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Comparison Between Semi- Automated Building Energy Simulation Processes Using BIM- Generated gbXML and IFC Formats in EnergyPlus.

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Abstract

Building Information Modeling (BIM) has been introduced to the Architecture, Engineering, Construction (AEC) industry to promote collaboration between various disciplines and to facilitate integrated workflow of building projects. In that sense BIM also potentially assists the process of Building Performance Simulations (BPS) by maintaining a reliable data repository for building geometry parameters. Among the most precise whole building simulation tools is EnergyPlus that provides thorough energy analysis, thermal load calculations and also requires careful building data input for successful simulation. Currently, information exchange between the BIM authoring tool and EnergyPlus is possible by extracting and translating building geometry for simulation input in a semi-automated process using two data formats: 1) gbXML (Green Building XML) or 2) IFC (buildingSMART, former AIA). However, the two formats have unique data structures, which retrieve building geometry differently. With focus on thermal energy simulations and data exchange workflows this paper aims to evaluate and compare the use of gbXML and IFC into the process of BPS with EnergyPlus.

Keywords

Building Information Modeling (BIM), gbXML, IFC, Building Performance Simulation (BPS), Thermal Simulation, EnergyPlus

Zusammenfassung

Building Information Modeling (BIM) wurde in Architektur, Ingenieurswesen und Konstruktionsindustrie eingeführt, um die Zusammenarbeit zwischen verschiedenen Disziplinen voranzutreiben und den ganzheitlichen Arbeitsablauf von Bauprojekten zu vereinfachen. Durch richtiges Modellieren mittels Building Information Modeling (BIM) wird durch den verlässlichen Datenexport der Aufbau von Gebäudesimulationen wesentlich erleichtert. Unter den exaktesten Simulationswerkzeugen befindet sich EnergyPlus, welches Energieverbrauch und Wärmebedürfnisse von Gebäuden kalkuliert. Die enorme Vielfalt an möglichen Input Variablen erlaubt sehr exakte und realitätsnahe Ergebnisse. Gegenwärtig wird der Informationsaustausch zwischen dem BIM Autorenwerkzeug und EnergyPlus möglich gemacht, indem die Gebäudegeometrie für den Simulationsinput in einen halb automatischen Prozess extrahiert und übersetzt wird. Hierfür werden zwei Datenformate verwendet: 1) gbXML (Green Building XML) und 2) IFC (buildingSMART, vorher: AIA). Es haben jedoch beide Formate einzigartige Datenstrukturen, welche die Gebäudegeometrie unterschiedlich bearbeiten. Das Ziel dieser Masterarbeit ist, mit dem Schwerpunkt auf Simulationen der Energieeffizienz und Ablauf des Datentransfers, den Nutzen von gbXML und IFC im Prozess von Gebäudensimula-tionen mit EnergyPlus zu evaluieren und zu vergleichen.

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1 INTRODUCTION

1.1 Overview

In recent years more attention is paid to improving the quality of exchanged data and to managing information integrity between professions involved in building projects. Building Information Modelling (BIM) promotes collaboration between disciplines by providing a single 3D CAD model, containing relevant parametric data about a building throughout its life cycle, which can be exported to various function-specific software for different purposes and analysis (Eastman 2008). The Architecture Engineering Construction (AEC) industry has developed two data formats to facilitate interoperability between software and to exchange building information between disciplines. One is gbXML format, developed initially by Green Building Studio (gbXML, 2014) to assist energy analysis. And the other one is IFC- an object-based, open file format, which has been developed by buildingSMART (former AIA) and has been used to transfer data among various participants in a building project (buildingSMART 2014).

For the purpose of Building Performance Simulations (BPS) both formats have the ability to extract building data from the BIM model, necessary for energy simulations, and transfer it to the respective software. For most physical simulated processes required information is building geometry and spatial data (Maile et al. 2013). However, gbXML and IFC have unique data scheme structures (Dong et al. 2007), which retrieve and store building data from the BIM model differently and therefore require separate processing by the receiving software. This potentially has an effect on how the original geometrical and spatial data from the BIM model is being translated. And since energy simulation tools perform computational analysis of physical performance of building models based on that information, final results generated from gbXML and IFC transfer are questioned. In addition, the performance of the formats highly depends on the accuracy of the original BIM model, which in some cases lacks enough information or contains geometric inconsistencies and therefore causes export difficulties.

With regards to transference of building geometry and spatial information for the purpose of building performance analysis, this paper aims to assess and compare the usage of IFC and gbXML data formats in separate workflows, observing consistency of building data, efficiency of the process and validity of results which are all relevant and essential points to BPS and supportive of effective building design. EnergyPlus is chosen as the simulation tool to which data will be transferred. At first, careful theoretical and practical research is done to investigate and establish the main differences and specifics of the two formats. Further on, several case models are developed in a BIM authoring tool and both data formats are tested in a typical workflow to reveal and conclude about their application and potential influencing factors during building geometry translation. In order to verify the significance of the native model and importance of creating a *"clean"* BIM model a second workflow, with the same case models, is set up in a different BIM authoring tool. In the end, the aim will be to analyze the main differences and capabilities of gbXML and IFC and their dependencies in a chosen work method, concerning the originating model, reliability of software and information management, all of which would have an impact over building performance simulations and the outcomes of such.

1.2 Motivation

Recent global demands for energy efficiency and sustainability of buildings have caused the AEC industry to employ Building Performance Simulations into building projects in order to justify and quantify design intent for as-built conditions (Bazjanac et al. 2011). Typically, results from these simulations have been regarded as guidelines for optimization of building performance and have turned out to posses great influence over the design and energy efficient characteristics of buildings (Bazjanac et al. 2011; Jones et al. 2013; Pollock et al. 2009).

Thermal simulation results in the very first stages of project serve as a guidance to HVAC systems design (Paradis 2010). Essential for thermal simulation are geometry, location and spatial distribution (Maile et al. 2013), therefore they will be the focus of the current research paper.

Building Information Modelling (BIM) benefits building thermal performance analysis and decision making by providing a 3D CAD model, acting as data repository for building models, (Hitchcock and Wong 2011; Jones et al. 2013; Maile et al. 2013) and providing the base input parameters for Building Energy Modelling (BEM). Where the BEM model is in fact the BIM model, containing all the necessary analytical information for conducting BPS. However, BIM tools and BPS tools have been developed separately to serve the specific needs and functions of the AEC industry. That has eventually raised the issue of preserving quality of transferred data when information is exchanged between disciplines and software. In order to avoid likelihood of human error during manual translation and to maintain the quality of transferred data, it has been suggested that the process is automated (Robertson and Perera 2002).

The two most used data formats for automated exchange of information between CAD tools and BPS tools, the gbXML and IFC, offer similar workflows, but still require different information processing. That is due to the fact that initially both data structures have been developed individually and for different reasons (gbXML 2014; buildingSMART 2014). The gbXML has a simple, easily understandable scheme which exports geometric, spatial information and their physical attributes only for the purpose of building performance analysis. This has made it the default 3D building data import format for many energy analysis software (gbXML 2014). The IFC on the other hand has been constructed so it is able to translate all building geometry and its attributes, as well as its physical and hierarchical relationships, making it a reliable and useful format for most disciplines (buildingSMART 2014). However, its implementation for energy analysis has been neglected as an option, because of its complex data structure (Hitchcock and Wong 2011) and only recently has it become more involved.

1.3 Objective

The distinction between the two formats is a preset for different information processing in the preparation and analysis of building models for BPS in EnergyPlus. This, essentially, has reflection on their ability to translate building geometry as a reliable data input. Furthermore, the two workflows are semi- automated and would require different amount of manual work and management when it comes to feeding back the results from the simulation. And finally, it questions the generated results by the simulations. Analyzing all these issues subsequently will give an insight on which factors, tools and processes have an effect and are essential for successful BPS.

This thesis will concentrate on thermal simulation, however it will be kept in mind that as a part in the energy analysis and design, this process has an effect over the whole course of BPS analysis.

1.4 Background

1.4.1 Overview

During the Building Information Modelling for Life Cycle Structures seminar at the Vienna Technical University last year (2013) in June, Professor Dr. Arto Kiviniemi, a notable researcher in the field of BIM and its implementation for the last 20 years, pointed out the rapid growing of BIM use in the AEC industry (PRAXISREPORT 2013). He also discussed the potential use of BIM in early assessment of sustainable design and development. And indeed, many other professionals and researchers in the area have supported their cases, regarding building performance analysis, through the use of BIM

(Maile et al. 2013; O'Donnell et al. 2013; Laine et al. 2007; Bazjanac et al. 2011; Hitchcock and Wong, 2011; Moon et al. 2011). Through BIM models designers and engineers get a detailed parametric description of a building model, which is utilized as the basis for energy simulations (Laine et al. 2007). This complex 3D CAD information is converted into thermal analytical surfaces through various software available on the market (Maile et al. 2013). However, exactly this conversion process is part of a greater issue, largely discussed in BIM areas, namely interoperability between software (BIM for LCS Seminar June 2013) and data exchange, which is partly being solved by the introduction of gbXML and IFC data formats.

Through BIM it has been observed that the efficiency of thermal performance management is increased (Laine et al. 2007)- allowing for multiple design scenarios to be tested in the early stages of a project, reducing time and errors in the process. That is, the BIM model providing the building geometry and spatial data necessary for the creation of BEM, removing the need for extensive manual input into the simulation tool. As such, the decision to automate the process of translation of information between software has shown its advantages (Robertson and Perera 2002; Bazjanac 2008, Bazjanac 2011).

Even though the development of this idea has been ongoing for many years now and has improved significantly, there are still no clear guidelines on how should a model be defined (Hitchcock and Wong 2011) in the BIM- authoring tool so it contains all the necessary information for extraction and generation of BEM via data format exchange. In the same time Wilkins and Kiviniemi (2008) describe one of the reasons for that to be the great difference between the data in the *"architectural view"* of the model and the *"thermal view"* of the same model. In current practices, it often happens that the original design model has too many errors or inconsistencies, making it impossible for gbXML and IFC to accurately translate building geometry.

1.4.2 Thermal Simulation: Relevance and Geometry

Simulation engines calculate only for 1- dimensional surfaces, so they require complex 3D CAD geometry to be broken down to *space boundary surfaces* (Jones et al. 2013). And there are a few software tools, which convert rich geometry into BEM and prepare it for simulation (Bazjanac 2009; Bazjanac et al. 2011; Hitchcock and Wong 2011). Space boundaries are actually the heat transfer surfaces of the building elements enclosing a space, or a thermal zone. In a 3D CAD model, heat transfer objects (wall, slab) separate minimum two spaces and have two heat transfer surfaces, each facing one of the spaces. In a *"clean"* model, the *normal direction* of the space boundaries point outwards of the space they bound (*Figure 1*), which is very important for determining the correct direction of heat transfer (Jones et al. 2013). Therefore, a data format, carrying the information about the relationship between building elements and spaces, should be able to store the information in such a way it is successfully processed and broken down to 1D surfaces.

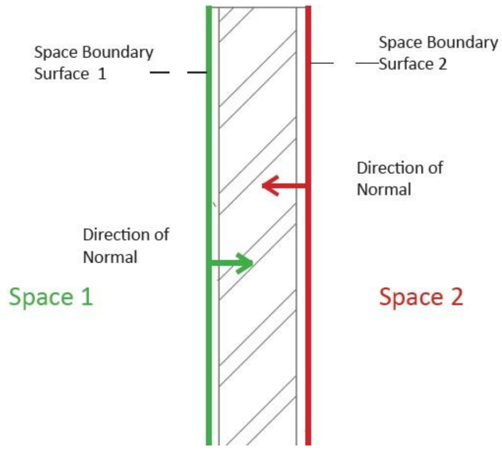


Figure 1: Space Boundary and Direction of Normal for heat transfer

1.4.3 Data formats: gbXML and IFC

The gbXML and IFC are the two most used informational infrastructures across the AEC industry for exchange of data between a CAD software and a simulation tool (Dong et al. 2007). They posses unique data structures because of their separate development to serve individual goals.

Green Building XML- gbXML

The gbXML has been developed strictly for the purpose of energy analysis (gbXML 2014). It was first conceived in 1999 by Green Building Studio Inc. Its official name is Open Green Building XML and is incorporated as California public non- profit organization. Its sponsors are BIM developers such as Autodesk, Bentley and Graphisoft. Its latest version (5.11), as of the time of writing, was released in November 2013. XML in gbXML stands for Extensible Markup Language, which is a straight- forward, flexible text format, designed to transfer data all over the Web (W3C 2014). It is used by industries and organizations to develop their own, customized data format for exchange of information, based on the XML language. It provides a consistent and robust scheme, however, the implementation of the format is complicated by the individual semantics of the respective schema or data model (Dong et al. 2007).

The gbXML retrieves analytical geometry, spatial data and non- geometrical information, directly from the BIM model and saves it in a text format. With regards to storing geometry data, it has three main elements (*Figure 2*) , which are used in the schema to describe and capture the information (gbXML Implementation Agreement Draft 2013).

- *ShellGeometry* node- defines the inner surface of a Space
- *SpaceBoundary* node- defines the centreline of a surface bounding Space
- *Surface* Node- defines the surface of a Space, with geometry characteristics similar to the Space Boundary. It also defines surfaces, such as Shading Devices. Defines openings.

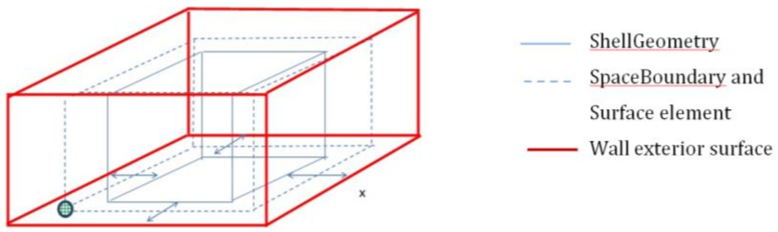


Figure 2: *gbXML geometry elements (gbXML Implementation Agreement Draft 2013)*

Software tools, consuming gbXML, do not always use all three descriptions of geometry to retrieve geometry. Most of them implement *ShellGeometry* and *SpaceBoundary* since they represent geometry more accurately in a combination. The rest would use solely the *Surface* element to obtain only the geometrical information needed to convert the gbXML data into correct representation of the building model (gbXML Implementation Agreement Draft 2013). The gbXML uses a "bottom-up" approach to structure the data schema(Dong et al. 2007), in which the sub- elements of a system are first described in greater detail and are then linked together to form the complexity of the whole unit.

Industry Foundation Class- IFC

Industry Foundation Classes or IFC, is an open data format used to exchange data within the building management and facility industry (ifcwiki 2014). It is the official international standard for Open BIM and is registered with the International Standardization Organization (ISO). It is developed and maintained by buildingSMART (the former AIA). The technical specification for the IFC is written using the EXPRESS data modelling language, which is certified under ISO16739 (buildingSMART 2014). EXPRESS data definition language is used to describe entities and relationships, including data verification rules in the data scheme. In addition it uses EXPRESS-G graphical data notations to display large information models (STEP 2014; buildingSMART 2014;

Dong et al. 2007). The IFC adopts the "top-down" approach, which creates a complex, hierarchical schema in a large data file (Dong et al. 2007).

- **Information Delivery Manual (IDM)**- is a standard, developed by buildingSMART to guide AEC professionals and software developers in defining processes and information flow in an integrated project (buildingSMART 2014). The main goal of the IDM is to ensure that all the relevant data for a specific task is described in the 3D BIM model in such a way that it is accurately consumed and processed by the respective software. *Information Delivery Manual for Design to Building Energy Analysis (buildingSMART 2007-2011)* delineates the exchange requirements for building energy analysis, such as defining spaces and associated energy information in the design of a BIM model so that the geometry used in the analysis is properly extracted.
- **Model View Definition (MVD)**- is for defining a certain data subset from the IFC schema, necessary for the exchange requirements described in the IDM. The main purpose of this technical manual is to guide software developers in their work on IFC implementation schemes. The MVD is kept updated to the IFC releases, and the latest one, as of the time of writing, was released in March, 2013 - the IFCx4.0. However, the used version in this thesis is IFC2x3 Coordination View 2.0. The reasons are explained further in the Method chapter.

Even though the IFC schema is capable of storing geometrical and spatial data relationships necessary for successful BPS (Maile et al. 2013) and the gbXML only manages the data representation (Dong et al. 2011.) without the relationships, gbXML is still largely and mostly preferred data format for implementation and analysis in BPS tools as it can be seen in *Table 1* below.

Table 1*: Software importing/exporting gbXML and IFC for building performance analysis (gbXML 2014; buildingSMART 2014)*

Industry Foundation Class (IFC)	**Green Building XML (gbXML)**
IDA ICE	Arup EnergySave
RIUSKA	Autodesk Green Building Studio
Symergy (v1.0)	Autodesk Ecotect
	Bentley Hevacomp
	Bentley AECOsim Energy Simulation
	blueCape blueCFD-AIR
	DesingBuilder
	EnergySoft, LLC- EnergyPro
	EDSL- Tas
	greenspaceLive Energy Desing and Analysis Tool
	HVAC Solution
	IES Limitied <Visual Environment>
	RaumGEO
	Green Building Information System (GBIS)
	TRACE 700
	E4 Tech
	DIALux

One of the reasons for that is that gbXML has a simpler schema, entirely focused on transferring data for energy and building performance analysis (gbXML 2014) offering easier implementation models. In the meanwhile the IFC has a more complex structure and way of storing data, making it hard for software vendors to implement it. However, buildingSMART is offering certification procedures, which help developers to integrate the IFC schema into their software (buildingSMART 2014), so potentially there is future for its improvement in this area.

In "Transforming BIM to BEM: Generation of Building Geometry for the NASA Ames Sustainability Base BIM" (O'Donnell et al. 2013) the application of IFC into building energy analysis is demonstrated and discussed in the context of semi-automated translation of building geometry from BIM to BEM. The paper provides recommendations on how to build the model in the BIM authoring tool and advises on successful data exchange method.

Moon (Moon et al. 2011) cover interoperability of gbXML between Autodesk Revit, Autodesk Revit MEP and several energy simulation and analysis tools, including EnergyPlus, which confirms certain existing issues with transferability of this format regarding building geometry and space composition. However, in this paper the process of how the data format was transferred to the respective programs is not discussed.

The research in this literature provides the basis and serves as a reference to constructing this paper.

1.4.4 Energy Simulation Tool

EnergyPlus is chosen as the whole building simulation tool, based on research into the offered accuracy of the simulation results. While the U.S. Department of Energy provides an extensive list with the available simulation programs on the market, numerous researches point to EnergyPlus and eQUEST as the most functional and up-to-date with practitioners' demands simulation software (Zhu et al. 2013; Maile et al. 2007; Attia 2010). They both have their strengths and weaknesses and in the end it is left up to the user to choose which software suits the project, purpose and their needs best.

2 METHOD

2.1 Overview

The aim of this paper is to analyze and compare the effects of semi-automated translation of building geometry on the process of BPS through gbXML and IFC. An outline of the process is shown below in *Figure 3*. The general discussion will be based on the results from standard practical approach to handling gbXML and IFC for generating BEMs for thermal simulation in a whole building energy simulation tool. In order to verify and illustrate whether or not there are significant discrepancies in the geometry translation by gbXML and IFC, several case studies will be created. The goal is to put both data formats to the test by employing them in the export and translation of the same building data from a respective case study model in two separate parallel workflows.

For the purpose, a typical workflow will be set up with the necessary software tools for conducting BPS. At different stages of the process certain points will be inspected as potential influencing factors. An important precondition for the seamless export of both data formats is the creation of a *"clean"* (Jones et al. 2013) 3D BIM model which has a comprehensive and consistent geometry structure, for which BIM- authoring tools are selected accordingly. Since gbXML and IFC require different pre-processing tools for BEM preparation, careful analysis is made of the available such programs with regards to their ability to successfully import gbXML or IFC respectively and to produce data format suitable for simulation. Finally, EnergyPlus is used for simulating and analyzing the results generated from the whole process.

It is important to point out that even though both gbXML and IFC have the possibility to transfer non- geometrical data, those capabilities will not be examined in this paper. The main reason for that is that despite the fact building performance simulations tools have been developed to take in as many input parameters and specifications of HVAC systems, occupancy and other loads, in reality none of them are able to operate without basic geometrical and spatial information.

An array of BIM models will be generated in Autodesk Revit and Graphisoft ArchiCAD, following guidelines for BIM geometry modelling (Maile et al. 2013). Once the 3D models are created and validated, four sets of data will be exported from the BIM software through IFC and gbXML. They will be further processed into SBT-1 and DesignBuilder respectively for geometry simplification and preparation of the output format for EnergyPlus. Once the simulation in EnergyPlus is performed, the results will be compared and a conclusion will be drawn about whether or not there is a significant impact on the outcomes.

