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Enhancing Building Energy Performance Simulation by Automating the Thermal Zoning Process in a BIM-based BEM Approach.

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Abstract

Building Energy Modeling (BEM) plays a critical role in reducing energy consumption in the Architecture, Engineering, and Construction (AEC) industry. However, creating accurate BEM models demands substantial expertise and effort. Building Information Modeling (BIM) offers an opportunity to automate this process by converting BIM data into BEM models, but this approach faces two main challenges: ensuring accuracy in BIM-based BEM models and managing high simulation times and computational loads, especially for large projects.

This thesis presents a methodology using BIM space boundaries to create thermal zones, analysed with various thermal zoning strategies and compared against a detailed base scenario. Results indicate that BIM-based BEM models show accuracy comparable to manually generated models. The zoning strategies lead to significant simulation time reductions of 82% to 90% and reduced energy load predictions by 10% to 20% when zoning is maintained on the same floor. Scenarios merging zones across floors result in further energy load reductions due to Gross Floor Area (GFA) changes, though they may affect temperature uniformity.

In conclusion, the methodology offers a balance between faster simulation times and accurate energy predictions, supporting informed decision-making in design. Future research could integrate large language models (LLMs) to improve space identification and enhance thermal zoning automation.

Zusammenfassung

Building Energy Modeling (BEM) spielt eine entscheidende Rolle bei der Reduzierung des Energieverbrauchs in der Architektur-, Ingenieur- und Bauindustrie (AEC). Die Erstellung präziser BEM-Modelle erfordert jedoch erhebliches Fachwissen und großen Aufwand. Building Information Modeling (BIM) bietet die Möglichkeit, diesen Prozess durch die Umwandlung von BIM-Daten in BEM-Modelle zu automatisieren. Diese Automatisierung bringt jedoch zwei Hauptherausforderungen mit sich: die Aufrechterhaltung der Genauigkeit der BIM-basierten BEM-Modelle und die Bewältigung langer Simulationszeiten sowie hoher Rechenlasten, insbesondere bei großen Projekten.

Diese Arbeit stellt eine Methodik vor, die Raumgrenzen aus BIM-Modellen nutzt, um thermische Zonen zu erstellen, die dann unter Verwendung verschiedener thermischer Zonierungsstrategien analysiert werden. Diese Strategien werden mit dem detaillierten Basisszenario verglichen, um ihre Leistungsfähigkeit zu bewerten. Die Ergebnisse zeigen, dass BIM-basierte BEM-Modelle eine vergleichbare Genauigkeit wie manuell erstellte Modelle aufweisen, während die verschiedenen Zonierungsstrategien zu einer erheblichen Reduktion der Simulationszeiten führen, die zwischen 82 % und 90 % liegen. Auch die prognostizierten Energiebedarfe sinken je nach verwendeter Zonierungsstrategie, mit Reduktionen von 10 % bis 20 % in Szenarien, die die Zonierung auf derselben Etage beibehalten. Szenarien, die Zonen über mehrere Etagen hinweg zusammenführen, führen jedoch zu noch größeren Reduktionen des Energiebedarfs aufgrund der erheblichen Verringerung der Bruttogeschossfläche (GFA), was zu ungenauen Temperaturverteilungen in hohen thermischen Zonen führen kann.

Abschließend bietet die vorgestellte Methodik einen Ausgleich zwischen der Reduktion der Simulationszeiten und der Aufrechterhaltung der Genauigkeit der Energiebedarfsprognosen, was sie zu einem wertvollen Werkzeug für fundierte Entscheidungsfindungen im Entwurfsprozess macht. Zukünftige Forschungen könnten den Einsatz von Large Language Models (LLMs) untersuchen, um den Automatisierungsprozess weiter zu verbessern, indem Raumnutzungen identifiziert und die Leistung der thermischen Zonierungsstrategien optimiert werden.

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List of Abbreviations

AEC	Architectural, Engineering and Construction.
AGC	Associated General Contractors of America
BEM	Building Energy Modelling
BEPS	Building Energy Performance Simulation
BIM	Building Information Modelling
BUI	Building File
DCK	Deck File
DOE	US Department of Energy
epw	EnergyPlus Weather
EUI	End User Intensity
gbXML	Green Building XML
GDP	Gross Domestic Product
GFA	Gross Floor Area
HBJSON	Honeybee JSON
HVAC	Heating, Ventilation and Air Conditioning
IAI	International Alliance for Interoperability
IDF	Input Data Format
IFC	Industry Foundation Classes
ISO	International Organization for Standardization

JSON	JavaScript Object Notation
LCA	Life Cycle Analysis
LKdb	LCA Knowledge database
LLM	Large Language Model
LOD	Level Of Development
NLP	Natural Language Processing
OGC	Open Geospatial Consortium
OOP	Object-Oriented Programming
PMV	Predicted Mean Vote
SBT	Space Boundary Tool
UML	Unified Modelling Language
XML	Extensible Markup Language

1 Introduction

1.1 Motivation

The Architectural, Engineering and Construction (AEC) industry accounts for 36% of global end-energy consumption (United Nations Environment Program, 2021). Interest in Building Energy Performance Simulation (BEPS) as a tool to reduce and optimise the current level of energy consumption has peaked, especially after introducing new regulations to achieve carbon neutrality (Wu et al., 2023). Traditionally, the creation of Building Energy Models (BEMs), essential for energy simulation, involves a labour-intensive process that requires manually inputting data such as geometry, materials, occupancy schedules and Heating, Ventilation and Air Conditioning (HVAC) systems. This process is often prone to errors and inefficiencies due to the fragmented nature of data exchange in the AEC Industry, where information is typically shared through documents, emails and drawings (Borrmann et al., 2018).

Building Information Modeling (BIM) offers a potential solution to these challenges by integrating both the physical and semantic aspects of a building into a single digital model. BIM provides a comprehensive and structured representation of building information that can be used across different project stages. By leveraging BIM, the manual creation of BEMs could be partially or fully automated, improving the efficiency, accuracy and consistency of energy simulations (Wu et al., 2023). This approach can enable a more integrated workflow, where the building geometry, material properties and operational data are directly transferred from BIM to BEM, reducing the risk of data loss and errors.

The possibility of a BIM-based BEM approach introduces several advantages for energy simulations in the AEC Industry. For instance, such a workflow allows energy models to be updated throughout the design and construction process, facilitating continuous performance assessments and supporting better design decision-making (Yeung et al., 2023). Previous research has extensively explored various workflows for BIM-based BEM. The process can be broken down into different key steps, which include geometry (step 1), materials (step 2), space type (step 3), thermal zone (step 4), space load (step 5) and HVAC system (step 6) (Gao et al., 2019).

Incorporating thermal zoning, in particular, benefits from a BIM-based approach. Thermal zones are critical in energy simulation, as they define areas of similar thermal behaviour within a building. A BIM-based workflow could streamline the zoning process by automatically identifying key parameters such as boundary conditions and space orientations (Shin & Haberl, 2022). A BIM-based BEM process can potentially make energy simulations more efficient and reliable by reducing the manual workload associated with thermal zoning and other steps.

1.2 Problem Statement

This thesis investigates the impact of automating thermal zoning within a BIM-based BEM process. While several BIM-based BEM workflows have been extensively studied and developed, the process still involves considerable manual input, particularly in defining thermal zones. Although BIM-based BEM significantly improves the efficiency of BEPS by enabling faster model creation, thermal zoning relies significantly on manual efforts. The approach developed in the current thesis is Open BIM based to ensure interoperability, allowing easier data exchange across various software platforms.

This thesis proposes a novel methodology for automating thermal zoning within the BIM-to-BEM transformation process. This approach utilises rooms, as defined in BIM, as the primary building blocks for thermal zoning in BEM. While rooms can be directly transferred into thermal zones, large and complex projects pose challenges due to multiple spaces with different usage types requiring longer simulation time and bigger computational capacity. The proposed methodology integrates factors such as orientation, space usage and external boundary conditions to efficiently group individual rooms into thermal zones for more efficient energy analysis.

1.3 Goal and Scope

This thesis addresses two primary research questions to evaluate the impact of automated thermal zoning in a BIM-based BEM process. The research questions and their corresponding hypotheses are outlined below.

1.3.1 Part I – BIM-based BEM

Research Question I: To what extent does integrating space types, thermal zones and space boundaries enhance the geometric transformation within the BIM-to-BEM process?

Hypothesis:

Integrating space boundaries into the BIM-based BEM process, using Open BIM schemas, enhances geometric transformation by improving the accuracy of energy models, reducing manual intervention and minimising discrepancies between architectural and energy models.

Description:

The first research question aims to understand the workflow necessary for an open BIM process to convert BIM to BEM. This involves comprehensively analysing open BIM schemas and the essential elements required for a reliable energy model. The thesis evaluates the potential target BEM schemas, highlighting their strengths and limitations. The workflow will also investigate how identifying space boundaries can facilitate the creation of thermal zones.

1.3.2 Part II – Simplifying the Energy Model

Research Question II: How do automated thermal zoning strategies impact the accuracy and efficiency of simulations resulting from the BIM-based BEM process?

Hypothesis:

Automated zoning strategies, such as merging similar rooms or spaces based on thermal properties and occupancy schedules, can enhance the BIM-based BEM transformation process. This methodology aims to simplify energy simulations, improve workflow efficiency and reduce computational demands without compromising the accuracy of energy performance predictions.

Description:

This section focuses on developing strategies for simplifying thermal zones by merging adjacent rooms with similar boundary conditions. Criteria will be established to identify rooms that can be effectively grouped. The objective is to assess the impact of this simplification, particularly in large models that require extensive simulation time or substantial computational resources.

1.4 Outline

Background and related works are separated into three subchapters, each addressing critical aspects of the study. The first subchapter explores key BIM concepts, emphasising the principles of Open BIM and the importance of effective data exchange for seamless interoperability. This foundational understanding is crucial for establishing a robust framework for further investigation. The second subchapter discusses BEM, examining its principles, utility and zoning processes required for developing accurate simulation models. This section is essential for understanding the specific challenges associated with thermal zoning and its implications for energy simulation accuracy. The final subchapter focuses on the BIM-based BEM process by analysing the existing challenges in implementing the approach. Identifying these obstacles lays the foundation for the subsequent methodological exploration.

Then, we define the methodology by describing the systematic approach used to address the research questions. This includes a detailed explanation of the BIM to BEM process, accompanied by the Unified Modelling Language (UML) diagram that illustrates this transformation. Furthermore, we outline the zoning process that is integral to creating an effective simulation model, highlighting the methodologies employed.

Afterwards, the prototypical implementation is explained by providing an in-depth analysis of the algorithm developed to automate the thermal zoning process. It discusses the various components necessary to address the previously stated research questions. Additionally, this section presents the prototype developed for simulation, followed by a comprehensive analysis of the simulation results. We compare and discuss these results in relation to the hypotheses established in Section 1.3.

Finally, in the concluding chapter we revisit the research questions, synthesising the findings and contributions of this thesis. It also addresses the limitations encountered during the study and offers recommendations for future research directions, outlining potential improvements for further investigations.

2 Background and Related Works

2.1 Building Information Modelling in Building Design Process

The AEC industry represents 13% of the world's Gross Domestic Product (GDP) and employs approximately 100 million people globally (World Economic Forum, 2023). Despite its significant economic impact, the industry has been slow to embrace digitalisation compared to other major industrial sectors (European Investment Bank, 2020). The BIM approach is presented as the solution for this lag in technology integration. It draws inspiration from the automotive and aerospace industries by utilising a centralised 3D model that integrates both geometric and semantic information from various AEC disciplines (Borrmann et al., 2018). This thesis specifically examines the use case of BIM for energy simulation.

2.1.1 BIM Definition

The Associated General Contractors of America (AGC) defines BIM as "The development and use of computer software models to simulate the construction and operation of a facility" (American Society of Heating, 2021). The BIM approach is based on setting up the design and construction process around a highly enriched 3D Model, which is updated and modified throughout the life cycle of the building (Borrmann et al., 2018). This centralisation enhances coordination across a construction project by streamlining information management. Traditionally, information was exchanged through documents and emails during various construction and operation phases, leading to gaps and inefficiencies, as illustrated in Figure 1. By contrast, BIM facilitates continuous project progress tracking, ensuring smoother and more efficient information exchange.

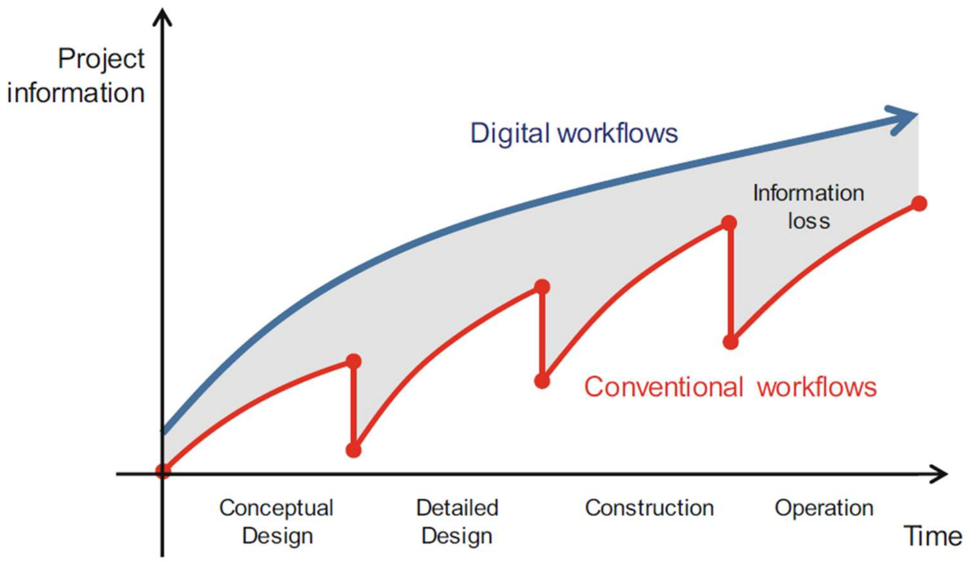

Figure 1: Loss of information caused by disruptions in the digital information flow (Eastman et al., 2011)

2.1.2 Data Exchange Mechanisms

As explained in the previous section, the BIM approach relies on a 3D model that federates information collected from the different industries participating in AEC projects. Thus, it allows for foreseeing inter-discipline clashes and inconsistencies in earlier phases of the project (Sacks et al., 2018). Figure 2 illustrates the intended data exchange model in a BIM approach, where the central Model can communicate with the various specialised peripheral models.

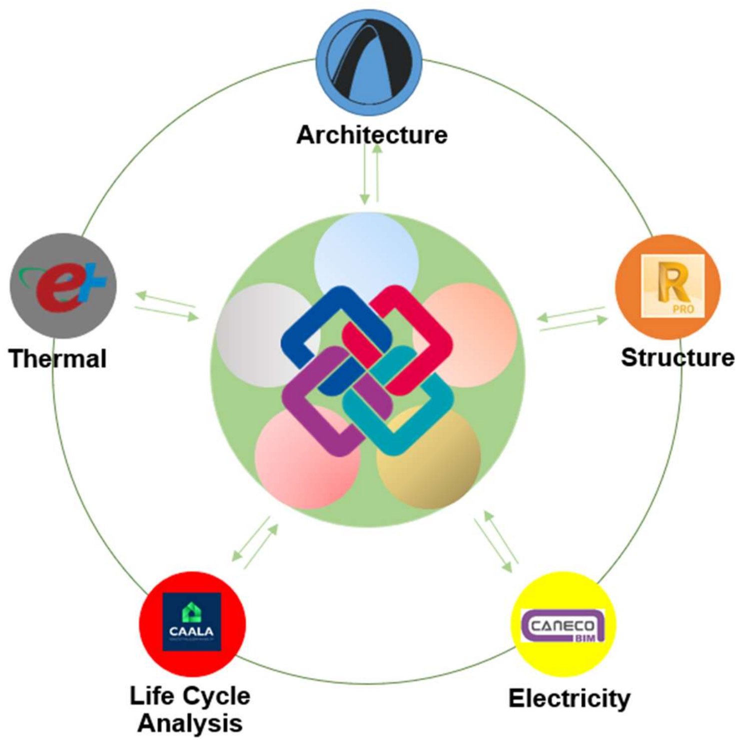

Figure 2: Simplified interaction schema between stakeholders in the BIM process (Own Schema)

There are two opposing approaches to achieving the required level of communication. The first approach is called Closed BIM. As schematised in Figure 3, it is set up within a closed environment where interoperability is only possible within the boundaries of a particular software provider (Forth et al., 2023).

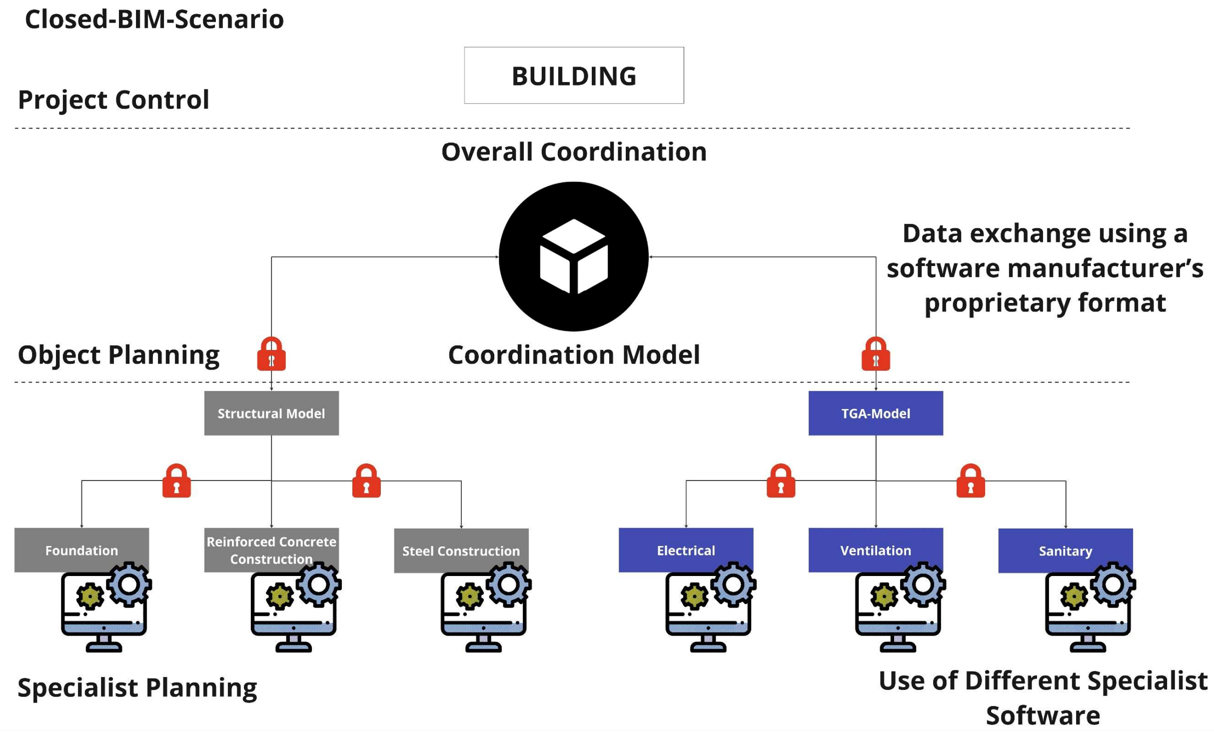

Figure 3: Closed BIM Exchange Scenario (Own Schema, Baunetzwissen Graphisoft, 2024)

The second approach is called Open BIM. It is defined as a collaborative process that is software neutral. It is designed, as illustrated by Figure 4, to allow effective shareability of project information and collaboration for all project participants without restrictions. Open BIM is based on six fundamental principles (Petie, BuildingSMART International, 2024):

- Interoperability is key to the digital transformation in the built asset industry.
- Open and neutral standards should be developed to facilitate interoperability.
- Reliable data exchanges depend on independent quality benchmarks.
- Open and agile data formats enhance collaboration workflows.
- Flexibility of choice of technology creates more value for all stakeholders.
- Long-term interoperable data standards safeguard sustainability.

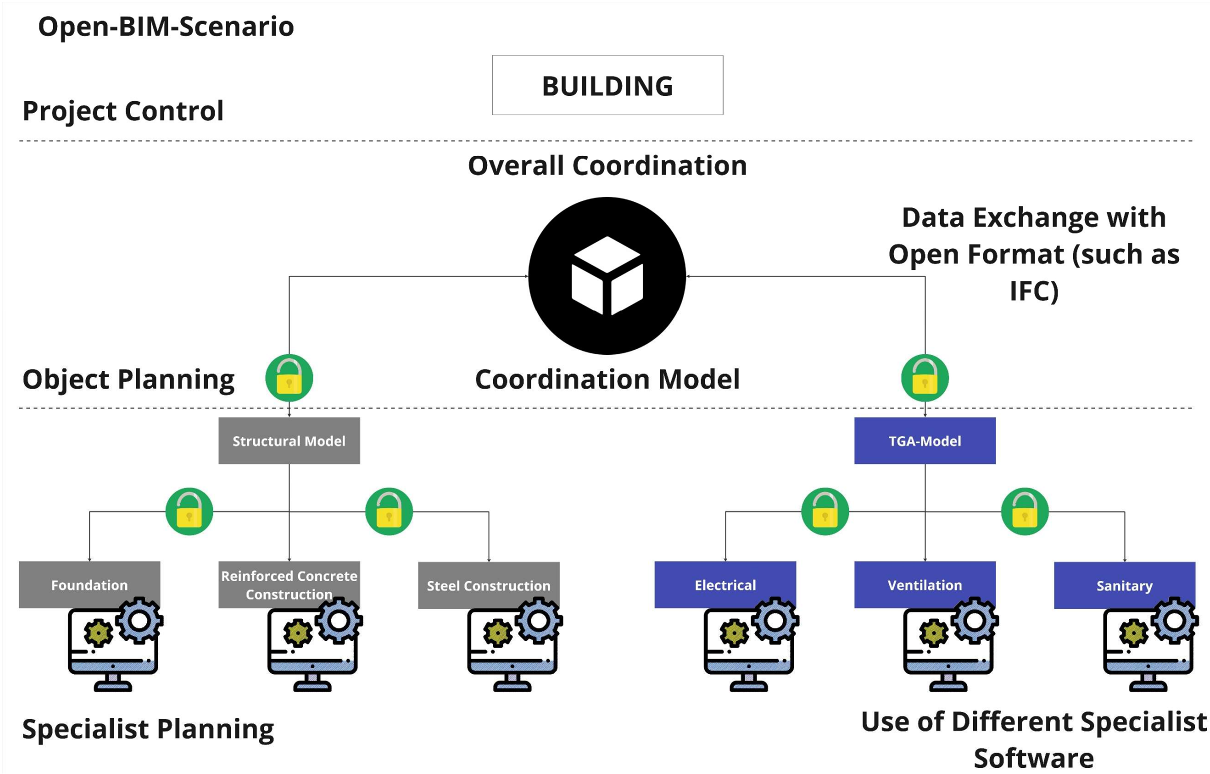

Figure 4: Open BIM Exchange Scenario (Own Schema, Baunetzwissen Graphisoft, 2024)

2.1.3 Industry Foundation Classes Schema

The IFC data format is internationally recognised and ISO certified standard for data exchange in the AEC industry. Originally developed by the International Alliance for Interoperability (IAI) in 1996, the IFC standard is currently maintained by the buildingSMART international organisation. IFC aims to improve collaboration and interoperability between different BIM software applications by providing a common, open data model (ISO 16739-1:2024, 2024). The interoperability of the IFC schema is based on the principles of Object-Oriented Programming (OOP), which uses class hierarchy and inheritance. This approach ensures the coherence of the schema, enabling easier code maintenance and offering greater flexibility in developing libraries and tools (Antunes et al., 2024).

