Master Thesis

A Framework for On-the-fly Energy Calculation of BIM Models

by

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Preface

This thesis is the result of the graduation research of the master track Building Engineering, specialization Building Technology & Physics of the faculty of Civil Engineering and Geosciences at the Delft University of Technology.

My interest in energy efficiency and parametric design dates back to the first year of my master's study. Through the courses I have taken, I learned that the energy usage of the building industry has taken up a large portion of the world. The concept of Nearly Zero Energy Building has risen in response to the need for energy saving. In the meantime, I learned that parametric design is a powerful tool that can optimize not only buildings but also the design process. It has led me to the topic of improving energy efficiency by utilizing parametric design. I am always convinced that automation will substitute a wide variety of the manual working and mingle with the design process. Having been educated for years to be a professional engineer, I noted that doing repetitive work does not make me a superior engineer. It is crucial to consistently optimize the work and working process.

This thesis focuses on the energy assessment in the early stage of building design. It tries to blur the boundary between architects and engineers to deliver the energy optimization to earlier step in the working stream. During the research, I realized it is challenging to achieve fully-automated assessment tool for energy efficiency, yet not impossible.

I would like to thank my graduation committee for supporting me during the research. Thank you Dr.ir. H.R. Schipper, Dr.ir. J.L. Coenders, Dr. R.M.J. Bokel, and Dr.ir. A. Rasooli for your professional insights and generous help. In addition, I would like to thank Dr.ir. H.R. Schipper again, and the study advisor Marian Roodenburg for their help and support when I had issues with my Visa. Finally, I would like to thank my family, friends and fellow students for their encouragement and understanding.

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Abstract

Researches have been conducted to involve the sustainability of energy in the building's early design stage. The methods used include the IEF-based method, the BIM-API-based method, and other approaches. However, these methods have not helped architects out in the early design stage since the complexity of the assessment is not decreased.

The contradiction of increasingly complex energy simulations and early conceptual designs forms a research gap in energy optimization. As changes in the early design stage have more effect on the buildings and make less cost, the introduction of on-the-fly energy assessment in the early stages is of great importance.

This thesis developed a framework to help boost energy efficiency in building design. The framework aims to improve the efficiency of energy assessment by providing simultaneous and on-the-fly energy performance assessment of the design. BIM software Revit and the visual programming environment Grasshopper were integrated via Rhino.Inside, a bridge between the BIM environment and others to perform the assessment. The workflow of the framework contains three parts: data input from BIM models and the determination method NTA 8800, the connection by Rhino.Inside and the computation of the Grasshopper script, the final results, and the report produced by the Grasshopper script.

A script in Grasshopper as a demonstration of the framework was developed as such that Revit models can be directly linked to the energy analysis, and the results can be returned simultaneously. The script was created based on a preliminary case study and two sets of studies were conducted to validate it. The case study of a tiny house was first investigated to test and validate the developed tool. The energy demand result of the developed tool has only a 3% difference for the case study calculated via Uniec 3, a verified software used in the Netherlands.

The developed tool was also validated through 4 variants with different configurations to find out if the tool is accurate and robust enough concerning dimensions and physical properties. The comparison of the results shows that the developed tool can produce steadily accurate results that vary within 5% from the standard outcome. In addition, the study indicates the framework's potential of optimizing the building's performance on energy efficiency as the proposed framework significantly shortens the time and workload compared to Uniec 3 which requires a body of manual input.

The study in this thesis integrates the BIM models and energy analysis to enhance the sustainability concept in the building design industry. It fills the gap in the application of semi-automated BIM to the BEM framework in the early design stage of buildings. The developed framework provides a useful tool and practical benefits to the field of energy efficiency. This study investigated the potential of applying on-the-fly energy assessment in early design stage, which could be developed further in future work to explore more or better solutions.

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1

Introduction

The energy efficiency of a building is the energy consumption level per square meter of floor area for a specific building function under certain climate conditions. The increase in energy efficiency is considered the key to reducing the significant portion of emissions on account of the building industry, and it also has a positive effect on construction cost and property values (Jeong et al. 2017, Hyland et al. 2013). However, energy assessment and improvement often take place in the late design stage, while the conceptual design has a remarkable impact on energy efficiency. This thesis aims to investigate and develop the method of involving energy assessment in the conceptual design stage of buildings for assisting the decision-making process.

This chapter will provide an introduction to the study by first discussing the background and context, followed by the research problem, the research aims, objectives and questions, the methodology and finally, the outline of the thesis.

1.1. Background

The global energy contribution from the building sector has increased by around 30% in developed countries, with heating, ventilating, and air conditioning (HVAC) systems taking 50% among all building services (Pérez-Lombard et al. 2008). In addition, the energy demand for cooling is not only essential for tropical and subtropical areas but also increasing in northern countries because of constantly updated building requirements and global warming (Katili et al. 2015).

In response to the need for energy saving and resilience to climate change, various policies have been published to take control. Energy Performance of Building Directive (EPBD) requires EU countries to ensure all new buildings were nearly zero-energy by the end of 2020. By definition, the term Net Zero Energy Buildings (nZEB) is referring to high energy performance and renewable energy sources (Kurnitski et al. 2014). The energy performance of a building is the demand for energy use for heating, cooling, ventilation, hot water, lighting, and others. The energy performance guidance BENG in the Netherlands requires all new buildings since January 1, 2021, should meet the requirements of nZEB. In the Netherlands, the Dutch technical agreement NTA 8800 is designated in the building regulations as a simple, transparent determination method.

To design energy-efficient architectures, a great deal of decisions need to be made regarding the geometry, the envelope, the equipment, etc., and these decisions are grounded on the outcome of the energy assessment. An energy assessment is a necessary and important step in optimizing building energy performance. Approaches to analyzing energy demand include using detailed building energy simulation tools, surrogate models, and dynamic objective functions (Kheiri 2018). Surrogate models are based on experimental measurements or detailed simulations, for instance, regression models and using Artificial Neural Network (ANN) as a meta-model have been studied by researcheres. The dynamic objective function is also a mathematical way of combining pattern search and adaptive tests.

According to the statistics from the review of Kheiri (2018), EnergyPlus is used most frequently among the assessment methods and it represents the detailed simulation tools.

