



A Methodology to Classify and Determine Data Sharing Requirements between OpenBIM Models and Energy Simulation Models

by

Janakiram Karlapudi

from

Amaravathi, India

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Responsible Professors

Prof. Dr.-Ing. habil. Karsten Menzel

Prof. Dr.-Ing. Raimar Scherer

Advisor

Suraj Sunil Kumar Shetty, BE, M.Eng

Dresden, November and 2018

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Abstract

Energy analysis of a building using traditional methods at every stage of the project is time-consuming and labour intensive. Thus, energy performance simulations of buildings are rarely introduced in all design stages of the project. However, energy analysis of buildings at different stages of the project will allow designers to make proper design decisions (design choices), which will help to enhance the design efficiency and optimization of energy saving measures. A BIM model consists of comprehensive information regarding all the organizations (architects, engineers, constructors, facility management, etc.) involved in the project and about all stages of the project life-cycle (design, construction, maintenance and operation). The seamless data transfer from the BIM model to the energy simulation model will make the energy simulation process much more easier and increase the design efficiency.

In this study, different approaches and methodologies for energy simulation in buildings and classification of these methodologies according to scope, the complexity of data processing, and granularity of resulted data is investigated. The information requirements for energy simulation based on each categorization (i.e. input data parameters and level of data granularity) is analyzed. A methodology for data sharing between the BIM model and the energy simulation model by using meta-data models (gbXML or IFC) is proposed. An analysis is performed to verify the availability of the required information for energy simulation in the meta-data models. A BIM model with the incorporation of all required information to perform a complex type of energy simulation is modelled in Revit 2019 and the same information is transferred to the IES<VE> 2018 (the energy simulation model) using interoperability file formats gbXML or IFC.

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List of Abbreviations and Symbols

BIM	Building Information Modelling
BEM	Building Energy Modelling
gbXML	Green Building eXtensible Markup Language
IFC	Industry Foundation Classes
GBS	Green Building Studio
AEC	Architecture, Engineering and Construction
XML	eXtensible Markup Language
MEP	Mechanical, Electrical, and Plumbing
FM	Facility Management
XSD	XML Schema Definition
ISO	International Organization for Standardization
IFD	International Framework for Dictionaries
IDM	Information Delivery Manual
MVD	Model View Definitions
BCF	BIM Collaboration Framework
bSDD	buildingSMART Data Dictionaries
BES	Building Energy Simulation
CFD	Computational Fluid Dynamic
HVAC	Heating, Ventilation and Air Conditioning
IAI	International Alliance for Interoperability
IES<VE>	Integrated Environmental Solutions <Virtual Engineering>
VAV	Variable Air Volume
DTV	Design Transfer View
RV	Reference View
U-value	Heat Transfer coefficient or Thermal Transmittance
R-value	Thermal Resistance
KJ/K	Kilo Joule / Kelvin
s	Second
L	Liter
W	Watts

1 Introduction

Building Information Modelling (BIM) leads to significant changes of the design process by introducing building energy analysis in the early stage of design and thereby shortening the distance between evolution and design. The main advantage of BIM for modelling energy in the design phase is design optimization based on design decisions or design choices. The decisions about when and what to simulate during design is important to understand the energy consumption of buildings and its importance for designers to make clear design choices [1].

The energy design process starts in the pre-design stage and continues through the building's occupation [2]. It is necessary to know what information is required in each stage of the design process to perform energy simulation. Manual input of information into these energy simulation models at every stage of the project is time-consuming and prone to errors. The critical problem is the iterative use of Energy simulation for design optimization of energy saving measures throughout all stages of the design process.

File exchange formats like Green Building eXtensible Markup Language (gbXML) and Industry Foundation Classes (IFC) allow data interoperability between the BIM model and the energy simulation model. Linking both BIM model and energy simulation model together with interoperable file exchange formats eliminates human interpretation errors and possible inconsistencies of information. Similarly, the interoperability of software enables designers to use simulated energy results as a decision-making feedback for design and strengthens the architect's ability to evaluate design performance.

The efficiency of interoperability between BIM model and energy simulation model is depending upon the data sharing requirements related to the project stages. These data sharing requirements depend on multiple aspects, such as the available data quality, the required input parameters, the methodology used to process data, and the expected outcomes of data processing (quality, robustness, precision).

1.1 Building Information Modelling (BIM)

Building Information Modelling is a “set of interacting policies, processes and technologies generating a methodology to manage the essential building design and project data in digital format throughout the building's life-cycle (refer Figure 1)” [3].

The National Institute of Building Science describes Building Information Modelling as “an improved planning, design, construction, operation, and maintenance process using standardized machine-readable information models for each facility, new or old, which contains all appropriate information created or gathered about that facility in a format useable by all throughout its lifecycle” [4]. Building Information Modelling is a rapidly emerging technology in the Architecture, Engineering and Construction (AEC) industry. By its definition, a BIM model contains the complete information about the life cycle of the building which includes data about the geometry of the building, geographical data, building-space-

relationships, building components, construction details, schedules, facilities, manufacturer details, fabrication process details and so on.

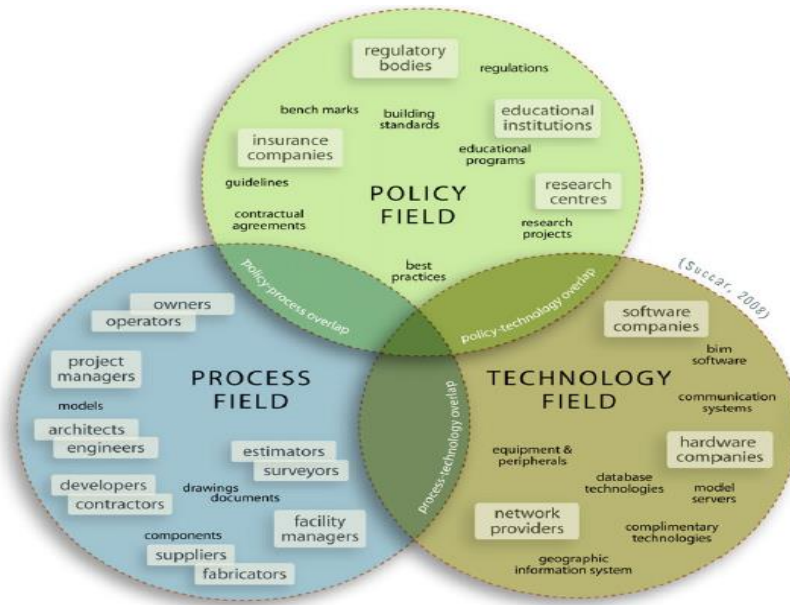


Figure 1: Three interlocking fields of BIM activity [3]

Simply, the term BIM describes the process of modelling the information for a single building or a group of technical elements over their entire life cycle. This information modelling covers both the product modelling and process modelling. The two important aspects of BIM are the process of adding information to an information model and the process of updating model components over their life cycle [5].

1.2 Benefits of BIM-based Energy Analysis

The sustainable design of the building is carried out by initiating the iterative energy analysis from the early design stages of the project. The energy analysis benefits all stages of the project and enables the building to be less dependent on the primary energy by adapting desirable design options. The impact of the site, building orientation, and sources of energy can be evaluated and improved by using a simple energy model during the Pre-design stage of the project. The solar exposure on the building depends on the site location and orientation of the building. The evaluated results from the early stage energy analysis help to identify the optimal orientation and massing of the building and thus reduces energy demand and operational cost. Note that the energy simulation which results from the early stage should only be used for comparison purposes because a large number of building design variables are still under development. During the design development stage, parametric modelling of the building adds significant value to the energy simulation because energy analysis facilitates the different design options, the resultant energy consumption and capital costs. These results help the design team to select desirable design options to reduce energy consumption and capital costs of the building [6].

BIM models contain a large range of information regarding the product and process. The main advantage of the integration of Building Energy Models (BEM) with BIM is to access

the information required for energy simulation and eliminates the need of creating an energy model [7]. There is a large range of advantages by using BIM-based energy analysis over traditional modelling process.

- i) BIM-based energy analysis allows iterative simulations for a wide range of scenarios to be performed within a short period of time.
- ii) The time saving from the reproduction of the energy simulation model could be spent on the simulation and design options [7].
- iii) The geometrical changes in the BIM model can be easily reflected in the energy analysis model by recreating or generating the energy model quickly with the help of the BIM program.
- iv) BIM tools like Revit have inbuilt building orientation options to optimize the solar load.
- v) BIM model “act as a single source of a model of information for all processes” [8].

The potential implementation of the BIM-based energy simulation for sustainable building design has begun and is evident in several case studies. The HAMK University of Applied Sciences has applied BIM-based energy analysis from the early stage of the design for the construction of two educational buildings (Figure 2) as an extension to the existing building in Visamäki campus located in Finland.

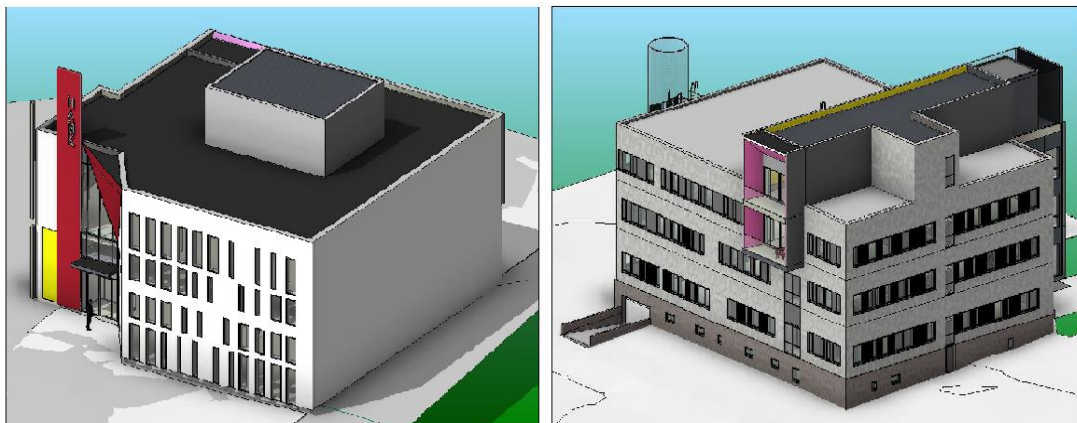


Figure 2: Revit model for the HAMK University Buildings [9]

Sustainable solutions were successfully identified by taking the BIM approach, which resulted in a reduction in energy demand and its effect on energy cost, especially the heating cost because of the location. Furthermore, positive results were achieved in the reduction of CO₂ emission. In this case study, a Revit architectural model for HAMK university building was analyzed within Revit and exported to Green Building Studio (GBS) through gbXML for further analysis in GBS. The BIM tool (Revit) was used as an early stage analysis tool to produce different design alternatives based on the design scenarios that affected energy modelling. The analysis of design alternatives shows the effect of building orientation at different angles, different kinds of glazing, different HVAC systems and different kind of external components like walls and roofs. The results obtained in GBS were compared based on the Energy conservation measures [9].

1.3 Interoperability and Data Exchange Schemas

The term interoperability represents the data sharing (or exchanging) between different software tools to eliminate the regeneration of data models. Data sharing is one of the key concepts to establish the successful implementation of BIM. The seamless data exchange will provide better collaboration between all fields of the AEC industry and it enables a reduction in time, cost and effort involved in the duplication of the data.

The capability for data exchange between engineering and analysis tools will lead to better energy-conscious decisions from the early stages of the design process. One of the main obstacles which prevent the wider adoption of BIM-based energy analysis is the issue with data exchange between the BIM model and the BEM model. There are several aspects influencing the seamless data exchange between the BIM model and energy analysis model. The quality of the data is one major aspect in the definition of data exchange requirements, eliminating the modelling of additional information in both software tools. The selection of data requirements for a specific facility management and sharing of that selected data will simplify the data exchange process and eliminate redundancy in the model generation process [10].

These difficulties in data sharing are improved along with the development of BIM metadata models or data exchange schemas. Two popular data exchange schemas are available for the data exchange in the field of the AEC industry. These are (i) green building eXtensible Markup Language (gbXML) and (ii) Industry Foundation Classes (IFC). The meta-data models IFC and gbXML have significantly improved the interoperability between BIM and BEM, by acting as a bridge between BIM and BEM. These data exchange schemas have also increased the transparency of the data transfer process because the language is both machine readable and human readable [11]. There are several tools available to check, view and validate the data presented in the interoperability file formats (.ifc, .xml). These checking and validation will help the user to rectify the manual data modelling errors.

1.3.1 gbXML

The term Green Building XML usually referred as gbXML. This schema saves the data in terms of XML (eXtensible Markup Language) language which is both machine readable and human readable language. The Green Building XML schema, or gbXML, was developed to “facilitate the transfer of building information stored in CAD-based building information models, enabling interoperability between disparate building design and engineering analysis software tools. This is all in the name of helping architects, engineers, and energy modellers to design more energy efficient buildings” [12]. gbXML is sponsored by organizations such as the U.S. Department of Energy, the National Renewable Energy Lab, Autodesk, Bentley System, and others.

The fundamental structure of the gbXML schema is shown in Figure 3 and it represents the hierarchy of the gbXML schema, which consists of Location, Building, Space, Surface, and Opening. gbXML imports the object-based elements (Walls, Roof, Floor, etc.) from the BIM tool as a virtual element with 2D surfaces. This is the reason for defining Walls, Floors, Roofs and Ceilings as a surface element in the gbXML structure.

The position of surface elements is represented based on two parent nodes. They are as follows.

- Space Boundary Node: which defines the centerline of the surface
- Shell Geometry Node: which defines the inner surface of the wall, etc.

Twice the difference between Space Boundary node and Shell Geometry node gives the thickness of the element. In the gbXML structure, Room and Shading Surfaces belong to the Building Space (refer in Figure 3). In Revit Architecture the user defines ROOMS and in Revit MEP (Mechanical, Electrical, and Plumbing) the user defines SPACES. The export process can be carried out based on either ROOM or SPACE. Rooms are defined by bound volumes. Spaces are defined by room bounding elements. The room bounding elements are Walls (Curtain, Standard), Roofs, Floors, Ceilings, Curtain System and Room Separation Lines. In all the cases, surfaces which do not belong to room bounding are treated as shading elements [13].

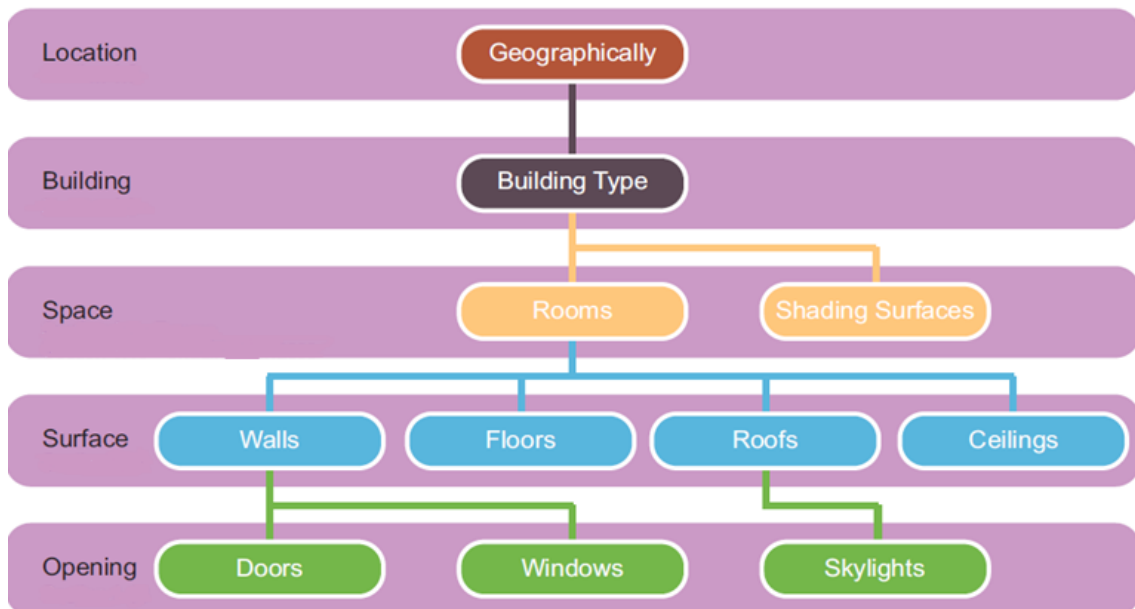


Figure 3: gbXML structure [13]

1.3.2 IFC

buildingSMART proposes an open data scheme called IFC to hold building information. It makes possible to exchange required data between different software applications. The main goal of buildingSMART is to enable the good quality of data sharing between multiple stakeholders throughout the life cycle of any built environment, irrespective of which software they are using [14]. The Industry Foundation Classes (IFC) “represent an open, international and standardized specification for Building Information Modelling (BIM) data that is exchanged and shared among the various participants in a building construction or facility management (FM) project” [15].

IFC is an open meta-data model used to store, manage and exchange the building information between software applications. An IFC file follows the STEP (Standard for the Exchange of Product Model Data - is also known as ISO 10303) physical file and XML exchange file formats for sharing or exchanging data. IFC specifies a data schema to explain about holding the data and relations between this data. The IFC data schema is defined in the EXPRESS data specification language and XML Schema Definition (XSD) language. Part 11 of ISO 10303 contains the formalized specification of EXPRESS – a standard data modelling language for product data. Part 28 of ISO 10303 explains the XML representation of Express schema and data, using XML schema.

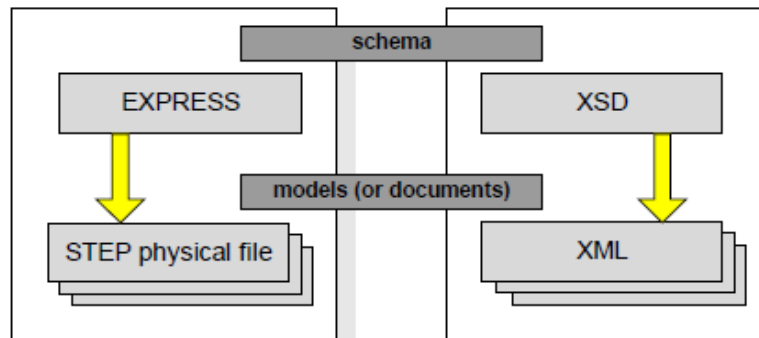


Figure 4: Schema and model differentiation for EXPRESS and XML [16]

The EXPRESS language can be represented in both text and graphical format. The graphical way of representation is also called EXPRESS-G. The major model components of an EXPRESS data schema are (1) Entities with (2) Attributes and (3) Data Types, (4) Supertypes, (5) Subtypes and (6) Algorithmic Constraints. Figure 5 represents the EXPRESS-G notation for major model components, and Figure 6 depicts the representation of the selected relationship between model components [5].

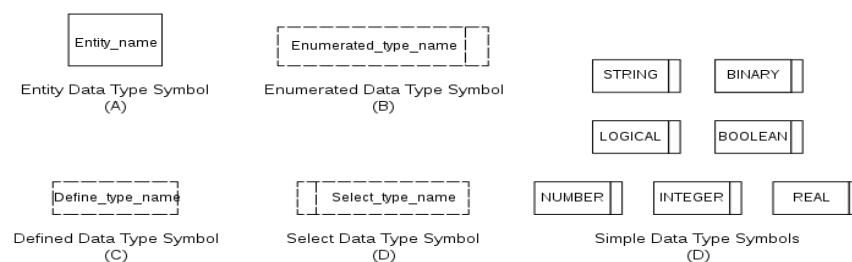


Figure 5: EXPRESS-G notation for model components [17]

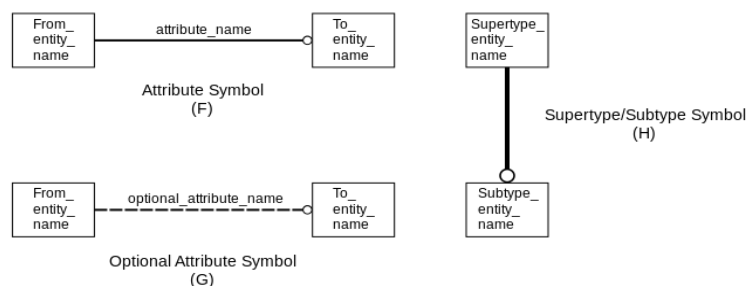


Figure 6: EXPRESS-G notation for relationships [17]

IFC4 – Addendum 2 (IFC4 ADD2) is the newest version of OpenBIM standards published in 2016, consists of 766 entities, 185 types and 206 enumerator types. The data schema architecture of IFC defines four conceptual layers, each individual schema is assigned to exactly one conceptual layer. Figure 7 shows the IFC schema architecture.

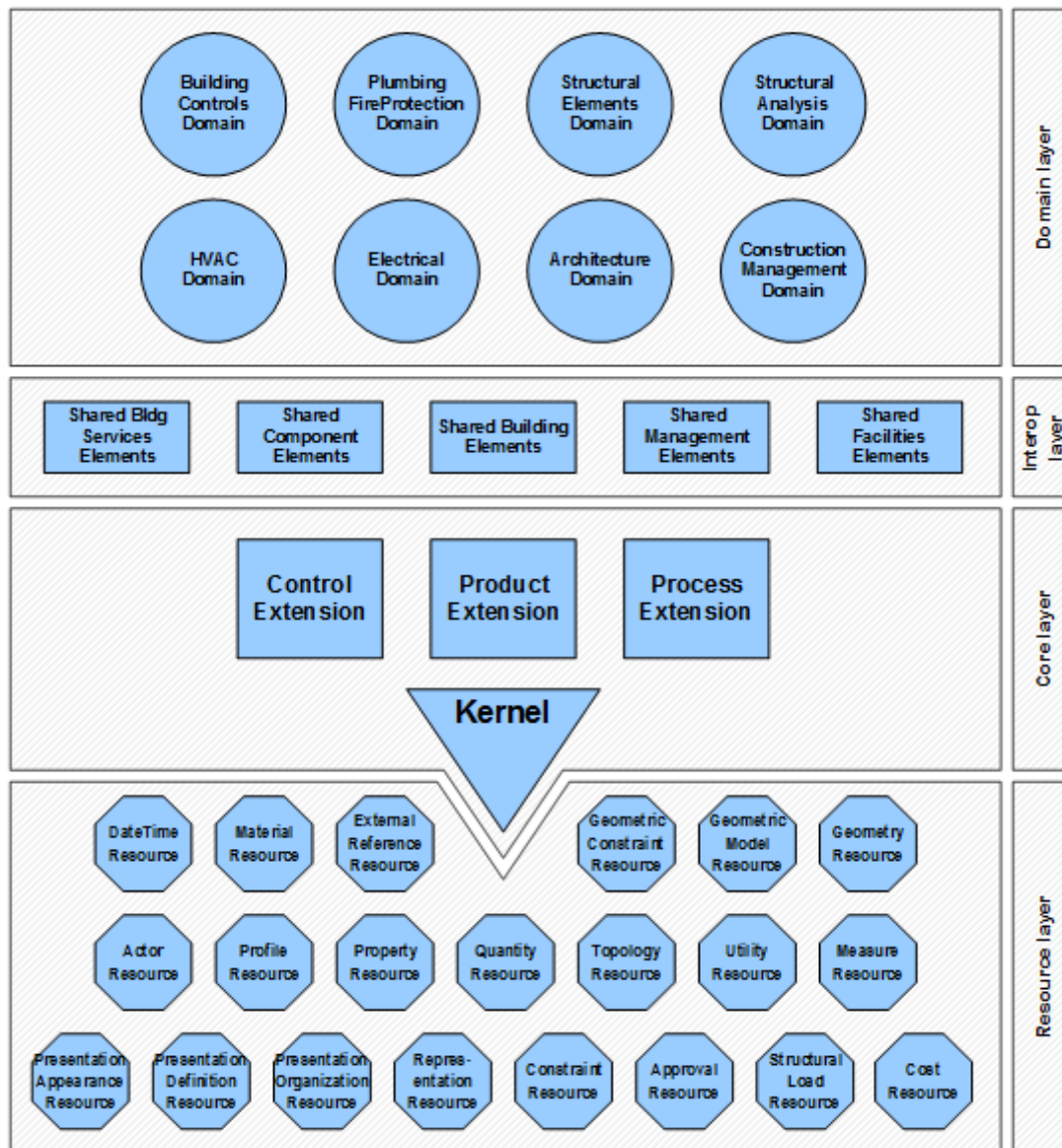


Figure 7: Data schema architecture with conceptual layers [15]

- 1) **Resource Layer:** which is the lowest layer in the IFC data schema architecture which provides commonly used resources and can be used or referred by classes in the other layer.
- 2) **Core Layer:** which is the next layer above the resource layer, which includes kernel schema and the core extension schemas. This core layer provides the basic structure of the IFC and defines most abstract generic concepts that will be specialized by higher layers of the IFC object model [18].
- 3) **Interoperability Layer:** defines objects which further specialize the core layer objects and are shared by more than one domain model or application model.

- 4) Domain Layer: provides model objects which support the applications used by domain experts.

Inheritance is one of the major modelling principles in IFC schema and is an alternative way to arrange the model components in BIM. Figure 8 represents the first five inherent levels (top part) of the IFC-inherent tree. The element (walls, slab, etc.) in a lower level inherits most of their attributes and modelling concepts from the top levels in the IFC schema. All IFC components originate from the *IfcRoot* entity. Components defined in the IFC-resource layer do not originate from the *IfcRoot* entity.

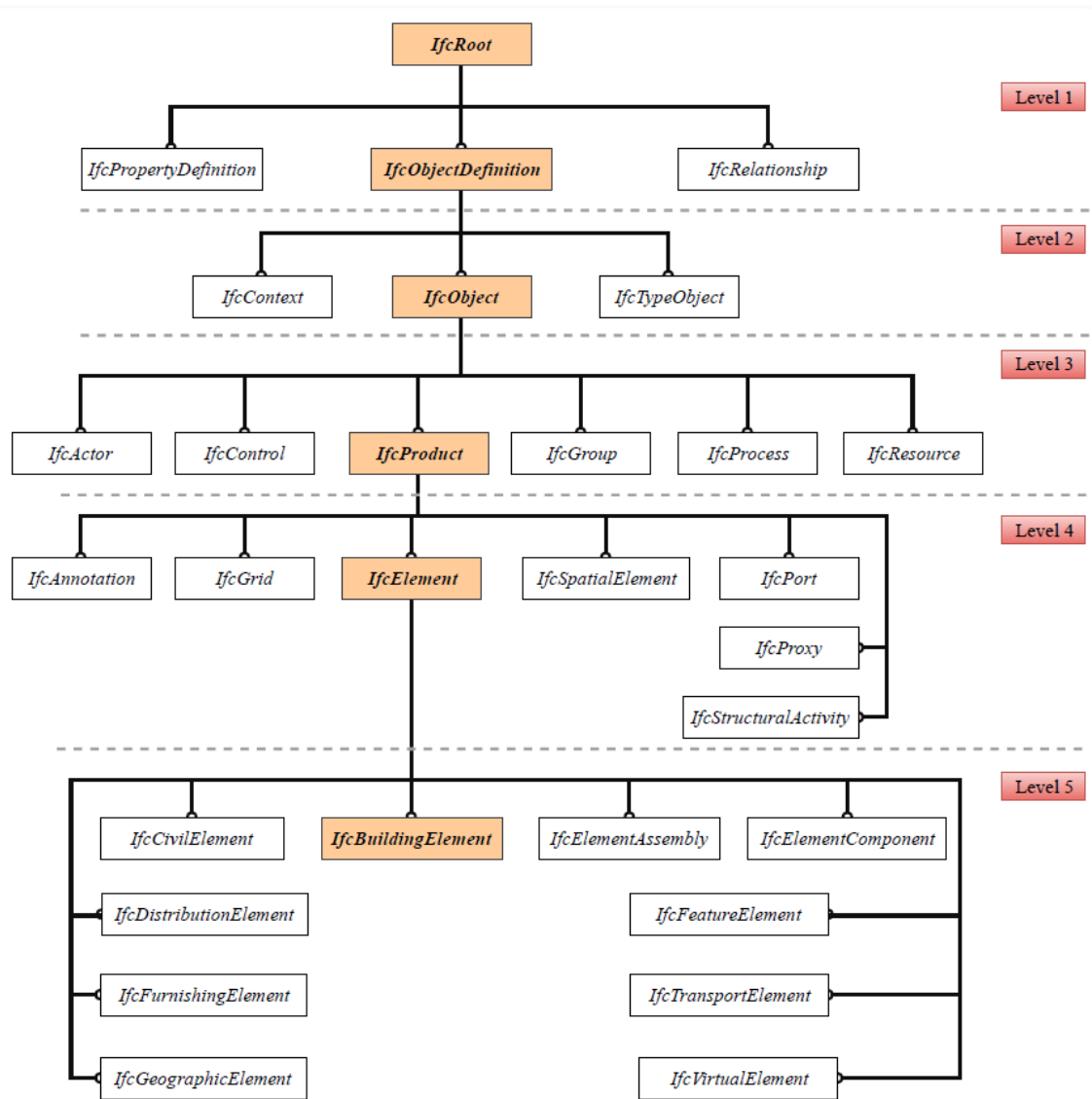


Figure 8: First five inherent levels in IFC data schema architecture

Objectified Relationships are another major modelling method in the IFC data schema. The relationship entity defines the relationship between different entities, elements and properties. The IFC data schema defines the relationships between entities or objects based on the Objectified Relationships. These objectified relationships are the easiest way to handle the relationships among the objects. The *IfcRelationship* entity is the supertype for all relationships in the IFC data schema. All these relationships are defined by two different types,

1-to-1 relationship and 1-to-many relationship. The following conventions are applied to most subtypes of the *IfcRelationship* entity.

- The two sides of the objectified relationships are named [15]
Relating+<name of the relating object> and
Related+<name of the related object>

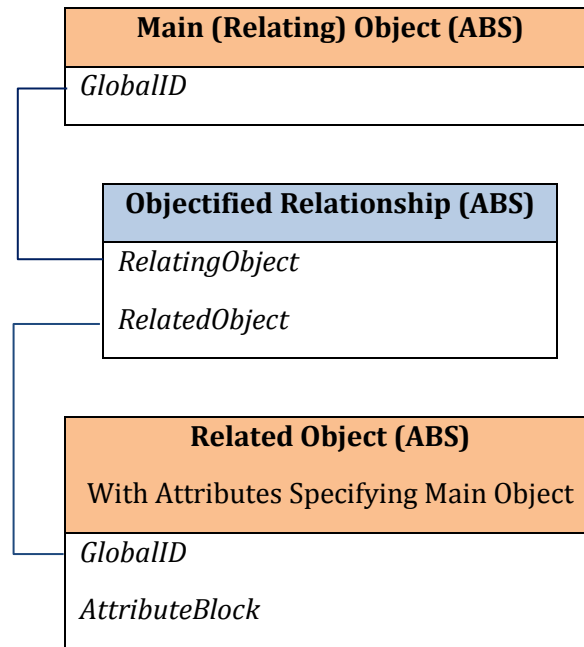


Figure 9: Simplified representation of an Objectified Relationship [5]

- In the case of a 1-to-many relationship, the related side of the relationship shall be an aggregate being a set 1: N

As mentioned previously, the object (e.g. wall) in IFC schema usually doesn't contain all the information regarding geometry, properties, material, etc. This kind of information saved with the different attributes presented in the IFC data schema. These attributes are linked to the object through objectified relationships. It means relationships are used to link the comprehensive data regarding objects which are stored in the other attributes or objects. These relationships can be added and disconnected over the life-cycle as per the requirements. There are six major relationships mentioned in the IFC data schema architecture. Figure 10 shows the subtypes of *IfcRelationship* and Table 1 describes the type and purpose of these subtype relationships.

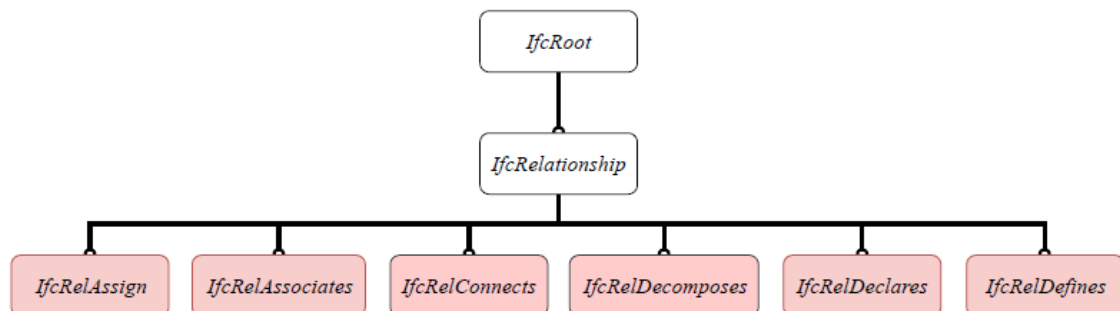


Figure 10: Major Relationships in the IFC data Schema [15]

Table 1: Description about Major Relationships in IFC data schema

<i>Relationship</i>	Purpose	No. of sub-type relationships
<i>IfcRelAssign</i>	The relationship that allows one object to navigate to other objects, or to model that a client object applies the services of a supplier object.	6
<i>IfcRelAssociates</i>	The relationship that refers to the source of the information	6
<i>IfcRelConnects</i>	The relationship that connects objects under some criteria. Constraints and semantics of defined by sub-types of this relationship	15
<i>IfcRelDecomposes</i>	Relationship used to navigate from the whole to the parts and vice versa; the whole depends on the definition of the parts and the parts depend on the existence of the whole	4
<i>IfcRelDeclares</i>	Declaration of objects or properties to project or project library	-
<i>IfcRelDefines</i>	Used for further definition of object occurrences, object instances, property sets, and the relation between each other	4

The relationships can define at any level of the IFC-Inheritance-Hierarchy and each level contains a particular set of relationships. The complete information about what relationships provide on what hierarchy level is given in Table 2. The below table describes the relationships belongs to a specific path of inherent hierarchy mentioned in Figure 8.

Table 2: Available Relationships at different levels of hierarchy

Attribute Name	Relationship	Used For
1st Level Hierarchy – Object Definition Level		
HasAssignments	<i>IfcRelAssigns</i>	RelatedObject
Nests	<i>IfcRelNests</i>	RelatedObject
IsNestedBy	<i>IfcRelNests</i>	RelatingObject
HasContext	<i>IfcRelDeclares</i>	RelatedDefinitions
IsDecomposedBy	<i>IfcRelAggregates</i>	RelatingObject
Decomposes	<i>IfcRelAggregates</i>	RelatedObjects
HasAssociations	<i>IfcRelAssociates</i>	RelatedObjects

Attribute Name	Relationship	Used For
2 nd Level Hierarchy – Object Level		
IsDeclaredBy	<i>IfcRelDefinesByObject</i>	RelatedObjects
Declares	<i>IfcRelDefinesByObject</i>	RelatingObject
IsTypedBy	<i>IfcRelDefinesByType</i>	RelatedObject
IsDefinedBy	<i>IfcRelDefinesByProperties</i>	RelatedObject
2 nd Level Hierarchy – Object Type Level		
HasPropertySets	<i>IfcPropertySetDefinition</i>	-
Types	<i>IfcRelDefinesByType</i>	RelatingType
3 rd Level Hierarchy – Product Level		
ReferencedBy	<i>IfcRelAssignsToProduct</i>	RelatingProduct
4 th Level Hierarchy – Element Level		
FillsVoids	<i>IfcRelFillsElement</i>	RelatedBuildingElement
ConnectedTo	<i>IfcRelConnectsElements</i>	RelatingElement
IsInterferedByElements	<i>IfcRelInterferesElements</i>	RelatedElement
InterferesElement	<i>IfcRelInterferesElement</i>	RelatingElement
HasProjections	<i>IfcRelProjectsElement</i>	RelatingElement
ReferencedInStructures	<i>IfcRelReferencedInSpatial- Structure</i>	RelatedElement
HasOpenings	<i>IfcRelVoidsElement</i>	RelatingBuildingElement
IsConnectionRealization	<i>IfcRelConnectsWithRealiz- ingElements</i>	RealizingElement
ProvidesBoundaries	<i>IfcRelSpaceBoundary</i>	RelatedBuildingElement
ConnectedFrom	<i>IfcRelConnectsElement</i>	RelatedElement
ContainedInStructure	<i>IfcRelContainedInSpatial- Structure</i>	RelatedElements
HasCovering	<i>IfcRelCoversBldgElements</i>	RelatingBuildingElement
4 th Level Hierarchy – Spatial Element Level		
ContainsElements	<i>IfcRelContainedInSpatial- Structure</i>	RelatingStructure
ServicedBySystems	<i>IfcRelServiceBuildings</i>	RelatedBuildings
ReferencesElements	<i>IfcRelReferencedInSpatial- Structure</i>	RelatingStructure

The IFC meta-model is complemented by the four other types of open standards defined by buildingSMART (see in Figure 11). These standards are IFD: the International Framework for Dictionaries (ISO 12006-3, 2007), IDM: the Information Delivery Manual (ISO: 29481 – Part 1 & 2, 2016), MVD: the Model View Definitions and BCF: the BIM Collaboration Framework.