The structure of IFC data can be likened to a tree, as illustrated in Figure 5. At its core is the resource layer, symbolising the roots that anchor the schema and supply the foundational resources needed for the system. The Core layer acts as the trunk, connecting the root to the upper layers and distributing essential information. The Interoperability layer represents the branches that further distribute this information to the Domain layer, which functions as the leaves, representing specific infrastructure entities (Antunes et al., 2024).

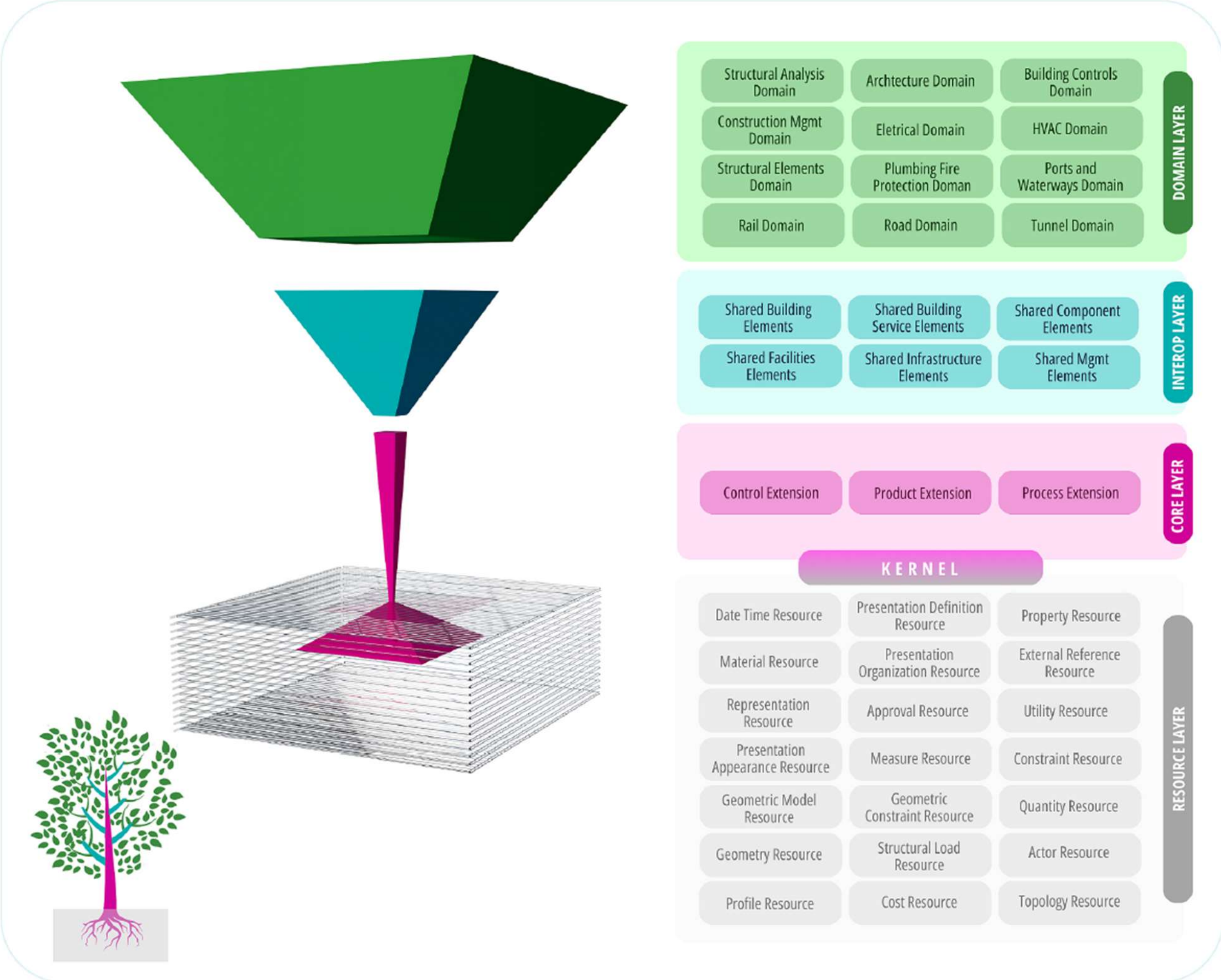

Figure 5: IFC Architecture Data -3D Tree- (Antunes et al., 2024)

Each entity under *IfcRoot* is defined by a globally unique identifier, a name and a description. Entities derived from *IfcRoot* can be created independently and are referred to as rooted entities. Non-rooted entities only exist if a rooted instance directly or indirectly references them. The *IfcRoot* class is further divided into three abstract subcategories:

- ***IfcObjectDefinition***: Describes object occurrences and types.
- ***IfcRelationship***: Captures the relationships between these objects.
- ***IfcPropertyDefinition***: Represents the properties and attributes associated with objects.

Each distinct element within the model is represented by an *IfcObject* entity, which serves as an independent piece of information that may contain or refer to other information.

2.1.4 Rooms and Spaces

BIM models are typically created from an architectural perspective since architects represent the central force driving AEC projects from conception to execution. An architectural BIM's geometry consists of detailed 3D elements like walls, slabs and openings (e.g., windows, doors and voids). In contrast, an energy model represents the building geometry as a collection of planar surfaces that define thermal spaces, as illustrated by Figure 6. As a result, transforming BIM model into BEM model involves a simplification process guided by specific rules designed to adapt the detailed architectural model to the needs of energy simulation (H. Chen et al., 2018).

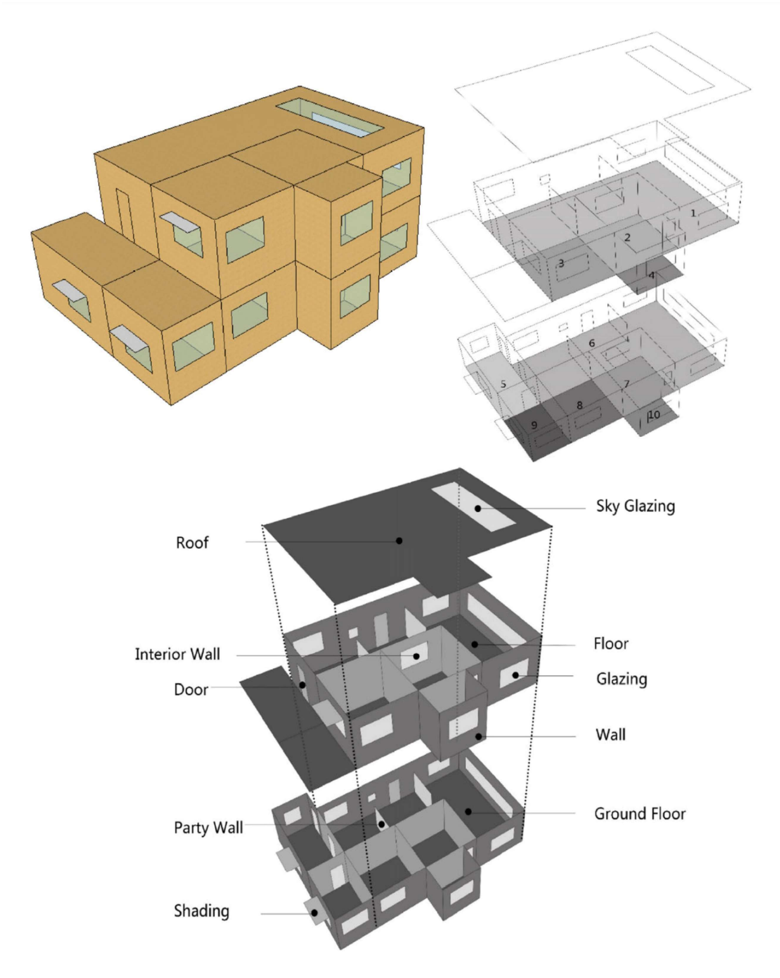

Figure 6: Hierarchical building space model (H. Chen et al., 2018)

2.1.5 Space Boundaries

Space boundaries are virtual objects that represent spaces and rooms in buildings (Weise et al., 2009). They are essential for various types of analysis, such as:

- **Quantity take-off for cost Estimating**: In early design stages, space boundaries are used to estimate material quantities. In this project phase, the Model has a low Level of Development (LOD), which means that many objects are not accurately modelled.

- **Facility Management work Package Estimating**: They are used to manage operation and maintenance for surfaces, such as repainting and carpet cleaning.
- **Energy Analysis**: BEM models are surface based, requiring space boundaries for the transformation process.

There are two types of space boundaries in the IFC Schema (BuildingSmart International, 2024), which are:

- **1st Level Space Boundaries**: Define boundaries of space without considering any change in the building element or spaces on the other side, depicted in Figure 7.
- **2nd Level Space Boundaries**: Define boundaries of space considering any change in elements or spaces on the other side, depicted in Figure 7.

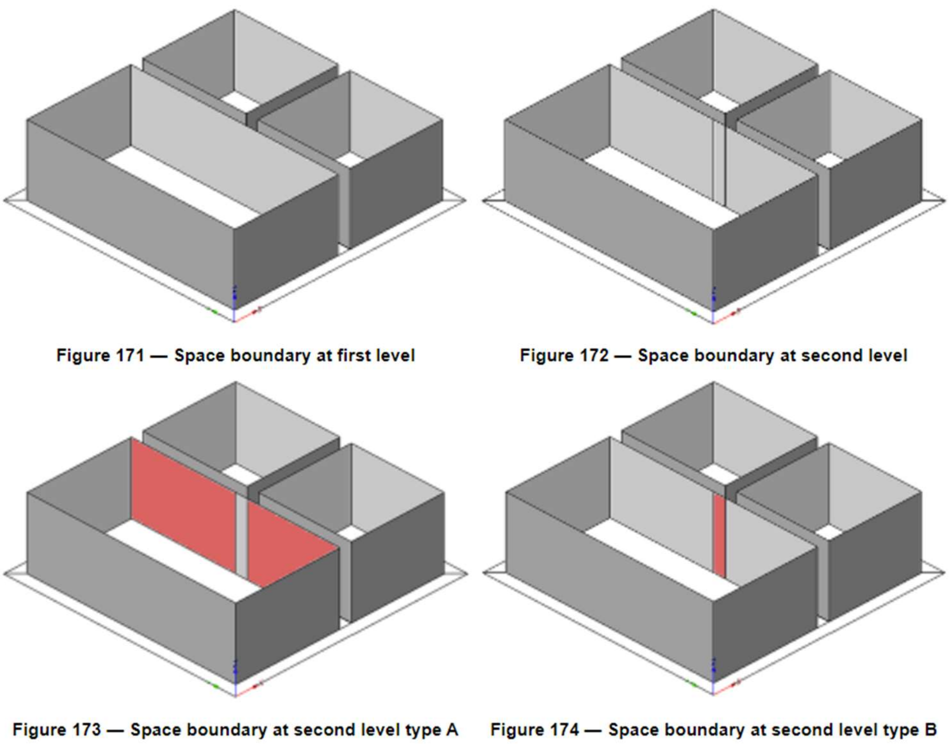

Figure 7: Differences between Space Boundaries Levels (BuildingSmart International, 2024)

Space Boundaries are defined in the IFC Schema using the *IfcRelSpaceBoundary* entity. It is used as the relationship between physical or virtual boundaries of spaces and building elements (Weise et al., 2009). This objectified relationship ensures that each component, including virtual elements and openings, can be defined by a boundary surface directly linking elements and spaces, as illustrated in Figure 8.

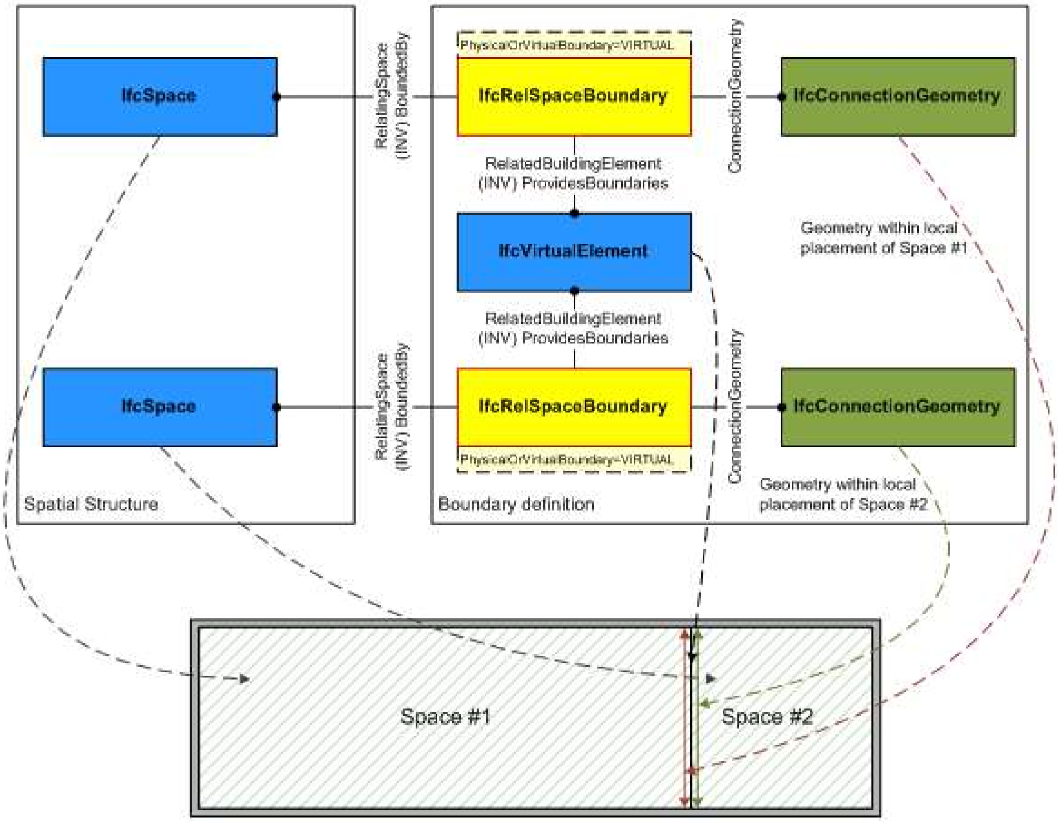

Figure 8: Space Boundary of physical element (BuildingSMART International, 2024)

Multiple geometry elements define the space boundaries in the IFC Schema depending on the Level (BuildingSMART International, 2024):

Table 1: Geometric Representation objects for Space Boundaries (BuildingSMART International, 2024)

1st level space boundary	2nd level space boundary
IfcSurfaceOfLinearExtrusion	*IfcCurveBoundedPlane*
IfcCurveBoundedPlane	*IfcFaceBasedSurfaceModel*
IfcCurveBoundedSurface	
IfcFaceBasedSurfaceModel	

Space Boundaries are also used to connect elements, such as *IfcProduct*, with the spaces they adhere to, such as *IfcWall*, *IfcWindow*, *IfcDoor*, *IfcRoof*, and *IfcSlab*. The following simplified schema could represent these relationships:

IfcBuildingStorey → *IfcSpace* → *IfcRelSpaceBoundary* → *IfcProduct* → *IfcCurveBoundedPlane*

Importing *IfcProduct* elements from the IFC model is insufficient to identify all the needed nested connections. To navigate the model in an orderly way, linking objects are essential. The IFC schema provides *IfcRelVoidsElement* and *IfcRelFillsElement*, which are used to link specific components, such as connecting windows and doors to the walls in which they are installed, as depicted in Figure 9. This ensures that the spatial relationships within the model are accurately maintained during the transfer process (Borrmann et al., 2018).

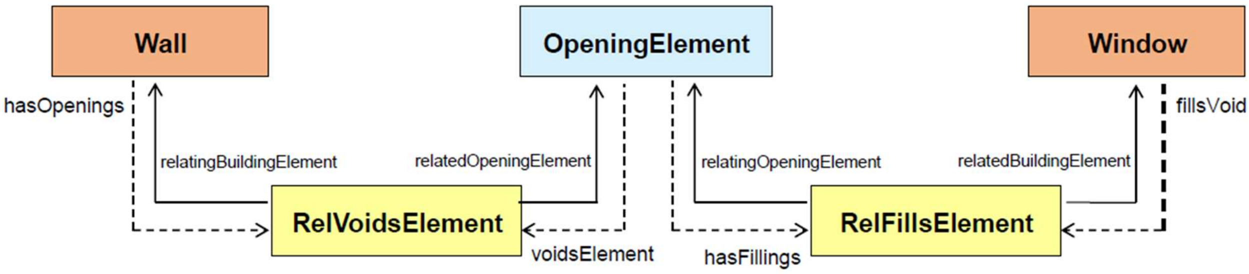

Figure 9: Relationship Schema between IfcWall / IfcWindow (Borrmann et al., 2018)

2.2 Building Energy Modelling in the Building Design Process

The demand for building infrastructure continues to grow to accommodate housing, commercial and administrative needs (American Society of Heating, 2021). As a result, improving building energy efficiency has become increasingly critical in mitigating energy consumption and emissions. In many economies, energy efficiency regulations have been introduced to ensure that buildings are designed, constructed and operated sustainably from conception through to end-of-life stages. In this context, BEM has emerged as a valuable tool for optimising energy performance through an iterative process to support the development of energy-efficient building designs.

2.2.1 Overview and Definition

BEM is a computational simulation process used to predict and analyse the energy consumption, environmental performance and thermal comfort of a building. The process involves creating a detailed 3D building model incorporating various physical and operational characteristics, such as architectural design, building systems, occupant behaviour and climate data (Shin & Haberl, 2019).

2.2.2 Inputs and Outputs

Energy simulation relies on a centralised kernel, such as EnergyPlus (Larochelle Martin & Monfet, 2024), which uses thermodynamic equations (e.g., Navier-Stokes equations) to calculate energy flows and consumption. These simulation tools require a range of important inputs to generate accurate outputs. The key inputs can be summarised as follows (Gao et al., 2019):

- **Building Geometry**: Information about the physical structure, including shape, size, orientation and spatial configuration.
- **Construction Materials**: Properties of walls, roofs, windows and insulation, such as thermal conductivity, density and heat capacity.
- **Mechanical Systems**: Specifications of HVAC systems, including type, efficiency and control strategies.
- **Lighting Systems**: Types and efficiencies of lighting fixtures and control methods.
- **Occupant Behaviour**: Occupancy patterns, schedules and internal heat gains from people, equipment and appliances.
- **Climate Data**: Local weather conditions, including temperature, humidity, solar radiation and wind speed.

These inputs are processed through the energy simulation to produce outputs that assess the optimal building energy results. The key outputs include:

- **Energy Consumption**: Detailed reports on the energy used for heating, cooling, lighting and other building services.
- **Energy Costs**: Estimates of operational costs based on energy consumption and local utility rates.
- **Thermal Comfort**: Indicators of indoor comfort, such as temperature and humidity levels, and Predicted Mean Vote (PMV).
- **Environmental Impact**: Data on emissions related to energy use, including carbon footprint and greenhouse gas emissions.

- **System Performance**: Efficiency metrics and performance indicators for HVAC and lighting systems.
- **Comparative Analysis**: Evaluations of different design options, retrofit measures, or operational strategies to improve energy efficiency and performance.

2.2.3 Thermal Zoning Criteria

A thermal zone is defined as a building area with consistent boundary and usage conditions, allowing spaces to be thermally treated in a uniform way and thereby enabling efficient control and maintenance. The literature used various other terminology to indicate thermal zoning, such as thermal blocks or HVAC zones. Thermal zones or blocks represent a portion of a building that can be controlled or maintained by a single thermostat. HVAC zones are components of the thermal blocks that should maintain the same temperature. Applying thermal design principles helps organise building spaces into functional thermal zones that share the same HVAC system (Shin & Haberl, 2019).

Several key parameters influence thermal zoning, including temperature, humidity, outside air ventilation, operating periods and pressurisation. Dividing buildings into thermal zones improves accuracy, as different parts of the same building can experience varying indoor environmental conditions, such as exposure to prevailing winds, solar radiation and differing occupancy schedules, which result in unequal heating and cooling requirements (Rodriguez & Fumo, 2021). Effective thermal zoning relies on key characteristics that ensure uniform thermal load management across all rooms within a zone. These characteristics include similar solar exposure and orientation, similar envelope exposure, occupancy type and density, shared schedules and incremental HVAC capacity. Rooms with different orientations or window sizes have distinct thermal needs, while perimeter rooms differ from core rooms regarding heating and cooling demands. Comparing a detailed model with a model using a core-perimeter thermal zoning strategy shows a decrease in calculated energy load by 16% to 19% (Fiorentini et al., 2020).

The automation of thermal zoning has been previously investigated. Following the zoning strategies defined by ASHRAE 90.1, the generation of multi-zone models has proved robust, especially in the early design stages. The arguments in favour of developing the AutoZoner are speed and reproducibility. Therefore, the use of the AutoZoner is reliable for providing fast feedback for decision-making during the early design stages (Dogan et al., 2016).

2.2.4 Building Energy Data Format

BEPS software has been used since the 1960s. They have slowly become integral to the building design process due to their precise nature. They allowed engineers to precisely estimate the energy load needed for heating or cooling of a building and thus design the appropriate HVAC system (Yeung et al., 2023). Different software uses different data formats depending on the predefined calculation model.

Input Data Format (IDF)

IDF is the native input file that EnergyPlus uses, the most widely used energy simulation engine. It is a file format representing building geometry, materials, HVAC systems, schedules and other parameters required for an energy simulation. Although it draws many strengths from its proximity to EnergyPlus, it has many weaknesses, mainly related to its syntax complexity and its limited ability to represent complex geometries.

BuildingSync

BuildingSync is a standard XML (Extensible Markup Language) schema developed by the US Department of Energy (DOE) to enable data exchange between energy audit tools and databases. It is designed for energy audits and data management, enabling the transfer of energy performance data across multiple software platforms. Nonetheless, the data format is unsuitable for BEM and its requirements regarding occupancy schedules and usage data.

Green Building XML (gbXML)

gbXML is an open schema developed specifically to exchange information between BIM tools and energy simulation software. It focuses on capturing geometric and other critical building information for energy analysis. It is widely supported by energy simulation engines such as EnergyPlus and is designed to easily facilitate data exchange between design models and simulation tools. Due to the schema being XML-based, it shows a lot of rigidity in data transfer, leading to data loss, especially with complex geometries of complex thermal zones.

TRNSYS Input Files (DCK, BUI)

TRNSYS is another widely used simulation tool, especially for dynamic simulation of buildings and energy systems. It defines building models using specific input formats such as DCK and BUI. It is well-suited for detailed transient system simulations, including thermal and solar energy systems. However, the data format is exclusive to TRNSYS software, which makes it hard to use with other energy tools.

Honeybee JSON (HBJSON)

HBJSON is a file format that stores data on BEM models and simulations. It is based on the JSON (JavaScript Object Notation) data structure. It is simulated using the Honeybee energy simulation library, an open-source tool for building performance analysis. HBJSON contains detailed information about building geometry, materials, constructions and other essential data required for energy simulation and analysis. Figure 10 illustrates the components of the LadyBug environment. The data format is flexible and can be used as a transitional layer from BIM tools and the IDF format used in EnergyPlus.

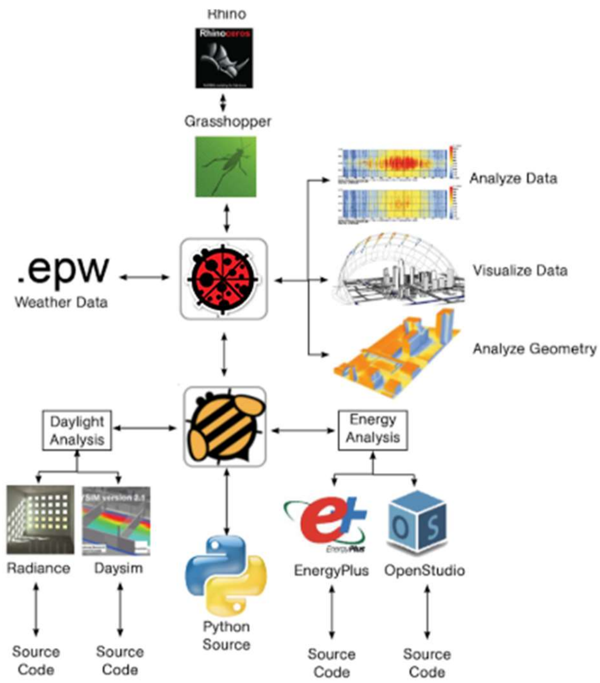

Figure 10: LadyBug environment (Honeybee Model Schema, 2024)

2.2.5 HBJSON Schema

An HBJSON Model is roughly composed of two parts: Properties and Rooms. The Properties part is further divided into energy, which is used for energy simulation, and radiance, used for lighting simulation. The energy part of the model has information such as the materials, constructions, HVACs, service hot water systems, program types, schedules and ventilation simulation control. In comparison, the radiance part of the model has information such as the modifiers, modifier sets, sensor grids and views (Honeybee Model Schema, 2024).