The whole design process can be divided into different stages, commonly involving conceptual design, schematic design, and detailed design (Feng et al. 2019). The basic building geometric parameters are decided in the conceptual design stage, for instance the orientation, the height, length, and width. The schematic design concerns the floor plan, number of floors, and the number of rooms. The conceptual design and schematic design are sometimes mingled and considered the early design stage. The detailed design concerns precise sizes and materials. Figure 1.1 presents the cost-influence curve of design process. The descending curve represents the possibility to influence impacts, which is high in the early design stage and low in the detailed stage and construction stage. The cost of design change during the design process is represented by the ascending curve, and the later design change, the more cost due to the change. Hence, energy optimization towards the early design stage is the key to promoting energy efficiency.

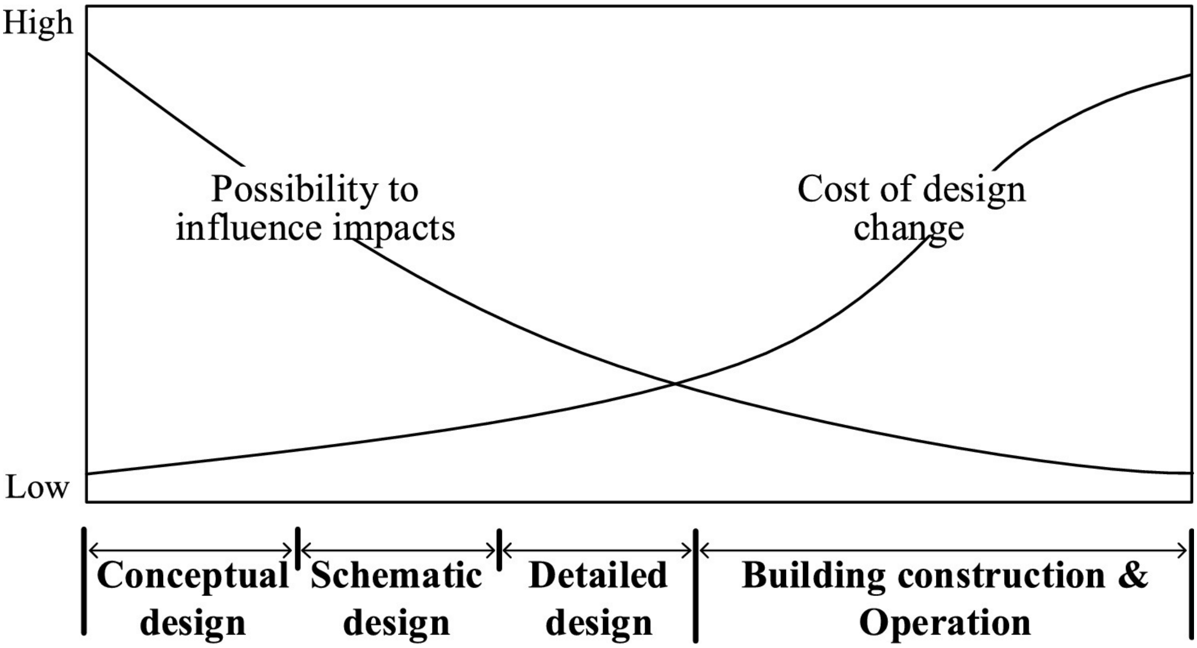


Figure 1.1: Cost-influence curve (Feng et al. 2019)

Building energy performance (BEP) simulations are widely used for the analysis of building energy and thermal comfort to increase sustainability. The BEP simulations provide a prediction of the building in operation conditions, helping the designers make decisions leading to more desired results. Detailed BEP simulations start with sufficient information from building geometric and HVAC designs(Bazjanac 2008), which happens more often in late design stages, otherwise, assumptions need to be made. Due to this fact, it is hard to involve energy performance simulations in the very early design stage. The energy simulation tools require a different model format than the architectural model, which means the conversion is necessary. On the one hand, manual translation of the architectural models into energy models can be time-consuming and has the potential of introducing errors in input data (Bazjanac 2009). On the other hand, reusing Building Information Modeling (BIM) data automatically in BEP models by current tools is difficult, because the intervention is needed (Jeong et al. 2014). If an element is recognized as not standard, the translation goes arbitrary, and it affects the simulation. The detection of such an error can be iterative and hard.

Compared to the dynamic simulation of the detailed method, the simplified method utilizes quasi-steady-state assessment, the selection between which is considered the trade-off between accuracy and simplicity (Ballarini et al. 2020). Even though both methods come in handy under specific conditions in the design process, there are limitations of adopting energy assessment methods. BEP tools are often used as an engine for simulations of modeling tools with user-friendly interfaces, but one needs special expertise to avoid meaningless input and output. The adoption of software simulations of building energy use is Building Energy Modeling (BEM), for which the skills for the software and comprehensive understanding of energy analysis are requisite.

Building performance optimization and automation of the process are topics that have been increasingly emphasized in recent researches Kheiri (2018). The energy optimization with conventional method happens in the late design stage, where the energy consultants may intervene, but the changes are normally high-cost (Hollberg et al. 2019). Therefore, having the energy assessment in the early stage is more beneficial to the energy. The engagement of automation also improves the efficiency of the optimization. However, the interoperability between BIM tools and energy-analyzing tools is a challenge to realize automatic optimization.

In short, the current energy performance assessment is involved inefficiently. At present, engaging energy analysis in the conceptual design stage to aid with the decision-making of designers who are not equipped with special expertise on energy efficiency remains a research gap. This paper aims to improve the efficiency of the building energy performance design in the early stage on the basis of the Dutch agreement NTA 8800.

1.2. Research Structure

As introduced in the previous section, energy optimization depends on the results of energy analysis, thus the energy assessment of buildings in the early design stage is quite essential. However, the current methods of energy assessment are not satisfactory for the early-stage design with mainly geometric parameters, nor conducive to assisting designers. As a result, the existing research is inadequate for energy efficiency development, as it focuses on the accuracy and overlooks the influence of changes in the early stage. In this section, the objective of the research is explained, and the research problems are derived based on the contexts. Furthermore, the methodology is formed.