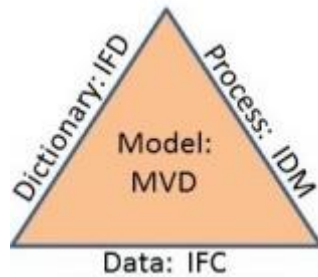


Figure 11: buildingSMART basic methodology standards [19]

The IFD standards provide a foundation for the buildingSMART Data Dictionary (bSDD). This will collect the attributes and vocabulary for the things presented in the data transfer. IFD acts as reference library which aims to support interoperability between software tools used in the AEC industry. The IDM proposes a methodology that “captures (and progressively integrates) business process whilst at the same time providing detailed user-defined specifications of the information that needs to be exchanged at a particular point within the project” [20]. In comparison, IDM proposes reusable, modular model functions which assist the development of further user requirements.

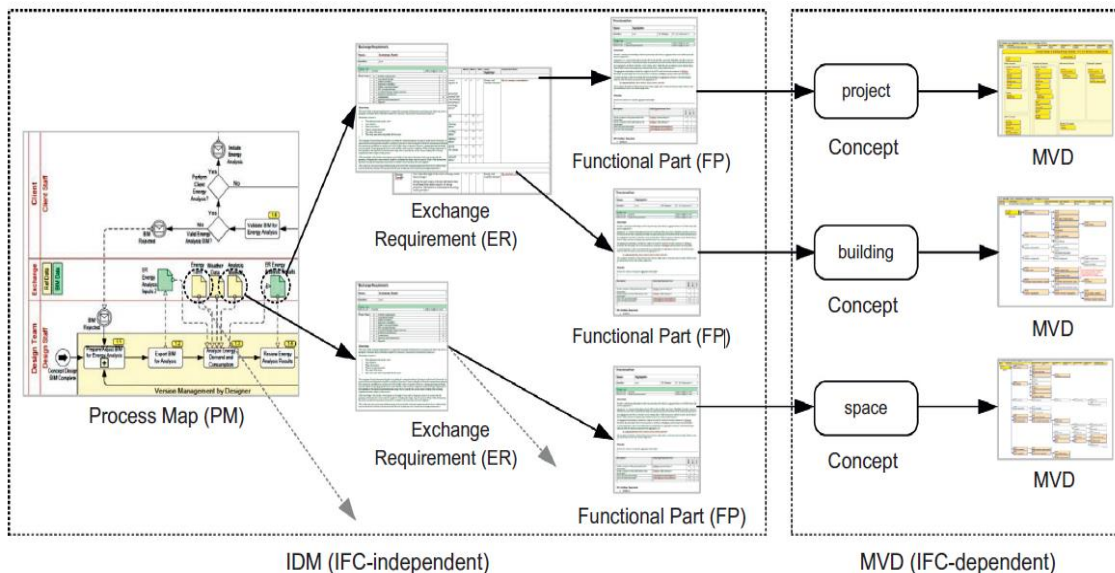


Figure 12: Framework for defining Exchange requirements [21]

MVDs are used to define relevant subsets of the IFC data scheme which are required to support specific data exchange requirements of the AEC industry. MVD is a way to specifically

indicate what data is required for a particular activity in the AEC sector. MVDs are used to develop software tools for a specific process in the industry. Figure 12 represents the two different parts of a framework for defining exchange requirements. The first part explains the components for a process controlled by the actors and exchange requirements associated with the specific process. The second part explains the interface between two different software applications based on the meta-model schema. The BIM-collaboration Framework (BCF) specifies an open standard XML schema that aims to enable workflow communication between different BIM-tools [19].

2 Building Energy Simulation

Building Energy Simulation (BES) is a methodology to assist engineers, designers and operators to provide more value on the comfort and needs of building owners and occupants. This simulation process is a method to analyse the energy consumption of buildings and results from the analysis will help to make appropriate design decisions. Similarly, the decisions regarding the operation of building services systems are dependent on the outcomes from the Building Energy Simulation.

BES provides the information regarding thermal comfort, visual & audible comfort, ventilation & indoor air quality, etc. and enables the designer to take appropriate design decisions regarding the orientation, form and size of the building. BES is excellent for analyzing different type of building service systems which affect overall user comfort and the energy consumption of the specific building. Introducing such energy simulations in the early design stages of the project can provide an opportunity to investigate more design solutions that significantly improve the building energy performance. So, it is recommended to perform building energy analysis from the early design stage of the building life cycle.

BES results will support the process of design and dimensioning the components of building fabrics (wall, slab, roof, etc.) and building service system (HVAC). BES can also be used in the period of building operation to determine the optimum operational schedule for building services system and optimum set points for the heating and cooling loads. In this regard, Building Energy Simulation can play a significant role in building design and operation. With the aid of expert inputs, Simulation results can be used effectively to find the optimum balance between comfort, cost and efficiency. In this section different energy simulation models and their required input data at different stages of the building life-cycle is described.

2.1 Categorization of Energy Simulation Models

There are several types of energy simulation models used to perform energy consumption calculations. All these models are categorized according to three major principles. They are as follows.

- Physical principles of energy (Heat) transfer
- Level of abstraction (indicates the amount of model complexity)
- Time dependency of input variables

The categorizations of the energy simulation models are presented in Table 3 according to the above-mentioned principles.

Table 3: Techniques for Building Energy Simulation [22]

Physical Principles	Level of Abstraction	Time-dependency
Thermal Radiation	Mono-Zone Models	Steady-state simulation Models
Conduction	Multi-Zone Models	Dynamic simulation Models
Convection/Advection	Zonal Models	
	CFD Models	

2.1.1 Based on Physical Principles

The thermal behaviour of the building fabric must be investigated by considering three physical principles in the energy simulation model.

Thermal Radiation:

This is the direct result from the motion of charged particles in the matter. This radiation also generates from the emission of electromagnetic waves. It represents the conversion of thermal energy into electromagnetic energy. It doesn't require matter to propagate the energy. Sunlight is one of the examples for the thermal radiation [23].

Conduction:

Conduction or thermal transmittance (U-value) represents the transfer of heat within the object or material because of microscopic diffusion and collision of particles. This heat transfer can happen in between two different objects which are in contact with each other. The inverse of conductivity is known as resistivity and also called as R-value [23].

Convection:

This principle explains the transfer of energy between bodies or materials by a material carrier (air or liquid). This energy transfer happens either by bouncy forces of fluid resulted from density variation or by the heated fluid is forced by an external source [23].

2.1.2 Based on Level of Abstraction

The requirement of input data for energy simulation is dependent on the design phase of the building life-cycle. If the simulation is at an early stage of the design, then the required data is restricted to the outer dimensions of the building and orientation. This level of abstraction will briefly explain the input data requirements for different models.

Mono-Zone Models:

Mono-Zone models represent the highest level of abstraction, it means the lowest level of details. Generally, this kind of simplified models are used in the early design stages for calculation of the energy consumption. In this model, the whole building is treated as a single box, which is enclosed by an external shell of the building. The whole space of the building is considered as a single zone i.e. it is assumed that all facilities in the building are operated under similar constraints. For the simulation of Mono-Zone models, material properties of

the outer shell of the building and HVAC system must be specified. Because of the simplicity, these models are used for simulating the buildings whose span is over multiple hundreds of meters. The frequency of the simulations is usually in the order of hours [22].

Multi-Zone Models:

These models are mostly similar to the Mono-Zone models in terms of modelling the outer shell of the building and the building spaces are separating into different modelling zones using interior building components. The material properties of the shell and indoor building components must be specified for energy simulation. The constraints for each zone and the parameters for the room conditioning and ventilation must be selected. These simulation models are used for the buildings whose spans are over multiple meters and simulation time steps are typically in the order of multiple minutes. It means the time gap between simulation to simulation is in the order of minutes [22].

Zonal Models:

In this case, a single space operated under a set of constraints is divided or decomposed into multiple modelling zones. E.g. in a single room some amount of space is accommodated for machinery like printers, computers, etc. and the other space is kept as empty. So here are two different modelling zones but the single system is serving for two zones. Another example, to allow for the modelling of two distinct faced type or opening of a distinct number of windows. The specification of boundaries conditions should be clear and in a consistent way. Usually, these models can span over multiple meters. Typically, simulations are completed in a few minutes [22].

CFD Models:

These CFD (Computational Fluid Dynamic) model is a micro level investigation. It provides an option to model a single space with high granularity using a high level of data. The purpose of this modelling method is to analyses the problem involving with the flow of fluids and to simulate the interaction of fluids with surfaces as defined by boundary conditions. CFD analysis provides a greater understanding of the airflow and heat transferring processes occurring within and around the building spaces [24]. These models are restricted up to the microenvironments for simulation purposes i.e. individual workspace or a single room. Usually, such models can span over multiple meters. If required, simulation time steps can be in the order of multiple seconds [22].

2.1.3 Based on Time Dependency

The difference between steady-state and dynamic simulation is dependent on the input parameters. For steady-state simulation, all the input parameters are constant throughout the simulations. For the dynamic simulations, the input parameters are varying over time during the simulations.

Steady-state Simulation Model:

This has been treated as a simple method to perform energy simulations. In this simple method, all the input parameters are averaged over a dedicated time period (e.g. annually) and the calculations of the internal gains are simplified. For example, the weather details at

a location over a year are averaged to peak heating and cooling loads. These peak loads are applied to the system to perform simulations. Usually, this simple method is used to perform the design of heating systems (to increase the temperature of the space or room) during the coldest weather period. Because of this coldest weather, the heating load from the sun, occupants, lighting and equipment won't affect much on the design of the heating system. Based on this assumption, steady-state calculation methods were deemed to be enough for the calculation of heating loads.

Dynamic Simulation Model:

In this simulation method, the parameters regarding the weather data files, occupant profiles, and scheduled internal gains are time-dependent. These details are provided on much shorter cycles (e.g. hourly). The dynamic simulation method is used to perform the cooling load (amount of load requires to cool down the temperature of space or room) calculations. For cooling load calculations, the complex effects of heat transfer (conduction, convection and radiation), heat storage (thermal mass of the material) as well as heat gains from occupancy, lighting and equipment are always considered to design efficient and optimized cooling system. It means the changeable conditions throughout the cooling period and even throughout the day has been always acknowledged in the dynamic simulation models.

Table 4: Comparison between Steady-state and Dynamic simulations [22]

Steady-state Simulations	Dynamic Simulations
Calculations based on the estimated peak loads	Allows for load variations over the period of time
Design of a system for the extreme conditions	Design of the system based on the hourly weather and occupancy data
Used for simplified heat gain calculations	Used for cooling load calculations based on the scheduled building operations
Sufficient estimate for heating loads	Essential to perform cooling load estimations
Often leads to oversized systems	Optimized systems

2.2 Information Requirements

Figure 13 clearly represents the required information to set up the energy simulation model, which is used to determine the energy consumption of the building. This section provides a general overview of the required categories of input data. The scope and the granularity of the input data are varying according to the type of energy simulation models as mentioned in section 2.1.

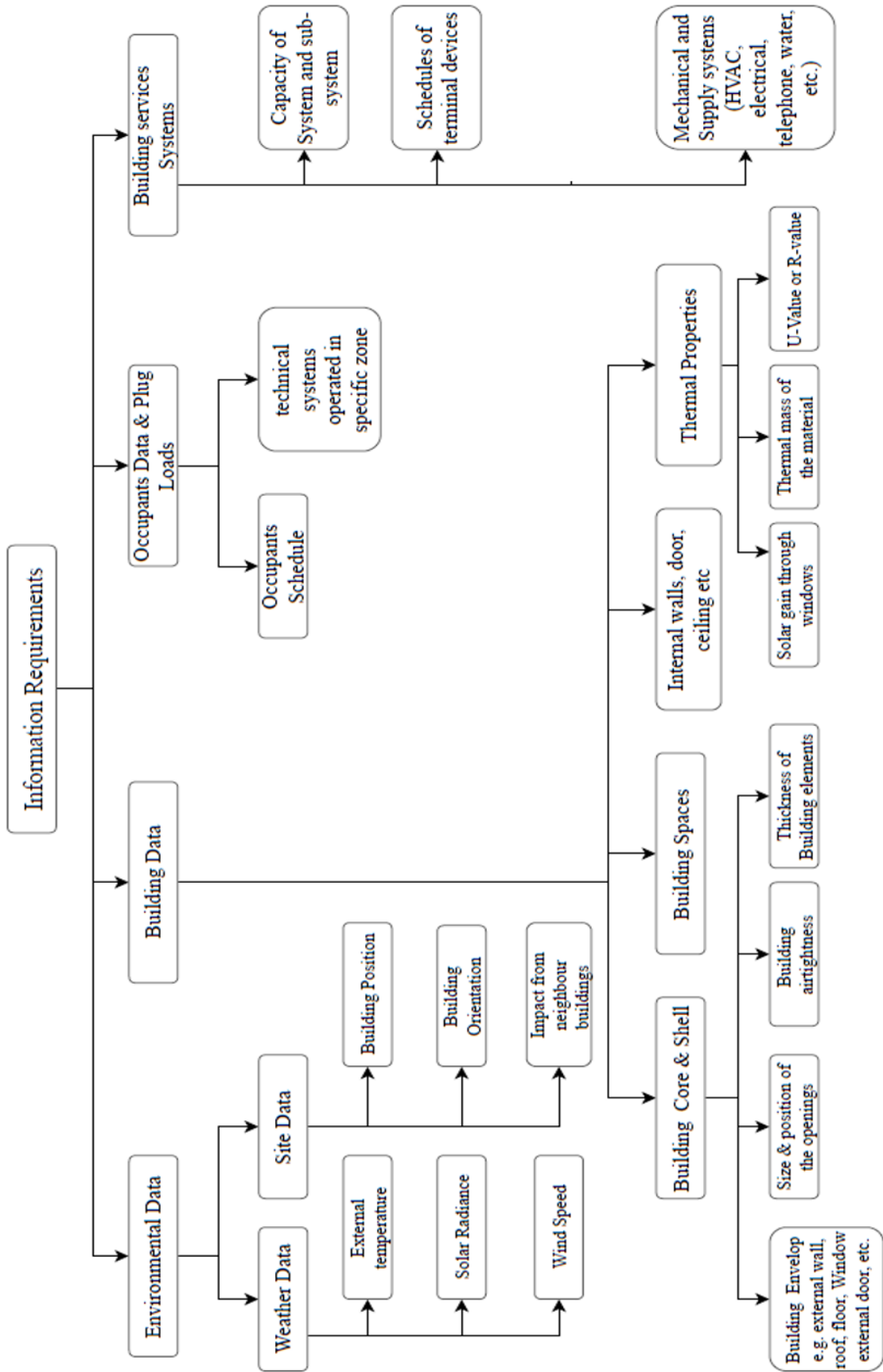


Figure 13: Information requirements to set up the Energy simulation model [22]

Required information is categorized into 4 different parts. In which,

Environmental data

This group of data summarizes the required information which describes the building's environment such as weather data and site information. Generally, the location (longitude, latitude and altitude) of the building is necessary to acquire the weather details like solar radiation, wind speed, dry bulb and wet bulb temperature details. Environmental data also includes the orientation and impact from neighbour elements (buildings, trees, etc.). These details are helpful to analyze the shading zones of the building. Environmental data may include information about soil, aquifer and groundwater (water temperature).

Building data

This group of data summarizes the information regarding building core and shell details, spaces, internal-non-bearing building elements and thermal properties of the materials used for the construction. The geometrical properties and thickness of each building fabric are also included in this group of data. The information regarding the spaces and about the building elements which are sharing the spaces or zones are also included.

Occupants Data & Plug Loads

This group of data refers the information about occupant schedules in the specific spaces and the information regarding the technical systems operated in specific zones, such as a computer, laboratory equipment, etc.

Building Services System and operational schedules

This group of data specifies the services systems like HVAC and their operational schedules. This can be including the required capacities of systems and the number of terminal devices for each system which is installed in a specified zone.

2.3 Level of Data Granularity

Table 5 explains the data requirements and their level of granularity based on the different energy simulation models. As mentioned in the earlier sections, the data requirements for an energy simulation would vary for the different phases of the building construction. The data requirements also depend on the level of abstractions explained in section 2.1.2. These levels of abstractions determine the required level of detail and granularity. Table 5 mentioned below is summarizing the required input information and proposed levels of details.

Table 5: Required Information and Level of Granularity [22]

<i>Element</i>	Mono-zone	Multi-zone	Zonal Model	CFD
<i>Exterior walls</i>	Required	Required	Required	Required
<i>Architectural details</i>	ignored	Ignored	Optional	Required
<i>Windows</i>	Required	Required	Required	Required
<i>Status of windows</i>	Ignored	Ignored	Optional	Required
<i>Interior walls</i>	Amalgamated	Zone separators	Only zone separators	Required
<i>Thermal energy</i>	Total of energy used	Per circuit	Per terminal device	Per terminal device
<i>Electrical energy</i>		Per zone	Split into loads from devices	Split into loads from devices
<i>Plug-loads</i>		Per zone	Group of devices	Single (relevant) device
<i>Occupants</i>	Ignored	Per zone	As group	Per workspace
<i>Fixture, Furniture, Equipment</i>	Ignored	Ignored	Optional	Required
<i>HVAC components</i>	Ignored	Ignored	Optional	Required
<i>Lighting components</i>	Ignored	Ignored	Optional	Required

3 Meta-Data Model for Data Sharing

A Meta-Data Model provides a comprehensive specification of information about AEC and facility management projects. It can hold the information from all type of organizations (such as architects, engineers, constructors and facility management) involved in the project and all stages of the project life-cycle including initial requirements, design, construction, maintenance, and operation. It is more usual for information to be exchanged about a particular topic and level of detail at a particular project stage. This section describes how the information regarding the energy simulation model is organized and managed in the meta-data models such as gbXML and IFC. The required information details for an energy simulation is mentioned in section 2 of this document.

3.1 gbXML Schema

gbXML is a meta-data schema for the data interoperability between different software tools in the AEC industry. This meta-data model is highly data enrich and capable of describing 500 types of the building elements and attributes. The below Figure 14 shows the hierarchical structure of the gbXML schema and explains the organization and management of the information in the schema.

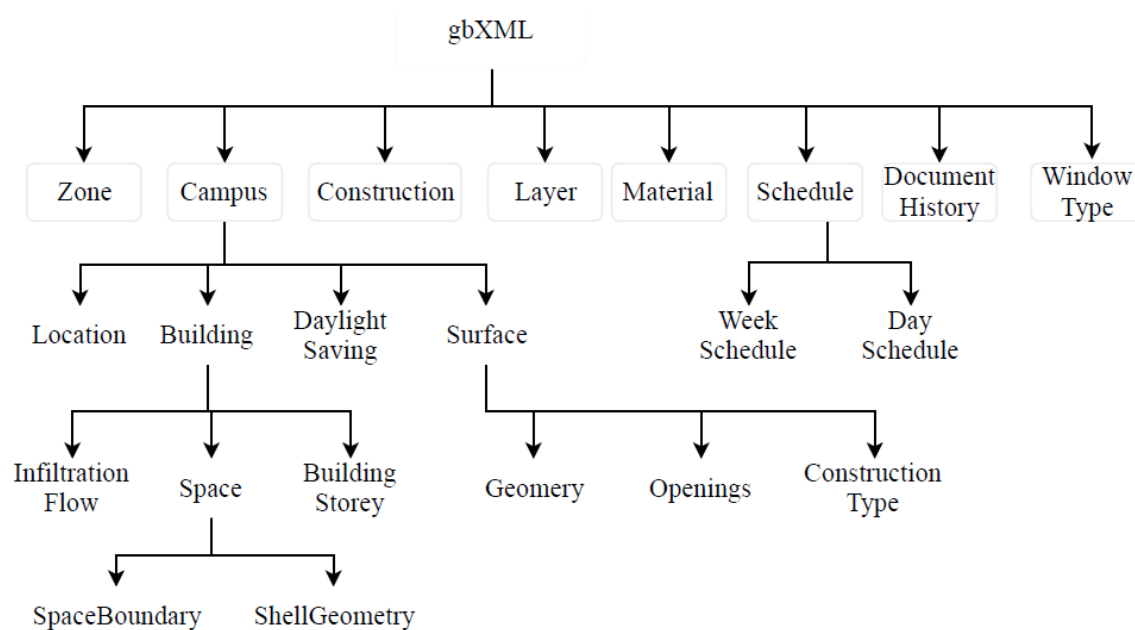


Figure 14: Hierarchy of the information organized in the gbXML Schema

A sample schema for the gbXML is presented in Appendix 7.1. There are different components defined in the gbXML library to hold the information from respective architectural or MEP models. Table 6 below represents components and explains their characteristics and the type of information carried by each component. Here, each component is defined by its own Reference Id. The main concept of this Reference Id is to create an Identification for

each component in the schema and to define the relationships between components based on Reference Id.

In a gbXML schema all building elements like a wall, floor, roof, ceiling, etc. are defined as a surface. The surface component defines the geometry and construction for the building element. It also contains the information regarding openings in the element. The detailed description about construction like layers in the element, material and thermal properties of each layer are defined separately and related to construction type in the surface component based on the Reference Id relationship. Similarly, the details about the type of window or door types are related to the opening using Reference Id relationships.

The “Building” component in gbXML (refer to Table 6) defines different levels in the building (Building Storey) and space type details in each level of the building. Space is defined by the room bounding elements (surfaces: wall, floor, roof, etc.). The bounding element of space is defined by two nodes such as Shell Geometry and Space Boundary. Shell Geometry defines the coordinates of the inner surface (towards space) and the Space Boundary defines the Co-ordinates of the centerline of the bounding element. It means the difference between these two node points is equal to the half of the thickness of the element. But, in the case of the internal wall or the space separating element, the centerline and both sides of the wall are defined because this internal wall is bounded by a space on its both sides. The operating schedules of spaces and the occupant’s schedules are defined separately and link to the spaces based on reference ID.

Table 6: Information organized in the gbXML schema

<i>Component</i>	Characteristics	Information carries
<i>gbXML</i>	XML schema represents the Building data	Units Type (SI or imperial), Unit for temperature, length, area, volume and version
<i>Campus</i>	A group of buildings that are geographically similar	Id, Location, Building, Surface, and Daylight savings
<i>Location</i>	Location details of a building	Longitude, Latitude, Elevation, and Location name
<i>Building</i>	One building data	Building type, area, name, Id, street address, Description, Building Storey, infiltration and its Spaces
<i>Infiltration flow</i>	Airflow into the building due to unwanted leakages	Describes Tight, loose and medium infiltration flow

<i>Component</i>	Characteristics	Information carries
<i>Space</i>	A room defined by its own set of Walls, Ceiling, and/or roof. Space may be an office, conference room, warehouse, or any other entity	Space Id, Reference building Storey Id, Reference zone ID, space type, Reference light schedule Id, Reference equipment schedule Id, condition type, Reference occupants schedule Id, Area and Volume of the space, name, description, Geometrical coordinates (shell geometry, space boundary), number of people, people heat gain (Latent & Sensible), light power per area
<i>ShellGeometry</i>	Defines the coordinates for the internal surface of walls (in terms of boundaries of a space)	Id, Cartesian Point, PolyLoop (set of cartesian points which defines the geometry)
<i>SpaceBoundary</i>	Defines centerline of a space bounding element and its relationship with the adjacent space.	Id, isSecondLevelBoundary, PolyLoop, etc.
<i>Building Storey</i>	Describes different levels (storey) of building	Id, Level, Name
<i>Surface</i>	A wall, floor, ceiling, roof. Each space (or room) will have its own set of surfaces	Surface Type, exposed to the sun, Id, Adjacent space ID, Reference construction ID, name, details about construction type, geometry and openings
<i>Geometry</i>	Shape and position of surface, space and openings	Id, azimuth, cartesian point, tilt, width (length), height
<i>Opening</i>	Opening in a surface, such as a door or a window, etc.	Opening type, Id, geometry, description of opening, width and height
<i>Daylight Saving</i>	This depends on the weather in a region	Daylight savings are mentioned or not

<i>Component</i>	Characteristics	Information carries
<i>Zone</i>	A group of rooms located in a building that is served by the same HVAC plant or VAV box. Each zone may contain a group of spaces (or rooms) that have their own set of unique set of characteristics such as similar orientation or temperature set point.	Id, name, description, flow, airflow changes per hour, flow per area, flow per person, outside air flow, Design heating temperature, design cooling temperature.
<i>Construction</i>	The type of composite construction (different layers) that makes up a wall, roof, floor, etc.	Id, U-value, Absorption, Roughness, Layer Id
<i>Layer</i>	Describes the material used in the layer	Layer Id and Material Id
<i>Material</i>	Describes the properties of materials which are presented in layers	Id, Name, R-value, thickness, conductivity, density and specific heat
<i>Schedule</i>	Defines the yearly wise schedule for occupants, equipment and lighting in a building space	Id, Type, Yearly schedule Id, Begin Date, End Date, name and week schedule Id.
<i>Week Schedule</i>	Defines the weakly schedule for occupants, equipment and lighting in a building space	Id, type, Day schedule Id, name
<i>Day Schedule</i>	Defines the daily schedule for occupants, equipment and lighting in a building space	Id, type, name and schedule values
<i>Document History</i>	Details about the gbXML file	Id, company name, GUID, product name, created by, etc.
<i>WindowType</i>	Defines the thermal properties of the window	Id, Solar Heat gain coefficient, U-value, Angle of incidence, etc.

3.2 IFC Schema

IFC is an open data schema which defines the specifications for data sharing (across all disciplines of AEC) between the technical applications, across the entire building life-cycle. IFC schema is inherently complex and broader to carry most of the exchange data. A BIM model can be equipped with enormous data related to all disciplines of the construction industry, but all data is not necessary for a specific business process. For this purpose, buildingSMART developed View Definitions (Model View Definitions) to reduce and filter the required information needed to be exchanged for a particular business process. These information requirements and its level of granularity are determined by the simulation methodology mentioned in the previous section 2.

In the present section, the IFC meta-data schema for the information required to perform energy simulation is described. Based on this specification, the data sharing process has been carried out between the BIM model and the BES model. IFC data schema defines information regarding objects as entities and attributes. The entity is a “class of information defined by common attributes and its constraints as defined in ISO 10303- part11” [15]. For example, *IfcWall*, *IfcDoor*, *IfcObject*, etc. are defined as entities in the IFC data schema. The attribute is a “unit of information within an entity, defined by a particular type or reference to a particular entity” [15]. For example, if we consider *IfcObject*, is an entity, then *IsDeclaredby*, *Declares*, *IsTypedBy*, and *IsDefinedBy* are the attributes for this entity (same as mentioned in Table 2). Figure 15 represents some of the IFC entities at different inheritance hierarchy levels, which carry the information regarding the energy simulation process. Figure 15 represents information about elements which are belonging to the *IfcObject* entity, all these elements are related to the different element types which belong to the *IfcTypeObject*. The properties of objects or elements are defined based on the object type.

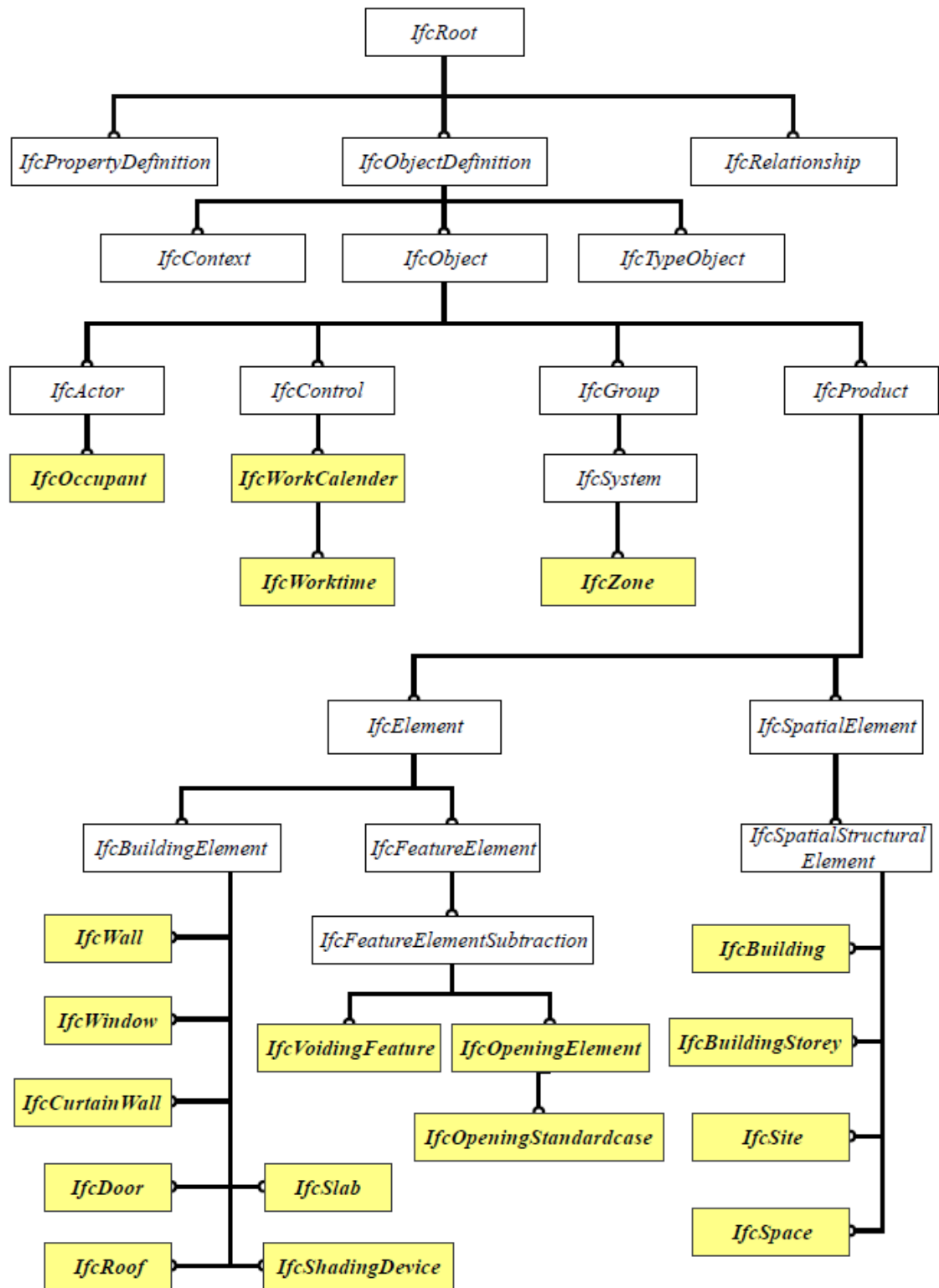


Figure 15: IFC based entities (Specifications) for Energy simulation data [15]

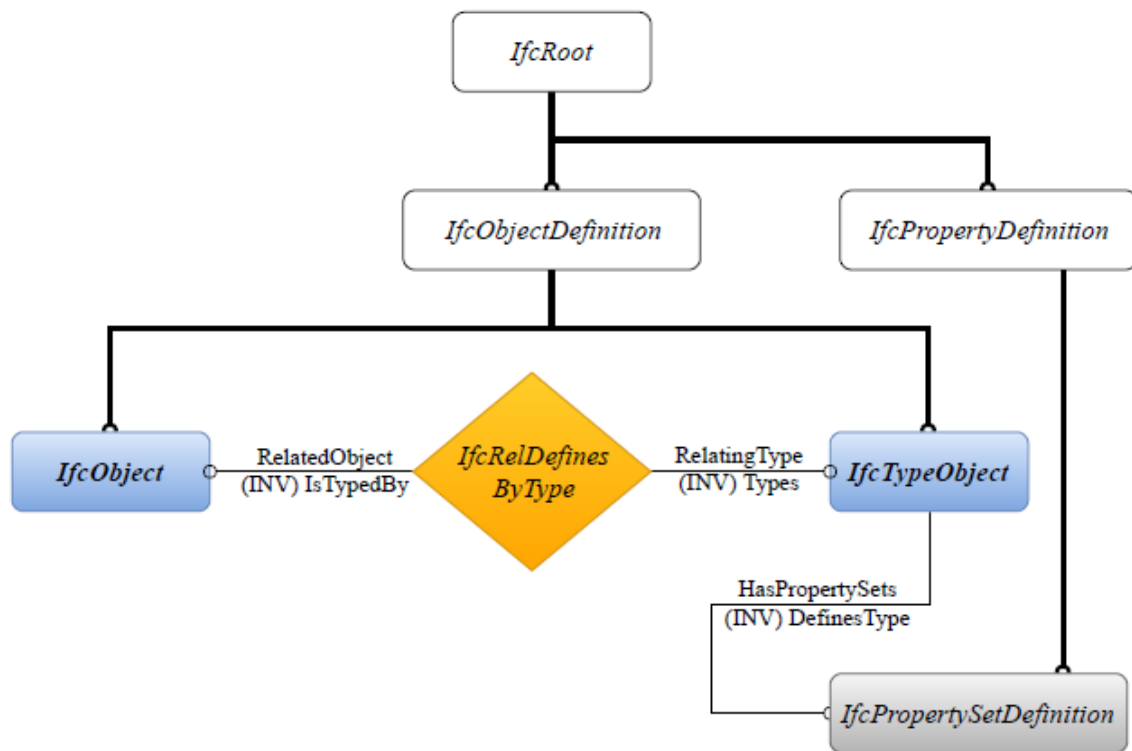


Figure 16: Relationship between object and Object Type [15]

3.2.1 Spatial Structural Elements

The decomposition of the spatial structure is shown in Figure 17 and it is the very basic method to represent all subsets (elements) in the project model according to the spatial arrangement. This method of decomposition of elements is very common to the many disciplines and design tasks for data exchange. This spatial structure (*IfcSpatialStructureElement*) consists of four subsets (refer Figure 15). They are as follows, Site, Building, Building Storey, Space. These subsets define the levels of the structure. All these spatial structure elements are linked together by using objectified relationship *IfcRelAggregates*.

Figure 17 represents the decomposition of spatial structural elements for a simple project which consists of two buildings. *IfcProject* is an uppermost container of the information and it provides Root instance to the exchange structure. The *IfcSite* entity in the IFC data schema is used to provide information about building site. This building site detail includes (refer Figure 18), (1) **RefLatitude**, **RefLongitude** and **RefElevation** to provide world latitude, longitude and elevation of a point within the site. Which is necessary to determine the weather data with respect to a specific location. (2) **LandTitleNumber**, which is used as a reference number to identify the site. (3) **SiteAddress**, which indicates the address of the site and mainly used for information purpose only [16].

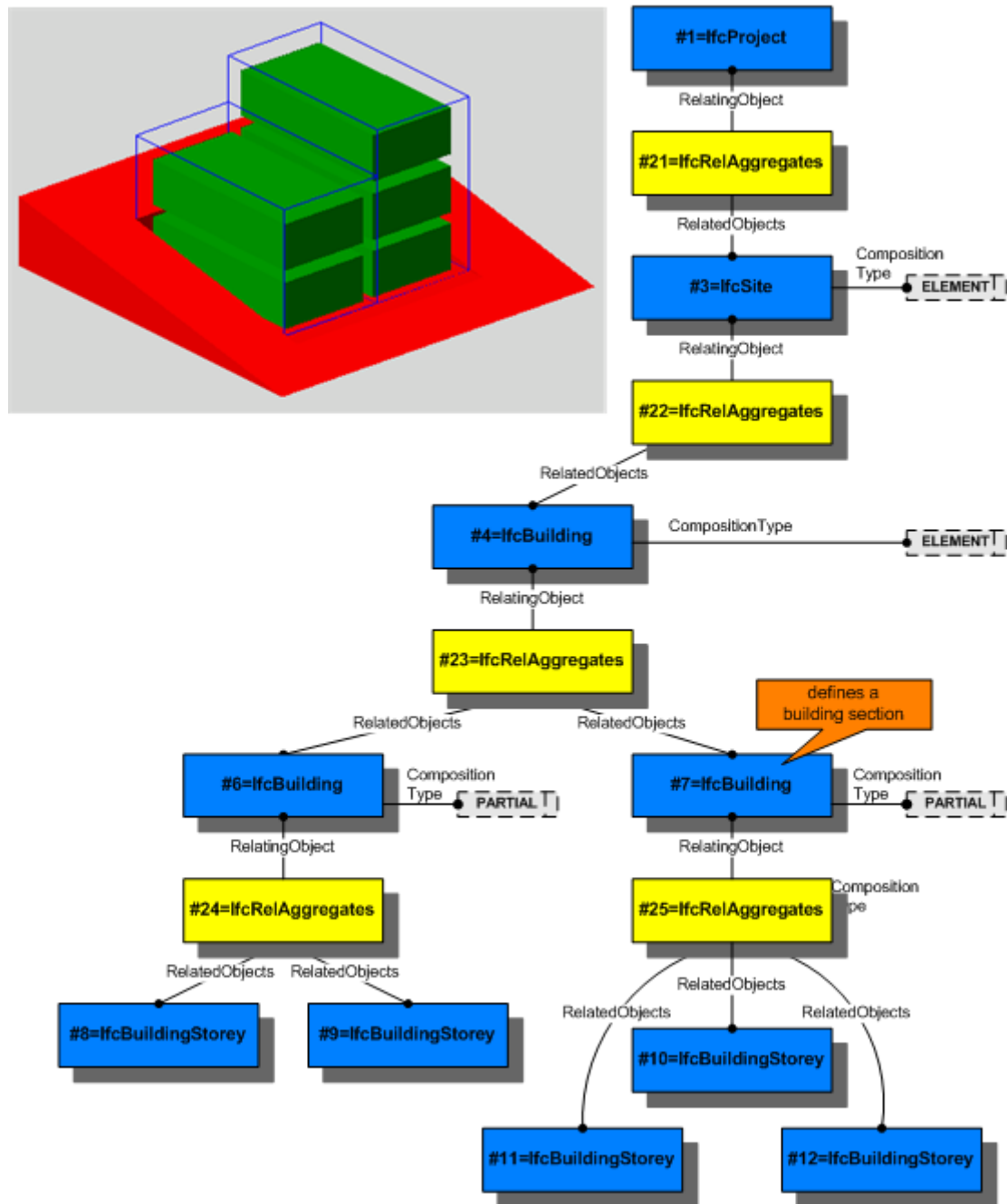


Figure 17: Spatial structure element composition [15]

The represented multi-storey building in Figure 17 is used as a model to explain the decomposition method. Each building (in Figure 17) having different storeys, which are defined properly in the IFC data schema using the decomposition method. Generally, Building is represented as *IfcBuilding*, which provides the additional information about building and is associated from the site. *IfcBuilding* provides a reference to the *IfcBuildingStorey*. Like the site, building entity also includes additional information such as **ElevationOfRefHeight**, **ElevationOfTerrain**, and **BuildingAddress** (Attributes). Building storey is represented as *IfcBuildingStorey* in IFC schema and it includes only the information about different storeys

of the building such as level of the storey. The building storey acts as a reference to the spaces, which belongs to that building storey. In the above example, each building storey is accompanied by different spaces.