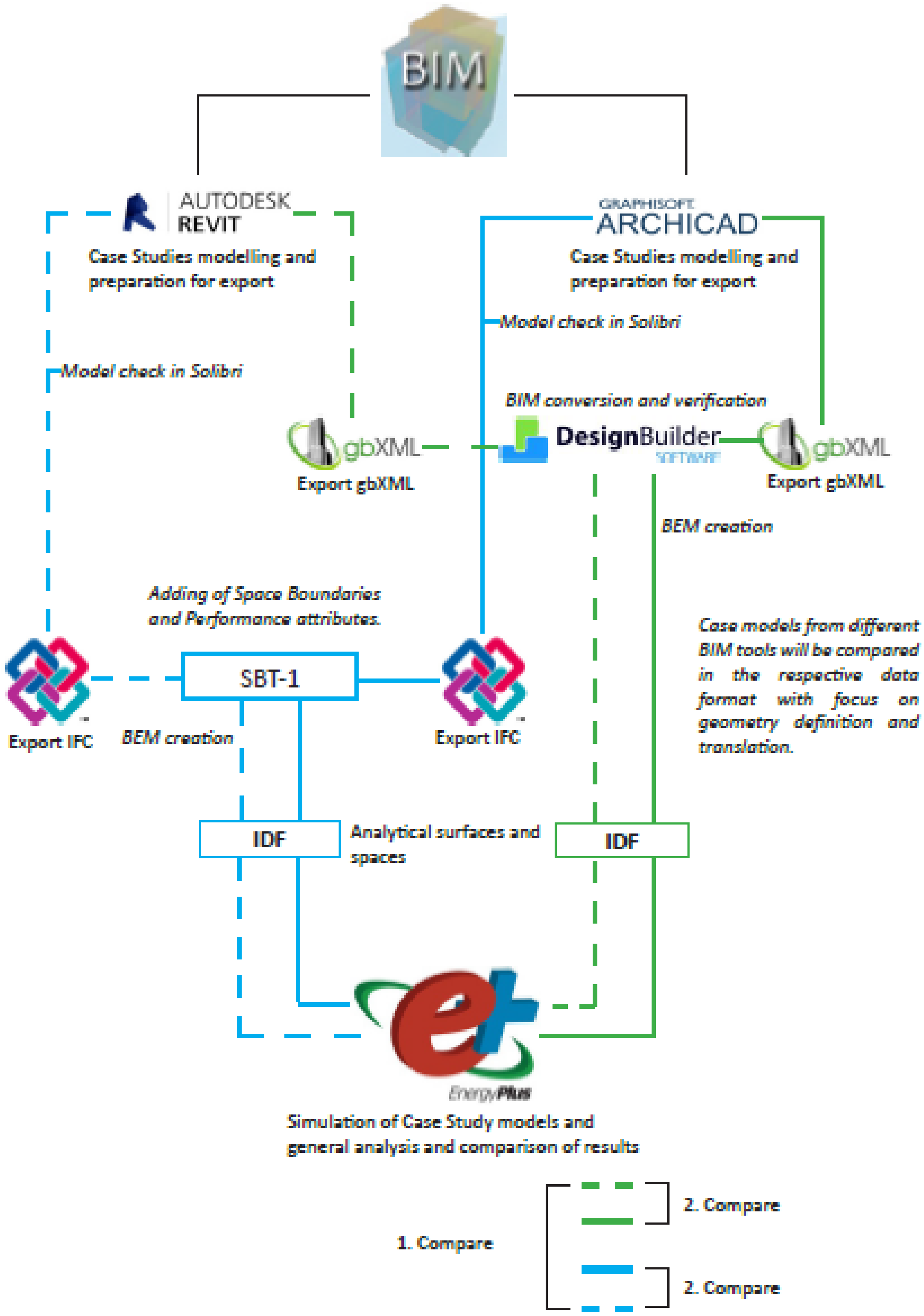


Figure 3: Thesis process diagram

2.2 Hypothesis

The main part of this research is based on the suggestion that there is variation in the extraction and transference of building geometry data, generated by a BIM authoring tool and exported by IFC and gbXML, and is researching whether or not it affects simulation results in EnergyPlus.

2.2.1 Research Questions

This thesis will aim to answer the following questions:

1. **How is building geometry data exported in gbXML and IFC?**

   a) What are the export capabilities of the two data formats?

   The basic characteristics of the two formats will be researched and described in detail. Deriving from there, a careful observation will be made over the accuracy of extracted BIM building geometry in several case models in comparison to the original model.

   b) How do they affect the accuracy of geometric information?

   The exported building information from gbXML and IFC is juxtaposed and put in parallel for further processing.

2. **What and how affects the quality of the building data in gbXML and IFC?**

   a) Export properties of BIM- authoring tools and implementation scheme of BEM pre-processing tools.

   In order to establish whether or not export capabilities and technical specifications of BIM- authoring tools affect the data in gbXML and IFC, building data of the same case model, exported as the same format, from two different BIM tools will be compared visually and analytically. Converted data from the pre-processing tools will also be similarly compared to conclude about software use and effect over the final input information for simulation in EnergyPlus.

3. **Whether or not quality of translated building data has an impact over simulation and generated results?**

   Considering previously gained knowledge (1. and 2.), the results from the simulations will be individually investigated and additionally compared to results from reference models, created separately in EnergyPlus for the purpose of evaluating automated translation of the building data for each case.

2.3 Selection of Software

It is important to understand how the core process develops. Consecutive steps and actions are denoted by the application of stand-alone tools used for creating, transforming and simulating building geometry. Each of the operations is a prerequisite for smooth interoperability between the BIM authoring tool and EnergyPlus.

The optimal decisions are made, regarding the choice of software, based on:

- careful research
- personal experience and knowledge

2.3.1 The BIM model

It all begins with the creation of the BIM model. Robertson and Perera (2002) point out that collection of data is one of the most critical parts in the simulation process. Therefore, it is essential that the original model is populated with information enabling successful creation of BEM.

Tobias Maile et. al. 2013 outline general guidelines for the geometry modelling of *"clean"* BIM models, used for energy performance simulations. It is important to understand the simulated physical processes, because they define the requirements for the contained information in the building model. And for heat transfer simulation important geometry elements are:

- surface area
- material properties
- relationship between surfaces and spaces
- relationship between materials and their properties and the surfaces
- relationship between two opposite surfaces for internal heat transfer

For that purpose, the chosen BIM- authoring software should have the tools to define building geometry and space, and their physical characteristics accordingly. The leading BIM- authoring tools nowadays are Autodesk Revit (Autodesk 2014), Graphisoft ArchiCAD (Graphisoft 2014), Bentley Microstation (Bentley Systems 2014), Nemetschek Vectorworks, Allplan (Nemetschek 2014), TEKLA (TEKLA 2014) (*Figure 4*). It seems that the current market share is notably dominated by Revit and ArchiCAD and so they are the chosen ones for the research of this paper.

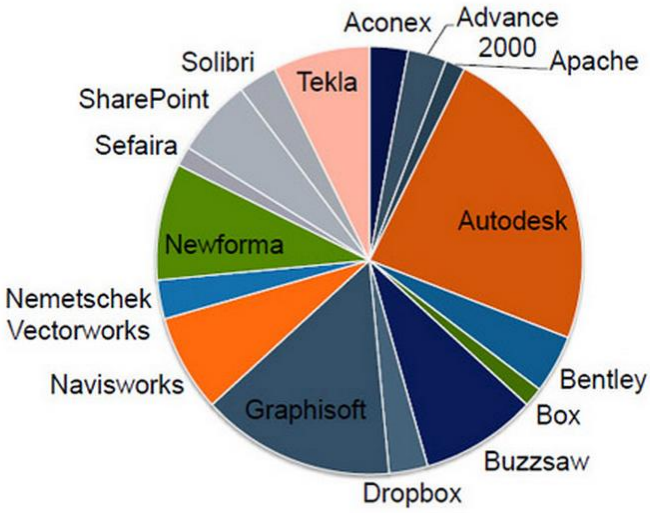


Figure 4: BIM solution tools for integrated work (Aconex survey 2013)

Revit

Autodesk Revit has been developed by Autodesk Inc. as a BIM platform in which 3D parametric tools for architectural, structural and MEP building design are available. It enables integrated design and offers open BIM through export of IFC and gbXML, as well as other formats. For the above-mentioned building model requirements, Revit provides generic parametric building components which can be modified and customized to the specific project (*Figure 5*).

In Revit building envelope components are defined as internal or external, such as Walls and Floor slabs, except for Roofs. When drawing in 3D space location parameters are set, such as levels and offsets, which account for surface areas and connection between elements, respectively for space design as well. Composite elements are described in the Properties bar, where materials are assigned to the separate layers, as well as their thickness, arrangement and physical properties. For spatial definition of the model, building elements are construed as either room/space bounding or not. The Space tool in the Analyze tab allows spatial information to be added to the model automatically, implied by the designed physical characteristics of the building elements.

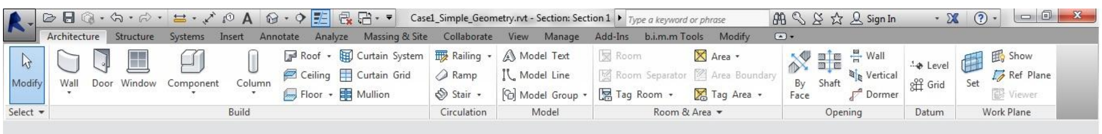


Figure 5: Revit main tab for building elements modelling

Revit has an integrated gbXML export configuration interface (Autodesk 2014), which validates the exported model through a rule- based verification process, checking if spaces and geometry are properly defined in accordance to the gbXML schema (*Figure 6*).

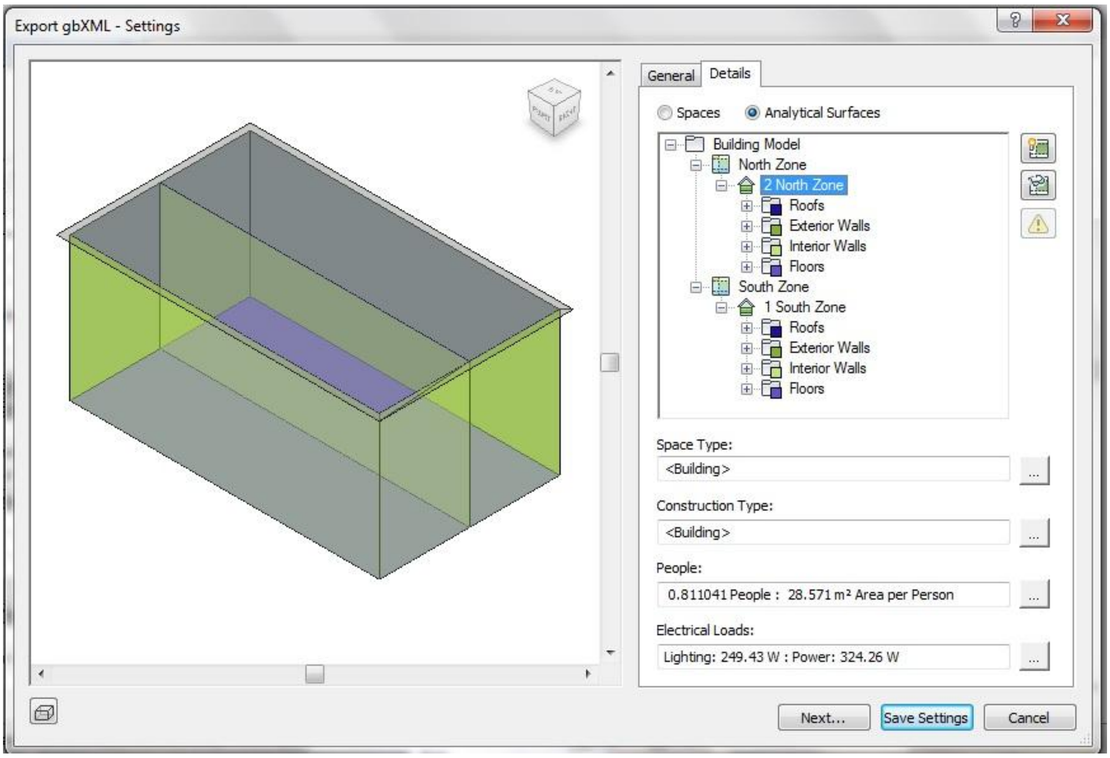


Figure 6: Revit export dialogue for gbXML

For IFC export, Revit has been certified by buildingSMART (buildingSMART 2014) and integrates an export interface via which the data to be extracted can be configured to comply with the exchange requirement of the view, and is coordinated with MVD (*Figure 7*). In addition, the elements in the building model are supported by an IFC global ID, ready for export.

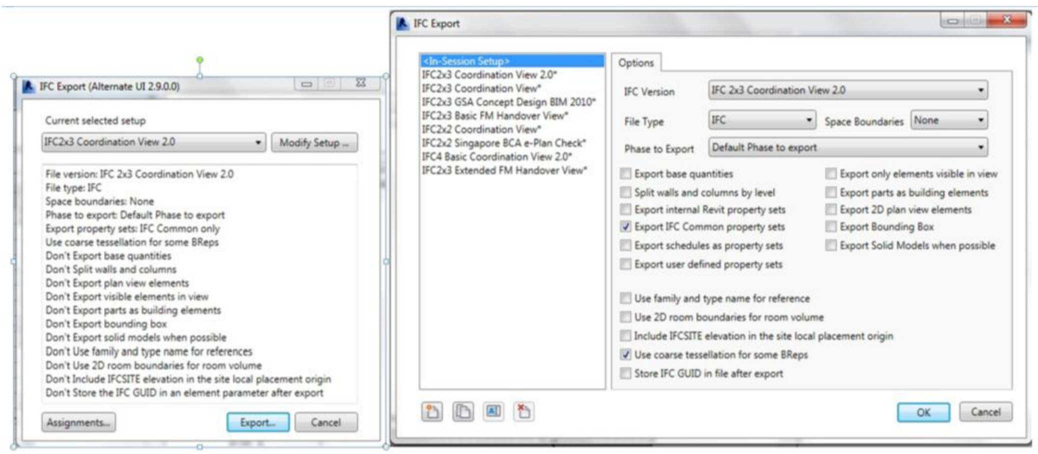


Figure 7: Revit export dialogue for IFC

ArchiCAD

ArchiCAD is a product of Graphisoft, which also uses parametrically defined building objects and thus supports BIM collaborative work. In principle it uses the same conventions for modeling building geometry as Revit (*Figure 8*). It uses slightly different definitions and principles of work when it comes to preparing the model for IFC and gbXML export.

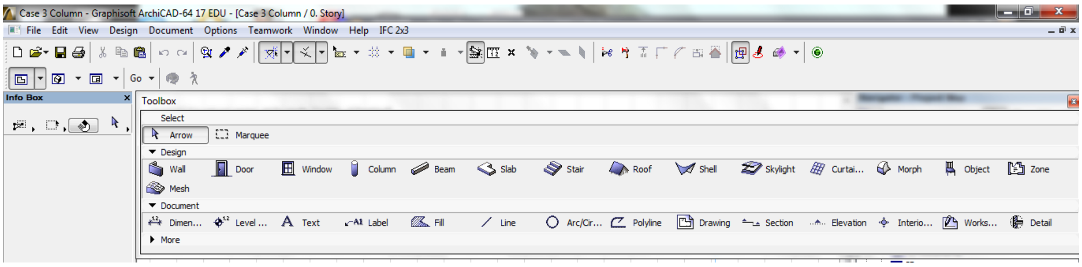


Figure 8: ArchiCAD main toolbox for building modelling

For gbXML export, additional Zone (equivalent of Space/Room in Revit) should be manually defined on the external side of the building envelope. Furthermore, the export function is done via a plug-in for gbXML export.

Those and other differences in the modelling and export definition might potentially affect the native data, which is extracted in the gbXML and IFC from the original BIM model. Therefore, both programs will be used separately to generate case building models.

2.3.2 The BEM model

As earlier mentioned, the Building Energy Model (BEM) is derived from the original BIM model and is the analytical data necessary for building performance simulation (Jones et al. 2013). That is, the building geometry and spatial model with the associated energy and thermal performance specifications needed for thermal simulation. Certain level of precision is required when extracting and converting data from BIM to BEM. Manual translation of such information is sometimes a tedious process, especially in more complex projects, so energy engineers tend to simplify or modify the model according to their knowledge and experience. This often leads to errors and questionable results from the simulation. In effect, such inconsistencies are omitted in an automated process, where gbXML or IFC are used to extract the needed data and the receiving analysis software obtains it through its implementation scheme for the respective format. The purpose of this action is to create a suitable data repository for energy simulation.

This operation applies in cases when there is no direct import of the data format to the energy simulation tool, as it is the case with EnergyPlus. Therefore the pre-processing software should also have the function to map elements from the gbXML coordinate schema and object classes from the IFC structure to EnergyPlus Input Data Dictionary (IDD) format in Input Data File (IDF) (U.S. Department of Energy 2014). For the benefit of this thesis and the process, such tools will be referred to as "BEM tools".

In the current situation and based on the information described before, the chosen pre-processing BEM tool, should be able to:

- import gbXML/ IFC data format
- retrieve accurate building geometry and spatial information
- integrate simulation functions with EnergyPlus or export IDF format

In the list of approved building energy software tools, provided by U.S. Department of Energy, there are several programs which can import 3D CAD data and use it for thermal loads calculation, HVAC or CFD analysis (U.S. Department of Energy 2014), however not in compliance with EnergyPlus. Their interoperability with the data formats will not be discussed in this paper.

gbXML BEM tool

The wide adoption of the gbXML data format into energy analysis software accounts for the many different scenarios of building performance analysis results. The reason is namely the implementation schema of the vendor programs, which decide which elements to import from the gbXML coordinate data to retrieve geometry (gbXML Implementation Guide 2013). gbXML elements are planar representation of collection of surfaces, defining building elements' geometry associated to thermal spatial configuration. Therefore their accurate conversion to Space Boundary surfaces depends on the receiving BEM modelling tool and its ability to assign such properties to the correct element.

Observing the requirements for successful simulation, mentioned above, the chosen BEM modelling tool should be able to precisely process the original building data and convert it to comprehensive analytical representation for simulation in EnergyPlus.

DesignBuilder

DesignBuilder supports the import of 3D CAD data and BIM through gbXML and allows energy design and simulation via EnergyPlus simulation engine (DesignBuilder 2014). It provides comprehensive and accurate 3D visual interface to thermal design specifications for the BEM model, by consuming the SpaceBoundary and Surface element of the gbXML coordinate schema. The integration with EnergyPlus environment allows for easier communication between the BEM model and the simulation tool. DesignBuilder also allows for IDF export, by mapping building elements to IDD format, preparing the BEM model for simulation in EnergyPlus. As a result, DesignBuilder is chosen for this thesis as the intermediate processing program for converting gbXML data into a suitable data format for thermal simulation. In addition, DesignBuilder has developed an extensive tutorial (DesignBuilder 2014) on how to create an analytical model in Autodesk Revit for the purpose of extracting and simulating building geometry with gbXML in DesignBuilder.

IFC BEM tool

IFC has been approved as the industry's standard for open BIM, because of its robust schema, capable of storing relational information between all disciplinary building elements in a 3D model (ifcwiki 2014). Because of its broad and complex schema, buildingSMART has developed the MVD which specifies the implementation of a subset from the IFC structure, related to Building Performance and described in the IDM. Several attempts have been made through the years to employ IFC into the BPS process, however inconsistency in the implementation by CAD vendors persists, the biggest challenge being the transformation of thermal space boundary geometry (Hitchcock and Wong 2011). As a result, the use of IFC in BPS has been regarded less, despite its possibility to store such data (buildingSMART 2014).

IFC Space Boundary Tool

An attempt at Lawrence Berkeley National Laboratory (LBNL 2014) has made some progress in that direction, by introducing a semi-automated process tool, called Space Boundary Tool (SBT-1) that retrieves building and spatial geometry data from the IFC schema and breaks it down to heat transferring surfaces. SBT-1 has been made commercially available and in its current and only version it imports IFC2x3 Coordination View 2.0, an earlier variant of the IFC schema, and exports v. 7.2 IDF format for EnergyPlus. Space Boundary Tool, or SBT-1 for short, has been developed by LBNL as the first of three component tools that are supposed to maintain semi- automated acquisition, translation and input for energy models (O'Donnell et al. 2013). SBT-1 is dealing with building geometry, while the second one would add internal loads to the model, and finally the HVAC one, also known as Simergy, acts as the graphical interface for EnergyPlus. At the time of writing, the only advanced of the three components is Simergy, which with its latest release has abandoned the import for gbXML and IFC (Simergy 2014).

SBT-1 is a rudimentary, standalone tool that consumes IFC and converts it to BEM in two steps. In the first sub process SBT-1 imports IFC rich geometry and adds space boundaries to it, determined by the relationship of geometry and space in the IFC (*IfcRelBoundary*). In the second, the space boundaries are converted into suitable for BEM heat transfer representations, with construction materials added to match the EnergyPlus IDF syntax. The produced IDF file contains space boundaries of 1st, 2nd or 3rd level (up to 5th), which determine the character of the thermal surface, i.e. whether it is external, internal or adiabatic relationship to the space they bound. The definition of the different levels of Space Boundaries is described in *An algorithm to generate space boundaries for building energy simulation,* (Rose and Bazjanac 2013), as follows:

- *1st level space boundaries are continuously visible regions of building element surfaces*
- *2nd level space boundaries are regions of 1st level space boundaries with a rate of one- dimensional thermal flow that is constant across their area.*
- *3rd level space boundaries are regions of 1st level space boundaries with no one-dimensional thermal flow through them due to the lack of an "other side" for heat to flow (adiabatic).*
- *4th level space boundaries are regions of 1st level space boundaries with no one-dimensional thermal flow through them and would be part of a 3rd level space boundary but for specific reference line placements in a generating CAD application.*
- *5th level space boundaries are regions of 1st level space boundaries that have no one- dimensional thermal flow through them due to the presence of angled building geometry*.