The model's geometry is completely defined in terms of composing Rooms comprised of several Faces, which then are parents to doors, apertures and shades. At the same time, the schema also allows independent shades, faces, apertures and doors. The thesis doesn't include the export of shading elements, which can be explored in further research. Figure 11 depicts the HBJSON geometry Schema.

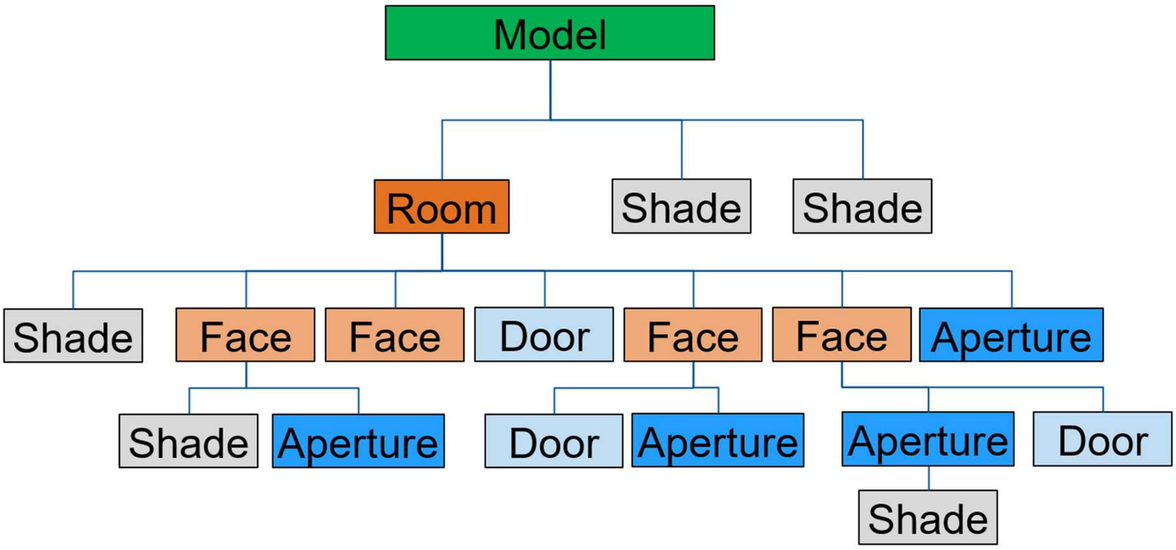

Figure 11: HBJSON Basic Schema (Honeybee Model Schema, 2024)

2.3 BIM-based BEM in the Building Design Process

The construction industry is currently shifting towards BIM to avoid the difficulties posed by 2D-based data systems. In addition, sustainability applied in the design process is gaining momentum thanks to the development of sustainability laws and certifications (Patel et al., 2023). BIM-based BEM presents an opportunity to make BEPS faster and more efficient. Furthermore, a centralised 3D Model can reduce data loss, bridging the gap between the architectural and energy efficiency design process. As previously discussed, transferring data from BIM models into BEM models include multiple levels (Gao et al., 2019), which will be discussed in the rest of this section.

2.3.1 Geometry Transfer

BIM and BEM models present a fundamental difference in how they define geometry. While BIM models present component elements in their real 3D representation, BEM models use planar representations. This transformation has been the focus of many research papers that have developed different methodologies. To address the gap, co-simulation architecture has been investigated. It allowed the import of data from an open BIM file format to a gbXML file format, which in turn could be converted to an IDF format and used as the basis for energy simulation (Yeung et al., 2023).

The transformation process could also be designed using a 3D Thermal Propriety Model (TPM). The method starts from the process of BIM scanning, which is used for data acquisition and then processed to create a 3D Model, which is then transferred to 3D TPM. The TPM is deconstructed by zone and then by element, which is used to generate an IDF file for simulation (Adán et al., 2023).

BIM to BEM workflows can also be based on graph techniques. The principle starts by creating a graph for each storey and linking it to its components. Then, identify adjacent storey graphs and create the corresponding connection surface, generally a slab. The vertical and tilted surfaces are processed to generate the related analytical spaces. Afterwards, inconsistencies are corrected to generate the IDF or gbXML file. The methodology is especially relevant in retrofitting, although reality capture tools such as 3D laser scanning are prone to create geometry clashes and other inconsistencies, which poses higher challenges for automation (Mediavilla et al., 2023).

2.3.2 Material Transfer

To improve the accuracy of BIM-based BEM methods, a system using an object-based approach was created to address simplified assumptions in material data. This system matches material names from IFC files (generated by ArchiCAD) with a predefined database of actual material properties using the Ruby program. It allows the addition of new material properties if they are not in the existing database (H. Kim et al., 2016). An automatic system for calculating building energy loads directly from BIM was also developed, which converts building geometry, material names and layer sets from IFC files into INP files. This system allows users to input additional information, such as material properties, thermal zones and site location, before calculating energy loads using DOE-2 (K. Kim & Yu, 2016). Additionally, a workflow for generating energy simulation models in OpenStudio directly from IFC files is successfully demonstrated by translating geometry, materials, window types and thermal properties data (Ramaji et al., 2016).

Natural Language Processing (NLP) extends on the premise of the previously explained method. The technology can enhance the automated matching of IFC elements, such as materials names to elements in the LCA knowledge database (LKdb). The resulting model provides reliable and consistent LCA results that can match materials up to a correctness of 89% (Forth et al., 2023).

2.3.3 Space types

Transferring space types and thermal zones have been investigated using diverse approaches. Such implementation is possible using an IFC file generated by ArchiCAD and simplifying it with the Space Boundary Tool (SBT-1) to create an IDF file. The corresponding material library in IDF format contains relevant thermal properties and material thicknesses, matching the fill type style in ArchiCAD. Simplified thermal zones are derived from the BIM model based on space names or IDs. At the same time, additional information like building location and simulation control data must be manually input via a Graphical User Interface (O'Donnell et al., 2013). However, the method has the drawback of requiring time-consuming BIM model preparation. Similarly, a methodology was also presented to extract building geometry, spatial data and zone data from ArchiCAD via IFC files, compiling it into DOE-2 input files to estimate building energy performance (H. Kim & Anderson, 2012).

The late acceleration in developing Large Language Models (LLM) has opened the door for better matching approaches to recognise space types to create zones. The methodology proposes to enrich data extracted from BIM using Semantic Textual Similarity (STS) combined with tuned LLMs. Room-specific space types and construction elements are matched in accordance with a database of possible space type names (Forth & Borrmann, 2024).

3 Methodology

3.1 General Framework

The general framework of our methodology is separated into three main parts, as illustrated in Figure 12. The first part is generating the open BIM model, which includes 2nd level space boundaries essential to describe the spaces in the BIM model. The framework uses the IFC data file as the basis for input data to create the BEM model since it provides all the elements needed for an accurate BEPS, such as geometry, construction materials, space type and space boundaries.

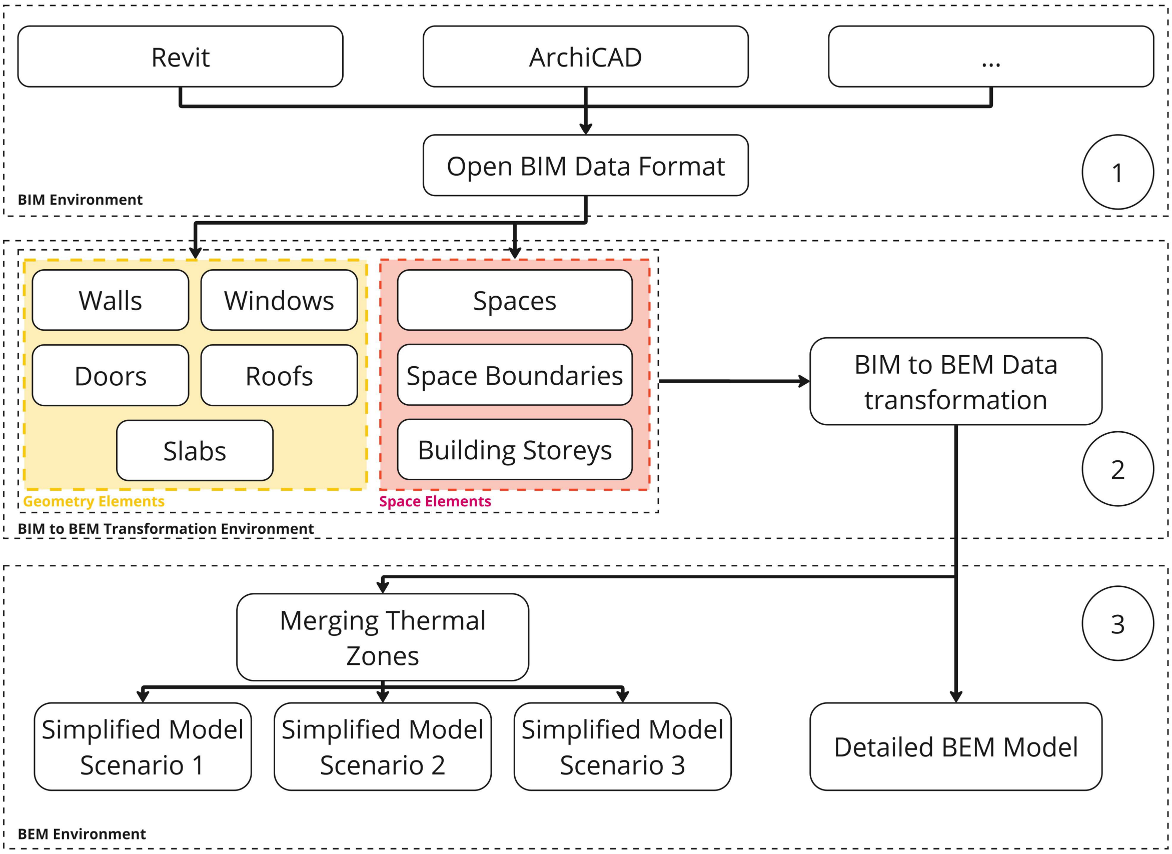

Figure 12: General Framework of the Thesis (own schema).

The second part organises the imported data into a specific data structure that can be used to define the resulting BEM models. The methodology differentiates two main types of data to be structured. The first is the data used to describe the geometry, such as walls, windows, doors, roofs and slabs, while the second describes the space organisation using spaces, space boundaries and building storeys. These groups of elements are combined to create the needed BEM model. The objective is to provide an automated process to convert all types of geometries into a specific energy model schema.

The third part sets up the different zoning criteria that define the three scenarios, and the methodology is set to analyse them. The implementation identifies rooms and compares properties to create thermal zones. The resulting models are simulated and compared in terms of computational load and impact on final simulation results.

3.2 BIM to BEM transformation process

In order to respond to the first research question, we will set up an automated BIM-based BEM transformation process. The process will be based on Open BIM tools to ensure seamless collaboration among various stakeholders, allowing data exchange across different software platforms. The basis for the approach will be the IFC format, which will serve as the central data structure for providing input.

3.2.1 Open BIM Data Export

As previously explained, the methodology is set to be open BIM-based to avoid being software-dependent. Regardless of the software used to generate the BIM model, it is exported into the open BIM data format, IFC. This methodology uses 2nd level space boundaries to capture external boundaries (walls, roofs, floors) and internal boundaries between different thermal zones to ensure precise energy simulations. Since the 1st level space boundaries only define the surfaces separating the building from the outside environment, they are less suitable for complex BEPS, which generally involve multiple zones with complex geometric shapes. By focusing on the 2nd Level space boundaries, the model can account for energy exchanges between adjacent spaces, which leads to more accurate results and can simplify the process of thermal zone merging, defined later.

3.2.2 Organising Energy Data

As explained in Section 3.2.1, the accurate definition of space boundaries is critical in converting IFC to BEM. Space boundaries describe the surfaces that separate different zones within the building and interact with external elements, significantly impacting the building's thermal performance. Therefore, the process is built on the 2nd level space boundaries as they are more suitable for exporting the required surface elements for an energy model. As illustrated in Figure 13, the implementation extracts geometry definitions of architectural elements as well as the spaces and space boundaries they define. These different types are connected by a system of IDs to make it easier to map the components of thermal zones and define the geometric relationships between building elements to define the BEM model.

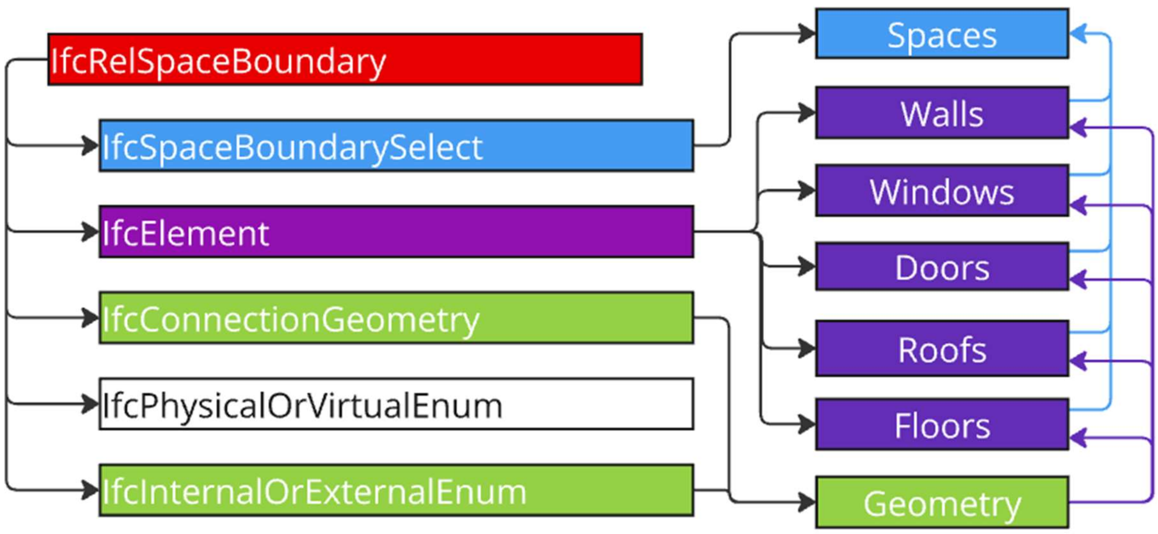

Figure 13: The use of Space Boundaries to extract all needed Information for BEM (Own Schema)

An *IfcSpace* represents a physically or virtually bounded volume, indicating a single room or a group of rooms. The spaces are bounded by space boundaries, which are defined by the connection of the space with a physical element such as walls, windows, floors, roofs, and slabs. They are also defined virtually as air separations, which are artificially defined. The defined spaces are analysed and transferred into thermal zones in the transformation process, as defined in Section 2.2.3. The process ensures that each zone corresponds to a distinct spatial area with unique thermal characteristics. Figure 14 illustrates the resulting thermal zones from space data transformation.

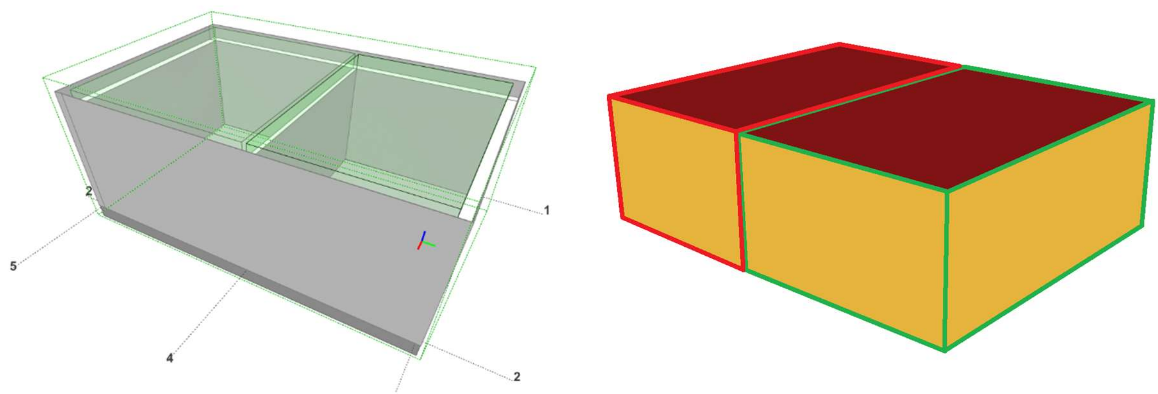

Figure 14: Converting Space Boundaries into Thermal Zones (Own Schema)

Figure 15 illustrates the link between space boundaries and building elements, including walls, floors, roofs, and windows. This connection facilitates an accurate representation of thermal exchange between spaces and their enclosing surfaces. For example, a wall dividing two zones has space boundaries on both sides, each associated with the adjacent spaces. This configuration allows the simulation to effectively capture heat transfer and energy flow between building components.

Space boundaries are used to transfer the geometry definition of each building element from BIM to BEM. They represent the physical surfaces that enclose spaces, providing precise geometric information about the area, boundary points and the normal vector defining the orientation of each element. This data is important for accurately defining BEM models. These geometric properties are extracted from the space boundaries and transferred to create the BEM model. This step ensures that the geometry of each space boundary aligns with the overall building structure used for BEPS.

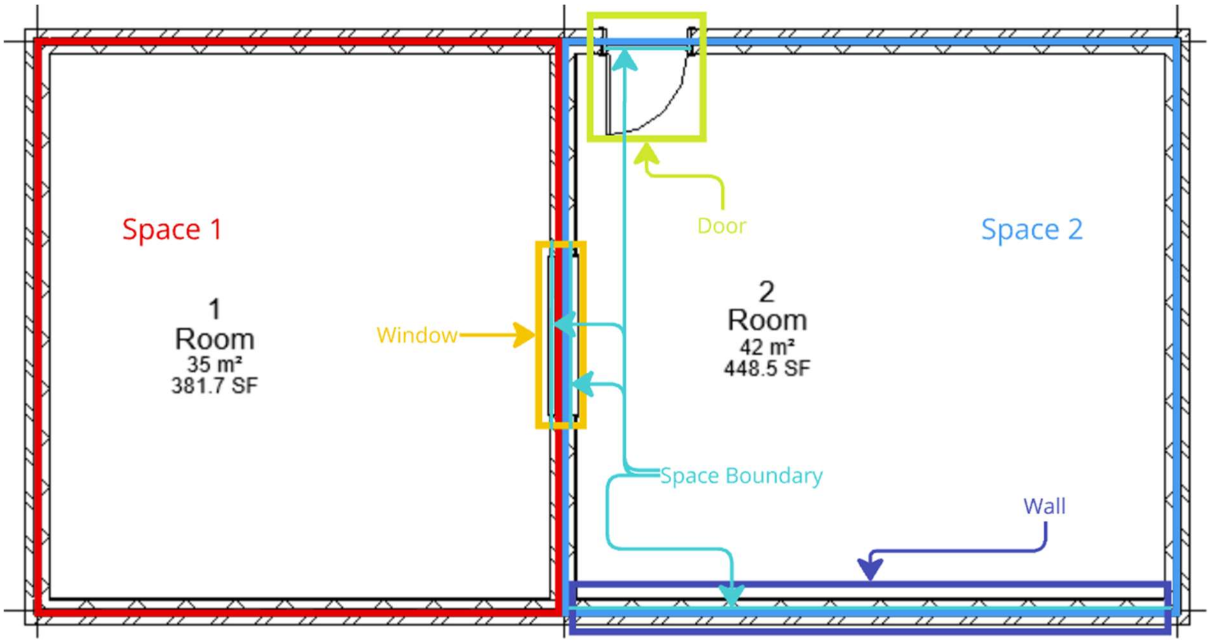

Figure 15: Connection of Space Boundaries with Building Elements (Own Schema)

3.2.3 Creating Energy Model

This stage organises the building data into a hierarchical framework that forms the basis for an accurate energy simulation. The process defines five primary categories, which play a central role in creating the BEM Model. The model is created in sections connected hierarchically from the parent element to various child elements comprising the leaves, in this case, apertures and doors. The apertures and doors are assigned to the appropriate parent faces, which in turn are allocated to the rooms they define.

Model

The Model represents the entirety of the building. It serves as a container for all the individual components that make up the simulation, including rooms, surfaces and building elements such as windows and doors. This structure is vital for integrating all relevant data about the building into a single, cohesive format.

Rooms

The Room category defines the various spaces within the building. Each room has distinct thermal properties, such as temperature setpoints, internal heat gains and ventilation requirements. By accurately defining each room's geometry and thermal behaviour, the conversion ensures that the energy model can simulate how heat flows through the building and how different spaces interact thermally.

Faces

The Face represents the surfaces that form the boundaries of the rooms. These include walls, floors, ceilings and any other surfaces that separate spaces or enclose the building. Each face is characterised by its geometry, which is imported from the relevant space boundary, the ID of the container room and the normal vector showing its orientation. These elements are essential for setting up the relationships between rooms, allowing for heat transfer between rooms or between the building and the external environment. The accurate definition of faces enables the model to account for energy loss or gain through building surfaces.

Apertures and Doors

Exporting apertures and doors involves two key aspects. The first is the geometry of these elements, imported via their space boundaries, as previously discussed. Additionally, each window or door must include information about the face to which it is attached, which is achieved by storing the ID of the face. Furthermore, the orientation direction is specified by a normal vector, indicating the direction from the room's interior to the exterior.

3.3 Automated merging process of thermal zones

The zoning process is based on a set of criteria which identify clustering possibilities needed to create the appropriate thermal zones (Wu et al., 2023):

- (I) They are adjacent to each other.
- (II) They are of similar space type.
- (III) They share the same setpoint and schedule.
- (IV) They are either in the same internal area or perimeter with the same orientation.