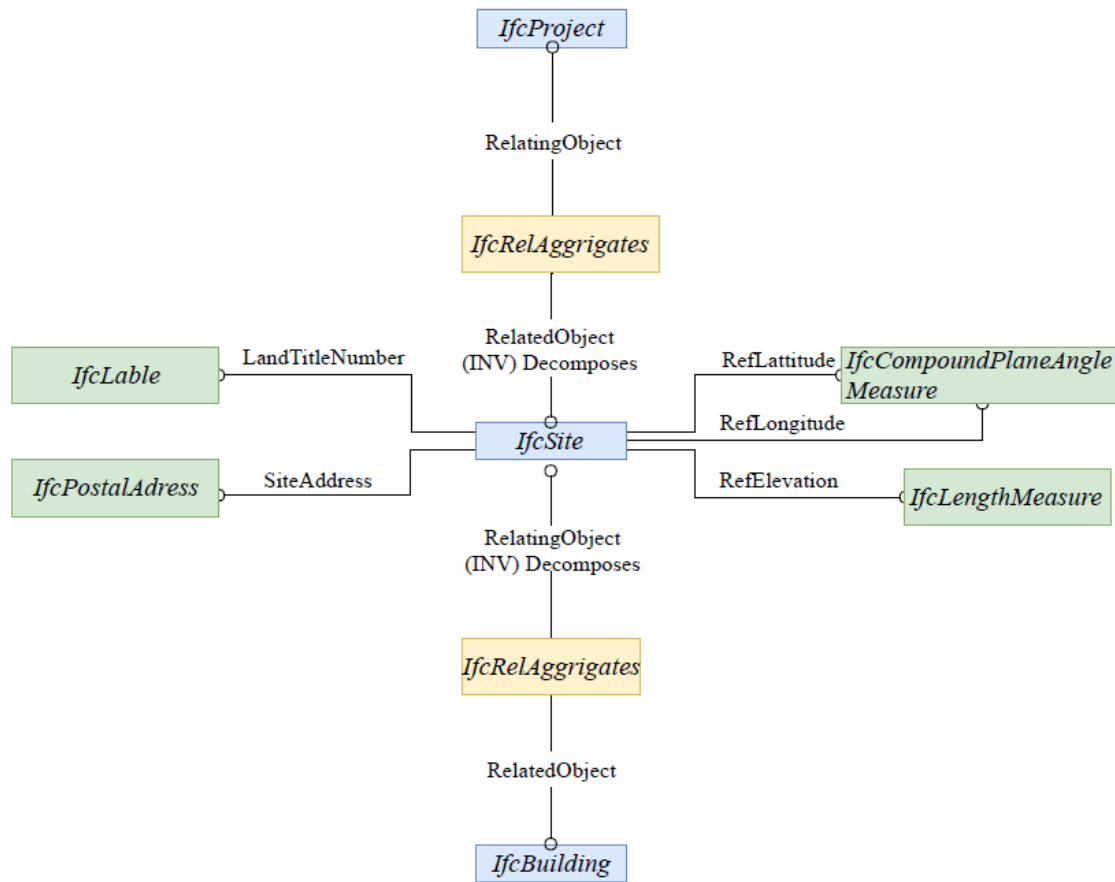


Figure 18: IfcSite entity in the IFC data Schema [15]

As similar to the Site, Building, and Building Storey, the building Space is represented as *IfcSpace* in the IFC data schema, is used to provide the area and volume of the room bounded by elements. The *IfcSpace* defines the attributes to provide further information about the building spaces, such as follows

- **Name**, which holds the unique name to space
- **LongName**, which the full name of the space.
- **ObjectType**, which holds the space type

Space boundary: space boundary defines the physical or virtual separators for space. It explains the relationship between space and its bounding elements such as wall, floor, roof, window, and door. The objectified relationship *IfcRelSpaceBounding* is used to link the bounding elements to space, which is clearly represented in the below Figure 19.

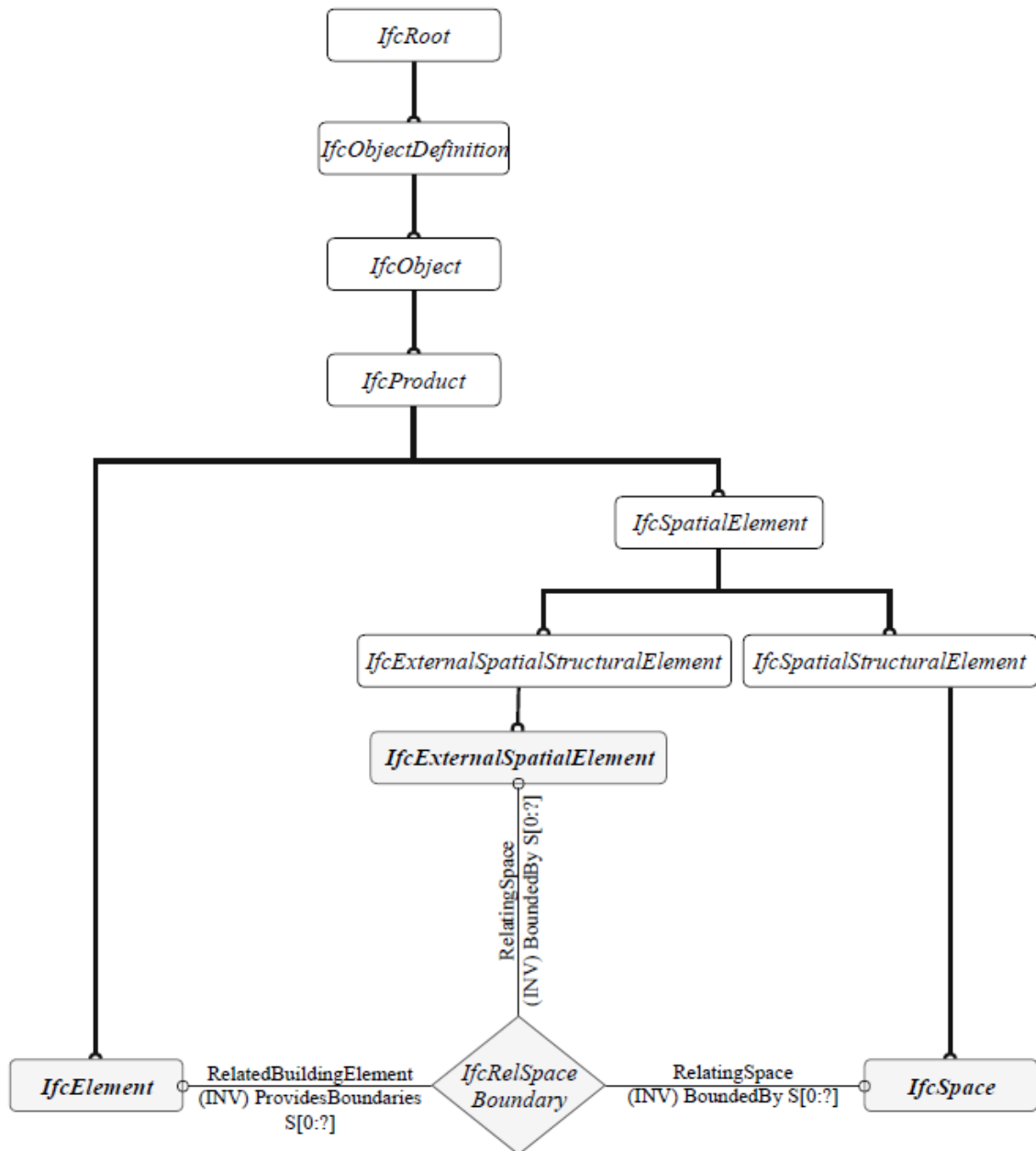


Figure 19: Space boundary relationship between Element and Space [15]

3.2.2 Concept of Zone

IFC schema defines the zone as *IfcZone* and it is a subtype of *IfcGroup* as shown in Figure 20. Zone represents the single or set of spaces in the building considered together for the purpose of providing engineering services. For example, lighting zones, HVAC zones, Heavy plug load zone, occupancy zone, etc. The zone name is defined by using the attribute called **LongName**. Figure 20 represents the objectified relationship *IfcRelServicesBuilding* to link the zone and space.

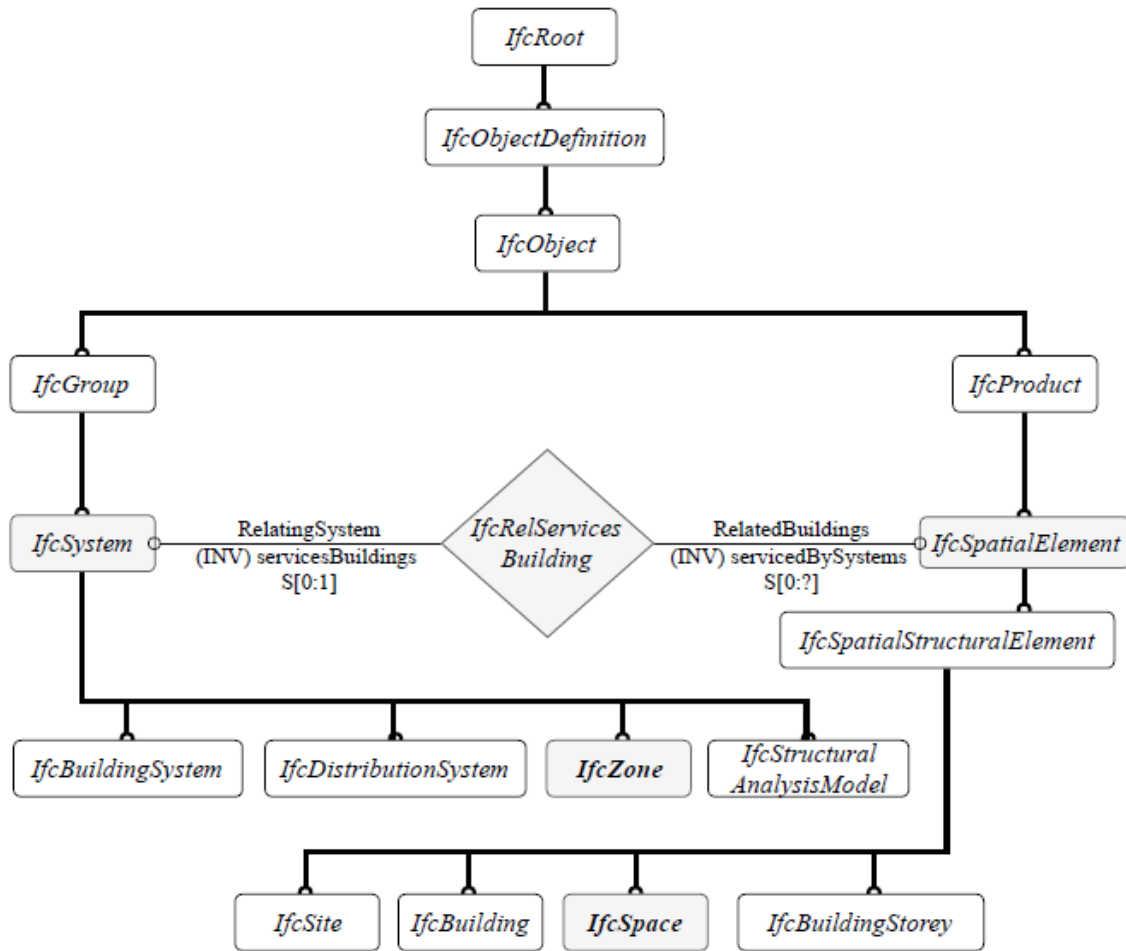


Figure 20: Objectified Relationship between Space and Zone [15]

3.2.3 Building Element

All the tangible elements (objects) of the building such as a wall, roof, window, door, etc. are accommodated as subsets of the *IfcBuildingElement* entity in the IFC data schema (refer in Figure 21). *IfcBuildingElementProxy* is the only subtype which is not belonging to the building objects list, but it provides the same functionality as subtypes of *IfcBuildingElement* and it is used to define the special type of the building element which is not mentioned in the subtypes list of the *IfcBuildingElement*. Each subtype further accommodates with different attributes and each of the subtypes inherits the attributes and relationships from the *IfcElement* entity. Spaces in the building are defined by the building elements. Figure 21 explains the objectified relationship between the building elements and space. This relationship is used to define what are the building elements related to a specific space in the building.

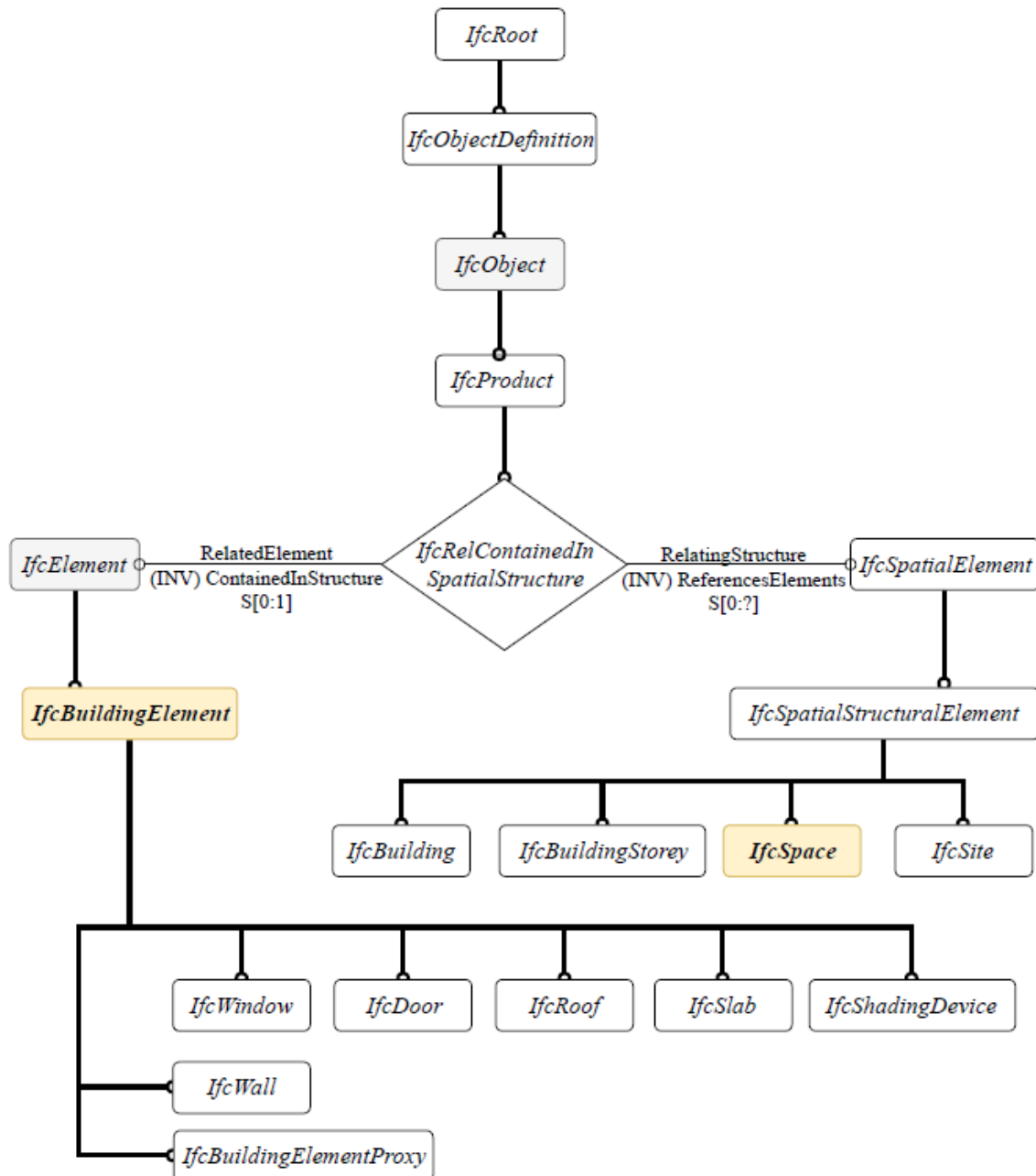


Figure 21: Objectified Relationship between Space and Element [15]

3.2.4 Opening and Filling

IfcOpeningElement is a subset of *IfcElement*, which forms an opening or void within another element. It means the opening is defined as an element in the IFC schema and which is placed or related to other elements such as a wall, slab, roof, floor, etc. in the building. The three features of the opening element are,

- Defines the element which creates the voids
- Defines the element which fills the void
- Openings representation

The relationship between the opening element and the element which is voiding is provided by *IfcRelVoidsElement*. Now an opening element is placed in the element which needs to be voided. This opening may be closed by another element such as a window or door. In this case the relationship, *IfcRelFillsElement* is used to link the opening element and the element which is going to fill the opening. Figure 22 shows the relations between elements and openings.

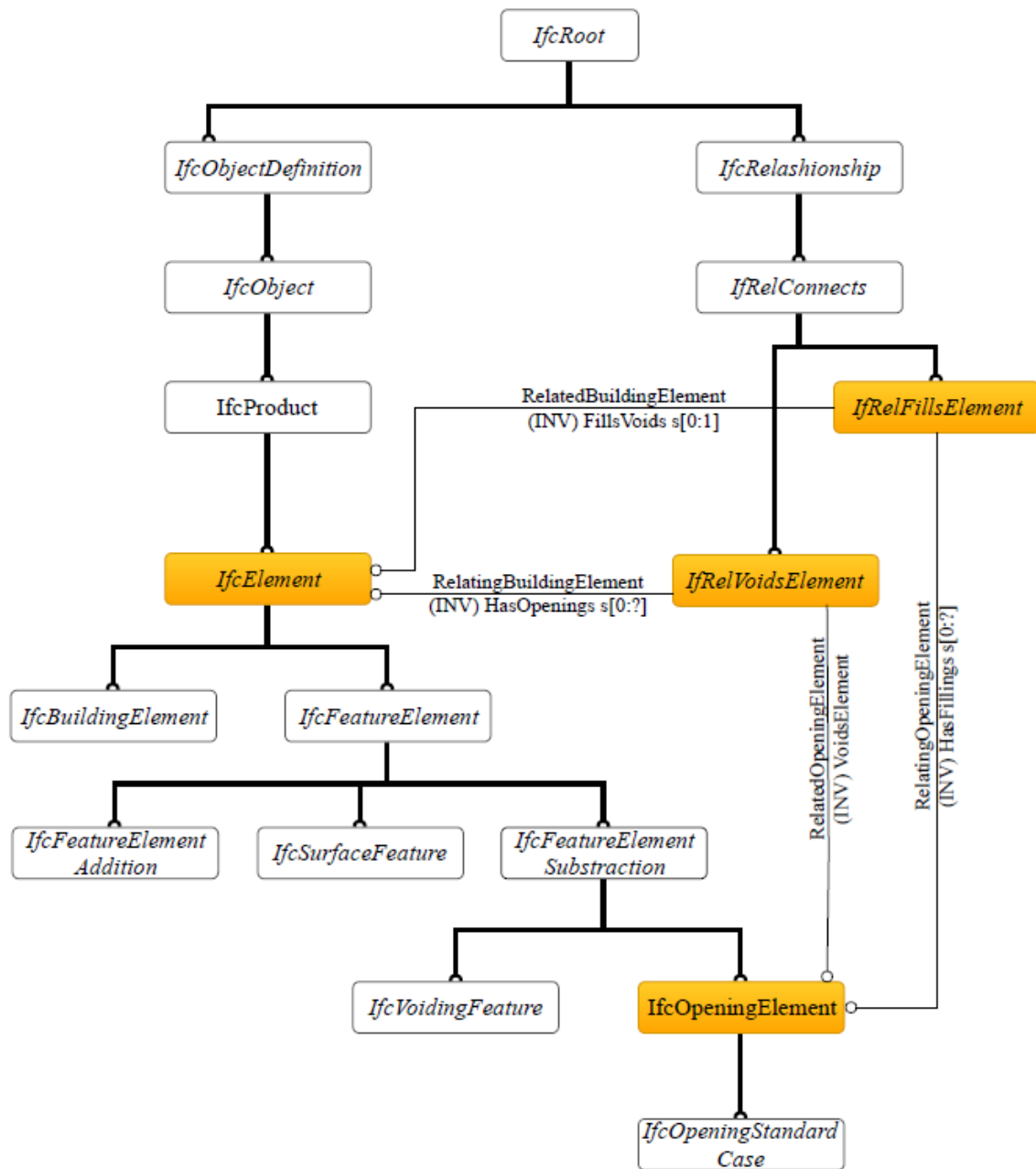


Figure 22: Relationship between building element and opening [15]

Fillings are usually defined as door and window elements in the building construction. These objects are represented as *IfcDoor* and *IfcWindow* in the IFC data schema. To place these elements within a wall or other element requires the existence of an opening. The figure below represents the filling elements, their types and the properties of those elements based on the type. Generally, element type helps to aggregate the properties of the element.

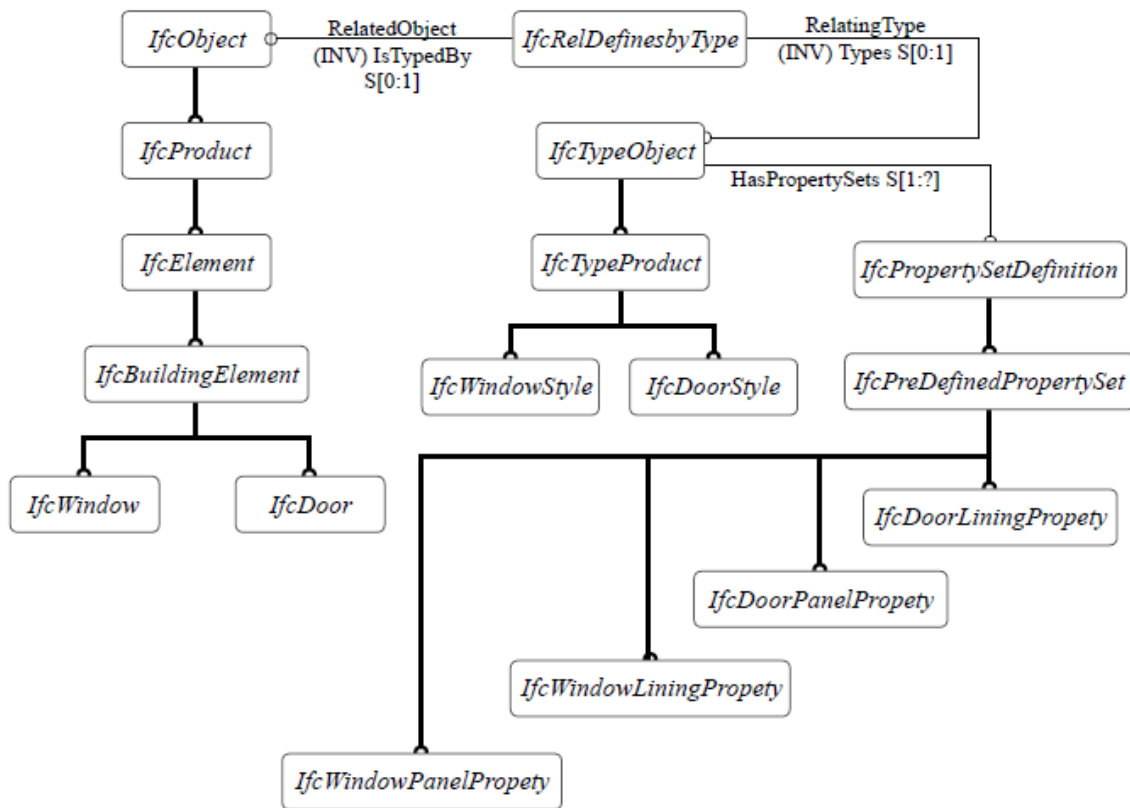


Figure 23: Relationship between Filling element and properties [15]

The entities *IfcDoor* and *IfcWindow* define the position of the filling element relative to the opening, opening direction of the filling element, overall width and height of the filling element and individual geometric representation. The object type entities *IfcDoorStyle* and *IfcWindowStyle* define the name and description of the style, operation type, and construction type (only the information). The property entities *IfcDoorLiningProperties* and *IfcWindowLiningProperties* define the depth and thickness of the panel and mullions, and transom parameters, if applicable. The *IfcDoorPanelProperties* and *IfcWindowPanelProperties* define the depth and width of the panel and operation type and position of the panel [16].

3.2.5 Geometry and Placement

Figure 24 shows the IFC data schema representation for the building object geometry, placement and their relationship. The geometric representation and the object placement are defined at *IfcProduct* level, so the same principle is equally applied for all subtypes. Therefore, a single concept of the geometric representation and placement is applied throughout the whole IFC schema and is the same for the *IfcSpace*, *IfcWall*, *IfcFlowSegment*, *IfcFurniture*, *IfcOpeningElement*, *IfcProxy*, etc.

The placement of an object is referred as *IfcObjectPlacement* in the IFC data scheme. This placement is carried out either by absolute (relative to the world coordinate system) or relative (relative to the object placement of another product) or constrained (relative to the grid axis) coordinate systems. The object placement defines the object coordinate system as either two-dimensional axis placement (*IfcAxis2Placement2D*) or three-dimensional axis placement (*IfcAxis2Placement3D*). The very common way of defining the object placement

based on relative co-ordinates systems is by using *IfcLocalPlacement* (refer to Figure 24). The *IfcGridPlacement* defines the placement of an object relative to the grid intersections.

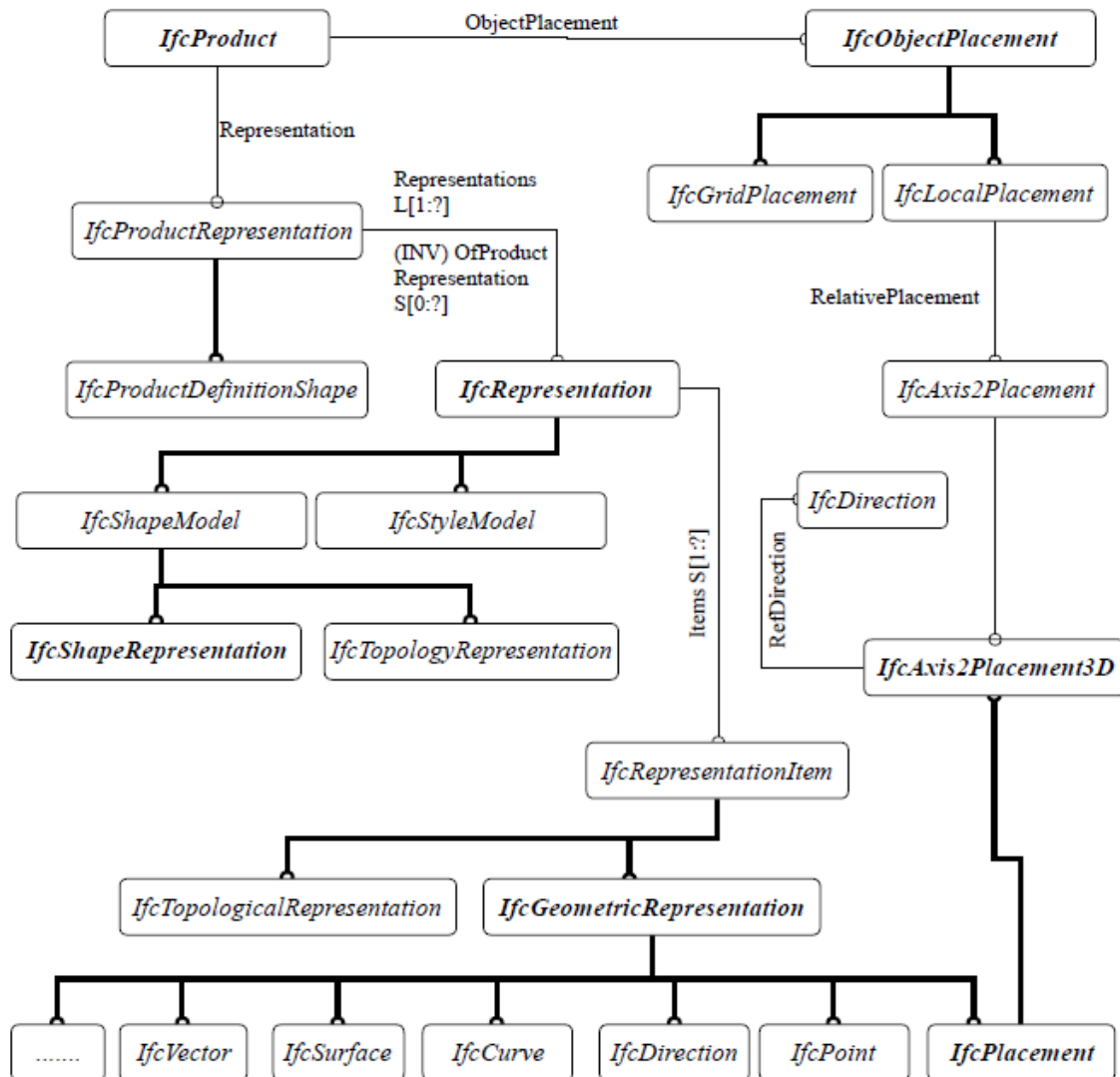


Figure 24: Geometric representation and Placement of an Object [15]

Representation of an object is associated with the product representation (see Figure 24). This provides a reference to the different geometric representations of an object. All geometric representations of the product are defined within the object placement which provides the object coordinate systems. An element defined as a subset of *IfcProduct* may have different geometric representations, all these representations of an object should be defined in the same object coordinate system. Each of the *IfcRepresentation* or *IfcShapeRepresentation* are identified by using representation items (*IfcRepresentationItem*). There are three ways to define the representation of the elements,

- Geometric representation
- Topological representation
- Mapped representation

The shape representation of the object is carried out by using *IfcGeometricRepresentation* entity.

3.2.6 Properties of Elements

IFC schema defines most of the information about an object in terms of attributes and the relationships between attributes. There are many types of information that a user might want to exchange that are not currently included within the entity. For this purpose, IFC developed a mechanism called Property definition, which allows defining expandable properties with objects. Figure 25 is representing two different ways of defining properties for an object. One is based on the type of object and another one is based on the object, both by using objectified relationships. The usual way of defining the properties is based on the object type but for the object whose object types are not available, properties are defined based on relationships.

In this methodology, the objectified relationship (*IfcRelDefinesByType*) is used to link the object with its object type, which is defined by a set of properties. The set of standard values defined in the *IfcPropertySet* is shared across multiple instances of that class. The *IfcProperty* subsets (Figure 26) allow for the definition of different property values within the private copy of the *IfcPropertySet* for each instance of the class. The *IfcPropertySet* class accommodates all sets of properties. It must contain at least one property and may contain as many as necessary.

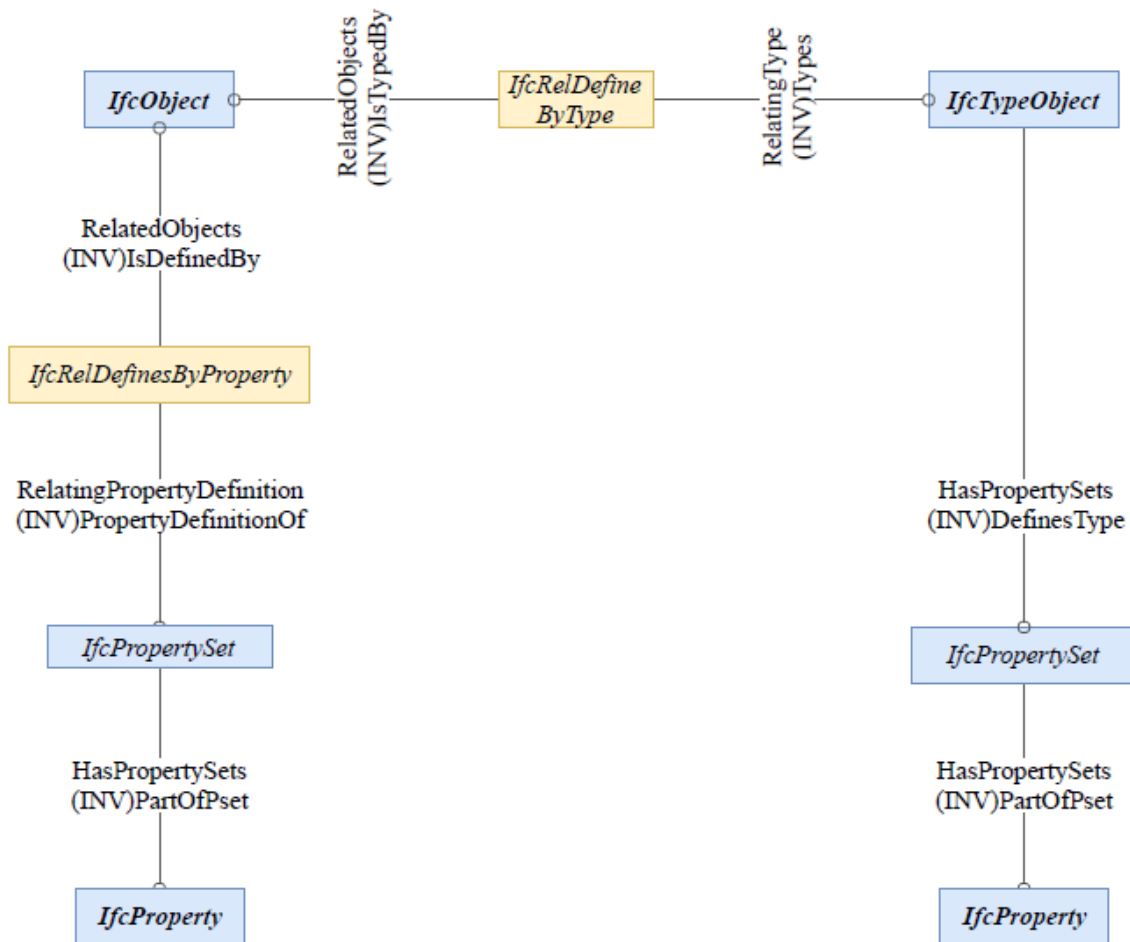


Figure 25: Objectified Relationship between Object and its Properties [15]

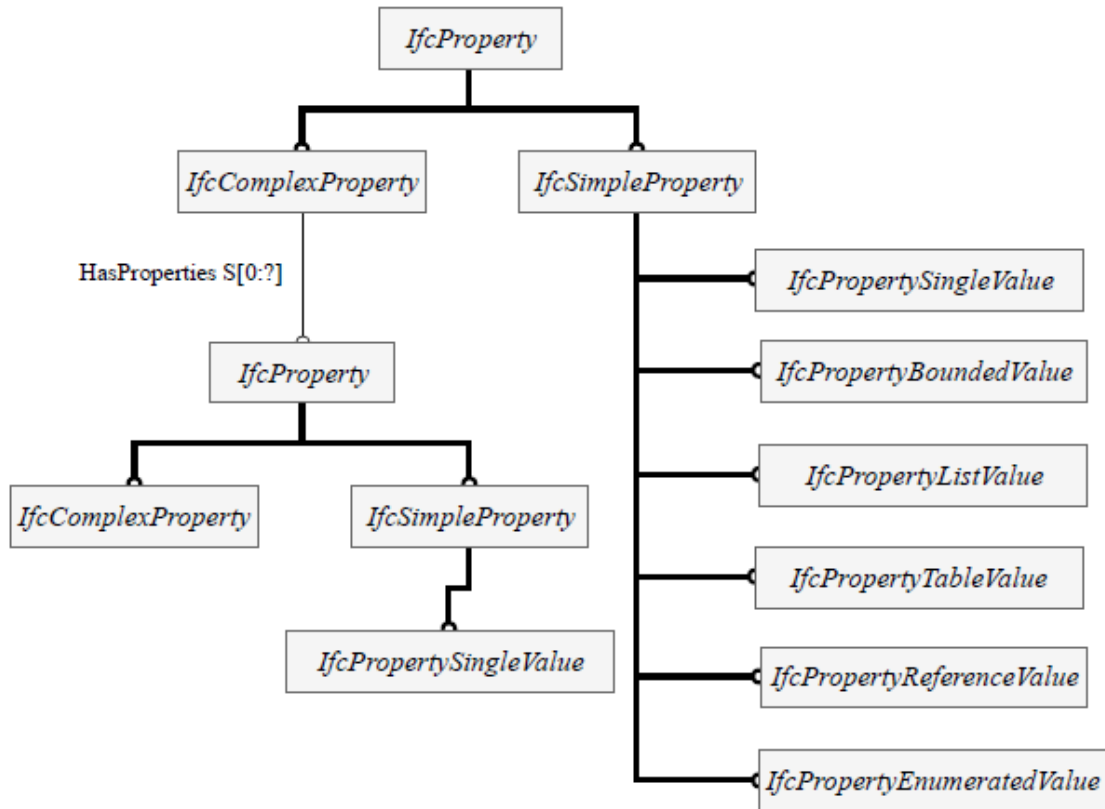


Figure 26: Definition of *IfcProperty* [15]

Figure 26 shows all the subsets belongs to the *IfcProperty* class. This *IfcProperty* is the common supertype for all the properties in the IFC data schema. *IfcPropertySingleValue* is the most used concept to carry the properties of an object. An *IfcPropertySingleValue* entity carries either a name and value pair or a name, value and unit triplet [16].