1.2.1. Research Aim and Objectives

Given the lack of research regarding energy assessment approach in early design stage, the research will aim to increase the efficiency of energy performance assessment of buildings in the early design stage. The main research objective is to develop an on-the-fly energy performance calculation method while repetitively modifying the building is allowed to enhance its energy efficiency.

Sustainability is a keyword to the building performance design due to the increasing awareness of energy saving. Energy simulation tools are developed with capability of sophisticated building simulations. However, with limited data in the very early design stage, the simulation tools tend to make assumptions that can significantly affect the results. Radwan (2021) developed an IFC-based tool to involve energy calculation in early design stage by python coding, but the interoperability reduces as the model is exported as IFC format. The second research objective of this thesis is to take advantage of the current BIM and modeling tools to develop an integrated tool as an demonstration which produces instant feedback on energy performance of the building, based on the current Dutch determination method NTA 8800.

1.2.2. Deliverable

The thesis proposes a method that aims to provide on-the-fly energy calculation for the early design stage of building. A tool based on the proposed framework will be developed in Grasshopper and validated with Uniec 3. The tool adopts the Dutch norm NTA 8800, considering mainly the chapters 5, 6, 7, and 8, and the focus is laid on residential buildings.

1.2.3. Research Questions

The main research question is:

"How can energy performance be assessed, in compliance with Dutch building law, in a very early design stage based on a preliminary BIM-model while modifications to the design can be made on-the-fly?"

The sub-questions are as follows:

1. What framework can be used to make the energy assessment on-the-fly?
2. What is the added value of the on-the-fly simulation method?
3. How can validated assessments be made in an early design stage?

1.2.4. Methodology

The methodology is formed according to the research objective and the research questions. It consists of four following parts.

First of all, suitable methods and tools need to be chosen through a literature review. A framework is summarized according to the latest research progress. On top of that, the experience from the recent researches is a valuable material for making decisions on the BIM software and the energy assessing software.

The second part is to identify the building data input and the climate data input according to NTA 8800 and determine the calculation method for early-stage design based on NTA 8800. The energy norm is a comprehensive document that needs to be simplified to apply in the developed tool.

The third part is to develop the energy calculation tool with the chosen software and test its functions. The tool is designated to serve as an energy-assessing engine for architects.

Finally, the tool is validated by Dutch-certificated software Uniec 3. The results are compared throughout test cases.

1.2.5. Research Significance and Scope

This thesis will contribute to the body of knowledge on energy optimization of buildings by developing an energy assessing framework and tool. It will help address the gap in the area and provide possible solutions to the research questions. The framework and the tool will serve as an engine for real-time energy analysis.

The scope of the thesis determines that the designed tool based on the developed framework has a certain use range. Having considered the workload in conjunction with the project duration, restrictions have to be made. The restrictions consist of two aspects. On the one hand, the energy demand indicator $Ewe_{H+C;nd:ventsys=C1}$, which represents the fundamental energy performance of the building, is the main output taken into consideration for development and validation. Thus, only a subset of the norm NTA 8800, including mostly Chapters 5, 6, 7, and 8, is focused on, and the other chapters serve as a database of values. On the other hand, the investigated building type is restricted to residential buildings. The residential buildings are typical and common usage functions for both existing and new buildings.

Main chapters of NTA 8800:

- 5 Application and determination of energy performance
- 6 Building boundary and schematic
- 7 Determination of heating and cooling requirements
- 8 Transmission
- 9 Heating
- 10 Cooling
- 11 Ventilation

- 12 Humidification and dehumidification
- 13 Determination of energy consumption for hot tap water
- 14 Lighting
- 15 Building automation
- 16 Building-related production of electricity
- 17 Climate data

1.3. Outline

This thesis is presented in 8 chapters. In Chapter 1, the context of the study has been introduced. The research aim, objectives, and questions have been identified. The methodology and the value of the research have been discussed.

In Chapter 2, the state of the art will be reviewed to evaluate and compare the current approaches and strategies regarding energy assessment, especially in the early design stage. Besides, the requirements of the Dutch determination document NTA 8800 will be presented. Finally, the BIM and simulation tools to be used will be introduced.

In Chapter 3, the theoretical framework will be discussed. Firstly, the workflow and functions of the framework will be presented. The detailed input parameters will be identified, and the energy calculation equations will be explained based on NTA 8800.

In Chapter 4, the framework will be put into practice. The operations of the developed tool will be demonstrated. The implementation of the tool based on the tiny house from IKEA will be presented.

In Chapter 5, the developed tool will be verified by a case study. The configurations of the cases will be presented first. Next, the results of the developed tool and Uniec 3 will be displayed. The results will also be compared and analyzed.

From Chapters 6 to 8, the discussion, conclusions, and recommendations will be presented respectively. The discussion will be about the verification of the framework and its limitations. Chapter 7 will answer the research questions, and the significance will be discussed as well. In Chapter 8, the possible future study will be presented for research purposes.

2

State of The Art

This chapter outlines the current state of the art regarding BIM, data transformation, BIM to BEP models translation process, and required data for energy performance analysis.

2.1. BIM-based Building Energy Modeling

Collaborative environments and interoperability is a topic that has attracted many researchers' attention concerning Building Information Modeling. A significant increase in the number of related research papers since 2014 is noted by Santos et al. (2017). The interoperability of BIM is also applied in building performance assessments. Chang & Hsieh (2020) analyzed 80 publications in BIM for green building design, and over 40% papers involved thermal and energy analysis, which indicates its importance in building performance design. The efficiency of Building Energy Modeling (BEM) is largely depending on the automation of the process since conventional BEM has a time-consuming and lengthy preparation process. Many studies work on improving the automation of the BIM-based BEM, in this section, the major methods are discussed.

2.1.1. IEF-based Method

Information Exchange Format (IEF) has been used to increase the interoperability between BIM tools for at least 20 years since Karola et al. (2002) developed BSPro COM-Server for Industry Foundation Classes (IFC) files.