2.3.3 EnergyPlus

EnergyPlus is the combined product of several research groups such as Lawrence Berkley National Laboratory (LBNL), US Army Construction Engineering Research Laboratory (CERL), the US Department of Energy (DOE) (Maile et al. 2007; U.S. Department of Energy 2014) and several others, and is based on the best features of two energy simulation programs- DOE-2 and BLAST developed initially in the 1970s and 1980s. In its algorithm it integrates loads and systems simulation, providing architects and engineers with more coherent results about building performance design. The heat balance algorithm is formulated on actual thermodynamic equations and the load calculations are developed after ASHRAE thermal comfort standards.

For this thesis, however, the focus will be on results of thermal loads in different zones, in order to define heat transfer through building surfaces. In reality, those results should act as indicators for choosing a building services system in the early stage of a project (Paradis 2010).

EnergyPlus accepts the IDF file (EnergyPlus 2014), which contains or should contain all the original parameters of a building model, defined in a BIM - authoring tool. In other words the IDF file has the variables enabling the algorithm of the *mathematical model* (Stanford Encyclopaedia of Philosophy 2013) to run a *simulation*. In the end, the generated results should represent the *approximate behaviour* of an actual building, deeming the input parameters as an essential part of the whole process.

2.4 Case Study Models

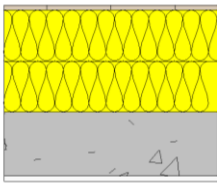
The main objective for the design of the Case Study models is to incorporate building elements, which have been frequently reported to have problems with geometry during export of either gbXML or IFC (Hitchcock and Wong 2011; Moon et al. 2011). The principle design will be kept as simple as possible in order to focus on more important issues during the process of BPS. Doing so will also give the opportunity to closely investigate the features of the given workflow and data format behaviour and in addition to more easily detect potential errors and observe obstacles in geometry and spatial translation.

All Case Studies contain basic geometry (walls, floor, roof) with certain thermal specifications defined (*Table 2 to* Table 5*)* and at least one space (zone) is assigned. Those are regarded as the minimum requirements for thermodynamic processes to be simulated.

The thermal specifications of the building elements are defined to be the same for all cases:

Table 2: Physical properties of the external wall construction for the case models.

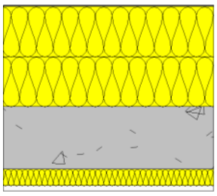
External Wall - 415mm, U-value - 0,14$Wm^{-2}K^{-1}$



Material	Thickness [mm]	Thermal Conductivity λ [$W(m{\cdot}K)^{-1}$]
Rendering	12	0.72
Rigid Insulation	120	0.035
Rigid Insulation	120	0.035
Precast Concrete	150	1.046
Vapour Retarder	0	0.167
Gypsum Wall Board	13	0.65

Table 3: Physical properties of the roof construction for the case models.

Roof - 446.2 mm, U-value - 0,12$Wm^{-2}K^{-1}$



Material	Thickness [mm]	Thermal Conductivity λ [$W(m{\cdot}K)^{-1}$]
Bitumen	1.6	1.15
Bitumen	1.6	1.15
Rigid Insulation	120	0.035
Rigid Insulation	150	0.035
Precast Concrete	150	1.046
Rigid Insulation	40	0.035
Plaster	13	0.51

Table 4: Physical properties of the ground floor slab construction for the case models.

Ground Floor Slab - 400 mm, U-value - 0,17$Wm^{-2}K^{-1}$

Material	Thickness [mm]	Thermal Conductivity λ [$W(m{\cdot}K)^{-1}$]
Concrete Screed	50	1.046
Precast Concrete	150	1.046
Rigid Insulation	100	0.035
Rigid Insulation	100	0.035

Table 5: Physical properties of the roof construction for the case models.

Internal Wall - 116mm, U-value - 4.84Wm^{-2}K^{-1}			
	Material	Thickness [mm]	Thermal Conductivity λ [W(m·K)$^{-1}$]
	Gypsum Wall Board	13	0.65
	Common Brick	90	0.54
	Gypsum Wall Board	19	0.65

Additionally:

- Window Low E Double Glass: 2x1.5m; 5.8x3.5m U-value 1.75Wm^{-2}K^{-1} and g= 0.62
- External Door Timber: 910x2110mm
- Internal Concrete Floor: 150mm

Cases 1 to 3 aim (*Figure 9* to *Figure 11*) at observing translation of basic geometry, Space Boundaries and Space/Zone definitions when there is a physical space boundary between zones, as well as description and interpretation of structural elements into BPS elements.

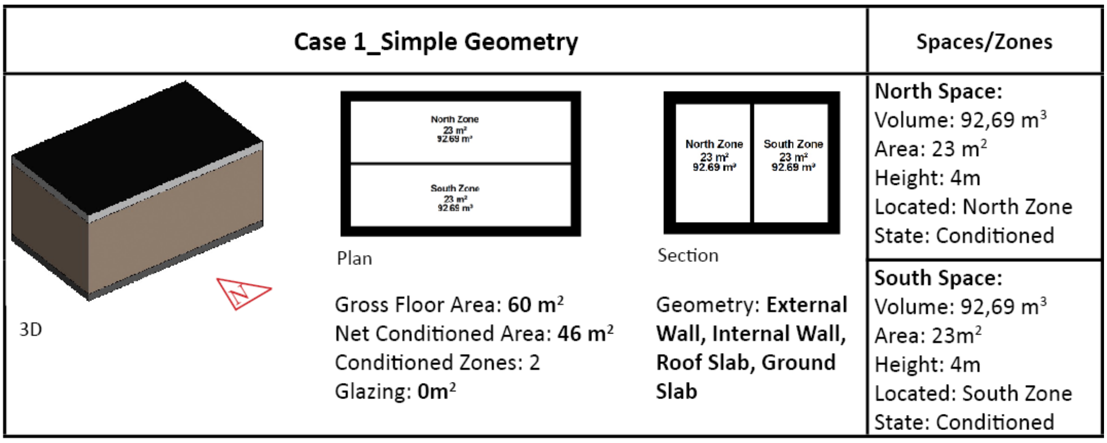


Figure 9: Case 1_Simple Geometry

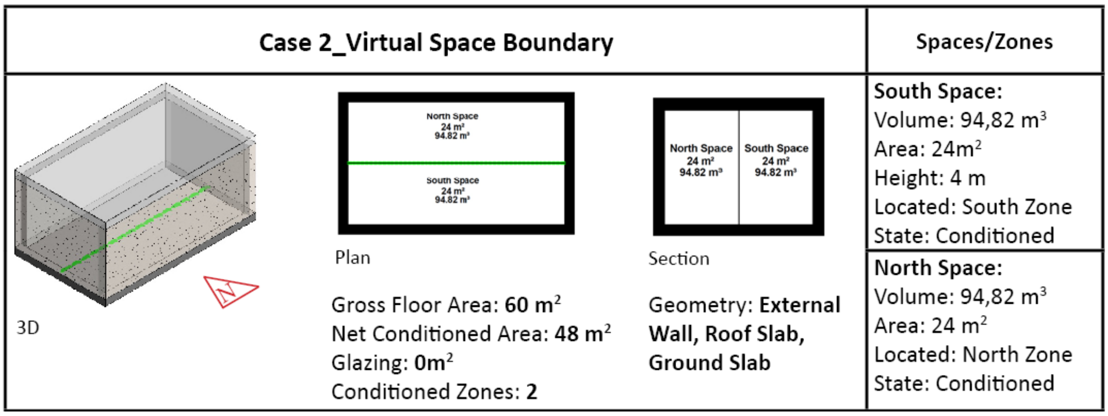


Figure 10: Case 2_Virtual Space Boundary

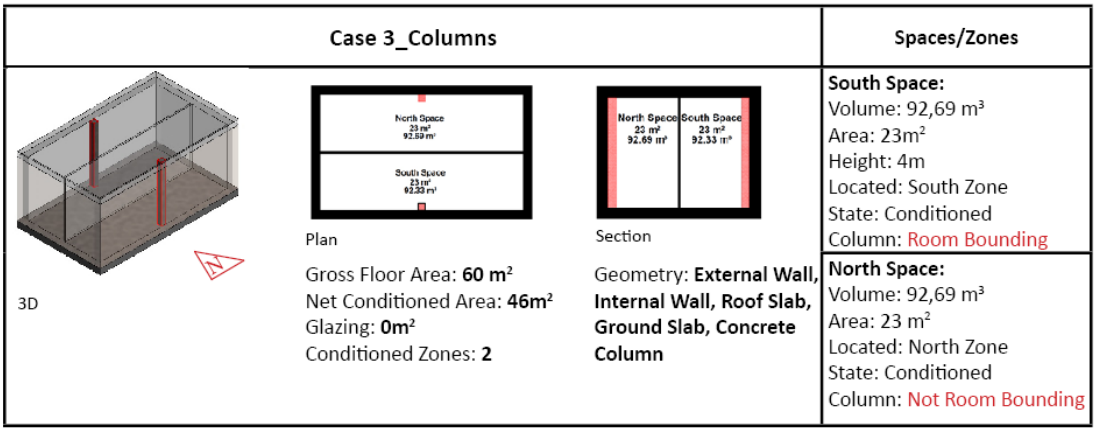


Figure 11: Case 3_Columns

Cases 4 and 5 (*Figure 12* and *Figure 13*) are developed to examine behavior of sub- surfaces such as windows and doors and their transformation into thermal space boundaries

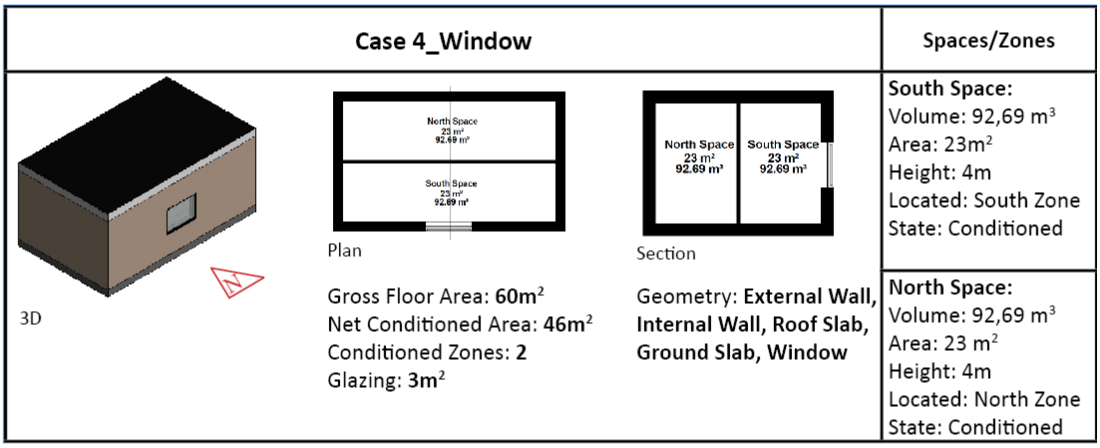


Figure 12: Case 4_Window

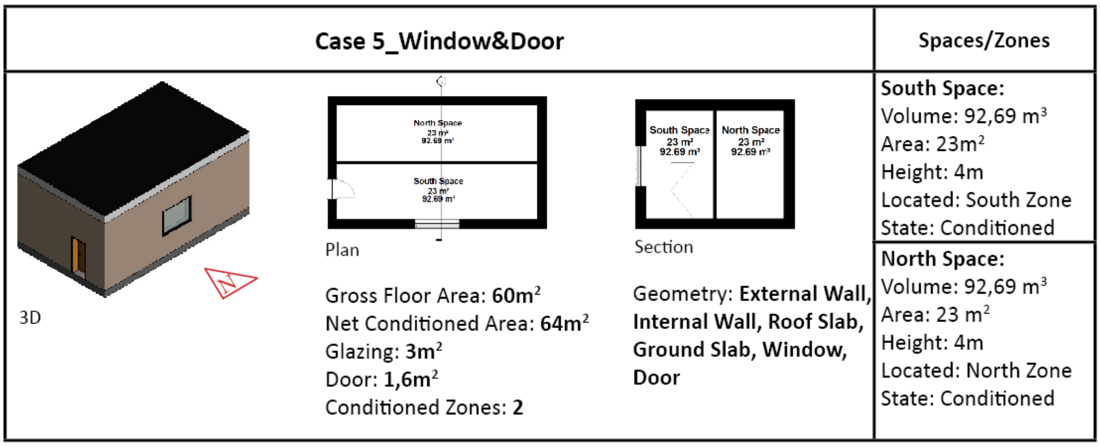


Figure 13: Case 5_Window and Door

Cases 6 to 8 (*Figure 14* to *Figure 16*) are dealing with commonly reported problems in translation of modelled shading elements, as well as architecturally occurring overhangs and overshadowing parts.

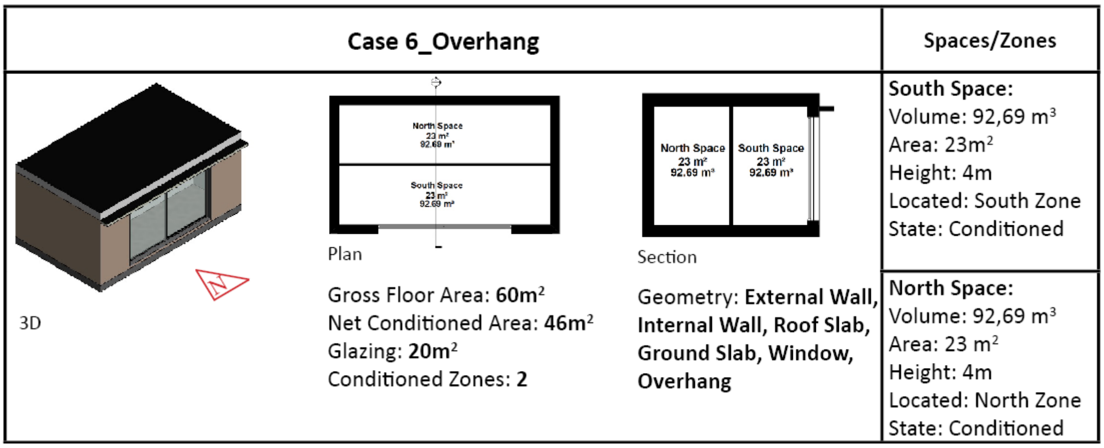


Figure 14: Case 6_Overhang

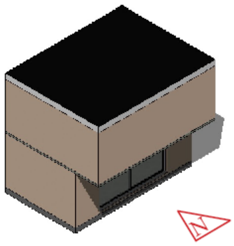
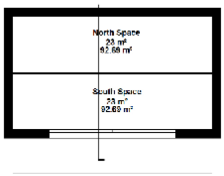
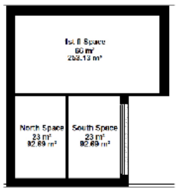
Case 7 Terrace			Spaces/Zones
 3D	 Plan Gross Floor Area: **140m²** Net Conditioned Area: **112m²** Glazing: **20m²** Conditioned Zones: **3**	 Section Geometry: **External Wall, Internal Wall, Roof Slab, Ground Slab, Window, External Floor Slab**	**South Space:** Volume: 92,69 m³ Area: 23m² Height: 4m Located: South Zone State: Conditioned
			North Space: Volume: 92,69 m³ Area: 23 m² Height: 4m Located: North Zone State: Conditioned
			1st Floor Space Volume: 253m³ Area: 66m² Height: 4m Located: 1st Floor Lvl State: Conditioned

Figure 15: Case 7_Terrace

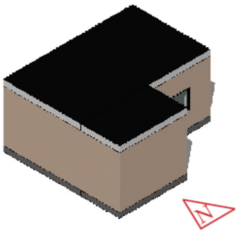
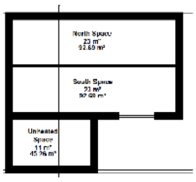
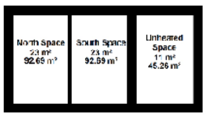
Case8 Overshadowing			Spaces/Zones
 3D	 Plan Gross Floor Area: **76m²** Net Conditioned Area: **46m²** Glazing: **3m²** Conditioned Zones: **2**	 Section Geometry: **External Wall, Internal Wall, Roof Slab, Ground Slab, Window**	**South Space:** Volume: 92,69 m³ Area: 23m² Height: 4m Located: South Zone State: Conditioned
			North Space: Volume: 92,69 m³ Area: 23 m² Height: 4m Located: North Zone State: Conditioned
			Unheated Space: Volume: 45m³ Area: 11m² Height: 4m Located: Unheated Zone State: Unconditioned

Figure 16: Case 8_Unheated Space

Finally, cases 9 and 10 (*Figure 17* and *Figure 18*) contain complex roof slab geometries, which are bound to cause issues in the definition of space boundaries due to their irregular position in 3D space.

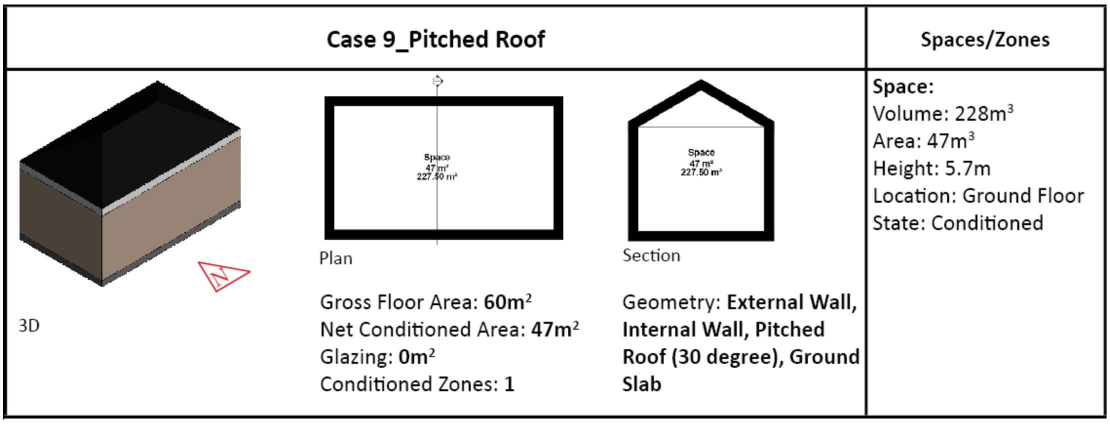


Figure 17: Case 9_Pitched Roof

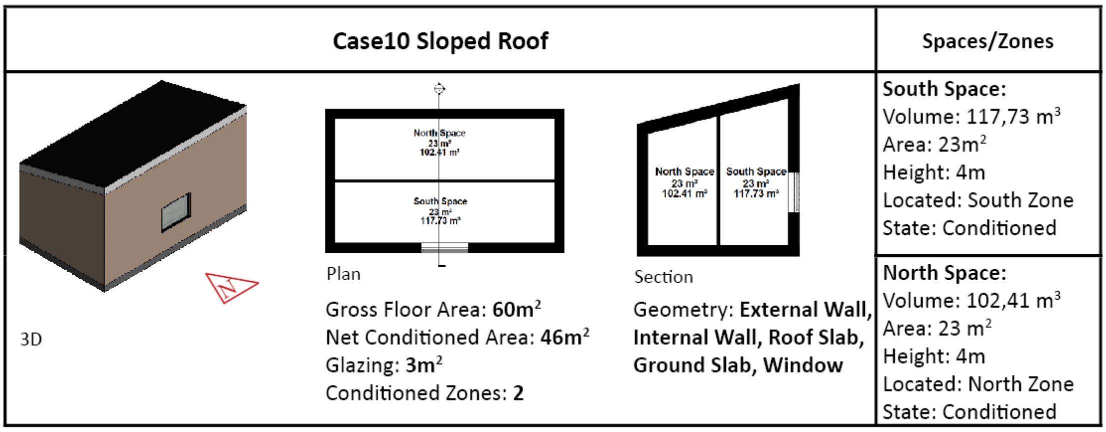


Figure 18: Case 10_Sloped Roof

Validation of the developed models in the BIM- authoring tool is not done. Instead, careful measures are taken in order to ensure the quality of the geometrical and parametric information in the BIM models, following the guidelines described in Tobias Maile et al. 2013. The designed geometry is kept uncomplicated so that it is a straightforward creation process, using basic parametric building elements in the BIM's software toolbox. The relationships between the components is maintained by the programs themselves (Autodesk Revit 2014; Graphisoft ArchiCAD 2014) thus providing *"clean"* connection for geometry and space.

2.5 Performance Study

The process of generating, extracting and transforming building geometry for the purpose of BPS is defined by an array of actions, necessary for successful workflow. These operations are visible in *Figure 20* and are done in consecutive steps and in different stages to outline a workflow, which will be investigated for the purpose of comparing the behaviour of the data formats.

1. BIM Case model design- case models are created in parallel in both Revit and ArchiCAD using identical definitions for the building elements and space with the available corresponding tools. The input parameters for modelling the building examples are the same in both BIM authoring tools, that way ensuring equal data basis for export.

The generated case study model is then exported and saved as gbXML and IFC format in the specified by the BIM program way. That means:

- Revit: one gbXML and one IFC
- ArchiCAD: one gbXML and one IFC

In order to verify the quality of the extracted data, the IFC files are imported into Solibri Model Viewer (*Figure 19*), a rule based software, checking for inconsistencies in the physical relationship of building geometry elements (Solibri 2014). It has been developed as part of the open BIM platform and provides robust algorithm based standards, which detect incorrect parametric definitions. The results are displayed in a table that informs the user about the errors in the model that do not comply with the rules.