3.2.7 Material Definitions

This section describes the relationship between building element and its material properties. Figure 27 shows the IFC specifications for the definition of element material parameters. The material parameters are related to the building elements using material association relationship and which allows assigning the same material definition to multiple subtypes of *IfcElement*. Here, the entity *IfcMaterial* is used in case of a single solid material and represents the material characteristics of the elements. The entity *IfcMaterialLayerSetUsage* is used in case of layered elements and which represents the positioning of the material layer set (*IfcMaterialLayerSet*) with respect to the reference axis or surface. The *IfcMaterialLayerSet* is associated with layers (*IfcMaterialLayer*) with different material in each layer and defines the positioning of an individual layer. *IfcMaterialLayer* defines the parameters (like thickness and material for construction) of a single layer of an element which is constructed of a number of layers.

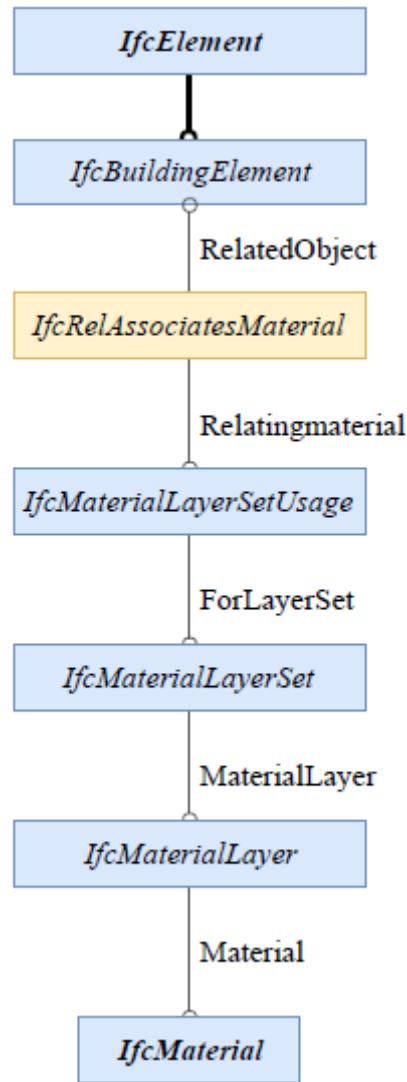


Figure 27: Definition of Material Parameters to Element [15]

3.2.8 Schedules Definition

The term schedules in the Energy Simulation Model represents the occupants schedule, building operation schedules, load schedules, terminal device schedules, etc. The *IfcWorkCalender* entity defines all these schedules details in terms of working and non-working hours in the IFC schema. Figure 28 clearly explains the IFC specifications for defining the schedules on energy simulation. Here, the entity *IfcWorkTime* represents the time period for the start and finish of the specific work and also references the Recurrence patterns. Sometimes this entity defines the set of time periods which indicates the exception of working times. The recurrence pattern is associated with work time and defines the “repetitive time period on the basis of regular recurrences such as each Monday in a week, or every third Tuesday in a month and the frequency of usage of Day Component. Position, and interval dependent on the recurrence type” [15]. The entity *IfcRecurrencePattern* clearly explains about the start and end time of work in a day, on which day the work is going to happen and the recurrence type (either weekly or monthly).

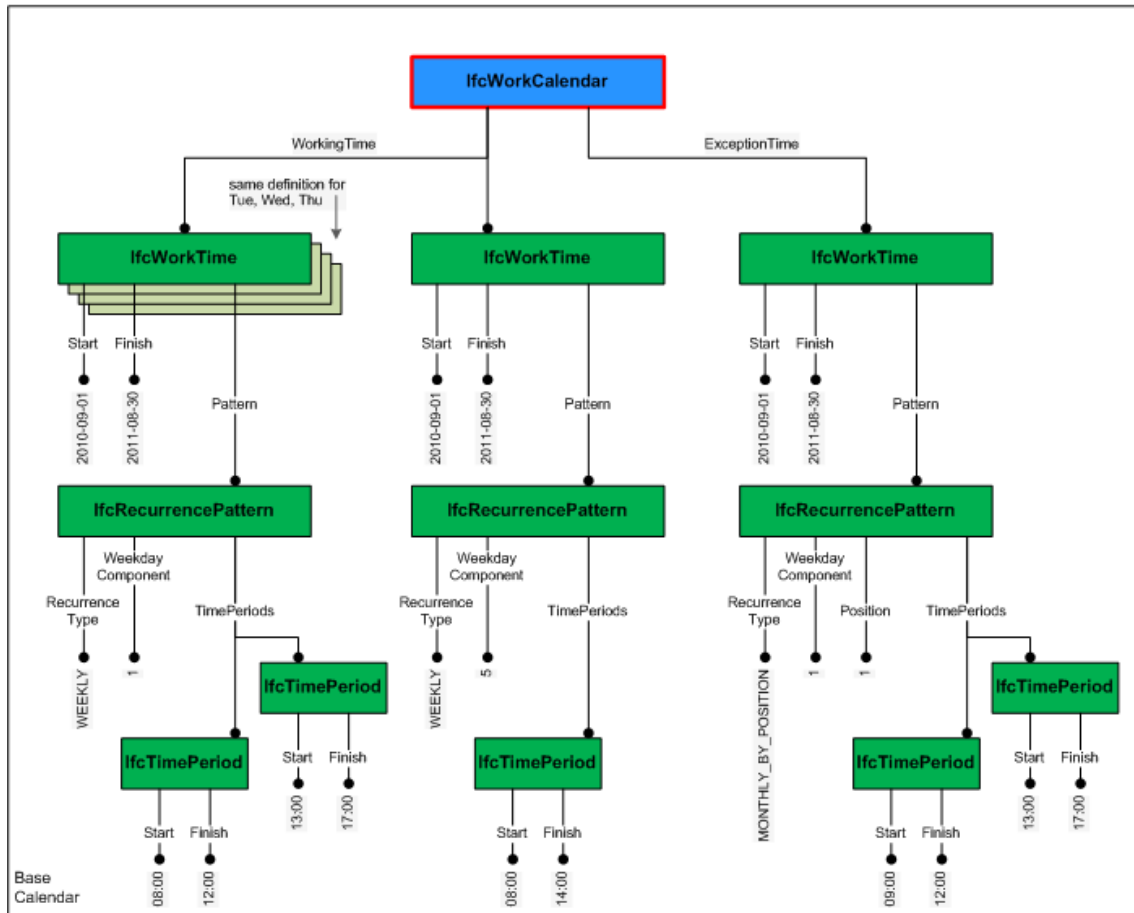


Figure 28: Schedule definition based on Work Calendar (& Recurrence Pattern) [15]

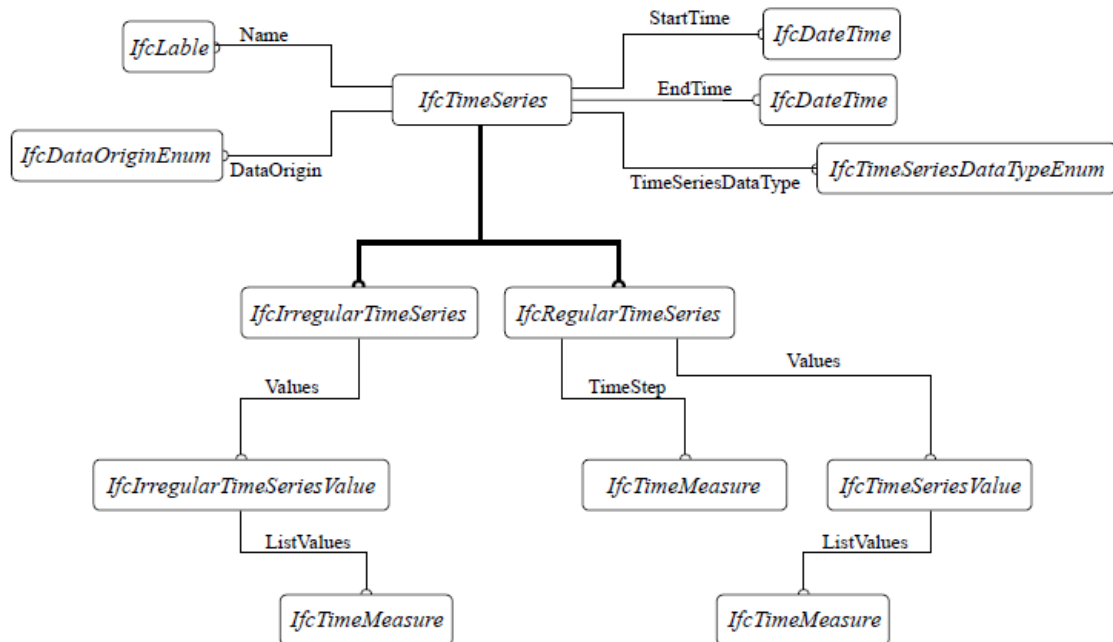


Figure 29: Schedule definition based on Time series and Property [15]

Figure 29 represents the definition of schedules of energy simulation based on the Time series patterns. *IfcTimeSeries* contains a set of time-stamped data entries. It means a collection of data associated with different time intervals. This time series is be either regular (*IfcRegularTimeSeries*) or irregular (*IfcIrregularTimeSeries*). In a regular time series, work is carried out in a regular manner and at predefined intervals. *IfcTimeMeasure* is associated with *IfcRegularTimeSeries* and defines the time step (period of the interval between work). In irregular time series, work will happen at an unspecified point in time and mostly cannot be characterized by a repeating pattern.

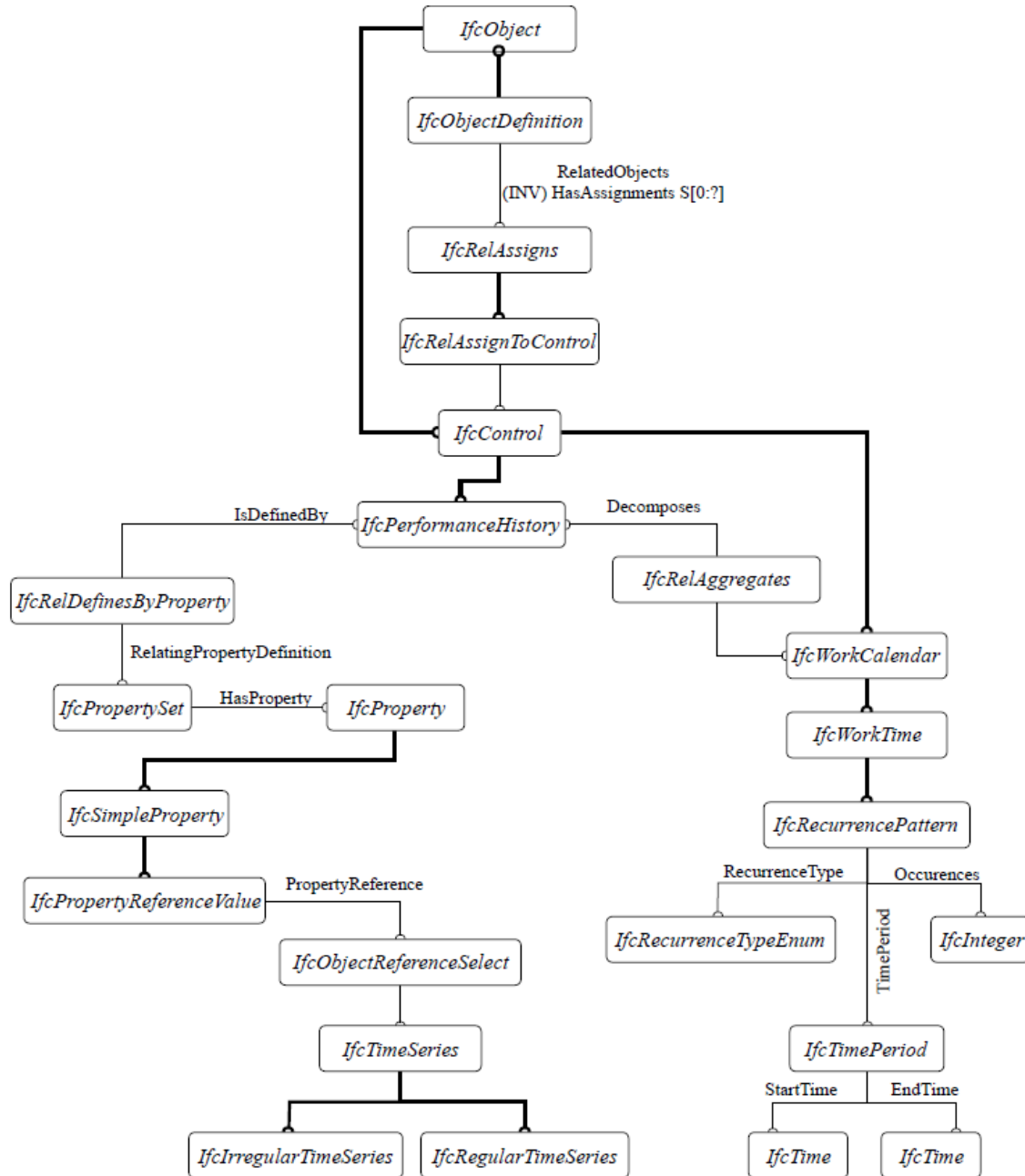


Figure 30: IFC schema for Schedule definition on Energy Simulation [25]

Figure 30 represents the new methodology to define the schedules using the IFC schema in energy simulation processes. In this method, the entity *IfcObject* is at the top level of the concept hierarchy and schedules for a specific process are defined at this entity. By using

this method, the spatial elements of the building can assign to the *IfcPerformanceHistory* via the *IfcRelAssignToControl* relationship. This *IfcPerformanceHistory* can be related to the recurrence pattern using a work calendar as shown in Figure 30 and also can relate to the regular and irregular time series using property set. This method can allow representing the detailed schedules of an entity [25].

4 Demonstration of data sharing between Revit and IES<VE>

This section describes the data sharing between a BIM tool and an Energy Performance Simulation tool for complex energy simulations (classifications are mentioned in section 2) using IFC & gbXML as an interoperable file format. The intention of this demonstration is to investigate the following,

- Level of data sharing (quality of data is going to transfer) between BIM and BES based on the data requirements to set-up an Energy Simulation Model,
- Adoption or implementation of meta-model data schemas in a BIM tool (Revit) for data export,
- Capability or adaptability of the energy simulation tool (IES<VE>) to import the data from gbXML and IFC file formats,
- Additionally, analyze and identify modelling errors in the BIM model by using Model Viewer tools.

The BIM model is created using Autodesk Revit 2019 and the same information model is imported to IES<VE> 2018 (Integrated Environmental Solutions <Virtual Engineering>), an energy analysis tool by using gbXML or IFC data schemas. The following steps are carried out to address the investigations mentioned above,

1. a detailed description of data transfer methodology,
2. guidelines for the successful implementation of data transfer to IES<VE>,
3. a complete description of modelled data in Revit,
4. verification of exported data (from Revit to gbXML or IFC) using model view checkers,
5. investigation of data in IES<VE>, which is imported from gbXML or IFC.

4.1 Test Methodology

The demonstration of data sharing is carried out based on two interoperability file formats such as gbXML and IFC. Figure 31, represents the methodology (the sequence of operations) for data sharing between Revit and IES<VE>. For the purpose of data sharing demonstration, complex types of energy simulation models are selected, such as Multi-zone model and Dynamic simulation model (mentioned in section 2). The required data for these simulation models are selected from Table 5, which explains the level of data granularity for each simulation model.

Initially, the BIM model is created in Revit 2019 and is incorporated with all required information to set-up a complex type of energy simulation model. The comprehensive BIM model is exported from Revit to the gbXML and IFC file formats (meta-data model schemas). These two interoperability schemas act as a neutral file format for the modelled BIM data and provide an access for software applications to import these data.

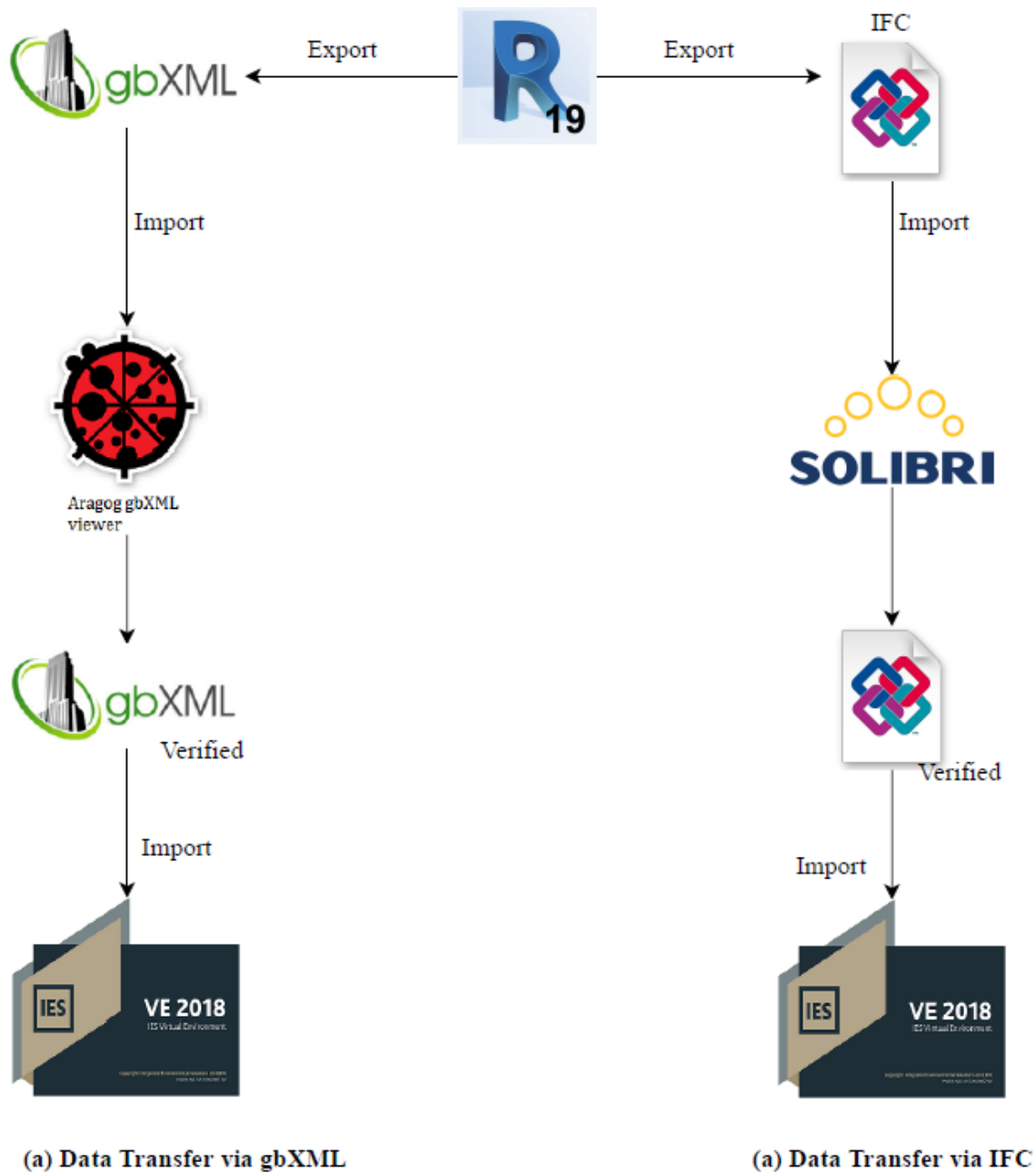


Figure 31: Methodology for the data sharing between BIM and BES

The gbXML file is now imported by the model view checker called Aragog gbXML viewer and similarly, the IFC file is imported by Solibri Model Viewer. The purpose of the model viewer is to identify whether the model data has been exported to interoperability file formats correctly or not. These viewer tools represent the BIM model as a virtual model or analytical model, which is the same representation used in the end software IES<VE> for energy simulation. This helps the user to rectify the modelling errors in the initial stage of the data sharing process. These model viewer tools provide the information regarding missing entities, issues and reports. This information is helpful to modify the BIM model according to the model viewer representation to rectify errors. Solibri enables the user to verify and understand how the modelled data is read by the IFC schema and how it is represented. This understanding will help the modeller to model the information in a favourable way for

successful export. The model viewer tools should be authorized by respective organizational bodies. Aragog gbXML viewer, which is certified by Green Building XML and Solibri Model Viewer, which is certified by buildingSMART international.

After performing the verifications and modifications, the verified IFC or gbXML file is imported by IES<VE> for the purposes of energy simulation. Further verifications regarding the data quality and correctness are performed in IES<VE>.

4.2 Guidelines for data transfer to IES<VE>

The Integrated Environmental Solutions (IES) Limited organization provides some important guidelines for the successful implementation of data transfer between Revit and IES<VE>. These guidelines are explained in a document named as “BIM + Building Performance Analysis Using Revit and IES Virtual Environment” [13]. These guidelines mainly help to reduce the user modelling errors and explains how the IES treats the modelled information. This section mainly focuses on the necessary information (in terms of checklist and data organization in IES) that need to be verified before the start of the data transfer process.

4.2.1 Checklist for data sharing between Revit and IES

a) Room:

Room or space must be defined for all areas of the building in the BIM model to create a fully enclosed building. Room or space is composed of different adjacencies (Roof, Ground Floor Slab, Floor, External wall, Internal wall, etc.). IES will understand the function of adjacencies based on the placement of the Room. For example, in IES, an external wall is a vertical surface that is not in contact with an adjacent room on one side, internal wall is a vertical surface that is in contact with adjacent rooms on both sides, Ground Floor Slab is a horizontal surface that is not in contact with any room below, Roof is a horizontal surface that is not in contact with any room above. The type and purpose of each element should be assigned correctly in the Revit based on this understanding. IES is a virtual environment, it will treat all elements as a 2D-surface element (refer to section 3.1).

b) Room Bounding Elements:

Room bounding elements are the elements which are bounded by room or space. It should be noted that the bounding element option in Revit should be enabled for all elements which are surrounded by space or room.

c) Define all Upper and Lower Boundaries:

It should be noted that the indication of the levels (which indicates the storeys in the building) for each floor must be integrated into the BIM model. IES provides surface element exactly at the position of levels and the volume calculations are performed by considering the difference between these levels.

d) Project Information:

The option “Project information” in Revit accommodates the information regarding project location, Energy settings and Building Identity data. Location of the project is the most

important criteria to perform energy performance analysis. The IES will redirect the weather data on the basis of location details and this weather data is used for calculations. The Energy settings option carries the information of building type, postal code, ground plane, project phase, and Sliver Space Tolerance. Further details about these options will be explained in the coming sections. It should be checked if all energy data are defined accurately or not.

e) Room Volume Computations:

The room volume calculations in Revit before exporting to IES should be performed and the same should be verified with the IES model after export. This will help to understand whether IES is designing the systems for accurate data or overwhelmed data.

f) Try to reduce the size of the model:

The elements which are not necessary should be eliminated. This will help the reduction in the size of the file.

4.2.2 Data Modelling in IES<VE>

The intent of this section is to explain how the energy analysis data is accommodated in IES<VE> application. Understanding this data accommodation in IES will help the user to easily identify or investigate the missing entities during import and export operations. Figure 32 shows the methodology for information modelling in IES for different analysis processes.

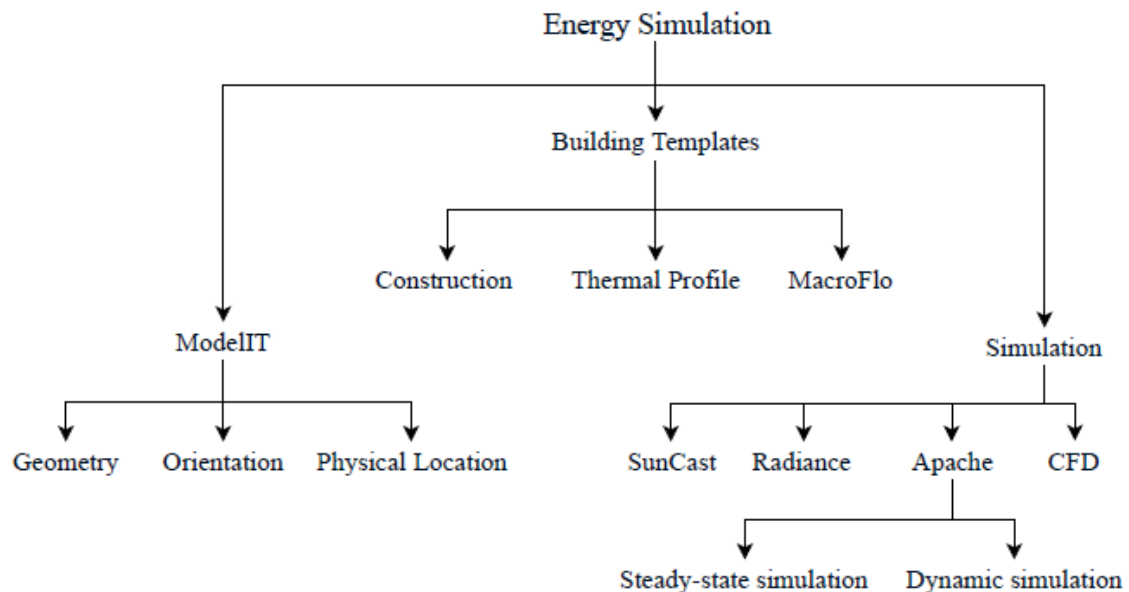


Figure 32: Data organization in IES<VE>

a) ModelIT – Model Builder:

ModelIT is a model building component integrated with many drafting tools and editing tools in the IES software. ModelIT is a module in IES to create and manage the geometry of the building. This module provides an interface to create and edit geometry (of building

spaces or rooms, building elements, local shadings, and openings) to represent the simple building models or very detailed full building models. Similarly, this module provides the location details of the building site (which helps to acquire the weather data) and the orientation of the building with respect to True North (which helps to know the sun path directions with respect to the building). The detailed information regarding the ModellT module is explained by the IES user guide named as “ModellT: Model builder” [26].

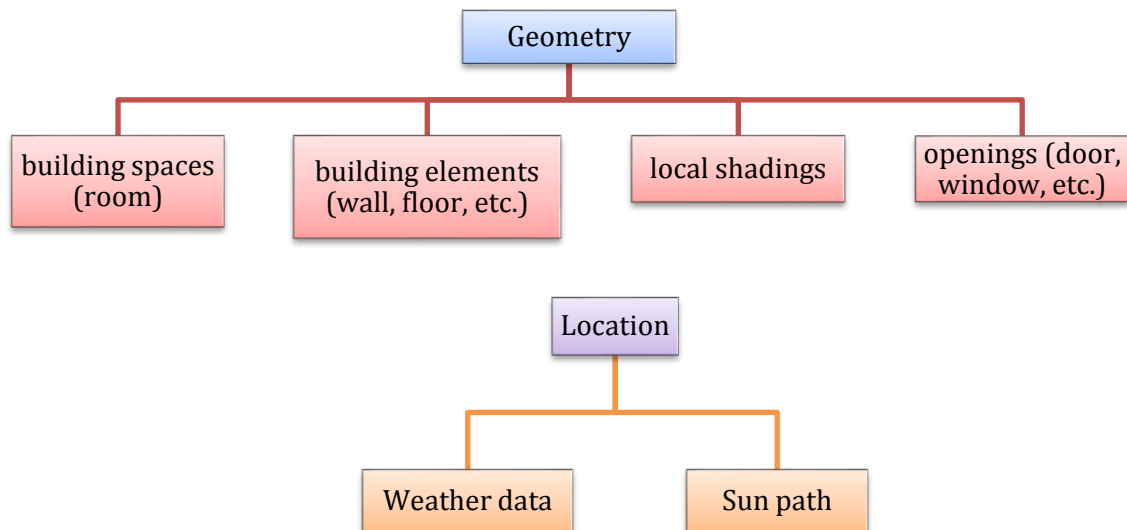


Figure 33: Components of ModellT module in IES<VE>

b) Building Template Management:

The concept of building template management module is to create the construction types and thermal profiles for the building model in IES and assign the same to the respective building elements and space types. Figure 34 represents all the respective components regarding the building template management module. The construction details template in the Building template management will explain about the materials details (Building material and its material properties) and layers arrangement (no of layers and thickness of each layer) in the building element. The thermal profile templates are related to each space type mentioned in the building and which are variable for different space types and all components are time-dependent. The major components involved in the thermal profile templates are Air exchange (describes the details about natural ventilation and auxiliary ventilation), Occupants data, Operational hours of the building, Internal gains due to Lighting, people, equipment in the building, and details about building services system (HVAC).

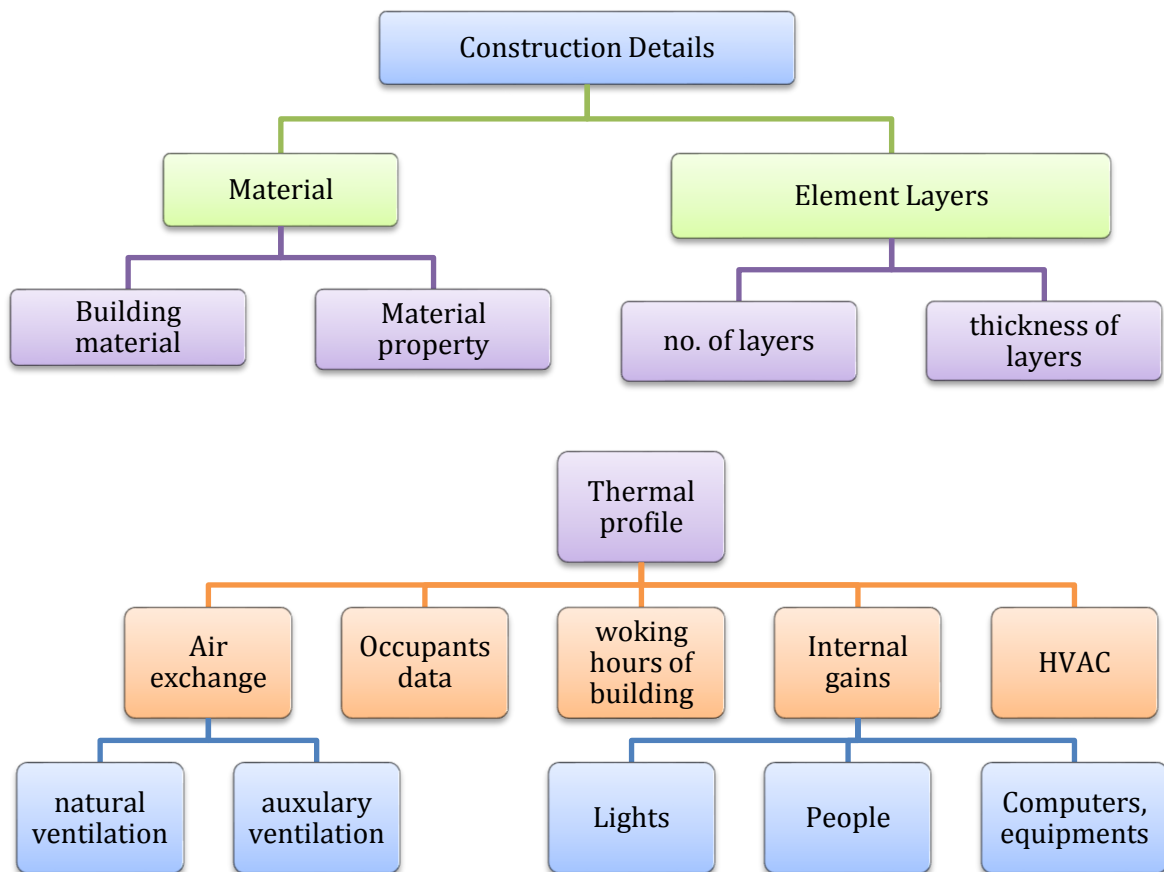


Figure 34: Information regarding Construction details and Thermal profiles in IES<VE>

c) Opening details:

The details mentioned in Figure 35 for the openings are required to perform the (Macro Flo) bulk air flow simulations in the IES. This simulation is performed to analyze the infiltration (unwanted air movement through the cracks or holes in building element) and natural ventilation in buildings. The module called MacroFlo in IES is used to provide opening details to model and to calculate the bulk air movement in and through the building, driven by wind and buoyancy induced pressure [27].

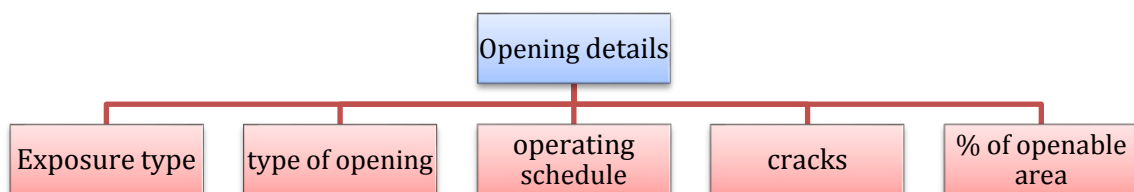


Figure 35: Required Opening details for Energy Simulation in IES<VE>

4.3 Modelled data in Revit (BIM model)

A Three-storey Simple Office Building (Figure 36) is considered for the demonstration of data transfer between the BIM model and the BES model. The BIM model which is incorporated with all the necessary information required for energy simulation is modelled in Autodesk Revit 2019. The building had been uniform geometry as represented in Figure 36.