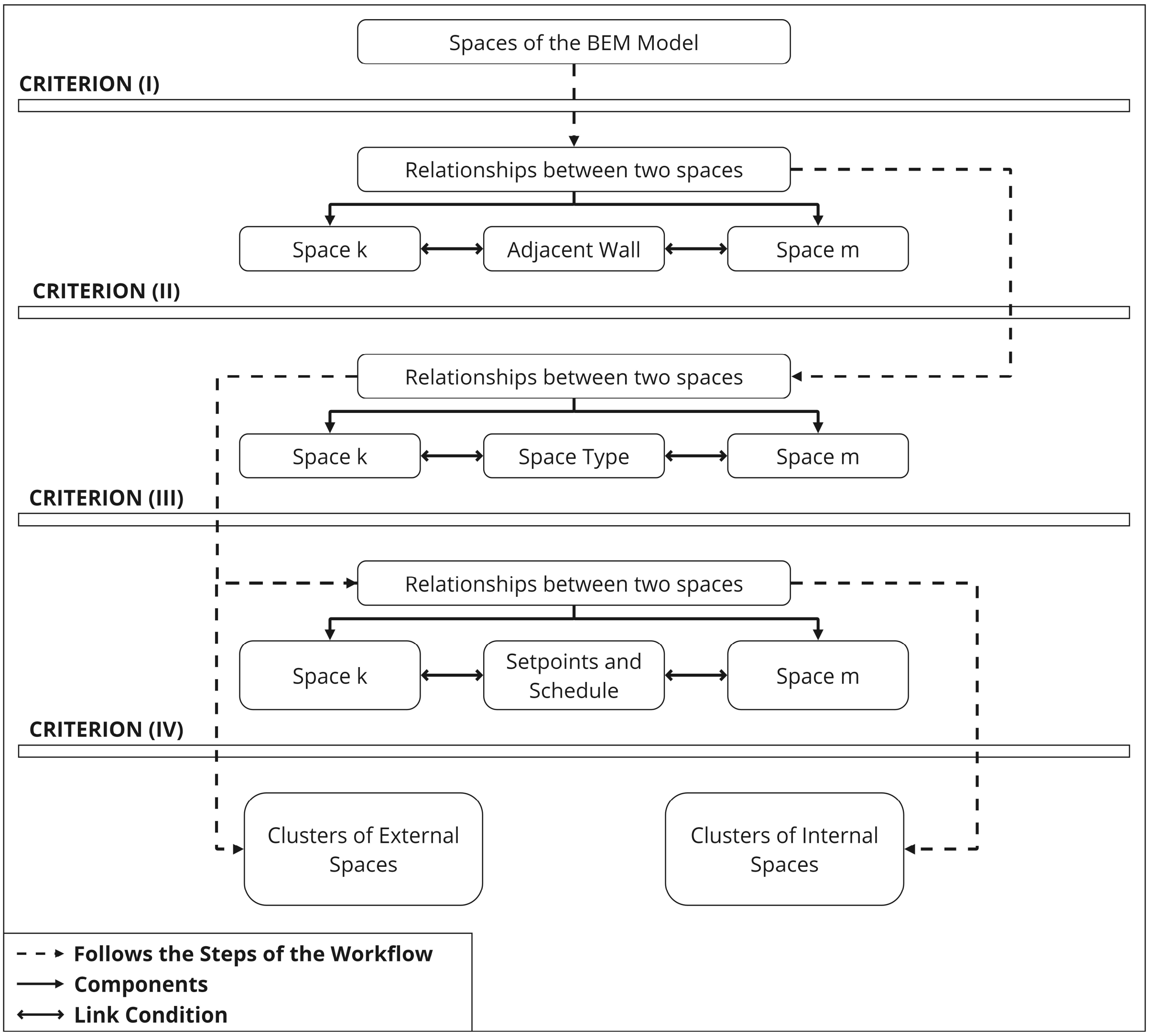

Figure 16: Workflow followed to merge spaces into thermal zones (Own Schema)

Using criterion (I), the spaces are clustered to include adjacent spaces which share common elements. The resulting clusters are filtered using criterion (II) to include spaces with similar space types. Then, the spaces are filtered to only include spaces with similar setpoints and schedules as defined by criterion (III). Using the last criterion

(IV), the spaces are differentiated by separating internal and external areas. On the one hand, once a space boundary defining a space is marked as external, they are identified as a perimeter space. On the other hand, spaces that have no external space boundaries are clustered as internal elements. This process separates the building into core and perimeter areas, which are treated separately (Shin & Haberl, 2019). Figure 16 illustrates the following workflow in detail.

3.3.1 Identify Connected Spaces

As previously discussed, the first step is identifying the connection between the spaces comprising the BEM model. The connections are organised as relationships connecting every two spaces through an adjacent element, such as walls or slabs. This process results in the following types of connections, illustrated in Figure 17:

- Two adjacent spaces that share an element as a direct connection, such as the red and orange spaces.
- Two spaces share a wall that spans through them but does not directly connect them, such as the red and blue spaces.
- Two spaces which are located far from each other but have a wall connecting them, such as the red and yellow spaces.

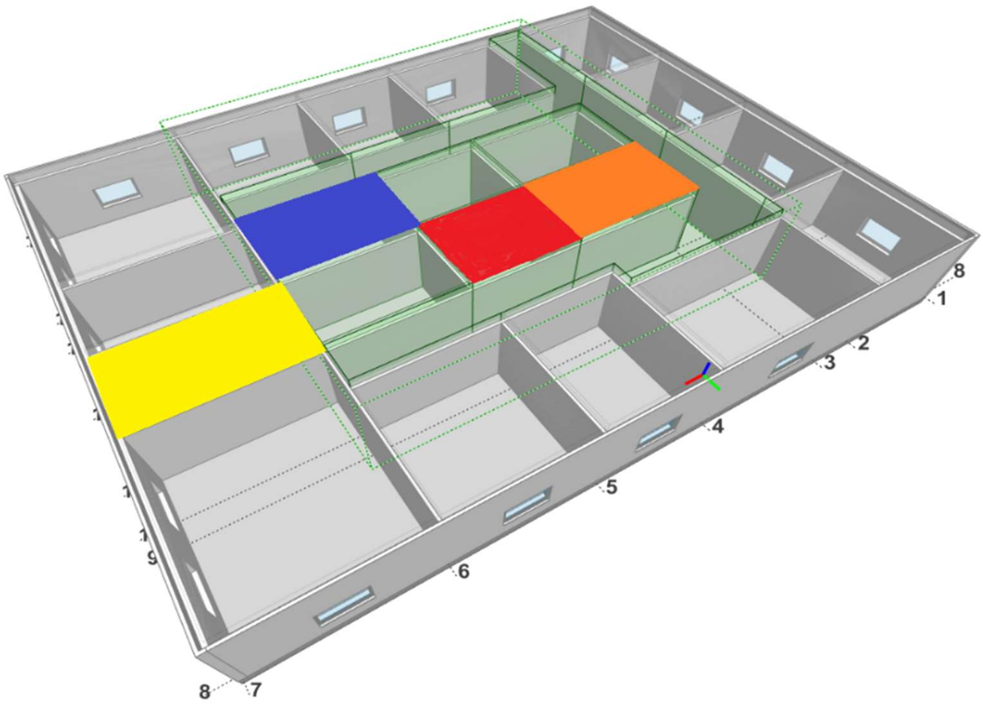

Figure 17: Identifying Adjacent spaces for a particular space (Own Schema)

3.3.2 Identify Mergeable Spaces

Similar Space Types

The space type is essential to identify which rooms could be merged. In the general definition of *IfcSpace*, the property used to determine the type is *IfcSpaceTypeEnum*. Unfortunately, it doesn't allow many choices, so it must be complemented using the name label. Identifying the space type using naming is a broad research topic and fine-tuned LLM provides acceptable results for automatically identifying space types from labels (Forth & Borrmann, 2024). The thesis focuses on simplifying the subject by using fixed names that could be directly compared; in our prototype, we will explicitly use words such as “OFFICE”, “CORRIDOR” and “WC”.

Similar Setpoints and Schedules

Setpoints and Schedules are defined depending on the usage type of the space. In our approach, we define them using default values already provided by the Honeybee schema, depending on the usage type. Table 2 defines the used schedules and setpoints:

Table 2: All default Schedule and Setpoint values used for the model (Honeybee Schema, 2024)

Heating Setpoint	20°C
Cooling Setpoint	26°C
Occupancy Schedule	100% Occupancy from 01h to 23h
People per Area	0.0565
Ventilation Flow per Area	0.000305
Electrical Equipment Watts per Area	10.33 W/m²
Lighting Watts per Area	10.55 W/m²
Infiltration Flow per Exterior Area	0.0002266

Similar Spatial positioning

In any building, spaces can generally be categorised into two primary zoning types: the core and the perimeter, as previously discussed in Section 3.3. To streamline the process of grouping spaces into these two archetypal spatial positions, we introduced a property called *IsExternal* at the Space Boundary level. This property is specifically designed to differentiate between core and perimeter spaces by identifying those that are in direct contact with the building's exterior. A space is classified as part of the perimeter zone if it contains at least one Space Boundary that interacts with the external environment.

To facilitate this identification, all Space Boundaries within the building model are assigned a normal vector, which defines the orientation of each boundary surface. By comparing the orientation of these vectors, we can assess the relative positioning of each space with respect to the external environment of the building, as shown in Figure 18. If the normal vectors of space boundaries have opposing directions, the respective spaces can be considered for merging into a single thermal zone, simplifying the overall zoning scheme.

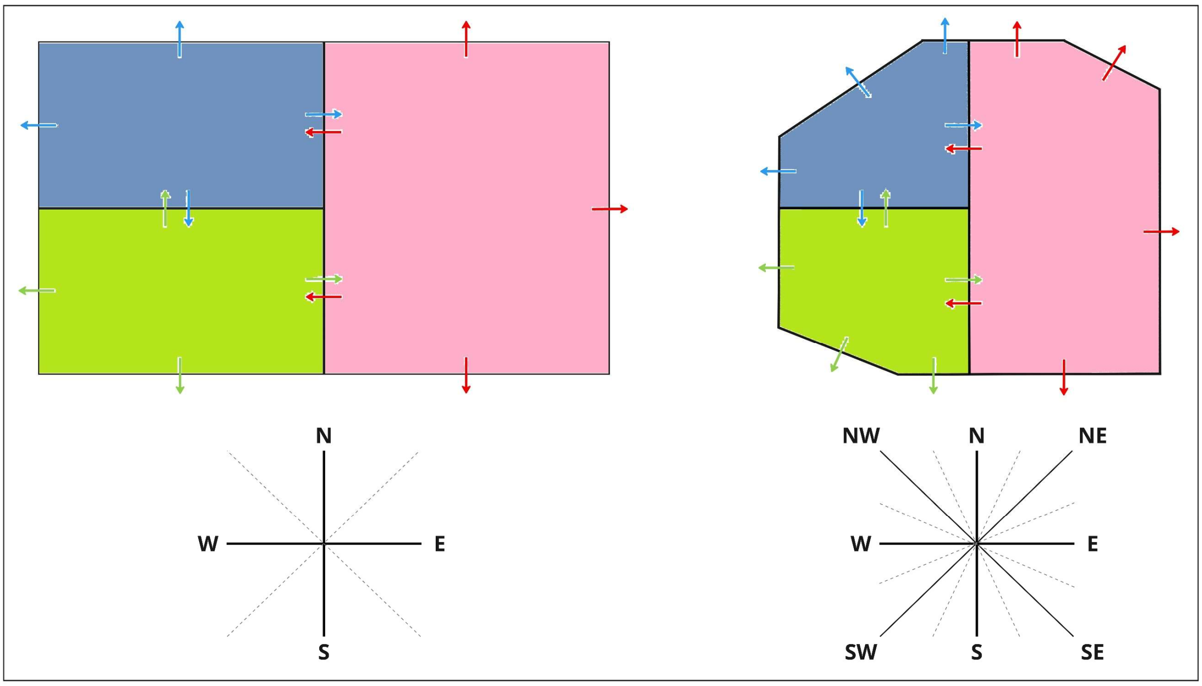

Figure 18: Examples of orientation definition (Z. WU et al. 2023)

3.3.3 Define Thermal Zoning Strategies

Once the previous criteria are met, the last step of the transformation and thermal zoning process is merging adjacent spaces with the same space type, setpoints, schedule and spatial cluster. Figure 19 illustrates how two zones are merged once conditions are met. The merging process follows three different strategies:

- ***Core-Perimeter Differentiation***: Zones are merged regardless of the difference in orientation or external conditions.
- ***Orientation-Based Floor Zoning***: Zones are merged if they share similar orientation and external conditions on each floor.
- ***Vertical Merged Zoning by Orientation***: Zones are merged vertically with similar orientation and external conditions.

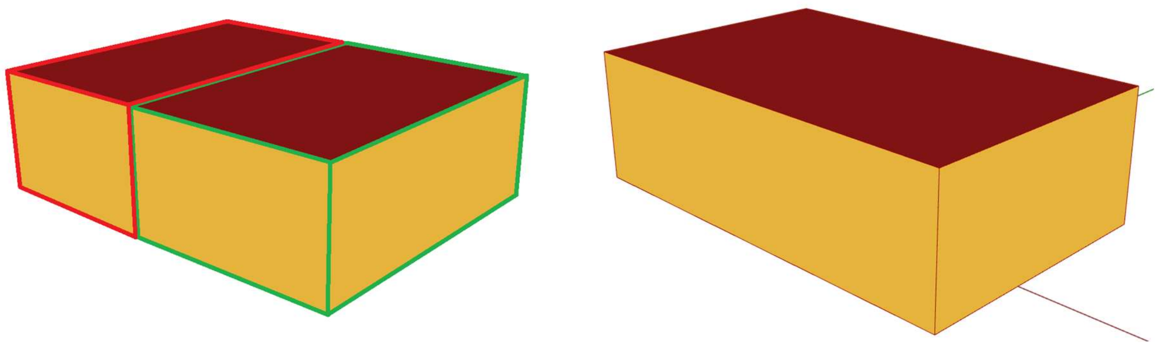

Figure 19: Merging Zones which fill the zoning criteria (Own Schema)

4 Prototypical Implementation

4.1 Workflow Description

The thesis begins with the export of an IFC file containing 2nd-level space boundaries (Step 1). In Step 2, the imported BIM data undergoes a transformation algorithm, with relevant information stored in intermediary classes (Step 3). Honeybee classes are then filled according to the HBJSON schema. This process results in four models created in Step 4: a detailed model with each space individually transformed into a thermal zone, along with three simplified models using different methodologies, core-perimeter differentiation, orientation-based floor zoning, and vertically merged zoning by orientation.

The model class functions as the algorithm's primary container for all energy model classes. Once complete, the energy models are serialised into JSON files representing the building energy data (Step 5). These files are then simulated using Honeybee in Step 6, and the results are subsequently analysed in Step 7. The described workflow is illustrated as follows in Figure 20.

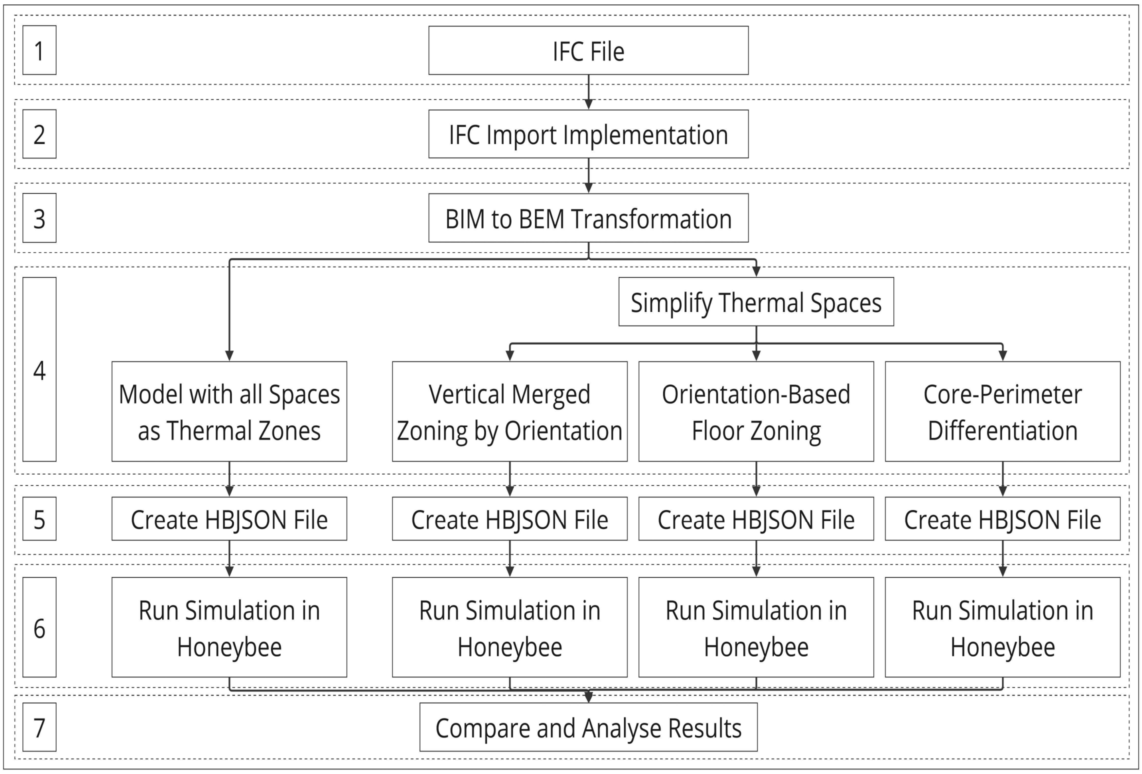

Figure 20: Workflow Followed in this Thesis (Own Schema)

4.2 Convert BIM to BEM

4.2.1 Model Input

As discussed previously, the goal is to start from the IFC Model as an open BIM tool and transfer information into a BEM model. The minimum needed export information is defined in Figure 21. In this context, the export will be based on the IFC4x3 version. The export is based on the 2nd level space boundaries. They offer significant advantages for accurate energy simulation. This includes understanding adjacency relationships between different spaces, accurately representing internal partitions and correctly modelling the interaction of spaces with surrounding elements like walls, roofs, slabs and floors. By incorporating 2nd level space boundaries, the exported model can better simulate the thermal exchanges between different zones.

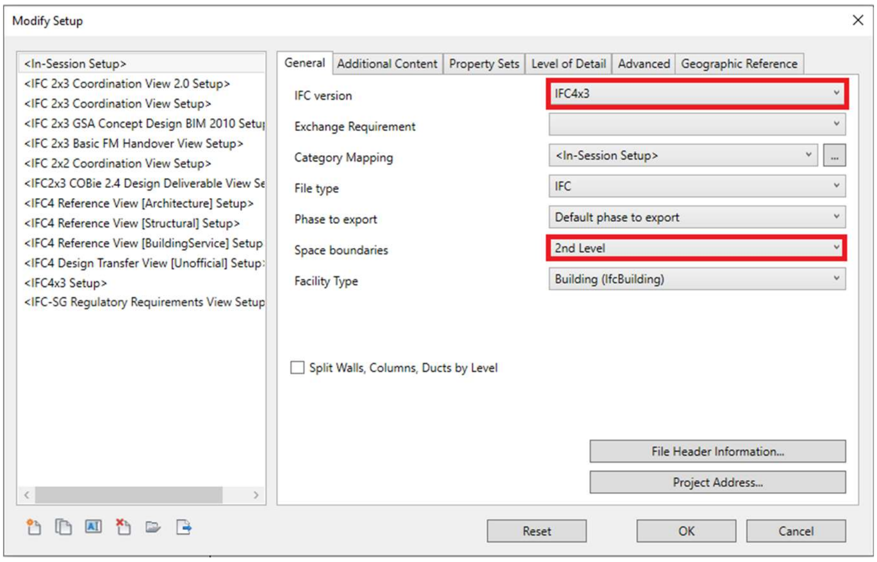

Figure 21: Export Information for an IFC Model, Revit Software (Own schema)

4.2.2 Implementation Design

Implementing the BIM-based BEM transformation process is structured and illustrated in the UML diagram shown in Annexe A, which will be explicated in Figure 22 and Figure 23. The code is organised into three main sections, each responsible for a specific aspect of the BIM to BEM transformation.

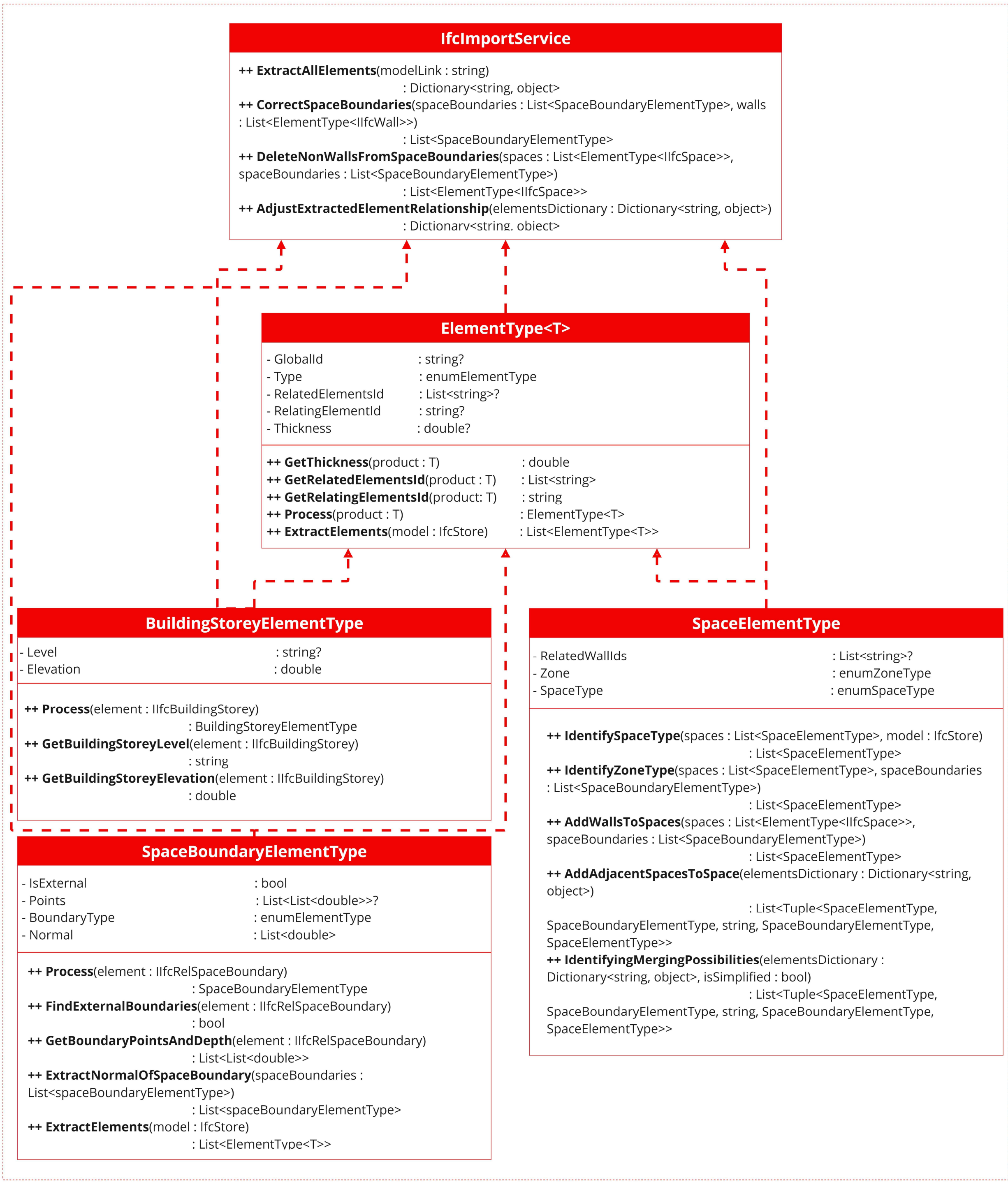

Figure 22: UML representing the Import section of the implementation (Own Schema)

The first section focuses on data import. It is used to extract the necessary data from the IFC file and, therefore, designed to interpret the complex structure of IFC to extract relevant information needed for energy simulation. An abstract class governs the extraction process, *ElementType*, which provides a blueprint for five specific classes of elements important for the conversion process from BIM to BEM in energy modelling. These elements are defined under the generic class, *ElementType<T>*, where T is specified as *IfcRoot*. This setup allows the software to focus on extracting specific

IFC entities such as *IfcRelSpaceBoundary*, *IfcBuildingStorey* and *IfcElement*. Within *IfcElement*, the implementation is particularly interested in a subset of elements essential for energy simulations: *IfcWall*, *IfcWindow*, *IfcDoor*, *IfcFloor*, *IfcSlab* and *IfcRoof*. These elements represent the building components that directly influence the thermal performance of the building and are important for accurate BEM. The process is represented in the UML in Figure 22.

The second section of the code is dedicated to the transformation process into the HBJSON data structures, which will be used in Energy Modeling. In this section, the software establishes an inheritance system that forms the backbone of the HBJSON structure. The process defines five primary classes central to the HBJSON format:

- ***Model***: Represents the overall building model, encompassing all the rooms, surfaces and elements involved in the simulation.
- ***Room***: Defines individual spaces within the building, each with its own thermal characteristics.
- ***Face***: Represents surfaces such as walls, floors and ceilings that define the boundaries of rooms.
- ***Aperture***: Specifies openings in the faces, such as windows, which are crucial for daylighting and thermal exchange.
- ***Door***: Defines door elements allowing passage between rooms or to the exterior.

