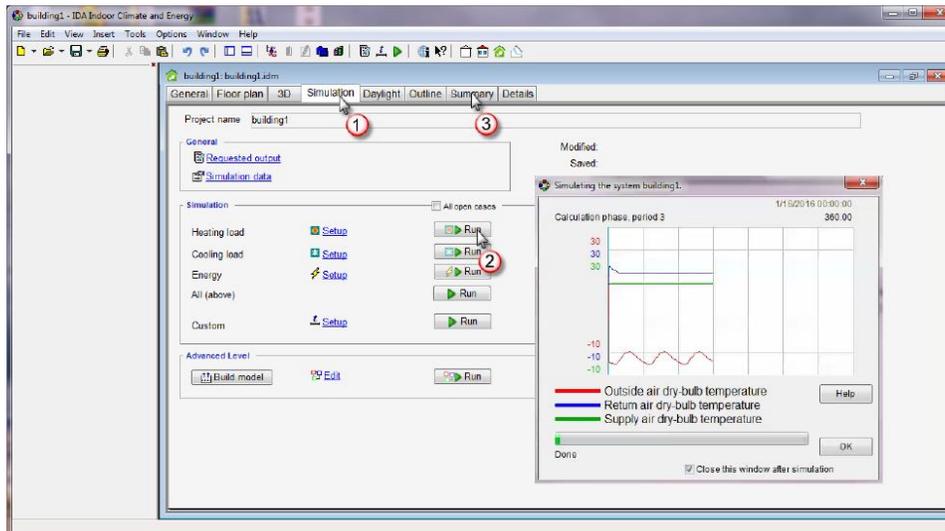
Figure A-5 IDA-ICE interface, Standard level, Simulation tab [108]

The Summary tab, generate an overview of main results from the simulation is given here. These results could be the heating required for each room, for each air handling unit, the heat delivered by the plant, or the power required from the utility to deliver this.
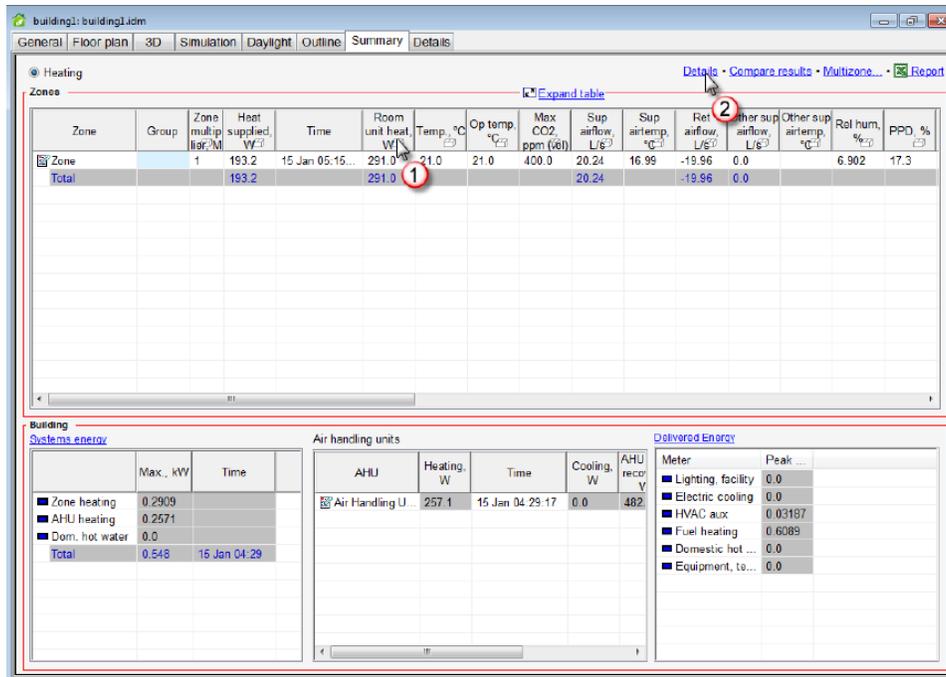
Figure A-6 IDA-ICE interface, Standard level, Summary tab [108]