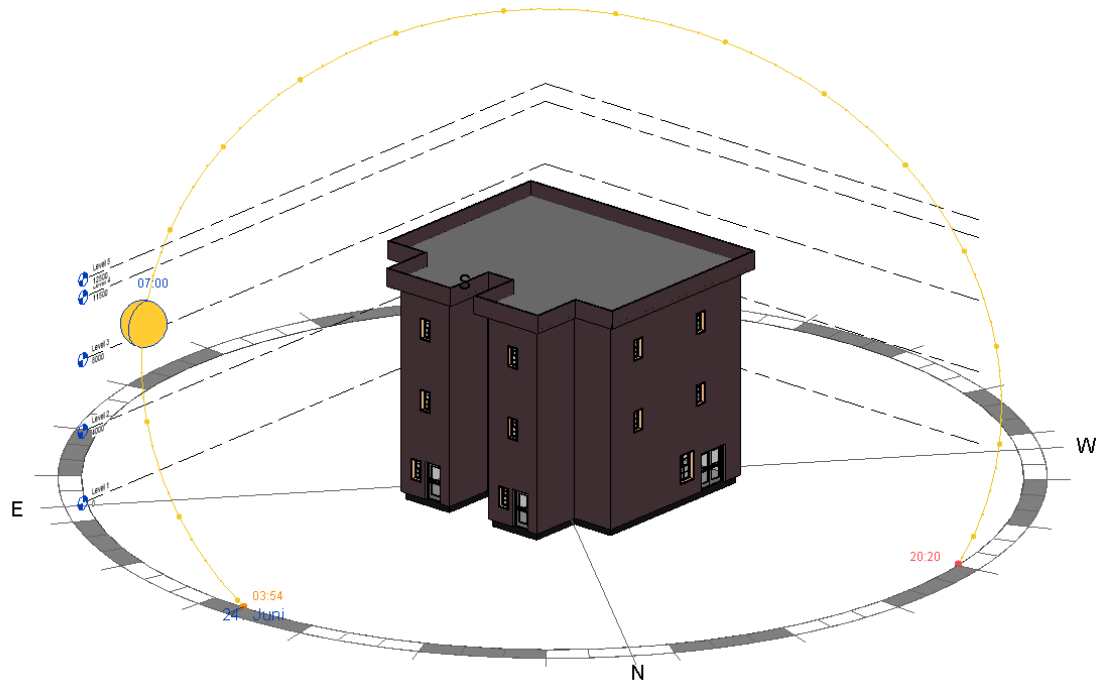


Figure 36: 3-Storey Simple Office Building - Revit model (BIM Model)

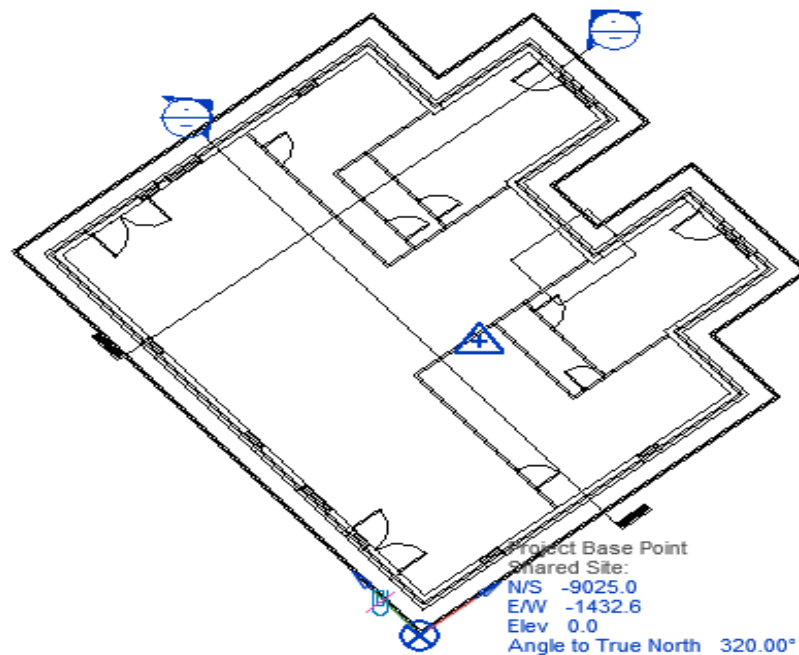


Figure 37: Site-Plan for the Office Building

Figure 37 shows the Site-Plan for the Office Building which includes the base point and site survey point of the building. The orientation of the building is considered as 320 degrees with respect to the True North. The location details for the building are considered as Nürnberger Straße 31A, 01069 Dresden, Saxony, Germany.

4.3.1 Model Construction

Each floor of the building is divided into three separate rooms and every room has been assigned different spaces and space types. The floor plan of each level in the building is shown in Figure 38, Figure 39, Figure 40 respectively. The model is constructed in Revit by using different Revit families. Relevant or similar families are used to construct different building components like walls, roof, floor, etc. and all these components are interconnected to avoid air gaps and overlaps. Revit provides a number of default constructions for each building component, but it also allows the user to define own material, properties, layers and thickness. These construction details and material information of the model were defined in Revit as summarized in Table 7.

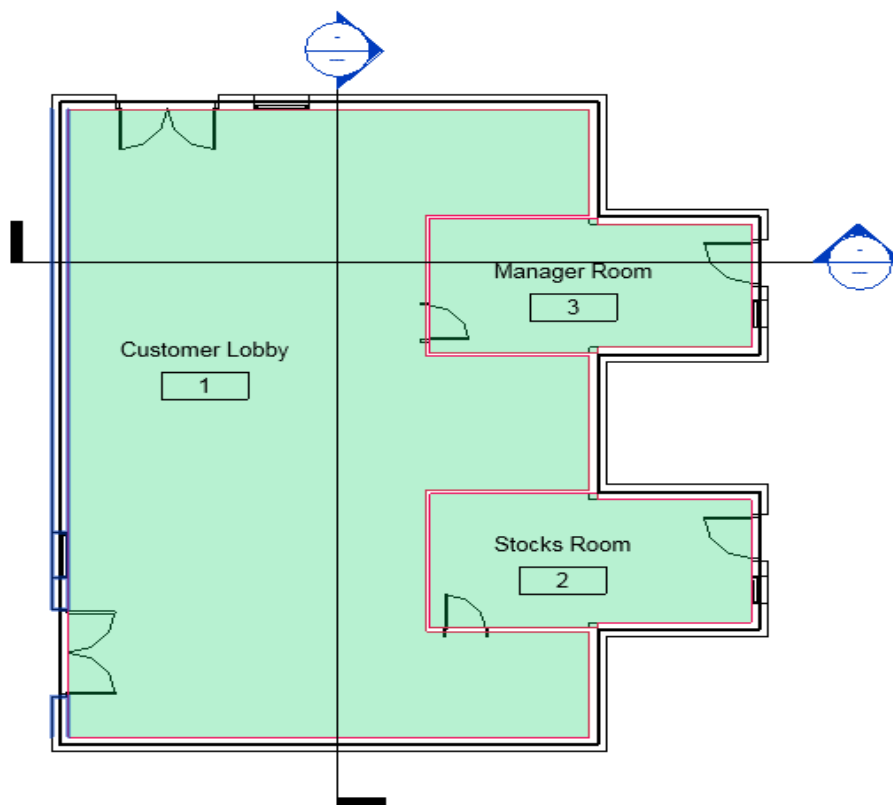


Figure 38: Floor Plan at Level-1 (Ground Floor) – Office Building

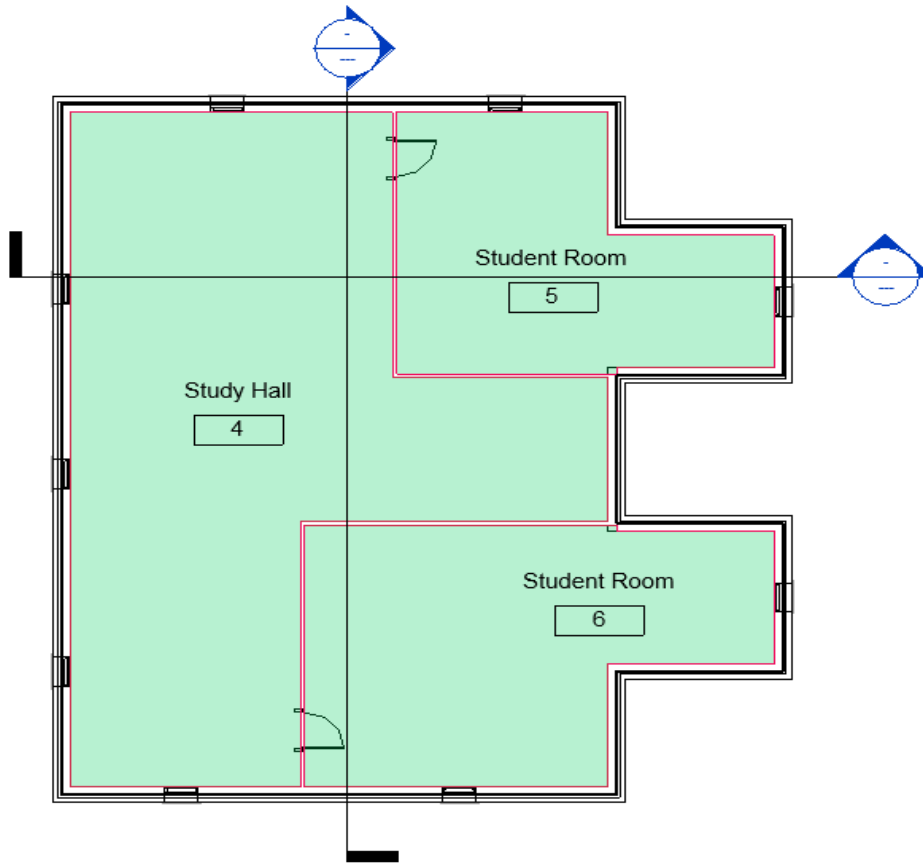


Figure 39: Floor Plan at Level-2 - Office Building

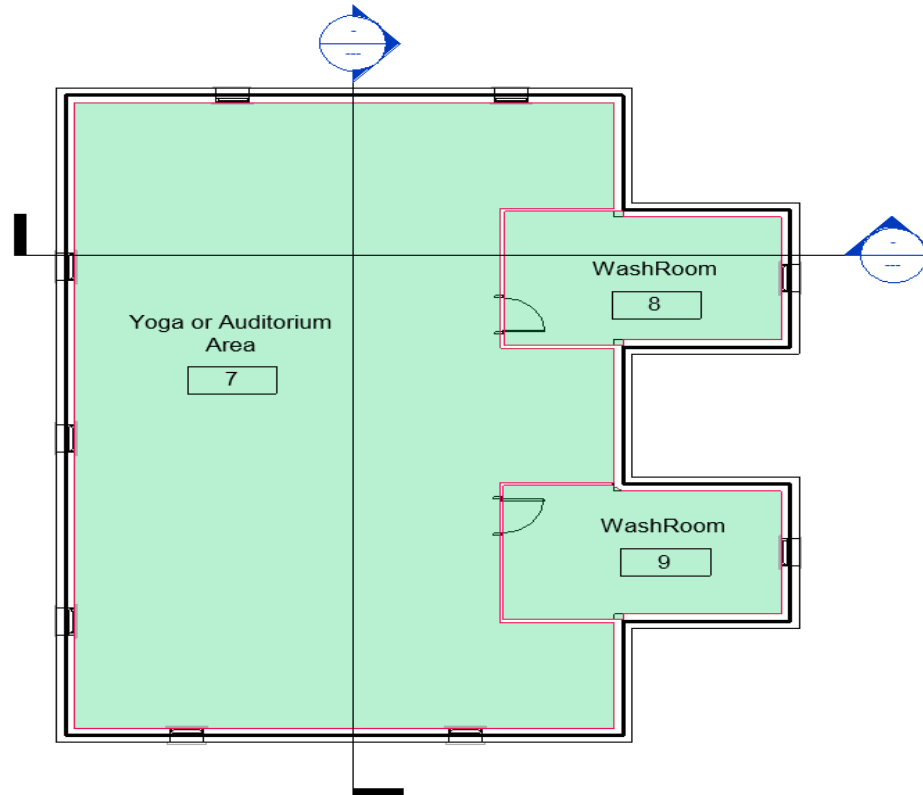


Figure 40: Floor Plan at Level-3 - Office Building

Table 7: Construction Details and Thermal properties of Building Elements

Element	Parameter	Value
External Wall (Construction Type: 101.6 mm Brick + 203.2 mm Concrete + 12.7 mm Gypsum wall Board)	Thickness	317.5 mm
	Thermal Resistance (R)	0.402 m ² .K/W
	Thermal Mass	41.91 KJ/K
	Heat Transfer Co-efficient (U)	2.4879 W/m ² .K
Internal Wall (Construction Type: 15 mm Plaster Board + 40 mm Cavity + 15 mm Plaster Board)	Thickness	70 mm
	Thermal Resistance (R)	1.6588 m ² .K/W
	Thermal Mass	3 KJ/K
	Heat Transfer Co-efficient (U)	0.6028 W/m ² .K
Parapet Wall (Construction Type: 90 mm Brick, common)	Thickness	90 mm
	Thermal Resistance (R)	0.1667 m ² .K/W
	Thermal Mass	10.89 KJ/K
	Heat Transfer Coefficient (U)	6 W/m ² .K
Door Type 1 (Exterior) French door, wood frame with double glass	width	1800 mm
	Height	2000 mm
	Thermal Resistance (R)	0.3374 m ² .K/W
	Heat Transfer Coefficient (U)	2.9639 W/m ² .K
Door Type 2 (Exterior NE side) Metal Frame with single clear glass	width	900 mm
	Height	2000 mm
	Thermal Resistance (R)	0.1525 m ² .K/W
	Heat Transfer Coefficient (U)	6.5580 W/m ² .K
Door Type 3 (Internal Door) Hollow core wood	width	750 mm
	Height	2000 mm
	Thermal Resistance (R)	0.3145 m ² .K/W
	Heat Transfer Coefficient (U)	3.1796 W/m ² .K

Element	Parameter	Value
Window Double glazed - domestic, single hung	width	450 mm
	Height	1100 mm
	Visual Light Transmittance	0.81
	Solar heat gain coefficient	0.76
	Thermal Resistance (R)	0.3196 m ² .K/W
	Heat Transfer Coefficient (U)	3.1293 W/m ² .K
Ground Floor 200 mm sand + 200 mm Concrete cast in site + 12.5 mm Damp proofing	Thickness	412.5 mm
	Thermal Resistance (R)	0.7991 m ² .K/W
	Thermal Mass	52.74 KJ/K
	Heat Transfer Coefficient (U)	1.2514 W/m ² .K
Intermediate Floor (Slab) 12.5 mm Plaster + 200 mm Concrete cast in site + 12.5 mm Damp proofing	Thickness	225 mm
	Thermal Resistance (R)	0.226 m ² .K/W
	Thermal Mass	31.60 KJ/K
	Heat Transfer Coefficient (U)	4.4134 W/m ² .K
Roof 155 mm Insulation + membrane + 50 mm Cavity + 12.5 mm Plaster	Thickness	217.5 mm
	Thermal Resistance (R)	6.4531 m ² .K/W
	Thermal Mass	1.74 KJ/K
	Heat Transfer Coefficient (U)	0.155 W/m ² .K
Room 1 Customer Lobby	Area	113.846 m ²
	Perimeter	58870 mm
	Volume	429.768 m ³
Room 2 Stocks Room	Area	16.774 m ²
	Perimeter	17790 mm
	Volume	63.323 m ³

Element	Parameter	Value
Room 3 Manager Room	Area	16.774 m ²
	Perimeter	17790 mm
	Volume	63.323 m ³
Room 4 Study Hall	Area	81.884 m ²
	Perimeter	46730 mm
	Volume	309.110 m ³
Room 5 Student Room	Area	28.264 m ²
	Perimeter	24225 mm
	Volume	106.697 m ³
Room 6 Student Room	Area	37.066 m ²
	Perimeter	27542 mm
	Volume	139.923 m ³
Room 7 Yoga or Auditorium Area	Area	119.921 m ²
	Perimeter	54912.5 mm
	Volume	419.722 m ³
Room 8 Wash Room	Area	13.844 m ²
	Perimeter	15790 mm
	Volume	48.455 m ³
Room 9 Wash Room	Area	13.895 m ²
	Perimeter	15747.2 mm
	Volume	48.634 m ³

4.3.2 Energy Model Preparation

Apart from the construction details assigned to building elements in Revit, the details regarding energy settings, space types and zones are required to perform an energy analysis of a building. Table 8 represents the details of location, the orientation of the building and energy settings for the building based on the building type. It includes information regarding different spaces and space types, which are assigned to the building area. The table below also explains the information related to the different zones, which are assigned to a set of spaces in the building. Energy settings of the building are defined in the Revit Model using the Project Information option in Manage toolbar. In energy settings, Sliver Space Tolerance defines the “narrow area bounded by parallel interior room -bounding components” [28], Analytical Space Resolution defines the “minimum gap between elements that will be ignored in creating the analytical model spaces” [29] and Analytical Surface Resolution is indicated as “Resolution smaller than this value will not be considered as a surface” [29]. The default values for these three parameters are considered as per the recommendations of Autodesk Revit for a balance of simulation accuracy and processing time [29].

Revit provides a number of default space types for the buildings and each space type are defined by the different number of specifications. These specifications are editable (refer to Table 8). The space types mentioned in this example are considered from some of default space types and its specifications are pre-defined in the Revit (e.g. Area per person, sensible heat gain, latent heat gain, light and power loads, schedules, etc.). Similarly, default zones are assigned to different set of spaces. The details regarding energy settings, space types and zones of this model were defined in the Revit as summarized in Table 8.

Table 8: Revit - Energy settings, Space Types and Zones for Office Building

Element	Parameter	Value/Type
Location	Nürnberg Str. 31A, 01187 Dresden	
Orientation	320 degrees	
Energy settings	Analysis Mode	Use Building Elements
	Ground Plane	Level 1
	Project Phase	New Construction
	Analytical Space Resolution	457.2 (Default)
	Sliver Space Tolerance	304.8 (Default)
	Analytical Surface Resolution	304.8 (Default)
	Building Type	Office

Element	Parameter	Value/Type
Energy settings	Building Operation Schedule	12/5 Facility
	Building Services System	VAV – Single Duct
	Outdoor Air Information	Outdoor Air Per Person: 8 L/s
	Export Category	Spaces
	Export Complexity	Complex with Mullions and Shading Surfaces
	Building Envelope	Use Functional Parameters
	Building Infiltration Class	Tight
Space 1 Customer Lobby	Zone	Zone1
	Condition Type	Heating & cooling
	Space Type	Bank Customer Area
Space Type – Bank Customer Area	Area per person	3.33 m ²
	Sensible Heat gain per person	65.94 W
	Latent Heat gain per person	30.77 W
	Light load density	16.04 W/m ²
	Power load density	16.15 W/m ²
	Occupancy schedule	8 AM to 5 PM
	Lighting schedule	6 AM to 11 PM
	Power schedule	6 AM to 11 PM
	Outdoor air per person	3.54 L/s
	Outdoor air per area	0.30 L/(s·m ²)
	Outdoor air method	by People and by Area
Space 2 & 3	Zone	Zone1

Manager Room and Stock Room	Condition Type	Heating & cooling
	Space Type	Bank Activity Area
Space Type - Bank Activity Area	Area per person	20.000 m ²
	Sensible Heat gain per person	73.27 W
	Latent Heat gain per person	58.61 W
	Light load density	16.15 W/m ²
	Power load density	16.15 W/m ²
	Occupancy schedule	On - 6 AM to 10 PM
	Lighting schedule	Office Lighting - 6 AM to 11 PM
	Power schedule	Office Lighting - 6 AM to 11 PM
	Outdoor air per person	2.36 L/s
	Outdoor air per area	0.30 L/(s·m ²)
	Outdoor air method	by People and by Area
Zone 1 (Includes Space 1,2&3)	Service Type	VAV – Dual Duct
	Cooling Information	Cooling set point – 23.32°C Cooling air temperature – 12.22°C
	Heating Information	Heating set point – 21.11°C Heating air temperature – 32.22°C
	Outdoor Air Information	From Space Type
Space 4 Study Hall	Zone	Zone2
	Condition Type	Heating & cooling
	Space Type	Dormitory Study hall
	Area per person	10.000 m ²

Space Type - Dor-mitory Study hall	Sensible Heat gain per person	73.27 W
	Latent Heat gain per person	45.43 W
	Light load density	11.95 W/m ²
	Power load density	5.81 W/m ²
	Occupancy schedule	8AM to 9PM
	Lighting schedule	6 AM to 11 PM
	Power schedule	6 AM to 11 PM
	Outdoor air per person	3.54 L/s
	Outdoor air per area	0.30 L/(s·m ²)
	Outdoor air method	by People and by Area
Space 5 & 6 Student Bed Room	Zone	Zone 2
	Condition Type	Heating & cooling
	Space Type	Dormitory Bedroom
Space Type - Dor-mitory Bedroom	Area per person	10.000 m ²
	Sensible Heat gain per person	73.27 W
	Latent Heat gain per person	45.43 W
	Light load density	11.95 W/m ²
	Power load density	5.81 W/m ²
	Occupancy schedule	24 hours
	Lighting schedule	Office Lighting - 6 AM to 11 PM
	Power schedule	Office Lighting - 6 AM to 11 PM
	Outdoor air per person	2.36 L/s
	Outdoor air per area	0.30 L/(s·m ²)

	Outdoor air method	by People and by Area
Zone 2 (Includes Space 1,2&3)	Service Type	VAV – Single Duct
	Cooling Information	Cooling set point – 23.32°C Cooling air temperature – 12.22°C
	Heating Information	Heating set point – 21.11°C Heating air temperature – 32.22°C
	Outdoor Air Information	From Space Type
Space 7 Yoga Room	Zone	Zone3
	Condition Type	Heating & cooling
	Space Type	Exercise Center
Space Type - Exercise Center	Area per person	0.667 m ²
	Sensible Heat gain per person	65.94 W
	Latent Heat gain per person	30.77 W
	Light load density	3.23 W/m ²
	Power load density	5.81 W/m ²
	Occupancy schedule	7 AM to 8 PM
	Lighting schedule	7 AM to 8 PM
	Power schedule	7 AM to 8 PM
	Outdoor air per person	2.36 L/s
	Outdoor air per area	0.30 L/(s·m ²)
	Outdoor air method	by People and by Area
Space 8 & 9 Wash Room	Zone	Zone3
	Condition Type	Heating & cooling
	Space Type	Rest Room

Space Type - Rest Room	Area per person	10.000 m ²
	Sensible Heat gain per person	73.27 W
	Latent Heat gain per person	58.61 W
	Light load density	9.69 W/m ²
	Power load density	3.23 W/m ²
	Occupancy schedule	On - 8 AM to 5 PM
	Lighting schedule	Office Lighting - 6 AM to 11 PM
	Power schedule	Office Lighting - 6 AM to 11 PM
	Outdoor air per person	0.00 L/s
	Outdoor air per area	0.00 L/s
	Outdoor air method	by People and by Area
Zone 3 (Includes Space 1,2&3)	Service Type	VAV – Dual Duct
	Cooling Information	Cooling set point – 23.32°C Cooling air temperature – 12.22°C
	Heating Information	Heating set point – 21.11°C Heating air temperature – 32.22°C
	Outdoor Air Information	From Space Type

4.4 Verification of the data exported from Revit

The intent of this section is to verify the exported data from Revit to gbXML or IFC file format using Model viewers. This verification process mainly concentrates on to know whether the modelled data is exported successfully or not, to evaluate data quality and to rectify the geometrical inconsistencies caused by modelling.

4.4.1 Export to gbXML

a) Export Categories:

The export process of modelled information from Revit to gbXML is based on two different export categories. They are as follows,

1. Based on Rooms (refer in Figure 41)
2. Based on Spaces (refer in Figure 42)

When the export process is carried out by using Rooms as an export category, then Revit only exports the information regarding geometry, construction details and specifications of rooms (area & volume). It won't include the information regarding spaces, space types and zones, which are mentioned in the model. But the export process based on the spaces as an export category, all the information (geometry, construction, space, space type and zone) included in the BIM model will transfer to the gbXML file. The information regarding the modelled data is summarized in Table 7 and Table 8. Thus, for this demonstration purpose, spaces are considered as an export category and the export process to gbXML is continued. Figure 41 and Figure 42 represent the difference between the two export categories.

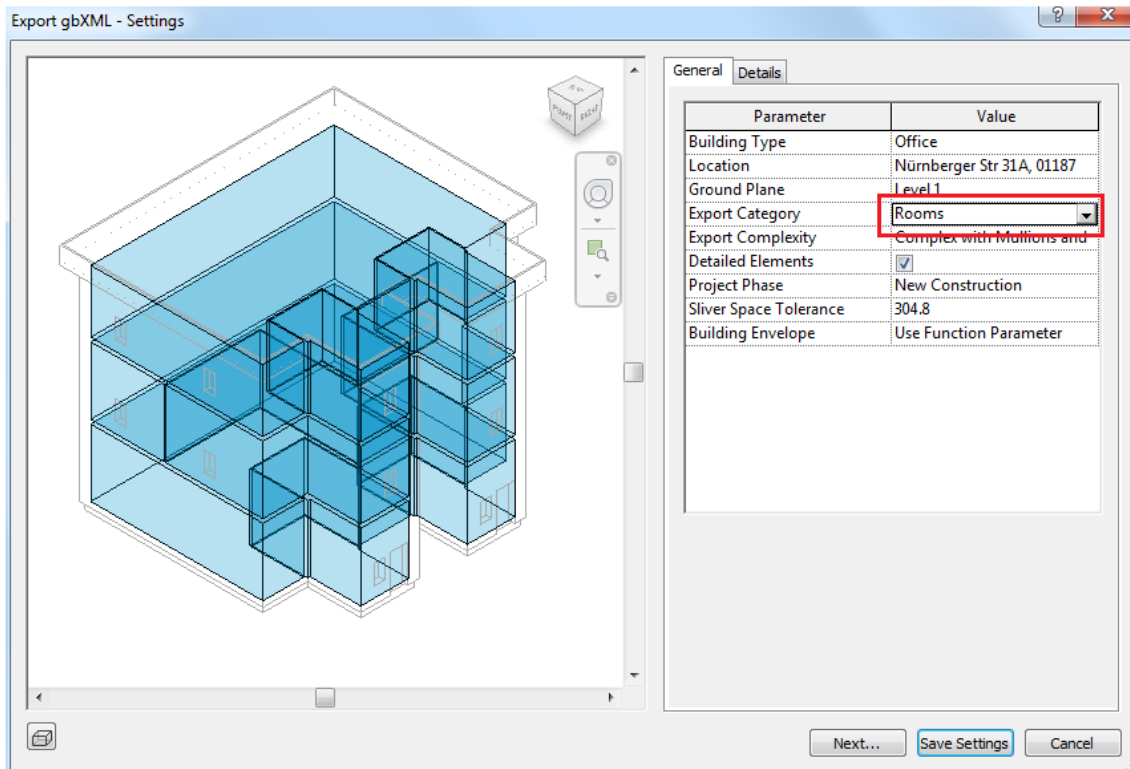


Figure 41: Data Export from Revit to gbXML – Based on Rooms

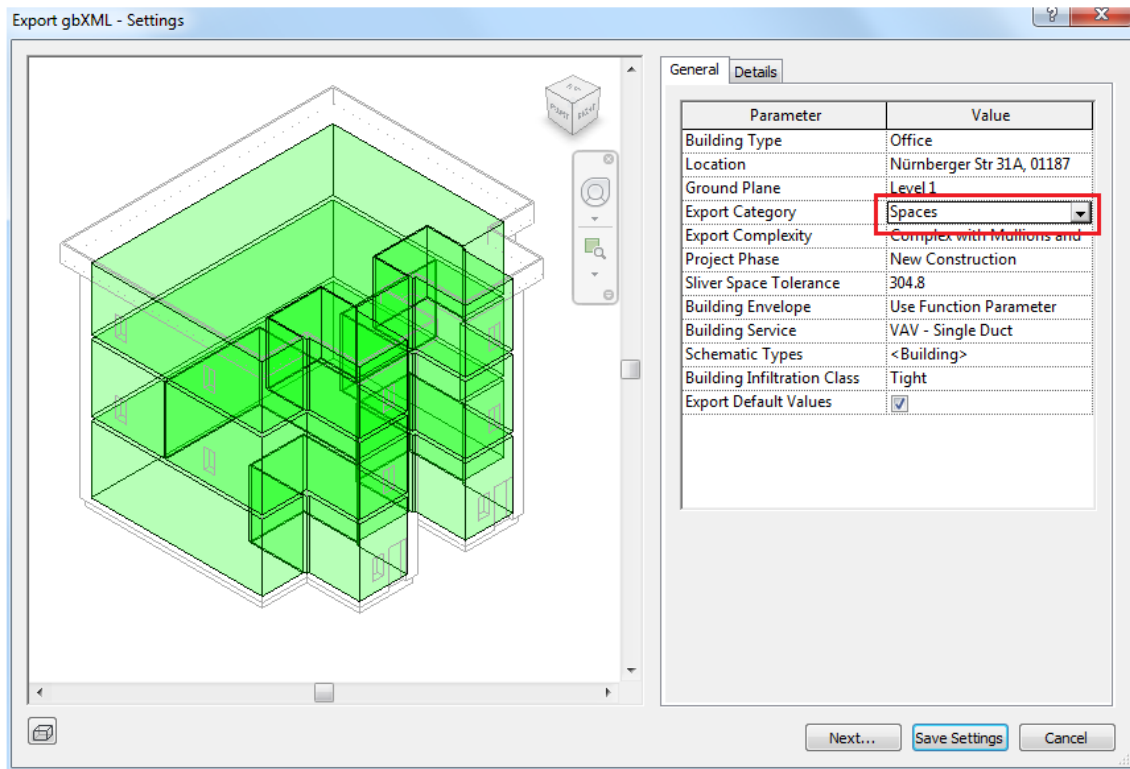


Figure 42: Data Export from Revit to gbXML – Based on Spaces

b) Model Viewer:

Aragoga gbXML Viewer 12.33 (From Ladybug Tools) is used as a model viewer in this demonstration. This Model viewer is recommended by the Green Building XML organization. The Model Viewer tool works based on the virtual environment and represents the 3-dimensional elements of the building in terms of 2-dimensional surfaces at the centre of the element. Similarly, the tool represents doors and windows as openings in the wall. Figure 43 represents how the BIM model is viewed in Aragoga gbXML Model Viewer. The gbXML file has been exported from Revit 2019. The viewer successfully represents the geometry of building and construction type (either exterior or interior and name), but it won't represent the thermal properties of the material, material layer details, energy settings, space types of building, etc. So, this tool is only used to verify and modify the modelling errors in the Revit model in terms of geometry. The information other than geometry (schedules, material, layers, location etc.) are verified by going through the gbXML file and the same mentioned in Appendix 7.1.

Aragoga gbXML Viewer is equipped with two menu columns, those are Left menu and Right menu. The left menu represents the importing options and specifications of the imported file, such as settings, reports, issues, numbers, etc. The Right menu deals with the representation of the surfaces, construction details and bounded space details.

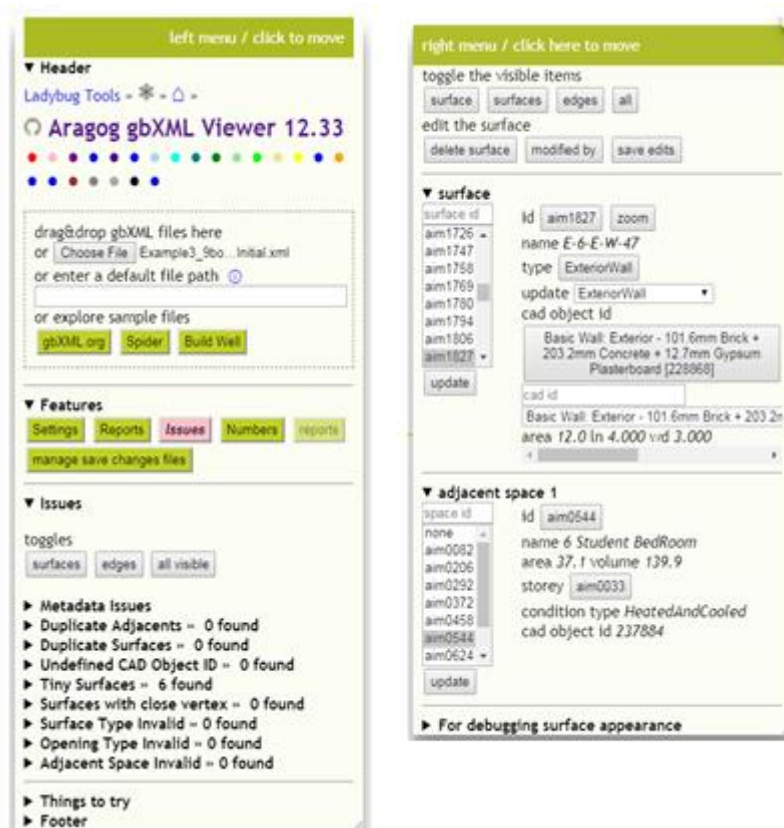
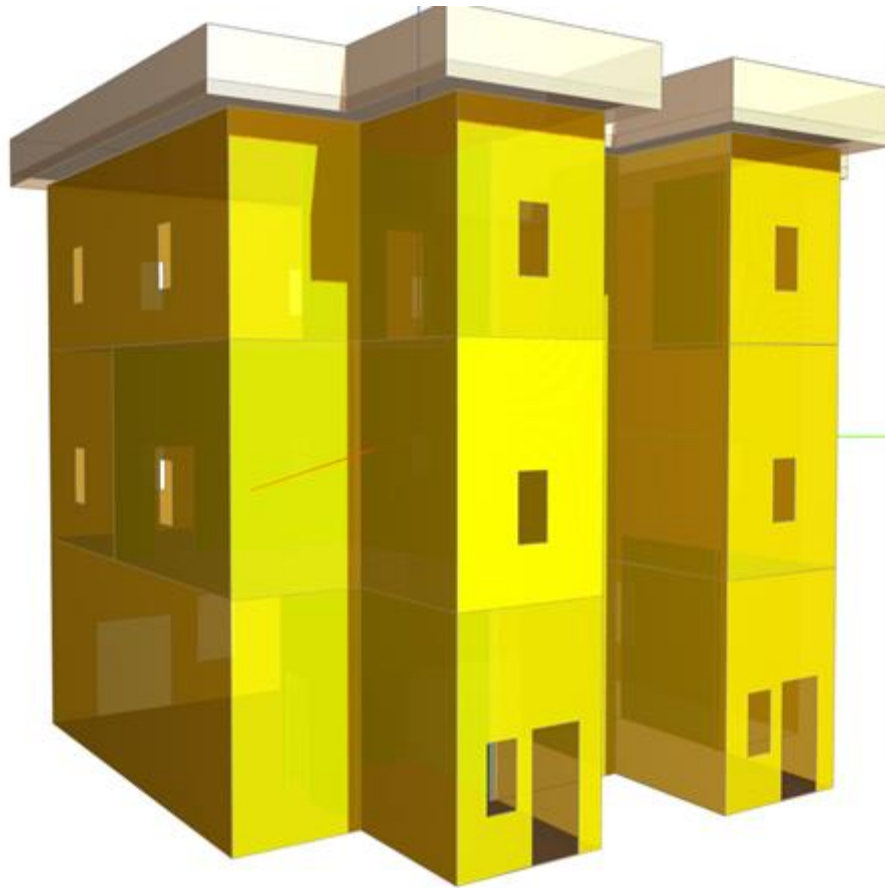


Figure 43: Representation of Office Building in Aragog Model Viewer

By investigating the gbXML file (Which contains the BIM data modelled in Revit) using the model viewer, there were some issues which were detected. They are as follows.

1. Creation of tiny surfaces for internal and external walls, exactly at the connection between walls (refer in Figure 46, Figure 47 and Figure 48).
2. Lack of connection between roof and external walls (refer in Figure 49).
3. The elevation difference between the Revit model and exported data (Figure 51).

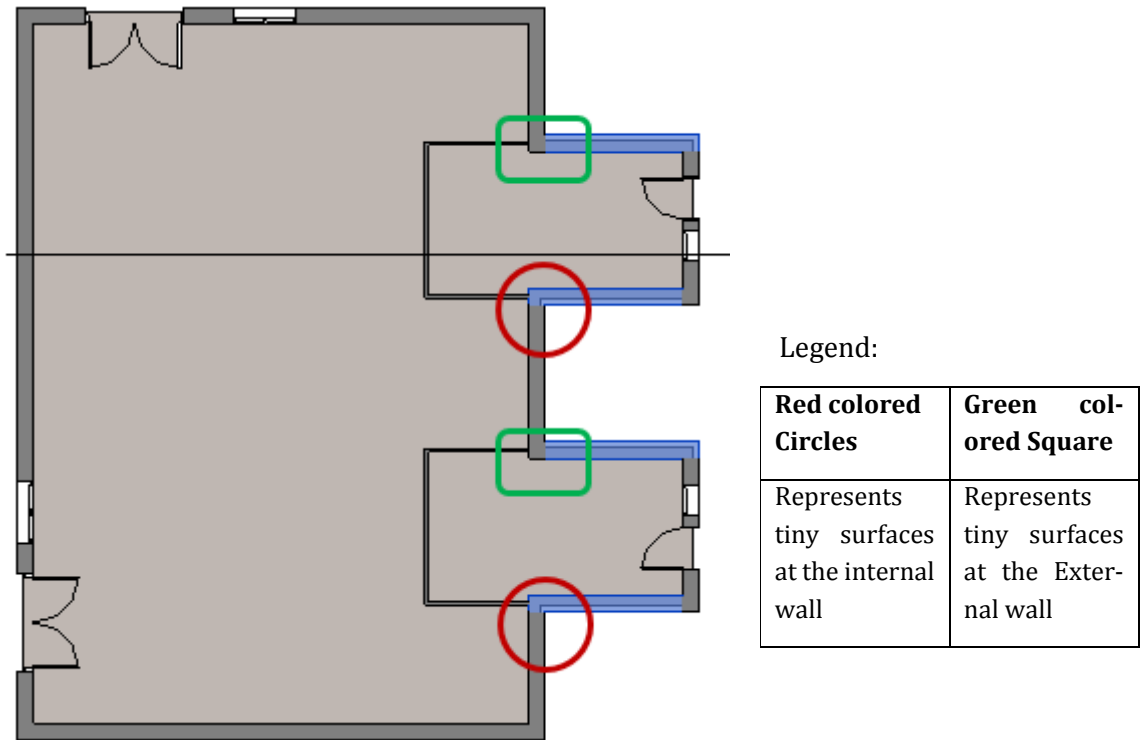


Figure 44: Connection location where Tiny surfaces are creating

The issues represented in Figure 46, Figure 47 and Figure 48 are the generations of tiny surfaces in the walls at some specific connections. These connection locations are marked in the above Figure 44. The red coloured circles represent the connections which create a tiny surface in the internal wall. Figure 46 represents this tiny surface in the model with the width of this surface is equal to 0.159 meter which is equal to the half of the thickness of the external wall (thick 317.5 mm). The functional type for the tiny surface is represented as internal but the external wall construction details are assigned to this surface (marked with a red coloured circle in Figure 46). There were some reasons for this error, they are

1. The viewer tool couldn't recognize the difference between external and internal walls because of the misinterpretation in identifying vector definitions for the position of elements in Revit.
2. Because of the virtual environment concept, that means the model viewer tool will create a 2D - surface exactly at the centre of both internal and external wall. The internal wall at this joint is defined till the internal surface of the external wall in the Revit model. So, the distance (which is equal to half of the external wall thickness 0.159 meters) between centre of the external wall and the ending point of the internal wall is

not defined according to the virtual environment and this viewer tool is assigning internal functional type to this tiny surface (in between internal wall and centre of external wall) because it is inside the external wall and assigning external wall construction details because this surface is part of the external wall.