Bazjanac (2008) proposes a methodology for IFC-based BIM for semi-automated BEP simulation. The methodology contains five steps, they are: populating IFC-based BIM with data; automated rule-based data transformation; modeling check; BEP simulation, and analysis of results. The methodology was possible partly except for HVAC designs because of compatibility and lack of data transformation tools for HVAC. The methodology saves time and effort significantly in preparing input files for simulations with EnergyPlus.

Bazjanac (2009) introduces Geometry Simplification Tool, also called as Geometry Simplification Tool (GST) / Input Definition Format (IDF) Generator to implement the proposed methodology. GST/IDF Generator transforms geometric data by embedded transformation rules into input information required by EnergyPlus. The methodology implementation and files needed for a comprehensive BEP simulation with EnergyPlus are presented in Figure 2.1, including thermal view geometry, thermal properties, internal loads and schedules, HVAC systems and plant, as well as their operating schedules, and simulation run control data. The initial window and the parameters definition window are shown respectively in Figure 2.2 and Figure 2.3, the IDF Generator allows the user to manually adjust input options.

The IFC-based method has the advantage that IFC is an open and standard 3D objected-oriented exchange mode of BIM authoring tools, it also represents any shape of the geometry. This characteristic allows the data transfer between different BIM authoring tools. For example, Ramaji et al. (2020)

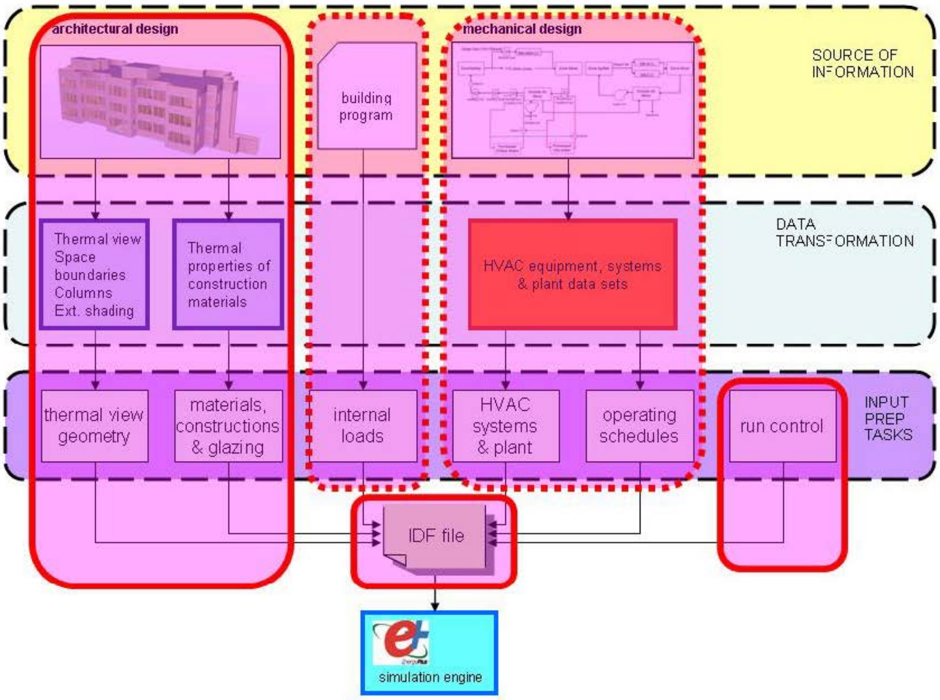


Figure 2.1: Complete implementation of the methodology for semi-automated BEP simulation (Bazjanac 2009)

has developed an algorithm in BIM server to transform BIM in IFC format into an energy model for OpenStudio with higher accuracy. However, trying to comprehensively and generically transform the data, the IFC method is considered to be complex. Although there are many studies in the IFC-based method, a reliable energy model can be applied after a manual check (Gao et al. 2019).

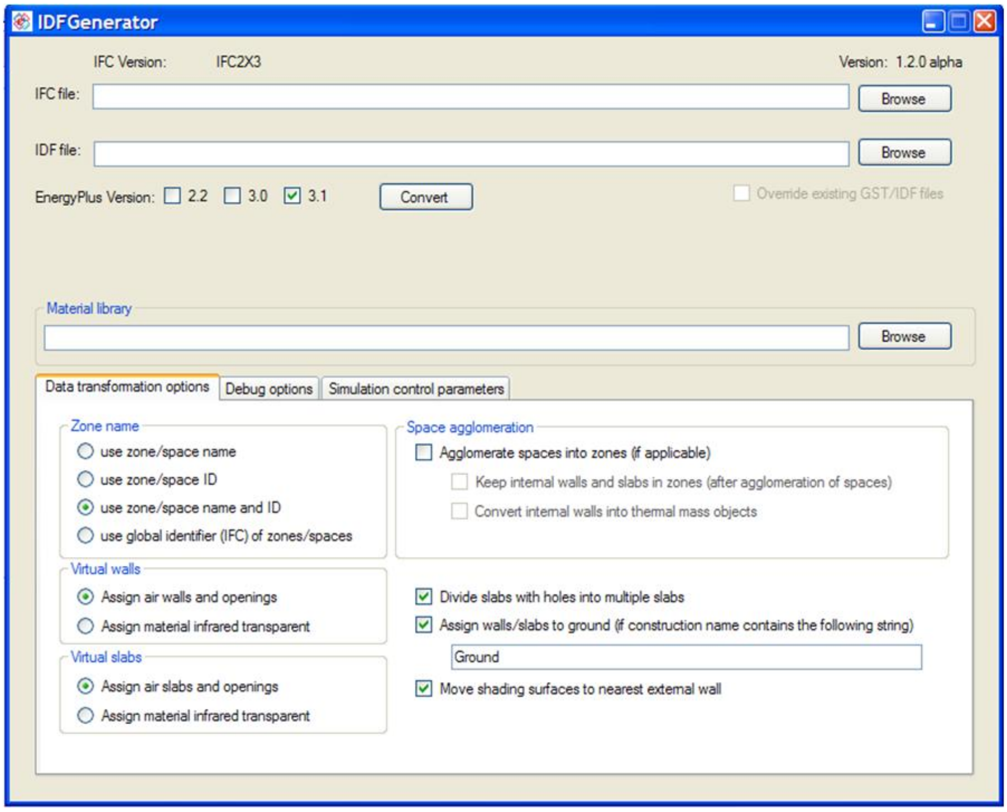
Another IEF is Green Building XML (gbXML), which is developed by Autodesk Green Building Studio. In contrast to the universality, the gbXML-based method only transfers required data. Utilizing BIM schemas like IFC and gbXML, the data can be transferred between BIM tools, and the building design is semi-automated, however, necessary information for calculation or simulation may be lost during the process according to Cheng & Das (2014) and Gao et al. (2019).