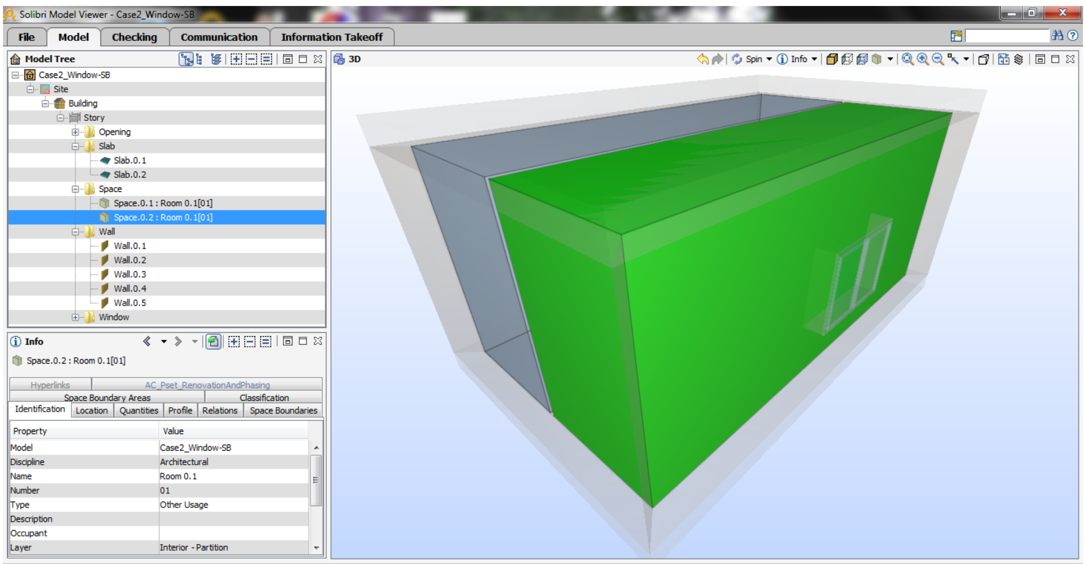


Figure 19: Solibri Model Viewer interface

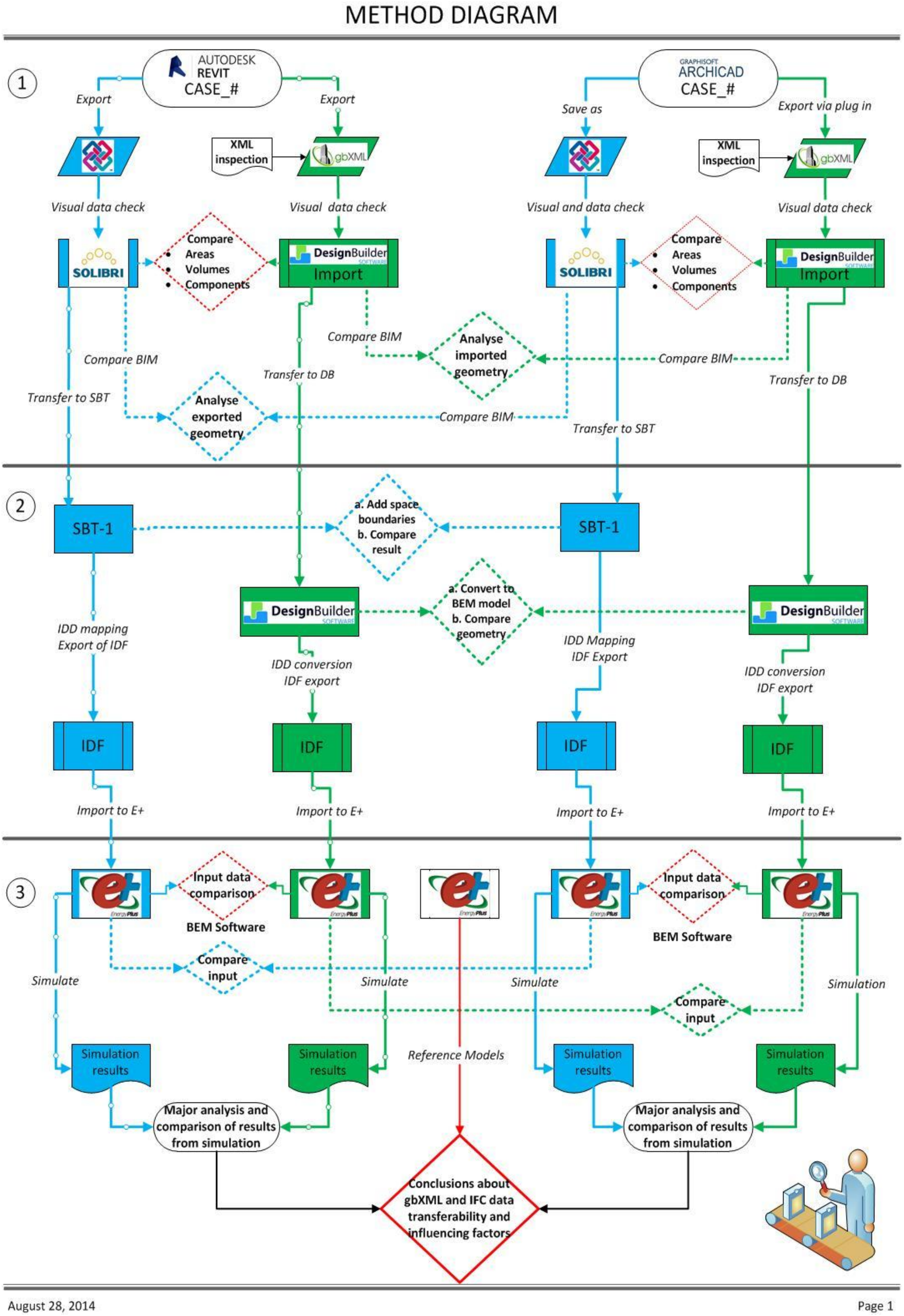


Figure 20: Method Diagram

Green Building XML, on the other hand, has only recently provided an online gbXML Validator (gbXML 2014) which uses pre-programmed test cases to compare and verify the schema of a generated gbXML. This however is not very helpful since all cases are unique and further developments should be awaited. gbXML can be verified in Revit export dialogue, or alternatively in the exported XML file(*Figure 21*).

```xml
<Surface id="su-8" surfaceType="ExteriorWall" constructionIdRef="ASHWL-66">
        <Name>N-4-E-W-8</Name>
        <AdjacentSpaceId spaceIdRef="sp-4-North_Space">
        </AdjacentSpaceId>
        <RectangularGeometry>
                <Azimuth>0.000000</Azimuth>
                <CartesianPoint>
                        <Coordinate>9.585000</Coordinate>
                        <Coordinate>5.585000</Coordinate>
                        <Coordinate>0.150000</Coordinate>
                </CartesianPoint>
                <Tilt>90.000000</Tilt>
                <Height>4.446200</Height>
                <Width>9.585000</Width>
        </RectangularGeometry>
        <PlanarGeometry>
                <PolyLoop>
                        <CartesianPoint>
                                <Coordinate>0.000000</Coordinate>
                                <Coordinate>5.585000</Coordinate>
                                <Coordinate>0.150000</Coordinate>
                        </CartesianPoint>
                        <CartesianPoint>
                                <Coordinate>0.000000</Coordinate>
                                <Coordinate>5.585000</Coordinate>
                                <Coordinate>4.596200</Coordinate>
                        </CartesianPoint>
                        <CartesianPoint>
                                <Coordinate>9.585000</Coordinate>
                                <Coordinate>5.585000</Coordinate>
                                <Coordinate>4.596200</Coordinate>
                        </CartesianPoint>
                        <CartesianPoint>
                                <Coordinate>9.585000</Coordinate>
                                <Coordinate>5.585000</Coordinate>
                                <Coordinate>0.150000</Coordinate>
                        </CartesianPoint>
                </PolyLoop>
```

Figure 21: XML schema of exported gbXML model

2. BEM Creation and IDF export

In the second phase formats are imported in the respective BEM modeling tools:

- IFC into SBT-1

The first step in using SBT for converting rich IFC geometry into analytical surfaces for simulation is to add Space Boundaries to the model. After this is done, the number of 1st, 2nd, 3rd level Space Boundaries is displayed (*Figure 22*). This is where the imported information from both IFC files will be compared again in order to examine BIM definitions from Revit and ArchiCAD.

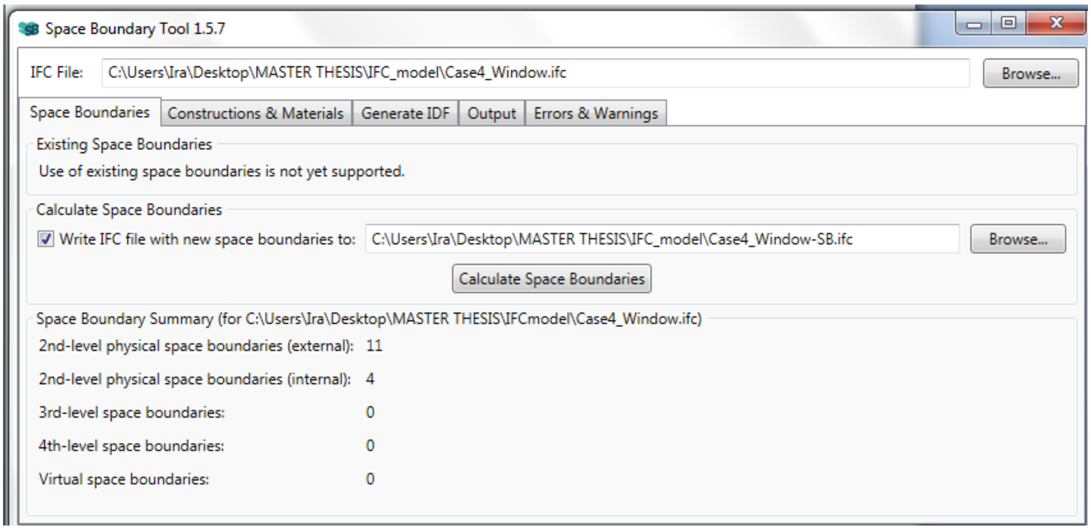


Figure 22: Space Boundary Tool interface

- gbXML into DesignBuilder

Imported Surfaces and Spaces are checked and compared into DesignBuilder 3D window and model tree, located to the left in the software's interfaces (*Figure 23*).

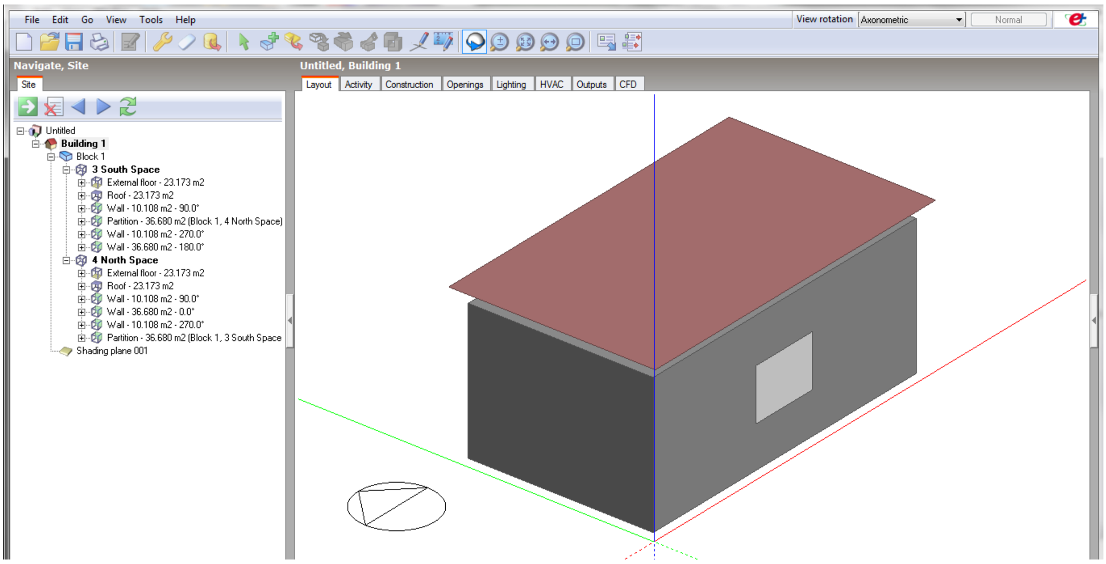


Figure 23: DesignBuilder Interface

After the BEM conversion IDFs are exported from SBT-1 and DesignBuilder. In addition SBT produces also a new IFC format which contains 2nd (or higher) level space boundaries.

3. Simulation

EnergyPlus offers enormous libraries of input parameters and gives many opportunities for alternative design options. In the current situation the point is to investigate the translation of building geometry data into space boundary coordinates, being the main input for thermal simulation. Therefore, the input parameters that will be scrutinized from the EnergyPlus v. 8.1 values in IDF editor window are:

- ***SiteLocation***- specifies the location of the building.
- ***GlobalGeometryRules***- indicates the method used to describe the input vertices of building surfaces.
- ***Zone***- defining the thermal zones in a project with their geometry and thermal specifications.
- ***BuildingSurface:Detailed***- this field contains the input values for heat transfer surfaces (walls, slabs), or Space Boundaries as earlier described. Their vertices and coordinates are denoted here.
- ***FenestrationSurface:Detailed***- geometry of heat transfer sub- surfaces is represented such as windows and doors.
- ***ShadingBuilding:Detailed-*** description of shading elements, which are relative objects and move with relative building geometry.

Once those input parameters are in place the model can be simulated and the respective results can be generated in various formats for inspection. There are several points, which will be important to review in the *AllSummary Report*, generated by EnergyPlus after simulation. A list of tables and figures are described in the general report, available in an HTML format, which will allow for careful analysis of certain indicators and comparison between the gbXML and IFC building model information:

- ***Site and Source Energy***- a table showing early energy use in kWh and $kWhm^{-2}$.
- ***Input Verification and Results Summary***- in this table the entry values for the simulation visible are, including building envelope data and performance parameters for thermal zones.
- ***Climatic Data Summary-*** containing information about the weather statistics data file, thermal performance of building elements, their opacity and gross area.
- ***Object Count Summary-*** shows the number of heat transfer surfaces entered as input for simulation. It will be easy to compare the number of Space Boundaries and related geometry.

In addition other points might be investigated, depending on the case study.

2.5.1 Evaluating Criteria

According to Maile et al. 2013, to achieve a successful simulation, there are a few criteria to which the process should respond to:

1. *First, the model in the originating application needs a certain level of quality.*
2. *Second, the originating application needs to successfully save the model into a data format.*
3. *Third, the used data format needs to be able to store all required information.*
4. *Fourth, the receiving application needs to successfully import the model from the data format.*

In addition is the definition by Bazjanac et al., 2011, which points to :

1. *Valid data.*
2. *Simulation software capable of using the data to properly evaluate the given design decision.*
3. *Analysis of simulation results that focuses on that design decision.*

While both sets of norms manage to overlap in the requirements about clean data, they also complement each other in the sense of interoperability between data formats and software. The stress is on the fact that even if some of the data are incorrect or not properly defined the results of the simulation could be questioned and even considered invalid (Bazjanac et al. 2011), making the need for accurate process a demand for successful simulation and reliable results.

Ultimately, the whole process of BPS is a collection of series of steps and operations, which logically have influence over each other. Based on the afore-mentioned requirements, the performance of the data structures (gbXML and IFC), their transferability of data will be evaluated with consideration to the efficiency and impact of the chosen programs.

Translation of Geometry

With effect to the correctness of the building data, which is input for simulation, the translation of building geometry information will be monitored in the different stages of the transition process.

Essentially, the major comparison and evaluation happens at the time of importing data as IDF to EnergyPlus, before simulating the case models. That is a detailed review of coordinates of the building elements and thermal performance parameters within the

EnergyPlus environment, as described before. The aim is to observe how and to what extent the exported data has been influenced by the pre-processing software.

Correct geometry would mean 100% matching of coordinates to the original BIM data and definitions of space boundaries. The elements that will be investigated at this point are: *Volume, Area* and *Geometry*, all of which account for the successful input for thermal simulation.

Workflow

The point will be to evaluate the advantages or disadvantages of conducting certain operations associated with a format or software tool. The workflow comprises also the amount of work and manual input to the process and how that can potentially affect the flow of information. Analysing the results and feeding back the information are also a factor in assessing the overall use of gbXML and IFC in conducting BPS.

Reliability of Results

As earlier mentioned, results from simulation of Case study models will be examined in EnergyPlus to find out whether there is a significant difference between gbXML or IFC generated data and what kind of effect it might have on BPS. The data for building geometry will be reviewed and energy consumption for the *Total Net Conditioned Area* (kWhm^{-2}) will be checked as a reference value for comparing the outcome from the different models.

The reliability of results will be discussed in direct connection to the correctness of geometry and its potential effects over the results from performance simulations. In other words it is a relevant point to the usability of the formats.

3 RESULTS

3.1 Overview

In an overall view and with regards to the general performance of gbXML and IFC data structures it is possible to say that both provide high level accuracy in extracting and storing building geometric data, however the final input for simulation is determined by the use of different programs. In other words, BIM authoring tools as well as BEM pre-processing tools and their employment have a significant impact over the exported geometric information that reaches the simulation engine. The following results are described, in the order of the conducted Performance Study.

3.1.1 Retrieved Geometry and Space (Step 1)

For the first stage of the workflow the comparison of building data is done with the extracted geometric information from the BIM authoring tools in gbXML and IFC. The summary of the performance of the two formats is presented below in Table 6. The analysed parameters in the retrieved formats for each case are:

- **Volume**(within space boundaries of Spaces)
- **Area** (net floor area of Spaces)
- **Geometry** (building components, structural elements, openings)

Table 6: *Comparison of extracted gbXML and IFC data*

Extracted building data	gbXML		IFC	
	Revit	ArchiCAD	Revit	ArchiCAD
Case1_Simple Geometry	✓	✓	✓	✓
Case2_Virtual Boundary	✓	✓	✓	✓
Case3_Column	✓	✓	✓	✓
Case4_Window	✓	✓	✓	✓
Case5_Window and Door	✓	✗	✓	✓
Case6_Overhang	✗	✓	✓	✓
Case7_Terrace	✓	✓	✓	✓
Case8_Unheated Space	✓	✗	✓	✓
Case9_Pitched Roof	✓	✓	✓	✗
Case10_Sloped Roof	✓	✗	✓	✓
Measured accuracy	90%	70%	100%	90%

Measured accuracy is the percentage (%) of correct data obtained by the formats in all ten case models, where precise building information in each model equals 10% of the whole ten (100%).

As Table 6 shows, there is high level of accuracy in the exported building data. The analysis are done by inspecting the generated XML files of gbXML and visualizing the IFC models in Solibri Model Viewer. Details of this process are described further in the individual Case Model Study.

3.1.2 Conversion of building data to BEM (Step 2)

In the second stage the extracted data is imported into the respective pre-processing BEM tool for the conversion of the data into analytical surfaces for heat thermal simulations and IDF creation. Some of the errors were noticed to have been caused by the definition of the native model in the BIM- authoring tool and some are due to the technical performance of the intermediate tools.

In this case the *Measured accuracy* of the data formats shows how the extracted information in gbXML and IFC has changed, again as a % of the total number of case models.

For the gbXML format, where relevant analytical surfaces are already defined in the gbXML scheme structure, DesignBuilder imports those elements, which describe the geometry most accurately. However as it can be seen from *Table 7*, it does not support all necessary representations of geometry and will be further discussed.

Space Boundary Tool, or SBT-1, as pre- processing tool for IFC, converts complex building geometry into associated space boundary representations. In a sense, it is a straightforward process which is defined by the modelled geometry relationships in BIM and the space boundary generative algorithm in SBT. What can be also seen in *Table 7* is that processed building data of the same models, but different BIM authoring tools, gives different results.

Table 7: Comparison of BEM generated data from gbXML and IFC

BEM generated building data	gbXML-DB		IFC- SBT-1	
	Revit	ArchiCAD	Revit	ArchiCAD
Case1_Simple Geometry	✓	✓	✓	✓
Case2_Virtual Boundary	✗	✗	✓	✓
Case3_Column	✓	✓	✗	✓
Case4_Window	✓	✓	✓	✗
Case5_Window and Door	✓	✗	✓	✗
Case6_Overhang	✗	✓	✓	✗
Case7_Terrace	✓	✓	✓	✗
Case8_Unheated Space	✓	✗	✓	✗
Case9_Pitched Roof	✗	✗	✓	✗
Case10_Sloped Roof	✗	✗	✓	✗
Measured accuracy	60%	50%	90%	30%

It also turns out, that the quality of the native BIM model has an effect over the performance of the transformed data. In other words, the same building components are defined differently in the BIM authoring tool and respectively geometry behaviour is affected by the pre-processing tool. More detailed analysis over this occurrence are further discussed.

3.1.3 EnergyPlus Simulation Results (Step 3)

In the next stage of the Performance Study, the transformed data formats are converted into IDFs and passed on to be imported and simulated into EnergyPlus.

IDD mapping and IDF input file

The IDD mapping occurs as an integrated action in the BEM pre-processing tools at the level of Export IDF function of both DesignBuilder and SBT-1. This is another important point in the whole process, which determines how the processed geometry and space are written out as IDF.