Actually, the Revit modelling concept follows the centre to centre approach. But, the diagrammatic representation of connections in Revit shows that the wall is connected to the face of the other wall (refer in Figure 44). It is the same case with all connections between walls in the model, but some two connections (marked with red coloured circles) only facing the problem with tiny surfaces, which is shown in Figure 46. It means the virtual environment for the Viewer tool places 2D surface at the centerline of the wall and it is eliminating part of the surface extended out from the connection between walls (which is not bounded with any space or room). But here in this specific problematic connection, the extended part of the external wall from the connection is presented inside the building and it is a part to creating an enclosed loop to define room or space (and have a relationship with space).

Similarly, the tiny surfaces are created in external walls at the connections marked with green coloured square in Figure 44. These tiny surfaces are defined as shading elements in the model viewer tool, which is represented in Figure 47 and Figure 48. The reason for the tiny surface here in this connection is also because of the virtual environment concept which is already explained above, but here the extended part of the wall is treated as a shading element. Shading elements in IES are the room bounding elements defined in the Revit model and which are not a part to create a closed loop to define either room or space. So, here the wall element in this connection is treated as a shading element because it not bounded by any space or not a part of the closed loop.

The confusion in the representation of the functional type and construction type for an element will affect the energy analysis of the building. So, representation of the connection (marked with red coloured circles) is changing in such a way that the extended portion of an external wall will be defined as a shading device. This representation change is presented in Figure 45. This change will produce the tiny shading elements inside the building at all four connections.

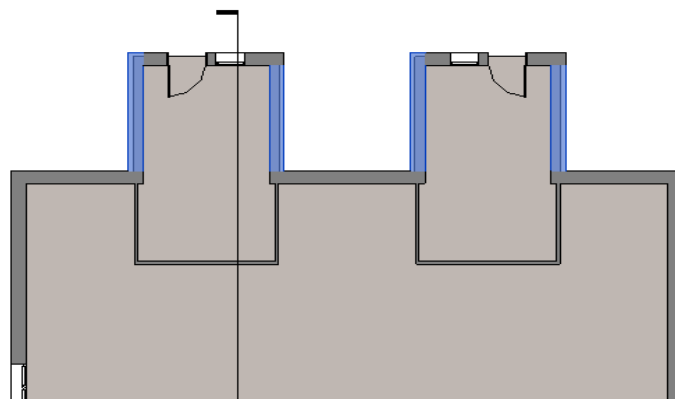
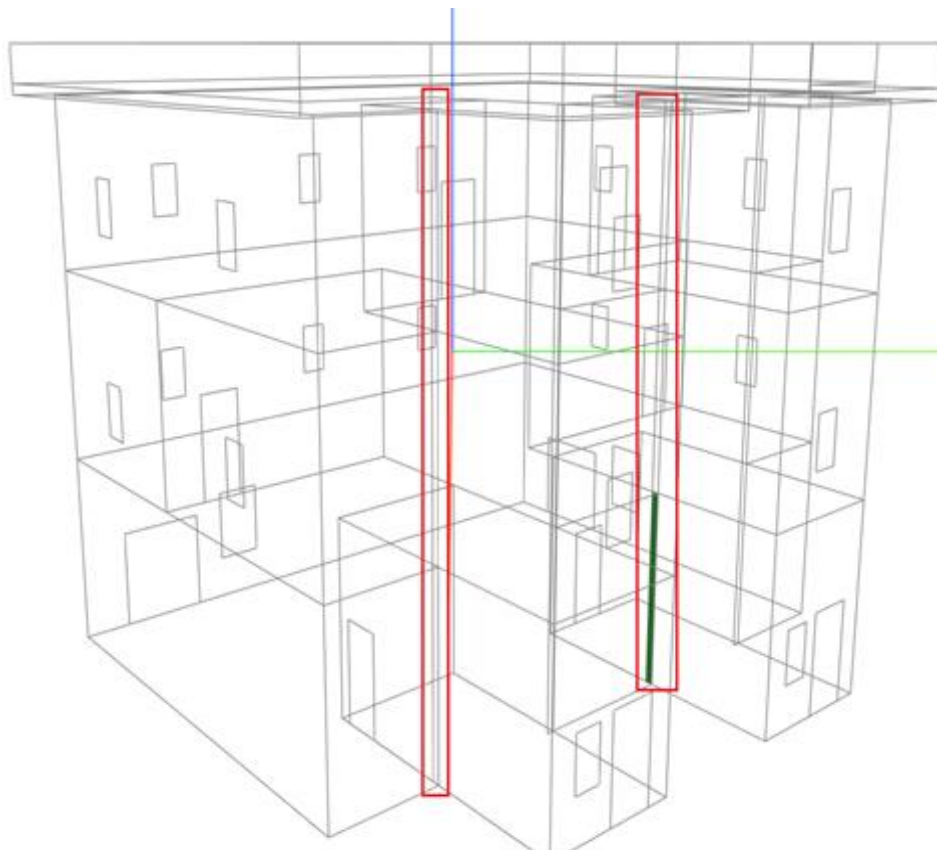


Figure 45: Change in the connection representation



Left menu

▼ Issues

toggles

surfaces edges all visible

► Metadata Issues

► Duplicate Adjacents » 0 found

► Duplicate Surfaces » 0 found

► Undefined CAD Object ID » 0 found

▼ Tiny Surfaces » 6 found

Surfaces that are smaller than a specified area,

Test size 0.68

surface id

aim1249

aim1307

aim1609

aim2062

aim2166

aim2444

zoom

surfaceType: InteriorWall

constructionIdRef: aim1023

id: aim1307

AdjacentSpaceId: [object Object],[object Object]

RectangularGeometry: [object Object]

PlanarGeometry: [object Object]

CADObjectid: Basic Wall: Exterior - 101.6mm Brick + 203.2mm Concrete + 12.7mm Gypsum Plasterboard [230012]

Name: N-1-3-I-W-15

height: 4

width: 0.159

area: 0.635

► Surfaces with close vertex » 0 found

► Surface Type Invalid » 0 found

► Opening Type Invalid » 0 found

► Adjacent Space Invalid » 0 found

right menu / click here to move

toggle the visible items

surface surfaces edges all

edit the surface

delete surface modified by save edits

▼ surface

surface id

aim1203

aim1215

aim1227

aim1249

aim1261

aim1273

aim1295

aim1307

update

id aim1307 zoom

name **N-1-3-I-W-15**

type **InteriorWall**

update InteriorWall

cad object id

Basic Wall: Exterior - 101.6mm Brick + 203.2mm Concrete + 12.7mm Gypsum Plasterboard [230012]

cad id

Basic Wall: Exterior - 101.6mm Brick + 203.2mm Concrete + 12.7mm Gypsum Plasterboard [230012]

area 0.6 ln 4.000 vrd 0.159

update

▼ adjacent space 1

space 1 id

none

aim0082

aim0206

aim0292

aim0372

update

id aim0082

name 1 Customer Lobby

area 113.8 volume 429.8

condition type HeatedAndCooled

storey aim0016

cad object id 233208

▼ adjacent space 2

space 2 id

none

aim0082

aim0206

aim0292

aim0372

update

id aim0292

name 3 Manager Room

area 16.8 volume 63.3

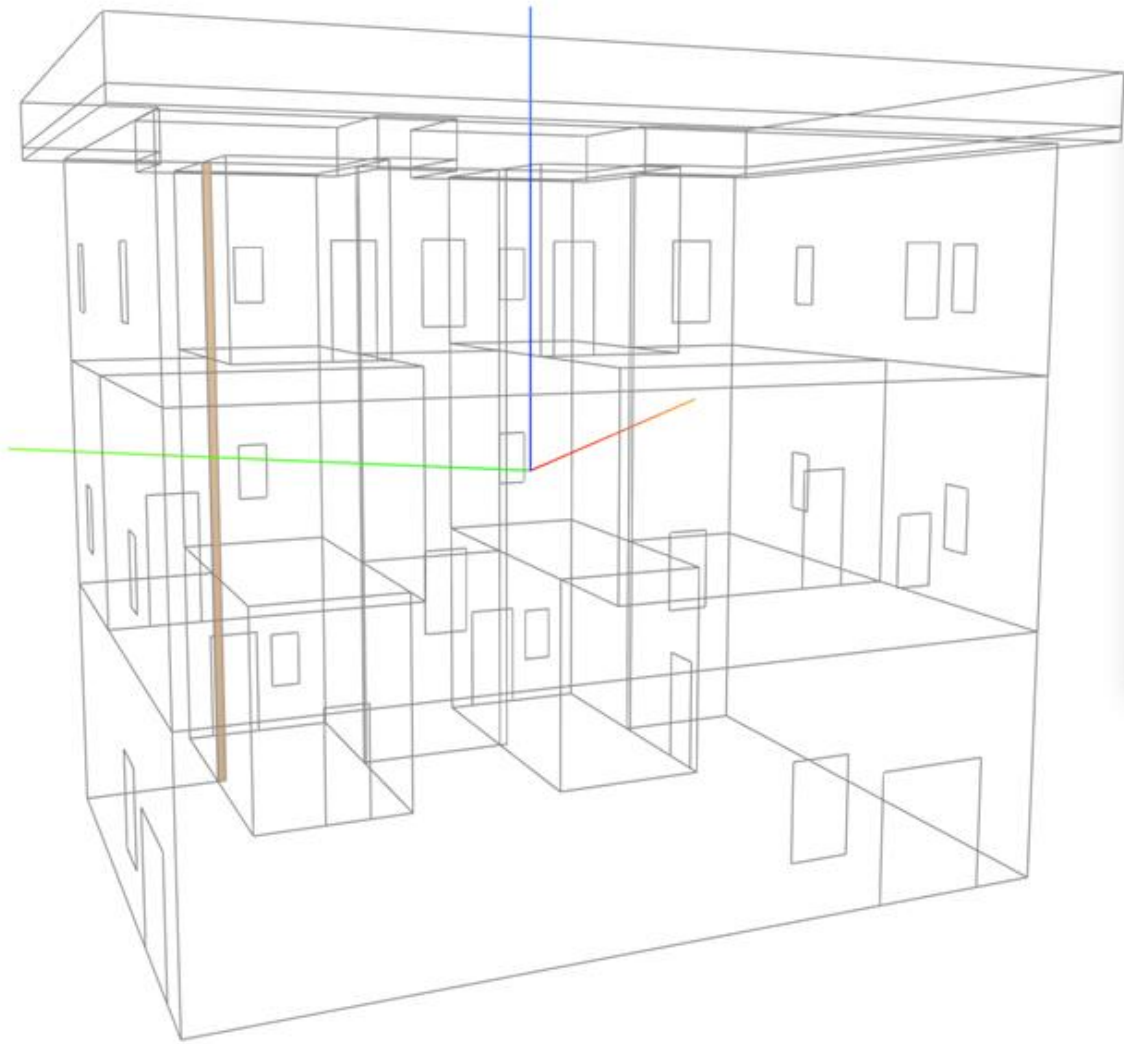
condition type HeatedAndCooled

storey aim0016

cad object id 233210

► For debugging surface appearance

Figure 46: Tiny Surface at the interior wall



right menu / click here to move

toggle the visible items

surface surfaces edges all

edit the surface

delete surface modified by save edits

▼ surface

surface id

aim2354 ▲

aim2364

aim2374

aim2384

aim2394

aim2404

aim2414

aim2424 ▼

update

id aim2424 zoom

name X-S-89

type Shade

update Shade

cad object id

Basic Wall: Exterior - 101.6mm Brick + 203.2mm Concrete + 12.7mm Gypsum Plasterboard [247923]

cad id

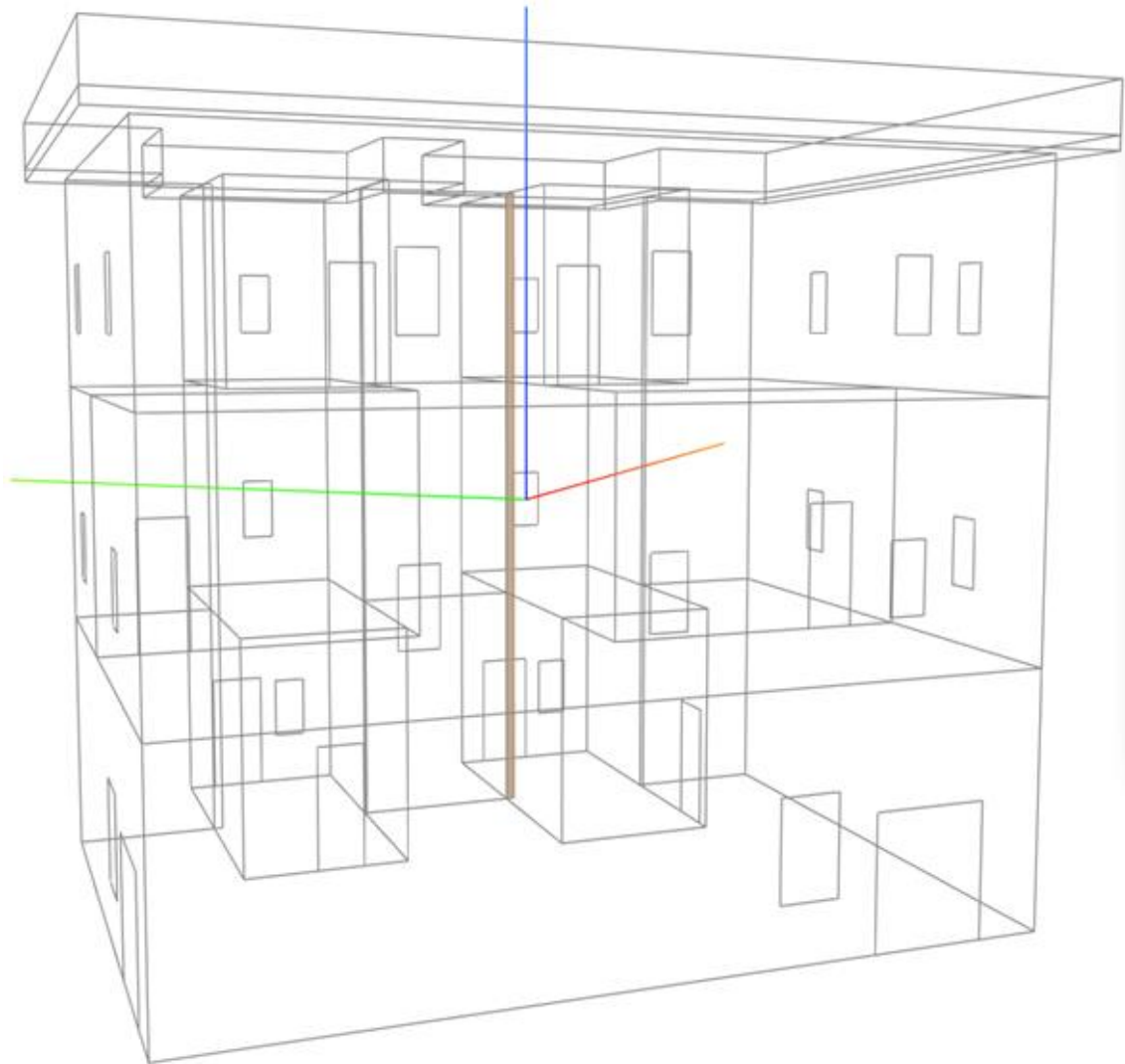
Basic Wall: Exterior - 101.6mm Brick + 203.2mm Concrete + 12.7mm Gypsum Plasterboard [247923]

area 1.8 ln 11.500 vol 0.159

no adjacent spaces

► For debugging surface appearance

Figure 47: Tiny Surface at the exterior wall 1



right menu / click here to move

toggle the visible items

surface surfaces edges all

edit the surface

delete surface modified by save edits

▼ surface

surface id

aim2364 ▲

aim2374

aim2384

aim2394

aim2404

aim2414

aim2424

aim2434 ▼

update

id aim2434 zoom

name X-S-90

type Shade

update Shade

cad object id

Basic Wall: Exterior - 101.6mm Brick + 203.2mm Concrete + 12.7mm Gypsum Plasterboard [248188]

cad id

Basic Wall: Exterior - 101.6mm Brick + 203.2mm Concrete + 12.7mm Gypsum Plasterboard [248188]

area 1.8 ln 11.500 wvd 0.159

no adjacent spaces

► For debugging surface appearance

Figure 48: Tiny Surface at the exterior wall 2

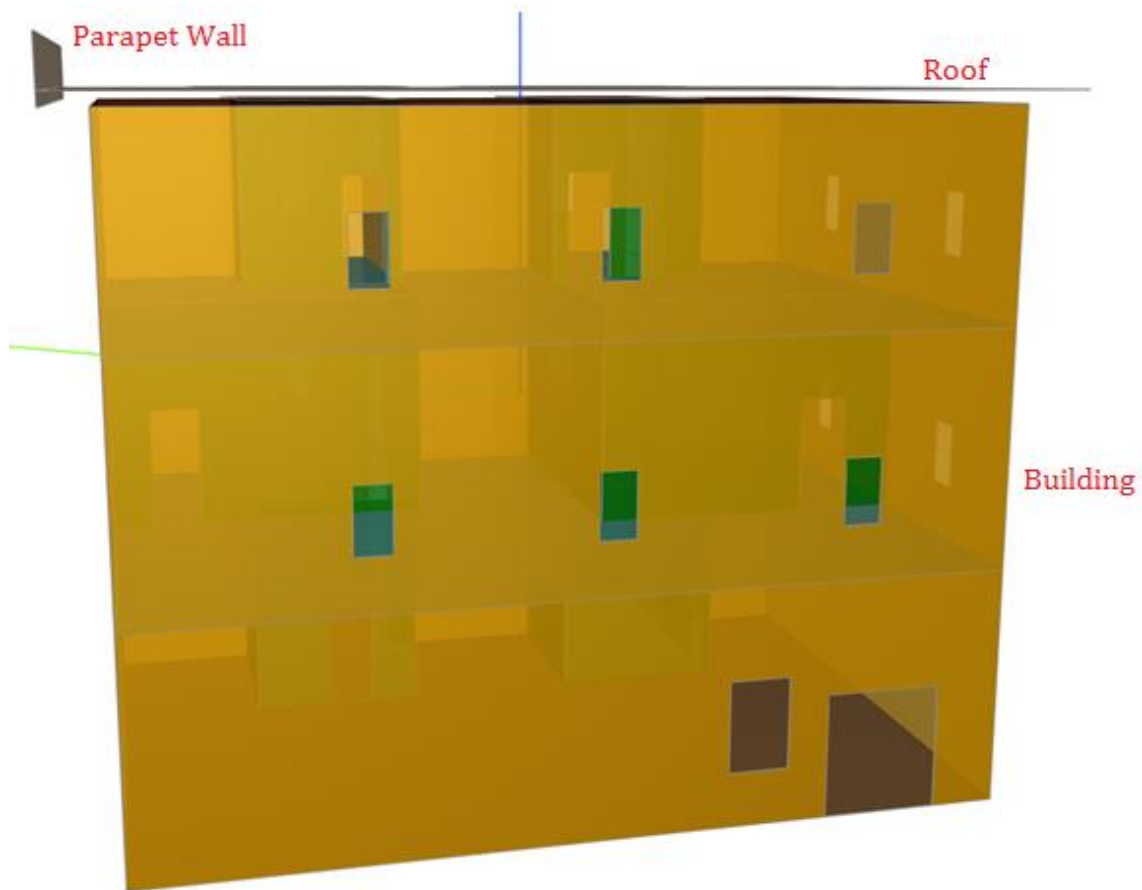


Figure 49: Lack of connection between Roof and External Wall

Another issue observed in the gbXML export process is the lack of connection between the roof and remaining building elements in the model. Some portion of the parapet wall is extended down from the roof level (from roof and parapet connection). These issues are clearly represented in Figure 49. The reason behind these Issues is because of the modelling representation in the Revit. Figure 50 is showing the sectional elevation of the building modelled in Revit. The external wall of the building is limited up to Level 4 (refer in Figure 50) and the parapet wall, Roof construction start from Level 4. It means the base of the Roof and Parapet wall exists at Level 4, but according to the virtual environment concept, the element is represented as the 2-D surface at its centre line. So, the Roof surface is created at the centre line and this resulted a gap between Roof and External wall with a width is equal to the half of the Roof thickness. Similarly, an extended part of the parapet wall from Roof surface to Level 4 (at down side of the roof) is generated in the Model Viewer tool, which is represented in Figure 49.

If the same gap is not checked and exported to IES, then the building analysis can't be performed accurately. So, the IES is adopted in such a way that the creation of surfaces for roof, slab or floor is exactly at the position of levels, which are defined in the BIM model (refer in section Checklist for data sharing between Revit and IES).

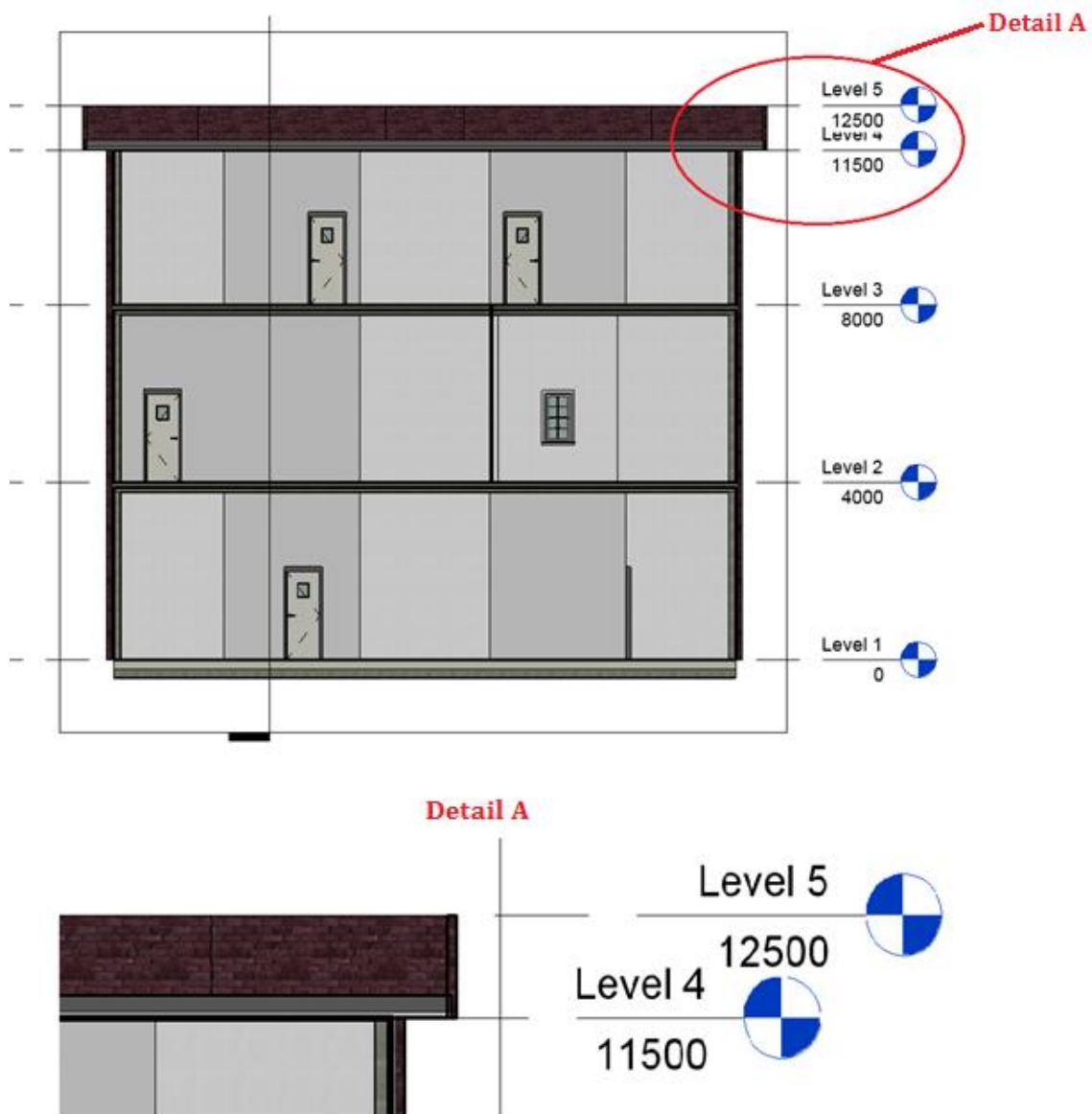
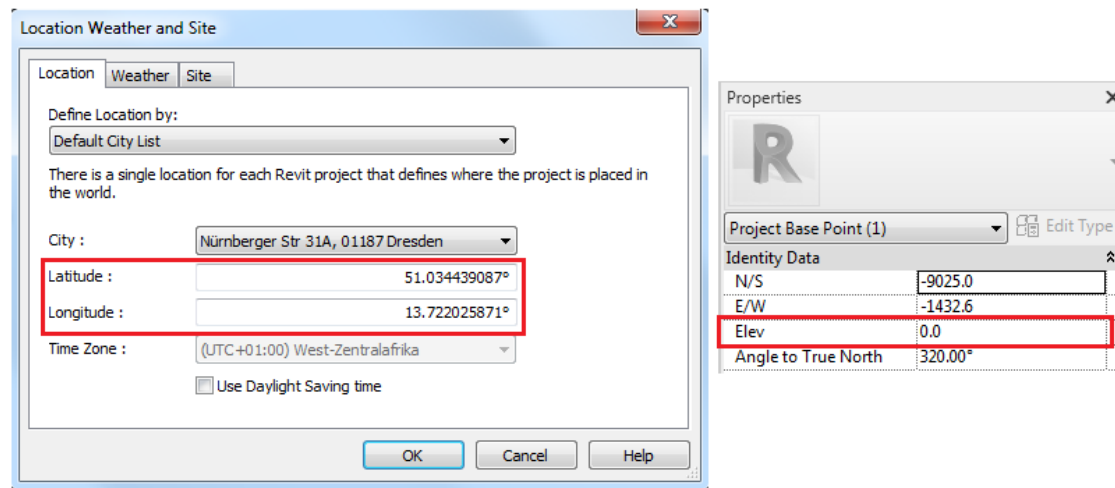


Figure 50: Sectional Elevation of the 3-Storey simple Building - Revit

Figure 51 represents another issue with the elevation of the building. The elevation of the building is wrongly exporting to the gbXML file. This is found by investigating the file. To know the reason for this miss match, different exercises are carried out by inputting different location details in Revit, but the results are same. It means incorrect elevation details are exporting to gbXML. The latitude and longitude of the building location are exporting correctly as represented in Figure 51.

For the energy simulation purpose, this incorrect elevation information is edited to correct ones and proceeded to the further process mentioned in the methodology (import process to IES<VE> simulation tool).



Elevation and Co-ordinates mentioned in Revit

```
<Location>
  <StationId IDType="WMO">162465_2006</StationId>
  <ZipcodeOrPostalCode>00000</ZipcodeOrPostalCode>
  <Longitude>13.72203</Longitude>
  <Latitude>51.03444</Latitude>
  <Elevation>230.124</Elevation>
  <CADModelAzimuth>0</CADModelAzimuth>
  <Name>Nürnberg Str 31A, 01187 Dresden</Name>
</Location>
```

Location details exported to gXML file

Figure 51: Difference in Site Elevation details between Revit & gbXML

4.4.2 Export to IFC

a) Export Specifications

Table 9 represents the export parameters mentioned in Revit for IFC export. Based on this parameters Revit will export the modelled data to IFC file. The export parameters are divided into different categories. They are as follows.

- General
- Additional content
- Property sets
- Level of detail
- Advanced

Each category has its own importance in the export process, but the General category plays a key role in the export process because it contains information regarding model view, space boundary, project location and construction phase details. For IFC export process, Design Transfer View (DTV) is used as Model View Definition (IFC version in Table 9). Generally, IFC 4 is equipped with two View Definitions, those are Design Transfer View (DTV) and Reference View (RV). Design Transfer View allows more entities (such as frame and lining details for doors and windows) for transfer between tools when compared to Reference View, and DTV supports the editing of the IFC file.

Table 9: Revit – IFC export specifications for a 3-storey simple office building

<i>Export Parameter</i>	Specification or Value
General	
<i>IFC version</i>	IFC4 Design Transfer View
<i>File type</i>	IFC
<i>Phase to export</i>	New Construction
<i>Space boundary</i>	2 nd level
<i>Project Origin</i>	Project base point
Additional content	
<i>Export 2D plan view elements</i>	Disabled
<i>Export linked files as separate IFCs</i>	Disabled
<i>Export only elements visible in view</i>	Disabled
Property Sets	
<i>Export Revit property sets</i>	Enabled
<i>Export IFC common property sets</i>	Enabled
<i>Export base quantities</i>	Disabled
<i>Export schedules as property sets</i>	Disabled
<i>Export user defined property sets</i>	Disabled
<i>Export parameter mapping table</i>	Disabled
Level of Detail	
<i>Level of detail for some element geometry</i>	High
Advanced	
<i>Export parts as building elements</i>	Disabled
<i>Allow use of mixed “Solid Model” representation</i>	Disabled
<i>Use active view when creating geometry</i>	Disabled
<i>Use family and type name for reference</i>	Disabled
<i>Use 2D room boundaries for room volume</i>	Disabled
<i>Include IFCSITE elevation in the site local placement origin</i>	Disabled
<i>Store the IFC GUID in an element parameter after export</i>	Disabled
<i>Export bounding box</i>	Disabled

Revit consists of default export layers, which consist of the data regarding the IFC classes with respect to the Revit element categories modelled in the file. The initial step in the export process is to load the export layers into Revit. Figure 52 represents the IFC export layer file in Revit 2019.

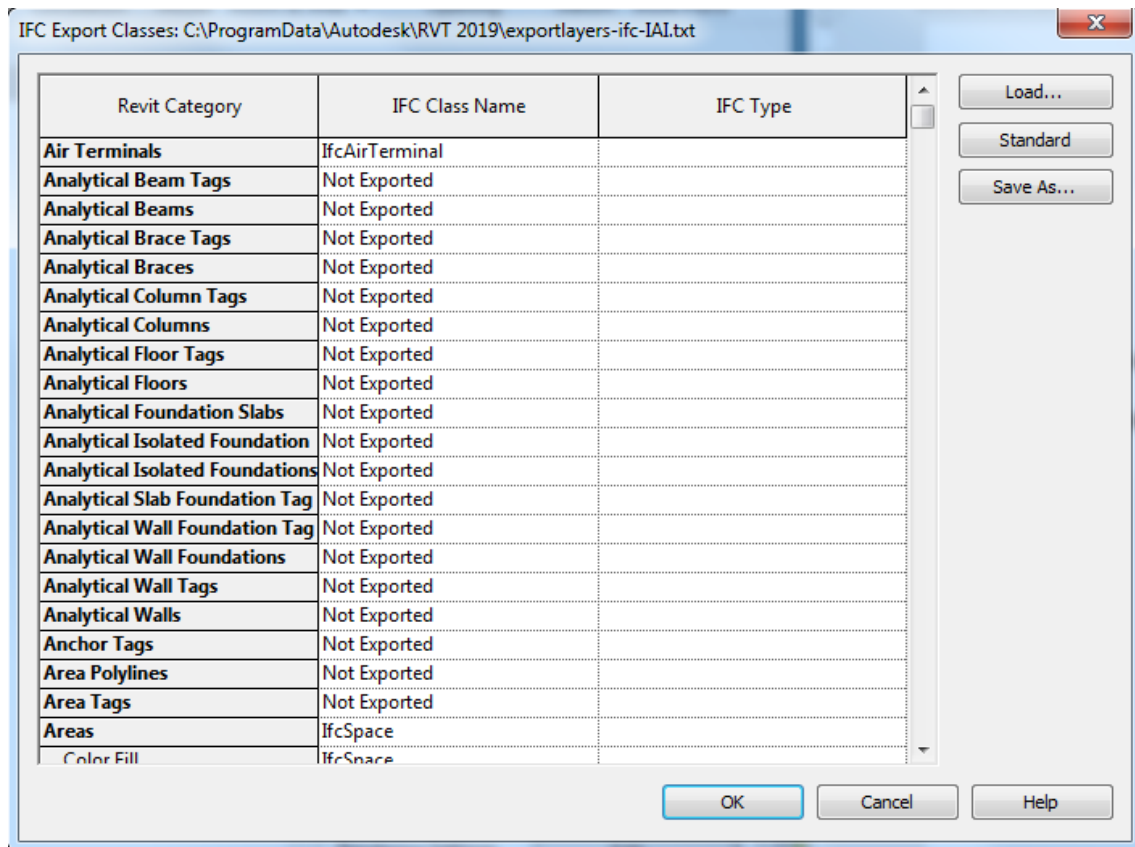


Figure 52: IFC export Layers mentioned in Revit 2019

After finishing the IFC-export set up the process, the modelled data has been exported to IFC (STEP – physical file format) file and the same file imported to the Model viewer tool to verify the data quality and modelling errors. The exported IFC file is attached in Appendix 7.2 for reference.

b) Model Viewer

The Solibri Model Viewer tool is used to import the IFC file for the purpose of data quality checking and verification of geometrical representations of the building components. The Solibri application has been developed based on the Industry Foundation Classes to represent the IFC STEP file in terms of the building model. This application has been authorized by buildingSMART (International home of OpenBIM) for model viewer purpose. The BIM model (3-Storey Simple Office Building) has been exported to IFC file from Revit and the same is imported to Solibri Model Viewer application, which is represented in Figure 53. Figure 54 represents the internal components of the building (by disabling the external walls), which is imported to the Solibri Model Viewer. The Solibri application's user interface consists of different model view options such as Model Tree, Info view, 3D view, etc. The Model Tree (presented in Figure 53) represents all components of the building and all are organized in different hierarchies. The Info view represents all the properties and data

assigned to these building components. 3-D view of the Solibri has been integrated with different viewer tools such as pan, zoom, move, etc.