2.1.2. BIM API-based Method

Based on Lawrence Berkeley National Laboratory's (LBNL) Modelica library, Yan et al. (2013) introduced a methodology that utilizes Autodesk Revit and its Application Programming Interface (API) to translate BIM models into object-oriented physical models for both thermal simulation and daylighting simulation. BIM to thermal modeling framework is called Revit2Modelica, and BIM to day lighting modeling is called Revit2Radiance. Figure 2.4 and Figure 2.5 present respectively the workflow of the physical BIM prototype and Revit2Modelica. The API method does not allow working with other BIM authoring tools, but the programming and implementation process is less difficult than the IFC method.

Jeong et al. (2014), similarly, develops a framework named BIM2BEM, that connects Autodesk Revit to Modelica. To complete a more seamless translation process, they created a Model View Definition (MVD) to define data exchange requirements. The Exchange MVD contains wrapper classes which adopt object semantics of Revit, and interface classes which involve object instances per Modelica language specifications.

Recently, an add-in for Revit and Rhino/Grasshopper named Pollination Cloud is developed, which combines the IEF-based method and the BIM API-based method. A schema namely Honeybee JSON (HBJSON) is created as a mediate file format between Revit and Rhino. Using the Pollination Cloud Revit add-in, one can export the BIM model to Rhino by HBJSON format. The model can also be



IFC Version: IFC2X3

Version: 1.2.0 alpha

IFC file:

IDF file:

EnergyPlus Version: ☐ 2.2 ☐ 3.0 ☑ 3.1

☐ Override existing GST/IDF files

Material library

Zone name
- ○ use zone/space name
- ○ use zone/space ID
- ● use zone/space name and ID
- ○ use global identifier (IFC) of zones/spaces

Virtual walls
- ● Assign air walls and openings
- ○ Assign material infrared transparent

Virtual slabs
- ● Assign air slabs and openings
- ○ Assign material infrared transparent

Space agglomeration
- ☐ Agglomerate spaces into zones (if applicable)
  - ☐ Keep internal walls and slabs in zones (after agglomeration of spaces)
  - ☐ Convert internal walls into thermal mass objects

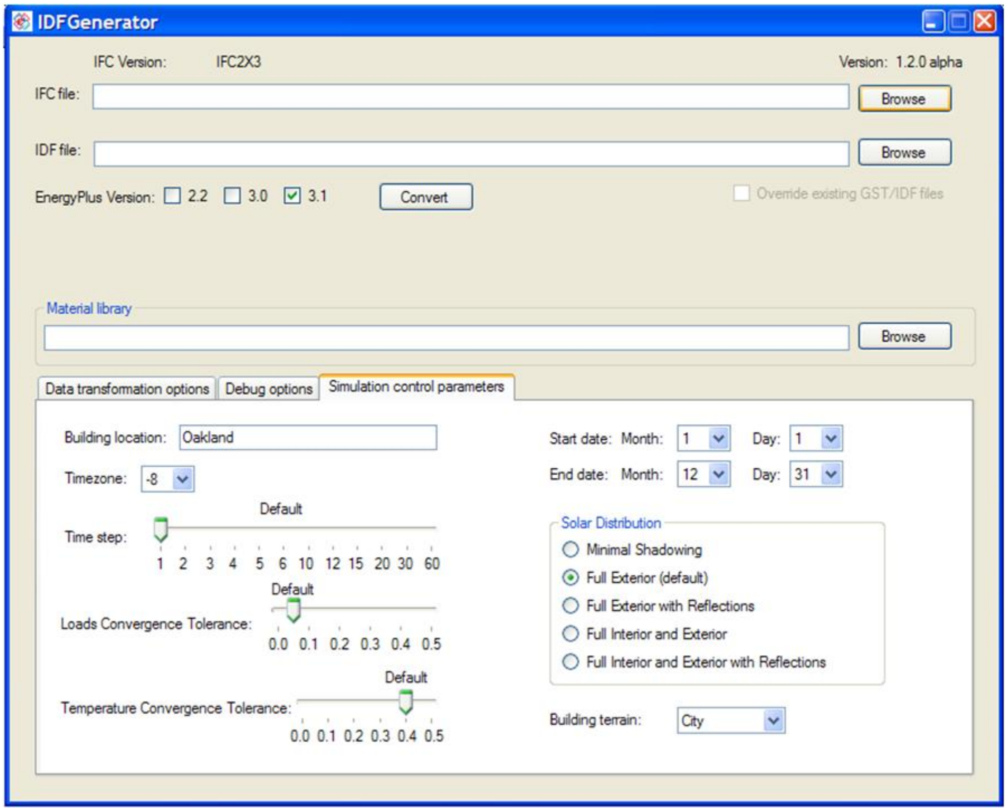
☑ Divide slabs with holes into multiple slabs

☑ Assign walls/slabs to ground (if construction name contains the following string)

Ground

☑ Move shading surfaces to nearest external wall

Figure 2.2: Initial window of the GST/IDF Generator GUI (Bazjanac 2009)



IFC Version: IFC2X3

Version: 1.2.0 alpha

IFC file:

IDF file:

EnergyPlus Version: ☐ 2.2 ☐ 3.0 ☑ 3.1

☐ Override existing GST/IDF files

Material library

Building location: Oakland

Timezone: -8

Time step:

Loads Convergence Tolerance:

Temperature Convergence Tolerance:

Start date: Month: 1 Day: 1

End date: Month: 12 Day: 31

Solar Distribution
- ○ Minimal Shadowing
- ● Full Exterior (default)
- ○ Full Exterior with Reflections
- ○ Full Interior and Exterior
- ○ Full Interior and Exterior with Reflections

Building terrain: City

Figure 2.3: Simulation run control parameters definition window (Bazjanac 2009)