The reviewed parameters are again *Volume, Area* of spaces and *Geometry* of the model. Their values can be found in the IDF Editor workspace window of EnergyPlus under:

- ***Zone***
- ***BuildingSurface:Detailed***
- ***FenestrationSurface:Detailed***
- ***Shading:Building:Detailed***

their definition being explained previously.

It should be noted that those parameters, describing building geometry and heat transfer surfaces, have not been changed for the purpose of simulation and left as they were translated. The materials and the construction elements of the composite building elements however have been edited for gbXML and IFC to contain the same layers, with identical thermal properties respectively, found under ***Materials*** and ***Construction*** in the IDF Editor. The reason being that in the end, if any difference in the simulation results, then it can be claimed that geometry is the only influencing factor.

In the following *Table 8* it becomes clear straight away that many of the input parameters have been overwritten for the SBT-1 generated IDFs. In other words, the original BIM building data has been transformed incorrectly towards the end stage of the BPS. The gbMXL data has also suffered inconsistent conversion, however on a much different scale in comparison to the IFCs.

Table 8: IDF generated building data for input in EnergyPlus

IDF generated building data	gbXML-IDF		IFC-IDF	
	Revit	ArchiCAD	Revit	ArchiCAD
Case1_Simple Geometry	✓	✓	✗	✗
Case2_Virtual Boundary	✗	✗	✗	✗
Case3_Column	✓	✓	✗	✗
Case4_Window	✓	✓	✗	✗
Case5_Window and Door	✓	✗	✗	✗
Case6_Overhang	✗	✓	✗	✗
Case7_Terrace	✓	✓	✗	✗
Case8_Unheated Space	✓	✗	✓	✗
Case9_Pitched Roof	✗	✗	✗	✗
Case10_Sloped Roof	✗	✗	✗	✗
Measured accuracy	60%	50%	10%	0%

In this case *Measured accuracy* is referring again to the accuracy of the given data for input for EnergyPlus simulation, compared to the original BIM one. Due to the numerous ways EnergyPlus allows for geometry and space to be calculated, it appears that most errors occur in the *Zone* volume calculation and will be further discussed.

Simulation Results

In the final step of the BPS process, the input data coming from gbXML and IFC is simulated into the EnergyPlus simulation engine. In order to verify how realistic the results are ten models are created solely in EnergyPlus and also simulated, to act as a reference to the translated data. The input values have been inserted manually and are to represent each of the Case Models, including all the geometry, construction and materials. With the only difference that they describe and include the actual heat transfer surfaces and geometries as originally modelled. From the generated results the value for Total Site Energy (kWhm^{-2}) has been chosen as the reference value for comparison between all three kinds of simulation. The assumption is that for each case, all models should perform similarly (*Figure 24* and *Figure 25*), providing they have the same weather file, geometry, construction and thermal specification.

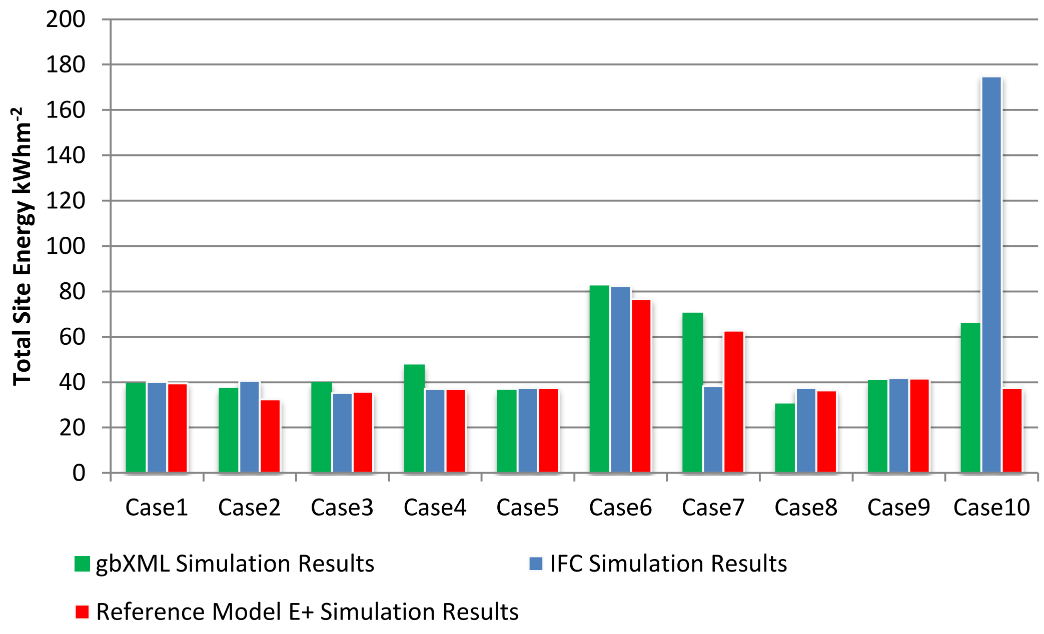


Figure 24: Comparison of simulation results- Revit

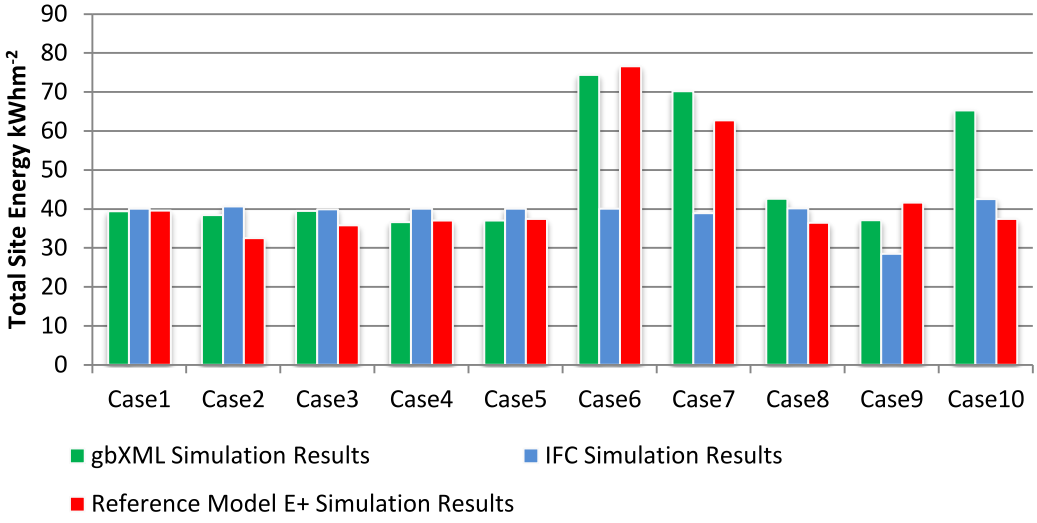


Figure 25: Comparison of simulation results- ArchiCAD

As it can be seen in the graphs above, the result values for Total Site Energy in each case and for both workflows are various and inconsistent. That will be also further discussed in the Discussion chapter.

3.2 Case Models Study

In this chapter each of the case models will be presented individually to give an insight into the process and results of each one of them.

3.2.1 Case 1_Simple Geometry

The first case displays no serious irregularities in the transitional process. The gbXML is exported correctly from Revit and ArchiCAD (*Table 9* and*Table 10*) and reviewed in XML format, while the IFC is checked using Solibri Model Viewer.

Table 9: Case 1- Exported data from Revit

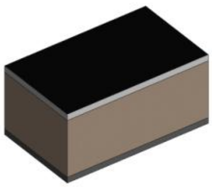
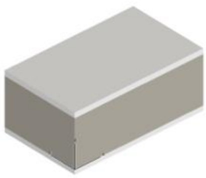
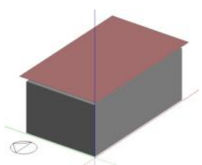
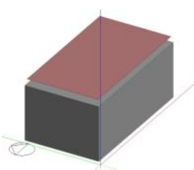
Autodesk Revit			BIM	gbXML	IFC
Case1_Simple Geometry	South Zone	Volume [m^3]	92.69	92.69	92.69
		Area [m^2]	23.173	23.173	23.17
		Geometry	0	0	0
	North Zone	Volume[m^3]	92.69	92.69	92.69
		Area [m^2]	23.173	23.173	23.17
		Geometry	0	0	0

Table 10: Case 1- Exported data from ArchiCAD

Graphisoft ArchiCAD			BIM	gbXML	IFC
Case1_Simple Geometry	South Zone	Volume [m^3]	92.69	92.69	92.69
		Area [m^2]	23.173	23.173	23.17
		Geometry	0	0	0
	North Zone	Volume [m^3]	92.69	92.69	92.69
		Area [m^2]	23.173	23.173	23.17
		Geometry	0	0	0

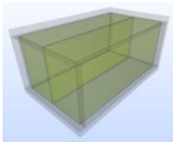
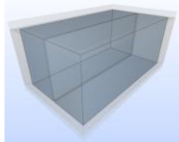
For the next step the data structures are imported respectively to DesignBuilder (DB) and Space Boundary Tool (SBT-1). The same parameters are compared again (*Table 11*) this time with regards to storing and transforming information for the purpose of creating BEM.

Table 11: Case 1- gbXML import to DesignBuilder

Revit gbXML	South	North	ArchiCAD gbXML	South	North
Volume [m^3]	92.69	92.69	Volume [m^3]	92.69	92.69
Area [m^2]	23.173	23.173	Area [m^2]	23.173	23.173
Geometry DesignBuilder			Geometry DesignBuilder		

The same geometry and parameters are observed in the exported IFCs from Revit and ArchiCAD, as described in *Table 12* after being visualized in Solibri Model Viewer (SMV).

Table 12:Case 1- IFC import to SBT-1

Revit IFC	South Zone	North Zone	ArchiCAD IFC	South Zone	North Zone
Volume [m^3]	92.69	92.69	Volume [m^3]	92.69	92.69
Area [m^2]	23.173	23.173	Area [m^2]	23.173	23.173
Geometry SBT-1			Geometry SBT-1		

The exported geometry and spaces are listed in the Model Tree in Solibri Model Viewer and can be reviewed after processing them in SBT.

The input parameters are again compared to the original in *Table 13* and certain irregularities are spotted for the IFC files.

Table 13: Case 1- IDF input values for EnergyPlus

Revit- IDF		gbXML	IFC	ArchiCAD- IDF		gbXML	IFC
South Zone	Volume [m^3]	92.69	126.13	South Zone	Volume [m^3]	92.69	128.66
	Area [m^2]	23.173	23.17		Area[m^2]	23.173	23.17
	Geometry	0	0		Geometry	0	0
North Zone	Volume[m^3]	92.69	57.83	North Zone	Volume [m^3]	92.69	55.3
	Area [m^2]	23.173	23.173		Area[m^2]	23.173	23.17
	Geometry	0	0		Geometry	0	0

And finally the results after the simulation shown below in *Table 14* display some discrepancies for the different models which will be discussed in detail later on.

Table 14: Case 1- Simulation Results in EnergyPlus

Case1_Simple Geometry	gbXML Total Site Energy kWhm^{-2}	IFC Total Site Energy kWhm^2	Reference model E+ Total Site Energy kWh/m^2
REVIT	39.59	40.03	39.57
ArchiCAD	39.39	40.02	39.57

3.2.2 Case 2_Virtual Boundary

The second case is identical to Case 1, with the only difference that instead of a separation wall, isolating North and South Space from each other, this time there is a virtual boundary. This affects the geometry and potentially the performance of the two assigned zones as there is no physical boundary between them. At first the data is again correctly exported to both gbXML and IFC, seen in *Table 15* and *Table 16*.

Table 15: Case 2- Exported data from Revit

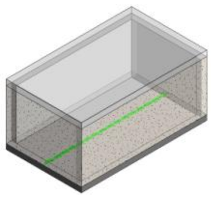
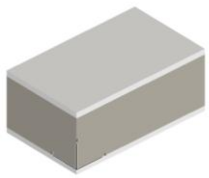
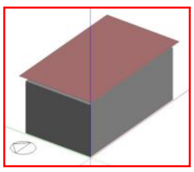
Autodesk Revit			BIM	gbXML	IFC
Case2_Virtual Boundary 	South Zone	Volume [m^3]	94.818	94.818	94.82
		Area [m^2]	23.7	23.7	23.7
		Geometry	0	0	0
	North Zone	Volume[m^3]	94.818	94.818	94.82
		Area [m^2]	23.7	23.7	23.7
		Geometry	0	0	0

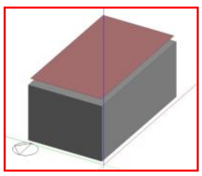
Table 16: Case 2- Exported data from ArchiCAD

Graphisoft ArchiCAD			BIM	gbXML	IFC
Case2_Virtual Boundary 	South Zone	Volume [m^3]	94.818	94.818	94.82
		Area [m^2]	23.7	23.7	23.7
		Geometry	0	0	0
	North Zone	Volume[m^3]	94.818	94.818	94.82
		Area [m^2]	23.7	23.7	23.7
		Geometry	0	0	0

In the transitional process to the pre-processing BEM tools, both gbXML formats have the Virtual boundary eliminated, leaving a single- zoned internal volume (*Table 17*).

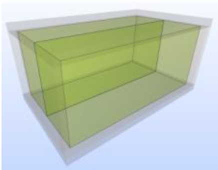
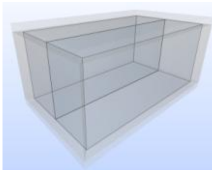
Table 17: Case 2- gbXML import to DesignBuilder

Revit gbXML	South	North
Volume m^3	189.64	189.64
Area m^2	47.409	47.409
Geometry Design-Builder		

ArchiCAD gbXML	South	North
Volume m^3	189.64	189.64
Area m^2	47.409	47.409
Geometry Design-Builder		

The processing of the IFC formats in SBT-1, as shown in *Table 18*, displays no complications in deriving the necessary space boundaries and volumes, as they were defined in BIM.

Table 18: Case 2- IFC import to SBT

Revit IFC	South	North	ArchiCAD IFC	South	North
Volume [m^3]	94.82	94.82	Volume[m^3]	94.82	94.82
Area [m^2]	23.7	23.7	Area [m^2]	23.7	23.7
Geometry SBT-1			Geometry SBT-1		

Further inspection of the IDF inputs in EnergyPlus proves that the translation of the gbXML formats has failed in recognizing the implied boundary as a separation between both spaces(*Table 19*).

Table 19: Case 2- IDF input values for EnergyPlus

Revit- IDF		gbXML	IFC	ArchiCAD- IDF		gbXML	IFC
South Zone	Volume [m^3]	189.64	60.72	South Zone	Volume [m^3]	189.64	131.5
	Area [m^2]	47.409	23.7		Area[m^2]	47.409	23.7
	Geometry	X	O		Geometry	X	O
North Zone	Volume[m^3]	189.64	128.92	North Zone	Volume [m^3]	189.64	58.14
	Area [m^2]	47.409	23.7		Area[m^2]	47.409	23.7
	Geometry	X	O		Geometry	X	O

Finally, in the simulation results, described in *Table 20*, there are certain differences in the final values for the *Total Net Conditioned Area* of ***47.41m²(Autodesk Revit).***

Table 20: Case 2- Simulation Results in EnergyPlus

Case2_Virtual Boundary	gbXML Total Site Energy kWh/m^2	IFC Total Site Energy kWh/m^2	Reference model E+ Total Site Energy kWh/m^2
REVIT	37.49	40.6	32.49
ArchiCAD	38.38	40.59	32.49

3.2.3 Case 3_Column

In the third case, the focus is on structural elements and their role in the definition of Space Boundaries. For the purpose two concrete 300x300mm columns are placed in each Zone of the model, the one in South Space being room-bounding and the one in the North is not. And as in the previous cases the information exported to gbXML and IFC is in compliance to the BIM model (*Table 21* and *Table 22*).

Table 21: Case 3- Exported data from Revit

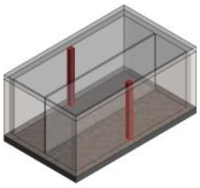
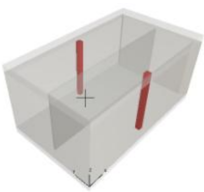
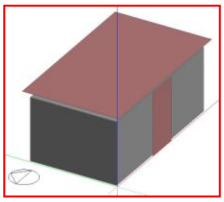
Autodesk Revit			BIM	gbXML	IFC
Case3_Columns		Volume [m^3]	92.33	92.33	92.33
	South Zone	Area [m^2]	23.083	23.083	23.08
		Geometry	0	0	0
		Volume[m^3]	92.69	92.69	92.69
	North Zone	Area [m^2]	23.173	23.173	23.17
		Geometry	0	0	0

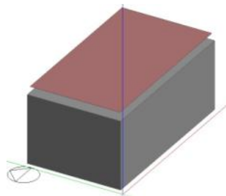
Table 22: Step 1- Exported data from ArchiCAD

Graphisoft ArchiCAD			BIM	gbXML	IFC
Case3_Columns		Volume [m^3]	92.33	92.33	92.33
	South Zone	Area [m^2]	23.083	23.083	23.08
		Geometry	0	0	0
		Volume[m^3]	92.69	92.69	92.69
	North Zone	Area [m^2]	23.173	23.173	23.17
		Geometry	0	0	0

During the import into DesignBuilder, the gbXML derived from the Revit model displays an unusual Shading plane on the external side of where the concrete column is placed in the South Space (*Table 23*). The same effect is not observed in the ArchiCAD gbXML.

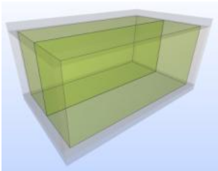
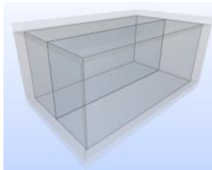
Table 23: Case 3- gbXML import to DesignBuilder

Revit gbXML	South	North
Volume [m^3]	92.33	92.69
Area [m^2]	23.083	23.173
Geometry Design-Builder		

ArchiCAD gbXML	South	North
Volume [m^3]	92.33	92.69
Area [m^2]	23.083	23.173
Geometry Design-Builder		

The IFC also derived from Revit in this case also presents unexpected results in the definition of the Space Boundaries in SBT-1, as described in *Table 24*.

Table 24: Case 3- IFC import to SBT-1

Revit IFC	South	North	ArchiCAD IFC	South	North
Volume [m^3]	92.33	92.69	Volume[m^3]	92.33	92.69
Area [m^2]	17.48	23.173	Area [m^2]	23.083	23.173
Geometry SBT-1			Geometry SBT-1		

The error in calculating the correct area of the floor space boundary is not visible at first, but can be read in the Model tree in SMV and will be discussed later on.

The analysis of the generated IDFs input values described in *Table 25* show Volume is not accurately calculated.

Table 25: Case 3- IDF input values for EnergyPlus

Revit- IDF		gbXML	IFC	ArchiCAD- IDF		gbXML	IFC
South Zone	Volume [m^3]	92.33	119.72	South Zone	Volume [m^3]	92.33	128.18
	Area [m^2]	23.083	11.47		Area[m^2]	23.083	23.08
	Geometry	O	X		Geometry	O	O
North Zone	Volume[m^3]	92.69	57.83	North Zone	Volume [m^3]	92.69	55.3
	Area [m^2]	23.173	23.17		Area[m^2]	23.173	23.17
	Geometry	O	O		Geometry	O	O

And finally the results show various numbers for the *Total Net Conditioned Area* of ***40.46m²*** for the Revit generated IFC-IDF and ***46.35m²*** for the ArchiCAD one and Reference Model as shown below in *Table 26*.

Table 26: Case 3- Simulation results in EnergyPlus

Case3_Columns	gbXML Total Site Energy kWh/m^2	IFC Total Site Energy kWh/m^2	Reference model E+ Total Site Energy kWh/m^2
REVIT	40.03	35.25	35.78
ArchiCAD	39.48	39.85	35.78

3.2.4 Case 4_Window

Case 4 contains a window, which potentially might cause problems during the conversion of sub-surfaces to space boundary surfaces or during export of data. The results display no such serious irregularities as shown in *Table 27* and *Table 28*.

Table 27: Case 4- Exported data from Revit

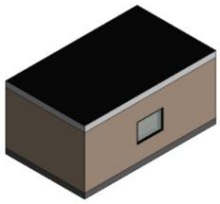
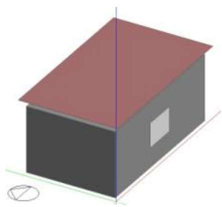
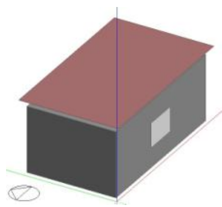
Autodesk Revit			BIM	gbXML	IFC
Case4_Window 	South Zone	Volume [m^3]	92.69	92.69	92.69
		Area [m^2]	23.173	23.173	23.273
		Geometry	0	0	0
	North Zone	Volume[m^3]	92.69	92.69	92.69
		Area [m^2]	23.173	23.173	23.17
		Geometry	0	0	0

Table 28: Case 4- Exported data from ArchiCAD

Graphisoft ArchiCAD			BIM	gbXML	IFC
Case4_Window 	South Zone	Volume [m^3]	92.69	92.69	92.69
		Area [m^2]	23.173	23.173	23.273
		Geometry	0	0	0
	North Zone	Volume[m^3]	92.69	92.69	92.69
		Area [m^2]	23.173	23.173	23.17
		Geometry	0	0	0

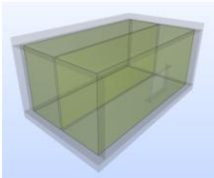
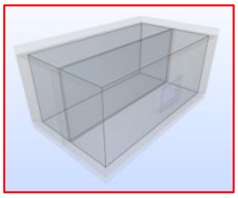
Table 29 also shows no problem in DesignBuilder.