In the Details tab, Key time series are displayed. It is possible to check extra boxes to select other time series diagrams.
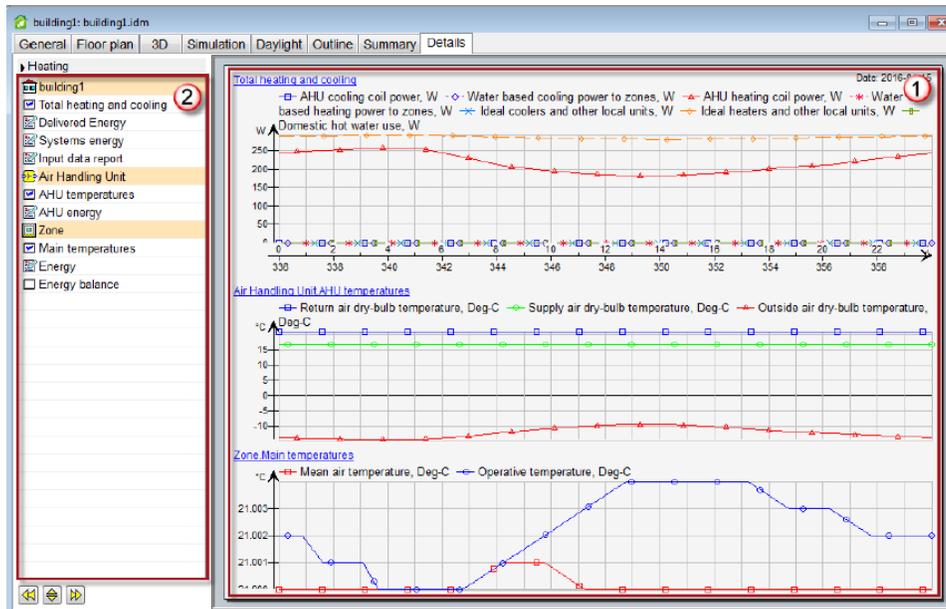
Figure A-7 IDA-ICE interface, Standard level, Details tab [108]

B. Appendix B

In his section, the properties of Room, Space, and Zone inside Revit platform are presented, respectively.

B.1 Room Properties

Following properties exist in the Revit interface, if Room element is selected, or placed inside an enclosed area [150].

| Name	Description
Constraints	
Level	The base level on which the room resides. A read-only value. See About Defining the Lower Boundary of a Room.
Upper Limit	The level from which to measure the upper boundary of the room. See About Defining the Upper Boundary of a Room.
Limit Offset	The distance at which the upper boundary of the room occurs, measuring from the Upper Limit level. Enter a positive number to go above the Upper Limit level, or enter a negative number to go below it. Enter 0 (zero) to use the level specified for the Upper Limit. The default is 10' (4000 mm). See About Defining the Upper Boundary of a Room.
Base Offset	The distance at which the lower boundary of the room occurs, measuring from the base level (defined by the Level parameter). Enter a positive number to go above the base level, or enter a negative number to go below it. Enter 0 (zero) to use the base level. The default is 0. See About Defining the Lower Boundary of a Room.
Dimensions	
Area	The net area computed from the room-bounding elements. A read-only value. See About Room Area.
Perimeter	The perimeter of the room. This is a read-only value. See About Room Area.
Unbounded height	The largest potential height of the room, based on the room height parameters: Level, Upper Limit, Limit Offset, and Base Offset. This value is read-only. See About Room Height. (The room's actual height may be changed by room-bounding elements, such as intervening floors and roofs. See About Ceilings and Floors in Room Volume Computations.)
Volume	The volume of the room when volume computation is enabled. See About Room Volume. A read-only value.
Identity Data	
Number	An assigned room number. This value must be unique for each room in a project. Revit warns you if the number is already used but allows you to continue using it. (See Reviewing Warning Messages or Warnings for Selected Elements.) Room numbers are assigned sequentially. See Create sequential room number tags.
Name	The room name, such as Conference Room or Kitchen.
Comments	User-specified information about the room.
Occupancy	Type of occupancy for the room, such as Retail.
Department	Department for which the room will be used.
Base Finish	Finish for the base.
Ceiling Finish	Finish for the ceiling, such as stucco.

Wall Finish	Finish for the wall, such as painted.
Floor Finish	Finish for the floor, such as carpeting.
Occupant	Name of the person, group, or organization that will use the room.
Phasing	
Phase	The project phase to which the room belongs. A read-only value based on view properties.

Table B-1 Room Properties in Revit

B.2 Space Properties

space properties in the Properties palette of Revit are as follows [151].