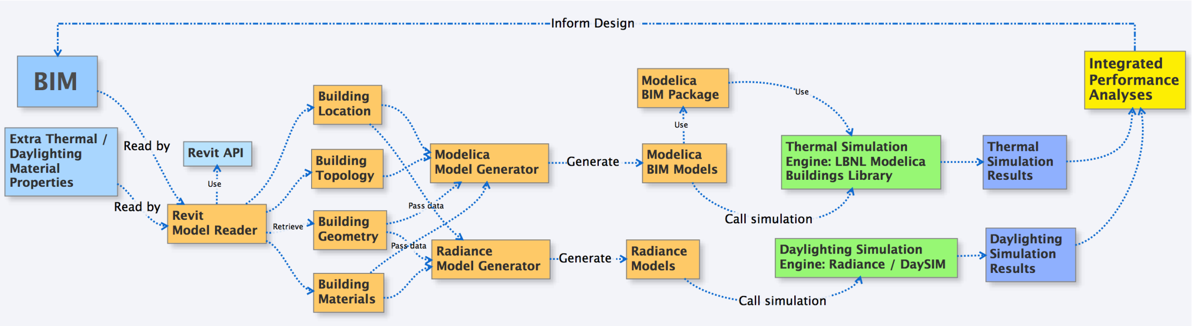


Figure 2.4: Workflow of PBIM: BIM to multi-domain (thermal and daylighting) simulations. In the diagram, the components of Integrated Performance Analyses to Inform Design will be implemented in the future. The gold color components represent our PBIM prototype components (Yan et al. 2013)

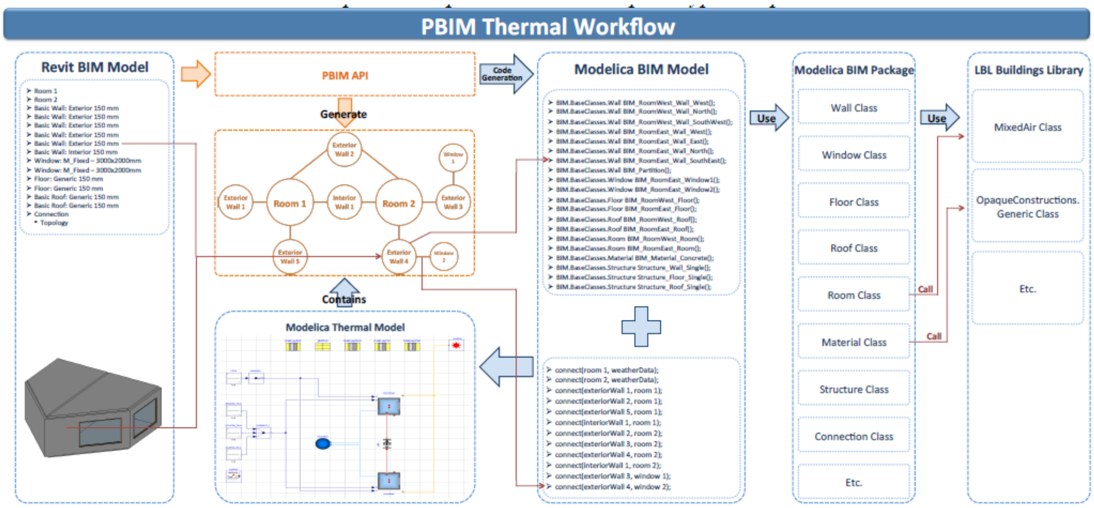


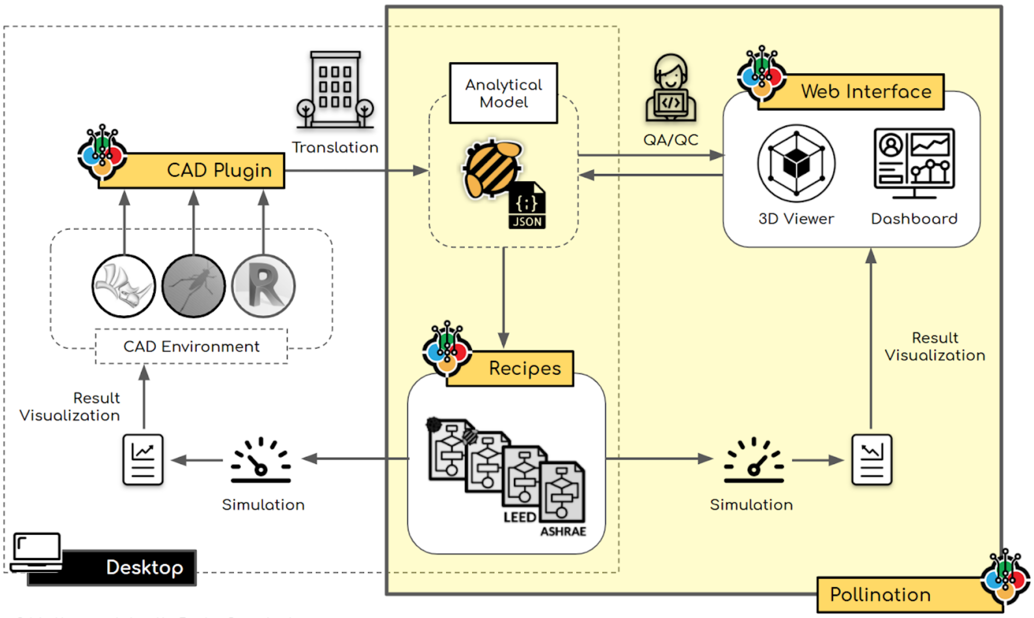
Figure 2.5: Revit2Modelica workflow (Yan et al. 2013)

exported to IES-VE and OpenStudio using gbXML file format. The HBJSON file has information for energy, daylight, and thermal comfort simulation (**?**). Figure 2.6 demonstrates the working principles of the Pollination Cloud and HBJSON.