Table 29: Case 4- gbXML import to DesignBuilder

Revit gbXML	South	North	ArchiCAD gbXML	South	North
Volume [m^3]	92.69	92.69	Volume [m^3]	92.69	92.69
Area [m^2]	23.173	23.173	Area [m^2]	23.173	23.173
Geometry Design-Builder			Geometry Design-Builder		

None of the IFC ArchiCAD models has the openings (sub-surfaces) recognized as Space Boundaries during the SBT-1 conversion (*Table 30*)

Table 30: Case 4- IFC import to SBT-1

Revit IFC	South	North	ArchiCAD IFC	South	North
Volume [m^3]	92.69	92.69	Volume[m^3]	92.69	92.69
Area [m^2]	23.173	23.173	Area [m^2]	23.173	23.173
Geometry SBT-1			Geometry SBT-1		

The *Volume* input values have been miscalculated for the IFC IDFs- *Table 31*. There is no windows input in *Fenestration* field for the ArchiCAD IFC model.

Table 31: Case 4- IDF input values for EnergyPlus

Revit- IDF		gbXML	IFC	ArchiCAD- IDF		gbXML	IFC
South Zone	Volume [m^3]	92.69	126.12	South Zone	Volume [m^3]	92.69	128.66
	Area [m^2]	23.173	23.17		Area[m^2]	23.173	23.173
	Geometry	O	O		Geometry	O	X
North Zone	Volume[m^3]	92.69	57.83	North Zone	Volume [m^3]	92.69	55.3
	Area [m^2]	23.173	23.17		Area[m^2]	23.173	23.17
	Geometry	O	O		Geometry	O	O

The results from the simulation vary from the reference model ones.

Table 32: Case 4- Simulation results in EnergyPlus

Case4_Window	gbXML Total Site Energy kWh/m^2	IFC Total Site Energy kWh/m^2	Reference model E+ Total Site Energy kWh/m^2
REVIT	47.84	36.97	36.97
ArchiCAD	36.56	40.02	36.97

3.2.5 Case 5_Window and Door

In this case model, values and geometry have been extracted accordingly (*Table 33* and *Table 34*).

Table 33: Case 5- Exported data from Revit

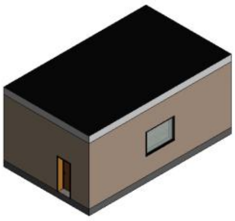
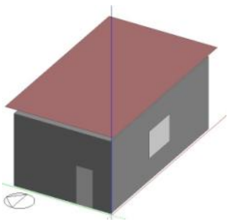
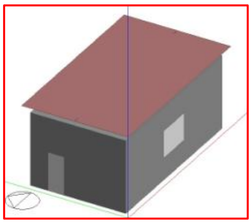
Autodesk Revit			BIM	gbXML	IFC
Case5_Window and Door 	South Zone	Volume [m^3]	92.69	92.69	92.69
		Area [m^2]	23.173	23.173	23.273
		Geometry	O	O	O
	North Zone	Volume[m^3]	92.69	92.69	92.69
		Area [m^2]	23.173	23.173	23.17
		Geometry	O	O	O

Table 34: Case 5- Exported data from ArchiCAD

Graphisoft ArchiCAD			BIM	gbXML	IFC
Case5_Window and Door 	South Zone	Volume [m^3]	92.69	92.69	92.69
		Area [m^2]	23.173	23.173	23.273
		Geometry	O	O	O
	North Zone	Volume[m^3]	92.69	92.69	92.69
		Area [m^2]	23.173	23.173	23.17
		Geometry	O	X	O

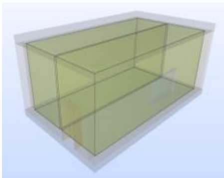
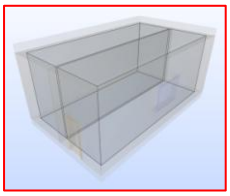
Observing the ArchiCAD model in Design Builder it is noticed that the External Door is not located where originally designed *Table 35*.

Table 35: Case 5- gbXML import to DesignBuilder

Revit gbXML	South	North	ArchiCAD gbXML	South	North
Volume [m^3]	92.69	92.69	Volume [m^3]	92.69	92.69
Area [m^2]	23.173	23.173	Area [m^2]	23.173	23.173
Geometry Design-Builder			Geometry Design-Builder		

The Window is again disregarded during the SBT-1 processing for the ArchiCAD IFC. *Table 36*.

Table 36: Case 5- IFC import to SBT-1

Revit IFC	South	North	ArchiCAD IFC	South	North
Volume [m^3]	92.69	92.69	Volume[m^3]	92.69	92.69
Area [m^2]	23.173	23.173	Area [m^2]	23.173	23.173
Geometry SBT-1			Geometry SBT-1		

The IDF input data for the ArchiCAD models is affected by earlier definition and conversion of building geometry- *Table 37*.

Table 37: Case 5- IDF input values for EnergyPlus

Revit- IDF		gbXML	IFC	ArchiCAD- IDF		gbXML	IFC
South Zone	Volume [m^3]	92.69	126.12	South Zone	Volume [m^3]	92.69	128.66
	Area [m^2]	23.173	23.17		Area[m^2]	23.173	23.173
	Geometry	O	O		Geometry	X	X
North Zone	Volume[m^3]	92.69	57.83	North Zone	Volume [m^3]	92.69	55.3
	Area [m^2]	23.173	23.17		Area[m^2]	23.173	23.17
	Geometry	O	O		Geometry	X	O

The results are presented below (*Table 38*).

Table 38: Case 5- Simulation results in EnergyPlus

Case5_Window and Door	gbXML Total Site Energy kWh/m^2	IFC Total Site Energy kWh/m^2	Reference model E+ Total Site Energy kWh/m^2
REVIT	36.74	37.45	37.39
ArchiCAD	37.03	40.02	37.39

3.2.6 Case 6_Overhang

Case 6 contains a horizontal overhang of 500mm above a large window, facing South. Geometry extraction only shows a fault in the Revit gbXML model which fails to recognize the overhang (*Table 39*). The ArchiCAD model is properly extracted- *Table 40*.

Table 39: Case 6- Exported data from Revit

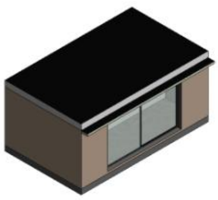
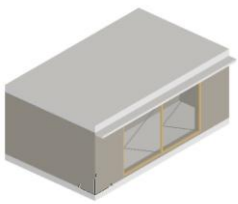
Autodesk Revit			BIM	gbXML	IFC
Case6_Overhang 	South Zone	Volume [m^3]	92.69	92.69	92.69
		Area [m^2]	23.173	23.173	23.273
		Geometry	0	X	0
	North Zone	Volume[m^3]	92.69	92.69	92.69
		Area [m^2]	23.173	23.173	23.17
		Geometry	0	0	0

Table 40: Case 6- Exported data from ArchiCAD

Graphisoft ArchiCAD			BIM	gbXML	IFC
Case6_Overhang 	South Zone	Volume [m^3]	92.69	92.69	92.69
		Area [m^2]	23.173	23.173	23.273
		Geometry	0	0	0
	North Zone	Volume[m^3]	92.69	92.69	92.69
		Area [m^2]	23.173	23.173	23.17
		Geometry	0	0	0

DesignBuilder shows no problems in retrieving the geometry from the gbXML formats. The mistake in the Revit gbXML is visible below in *Table 41*.

Table 41: Case 6- gbXML import to DesignBuilder

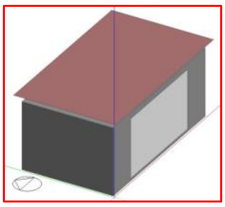
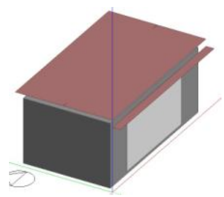
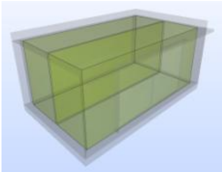
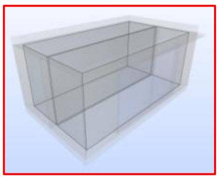
Revit gbXML	South	North	ArchiCAD gbXML	South	North
Volume [m^3]	92.69	92.69	Volume [m^3]	92.69	92.69
Area [m^2]	23.173	23.173	Area [m^2]	23.173	23.173
Geometry Design-Builder			Geometry Design-Builder		

Table 42 shows again that the large Window in the ArchiCAD model is not converted to a Space Boundary.

Table 42: Case 6- IFC import to SBT-1

Revit IFC	South	North	ArchiCAD IFC	South	North
Volume [m^3]	92.69	92.69	Volume[m^3]	92.69	92.69
Area [m^2]	23.173	23.173	Area [m^2]	23.173	23.173
Geometry SBT-1			Geometry SBT-1		

In the IDF input , the missing overhang is marked for Revit gbXML and no Window for ArchiCAD IFC. (*Table 43*)

Table 43: Case 6- IDF input values for EnergyPlus

Revit- IDF		gbXML	IFC	ArchiCAD- IDF		gbXML	IFC
South Zone	Volume [m^3]	92.69	55.49	South Zone	Volume [m^3]	92.69	128.66
	Area [m^2]	23.173	23.17		Area[m^2]	23.173	23.173
	Geometry	X	0		Geometry	0	X
North Zone	Volume[m^3]	92.69	56.9	North Zone	Volume [m^3]	92.69	55.3
	Area [m^2]	23.173	23.17		Area[m^2]	23.173	23.17
	Geometry	0	0		Geometry	0	0

In the results after the simulation it can be seen that the missing window in the Archi-CAD IFC model has an effect over the computation of the thermal loads- *Table 44*.

Table 44: Case 6- Simulation results in EnergyPlus

Case6_Overhang	gbXML Total Site Energy kWh/m^2	IFC Total Site Energy kWh/m^2	Reference model E+ Total Site Energy kWh/m^2
REVIT	82.7	82.43	76.59
ArchiCAD	74.38	40.02	76.59

3.2.7 Case 7_Terrace

For this case it is interesting to observe the shading that occurs because of the cantilevered construction of the 1st Floor. Geometry analysis after extraction show no irregularities - *Table 45* and *Table 46*.

Table 45:Case 7- Exported data from Revit

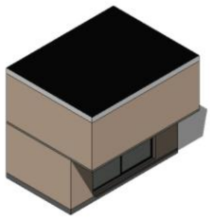
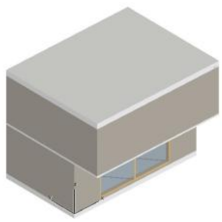
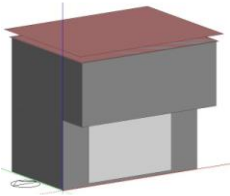
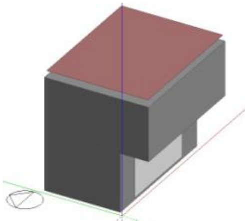
Graphisoft ArchiCAD			BIM	gbXML	IFC
Case7_Terrace 	South Zone	Volume [m^3]	92.69	92.69	92.69
		Area [m^2]	23.173	23.173	23.273
		Geometry	0	0	0
	North Zone	Volume[m^3]	92.69	92.69	92.69
		Area [m^2]	23.173	23.173	23.17
		Geometry	0	0	0
	1st Floor Zone	Volume[m^3]	253.133	253.133	253.13
		Area [m^2]	65.749	65.749	65.75
		Geometry	0	0	0

Table 46: Case 7- Exported data from ArchiCAD

Graphisoft ArchiCAD			BIM	gbXML	IFC
Case7_Terrace 	South Zone	Volume [m^3]	92.69	92.69	92.69
		Area [m^2]	23.173	23.173	23.273
		Geometry	0	0	0
	North Zone	Volume[m^3]	92.69	92.69	92.69
		Area [m^2]	23.173	23.173	23.17
		Geometry	0	0	0
	1st Floor Zone	Volume[m^3]	253.133	253.133	253.13
		Area [m^2]	65.749	65.749	65.75
		Geometry	0	0	0

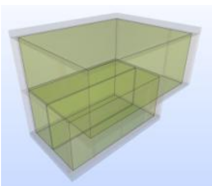
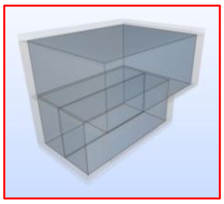
The retrieved geometry in DesignBuilder also doesn't show any serious errors: *Table 47*

Table 47: Case 7- gbXML import to DesignBuilder

Revit gbXML	South	North	1st Floor	ArchiCAD gbXML	South	North	1st Floor
Volume [m^3]	92.69	92.69	253.13	Volume [m^3]	92.69	92.69	253.13
Area [m^2]	23.173	23.173	65.75	Area [m^2]	23.173	23.173	65.75
Geometry DesignBuilder				Geometry Des-ignBuilder			

In the SBT- 1 post IFC models there are also no inconsistencies that affect building or spatial data, except for the missing window space boundary in the ArchiCAD model (*Table 48*).

Table 48: Case 7- IFC import to SBT-1

Revit IFC	South	North	1st Floor	ArchiCAD IFC	South	North	1st Floor
Volume [m^3]	92.69	92.69	253.13	Volume[m^3]	92.69	92.69	253.13
Area [m^2]	23.173	23.173	65.75	Area [m^2]	23.173	23.173	65.75
Geometry SBT-1				Geometry SBT-1			

The produced IDFs contain the previously noticed errors for the IFC models, as it can be seen in *Table 49*.

Table 49: Case 7- IDF input values for EnergyPlus

Revit- IDF		gbXML	IFC	ArchiCAD- IDF		gbXML	IFC
South Zone	Volume [m^3]	92.69	156.57	South Zone	Volume [m^3]	92.69	159.56
	Area [m^2]	23.173	23.17		Area[m^2]	23.173	23.173
	Geometry	O	O		Geometry	O	X
North Zone	Volume[m^3]	92.69	88.68	North Zone	Volume [m^3]	92.69	86.2
	Area [m^2]	23.173	23.17		Area[m^2]	23.173	23.17
	Geometry	O	O		Geometry	O	O
1st Floor Zone	Volume[m^3]	253.13	189.01	1st Floor Zone	Volume [m^3]	253.13	189.02
	Area [m^2]	65.75	112.07		Area[m^2]	65.75	112.09
	Geometry	O	O		Geometry	O	O

The results from the simulation in EnergyPlus (*Table 50*) vary between the gbXML and the IFC. The potential reasons for that will be further discussed, but it is suggested that the SBT-1 doubles the boundary surfaces of internal elements.

Table 50: Case 7- Simulation results in EnergyPlus

Case7_Terrace	gbXML Total Site Energy kWh/m^2	IFC Total Site Energy kWh/m^2	Reference model E+ Total Site Energy kWh/m^2
REVIT	70.7	38.29	62.73
ArchiCAD	70.17	38.86	62.73

3.2.8 Case 8_Unheated Space

Unheated spaces have been reported to cause a problem when exported for simulation, so are normally left out of the input for energy simulations. The current case shows how that is not necessary and potentially also has an effect over the results. In the Revit workflow the extracted geometry is with no irregularities *Table 51*, in contrast to the ArchiCAD one in *Table 52* .

Table 51: Case 8- Exported data from Revit

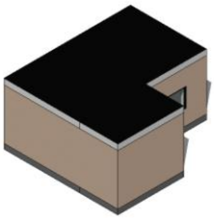
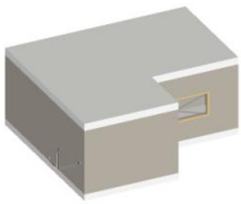
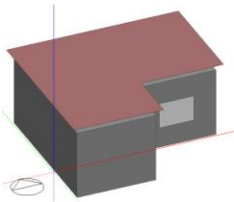
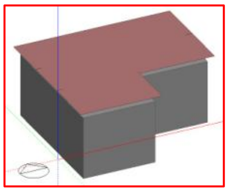
Autodesk Revit			BIM	gbXML	IFC
Case8_Unheated Space 	South Zone	Volume [m^3]	92.69	92.69	92.69
		Area [m^2]	23.173	23.173	23.273
		Geometry	0	0	0
	North Zone	Volume[m^3]	92.69	92.69	92.69
		Area [m^2]	23.173	23.173	23.17
		Geometry	0	0	0
	Unheated Zone	Volume[m^3]	253.133	253.133	253.13
		Area [m^2]	65.749	65.749	65.75
		Geometry	0	0	0

Table 52: Case 8- Exported data from ArchiCAD

Graphisoft ArchiCAD			BIM	gbXML	IFC
Case8_Unheated Space 	South Zone	Volume [m^3]	92.69	92.69	92.69
		Area [m^2]	23.173	23.173	23.273
		Geometry	0	0	0
	North Zone	Volume[m^3]	92.69	92.69	92.69
		Area [m^2]	23.173	23.173	23.17
		Geometry	0	X	0
	Unheated Zone	Volume[m^3]	45.263	45.263	45.26
		Area [m^2]	11.316	11.316	11.32
		Geometry	0	X	0

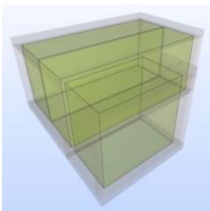
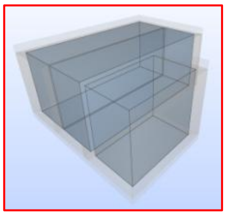
The error in the ArchiCAD gbXML is first noticed during the review of the XML schema and later on confirmed when imported to DesignBuilder (*Table 53*). Further analysis show that the window has been relocated during gbXML extraction from its modelled location to the partition wall between the South and Unheated Space.

Table 53: Case 8- gbXML import to DesignBuilder

Revit gbXML	South	North	Unheated	ArchiCAD gbXML	South	North	Unheated
Volume [m^3]	92.69	92.69	45.263	Volume [m^3]	92.69	92.69	45.263
Area [m^2]	23.173	23.173	11.316	Area [m^2]	23.173	23.173	11.316
Geometry DesignBuilder				Geometry Design-Builder			

Apart from not recognizing the window as a space boundary, *Table 54* shows no other irregularities for the processed IFCs.

Table 54: Case 8- IFC import to SBT-1

Revit IFC	South	North	Unheated	ArchiCAD IFC	South	North	Unheated
Volume [m^3]	92.69	92.69	45.26	Volume[m^3]	92.69	92.69	45.26
Area [m^2]	23.173	23.173	11.32	Area [m^2]	23.17	23.17	11.32
Geometry SBT-1				Geometry SBT-1			

The marked errors in *Table 55* are the suggested mistakes made earlier in the process. Whether it is due to BIM modelling or extraction of data cannot be confirmed without further and deeper expertise into the technical specifications of the BIM- authoring tool and the extraction capabilities of the gbXML, which are not the point of this paper.

Table 55: Case 8- IDF input values for EnergyPlus

Revit- IDF		gbXML	IFC	ArchiCAD- IDF		gbXML	IFC
South Zone	Volume [m^3]	92.69	128.87	South Zone	Volume [m^3]	92.69	126.24
	Area [m^2]	23.173	23.17		Area[m^2]	23.173	23.173
	Geometry	O	O		Geometry	X	X
North Zone	Volume[m^3]	92.69	57.83	North Zone	Volume [m^3]	92.69	55.3
	Area [m^2]	23.173	23.17		Area[m^2]	23.173	23.17
	Geometry	O	O		Geometry	O	O
Unheated Zone	Volume[m^3]	253.13	44.03	Unheated Zone	Volume [m^3]	253.13	45.27
	Area [m^2]	65.75	11.32		Area[m^2]	65.75	11.32
	Geometry	O	O		Geometry	X	O

The results in *Table 56* are again not matching to the reference models. However, it can be said that even though Unheated Space has no assigned loads and thermal properties, the simulation is run without any problems.

Table 56:Case 8- Simulation results in EnergyPlus

Case8_Unheated Space	gbXML Total Site Energy kWh/m^2	IFC Total Site Energy kWh/m^2	Reference model E+ Total Site Energy kWh/m^2
REVIT	30.57	37.39	36.42
ArchiCAD	42.58	40.14	36.42

3.2.9 Case 9_Pitched Roof

For this case it is interesting to observe the assignment of inclined surfaces to be space bounding and thermally active . A pitched roof model of 30 degrees is successfully extracted from the BIM- authoring tools - *Table 57* and *Table 58*.