In addition to these primary classes, this section defines intermediate classes and structures that handle the various attributes and configurations required for BEM. These include energy schedules, default materials and boundary conditions, which are essential for accurately simulating the building's energy performance.

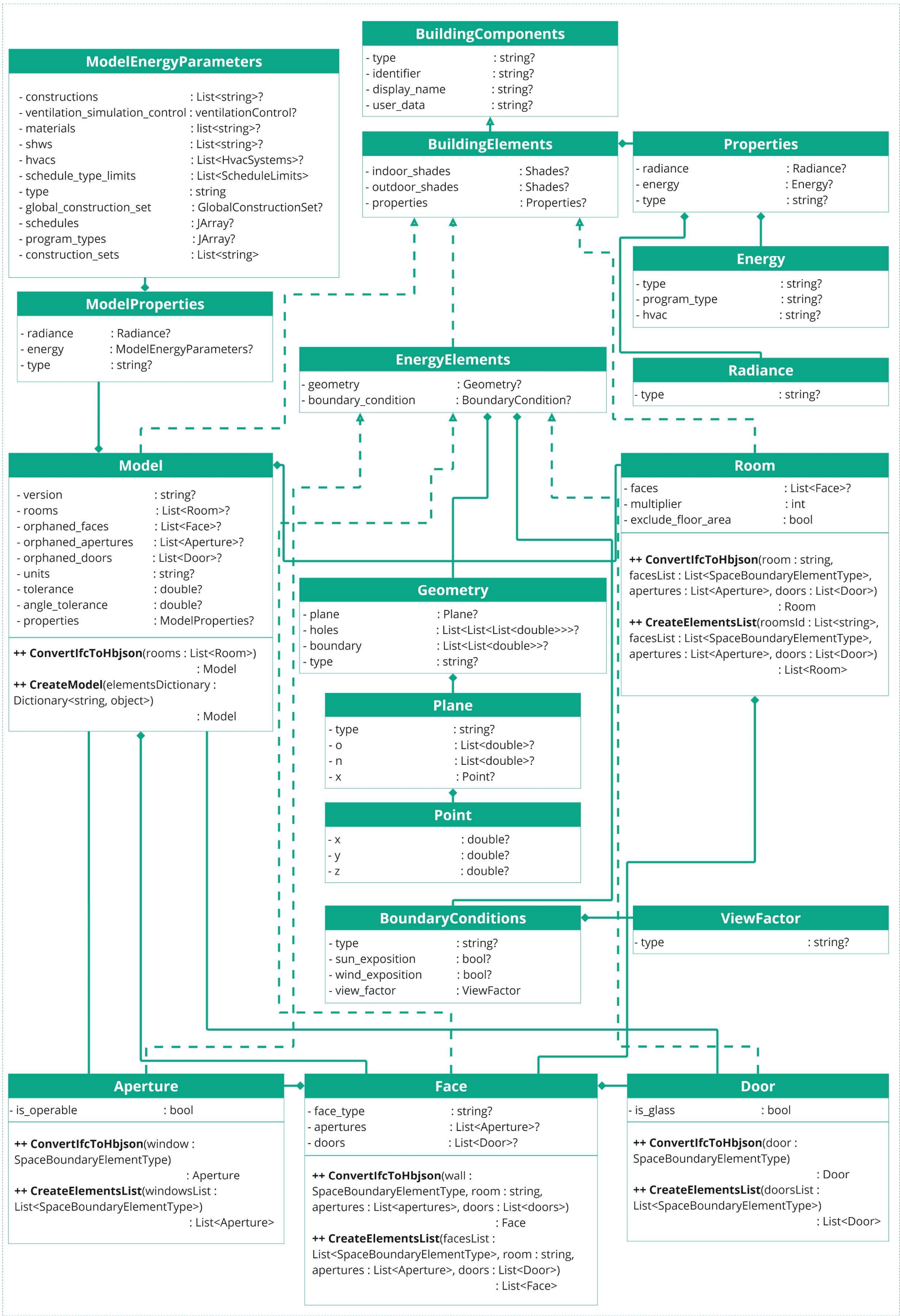

Figure 23: UML representing the transformation section of the implementation (Own Schema)

4.2.3 Geometry Processing

The *IfcImportService* is an important component of the prototypical implementation. it is pivotal in importing and processing data from IFC files into BEM. This section of the implementation is structured around a series of classes, each designed to handle specific IFC elements ensuring that the necessary properties are extracted and structured effectively.

Converting Geometry Elements

The *ElementType* class is at the core of the IFC data import process. It is designed as a generic class, capable of adapting to various types derived from the *IfcRoot*. This flexibility allows it to handle a wide range of IFC elements while maintaining a consistent structure for data extraction. The primary properties of this class include:

- ***GlobalId***: A string uniquely identifying each IFC model element. This identifier is crucial for tracking and referencing elements throughout the conversion process.
- ***Type***: An Enum specifies the element's type being imported. This could represent anything from a wall to a window, allowing the software to appropriately categorise and process each element.
- ***RelatedElementsId***: A list of strings that contains the identifiers of elements related to the current element. This property is essential for understanding relationships within the model, such as which Windows are linked to a wall or which Space Boundary is linked to an Element.
- ***RelatingElementId***: A string that identifies the element to which the current element is connected. This property helps establish parent-child relationships, such as a wall being part of a specific room.

The *ElementType* class includes several functions to extract these properties from the IFC data. The key method systematically retrieves the necessary properties relevant to the conversion goal for each element type. This method ensures that all required data is collected in a uniform manner, making it easier to integrate into the subsequent stages of the conversion process.

Converting Space Boundaries

The *SpaceBoundaryElementType* class is a specialised subclass of *ElementType<IIfcRelSpaceBoundary>*. It extends the capabilities of the generic *ElementType* by introducing additional properties specific to space boundaries, which are important to define the geometry and relationships of building elements in energy simulations:

- ***IsExternal***: A Boolean that indicates whether the space boundary is external or internal. This distinction is vital for energy simulations, as external boundaries typically have different thermal properties than internal ones.
- ***Points***: A list of lists of doubles representing the coordinates that define the boundaries of the space. This geometric data precisely maps out the physical space within the building model.
- ***BoundaryType***: An Enum that categorises the type of *IfcElement* to which this boundary is related. This classification helps associate boundaries with specific building elements, such as walls, floors, or roofs.
- ***Normal***: A list of doubles that defines the normal vector of the space boundary, pointing from the inside to the outside. This vector is crucial for understanding the orientation of the boundary, which can influence factors like heat transfer and airflow in energy simulations.

Space boundaries are a pivotal element in the import process because they form the foundation for defining the geometry of the building elements. The *SpaceBoundaryElementType* class ensures that these boundaries are accurately linked to the relevant elements via the *RelatedElementId* property. These relationships are then used to generate the corresponding elements in the HBJSON file, which is essential for creating a precise BEM.

<u>Converting Building Storey</u>

The *BuildingStoreyElementType* class is designed to represent the different floors of the building. This class plays a key role in organising the data structure of the rooms by their vertical position. It is important to correctly model multi-level buildings in HBJSON:

- ***Elevation***: A double property that stores the vertical position of the space boundary within the building. This value helps place each space at the correct height relative to others, ensuring the building's floors are accurately represented.
- ***Level***: a string property used for naming the levels to which rooms adhere.

The *BuildingStoreyElementType* class groups all spaces and their associated boundaries according to the building floor they belong to. This structured organisation is critical for creating distinct floors in the HBJSON schema. By accurately mapping each space to its corresponding storey, the class facilitates the generation of a coherent and realistic BEM model that reflects the vertical organisation of the building.

Converting IFC to HBJSON

The *IfcToHbjsonConversionService* transforms the extracted IFC data into the HBJSON format. The methods systematically process various building components, ensuring they are accurately represented in the HBJSON model. The process of transformation is concordant with the HBJSON schema, which is set as follows:

- *Zones and Space Boundaries*

In HBJSON, zones are represented using the Room class, which encapsulates the spatial divisions within the building. The conversion process for zones and space boundaries involves the following:

- ***Space Boundary Assignment***: The software uses the *RelatingElementId* property to assign space boundaries to their respective spaces. This property links each boundary to the space it defines, facilitating the organisation of spaces within the HBJSON model.
- ***Room Creation***: Once the space boundaries are assigned, they are transferred to their corresponding Room instances within the HBJSON model. Each room is then populated with associated faces, apertures and doors.
- ***Model Integration***: The rooms are adjusted and configured with additional properties required for energy simulation. These properties are then incorporated into the HBJSON model, ensuring each room is accurately represented and ready for simulation.

This process not only simplifies the representation of rooms but also ensures that all relevant elements, such as faces, apertures and doors, are correctly linked and accounted for within the HBJSON model, providing a clear and accurate depiction of the building's internal zones.

- *Faces*

In the context of HBJSON, walls, floors, ceilings and roofs are collectively managed under the Face class. The conversion process begins with the space boundaries extracted using the *IfcImportService*. These space boundaries are categorised using an Enum, allowing the software to identify and differentiate the boundaries required to define the faces of the building. The conversion process involves several steps:

- ***Categorisation***: The implementation first filters and categorises the space boundaries based on their types (walls, floors/ceilings and roofs).
- ***Aggregation***: The boundaries are aggregated into a single list once categorised. This list represents all the significant surfaces that will form the building's envelope in the HBJSON model.

- ***Face Creation***: The aggregated boundaries are then systematically converted into instances of the Face class. A corresponding Face instance with the necessary properties is created for each boundary.
- ***Geometry Definition***: Geometry instances are created for each face, with the boundary points from the space boundary accurately transferred into the Boundary instance. This ensures that the geometry of each face is correctly defined.
- ***Integration of Doors and Apertures***: Each Face instance is also checked if it includes doors and apertures. These elements are integrated within the face, ensuring the HBJSON model accurately reflects the building's geometry.

This process results in a comprehensive list of Face objects, each representing a part of the building's envelope and ready for use in energy simulation.

- *Apertures and Doors*

The treatment of apertures and doors in the conversion process is handled similarly due to their analogous characteristics. Both elements start with space boundaries, filtered to isolate only the relevant boundaries corresponding to windows and doors. The conversion process includes:

- ***Instance Creation***: Instances of the Door and Aperture classes are created, with properties defined according to their specific characteristics.
- ***Geometry Definition***: Similar to the faces, geometry instances are created for apertures and doors, with boundary points transferred into the Boundary property of each instance.
- ***Face Assignment***: The lists of aperture and door instances are filtered to assign each element to its corresponding face. The geometry of each aperture and door is adjusted to ensure they are correctly positioned within the face to which they belong, as illustrated in Figure 24. This geometric alignment is important to accurately represent the relationship between these elements and the larger building surfaces.

By treating apertures and doors in this structured manner, the implementation ensures that they are correctly integrated into the HBJSON model, preserving the integrity of the building's envelope in the energy simulation.

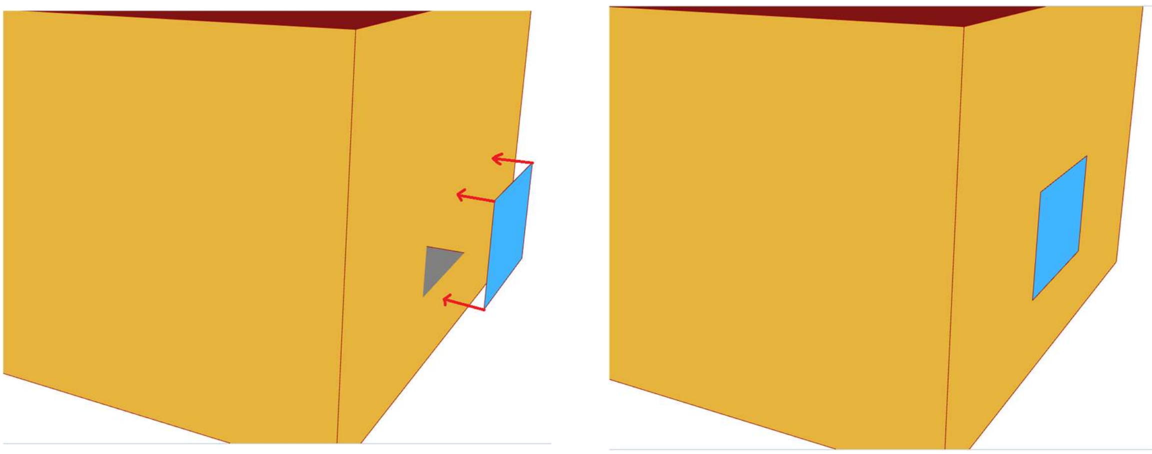

Figure 24: The Problem coming from importing Space Boundaries of Apertures/Doors in comparison to importing Walls (Own Schema)

4.3 Simplify Energy Model

The simplification process relies on the class *SpaceElementType*, which inherits from *ElementType<IIfcSpace>*. It introduces new properties essential for identifying mergeable spaces to create thermal zones. The properties are as follows:

- ***RelatedWallIds***: a list of strings that links the space with the wall IDs registered.
- ***Zone***: an Enum that differentiates zones with external boundaries, representing the perimeter zones and zones with no external boundaries, representing the core zones.
- ***SpaceType***: an Enum that differentiates between space types such as OFFICE, BEDROOM, BATHROOM, CORRIDOR and OTHER.

Spaces are the cornerstone of the defined clustering method. The previously discussed criteria will be checked to create rooms in the defined target HBJSON file.

4.3.1 Identify Thermal Zones

To decide that spaces can be merged into a thermal zone, it is essential to check if they are adjacent and share the same border. The *SpaceElementType* class is used to represent spaces and identify the type and properties of the space. A list of tuples is created, which indicates the two adjacent spaces, by finding their shared wall using the *RelatedWallIds* property. This approach creates wrong connections since walls that extend through multiple zones are also considered part of the isolated connections, as shown in Figure 25.

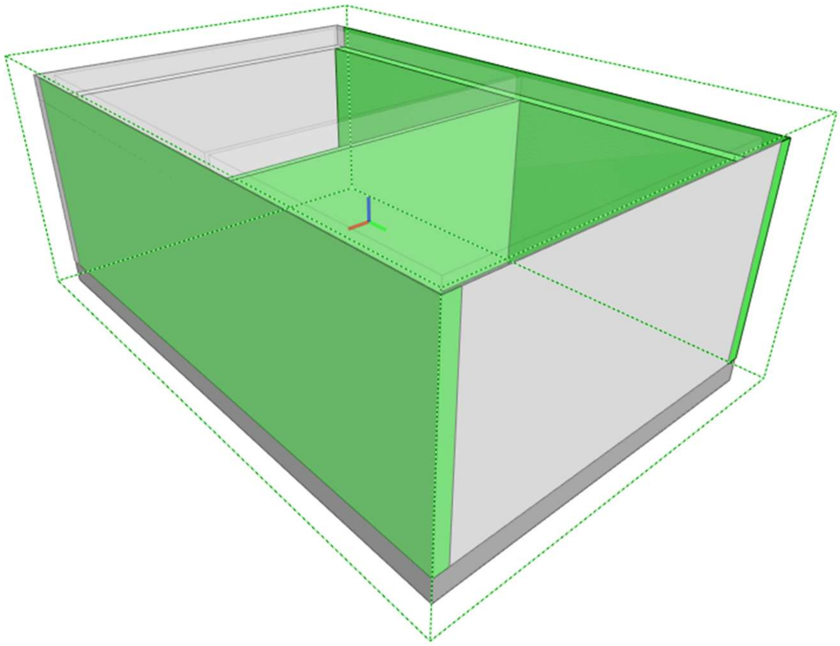

Figure 25: Selected Walls by identifying adjacent spaces (Own Schema)

The normal vectors are compared using the connected space boundaries to filter out these connections, as illustrated in Figure 26. If the normal vectors have a similar direction, the wall extends through the spaces. If they have opposite directions, the wall separates the two spaces. The first connections are filtered out, while the list only keeps the second connections.

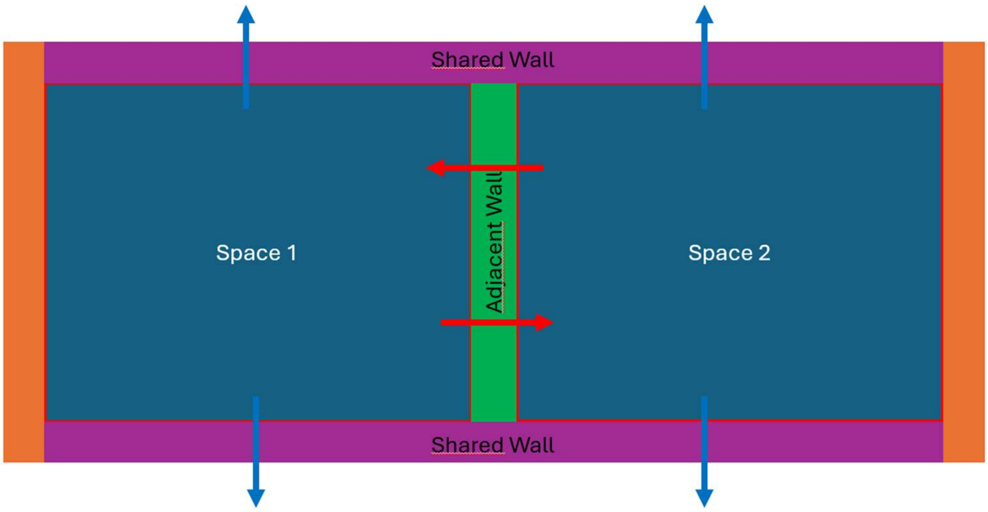

Figure 26: using normal vectors to filter out incorrect adjacent walls (Own Schema)

The list of relationships would still have incorrect connections. Some zones are on opposite sides of the adjoining wall, as illustrated in Figure 27. In this case, the solution is to compare the coordinates of the relative space boundaries to the wall and the zones to see if the coordinates are close to the margin of the wall thickness value. This allows filtering out all these types of relationships in the list of relationships.

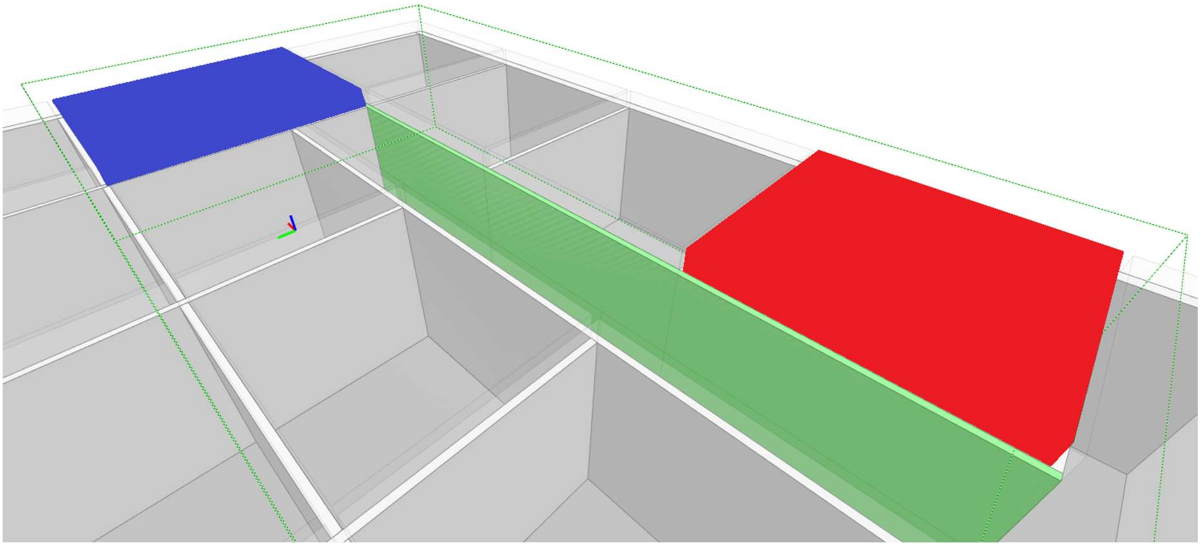

Figure 27: Two Zones sharing the same Wall and having Space Boundaries with opposite normal vectors (Own Schema)

4.3.2 Simplification Scenarios

This thesis aims to try multiple simplification strategies and check their accuracy compared to the original model. The simplified models follow different assumptions and use various criteria, creating different simplification levels. The methodology uses the *LongName* property of the *IfcSpace for space classification, as explained in Section 3.3.3.* As previously established, the thesis uses predefined setpoints and schedules, which are compared to check for the mergeability of thermal zones.

Core-Perimeter Differentiation

To simplify the model in accordance with this method, separation is made first between the core and perimeter spaces. The spaces with the same space type are merged with the condition that they belong to the same group, core, or perimeter zones. This simplifies the model into zones impacted by the outside conditions and zones isolated from the outside conditions, as shown in Figure 28.

Orientation-Based Floor Zoning

This simplification process uses the zones' orientation as an additional classification condition. It starts by separating core and perimeter zones. Then, the implementation is checked for a similar number of external walls. The resulting model includes internal zones with the same space type and external zones with the same space type and that share identical orientations, as illustrated in Figure 29.

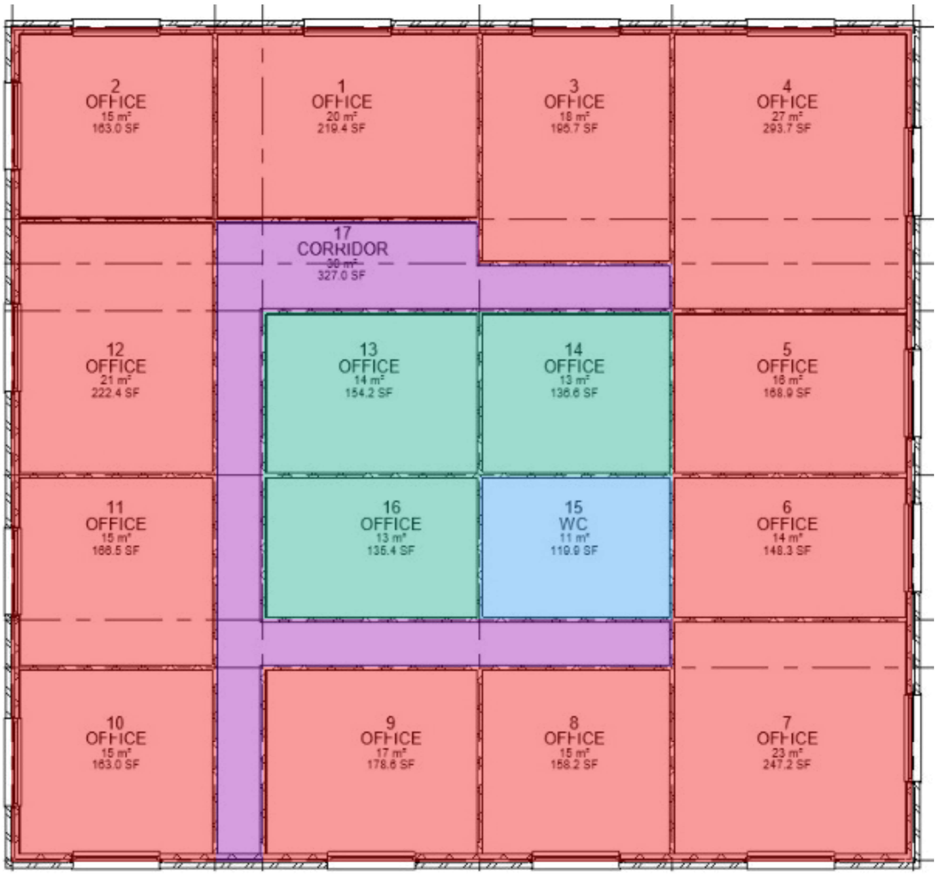

Figure 28: Separating Core and Perimeter areas (Own Schema)

Figure 29: Merging rooms to create final simulation zones (Own Schema)

<u>Vertical Merged Zoning by Orientation</u>

The simplification process uses the same process as the previous methodology. Furthermore, the check of adjacency is not just floor restricted. The implementation checks adjacency using space boundaries related to slabs, floors and roofs. Therefore, the simplification could also be done through multiple floors, as shown in Figure 30.