2.1.3. Other Methods

To utilize automated translation in the early design stage where BIM models are often incomplete for a full BEP simulation, Pratt et al. (2012) shifts the focus to the modeling process and describes a framework containing a modeling protocol, a communication protocol, and a translation protocol (Figure 2.7). Three actors are considered in the protocols, first, a CAD tool user, namely the designer, a communicating program of CAD model, and a translator that makes energy models using the received data (Figure 2.8). The prototype of the framework performed EnergyPlus analysis with models generated in SketchUp, Grasshopper for Rhinoceros, and 3ds Max. Yet the bidirectional link has not been implemented. The bidirectional link can send and receive information, and it allows identification and modification corresponding to the BEP simulation.

Utkucu & Sözer (2020) developed a framework to determine the interoperability between BIM software to evaluate building energy performance. Four steps are considered in the framework: optimization of the building facade, energy simulation and optimization, study of natural ventilation, and the investigation of design quality.



Original icons are designed by: Eucalyp, Payungkead Im-anong, Adrien Coquet, LAFS, Shocho, and Andrejs Kirma.

Figure 2.6: The HBJSON format workflow (Roudsari 2021)

Figure 2.7: The prototype implementation allows a single user to simultaneously model, simulate, and view BES results. The workstation's left screen shows the CAD input, while the center shows the translated model and the right contains BES output (Pratt et al. 2012)

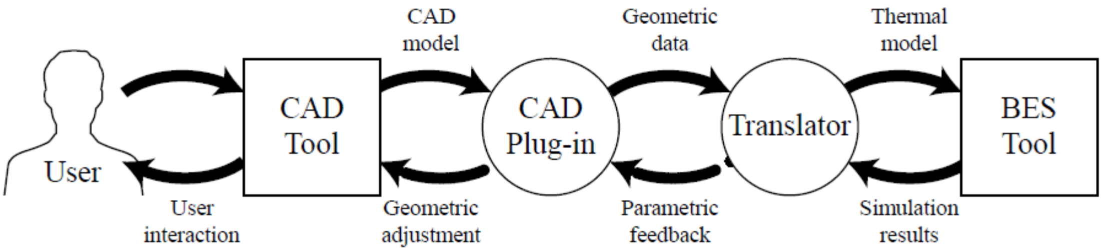


Figure 2.8: Three actors involved in building design and analysis (Pratt et al. 2012)

2.1.4. Discussion

Some improvements can be done based on the current study. The related studies are rather early, now that not only new BIM tools are developed, but the BEP simulation tools have also been renewed, therefore, the translation framework needs to be updated. Although the IEF-based method has been studied for years, it is still at an initial stage (Gao et al. 2019). The gbXML-based method is used specifically in energy design, it transfers not only the geometry but also the material and thermal zone. However, it has limitations on the shapes of geometry because the format only supports regular shapes. BIM API-based method has a reliable transformation of building geometry compared to the IES-based method since it does not require an import or export process via exchange formats. The downside is that the preparation of the BIM file is required. The strength and limitations are listed in Table 2.1.

	Strength and limitations	**Examples**
IFC-based method	ISO-certificated and aims to provide a universal basis; The process is comprehensive and complex.	IFC-based IDF converter; IFC-based HVAC interface; etc.
Green Building XML-based method	Only focuses on required data; Only accepts rectangular shapes and simplified geometry; More straightforward than the IFC-based method; Requires the preparation of the BIM model.	BIM-based Ecotect with green building certification; Revit to Ecotect & Revit to DesignBuilder; etc.
BIM API-based method	It utilizes Object-Oriented Physical Modeling (OOPM); Pre-processing on the BIM model is required.	BIM2BEM using Model View Definition; Revit2Modelica; Pollination Cloud plug-in; etc.
Other method	Manual input of required information is needed.	Design Performance Viewer; other Revit add-in; etc.

Table 2.1: The characteristics and examples of BIM-based BEM methods

To a different extent, the translation from BIM models to BEP models requires manual assignment. Current frameworks need to be validated for complex buildings, especially for high-rise buildings with novel facades in the future. The interoperability between different software brings flexibility. Taking into account the increasingly complex building geometry, and the current development of different transforming methods, the BIM API-based method has great potential of realizing more seamless automation.

2.2. Energy Analysis Requirements

2.2.1. Indicators

To achieve the requirements of nZEB, the building must have zero or a very low energy demand, and the energy demand should also be compensated by renewable energy. Three indicators of energy performance according to BENG are:

1. BENG 1: the maximum energy requirement in kWh per m 2 of usable surface per year; influencing factors: insulation of the building envelope, air-tightness, compactness of the building, sun shading, orientation.

2. BENG 2: the maximum primary fossil energy consumption, also in kWh per m 2 usable surface per year; influencing factors: thermal envelope of a building, efficiency of installations, application of renewable energy.

3. BENG 3: the minimum share of renewable energy in percentage; influencing factors: PV panels, solar boiler, wind energy, energy from outside air, heat pump based on ground heat or ambient heat.

Besides, indoor comfort is also considered as another secondary indicator TO_{July} is introduced to prevent overheating in summer. The influencing factors include window dimensions, sun shading, building mass, and ventilation type. This calculation is required when no active cooling system is present.

In the Netherlands, houses, apartments, and public buildings that are being built, sold, or rent, must have energy labels. Offices are required to have at least an energy label C since 2023, otherwise, they are not allowed to use it as an office. Energy labels from A to G are determined based on mainly standard NTA 8800, BRL 9500, and ISSO 82.1 as well. Energy labels are required at the start stage, delivery stage, and also for existing buildings.

Various software programs have been developed for calculating energy performance. Vabi EPA NTA 8800 is one of the certificated software according to NTA 8800. Vabi EPA NTA 8800 can test the BENG requirements for a complex, test the TO-July, and determine the energy label for homes. This thesis mainly takes BENG 1 into consideration.

2.2.2. Input Data

The accuracy of the energy performance analysis depends on the input data. The input data required are mainly the building geometry, weather data, HVAC systems, internal loads, operating strategies, and schedules (Maile et al. 2007), as shown in Figure 2.9. Besides the typical input data needed for building energy performance analysis above, Bazjanac (2009) also included the thermal properties of construction materials and assemblies using EnergyPlus 2009 as the simulation engine. For the use of design and optimization, Utkucu & Sözer (2020) considered specifically the building envelope and HVAC systems regarding the building's specifications.