Parameter	Description
Constraints	
Level	The base level on which the space resides. This is a read-only value.
Upper Limit	The level from which to measure the upper boundary of the space.
Limit Offset	The distance at which the upper boundary of the space occurs, measuring from the Upper Limit level. Enter a positive number to go above the Upper Limit level, or enter a negative number to go below it. Enter 0 (zero) to use the level specified for the Upper Limit. The default is 10' (4000 mm).
Base Offset	The distance at which the lower boundary of the space occurs, measuring from the base level (defined by the Level parameter). Enter a positive number to go above the base level, or enter a negative number to go below it. Enter 0 (zero) to use the base level. The default is 0.
Electrical - Lighting	
Average Estimated Illumination	Illumination for the space.
Room Cavity Ratio	This parameter is automatically calculated based on room dimensions to determine illumination calculations. See Lighting Calculations.
Lighting Calculation Workplane	The level used as the base for calculating Illumination.
Lighting Calculation Luminaire Plane	
Ceiling Reflectance	The reflective property based on color and surface of the ceiling.
Wall Reflectance	The reflective property based on color and surface of the walls.
Floor Reflectance	The reflective property based on color and surface of the floor.
Electrical - Loads	
Design HVAC Load per area	Total HVAC load for the space. This value can be specified, calculated by the heating and cooling loads analysis tool, or read from a gbXML file.
Actual HVAC Load	Total heating load for the space calculated by the integrated heating and cooling loads analysis tool.
Actual Lighting Load	

Design Other Load per area	Total Other load for the space. This value can be specified, calculated by the heating and cooling loads analysis tool, or read from a gbXML file.
Actual Other Load	Total Other load for the space calculated by the integrated heating and cooling loads analysis tool.
Actual Receptacles Load	
Mechanical - Airflow	
Specified Supply Airflow	Supply airflow introduced in the space. This value can be specified, calculated by the integrated heating and cooling loads analysis tool, or read from a gbXML file.
Calculated Supply Airflow	Total airflow required to head and cool the space. This value can be calculated by the integrated heating and cooling loads analysis tool or read from a gbXML file.
Actual Supply Airflow	Total supply airflow in the space. This value is the sum of the airflow for all supply air terminals in the space.
Return Airflow	Determines how the return airflow is calculated for the space. You can select one of the following values: Specified: Activates the Specified Return Airflow parameter to specify the return airflow. Specified Supply Airflow: Return airflow matches the value for this parameter. Calculated Supply Airflow: Return airflow matches the value for this parameter. Actual Supply Airflow: Return airflow matches the value for this parameter.
Specified Return Airflow	Total return airflow removed for the space. You can specify this value only if Specified is selected for the Return Airflow parameter. If not, this parameter is unavailable and the value is determined by the value selected for Return Airflow (see above).
Actual Return Airflow	Total return airflow in the space. This value is the sum of the airflow for all return air terminals in the space.
Specified Exhaust Airflow	Total exhaust airflow for the space. You specify this value.
Actual Exhaust Airflow	Total exhaust airflow for the space. This value is the sum of the airflow for all the exhaust air terminals in the space.
Outdoor Airflow	Outdoor airflow required for a space. This is a read-only value. See Outdoor Air Information for Zones.
Dimensions	
Area	The net area computed from the room-bounding elements. A read-only value.
Perimeter	The perimeter of the room. This is a read-only value.
Unbounded Height	The largest potential height of the room, based on the room height parameters: Level, Upper Limit, Limit Offset, and Base Offset. This is a read-only value. (The room's actual height may be changed by room-bounding elements, such as intervening floors and roofs.
Volume	The volume of the room when volume computation is enabled. This is a read-only value.
Computation Height	
Identity Data	