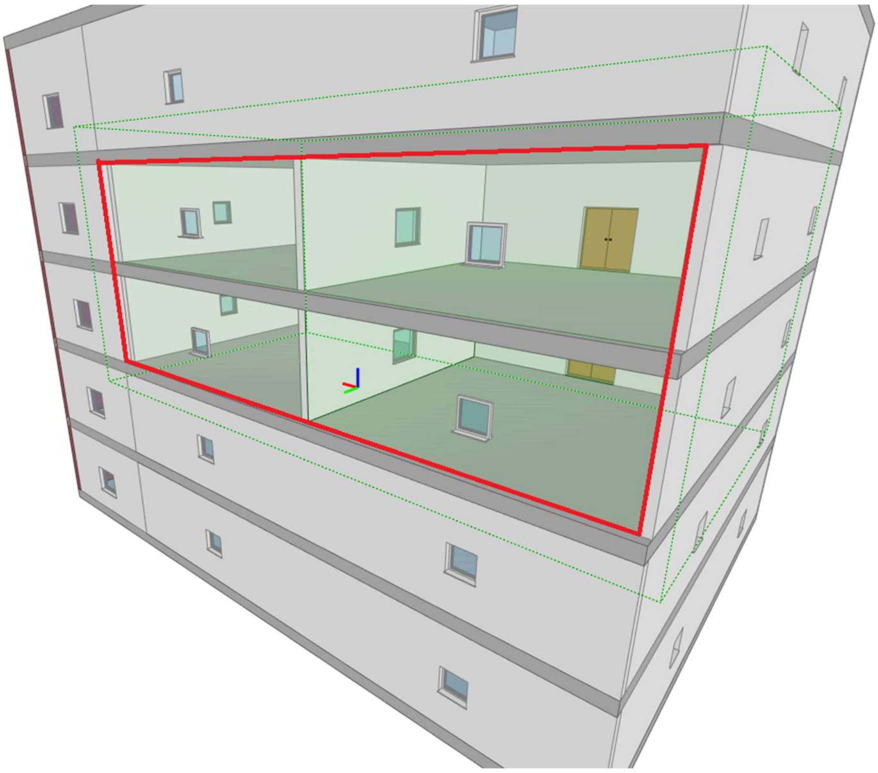

Figure 30: Merging rooms from different floors to create zones for simulation (Own Schema)

4.3.3 Model Simulation

The HBJSON files are uploaded into Rhino3D´s Grasshopper tool using the Honeybee plugin. This process is separated into three main sections. The first section is a model checker. It generates a report explaining if the model can be simulated and follows the HBJSON schema, as shown in Figure 30. The second section is used to manually check the thermal zones and the correctness of their components. The Honeybee modules are shown in Figure 31. Finally, the third section simulates the models in the Munich climate using the EnergyPlus Weather (epw) file. The section is shown in Figure 32.

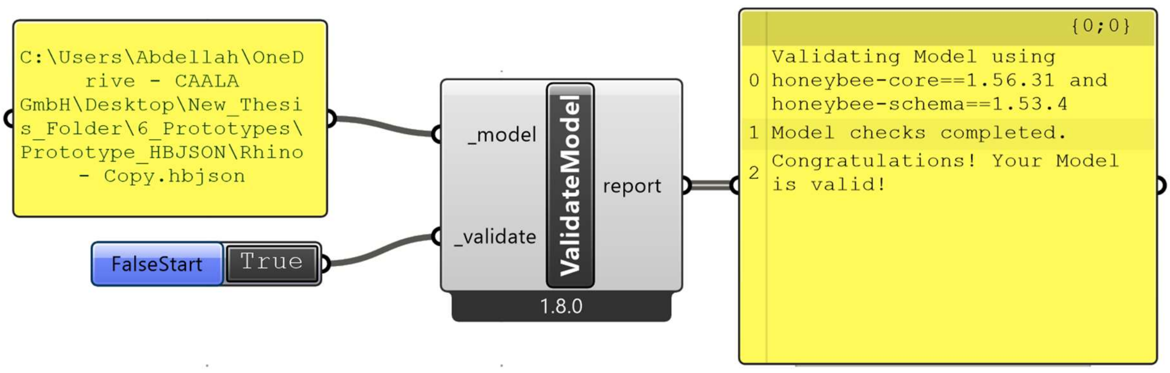

Figure 30: Model with no issues and can be simulated (Own Schema)

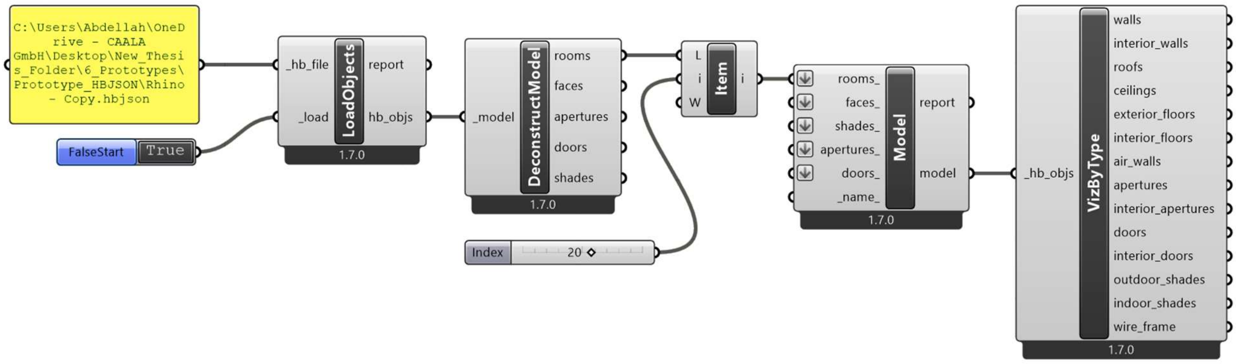

Figure 31: Manual Model Checker (Own Schema)

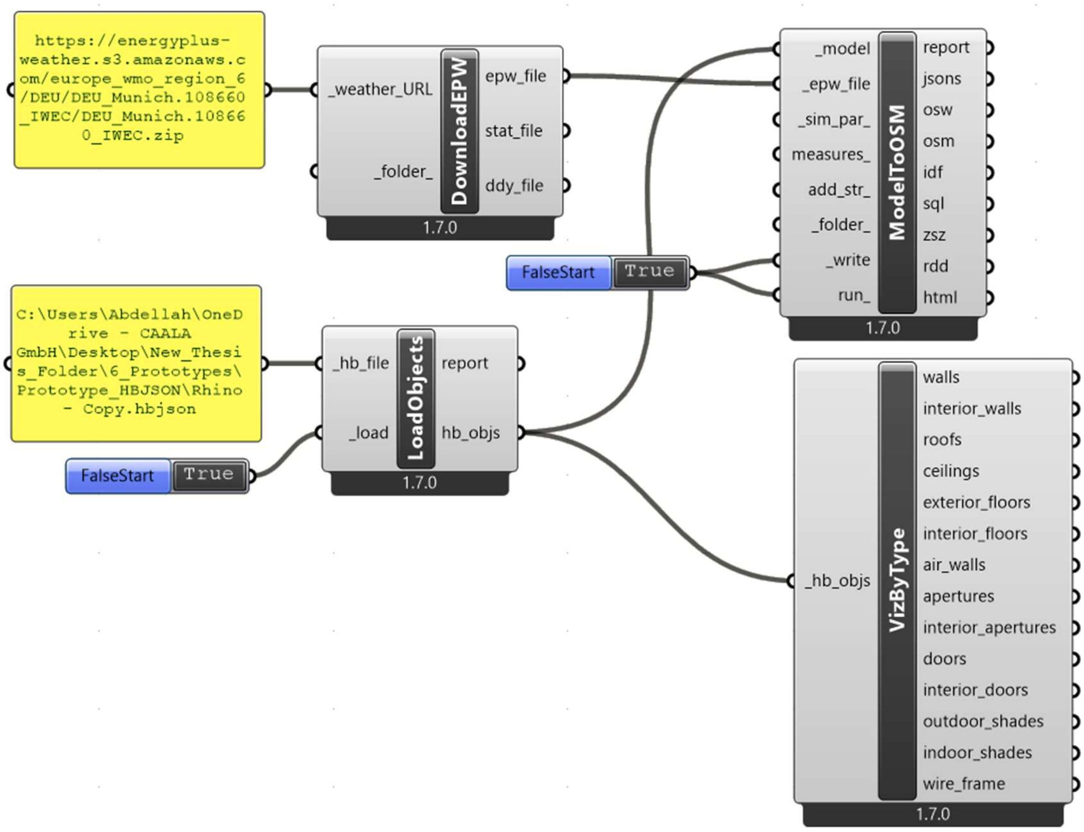

Figure 32: Energy Simulator Section (Own Schema)

4.4 Case Studies Validation

The implementation described in Section 4 is tested using two case studies of different sizes to assess the optimisation potential of the methodology. Case Study I is used to validate the methodology results. By comparing the energy results of the implementation of the BIM-based BEM to manually generated BEMs in the different thermal zoning strategies: (I) Core-Perimeter Differentiation, (II) Orientation-Floor Zoning, and (III) Vertical Merged Zoning by Orientation. Case study II estimates the gain in simulation time in large models. Table 3 indicates the thermal properties of the envelope components used in the analysis. The heating and cooling loads are calculated using the Ideal Air Load System.

Table 3: Thermal Properties for the Model Components

Climate Region	U-factor: W/(m².K)					
	Exterior Walls	Interior Walls	Windows	Doors	Floor	Roof
Munich	0,2359	7,9401	5,5617	3,7021	0,1174	0,1174

4.4.1 Case Studies Description

Case Study I – Small Model

The model represents small-sized buildings with relatively simple geometries. It is an office building with office, bathroom and corridor spaces. The building has six floors, each with 17 spaces, meaning the detailed BEM model has 102 spaces. Figure 33 shows the 3D model for case study I, while Figure 34 shows the floor plan of the building.

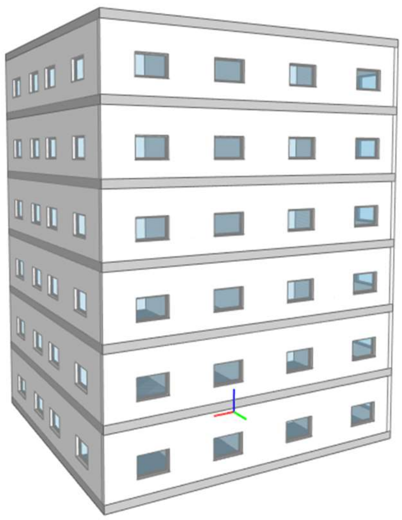

Figure 33: Case study representing Small Buildings (Own Schema)

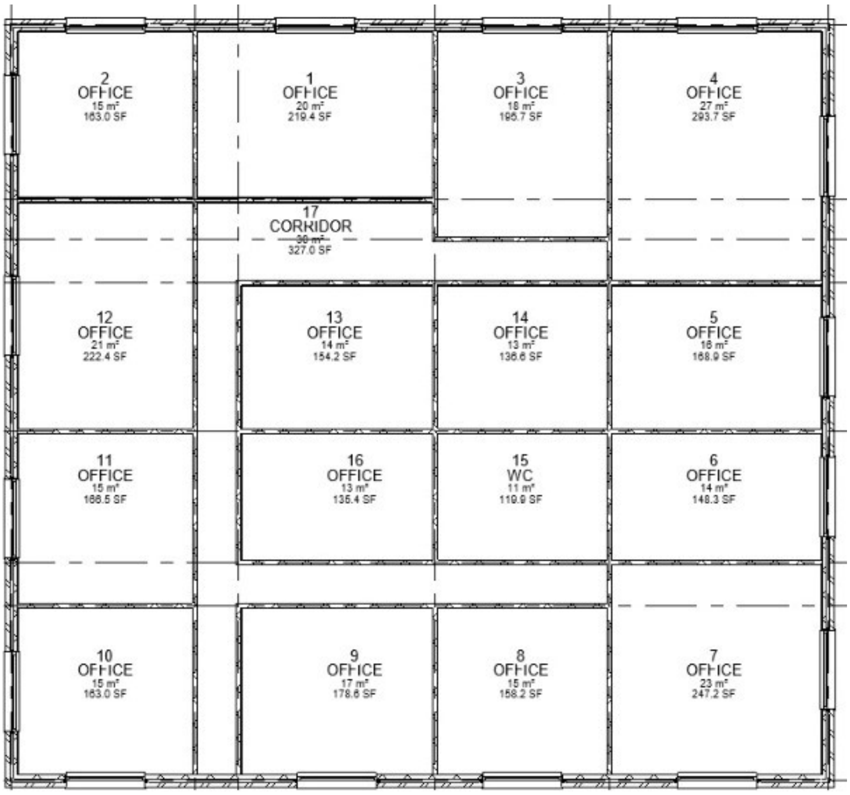

Figure 34: Case Study I Floor Plan (Own Schema)

Case Study II – Large Building

The model represents large-sized office buildings. It has multiple space types, including office spaces, bathrooms, corridors, and stairs. The building has six floors, each with seven separate zones. The total space number by floor is 256, meaning the detailed BEM model has 1536 spaces. Figure 35 shows the 3D model for case study II, while Figure 36 shows the floor plan of the building.

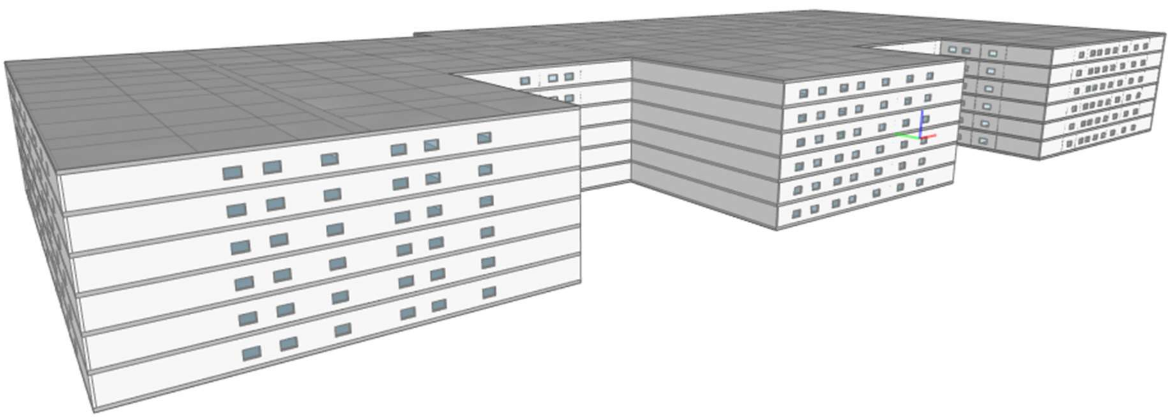

Figure 35: Case Study II representing Large Buildings (Own Schema)

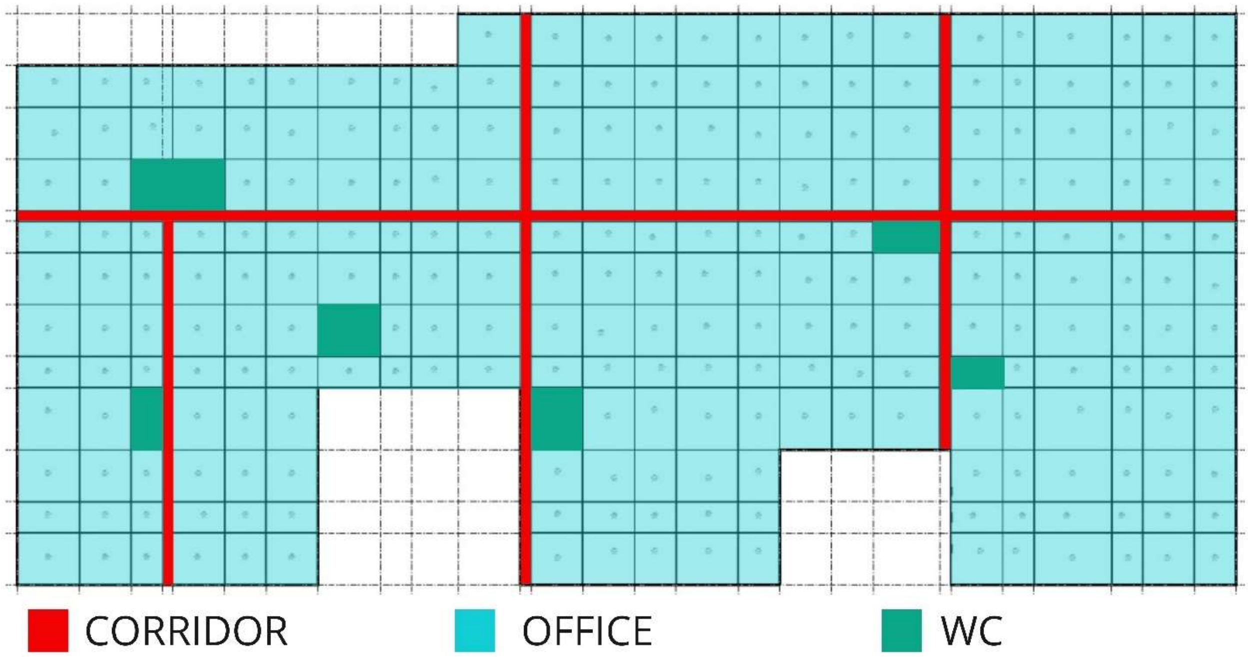

Figure 36. Case Study II Floor Plan (Own Schema)

4.4.2 Performance Evaluation Criteria

This study hypothesises that simplifying thermal zoning in building energy models will significantly reduce computational time while introducing a manageable inaccuracy in predicting energy demand. The detailed model, with fine-grained zoning, is expected to provide more precise estimates of heating and cooling loads by capturing the unique thermal behaviour of individual spaces, especially those with varying orientations and internal loads. In contrast, the simplified model, which merges similar zones, is predicted to offer faster simulations due to reduced computational complexity but will likely exhibit differences in energy demand. Specifically, it is anticipated that merging thermal zones will result in lower heating and cooling loads, as the model averages the temperature and load fluctuations across larger areas, thus smoothing peak demands and internal heat transfers (Shin & Haberl, 2022). While this simplification is expected to reduce energy consumption predictions, the trade-off in accuracy should remain within acceptable margins for early design stages, where rapid simulations are more critical than detailed precision.

5 Results

To test the hypothesis outlined in Section 1.3, the results section is structured into two main parts. The first part uses the first case study to assess the accuracy of the BIM-based BEM model by comparing its simulation outcomes with those from a manually generated model, verifying the fidelity of the BEPS results. The second part employs the second case study to evaluate the impact of various thermal zoning strategies on simulation time and estimated energy consumption.

5.1 Validation of the Implementation

5.1.1 BIM to BEM Transformation

As previously explained, this part is interested in measuring the accuracy of a BIM-based BEM Transformation by comparing it to a manually generated model. In order to measure accuracy, only the first case study is used. For this section, a BEM model is generated manually with the same geometric properties as Study Case I, as shown in Figure 37.

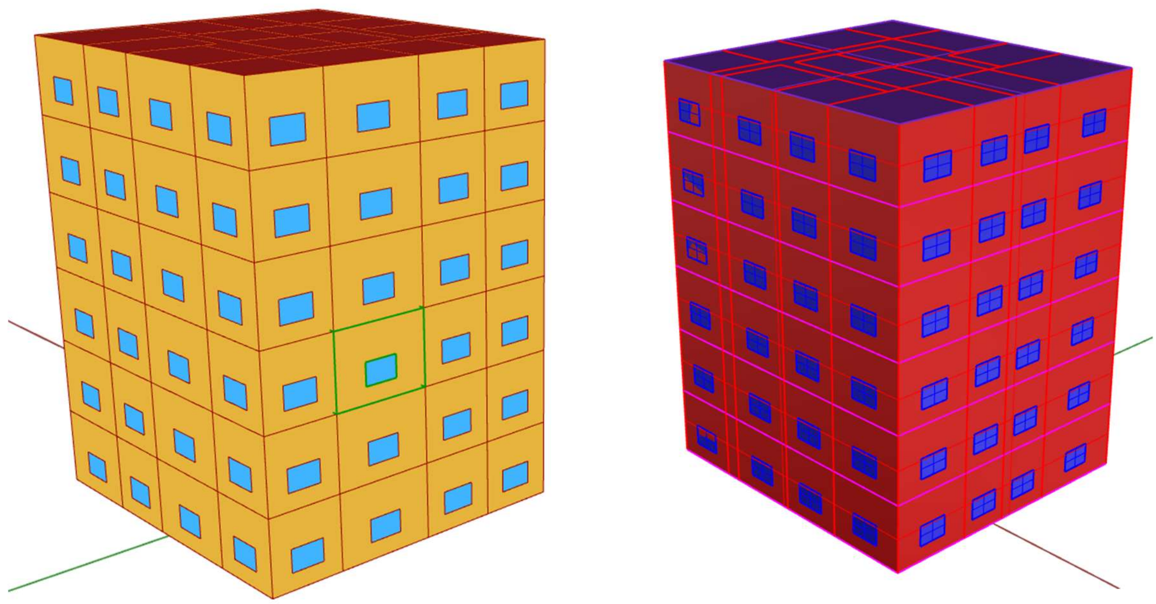

Figure 37: Case Study I - Automatically and Manually Generated BEM Models (Own Schema)

Table 4: Comparing Results of the Case Study I

	Automatically Generated BEM Model	Manually Generated BEM Model
Gross Floor Area	1941,06	1941,06
Number of Zones	102	102
Heating End User Intensity kWh/year.m²	283,94	265,55
Cooling End User Intensity kWh/year.m²	4,01	3,62
Lighting End User Intensity kWh/year.m²	26,96	26,96
Electrical Equipment End User Intensity kWh/year.m²	42,32	42,32
Total End User Intensity (EUI) kWh/year.m²	357,23	338,45

Table 4 illustrates the difference in simulation results between the BIM-based BEM model and the manually generated BEM model. The results show a difference in heating and cooling loads. The heating EUI resulting from the simulation of the BIM-based BEM model is 283,94 kWh/year.m², while the manually generated BEM model shows 265,55 kWh/year.m², a difference of 6,47%. The cooling EUI resulting from the simulation of the BIM-based BEM model is 4,01 kWh/year.m², while the manually generated BEM model shows 3,62 kWh/year.m², a difference of 9,87%. The lighting and electrical equipment EUI show no difference since they are calculated using the usage intensity per GFA, as explained in Section 3.3.2.

The total EUI of the two models shows a difference of 5,26%, with BIM-based BEM resulting in 357,23 kWh/year.m² and the manually generated BEM model resulting in 338,45 kWh/year.m².

The difference in heating and cooling loads can be explained by comparing the data in the HBJSON files of the two models. As discussed in Section 2.2.5, HBJSON files require additional compulsory geometry related data. In this case, tolerance and angle tolerance are important to understand the difference in the heating and cooling load. Tolerance means the number of decimal places considered by the simulation. In the case of BIM-based BEM, the transferred coordinates of the geometric components have different decimal places. It creates inconsistencies in geometry, resulting in small cracks in the connections between components. Henceforth, the thermal zones are subject to higher infiltration rates, slightly altering heating and cooling load demand.