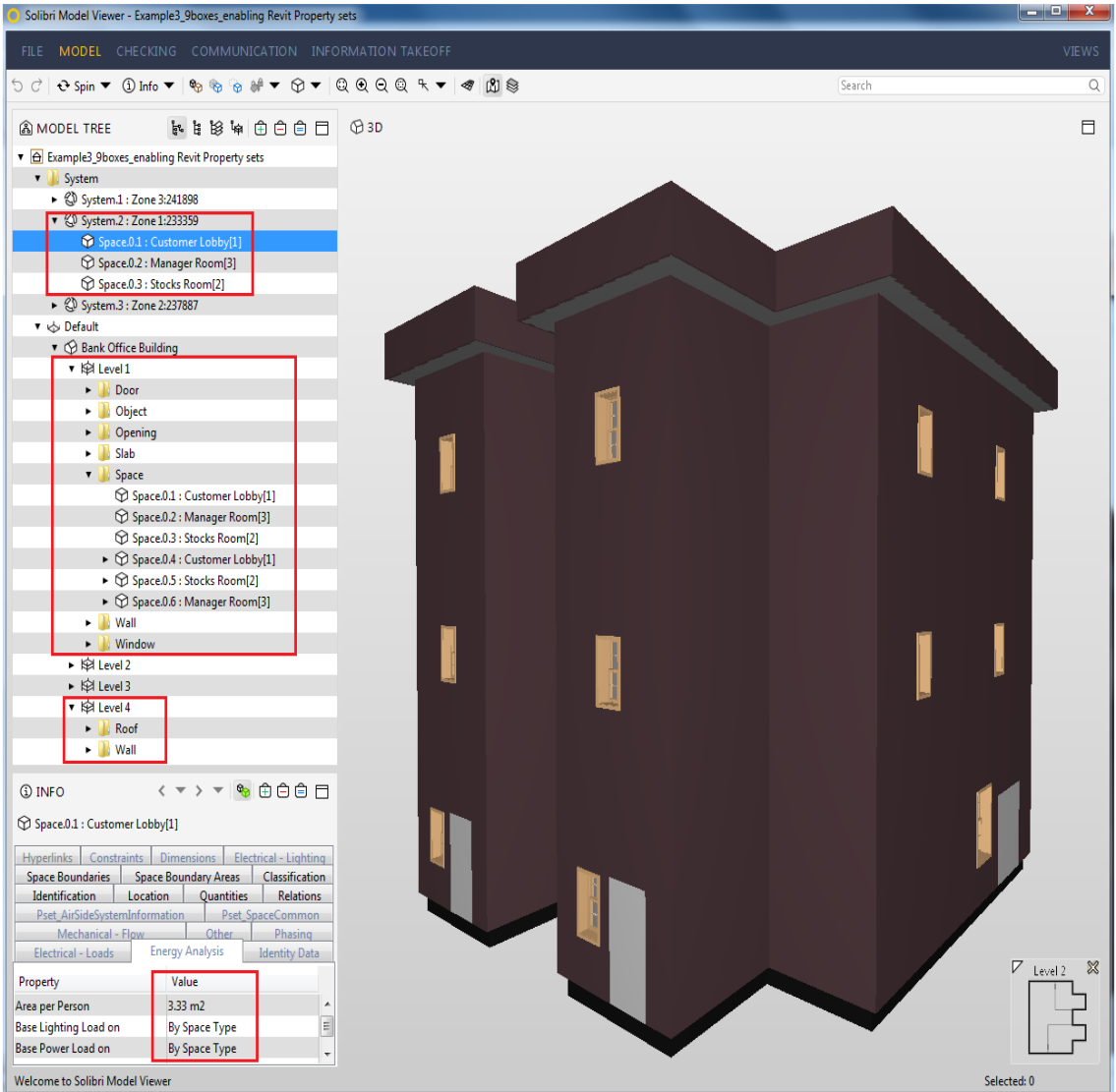


Figure 53: BIM model representation in Solibri Model Viewer

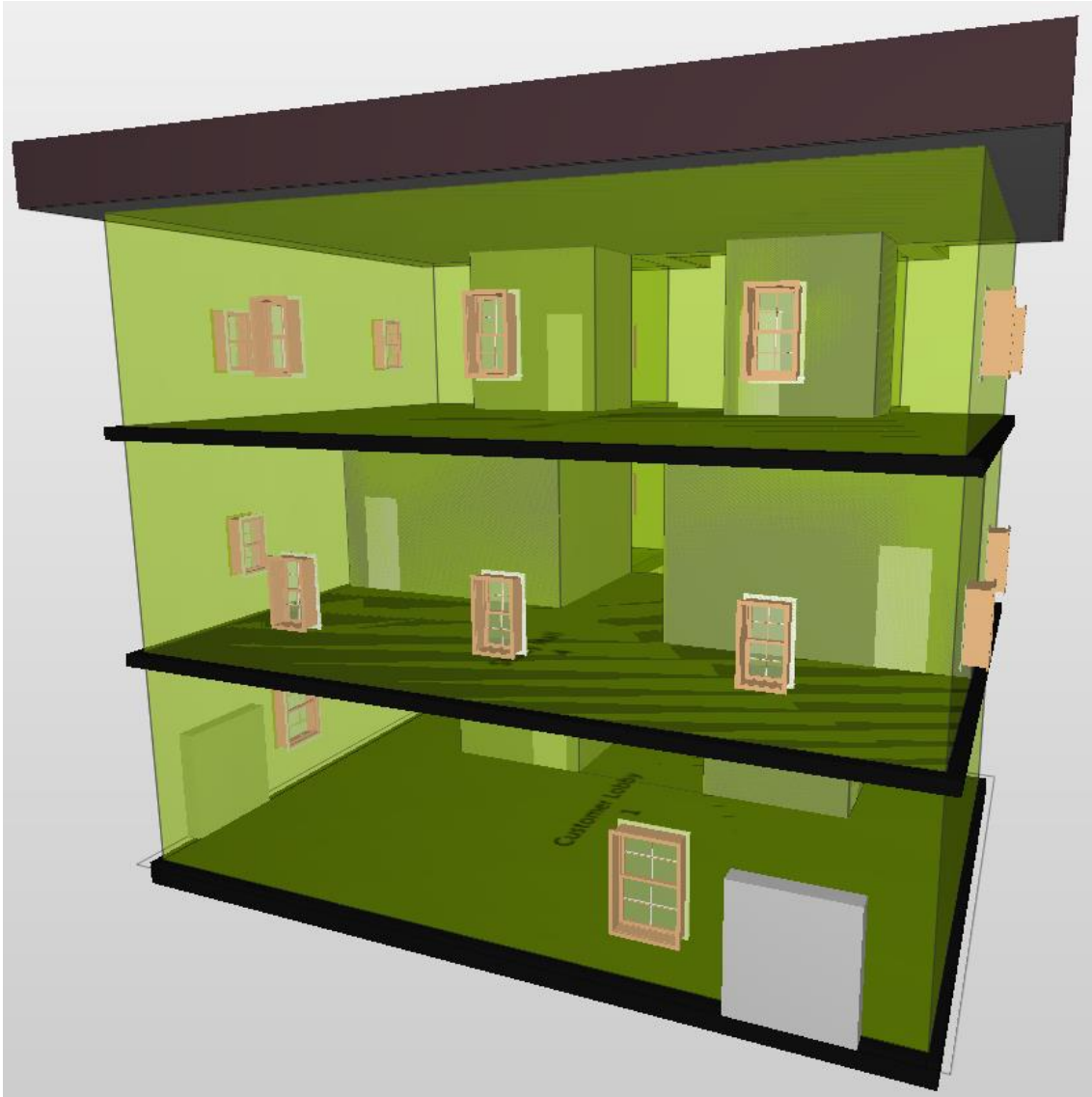


Figure 54: Internal geometry and spaces of the Building - Solibri Model Viewer

The table below clearly explains about the organization of the imported data in Solibri Model Viewer. As represented in Figure 53, all components of the building are organized in different hierarchies (refer Model Tree in Figure 53). The system hierarchy in the Model Tree view (in Solibri) defines the information regarding different Zones and the spaces related to these Zones. Similarly, the Default hierarchy in the Model Tree view (in Solibri) indicates the functional type for building and different storeys available in the building. Each Storey or Level of the building includes the information regarding all building components or Elements such as Wall, Space, Opening, Window, Slab, Door, Object. Each element is represented with a unique GUID, which is defined by the Identification parameter mentioned in Table 10. By investigating the Solibri Model Viewer's data structure it is observed that maximum information modelled in Revit has been successfully exported to IFC and same is imported to Solibri Model Viewer.

Table 10: Organization of Imported data in Solibri Model Viewer

<i>Building Components (Model Tree)</i>	Information regarding Building Components (Info view)
<i>System-1 (Zone 3)</i>	Identification, Relation, constraints, Dimensions, Energy Analysis, Identity Data, Phasing, Pset_AirSideSystemInformation, Pset_Zone, Other
<i>Default</i>	Identification, Location (coordinates), Relations, Identity Data, Other
<i>Bank Office Building</i>	Identification, Site (Default), Quantities (Gross Area), Relations, Pset_BuildingCommon (no-of storeys)
<i>Level</i>	Identification, Site, Building, Quantities, Relations, constraints (Elevation, Elevation Base), Identity Data, Other, Pset_BuildingStoreyCommon
<i>Elements in Level 1</i>	Wall, Window, Space, Slab, Opening, Door and Object (Lining & Frame details of Window)
<i>Space 1 – Customer Lobby (Space details)</i>	Identification, Location (Site, building, floor), Quantities, Relations, Space Boundaries (Door, slab, wall, window), Space Boundary Areas, Constraints, Dimensions (Area, Volume and Perimeter), Electrical Lighting, Electrical Loads, Energy Analysis, Mechanical Flow, Phasing, Pset_AirSideSystemInformation, Pset_SpaceCommon
<i>Space 4 – Customer Lobby (Room details)</i>	Identification, Location, Quantities, Relations, Constraints, Dimensions, Pset_AirSideSystemInformation, Pset_SpaceCommon, Phasing, “Energy Analysis”
<i>Door 1</i>	Identification, Location, Quantities, Profile, Relationship, Classification, Analytical Properties, Constraints, Construction, Dimensions, Identity Data, Ifc Dimension, IfcDoorPanelProperties, Materials and Finishes, Phasing, other, Pset-DoorCommon, Pset_EnvironmentalImpactIndicators
<i>Opening</i>	Identification, Location, Quantities, Profile, Relations
<i>Slab</i>	Identification, Location, Quantities, Material, Relations, Analytical Properties, Constraints, Construction, Dimensions, Identity Data, Materials & Finishes, Other, Phasing, Pset_EnvironmentalImpactIndicators, Pset_ReinforcementBarPitchOfSlab, Pset_SlabCommon, Structural
<i>Wall</i>	Identification, Location, Quantities, Material, Profile, Relations, Analytical Properties, Constraints, Construction, Dimensions, Identity Data, Materials & Finishes, Other, Phasing, Pset_EnvironmentalImpactIndicators, Pset_ReinforcementBarPitchOfWall, Pset_WallCommon, Structural

<i>Window</i>	Identification, Location, Quantities, Relations, Analytical Properties, Constraints, Construction, Dimensions, Identity Data, Ifc Dimensions, Materials & Finishes, Other, Phasing, Pset_EnvironmentalImpactIndicators, Pset_WindowCommon
<i>Object (defining Window Frame details)</i>	Identification, Location, Quantities, Material, Profile, Relations, Constraints, Construction, Dimensions, Identity Data, Materials & Finishes, Other, Phasing, Pset_EnvironmentalImpactIndicators, Pset_BuildingElementProxyCommon

Apart from the successful data export and import process, there were small issues regarding the representation of space type, shading device, the definition of room and orientation of the building in the Solibri Model Viewer. As mentioned in Section 3.2 of this document, IFC schema treats the space type also as a building object (like opening) but this is not represented in the components list mentioned at “Level 1” of the “Default” hierarchy in Solibri (refer in Figure 53 – marked with red coloured box). The space type of a particular space is defined as a property which is mentioned under the Energy Analysis option (refer in Figure 55).

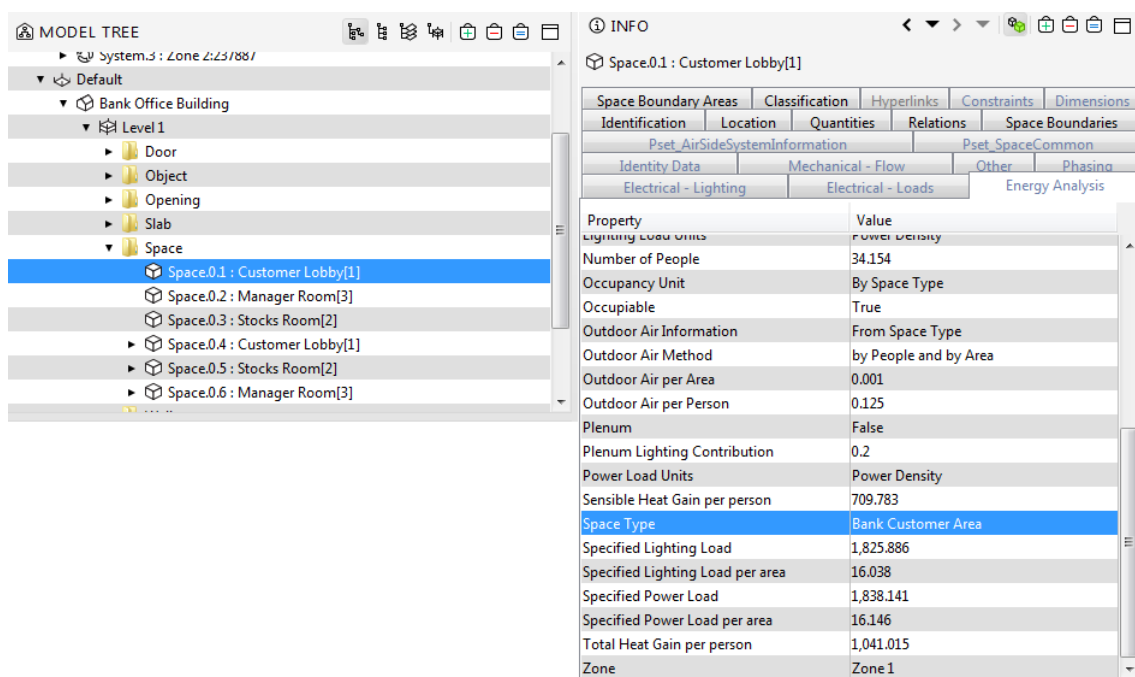


Figure 55: Relation between Space & Space Type - Solibri Model Viewer

The parapet wall and the roof extension (roof offset) modelled in Level 4 of the building (in Revit) needs to be treated as a shading device for energy analysis purposes. However, these elements are represented as wall element (for parapet wall) and roof element (for an extended part of the roof) in Solibri Model Viewer (refer in Figure 53). In the Revit model, both room and space are defined for efficient data export process. IFC schema identifies both space and room as space element (*IfcSpace*) (refer in Figure 53). In the Revit model, there is no option for defining energy analysis parameters to the room but in the Solibri application, it is representing the Energy analysis parameters for the room. Figure 56

represents these energy analysis parameters, which are assigned to Room. Similarly, the orientation of the building is not represented in the Solibri Model Viewer.

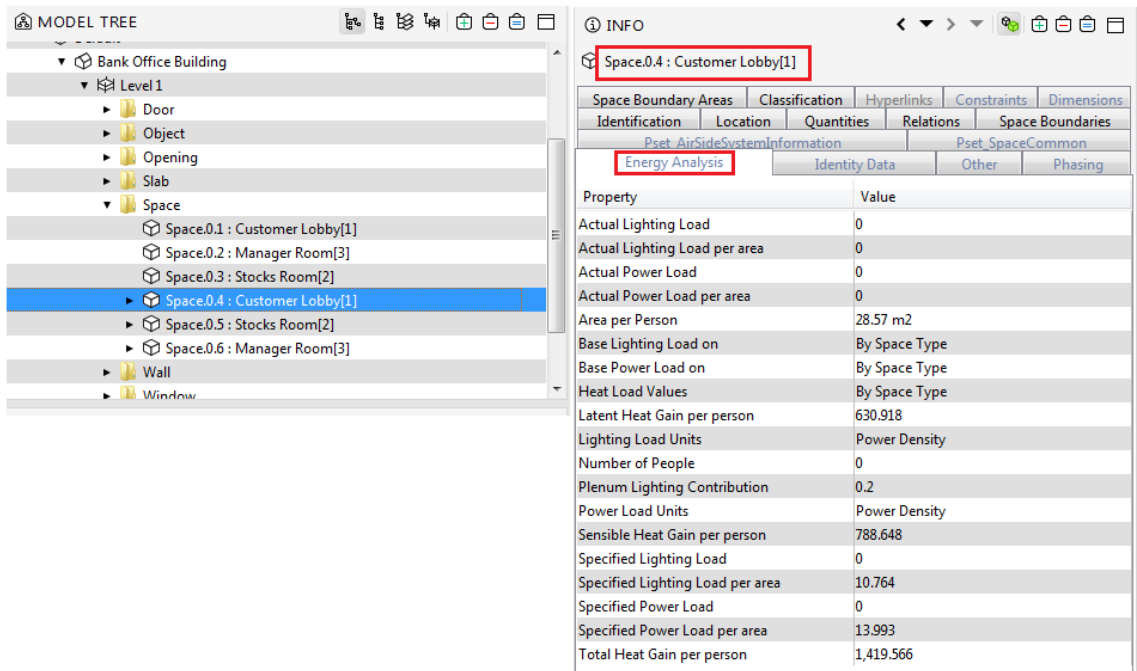


Figure 56: Energy Analysis data for ROOM - Solibri Model Viewer

4.5 Investigation of data imported to IES<VE> (BES model)

After verification of the quality of input data using Model Viewer tools, the data has been transferred to IES<VE> 2018. The intent of this section is to investigate the data import capabilities of IES from gbXML & IFC and to verify the quality of imported data. This verification process is carried out separately for each interoperability file format and the results were discussed.

4.5.1 Import from gbXML

In this import process, modelled data (BIM model) exported to the gbXML file format and the same has been imported to IES application to perform an energy analysis of the building.

a) Import Statistics

The IES application generates a small report after every successful import of the BIM model and explains all the import statistics. Appendix 7.3 represents the IES<VE> import statistics file, which has been developed during the process of data import from gbXML to IES. Import statistics report mainly concentrates on the representation of area and volume of each room or space, which are importing to IES. It also explains about surfaces, which define the room, and intersections between these surfaces. The report provides some statistics regarding number of surfaces and spaces of the BIM model, that imported successfully. The time taken for this import process is recorded.

The values regarding the area and the volume of each space in the IES model have been taken from the import statistics report and are listed in the table below. A comparison of room volumes between the BIM model and the BES model has been carried out. The difference in volume is presented in terms of percentage of volume difference with respect to the BIM model (refer to Table 11). From the table below, it can be observed that the volume difference is more than 10% for all the room types (other than Yoga room) in BES model and this may cause the design of oversized energy systems.

Table 11: Volume comparison between the BIM model and BES model – gbXML import

<i>Building Space</i>	Floor Area (m²)		Volume (m³)		% of volume change in IES w.r.t Revit
	Revit	IES	Revit	IES	
<i>Customer Lobby</i>	113.846	113.846	429.768	484.190	12.66%
<i>Stock Room</i>	16.774	16.774	63.323	73.905	16.71%
<i>Manager Room</i>	16.774	16.774	63.323	73.905	16.71%
<i>Study Hall</i>	81.884	81.884	309.110	347.507	12.42%
<i>Student Bed Room 1</i>	28.264	28.264	106.697	124.0	16.25%
<i>Student Bed Room 2</i>	37.006	37.066	139.923	160.493	14.7%
<i>Yoga Room</i>	119.921	119.921	419.722	444.443	5.89%
<i>Rest Room for Men</i>	13.844	13.844	48.455	54.167	11.79%
<i>Rest Room for Women</i>	13.895	13.895	48.634	54.390	11.84%

The increment of room volume in the BES model (when compared to the BIM model) is because of the volume calculation methodology. In Revit, area and volume of the room has been calculated based on the internal surfaces of the room bounding elements. It means for calculations Revit considers only the internal distance between walls, roof and floor. For example,

Room type = Customer Lobby (Existed in between Level 1 and Level 2 – refer in Figure 38 and Figure 50)

Room Height (Distance between Level 1 & 2 – refer in Figure 50) = 4.0 m

Internal room area from Revit (from Table 7) = 113.846 m²

Thickness of floor at Level 2 (from Table 7) = 225 mm = 0.225 m

Internal distance between ground floor to floor at Level 2 = 4 – 0.225 = 3.775 m

Volume of the room = area x clear height = 113.846 x 3.775 = 429.769 m³ (refer to Table 11)

IES imports co-ordinates related to both the centre line of the element and internal surface of the element, which is shown in Figure 58. The green colour line represents Local shadings, the blue colour line represents the centre line of the element and pink colour line represents the internal surface of the element in IES (refer in Figure 58). Table 11 shows that

the values for areas in both Revit model and IES model are equal, it means IES also uses the internal surface of the element (it means the internal distance between elements) for area calculations. But for volume calculations, IES uses the centerline method (centre to centre distance). It calculates the area between centre to centre of walls and multiplies this area with the height difference between levels for volume calculations. For example,

Room type = Customer Lobby (Existed in between Level 1 and Level 2 – refer in Figure 38 and Figure 50)

Room Height (Distance between Level 1 & 2 – refer in Figure 50) = 4.0 m

The area between centre to centre of walls (from Table 13) = 121.048 m²

Volume of the room = area x clear height = 121.048 x 4 = 484.192 m³ (refer to Table 11)

From this calculation, it has been observed that gbXML creates a surface exactly at levels location (mentioned in Revit) for the purpose of floor, slab, and roof.

b) Model Geometry & Orientation

The geometry, location and orientation of the BES model can be observed in Figure 58 and Figure 57. The location and rooms (or spaces) of the building has been successfully imported to the IES application and these details are marked with red coloured box and green coloured box respectively in Figure 58. Based on this location details, weather data can be acquired automatically in the IES application. The orientation of the building is also imported successfully, which can be observed by comparing Figure 36: 3-Storey Simple Office Building - Revit model (BIM Model) with Figure 57: BES model representation – Model import from gbXML.

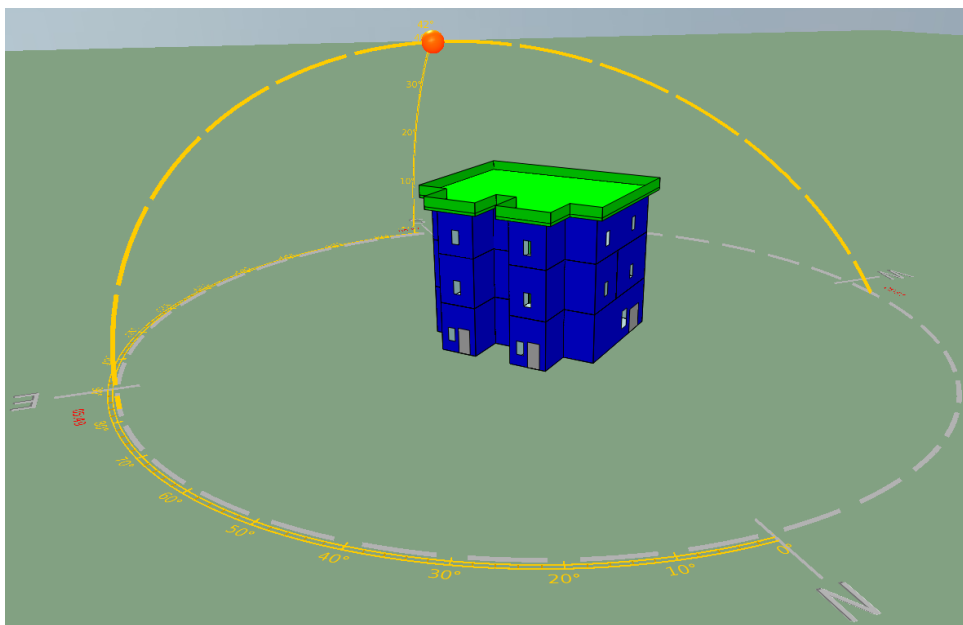


Figure 57: BES model representation – Model import from gbXML

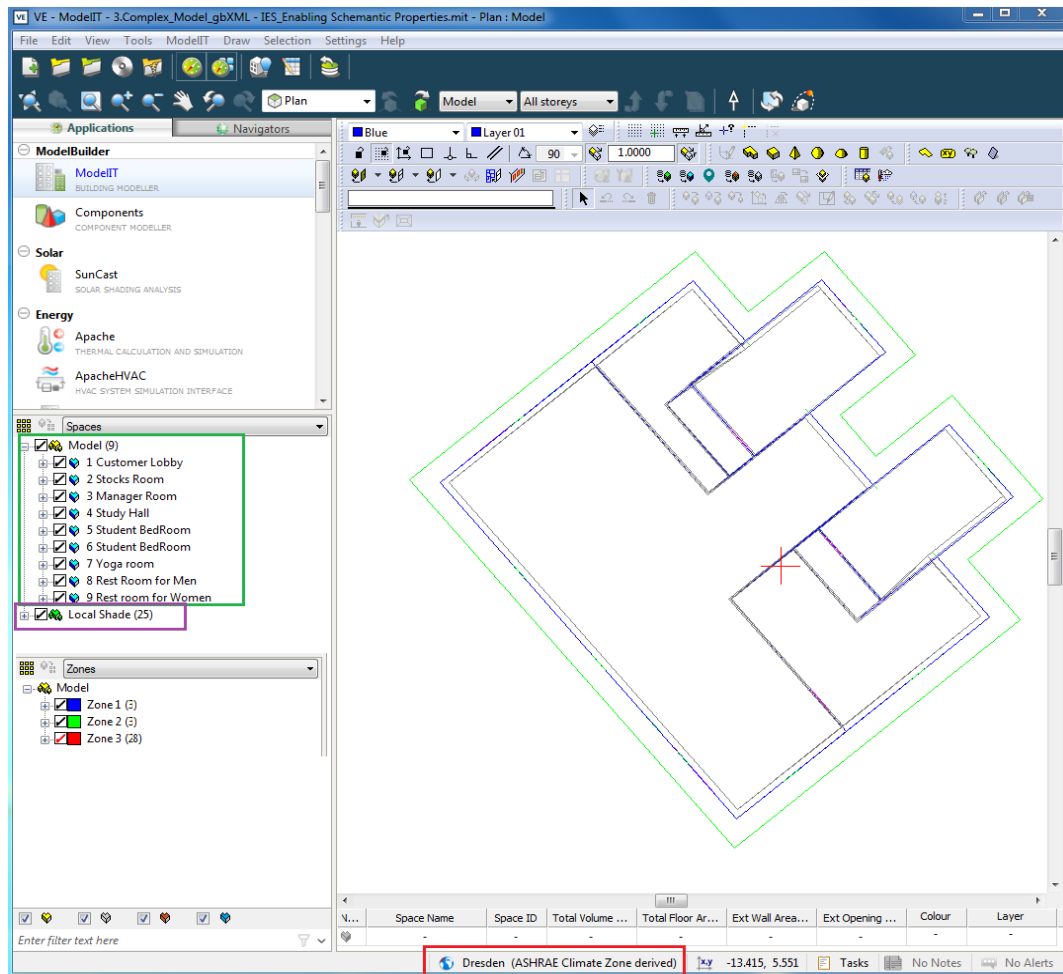


Figure 58: IES interface (BES Model Plan view) – Model import from gbXML

The only issue with the BES model geometry is in terms of local shadings. Figure 59 clearly highlights the tiny surfaces (4 numbers in each level), which are created in each level of the model. The same issue had been developed in the model viewer and the reasons for this problem has been clearly explained in section 4.4.1. The IES application treats these as local shadings because there was no proper definition for these surfaces in the BIM model. Because of this reason, the number of local shadings is represented as 25 in Figure 57 (Marked with pink coloured box).

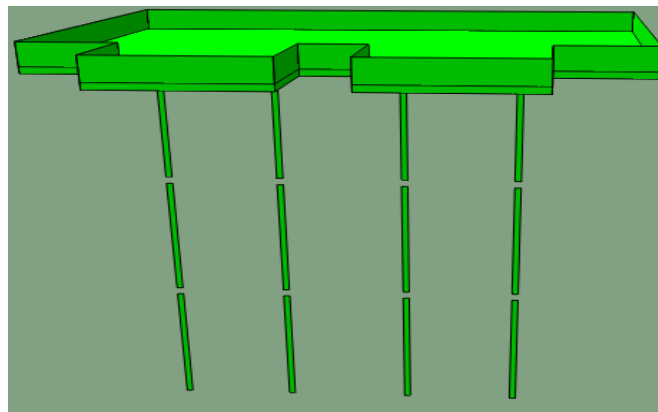


Figure 59: Local Shadings in the BES model – Model import from gbXML

In the BIM model, it is defined that each space belongs to a particular Zone (energy system) and these details are mentioned in Table 8. Figure 58 represents that, Zone 1 consists of 3 spaces, Zone 2 includes 3 spaces, but Zone 3 is having 28 spaces. In the IES model, it is considering all the local shading elements (including tiny surfaces) belong to the Zone 3. Generally, Zone is defined for the spaces and each space is bounded by bounding elements. So, these bounding elements belong to the particular Zone. Here in the case of local shadings, all these surfaces are not space bounding elements. So, the IES application automatically assigns Zone 3 to these local shading surfaces.

c) Construction details

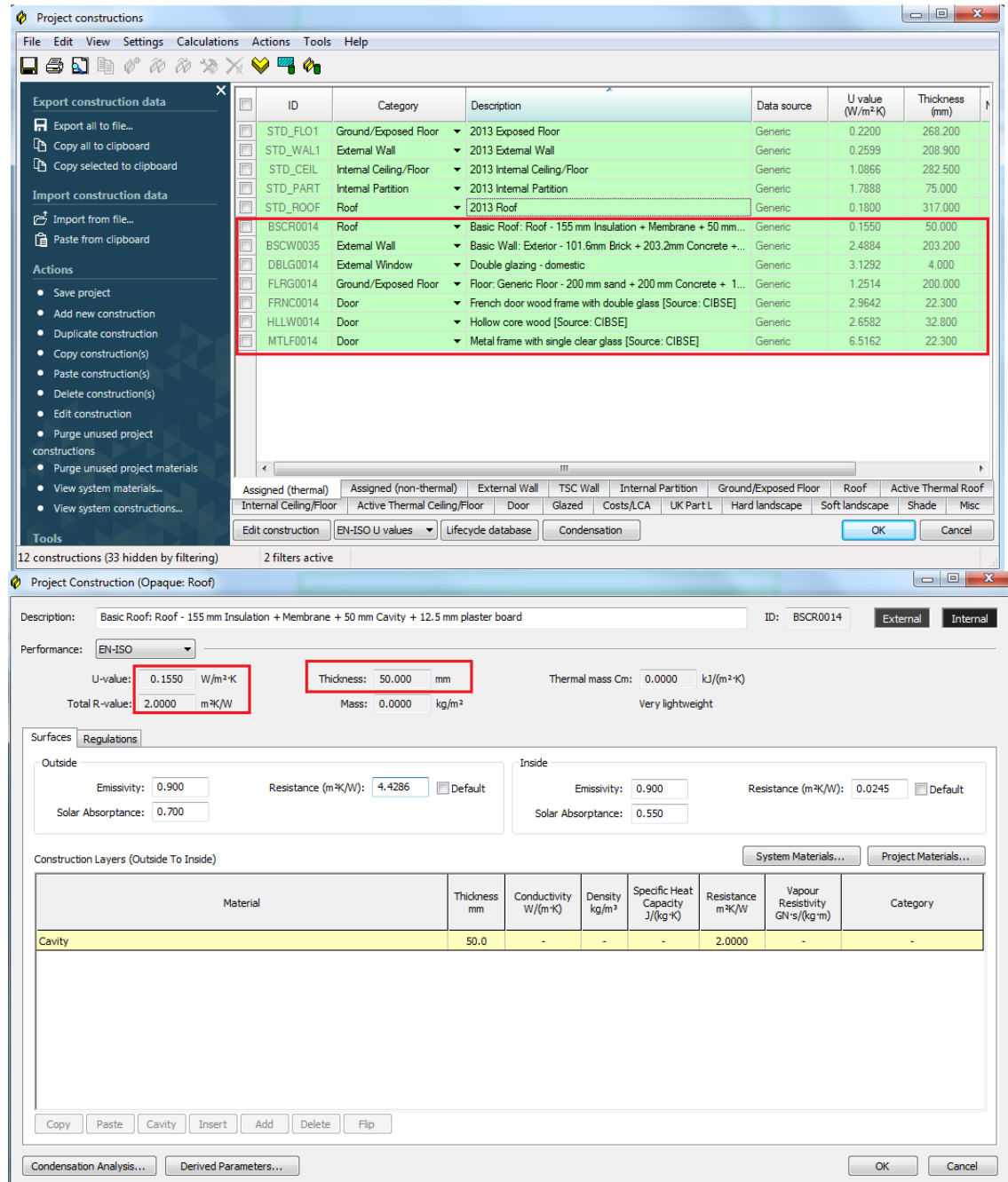


Figure 60: Construction details of BES model- Model import from gbXML

Figure 60 clearly represents all imported construction details, which are marked with a red coloured box. From Figure 60, it is observed that all construction type names and thermal transmittance value (u-value) for each construction type (other than door type – hollow core wood) has been successfully imported from gbXML to IES. But the thickness and layered structure of the construction type is not imported to IES. The construction type, thickness and material information mentioned in the BIM model are successfully exported to gbXML but the same is not being imported to IES from gbXML. It represents that the IES application is failing to successfully import these construction details from gbXML.

The thickness of the construction type represented in Figure 60 is equal to the thickness of the core layer of the same construction type defined in the BIM model. For example, Roof element is constructed with 155 mm thick Insulation as outer finish, 50 mm thick cavity as a core layer and 12.5 mm thick plasterboard as an inner finish (refer in Figure 60). The thermal transmittance (U-value) value for whole the roof type and the thermal resistance (R-value), thickness values for the cavity layer of the roof are imported to IES. It means IES does not recognize different layers in the same construction type.

d) Thermal Profile

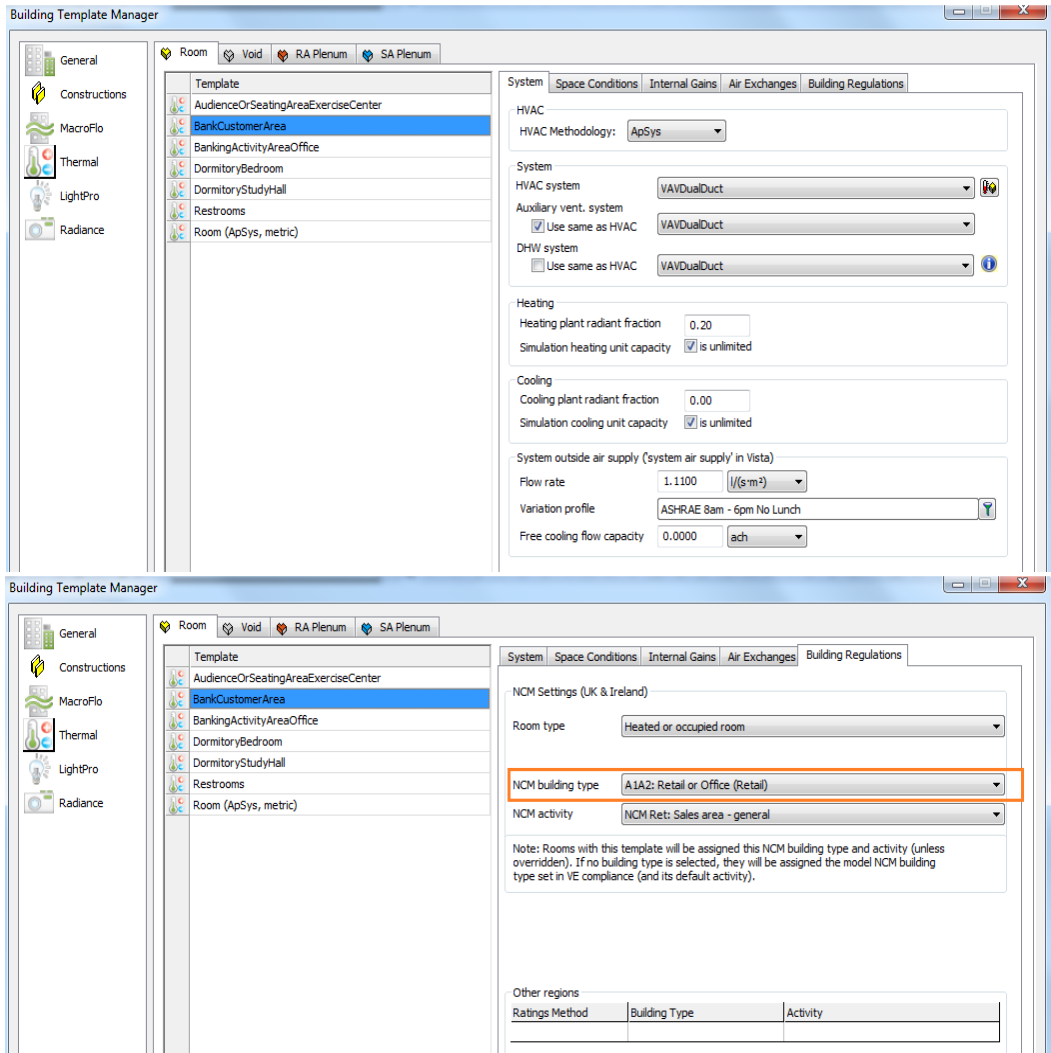


Figure 61: Thermal profiles of BES model– Model import from gbXML

Figure 61 represents all space types, which are imported to IES from gbXML. It can be observed that IES successfully imported all space types defined in the BIM model and it also imported Building services system (HVAC) defined to each zone during the gbXML export process (refer to Table 8). IES did not import all other energy settings and information mentioned in the BIM model but it redirected to the information defined in the IES library for energy analysis based on the imported space type. For example, the space type “Bank Customer Area” has been assigned for a space called customer area in the BIM model, the IES model verified this imported space type and selected a space type called “Retail and Office” from its library based on the imported space type. The energy settings like air exchange, internal gains, space condition, etc. are considered according to space type Retail or Office (in IES library). This redirected information is approximately equal to the defined information for the energy model in Revit and this is an editable data type. Because of this reason, IES is only importing the space type and skipping the information defined in Revit based on space type (refer to Table 8).

The defined schedules for occupants and building operations (lighting, power supply) for each space types are not imported to the IES model. Generally, all these schedules are based on the space type and are editable too. It means, all these schedules are variable from building to building even though the space type is the same. Thus, the IES application also makes this schedule definition as user-defined and it differs from every purpose. Similarly, all imported data is editable, and it facilitates the user to modify and edit the information at any time of simulation.

The summary of the data transfer process between Revit and IES using gbXML as interoperability file format is presented in the below table.

Table 12: Summary of the data transfer process using gbXML

<i>Parameter</i>	Description
<i>Location & coordinates</i>	Location details, latitude and longitude are imported successfully but the elevation of the building is imported inaccurately.
<i>Orientation</i>	The orientation of the building is successfully imported.
<i>Geometry</i>	The geometry of all elements (core & shell details) of the building is successfully imported to IES.
<i>Construction details</i>	Only the construction type name and U-values of each construction type are imported, but the thickness and material for the construction type are not imported.
<i>Thermal properties</i>	IES is failed to import thermal properties mentioned in the BIM model but redirected to its library for thermal properties based on the space type.
<i>Space</i>	Successfully imported all spaces and space types to IES.
<i>Zone</i>	Zone details and building services system assigned for the zone are imported successfully.
<i>Schedules</i>	IES is failed to import schedule details from gbXML.