Number	An assigned space number. This value must be unique for each space in a project. Revit warns you if the number is already used but allows you to continue using it.
Name	The space name, such as Restroom or Kitchen.
Room Number	An assigned room number. This value must be unique for each room in a project. Revit warns you if the number is already used but allows you to continue using it.
Room Name	The room name, such as Conference Room or Kitchen.
Image	
Comments	User-specified information about the space.
Occupant	Name of the person, group, or organization that will use the space.
Phasing	
Phase	The project phase to which the space belongs. A read-only value based on view properties.
Energy Analysis	
Zone	The name of the zone assigned to the space.
Plenum	Indicates if the space is a plenum space. If checked, the space is defined as a plenum. This parameter is used during loads analysis.
Occupiable	Indicates if the space is occupiable or not. If checked, the space is defined as occupied. Clear the check box for shafts, chases, restrooms, and other spaces that typically would be defined as unoccupied. This parameter is used during loads analysis.
Condition Type	Determines how heating and cooling loads are calculated. When set to Unconditioned, no loads are be calculated. When set to Heated, only heating loads are calculated; when set to Cooled, only cooling loads are calculated. All other settings contribute to the loads calculation. You can select one of the following types: Heated Cooled Heated and cooled Unconditioned Vented Naturally vented only The value for this parameter is exported as the conditionType attribute. Note: Conditioned and Unconditioned spaces must not be mixed within a particular zone. SeeAbout Unconditioned Spaces.
Space Type	You can select the type of space from the Space Type Settings dialog. You can also modify parameter settings for the selected space type. The value for this parameter is exported as the spaceType attribute.
Construction Type	Specifies the type of construction (Roofs, Walls, Floors, etc.) for the space. You can open the Construction Type dialog to select a construction type or define custom constructions for the space.

People	Opens the People Loads dialog where you specify how people loads are calculated for the space.
Electrical Loads	Opens the Electrical Loads dialog where you specify how electrical loads are calculated for the space.
Outdoor Air Information	When a space is selected, this property displays whether outdoor air information is from the space type or from the zone. When a zone is selected, defines whether outdoor air information is from the space type or from the zone. To change this setting, select the zone and click Edit to open the Outdoor Air Information dialog.
Outdoor Air per Person	When a space is selected, this property displays the amount of outdoor air required for each person (in a space) for all spaces in the zone. This value is specified for each zone.
Outdoor Air per Area	When a space is selected, this property displays the amount of outdoor air per occupied square area of all spaces in the zone. This value is specified for each zone.
Air Changes per Hour	When a space is selected, this property displays the number of times per hour that the air volume of all occupied spaces in the zone is replaced. The value is specified for each zone.
Outdoor Air Method	When a space is selected, this property displays the calculation method for outdoor air demand in a space. Use the Building/Space Type Settings dialog to specify one of the following methods: by People and by Area by ACH Max (by People, by Area) Max (by ACH, by People and by Area) Max (by ACH, by Area, by People)
Calculated Heating Load	Total heating load for the space. This value can be calculated by the integrated heating and cooling loads analysis tool or read from a gbXML file. "Not Computed" displays prior to the project receiving loads analysis results.
Design Heating Load	Total heating load for the space. This value can be specified, calculated by the integrated heating and cooling loads analysis tool, or read from a gbXML file.
Calculated Cooling Load	Total cooling load for the space. This value can be calculated by the integrated heating and cooling loads analysis tool or read from a gbXML file. "Not Computed" displays prior to the project receiving loads analysis results.
Design Cooling Load	Total cooling load for the space. This value can be specified, calculated by the integrated heating and cooling loads analysis tool, or read from a gbXML file.

Table B-B-2 Space Properties in Revit

B.3 Zone Properties

The properties of a Zone in Revit are described in Table B-3 [152].

Parameter	**Description**
Constraints	

Level	The base level on which the zone resides. This is a calculated value.
Mechanical - Airflow	
Calculated Supply Airflow	The total supply airflow for the zone calculated by a heating and cooling loads analysis, or read from an imported gbXML file.
Calculated Supply Airflow per area	The Calculated Supply Airflow of the zone divided by the total area of the zone. This value is calculated by a heating and cooling loads analysis, or read from an imported gbXML file.
Dimensions	
Occupied Area	The sum of the areas for all of the occupied spaces in the zone. This is a calculated value.
Gross Area	The sum of the areas for all of the occupied and unoccupied spaces in the zone. This is a calculated value.
Occupied Volume	The sum of the volumes for all occupied spaces in the zone. This is a calculated value.
Gross Volume	The sum of the volumes for all occupied and unoccupied spaces in the zone. This is a calculated value.
Perimeter	The sum of the perimeters for all the spaces in the zone. All common parameters shared by these spaces are omitted from the calculation. This is a calculated value. Note: To improve performance, this parameter is disabled for Default zones.
Identity Data	
Comments	Text comments for the zone.
Name	Name of the zone. Each name must be unique.
Phasing	
Phase	The project phase to which the zone belongs. This is a read only value based on the view properties. See Working with Phases and Zones for more information about phases and zones.
Energy Analysis	
Service Type	The heating and cooling service for the zone. You can select a specific service type or accept the default specified as the <Building> service type for the zone.
Coil Bypass	The manufacturer's coil bypass factor. This is a measure of efficiency that indicates the volume of air passing through the coil that is unaffected by the coil temperature.
Cooling Information	Opens the Cooling Information dialog where you specify the cooling information for the zone.
Heating Information	Opens the Heating Information dialog where you specify the heating information for the zone.
Outdoor Air Information	Opens the Outdoor Air Information dialog where you specify the outdoor air information for the spaces in the zone.
Outdoor Air Method	The method for calculating outdoor air for the zone. The calculation method ASHRAE 62.1 implements the Ventilation Rate Procedure from ASHRAE Standard 62.1. For a valid calculation result using this method, the Primary Airflow must be defined for each space in the zone.
Outdoor Air Method Settings	Opens the Outdoor Air Calculation Setting dialog where you specify the outdoor air calculation information for the spaces in the zone.