5.1.2 Thermal Zoning Strategies

The BIM model for Case Study I is created using Revit 2025. As previously explained, the resulting IFC model should have second-level space boundaries. The implementation uses the generated IFC file to create a BEM model following the HBJSON schema. Manually generated BEM models using the thermal zoning strategies explained in Section 4.3.2 are created for comparison purposes. The analysed thermal zoning strategies: Core-Perimeter differentiation indicated by "Core-Perimeter", the Orientation-based floor zoning indicated by "Orientation", and Vertical merged zoning by orientation indicated by "Vertical". The heating and cooling loads are calculated using the Ideal Air Load System. The resulting models from running the prototypical implementation are represented in Figure 38, Figure 39 and Figure 40. The BIM-based BEM model is compared to the manually generated model for each thermal zoning strategy. The resulting merged zones are then compared to the base scenario to check for differences in terms of Total Energy Load.

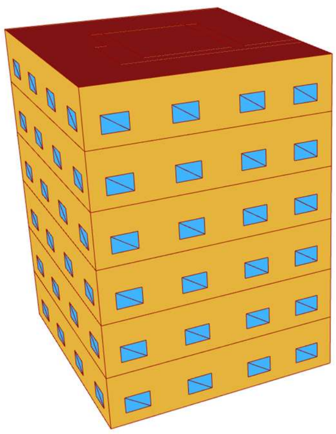

Figure 38: Case Study I: Core-Perimeter Differentiation

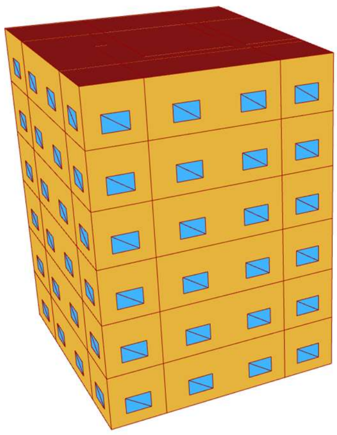

Figure 39: Case Study I: Orientation-based floor zoning

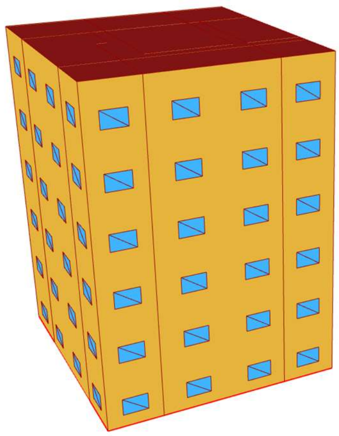

Figure 40: Case Study I: Vertical merged zoning by orientation

Core-Perimeter differentiation

Table 5: Comparing Results of the Core-Perimeter Differentiation Strategy applied in Case Study I

	Automatically Generated BEM Model	Manually Generated BEM Model
Gross Floor Area	1941,06	1941,06
Number of Zones	18	18
Heating End User Intensity kWh/year.m²	205,09	186,18
Cooling End User Intensity kWh/year.m²	4,77	4,40
Lighting End User Intensity kWh/year.m²	26,96	26,96
Electrical Equipment End User Intensity kWh/year.m²	42,32	42,32
Total End User Intensity (EUI) kWh/year.m²	279,18	259,86

Comparing the BIM-based Model and the Manually generated model, there is a Total load reduction from the base scenario. The BIM-based model shows a 21,85% reduction in Total EUI from the detailed scenario, while the manually generated model shows a 23,22% reduction, as detailed in Table 5. Comparing the two results shows a 6,92% relative difference, confirming that the methodology used shows identical results to manually generated thermal zoning.

The simulation energy load results are separated in accordance with the Core-Perimeter differentiation thermal zoning. The relative values are plotted for analysis, as illustrated in Figure 41. The results show some outliers for both the BIM-based BEM model and the manually generated BEM. The corridor zones show higher differences with outliers in both cases for the upper floor. Both the core and perimeter zones show lower changes. Since the geometry of the corridor is more complicated, the change in its contact zones augments the surfaces of contacts. In the case of the corridor, the zone is enveloped by one perimeter zone, as shown in Figure 28. In the base scenario, the corridor zone is enveloped by multiple zones with different load responses depending on their boundary condition, making it more stable.

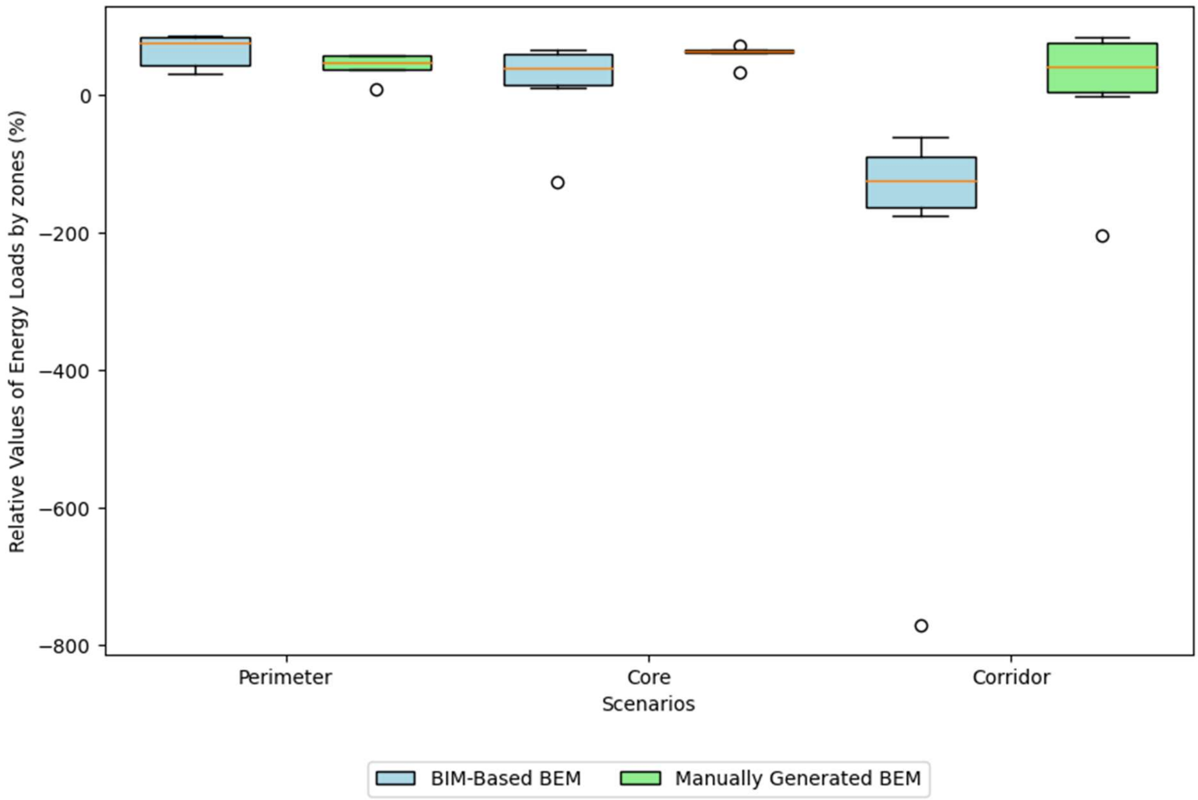

Figure 41: Relative Value of Total Energy Load by Thermal Zone (Perimeter, Core, Corridor)

Orientation-based floor zoning

Table 6 shows that the zoning strategy similarly affects the BIM-based and manually generated models. The BIM-based model shows a 10,34% reduction in total EUI from the detailed scenario, the manually generated model shows an 11,48% reduction. Comparing the two results shows a 6,45% relative difference, confirming that the methodology used shows identical results to manually generated zoning.

The simulation energy load results are separated in accordance with the orientation-based floor zoning. The relative values are plotted for analysis, as illustrated in Figure 42. The results show bigger relative values of the energy load in the corner zones (NE, NW, SE, SW). The geometries of these zones are not changed from the base scenario to the orientation-based thermal zoning. Nonetheless, the contacting zones are different since they are merged and, therefore, have bigger volumes, which change the exchange rates with the corner zones.

Table 6: Comparing Results of the Orientation-based floor zoning Strategy applied in Case Study I

	Automatically Generated BEM Model	Manually Generated BEM Model
Gross Floor Area	1941,06	1941,06
Number of Zones	18	18
Heating End User Intensity kWh/year.m²	246,43	226,28
Cooling End User Intensity kWh/year.m²	4,54	4,02
Lighting End User Intensity kWh/year.m²	26,96	26,96
Electrical Equipment End User Intensity kWh/year.m²	42,32	42,32
Total End User Intensity (EUI) kWh/year.m²	320,25	299,58

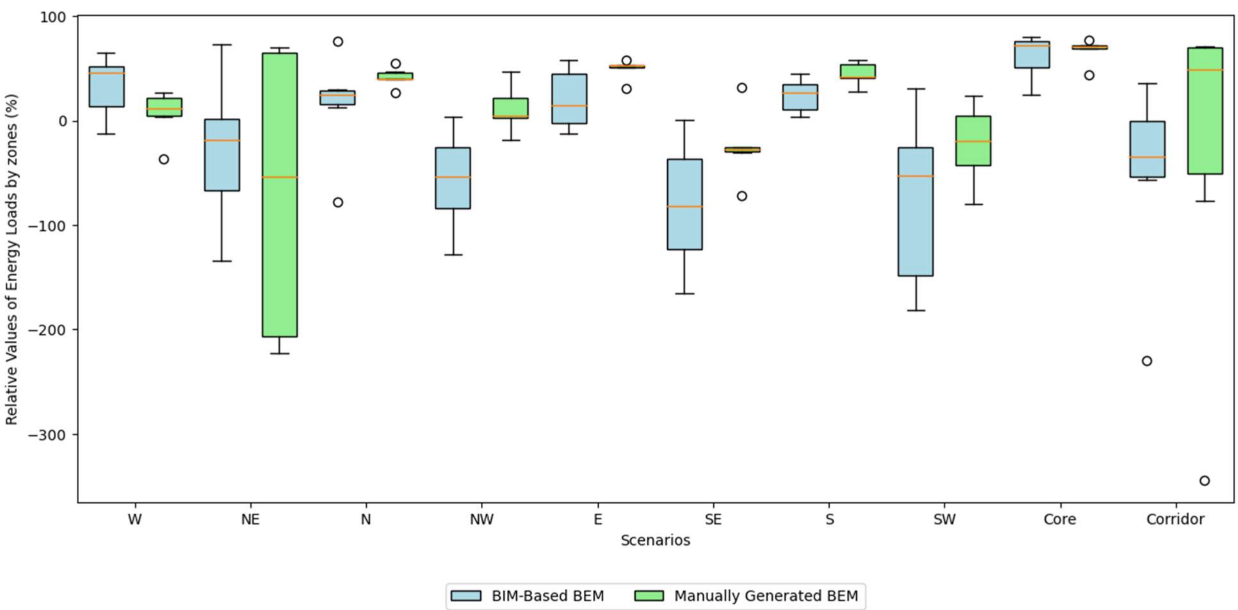

Figure 42: Relative Value of Total Energy Load by Thermal Zone (W, NE, N, NW, E, SE, S, SW, Core, Corridor)

Vertical merged zoning by orientation

Table 7: Comparing Results of the Vertical merged zoning by orientation Strategy applied in Case Study I

	Automatically Generated BEM Model	Manually Generated BEM Model
Gross Floor Area	323,51	323,51
Number of Zones	9	9
Heating End User Intensity kWh/year.m²	639,20	628,11
Cooling End User Intensity kWh/year.m²	8,94	11,99
Lighting End User Intensity kWh/year.m²	26,96	26,96
Electrical Equipment End User Intensity kWh/year.m²	42,32	42,32
Total End User Intensity (EUI) kWh/year.m²	717,42	709,38

Table 7 shows that the zoning strategy also has a similar effect on the BIM-based and manually generated models. The BIM-based BEM model shows a 200,83% increase in total EUI from the detailed scenario, while the manually generated model shows a 209,60% increase. Comparing the two results shows a 1,12% relative difference, confirming that the methodology used shows identical results to manually generated zoning.

The thermal zoning strategy reduces the number of thermal zones to nine values. Figure 43 shows the difference between the relative values for the BIM-based BEM model and the manually generated model. There are clear differences between the models in the NW zone. The BIM-based BEM model shows a big outliner, with a reduced Energy Load of 81.20%, which is compensated by the neighbouring zone, the West zone, by 57,68%. The corridor zone also shows a difference between the two models. In contrast, the BIM-based BEM model shows a reduction of 20,28%, while the manually generated BEM model shows an augmentation of 25,76% compared to the respective base scenario.

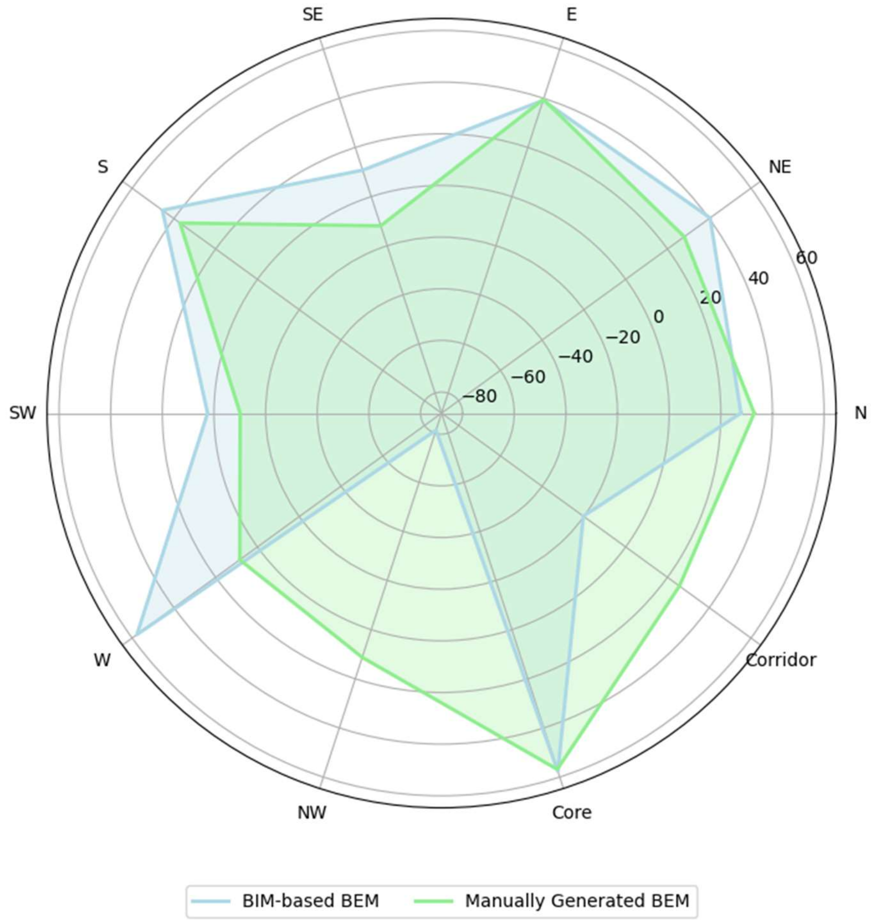

Figure 43: Relative Value of Total Energy Load by Thermal Zone for the BIM-based Model and the Manually Generated BEM (W, NE, N, NW, E, SE, S, SW, Core, Corridor)

5.1.3 Discussion

Comparing the impact of the thermal zoning strategies on the BEM models shows that the BIM-based model and manually generated model behave similarly. The Total Energy Load is reduced compared to the base scenario depending on the thermal strategy. Nonetheless, the vertical merged zoning strategy shows a significant increase in Total EUI, reaching 200%, as illustrated in Section 5.1.2. This abnormality in the trend we discussed is mainly due to the reduction of the GFA. Figure 44 shows the actual impact on the total energy load, which is reduced by 66,53% for the BIM-based BEM model and by 65,07% for the manually generated BEM model. This trend can be confirmed by other scientific work, for example, using a Grid-based thermal zoning method, which compares models with detailed thermal zones and different merged models, also showing a decrease between 11% and 24% (Shin & Haberl, 2022). Another research evaluated the impact of the core and perimeter differentiation on total annual energy load, showing a decrease ranging from 11% to 15,2% (Y. Chen & Hong, 2018). Grouping rooms with similar thermal characteristics into a single zone represents the most efficient approach, whereas the least efficient scenario is the single-zone model. The simplification scenarios had different impacts, varying from 7% to 24% (Elhadad et al., 2020). In conclusion, the impact of the implemented methodology produces similar results to the manual process. Different thermal zoning strategies have different impacts on the energy load of the model.

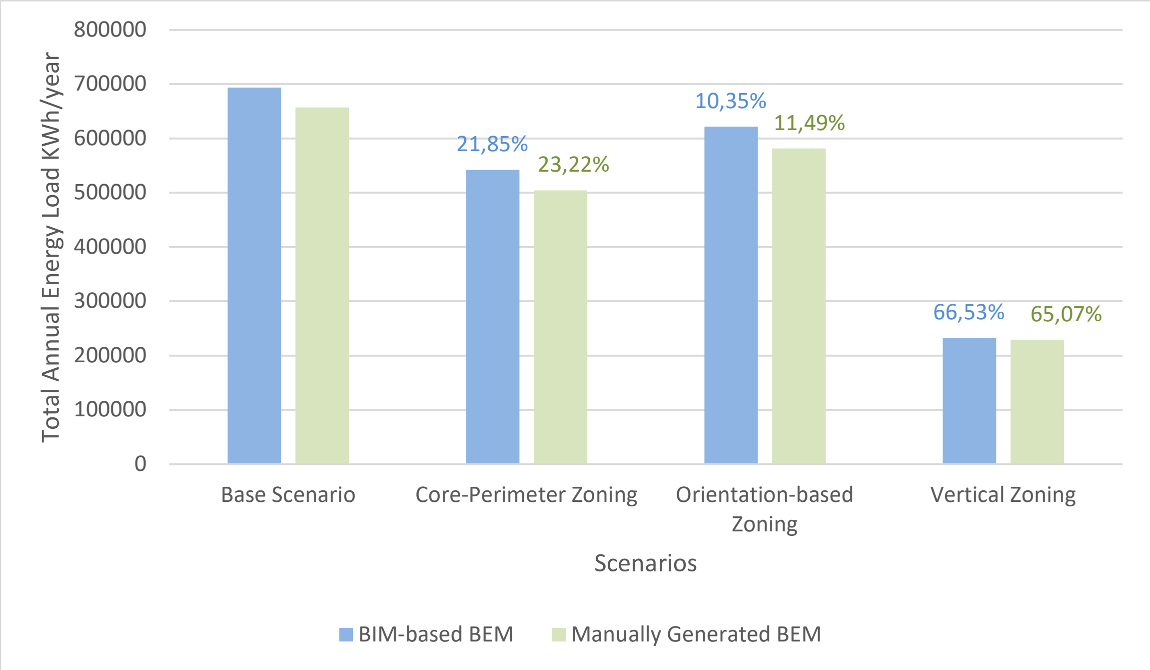

Figure 44: Total Annual Energy Load per Year in kWh/Year for different Scenarios applied for the BIM-based BEM Model and the Manually Generated BEM Model (Case Study I)

5.2 Application of the Implementation

5.2.1 Overview of the Case Study II

The BIM model used for the case study is created using Revit 2025. As previously explained, the resulting IFC models should include second-level space boundaries. Once the implementation is run using the IFC file of case study II as input, four BEM models are generated for each case study. As explained in Section 4.3.2, the analysis will compare the detailed BIM-based BEM model, which is the Base Scenario and the thermal zoning strategies: Core-perimeter differentiation, Orientation-based floor zoning and vertical merged zoning by orientation. The heating and cooling loads are calculated using the Ideal Air Load System. The resulting model from the prototypical implementation for Case Study II is represented in Figure 45.

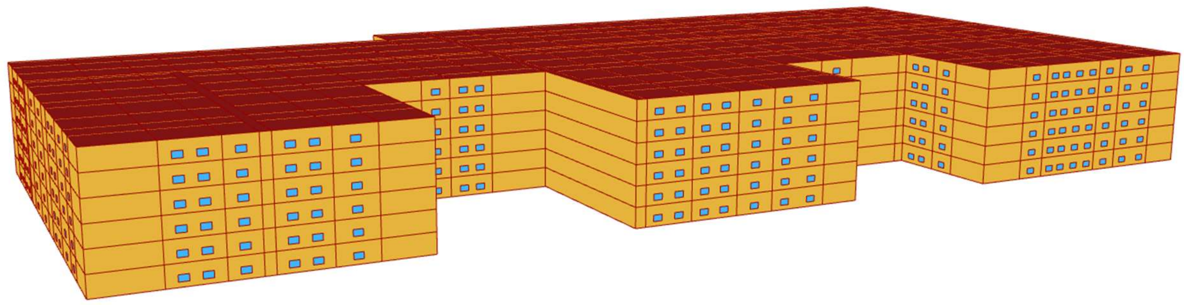

Figure 45: Case Study 2 - Resulting BEM Model (Own Schema)

5.2.2 End Use Energy

Figure 47 presents the total annual energy loads (kWh/year) for the different analysed thermal zoning strategies for case study II. Figure 48 shows the **EUI** in kWh/year.m² for the different thermal zoning strategies. the impact of the strategies shows similar trend behaviour to Case Study I results analysed in Section 5.2.

For Case Study II, the base scenario results in a total annual energy consumption of 30286381,07 kWh/year, comprising of a heating load of 20408900,00 kWh/year, a cooling load of 453481,07 kWh/year, a lighting load of 3666000,00 kWh/year, and an equipment load of 5758000,00 kWh/year. Applying the different thermal zoning strategies has varied effects on the energy load.

Regarding the heating load, the core-perimeter thermal strategy yields a significant reduction of 21,26%, decreasing the load to 16070000,00 kWh/year. The orientation-based thermal zoning strategy results in a reduction of 18,96%, with the heating load dropping to 16540000,00 kWh/year. The vertical merging thermal zoning strategy demonstrates the most substantial reduction of 66,15%, lowering the load to 6908000,00 kWh/year.

The cooling load also shows a change in all thermal zoning strategies. The core-perimeter thermal strategy sees a decrease of 21,26%, with the cooling load decreasing to 357071,71 kWh/year, while the orientation-based thermal zoning strategy experiences a 22,87% decrease to 349754,57 kWh/year. Using the vertical merging thermal zoning strategy, the cooling load decreases significantly by 84.81%, with the load dropping to 68900,34 kWh/year.

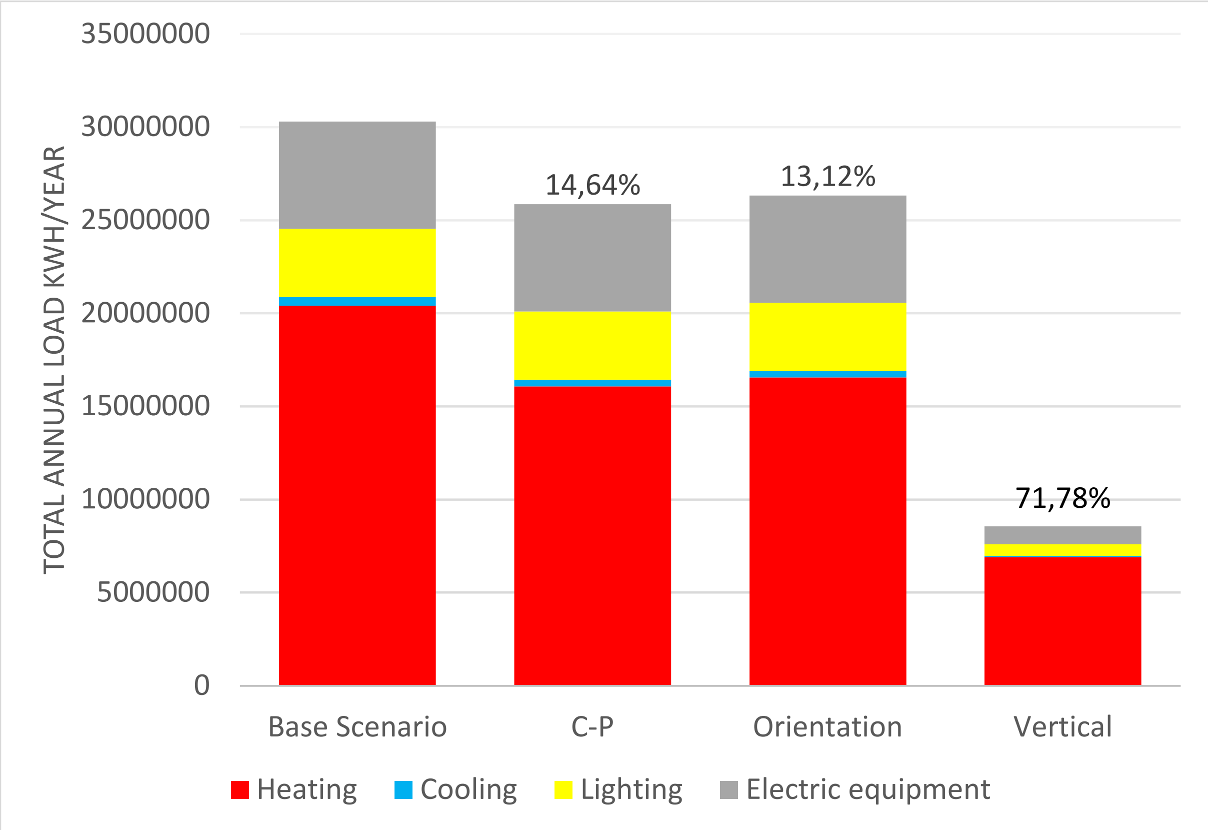

Figure 46: Annual Energy Load per Year in kWh/Year for different Thermal Zoning strategies (Case Study II)

Compared to the base case, lighting and equipment loads remain unchanged using the core-perimeter or the orientation-based thermal zoning strategy. However, using the vertical merging thermal zoning strategy, the loads are reduced by 83.33%. The change in the load is due to the considerable decrease in the GFA from 135960 m² to 22660 m², which is caused by merging zones vertically.