Table 57: Case 9- Exported data from Revit

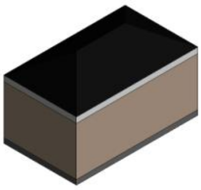
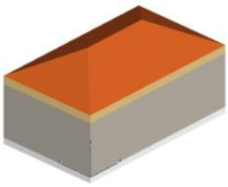
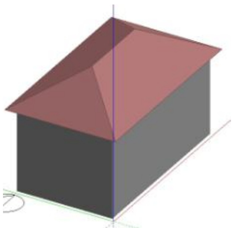
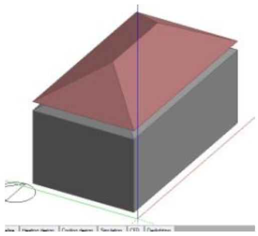
Autodesk Revit			BIM	gbXML	IFC
Case9_Pitched Roof 	Space	Volume [m³]	227.495	227.495	227.45
		Area [m²]	46.98	46.98	46.98
		Geometry	0	0	0

Table 58: Case 9- Exported data from ArchiCAD

Autodesk Revit			BIM	gbXML	IFC
Case9_Pitched Roof 	Space	Volume [m³]	227.495	227.495	227.45
		Area [m²]	46.98	46.98	46.98
		Geometry	0	0	0

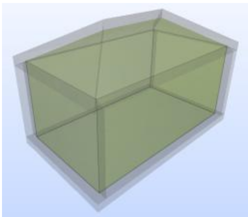
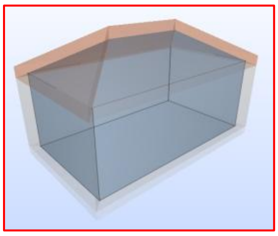
Both gbXML models are incorrectly imported into DesignBuilder. The values being taken from DesignBuilder program model tree and displayed in *Table 59*.

Table 59: Case 9- gbXML import to DesignBuilder

Revit gbXML	Space	ArchiCAD gbXML	Space
Volume [m³]	218.83	Volume [m³]	197.31
Area [m²]	45.562	Area [m²]	45.985
Geometry Design-Builder		Geometry Design-Builder	

Interestingly, the IFC derived from ArchiCAD and processed in SBT- 1 also shows incorrect value for the Volume- *Table 60*. In addition, for the same model, the roof has been disregarded completely as a heat transferring surface.

Table 60: Case 9- IFC import to SBT-1

Revit IFC	Space	ArchiCAD IFC	Space
Volume [m^3]	227.495	Volume[m^3]	205.29
Area [m^2]	46.98	Area [m^2]	46.98
Geometry SBT-1		Geometry SBT-1	

The IDF input values for EnergyPlus contain the above-mentioned errors and are shown in *Table 61*.

Table 61: Case 9- IDF input values for EnergyPlus

Revit- IDF		gbXML	IFC	ArchiCAD- IDF		gbXML	IFC
	Volume [m^3]	218.83	227.495		Volume [m^3]	197.31	126.42
Space	Area [m^2]	45.562	46.98	Space	Area[m^2]	45.985	46.98
	Geometry	O	O		Geometry	O	X

The results are inconsistent and potentially affected from the geometry errors (*Table 62*).

Table 62: Step 3- Simulation results in EnergyPlus

Case9_Pitched Roof	gbXML Total Site Energy kWh/m^2	IFC Total Site Energy kWh/m^2	Reference model E+ Total Site Energy kWh/m^2
REVIT	40.58	41.83	41.58
ArchiCAD	37.06	28.46	41.58

3.2.10 Case 10_Sloped Roof

This case is similar to the previous, however this time South and North Spaces contain different volumes and geometry (*Table 63*) and will be compared to initial cases. And surely, as it can be seen in *Table 64*, the gbXML exports the wrong values.

Table 63: Case 10- Exported data from Revit

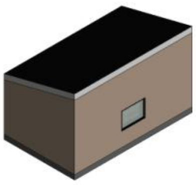
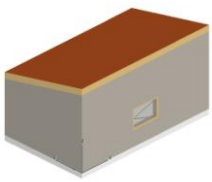
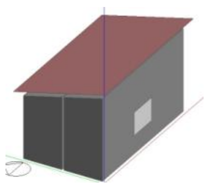
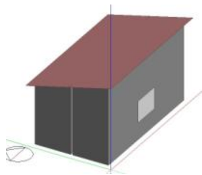
Autodesk Revit			BIM	gbXML	IFC
Case10_Sloped Roof		Volume [m^3]	117.73	117.73	117.73
	South Zone	Area [m^2]	23.173	23.173	23.273
		Geometry	0	0	0
		Volume[m^3]	102.41	102.41	102.41
	North Zone	Area [m^2]	23.173	23.173	23.17
		Geometry	0	0	0

Table 64: Case 10- Exported data from ArchiCAD

Graphisoft ArchiCAD			BIM	gbXML	IFC
Case10_Sloped Roof		Volume [m^3]	117.73	132.97	117.73
	South Zone	Area [m^2]	23.173	23.173	23.273
		Geometry	0	0	0
		Volume[m^3]	102.41	132.97	102.41
	North Zone	Area [m^2]	23.173	23.173	23.17
		Geometry	0	0	0

The error from the ArchiCAD gbXML is transferred into DesignBuilder (*Table 65*), however, similar miscalculation of volume happens for the Revit model.

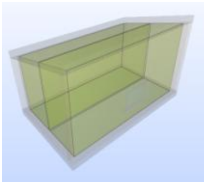
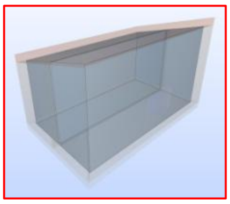
Table 65: Case 10- gbXML import to DesignBuilder

Revit gbXML	South	North	ArchiCAD gbXML	South	North
Volume [m^3]	110.69	96.152	Volume [m^3]	110.71	96.16
Area [m^2]	22.013	22.013	Area [m^2]	22.013	22.013
Geometry Design-Builder			Geometry Design-Builder		

The processed IFCs contain no error, except for the ArchiCAD one, which as in the previous Case 9, has the roof completely ignored during addition of space boundaries-

Table 66.

Table 66: Case 10- IFC import to SBT-1

Revit IFC	South	North	ArchiCAD IFC	South	North
Volume [m^3]	117.73	102.41	Volume[m^3]	117.73	102.41
Area [m^2]	23.173	23.173	Area [m^2]	23.173	23.173
Geometry SBT-1			Geometry SBT-1		

The geometrical and spatial inconsistencies reach the EnergyPlus engine as shown below in *Table 67*.

Table 67: Case 10- IDF input values for EnergyPlus

Revit- IDF		gbXML	IFC	ArchiCAD- IDF		gbXML	IFC
South Zone	Volume [m^3]	110.69	157.28	South Zone	Volume [m^3]	110.71	126.42
	Area [m^2]	22.013	23.17		Area[m^2]	22.013	23.173
	Geometry	O	O		Geometry	O	X
North Zone	Volume[m^3]	96.152	61.13	North Zone	Volume [m^3]	96.16	14.02
	Area [m^2]	22.013	23.17		Area[m^2]	22.013	23.17
	Geometry	O	O		Geometry	O	O

And finally it can be seen (*Table 68*) that the simulation results have been affected by exchanged irregularities.

Table 68:Case 10- Simulation results in EnergyPlus

Case3_Columns	gbXML Total Site Energy kWh/m^2	IFC Total Site Energy kWh/m^2	Reference model E+ Total Site Energy kWh/m^2
REVIT	66.19	174.78	37.46
ArchiCAD	65.28	42.55	37.46

4 DISCUSSION

This chapter discusses at first the performance of gbXML and IFC data formats in the current context, by answering the Research Questions asked in the beginning of this paper. It will be then followed by a discussion in a general context, which concerns semi- automated BPS process in early stage design with gbXML and IFC (based on the Evaluation Criteria).

4.1 Research questions

1. How is building geometry data exported in gbXML and IFC?

a) What are the export capabilities of the two data formats?

Both gbXML and IFC have shown sufficiently high efficiency in successfully extracting and storing building geometry data and its non-geometric specifications. Only four in all twenty exported gbXML formats appears to be incorrect and only one of the IFCs.

Essentially, IFC has the opportunity to depict any kind of geometry (Fig. 24) based on relative information. It establishes associative links between different classes and sub-classes (sub-types) and through referencing the defined information in them builds a 3D representation of geometry.

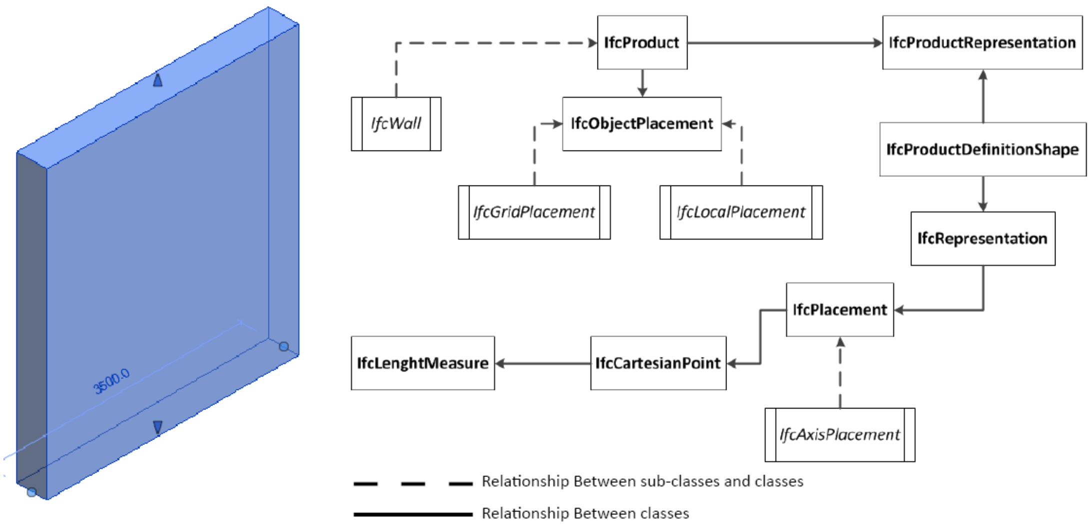


Figure 26: IFC data diagram of relationship between classes and subclasses

The gbXML schema retrieves and assigns the geometric and planar representation of building elements under pre-defined labels restricting the ability to logically allocate all building data (Fig. 25). The *Surface* element of its schema, for example, has two representations *PlanarGeometry* and *RectangularGeometry*. *PlanarGeometry* specifies basic attributes and plane insertion point, while *RectangularGeometry* depicts the surface with four *CartesianPoint* in a *PolyLoop*, each having three coordinates (*x,y,z*).

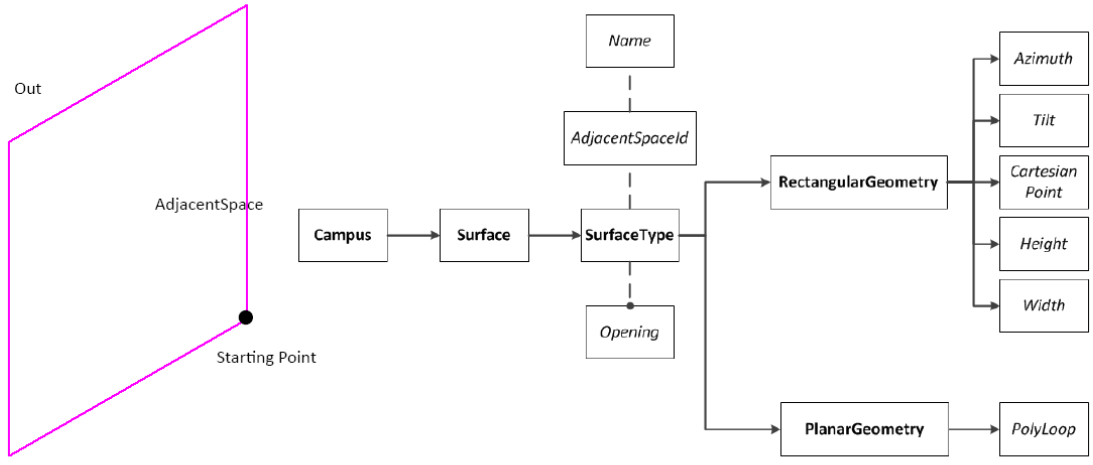


Figure 27: gbXML data Surface element attributes

And the pre-defined SurfaceType elements are:

- *ExteriorWall*
- *UndergroundWall*
- *InteriorWall*
- *Air*
- *InteriorFloor*
- *UndergroundSlab*
- *RaisedSlab*
- *Ceiling*
- *UndergroundCeiling*
- *Roof*
- *Shade*
- *FreestandingColumn*
- *EmbeddedColumn*

b) How do they affect the accuracy of geometric information?

In the extracted gbXML formats from Revit, Case 6 appears not to have the overhang defined in the schema as a shading plane. In the meanwhile every other case model contains in the gbXML schema at least one *surfaceType* element called *"Shade"* when there is no actual shading plane defined in the BIM model. In the export dialogue for gbXML from Revit, a model check is made before the actual export where in ArchiCAD this is impossible.

The ArchiCAD gbXML model seems to have difficulties in exporting spaces of irregular volumes, as it is the case with model 10, next to failing to retrieve the 3D coordinates of sub-surfaces in Case 5 and Case 8 (Results Chapter). Unfortunately the inability to check the modelled information in ArchiCAD before exporting it to gbXML prevents from establishing the actual reason for that mistake.

This poses a problem for gbXML when there is no reliable tool that can verify the extracted information. Either visually or computationally. The gbXML export dialogue for Autodesk Revit gives a primary indication for a valid model, however as it is the case with the shading planes, not everything is detectable.

The IFC format on the other hand has the complete list of geometry and spaces, which in almost all cases turns out to be correct and can be verified in Solibri Model Viewer. The only time that the IFC model does not contain all as specified is when the calculated volume of the Space in Case 9 is less than defined in ArchiCAD (Results *Table 60*)

2. What and how affects the quality of the building data in gbXML and IFC?

For the current Case Model Study, the results show that there is some influence over the quality of the data exported from Autodesk Revit and Graphisoft ArchiCAD. Initially, there are no visible discrepancies between the original model and the extracted, however, during the post BEM conversion, it is noticed that certain attributes of geometry have been affected for IFC. Those errors are at first visible in SBT-1 Space Boundaries window and after in Solibri Model Viewer 3D window.

An instance is the definition of sub-surfaces in ArchiCAD, which after processing the IFC files in SBT-1 are not recognized as space bounding elements, thus not appearing as heat transfer surfaces(Cases 4 to 8 and 10) in EnergyPlus (*Figure 28*). While this problem does not exist for the IFCs derived from Revit, the ArchiCAD ones are in essence damaged on that account. In addition, Case 9 and 10 ArchiCAD IFCs contain inclined roof slab elements, which are also completely ignored during SBT-1 conversion. This also occurs for the Revit Case 9 and 10, however, the roof is still partially defined (*Figure 29*).

Revit *Case 3_ Column*, in contrary to the same case in ArchiCAD, after being converted in SBT-1, produces unexpected Space Boundaries related to the structural column in the south space. Leading to a clue that somewhere in Revit something has been overlooked.

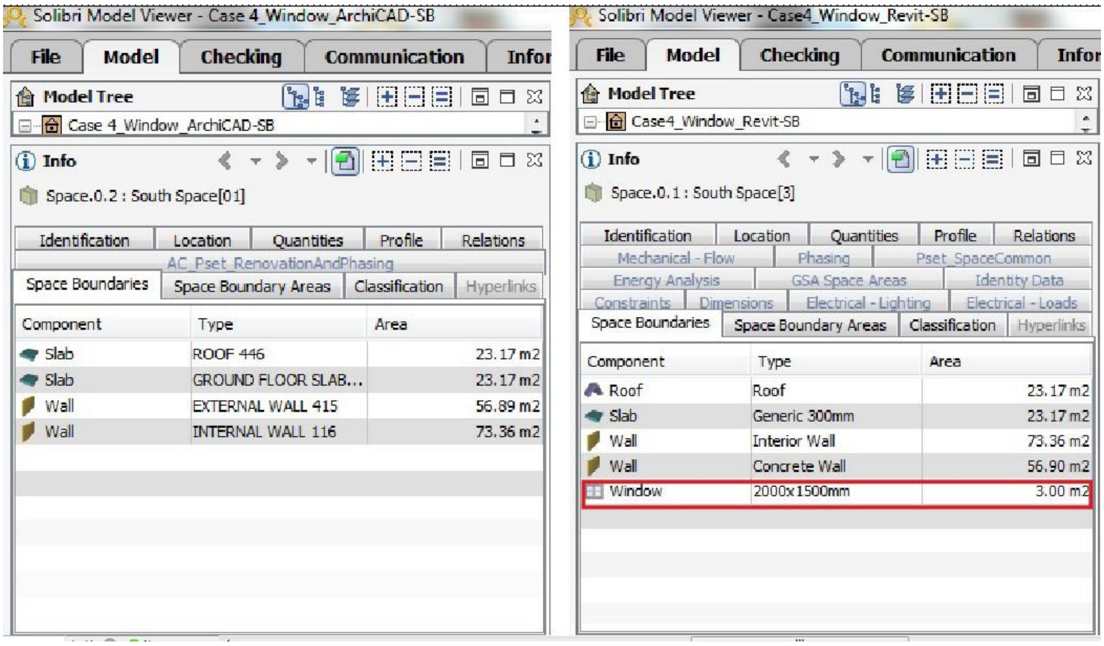


Figure 28: Case 4- Missing Window space boundaries in post SBT IFC model

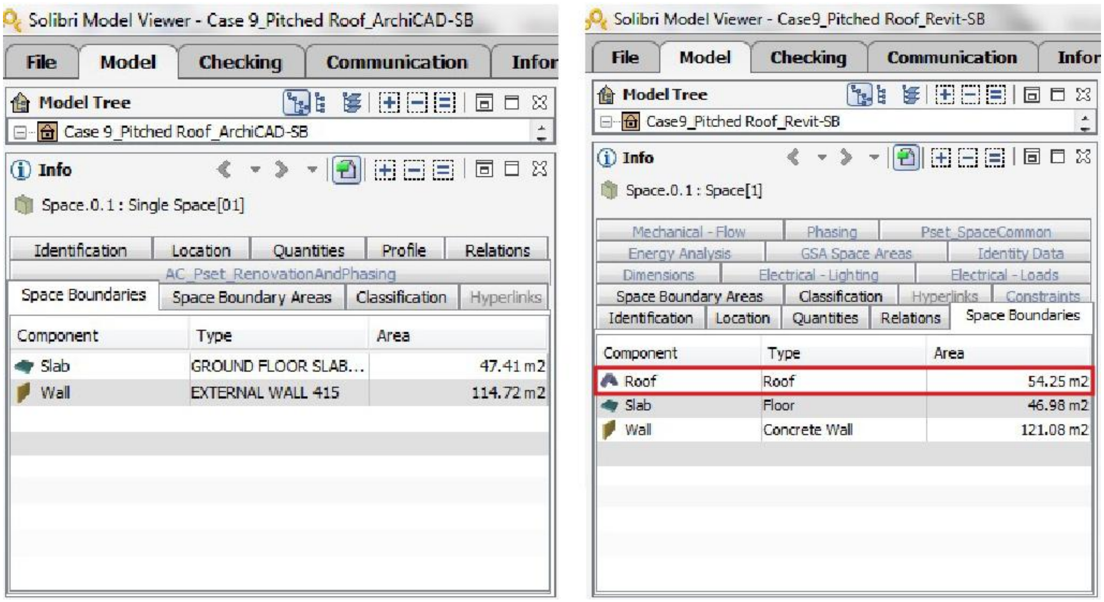


Figure 29: Case 9- Missing Roof space boundaries in post SBT IFC model

Another example are Case 5 and Case 8, gbXML derived data from ArchiCAD. It turns out that the described geometric coordinates of the External Door in Case 5 and Window in Case 8 have been written out incorrectly (*Table 35* and *Table 53* in Results).

However, since this error does not appear in the same cases generated from Revit, a supposition is made that the mistake occurs within the ArchiCAD modelling tool.

In the same time it turns out not only the BIM authoring tools influence the exported building data but BEM creation also modifies the quality of geometry and space when it translates the imported formats into IDF, to be accepted by EnergyPlus.

As seen in the Results chapter, DesignBuilder fails to import the implied boundary for Case 2 for both Revit and ArchiCAD models, and it miscalculates the volumes of spaces in Case 9 and 10 (see Results Chapter)in addition to not recognizing the partition internal wall in Case 10. This leads to wrong IDD mapping and incorrect input values for energy simulation. It can be assumed that DesignBuilder's underlying implementation scheme for gbXML has not included translation of certain elements from the gbXML data structure and as a result it instead approximates the geometrical representation.

In attempt to be an integrated tool for designers and building scientists, DesignBuilder cannot be used simply as a intermediate, pre-processing tool for importing gbXML and exporting IDF. It has a wide arrange of on- board tools, which allow the users to manually modify building geometry, its thermal specifications and performance. Without sufficient knowledge of the software and no control over the analytical BEM model, the mapping IDD process during IDF export generates a list of default input values for various simulated operations in EnergyPlus, including *Schedules, Loads* and *Material*s. In the current context, those parameters were later changed or completely removed in the IDF Editor for EnergyPlus in order to adjust the intake for simulation to the IFC generated ones. All definitions concerning geometry were left intact.

On the other hand, SBT-1 has progressed to the point of a commercially available, rudimentary tool, certified for compliance by buildingSMART with the IFC 2x3 Coordinate View 2.0 format which is a default configuration for BIM model export as IFC.

After importing IFC, SBT- 1 continues on to add Space Boundaries to associated building geometry, and to create an analytical BEM model for simulation. The Space Boundaries are then presented as a total number, and according to the function they are fulfilling are classified as 2nd Level (External and Internal), 3rd Level, 4th Level and Virtual Boundaries.

During the Case Model Study all IFC models, containing internal elements such as partition wall or internal floor, have the surface area of those elements doubled. For example, the bounding surface of the Internal Wall to South Space in *Case 1_Simple Geometry*, originally defined to have an area of 36.68 m2, after being processed in SBT-1 ends up being 73.36 m2(*Figure 30*). This is recognized in SBT interface, after adding Space Boundaries - it displays generated 4 2nd-level physical space boundaries (internal), where they actually should be 2, one for South Space and one for North Space.