Outdoor Air	The total outdoor air for a zone. This is a calculated value.
Calculated Heating Load	The total heating load for the zone calculated by a heating and cooling loads analysis, or read from an imported gbXML file. Not Computed is displayed prior to a heating and cooling analysis, or gbXML import.
Calculated Heating Load per area	The Calculated Heating Load of the zone divided by the total area of the zone. This value is calculated by a heating and cooling loads analysis, or read from an imported gbXML file. Not Computed is displayed prior to a heating and cooling analysis, or gbXML import.
Calculated Area per Heating Load	The total area of the zone divided by the Calculated Heating Load of the zone. This value is calculated by a heating and cooling loads analysis, or read from an imported gbXML file. Not Computed is displayed prior to a heating and cooling analysis, or gbXML import.
Calculated Cooling Load	The total cooling load for the zone calculated by a heating and cooling loads analysis, or from an imported gbXML file. Not Computed is displayed prior to heating and cooling analysis or gbXML import
Calculated Cooling Load per area	The Calculated Cooling Load of the zone divided by the total area of the zone. This value is calculated by a heating and cooling loads analysis, or read from an imported gbXML file. Not Computed is displayed prior to a heating and cooling analysis, or gbXML import.
Calculated Area per Cooling Load	The total area of the zone divided by the Calculated Cooling Load of the zone. This value is calculated by a heating and cooling loads analysis, or read from an imported gbXML file. Not Computed is displayed prior to a heating and cooling analysis, or gbXML import.

Table B-3 Zone Properties in Revit

C. Appendix C

According to Eastman [3], most common exchange formats in the AECOO industry are as summarized in Table C-C-1.

Image (Raster) Formats	
JPG, GIF, TIF, BMP, PNG, RAW, RLE	Raster formats vary in terms of compactness, number of possible colors per pixel, transparency, compression with or without data loss
2D Vector Formats	
DXF, DWG, AI, CGM, EMF, IGS, WMF, DGN, PDF, ODF, SVG, SWF	Vector formats vary regarding compactness, line formatting, color, layering and types of curves supported; some are fi le-based and others use XML.
3D Surface and Shape Formats	
3DS, WRL, STL, IGS, SAT, DXF, DWG, OBJ, DGN, U3D PDF(3D), PTS, DWF	3D surface and shape formats vary according to the types of surfaces and edges represented, whether they represent surfaces and/or solids, material properties of the shape (color, image bitmap, and texture map), or viewpoint information. Some have both ASCII and binary encodings. Some include lighting, camera, and other viewing controls; some are fi le formats and others XML.
3D Object Exchange Formats	
STP, EXP, CIS/2, IFC	Product data model formats represent geometry according to the 2D or 3D types represented; they also carry object type data and relevant properties and relations between objects. They are the richest in information content.
AecXML, Obix, AEX, bcXML, AGCxml	XML schemas developed for the exchange of building data; they vary according to the information exchanged and the workfl ows supported.
V3D, X, U, GOF, FACT, COLLADA	A wide variety of game fi le formats vary according to the types of surfaces, whether they carry hierarchical structure, types of material properties, texture and bump map parameters, animation, and skinning.
SHP, SHX, DBF, TIGER, JSON, GML	Geographical information system formats vary in terms of 2D or 3D, data links supported, fi le formats and XML.

Table C-C-1 Most common data exchange formats in the AECOO industry [3]