Overall, the total energy load in the core-perimeter thermal zoning strategy decreases by 14,64% to 25851071,71 kWh/year. The orientation-based thermal zoning strategy sees a reduction of 13,12%, resulting in a load of 26313754,57 kWh/year. The vertical thermal zoning strategy exhibits the largest reduction, decreasing the total energy load by 71,78% to 8547566,24 kWh/year. These results highlight the varying impacts of thermal zoning simplifications on the energy consumption components.

As depicted in Figure 47, the base scenario shows a total EUI of 241,90 kWh/year.m², which can be subdivided into heating EUI of 170,60 kWh/year.m², cooling EUI of 1,98 kWh/year.m², lighting EUI of 26,97 kWh/year.m² and electrical equipment with 42,35 kWh/year.m². The heating EUI is reduced by 30,72% for the core-perimeter thermal zoning strategy, 28,69% for the orientation-based thermal zoning strategy, and an increase of 78,71% for the vertical thermal zoning strategy. The cooling EUI is increased by 32,36% for the core-perimeter thermal zoning strategy, 29,64% for the orientation-based thermal zoning strategy, and 53,28% for the vertical thermal zoning strategy. The lighting and equipment EUI are the same across different scenarios. Therefore, the total EUI compared to the base scenario decreased by 21,40% for the core-perimeter thermal zoning strategy, 19,99% for the orientation-based thermal zoning strategy, and increased by 55,95% for the vertical thermal zoning strategy.

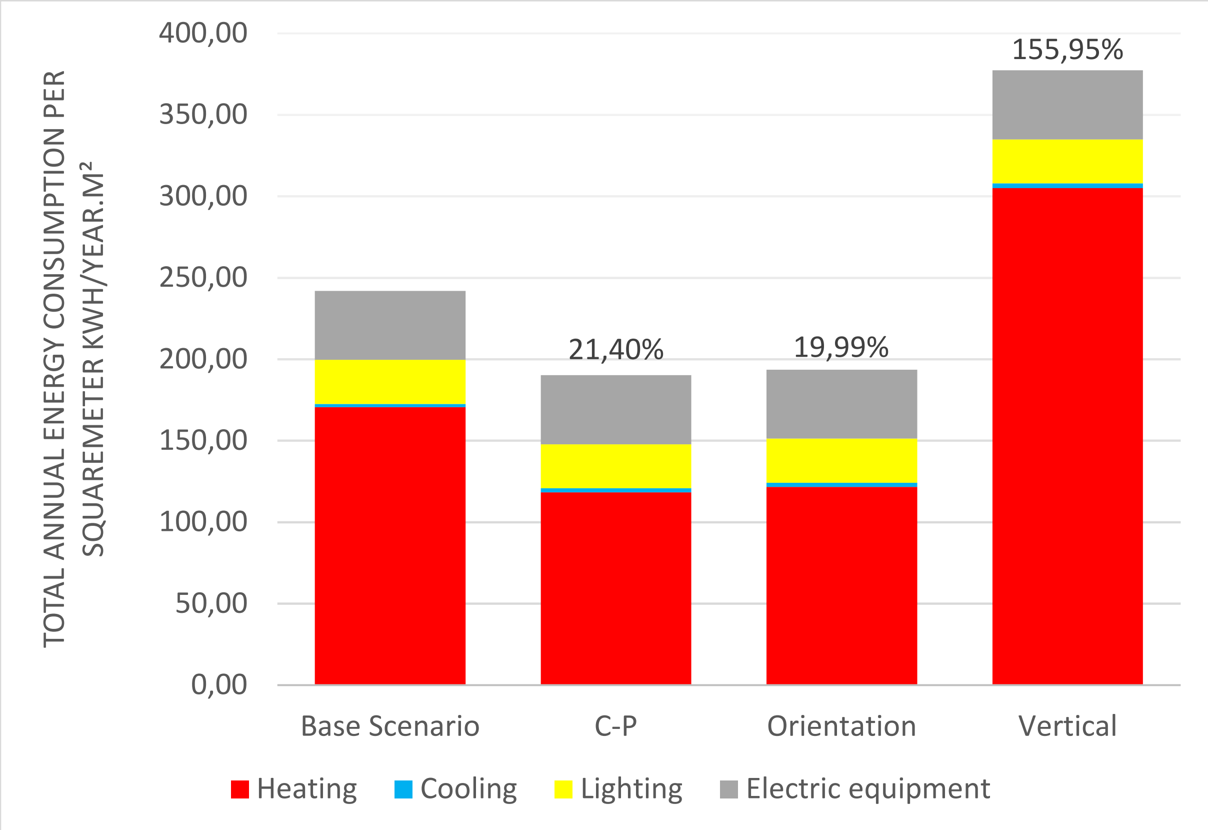

Figure 47: Annual End Use Intensity in kWh/Year.m² for different Scenarios (Case Study II)

5.2.3 Simulation Time

The simulation times reflect a drastic reduction in simulation time: the detailed model requires 12 hours 34 minutes and 3 seconds to run, whereas the core-perimeter thermal zoning strategy completes in just 2 hours 14 minutes and 18 seconds, reducing simulation time by 82,19%, the orientation-based thermal zoning strategy takes 3 hours 19 minutes and 5 seconds which is a 73,60% reduction, and the vertical thermal zoning strategy finished in 1 hour 13 minutes and 21 seconds reducing simulation time by 90,27%, as illustrated in Figure 48.

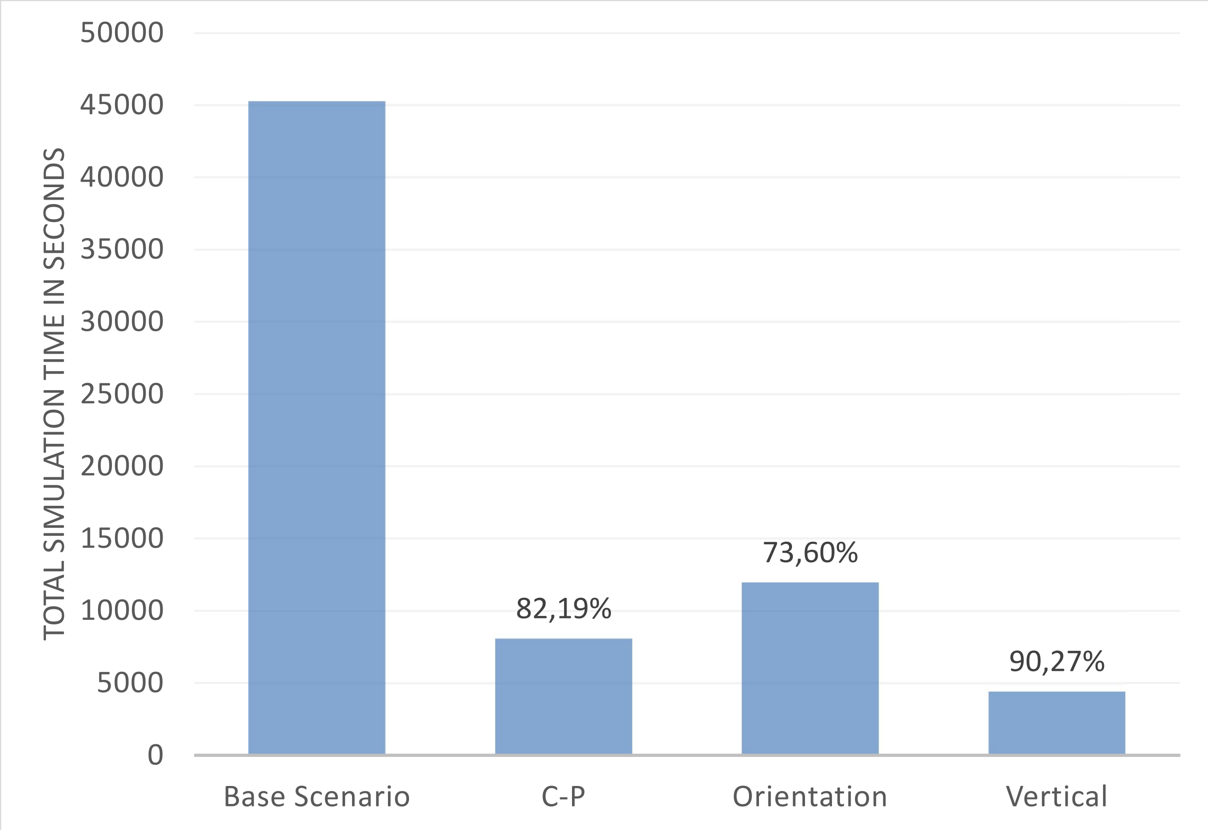

Figure 48: Simulation Time in seconds for different Scenarios (Case Study II)

5.2.4 Discussion

The results demonstrate that thermal zoning strategies have varied effects on reducing total energy loads, with orientation-based thermal zoning yielding the least deviation from the base scenario. This approach allows design processes to maintain results close to those of a detailed model while benefiting from simplified calculations. Although all strategies significantly reduce simulation time, orientation-based zoning provides the most balanced outcome, optimising energy prediction accuracy and computational efficiency. Integrating this prototypical implementation into the design workflow would facilitate more efficient decision-making by enabling faster feedback loops and improving workflow productivity, ultimately supporting a more streamlined design-to-simulation process.

6 Conclusion

6.1 Review of Research Questions

This master's thesis explored two primary research questions. The first centred on developing a BIM-based BEM methodology, Section 3.2, focusing on using space boundaries to transform BIM spaces into thermal zones. The second research question examined various thermal zoning strategies and their effects on energy simulation outcomes and simulation time, Section 3.3. The key findings for each research question are summarised below.

Research Question I: To what extent does integrating space types, thermal zones and space boundaries enhance the geometric transformation within the BIM-to-BEM process?

Hypothesis: Integrating space boundaries into the BIM-based BEM process, using Open BIM schemas, enhances geometric transformation by improving the accuracy of energy models, reducing manual intervention and minimising discrepancies between architectural and energy models.

Implementing a BIM-based BEM methodology that integrates space types and space boundaries significantly enhances the BEM geometric representation. Accurately defining space boundaries enables the creation of more precise energy models. This detail level helps accurately model thermal zones, resulting in a more reliable energy demand prediction. Thus, the resulting BEM models greatly reduce manual intervention, as automation eliminates the need for manual zoning adjustments. This process leads to a faster and more reliable exchange of information that could be applied in the different stages of the design process. As a result, the enhanced geometric transformation provides accurate simulation outputs, such as heating and cooling loads, which are important for optimising building energy performance.

Research Question II: How do automated thermal zoning strategies impact the accuracy and efficiency of simulations resulting from the BIM-to-BEM transformation process?

Hypothesis: Automated zoning strategies, such as merging similar rooms or spaces based on thermal properties and occupancy schedules, can enhance the BIM-based

BEM transformation process. This methodology aims to simplify energy simulations, improve workflow efficiency and reduce computational demands without significantly compromising the accuracy of energy performance predictions.

The findings demonstrate that automated thermal zoning strategies enhance the BIM-to-BEM transformation by significantly improving computational efficiency, particularly for large and complex building projects. Simplified zoning models considerably reduce simulation times, making them a valuable tool for early-stage design analysis where rapid feedback is essential, as illustrated in Simulation Time in seconds for different Scenarios (Case Study II). However, the results also highlight the trade-offs between accuracy and efficiency. While efficiency gains are notable, excessive zoning simplification can lead to substantial reductions in the calculated energy load predictions, compromising the accuracy of the results. Therefore, the challenge lies in balancing between reducing model complexity and maintaining the precision of energy demand forecasts. Merging zones from different floors reduces the GFA while creating big volumes that change the behaviour of the thermal zones. the vertical thermal zoning strategy could be enhanced by adjusting simulation results using a floor multiplier (Y. Chen & Hong, 2018). Ultimately, automated zoning can be a powerful strategy, but careful management of the simplification process is required to ensure its practical application in different phases of building energy analysis.

6.2 Limitations

Despite the promising performance of the methodology, several limitations remain that could benefit from further refinement or expansion.

The first limitation of the BIM-to-BEM process is its strong dependence on data quality, particularly in defining space boundaries. In industrial models, space boundaries are often poorly defined, negatively impacting the geometric transformation's accuracy. Definition of zones not limited by architectural elements (Own Schema) shows a scenario where a zone spans multiple rooms with different space types, such as office spaces, corridors, and stairwells, due to imprecise boundary definitions. These inaccuracies make it difficult to determine which surfaces are thermally interacting with adjacent spaces. Furthermore, defining rooms and spaces in BIM software remains challenging, especially when dealing with geometries like roofs or floors in contact with specific zones. This leads to significant information loss in thermal boundary data.

A second limitation is the need to extend the process to accommodate other data formats. Certain element types, such as *IfcCurtainWall*, are not well-supported in the current transformation process. These elements combine the characteristics of both walls and windows, which makes it difficult to categorise them within the conventional energy model framework.

Finally, the methodology relies on strict zone naming conventions, while in practice, industrial models often have inconsistent zone naming due to differences in language, regional standards, or the preferences of individual modellers. This inconsistency complicates the automation of zoning and boundary assignments, increasing the need for manual intervention to resolve these discrepancies.

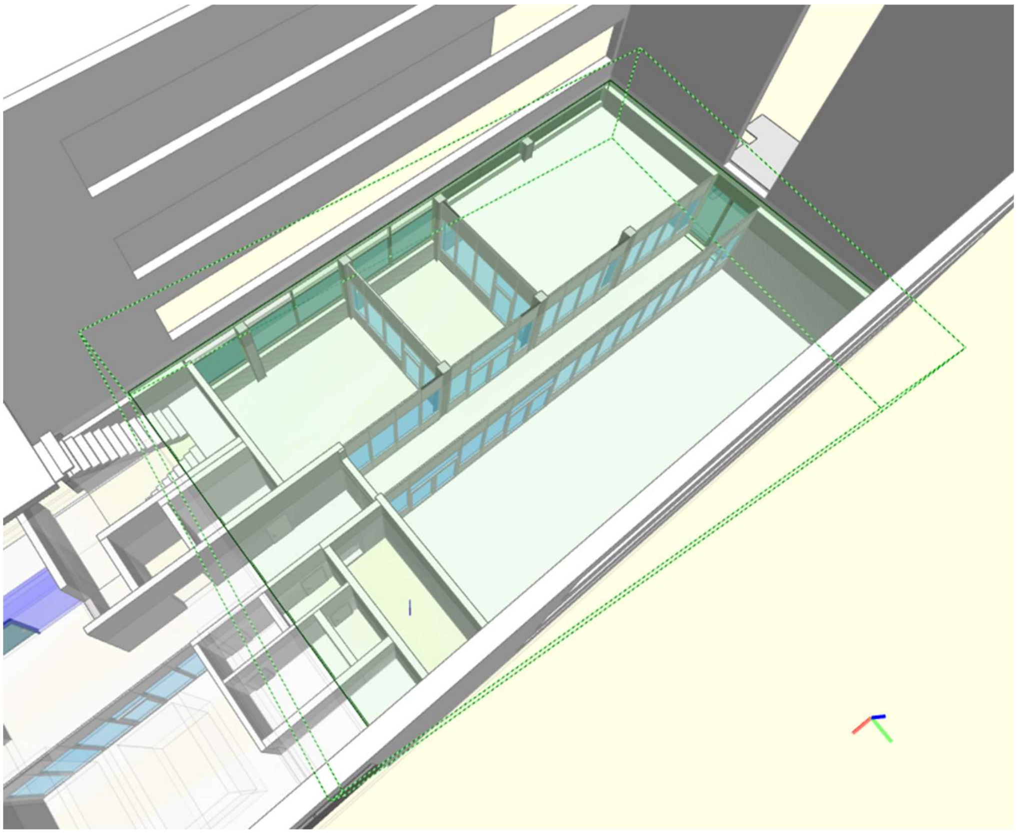

Figure 49: Definition of zones not limited by architectural elements (Own Schema)

6.3 Outlook

An extensive outlook for future work should address the key limitations identified in Section 6.2, focusing on improving the BIM-to-BEM transformation process and enhancing the accuracy and efficiency of energy modeling.

First and foremost, addressing the issue of space boundary quality is critical for achieving more reliable geometric transformations. The current methodology struggles with poorly defined space boundaries, particularly in complex industrial models. Future research could focus on developing automated methods to generate or correct 2nd space boundaries (Ying & Lee, 2021). Machine learning techniques, for example, could be explored to automatically detect and correct inaccurate boundary definitions based on adjacent geometries and their limiting elements. This improvement would help refine the identification of thermally interacting surfaces with neighbouring zones, leading to a more precise BEM model generation process.

Extending the transformation process to accommodate more complex architectural elements, such as *IfcCurtainWall*, is another key area for future research. As these elements combine both wall and window characteristics, their accurate representation in energy models is essential for providing a complete assessment of a building's thermal performance. Developing new algorithms or enhancing existing ones to handle these composite elements will ensure that the BIM-to-BEM transformation can fully support various building components, making it suitable for more complex projects.

Another significant area for future research is the integration of advanced natural language processing techniques, such as LLMs, to automate the identification and categorisation of spaces for conversion into thermal zones. In current industrial practice, inconsistent zone naming due to regional differences, language barriers, or varying practices among modellers, poses a challenge to efficient automation. LLMs have shown promising results in understanding and standardising such inconsistencies. By training LLMs on large datasets of building information, these models can automatically recognise and classify spaces with greater accuracy, regardless of naming conventions, thus streamlining the zoning process and reducing manual intervention (Forth & Borrmann, 2024).

In addition, expanding the methodology to incorporate more diverse building typologies, occupancy patterns, and usage scenarios could further improve the generalizability of the proposed approach. Testing the method across different climates, building sizes, and design stages would provide valuable insights into its robustness and limitations in various contexts.

Overall, by addressing these limitations and incorporating advanced computational techniques, future research can push the boundaries of BIM-to-BEM transformations, making energy modeling more accurate, efficient, and widely applicable across different sectors of the AEC industry.

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Annexe A

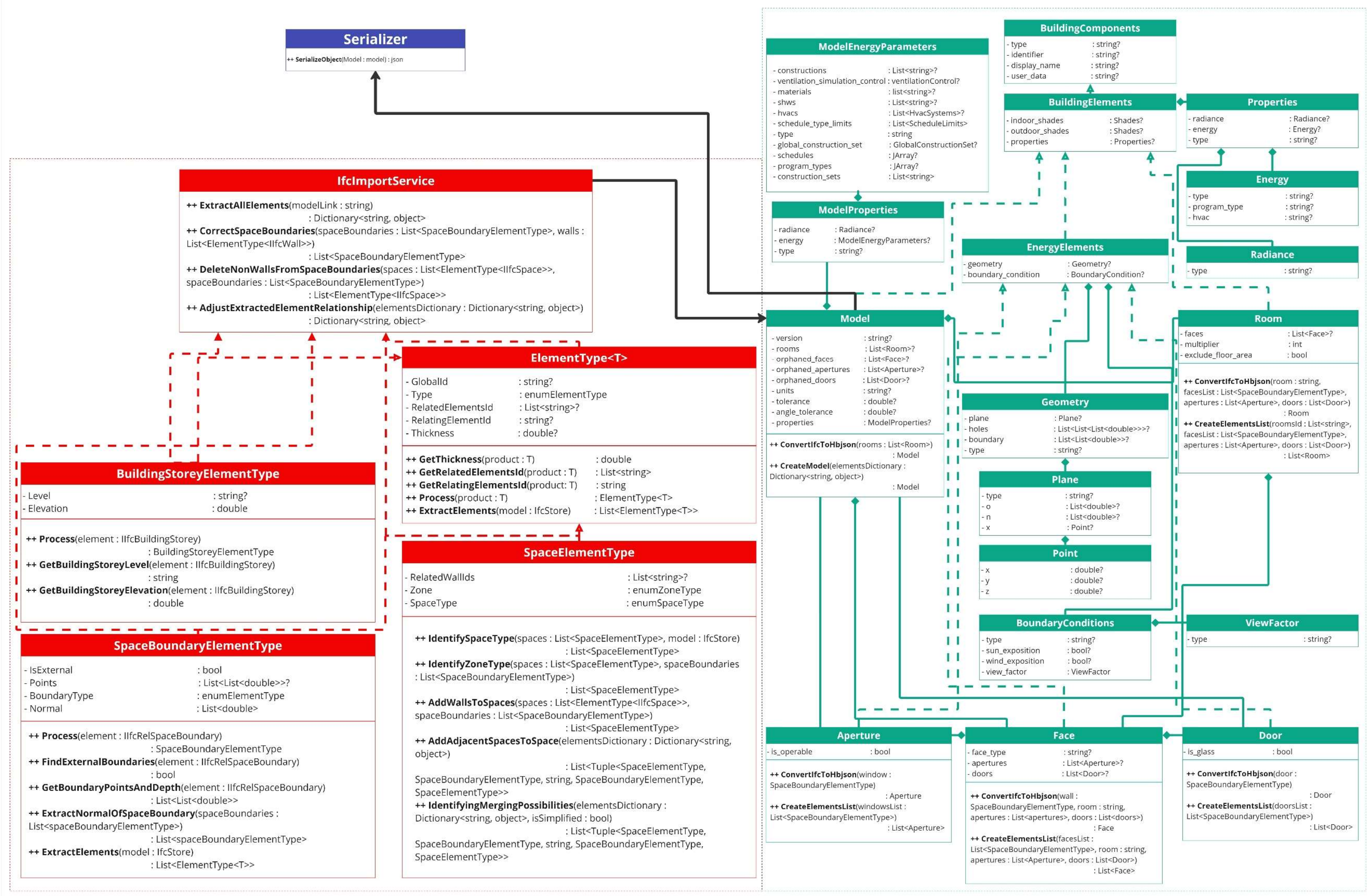

Figure 50: UML of the Software (Own Schema)

Erklärung

Hiermit erkläre ich, dass ich die vorliegende Bachelor-Thesis selbstständig angefertigt habe. Es wurden nur die in der Arbeit ausdrücklich benannten Quellen und Hilfsmittel benutzt. Wörtlich oder sinngemäß übernommenes Gedankengut habe ich als solches kenntlich gemacht.

Ich versichere außerdem, dass die vorliegende Arbeit noch nicht einem anderen Prüfungsverfahren zugrunde gelegen hat.

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