4.5.2 Import from IFC

In this import process the modelled data (BIM model) was exported to the IFC file format. The same data was imported to IES application to perform an energy analysis of the building.

a) Import Statistics

As mentioned in the earlier section 4.5.1 (Import from gbXML), after every successful import process IES generated an import statistics report. Appendix 7.3 represents the IES<VE> import statistics file, which has been developed during the process of data import from IFC to IES. This import statistics report explains the details of area and volume values for each space, elements bounded by the space and its intersections. It also explains about the time taken for the import process and the number of elements that have been imported to IES.

The table below consists of the values regarding space area and the volume. These values are taken from the import statistics report. It provides information regarding the percentage of volume change between BIM model spaces and IES model spaces. It is observed that the volume of spaces in IES is equal for both import processes (by comparing Table 11 and Table 13). It means the volume calculation process for both the import processes are the same and the surfaces for the roof, floor and slab are provided at levels locations (mentioned in Revit). The area value imported to IES is different from the BIM model (Revit) because area calculations are performed from centre to centre distance between walls in IES. In the IFC export process, only the centre line of the element has been imported to the IES application and it is represented with a blue coloured line in Figure 62. It means a 2-D virtual surface is provided exactly at the centre of the element for energy analysis purposes. From Table 13, it is observed that the maximum room volume difference between the BIM model and IES model is more than 10% and it may cause the design of oversized building services system.

Table 13: Volume comparison between the BIM model and BES model – IFC import

<i>Building Space</i>	Floor Area (m²)		Volume (m³)		% of volume change in IES w.r.t Revit
	Revit	IES	Revit	IES	
<i>Customer Lobby</i>	113.846	121.048	429.768	484.190	12.66%
<i>Stock Room</i>	16.774	18.476	63.323	73.905	16.71%
<i>Manager Room</i>	16.774	18.476	63.323	73.905	16.71%
<i>Study Hall</i>	81.884	86.877	309.110	347.507	12.42%
<i>Student Bed Room 1</i>	28.264	31.0	106.697	124.0	16.25%
<i>Student Bed Room 2</i>	37.006	40.123	139.923	160.493	14.7%
<i>Yoga Room</i>	119.921	126.984	419.722	444.443	5.89%
<i>Rest Room for Men</i>	13.844	15.476	48.455	54.167	11.79%
<i>Rest Room for Women</i>	13.895	15.540	48.634	54.390	11.84%

b) Model Geometry and Orientation

The geometry and the location of the building in the IES application are represented in Figure 62. The data transfer methodology using IFC has been successfully imported the geometry, space or room and location of the building to the IES application. Figure 63 is representing the orientation of the building, which is different when compared to the BIM model in Figure 36. The actual orientation of the building is mentioned as 320 degrees to the true north but in the IES application, the model is oriented at an angle of 40 degrees to the true north. It indicates the error regarding the direction of the model rotation in the IFC file (during the export of the model from the Revit to IFC). This can be observed by comparing the models shown in Figure 36, Figure 57 and Figure 63.

The roof extension and the parapet wall modelled in the BIM model is not imported to the IES from IFC even though the details regarding these elements are presented in the IFC file (refer in Figure 53). The main reason for this is that elements are not bounded to any space in the model. If we try to import non-bounded elements from IFC to IES, then the IES leaves an error message stating “The IFC file does not contain Space Boundary entities. These are required to provide the geometry for thermal analysis”. Here, in this case, the roof extension and parapet wall elements act as a local shading to the building and show their impact on solar exposure on the building. From Revit to gbXML export process, these non-bounded elements will export as shading devices because of the understanding between Revit and gbXML. But in the case of Revit to IFC export process, the non-bounded elements also export as building element (either wall, roof, slab or floor).

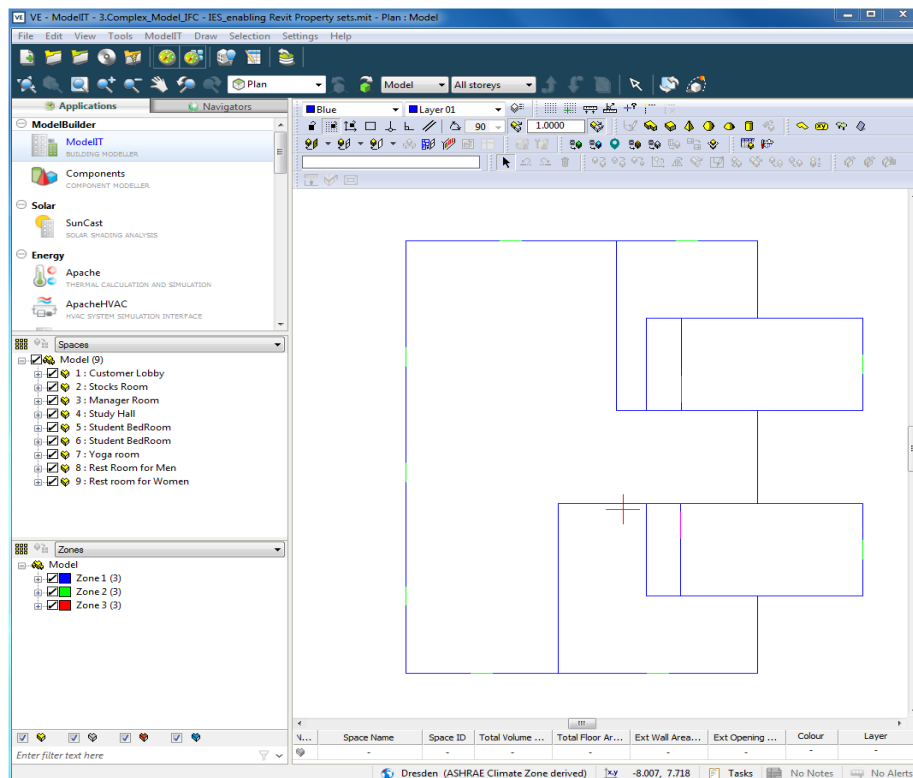


Figure 62: IES interface (BES Model Plan view) – import from IFC

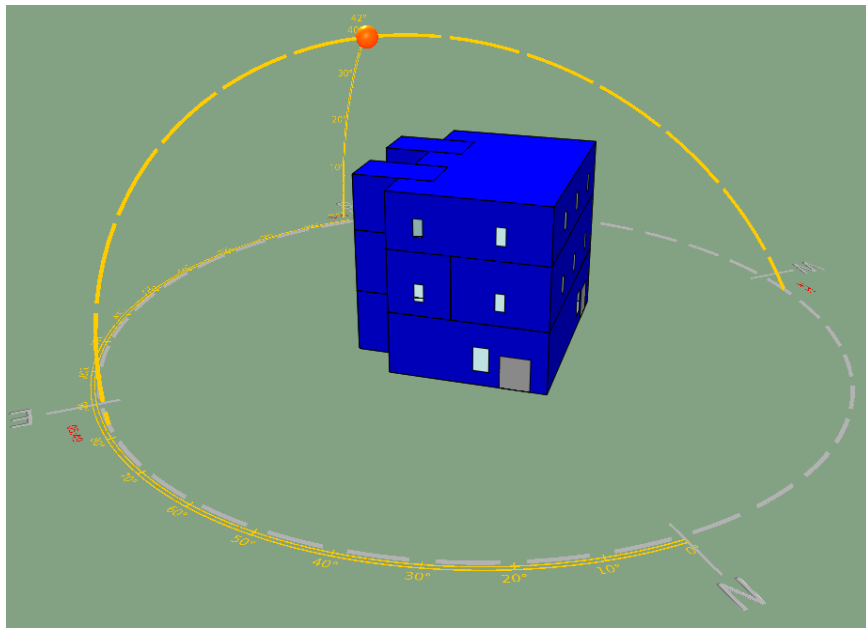


Figure 63: BES model representation – Model import from IFC

c) Construction Details

From Figure 64, it is observed that the construction details mentioned in the BIM model are not imported to the IES model from IFC. Revit has successfully exported all construction details to the IFC and this has been verified by using Solibri Model Viewer (refer to Table 10).

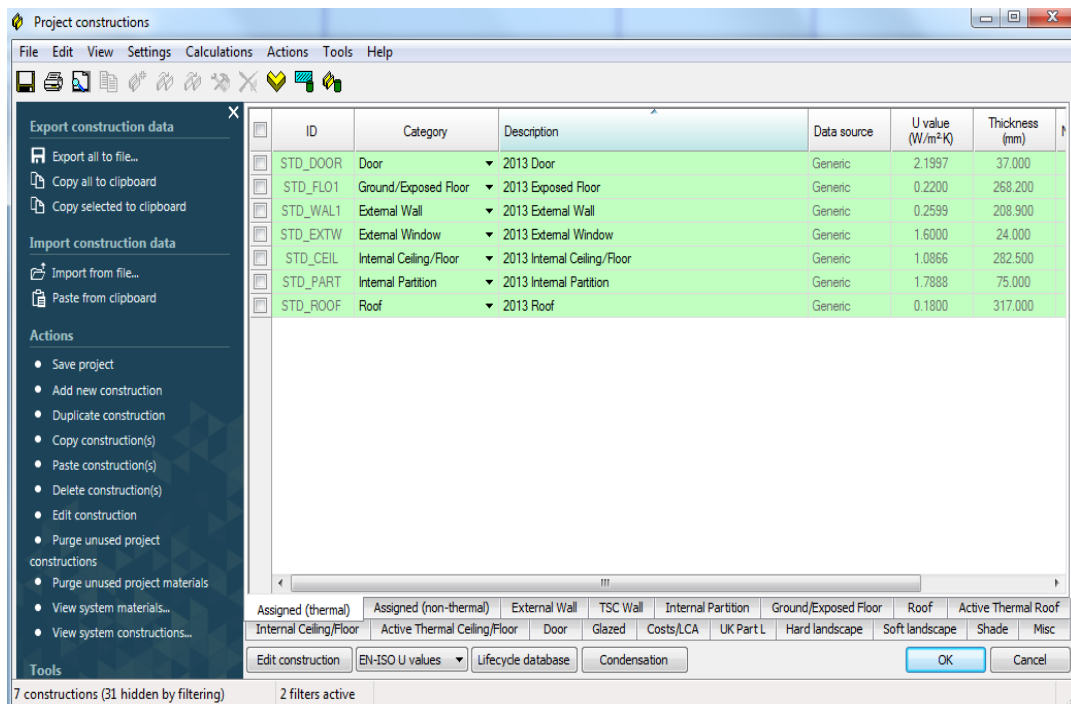


Figure 64: Construction details of BES model– Model import from IFC

d) Thermal Profile

Like the gbXML import process, the IES successfully imports space types modelled in the BIM model, which is represented in Figure 65. In IFC import process, IES is not importing the building services system because this information is not attached to the Zones directly, unlike in gbXML these services system details are attached to each Zone during the export process in Revit. With the help of these space types, IES redirects to its libraries and assigns the similar space types to the spaces in the IES model (refer in Figure 65). The information regarding air exchange, internal gains, space conditions, etc. are extracted from this similar space types identified from IES library. The occupant schedule, lighting schedule and power schedules are also not imported from IFC. It is observed that even Revit does not export the information regarding schedules to IFC. It has been investigated by using Solibri Model Viewer. The IFC schema has the capability to transfer the schedules information related to an object (either element or space), which is mentioned in section 3.2.8. the space type information regarding yoga room is missing in IES model.

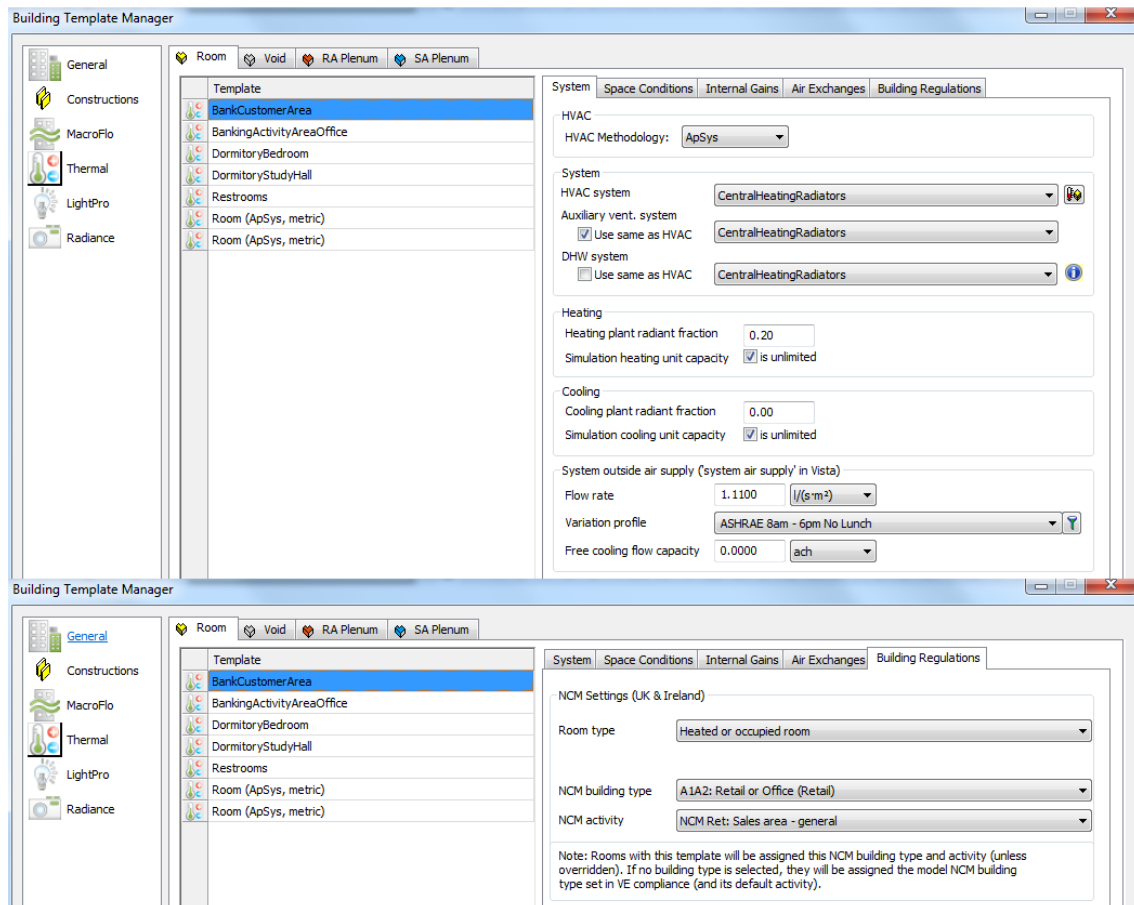


Figure 65: Thermal profiles of BES model– Model import from IFC

The summary of the data transfer process between Revit and IES using IFC as interoperability file format is presented in Table 14.

Table 14: Summary of the data transfer process using IFC

<i>Parameter</i>	Description
<i>Location & coordinates</i>	Location details, latitude, longitude and elevation are imported successfully to IES.
<i>Orientation</i>	The orientation of the building is imported in reverse direction.
<i>Geometry</i>	The geometry of all elements (core & shell details) of the building is successfully imported to IES. Elements like shading devices are not imported to IES.
<i>Construction details</i>	IES is completely failed to import construction details from IFC.
<i>Thermal properties</i>	IES is completely failed to import thermal properties of the elements defined in the BIM model.
<i>Space</i>	Successfully imported all spaces and space types (other than yoga room space type) to IES and Failed to import elements which are not bounded to spaces.
<i>Zone</i>	Zone details are imported successfully.
<i>Schedules</i>	IES is failed to import schedule details defined in the BIM model.

5 Conclusion and Future Work

5.1 Conclusion

Building Information Modelling (BIM) is a rapidly emerging technology in the AEC industry because of its capability to manage essential building design and project data throughout a building's life-cycle. The seamless data sharing between different software applications will provide the better software collaboration between all field of the AEC industry, but it is currently not in common practice. One of the main reasons for this is the lack of research on data transfer between different software applications. Common data exchange formats like IFC and gbXML, are the feasible solution to improve the interoperability between different software applications. But these formats don't work as expected especially in a detailed modelling. Hence, a constant research and development with respect to this should be conducted. One more main aspect is modelling errors, which affect the quality of data sharing between different software applications. A set of rules must be assigned when an information is modelled. The modelers should be aware regarding why and what data they are modelling and where it should be used.

Similarly, in this thesis, different aspects of data sharing between a BIM model and an energy performance simulation model was explored. Both the data sharing, and modeling aspects were investigated using the neutral file exchange formats. The important findings from this specific topic is listed below in tabulated format.

Table 15: Observations from the data transfer Demonstration

Data transfer to IES through gbXML	Data transfer to IES through IFC
Geometry and Orientation of the building are successfully imported	The geometry of the building is imported successfully, but the orientation is imported in reverse direction
Site location and Coordinates (Longitude, Latitude) are correctly imported from the BIM model, but the elevation of the building is wrongly exported to a gbXML file from Revit.	Site location and Coordinates (Longitude, Latitude and Elevation) are successfully imported to energy simulation model
Elements which are not bounded by space are imported as shading elements	Elements which are not bounded by space is not imported to IES
A 2-D surface at the centre line and the inner surface of the walls are imported to IES	Only the 2D- surface at the centerline of the wall is imported to IES even though the thickness of the material presented in the IFC file
The surface for the roof or floor is represented at the levels mentioned in the Revit (unbounded height of the element)	The surface for the roof or floor is represented at the levels mentioned in the Revit (unbounded height of the element)

Data transfer to IES through gbXML	Data transfer to IES through IFC
Geometry and representation of core & shell of the building (walls, slab, floor, opening, etc.) are imported successfully	Geometry and representation of core & shell of the building (walls, slab, floor, opening, etc.) are imported successfully
Only construction type name and the U-values of each construction type (roof, wall, window, door, slab, floor) are imported successfully, but the imported U-Value for Door type – Hollow core wood is a wrong value	Failed to import all construction details even though properly defined in the IFC file (successfully exported from Revit to IFC)
The thickness and layered structure of the construction type are missing, but the thickness and R-value for the core layer of the construction type is imported	Failed to import all construction details even though properly defined in the IFC file (successfully exported from Revit to IFC)
Thermal mass and thermal resistance values of the construction type are missing	Failed to import all construction details
Space types are successfully imported, and HVAC system mentioned for Zone during the export process in Revit is imported	Space types are imported successfully, but building service system is not imported
The actual thermal properties defined in the Revit is not imported but the information regarding internal gains are imported from the IES library based on the similar space type	The actual thermal properties defined in the Revit is not imported but the information regarding internal gains are imported from the IES library based on the similar space type
Failed to import occupancy and building operating schedules	Failed to import occupancy and building operating schedules.
Creating unnecessary tiny surfaces for walls and treated as Local shadings	Successful execution
Openings operating schedules are not imported	Openings operating schedules are not imported

From the demonstration results, it is observed that both the gbXML import and the IFC import are having their own pros and cons in the data transfer process. The data transfer between Revit (the BIM model) and IES (the Energy simulation model) is not efficient. The IES application completely failed to import the construction details and the thermal properties of space from an IFC schema. Even though IES imported this information from gbXML schema, this information is inefficient, and some values are inaccurate. IES is successfully imported the building core and shell (wall, roof, slab, opening, internal partitions, floor, etc.) details other than the elements which are not bounded by space (roof extension and parapet

walls, etc.) from the IFC data schema. The reason for this is that IES does not have the capability to import the building components which are not bounded to a space from IFC.

During the gbXML import process, it creates unnecessary tiny surfaces for the external and internal wall in the IES model. This problem can't be eliminated because these tiny surfaces are created in the processes of representing 3-D elements as 2-D surfaces for energy simulation purpose. For simple models, these tiny surfaces can be identified and deleted before proceeding with the energy analysis, but for complex models, it is difficult to identify these tiny surfaces individually and to eliminate them.

IES has successfully imported the space types assigned to spaces in the BIM model from both the IFC and gbXML schemas. Based on this imported space type, IES is trying to import the thermal properties (internal gains, infiltration, schedules, etc.) of spaces from similar space types defined in the IES library. From both the import processes it is observed that each space of the IES model has more than 10% of extra space volume when compared to the Revit model (BIM model). This volume increment in the energy simulation model may cause the design of an oversized system.

It is observed that the information regarding construction details and thermal profiles is presented in both meta-data model schemas, but the same is missing in IES. It means even though information available in the meta-data models, IES is not capable to import construction details and thermal profile information from gbXML or IFC.

5.2 Future Work

1. The problem with tiny surfaces, which are developed during the gbXML import process is never solvable because of the methodology (explained in above sections) adopted by gbXML schema (to import geometry of the building from Revit). But the problem with the import of non-bounded elements in IFC import process can be investigated. In Revit 2019, the export layer set (refer in Figure 52) is not well defined with all the entities of the IFC schema. There is no information regarding the shading device (*IfcShadingDevices*) mentioned in the export layer set and Revit does not define properly about this shading surface. This can be improved further.
2. Similarly, IFC has a well-defined schema (refer in Figure 28, Figure 29 and Figure 30) for importing schedule data from Revit, but Revit has failed to export this data to the IFC file. Because of the improper development of the IFC export layer set in Revit 2019. The IFC export layer doesn't contain any time schedule entities like *IfcTimePeriod*, *IfcWorkCalender*, *IfcWorkTime*, etc.
3. IES does not import thermal properties of spaces defined in Revit. IES only imported space types related to each space. Based on these space types, it is trying to redirect to its library and getting information on thermal properties of similar space types. Further research in this library data and linking of these libraries to Revit will be carried out.
4. Further data transfer demonstrations should be carried out for complicated building geometries, different geometric gap shapes and more energy settings.
5. Implementing curved surfaces and curtain walls in the demonstration examples.

6 References

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7 Appendix/Appendices

7.1 gbXML - Interoperability file

Here, the gbXML file for the Example demonstration (3-Storey Simple Building) is attached as an Icon. Please double click (which works in word document only) on below icon to view and verify XML schema for the BIM model.



3-Storey Simple
Building

Icon: gbXML file

```
<gbXML useSIUnitsForResults="true"
  <Campus id="aim0002">
    <WindowType id="aim1059">
    <Construction id="aim0908">
    <Construction id="aim0935">
    <Construction id="aim0950">
    <Construction id="aim0971">
    <Construction id="aim0998">
    <Construction id="aim1014">
    <Construction id="aim1023">
    <Construction id="aim1029">
    <Construction id="aim1038">
    <Layer id="aim0912">
    <Layer id="aim0939">
    <Layer id="aim0954">
    <Layer id="aim0975">
    <Layer id="aim1000">
    <Layer id="aim1016">
    <Layer id="aim1025">
    <Layer id="aim1033">
    <Layer id="aim1042">
    <Material id="aim0913">
    <Material id="aim0920">
    <Material id="aim0927">
    <Material id="aim0942">
    <Material id="aim0955">
    <Material id="aim0962">
    <Material id="aim0976">
    <Material id="aim0983">
    <Material id="aim0990">
    <Material id="aim1001">
    <Material id="aim1007">
    <Material id="aim1018">
    <Material id="aim1043">
    <Material id="aim1050">
    <Schedule type="Fraction" id="aim0092">
    <Schedule type="Fraction" id="aim0098">
    <Schedule type="Fraction" id="aim0216">
    <Schedule type="Fraction" id="aim0382">
    <Schedule type="Fraction" id="aim0468">
    <Schedule type="Fraction" id="aim0634">
    <Schedule type="Fraction" id="aim0640">
    <WeekSchedule type="Fraction" id="aim0090">
    <WeekSchedule type="Fraction" id="aim0096">
    <WeekSchedule type="Fraction" id="aim0214">
    <WeekSchedule type="Fraction" id="aim0380">
    <WeekSchedule type="Fraction" id="aim0466">
    <WeekSchedule type="Fraction" id="aim0632">
    <WeekSchedule type="Fraction" id="aim0638">
    <DaySchedule type="Fraction" id="aim0089">
    <DaySchedule type="Fraction" id="aim0095">
    <DaySchedule type="Fraction" id="aim0213">
    <DaySchedule type="Fraction" id="aim0379">
    <DaySchedule type="Fraction" id="aim0465">
    <DaySchedule type="Fraction" id="aim0631">
    <DaySchedule type="Fraction" id="aim0637">
    <Zone id="aim0067">
    <Zone id="aim0072">
    <Zone id="aim0077">
    <DocumentHistory>
  </gbXML>
```

Figure: gbXML Shema structure – sample example

7.2 IFC – Interoperability file

Here, the IFC file for the Example demonstration (3-Storey Simple Building) is attached as an Icon. Please double click (which works in word document only) on the below icon to view and verify XML schema for the BIM model.



3-Storey simple
Building_IFC schema

Icon: IFC – STEP physical file

```
FILE_DESCRIPTION(('ViewDefinition [DesignTransferView_V1.0]'),'2;1');
FILE_NAME('001','2018-10-18T15:20:03',(''),(''),'The EXPRESS Data Manager Version
5.02.0100.07 : 28 Aug 2013','20180328_1600(x64) - Exporter 19.1.0.0 - Alternate UI
19.1.0.0','');
FILE_SCHEMA(('IFC4'));
ENDSEC;

DATA;
#1= IFCORGANIZATION($,'Autodesk Revit 2019 (ENU)',$, $, $);
#5= IFCAPPLICATION(#1,'2019','Autodesk Revit 2019 (ENU)', 'Revit');
#6= IFCCARTESIANPOINT((0.,0.,0.));
#10= IFCCARTESIANPOINT((0.,0.));
#12= IFCDIRECTION((1.,0.,0.));

#100= IFCAXIS2PLACEMENT3D(#96,#20,#98);
#101= IFCDIRECTION((0.642787609686539,0.766044443118978));
#103= IFCGEOMETRICREPRESENTATIONCONTEXT($,'Model',3,0.01,#100,#101);
#107= IFCGEOMETRICREPRESENTATIONSUBCONTEXT('Axis','Model',*,*,*,*,#103,$,.GRAPH_VIEW.,$);

#112= IFCPROJECT('1NlfGRPBX2E9Gkg2i61rrt',#42,'001',$, $, 'Simple
Building','Continuing',(#103),#94);
#123= IFCPOSTALADDRESS($,$,$,('N\X2\00FC\X0\rnberger Str. 31A, 01187
Dresden'),$, '','N\X2\00FC\X0\rnberger','Str 31A','01187 Dresden');
#127= IFCBUILDING('1NlfGRPBX2E9Gkg2i61rrs',#42,'Bank Office Building',$, $, #33,$,'Bank Office
Building',.ELEMENT.,$, $, $);

#623= IFCPROPERTYSSINGLEVALUE('Name', $, IFCLABEL('Customer Lobby'), $);
#631= IFCPROPERTYSET('0mSibrIzj7AvH3Ph6ZTpkK', #42, 'Pset_AirSideSystemInformation', $, (#623));
#639= IFCPROPERTYSSINGLEVALUE('Reference', $, IFCIDENTIFIER('Customer Lobby 1'), $);
#640= IFCPROPERTYSSINGLEVALUE('IsExternal', $, IFCBOOLEAN(.F.), $);
```

Figure: IFC-STEP physical file – sample example

7.3 IES<VE> Import Statistic Report

Import log for gbXML file H:\anakraam Karapudiri\Revit_Exercise3\Complex Model\Example3_9boxes_enabling_Schematic Type.xml

Checking for the following import rules

Valid closed shell: No
Adjacencies: Yes
Intersecting spaces: Yes

Importing spaces

The file contains 25 obstruction surfaces (0 failed to import)

9 spaces were imported successfully out of a total of 9 in the gbXML file.Importing spaces took 12 seconds

BIM Import Statistics

BIM Source package:
Adjacency Separation Distance (m): 0.100

Shell import settings:

- Include space boundaries resulting from columns: No
- Minimum space boundary area: 0.500 (m²)
- Attempt to fix shell surface orientations: Yes
- Attempt to heal bad geometry by adding surfaces to close the shell: Yes
- Maximum number of unmatched edges to allow: 10
- Maximum number of surfaces to allow in space boundary: 1000
- If fails, extrude the space from the floor footprint (reattaching openings): Yes

Room (space)			Raw (space boundaries in file)				Processed (space boundaries after geometry healing)				Other issues		
BIM ID	Imported ID	Name	Bounded	Unmatched edges [1]	Missing area [2]	Floor area (m ²) [3]	Volume (m ³)	Bounded	Unmatched edges [1]	Missing area [2]	Missing area ratio	Floor area (m ²) [3]	Volume (m ³)
aim0032	AIM0020	1 Customer Lobby	x	26	242.095	0.500	113.846	322.793	✓	0	0.000	113.846	484.190
aim0206	AIM0260	2 Stock Room	x	8	36.953	0.335	16.774	49.270	✓	0	0.000	16.774	73.905
aim0292	AIM0220	3 Manager Room	x	8	36.952	0.335	16.774	49.270	✓	0	0.000	16.774	73.905
aim0372	AIM0320	4 Study Hall	x	32	0.000	0.000	0.000	115.636	✓	0	0.000	81.884	347.507
aim0458	AIM0480	5 Student BedRoom	x	26	0.000	0.000	0.000	41.333	✓	0	0.000	28.264	124.000
aim0544	AIM0540	6 Student BedRoom	x	26	0.000	0.000	0.000	53.498	✓	0	0.000	37.066	160.483
aim0624	AIM0640	7 Yoga room	x	26	254.425	0.562	0.000	288.665	✓	0	0.000	119.921	444.443
aim0748	AIM0760	8 Rest Room for Men	x	8	30.953	0.351	0.000	36.111	✓	0	0.000	13.844	54.167
aim0828	AIM0800	9 Rest room for Women	x	16	34.624	0.392	0.000	28.630	✓	0	0.000	13.895	54.390
TOTALS				172	636.002				0	0.000			

Notes:

1. Unmatched edges: Shows how many surface edges do not match up with other surface edges. A non-zero value can indicate that the room is not bounded, but it can also indicate that there are unmatched vertices on matched edges (which is not really a problem).
2. Missing area is the sum of surface area vectors along their orientations. A zero value indicates that the room has bounded manifolds, but not necessarily just one. But a non-zero value always indicates that the room is not bounded (because of unmatched edges, overlapping surfaces, or surfaces oriented wrongly).
3. A zero floor area indicates that the floor(s) have an inverted orientation or are missing entirely.

Figure: IES<VE> import statistics file – gbXML import

Import log for IFC STEP file H:\Janakiram Karlapudil\Revit_Exercise\3.Complex Model\Example3_9boxes.ifc

Checking for the following import rules

Valid closed shell: Yes
Adjacencies: Yes
Intersecting spaces: Yes

Importing spaces

Importing spaces took: 2 seconds

9 spaces were imported successfully out of a total of 9 in the IFC STEP file

BIM Import Statistics

BIM Source package:
Adjacency Separation Distance (m): 0.100

Shell import settings:

- Include space boundaries resulting from columns: No
- Minimum space boundary area: 0.500 (m²)
- Attempt to fix shell surface orientations: Yes
- Attempt to heal bad geometry by adding surfaces to close the shell: Yes
- Maximum number of unmatched edges to allow: 10
- Maximum number of surfaces to allow in space boundary: 1000
- If fails, exclude the space from the floor footprint (reattaching openings): Yes

Room (space)			Raw (space boundaries in file)				Processed (space boundaries after geometry healing)				Other issues		
BIM ID	Imported ID	Name	Bounded	Unmatched edges [1]	Missing area [2]	Floor area (m ²) [3]	Volume (m ³)	Bounded	Unmatched edges [1]	Missing area (m ²) [2]	Missing area ratio	Floor area (m ²) [3]	Volume (m ³)
0	00000000	1: Customer Lobby	✖	26	242.095	0.500	322.793	✓	0	0.000	0.000	121.048	484.190
1	00000001	2: Stocks Room	✖	20	44.062	0.400	0.635	✓	0	0.000	0.000	18.476	73.905
2	00000002	3: Manager Room	✖	20	44.062	0.400	0.635	✓	0	0.000	0.000	18.476	73.905
6	00000006	4: Study Hall	✖	16	173.754	0.475	231.672	✓	0	0.000	0.000	86.877	347.507
7	00000007	5: Student BedRoom	✖	21	82.486	0.509	2.000	✓	0	0.000	0.000	31.000	124.000
8	00000008	6: Student BedRoom	✖	21	102.102	0.528	2.000	✓	0	0.000	0.000	40.123	160.493
12	00000012	7: Yoga room	✖	9	15.260	0.034	436.813	✓	0	0.000	0.000	126.984	444.443
13	00000013	8: Rest Room for Men	✖	20	21.000	0.238	21.000	✓	0	0.000	0.000	15.476	54.167
14	00000014	9: Rest room for Women	✖	14	25.959	0.294	28.630	✓	0	0.000	0.000	15.540	54.390
TOTALS				167	750.781				0	0.000			

Notes:

- 1: 'Unmatched edges' shows how many surface edges do not match up with other surface edges. A non-zero value can indicate that the room is not bounded, but it can also indicate that there are unmatched vertices on matched edges (which is not really a problem).
- 2: 'Missing area' is the sum of surface area vectors along their orientations. A zero value indicates that the room has bounded manifolds, but not necessarily just one. But a non-zero value always indicates that the room is not bounded (because of unmatched edges, overlapping surfaces, or surfaces oriented wrongly). (All surfaces must be oriented outwards from the room using a right-hand rule, i.e. the surface vertices must be in anticlockwise order when viewed from outside the room.)
- 3: A zero floor area indicates that the floor(s) have an inverted orientation or are missing entirely.

Figure: IES<VE> import statistics file - IFC import

7.4 BES model – Thermal Profile Data

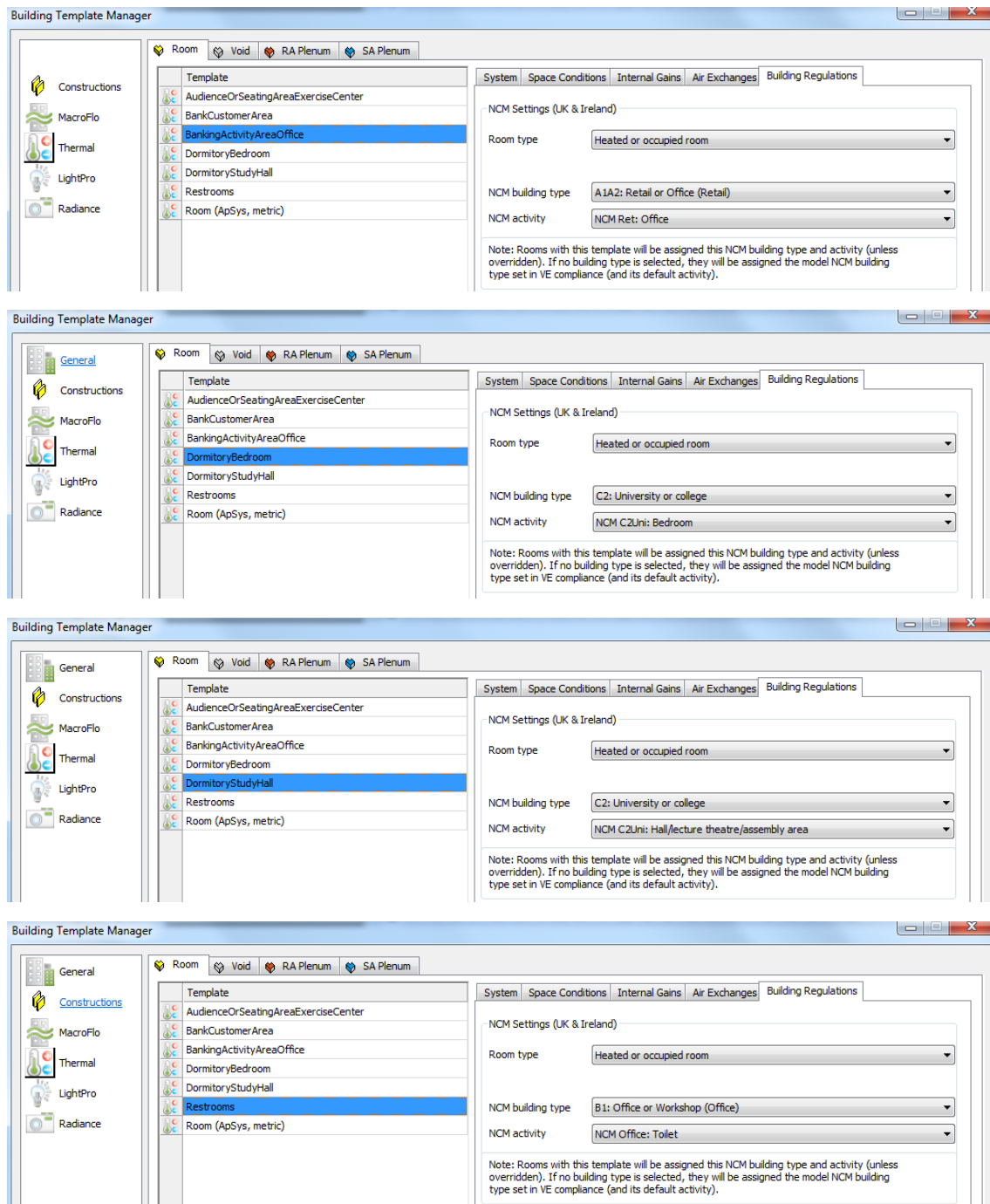


Figure: Space type definitions in the BES model