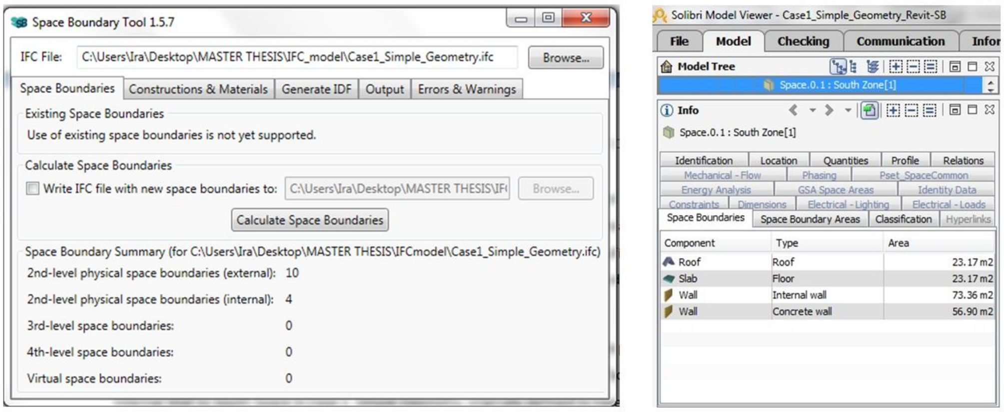


Figure 30: Case 1- Doubling of internal surfaces in SBT and seen in SMV

After noticing this irregularity, an attempt was made to establish what the reason might by, by contacting the software support for SBT-1. After no answer or help was gathered, the generated information was used as it is for simulation. It will be further discussed whether or not this would have an influence over the results from Energy-Plus.

In addition, during IDF export, SBT- 1 also like DesignBuilder sets default input parameters for EnergyPlus. Such are the ones for the Zone calculation method (*Figure 31*) set to *autocalculate,* which would mean for EnergyPlus to find approximate values for Height, Volume and Area and use them in its subsequent calculations. As a result, the volumes have been incorrectly computed (see Results chapter).

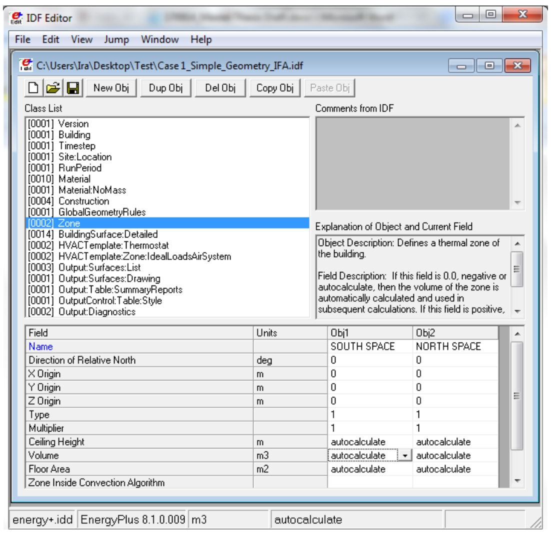


Figure 31: Case 1- IFC IDF Editor for Zone calculation

SBT has a straightforward, simple interface allowing the user to perform basic operations over the IFC analytical model, such as adding Materials and Construction to Building elements and exporting IDF for EnergyPlus, with as little manual input as possible. However, in its current state it requires much more improvements to enhance the accuracy of the processed IFC and to increase the capacity of the intake information which it can process, such as other non- geometrical specifications. Unfortunately, as of the time of writing this chapter the official funding and further development of this tool were suspended on the 1st of August, 2014, until further change (SBT 2014).

3. Whether or not quality of translated building data has an impact over simulation and generated results?

The Input Data Files, or IDFs, generated from DesignBuilder and SBT-1 considerably differ in their content and definition. SBT-1 produces IDFs describing building geometry and space and their constructive materials. By default it sets the *Timestep* and *Run-Period* for the simulation, which are concerned with the frequency of the algorithmic computation and the simulated period. As mentioned before, without knowledgeable human interference in the IDF export the input for EnergyPlus is set by default and contains extensive information. This can be controlled in the IDF Editor environment of EnergyPlus, however it becomes redundant once the priorities for the simulation are known.

For the current Case Model Study, the input IDFs from DesignBuilder had to be manually modified to match the input from the SBT-1 IDFs. This way ensuring equal basis for simulation, not involving geometry in the changes and making sure that there are equal internal loads, construction and materials for the imported space boundaries.

EnergyPlus is an extensive and complex simulation tool which performs series of calculations at the same time to deliver the most accurate building performance results. It does not approximate, rather works with exact values that are set via the IDF Editor window in the fields for input data parameters.

The results generated from the simulation of the Case Models are inconsistent and variable. In comparison to the Reference Model simulation results it cannot be also determined whether or not the gbXML or IFC ones are more correct (*Table 69* and *Table 70*). Supposedly a reason for that would be the imported false shading planes from the gbXML format or the doubled boundary surfaces of interior elements in the SBT-1 produced IDFs.

Table 69: Simulation Results EnergyPlus (kWhm^{-2})- Revit

Revit	gbXML Total Site Energy kWhm^{-2}	IFC Total Site Energy kWhm^{-2}	Reference model E+ Total Site Energy kWhm^{-2}
Case1_Simple Geometry	39.59	40.03	39.57
Case2_Virtual Boundary	37.49	40.6	32.49
Case3_Columns	40.03	35.25	35.78
Case4_Window	47.84	36.97	36.97
Case5_Window&Door	36.74	37.45	37.39
Case6_Overhang	82.7	82.43	76.59
Case7_Terrace	70.7	38.29	62.73
Case8_Unheated Space	30.57	37.39	36.42
Case9_Pitched Roof	40.85	41.83	41.58
Case10_Sloped Roof	66.19	174.78	37.46

Table 70: Simulation Results EnergyPlus (kWhm^{-2})- ArchiCAD

ArchiCAD	gbXML Total Site Energy kWhm^{-2}	IFC Total Site Energy kWhm^{-2}	Reference model E+ Total Site Energy kWhm^{-2}
Case1_Simple Geometry	39.39	40.02	39.57
Case2_Virtual Boundary	38.38	40.59	32.49
Case3_Columns	39.48	39.85	35.78
Case4_Window	36.56	40.02	36.97
Case5_Window&Door	37.03	40.02	37.39
Case6_Overhang	74.38	40.02	76.59
Case7_Terrace	70.17	38.86	62.73
Case8_Unheated Space	42.58	40.14	36.42
Case9_Pitched Roof	37.06	28.46	41.58
Case10_Sloped Roof	65.28	42.55	37.46

An illustration of the absolute error between the results of the simulated case models and the reference models is shown in *Figure 32* and *Figure 33* for the respective workflows.

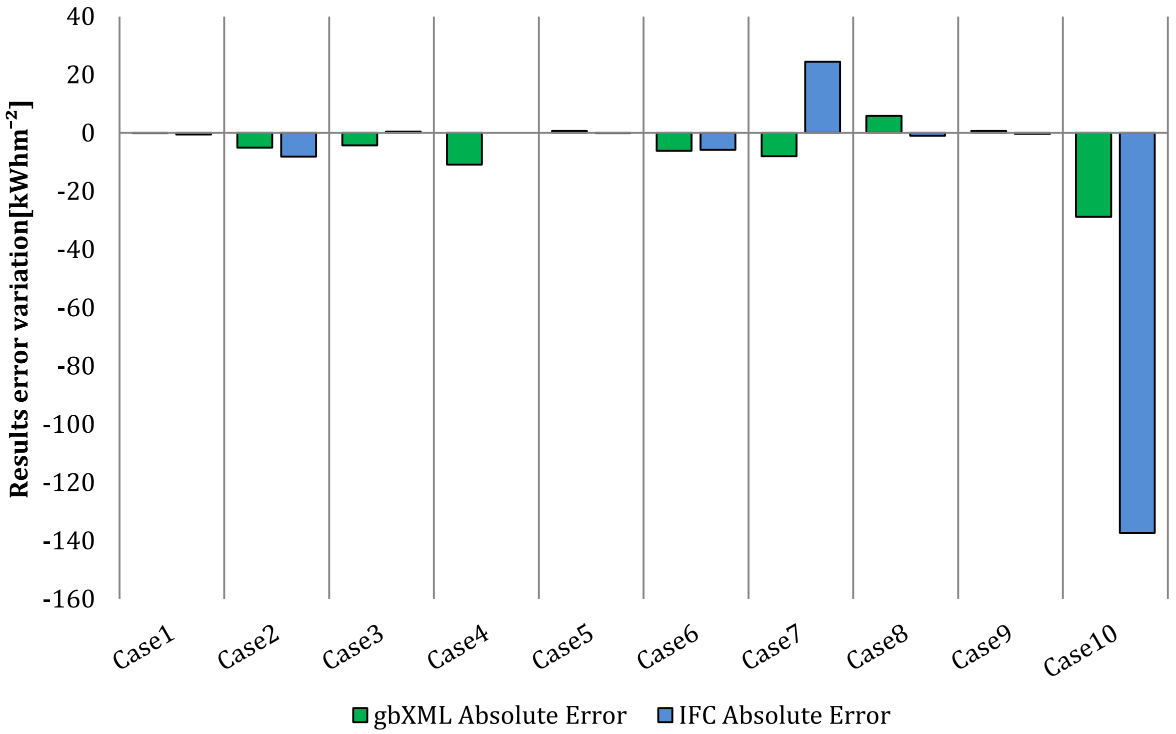


Figure 32: Error variation in case model results- Revit

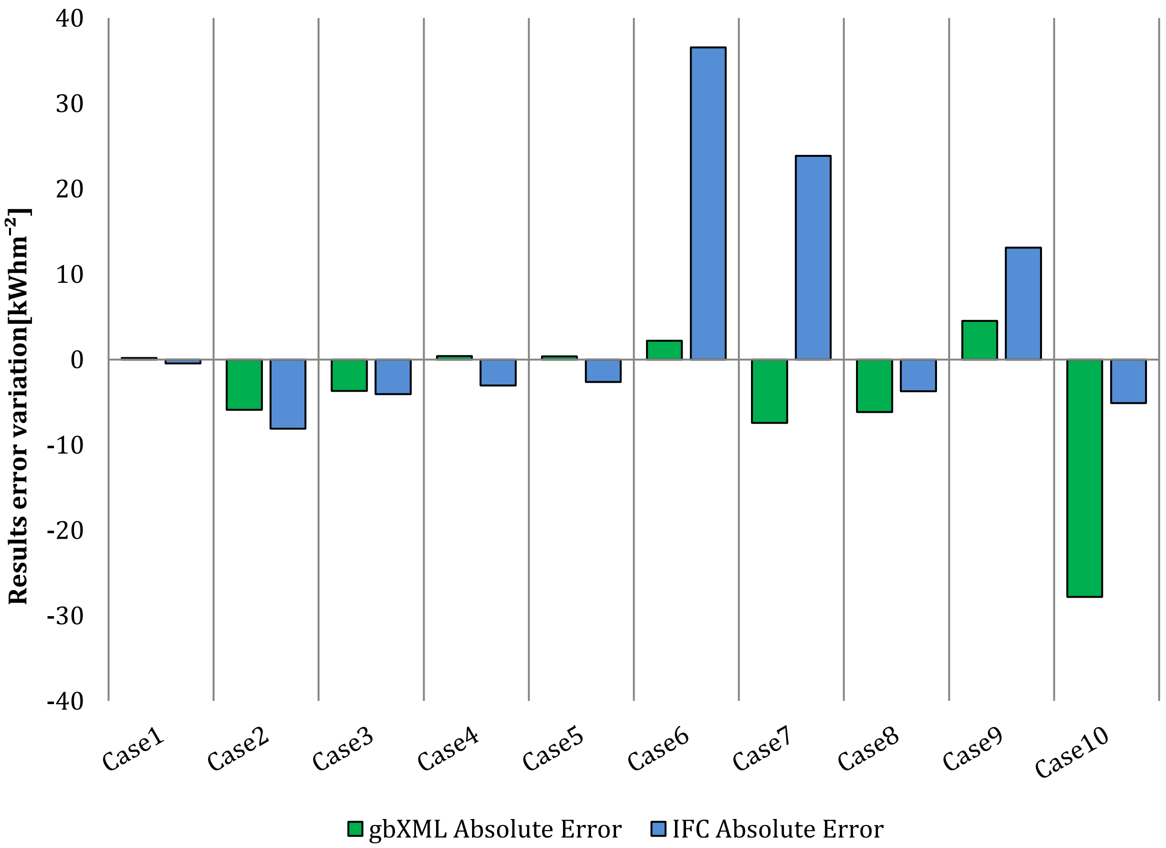


Figure 33: Error variation in case model results- ArchiCAD

Therefore, as an experiment, those inaccuracies in geometry input were fixed manually in the IDF editor for all case models, generated from Revit.

The input values that have been edited are the ones visibly wrong. Unfortunately it is physically too difficult to check all the parameters describing geometry, unless there is an automated way to extract and verify the data. For all case models is valid:

- For IFC: deleting the doubled internal surfaces from *BuildingSurface:Detailed* and inputting actual values for *Volume* and *Area* in the *Zone* field.
- For gbXML: deleting the shading surfaces from *ShadingSurface:Detailed*

And most certainly, after simulating the edited files, there has been an improvement for the IFC files as shown in *Figure 34*. below. However, the gbXML actually moves away from the value obtained in the reference models.

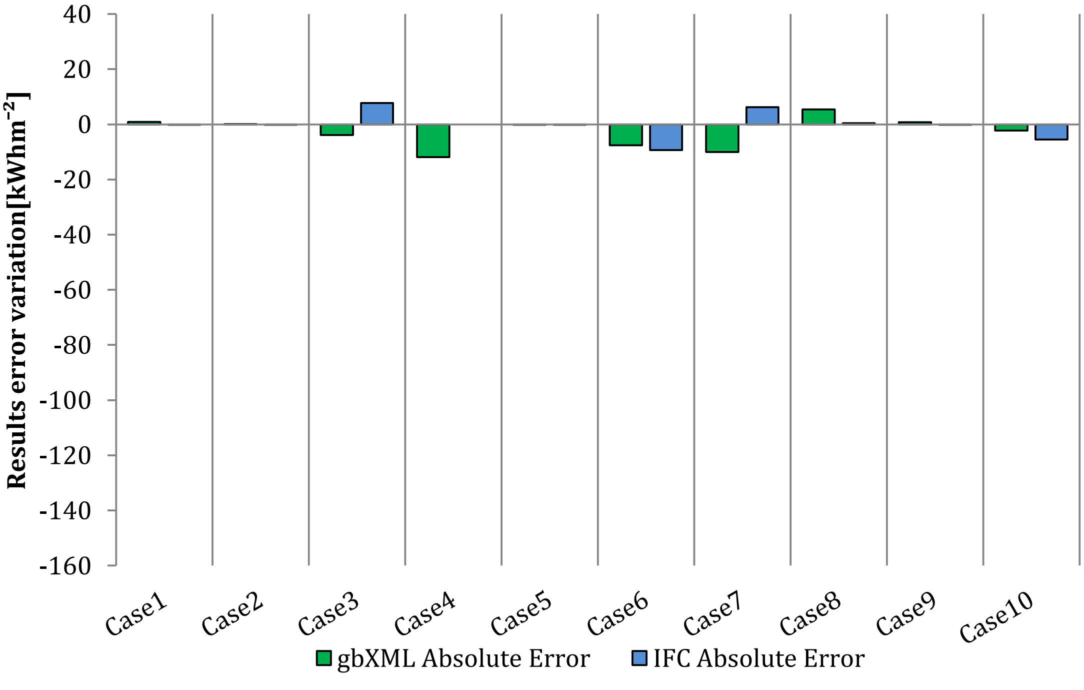


Figure 34: Modified case model results - Revit

So even though the values are still not exactly equal, a significant improvement has been made, from the initial values, deeming geometry to be of importance to the simulation results and having an effect over the analysis.

4.2 General Discussion

4.2.1 Geometry exchange with gbXML and IFC data format

The capabilities of gbXML and IFC to derive specific thermal information from a building model are characterized with their different data structures and method of storing geometry, space and related information. In that sense, it is difficult to directly compare their effectiveness, but only by the results they give eventually.

The gbXML recognizes and defines the required information for energy analysis from the BIM model itself and locates that information under pre-defined elements in its schema. That being so, stresses on the fact that the created model and its geometry have to be sufficiently accurate at the time of export. However, it is hard to verify the extracted information and that further complicates the process and impacts the results of the simulation.

IFC has a fairly complicated data structure and strict hierarchy, which defines relationships between building elements and space in a contingent manner. This is why it is important that the information in the BIM model is structured in accordance to IDM for the designers. The interpretation of building geometry relevant to energy simulations in the IFC schema is defined in the MVD, which on the other hand is controlled with the IFC export configuration. This provides a more coherent data structure for further processing. The corresponding software for simplifying and translating the rich geometrical information, should also comply with the technical specifications of MVD and be able to correctly assign heat transfer surfaces (or space boundaries) to the analytical BEM model. In addition the exported information can be validated through various visualisation and rule-based software, which increase the potential of utilizing IFC for the purpose of BPS.

As a result, it could be stated that given the information in the BIM model has been precisely defined, both gbXML and IFC perform to their expectation. So that leaves the matter with the *"clean"* model to be resolved by designers, who are in control of the native information provided in the BIM authoring tool. Essentially, in the early stage of a project, detailed and extensive parametric modelling is not required. As previously stated, the allocation of main usage zones and enclosing building elements with their known physical properties are sufficient data to be passed on for thermal and energy analysis.

In the framework of Building Performance Analysis, using gbXML and IFC data to conduct thermal analysis stipulates a long workflow and requires understanding of the simulated physical processes and grasp of programs used. Furthermore, validation of the exported model data still needs to be improved since errors in the translation of geometry are hard to detect in the course of the analysis.

The lack of means of direct import of gbXML and IFC into EnergyPlus additionally encumbers the process since the pre-processing BEM tool converts the extracted information into a different format and presumably affects the quality of the data.

4.2.2 Workflow

Following the principle of extracting and translating building geometry information for the purpose of BPS with gbXML and IFC is in itself a tedious and long process. In reality this method of conducting BPS suggests extensive workload in exporting, verifying, converting, importing, simulating and analysing building data. In addition the fact that there is no direct feedback to the original model which can propose improvements to the design prolongs the overall process and can be overlooked. Not many iterations of the model can be thus tested and analysed.

In addition, certain level of knowledge is required of the whole process, used tools and how certain technical specifications can influence the final input in EnergyPlus.

Instead more effort has been now directed in the way of creating integrated analysis tools to the BIM authoring tools which can guide the design to a more stable energy frame before proceeding to exporting the information for more detailed analysis (Autodesk 2014; Graphisoft 2014). However, an inlying tool would require a certain level of knowledge and grasp of the underlying program by the designers.

4.2.3 Reliability of Results

The conducted analysis over the performance of gbXML and IFC data formats show that at this stage of development it is safer to work with gbXML than IFC during the process of Building Performance Analysis. After all gbXML has been developed solely for the purpose of energy analysis and any further improvements will be made in this direction. In the same time IFC offers a much more reliable transference of geometrical data and it will be a matter of future investment to potentially bring more benefits.

As it turns out, the geometric input parameters for EnergyPlus have an influence over the simulation results and will be more reliable, providing the quality of the data has been preserved during the exchange process.

5 CONCLUSION AND RECOMMENDATIONS

In the course of evaluating and comparing the use of IFC and gbXML for the purpose of BPS, it becomes clear that both data formats are capable of extracting and transferring spatial and geometrical information from BIM models. Successful data export is strongly related to quality of the building model, generated in BIM- authoring tool. In order to preserve the quality of the data, their performance is highly dependent on the receiving software, which convert and prepare the information for input to EnergyPlus.

In its default schema, populated with building semantics, gbXML stores thermal building geometry in a pre-defined structure, which fails to preserve a stable correlation between the building elements. Its primary function is to facilitate work between BIM and building performance analysis and has been the preferred format for that purpose. Future improvements should be focused on making it a more reliable and robust data format.

IFC has been developed with conjunction to the needs of the AEC industry to assists integrated BIM work and exchange of building data between disciplines. In its service as an open data format, it provides a contingent and hierarchical informational structure, which carries the needed building geometry for conducting building performance analysis. More efforts should be done by energy software vendors to use this format, because if its promising way of storing and translating data.

For the particular workflow studies both gbXML and IFC are susceptible to implementation schemes of pre-processing BEM tools. While DesignBuilder, used for gbXML data conversion and IDF export, provides an integrated platform for energy analysis with BIM and EnergyPlus, it requires expertise using the software to appropriately prepare the data for simulation in EnergyPlus. On the other hand SBT-1 for IFC is a basic tool for simplification of geometry, but its potential to convert complex geometry into Space Boundaries has not been developed and at this stage is disrupted.

EnergyPlus is a powerful, whole building simulation tool, which requires precise input data for generating reliable outcome. Results show that incorrect building geometry data can produce misleading results. The overall approach to using gbXML and IFC to perform BPS in EnergyPlus is a laborious process with no direct feedback to the original model and almost no validation of data. It requires a grasp of the whole workflow and underlying knowledge of the simulated physical processes to successfully conduct building performance analysis.

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