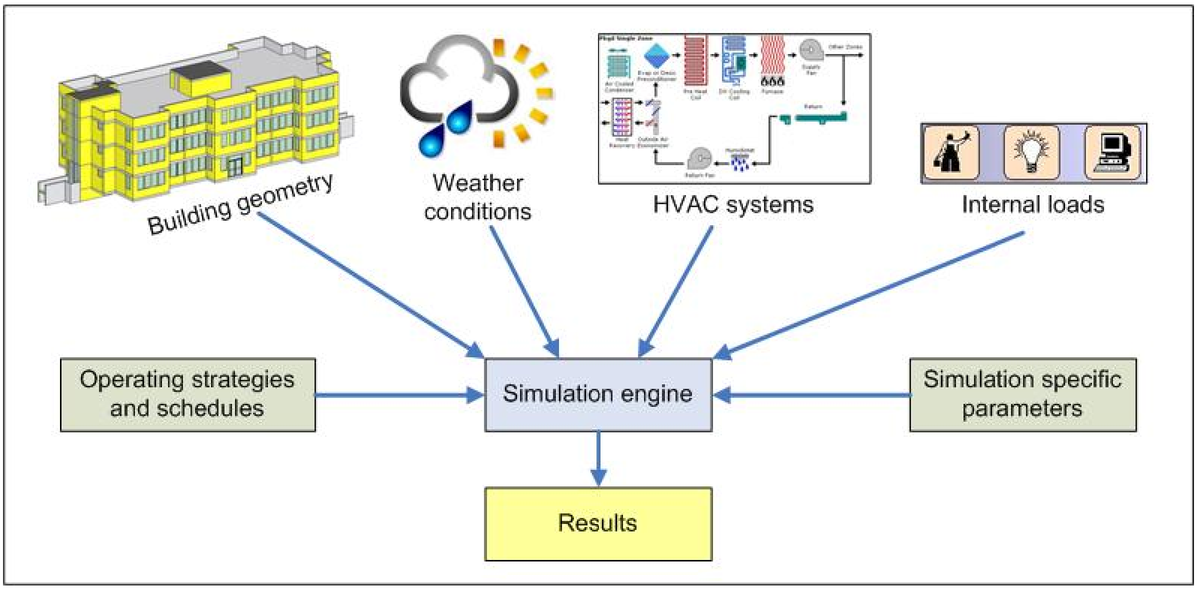


Figure 2.9: General data flow of simulation engines (Maile et al. (2007))

BENG 1 elaborated on the influential parameters, which include the window-glass ratio, insulation factor, air tightness, thermal bridges, as well as the geometry and location of a building.

2.3. BIM Tools and Simulation Tools

The choice of BIM authoring tools and simulation engine is related to the interoperability between them. In this section, the BIM tools and simulation tools used will be introduced.

2.3.1. BIM Authoring Tool

There are various BIM authoring tools have been used in the research. Jeong et al. (2014) and Yan et al. (2013) created BIM-based transferring framework through Autodesk Revit API. While Cao et al. (2014) and Remmen et al. (2015) respectively used SimModel, and Space Boundary Tool in combination with SimModel. The mostly used BIM authoring tool in the studies on thermal and energy analysis is Autodesk Revit (Chang & Hsieh 2020), which has high interoperability with simulation tools.

Rhino.Inside.Revit is an application that utilizes the Revit API and connects to the Rhino (Rhino 7) and Grasshopper, enhancing the interoperability of BIM authoring tools. With environmental plug-ins like Ladybug and Honeybee, designers can conduct various simulations. Rhino.Inside.Revit enhances the connection between Revit and Rhino/Grasshopper by conveying data without file format exchange.

Additionally, Grasshopper is a visual programming tool that empowers users to customize commands on the design.

2.3.2. Simulation Tools

There are multiple plug-ins for Grasshopper that enables energy simulations. For instance, Ladybug and Honeybee are often combined in use, as the former imports standard EnergyPlus weather file (.EPW), and the latter connects Grasshopper to OpenStudio, Daysim, Radiance, and EnergyPlus for energy and daylighting simulation. In addition, Archisim Energy Modeling engages EnergyPlus as the engine for BEP simulation. UrbanDaylighting simulates daylighting on the urban scale, while DIVA-for-Rhino enables daylighting and energy modeling in both building and urban scale (Rogler 2015).

However, the detailed simulations are not suitable for an early-stage design. To practice NTA 8800 in the developed tool, it is decided to create customized programming script within Grasshopper so that the equations can be made-to-order.

In conclusion, the integration of Revit-Rhino.Inside-Grasshopper is adopted as the working structure. It takes advantage of the flexibility, visualization, speed, and quality of parametric design and visual programming.

3

Framework Development

This chapter will demonstrate the overview of the Dutch energy determination method NTA 8800, then the framework of the tool to be developed will be introduced. The input for the developed tool will be specified in both geometrical and thermal aspects. Then the energy calculation based on NTA 8800 will be elaborated for the structure of the developed tool.

3.1. Conceptual design

The developed method aims to benefit the designers on the energy assessment in the early design stage. The tool is connected directly to the BIM software and provides energy performance assessment. The calculation method is based on NTA 8800, which has come into force in the Netherlands. The functions that can be achieved using the developed tool are introduced in this section. In addition, the scope limitations have been made for the use of the tool.

3.1.1. BIM-BEM Tool Framework

The aim of this tool is to improve the sustainability in building industry by developing an BIM-based BEM program that involves building energy calculation in early design stage, as the request of NZEB in Europe. The tool should help with the decision-making process by providing effective calculation results and proper suggestions on how to reduce the energy demand in early design strategies. As discussed in the state-of-the-art, the data conveyed from BIM to BEM process has been studied by a number of researchers, and its importance has also been stressed. The parametric modeling software Rhino and Grasshopper has the potential to be widely used in BIM-BEM design process, due to its powerful functions with geometries, and the easy accessibility together with quick processing ability of the BIM API-based method. Interaction between the geometry and the energy performance is close as the parameterized geometry can easily be changed and synchronized to BIM software.

The proposed tool is built based on the BIM API-based method, with the determination method provided by the document NTA 8800, it can calculate the energy performance of a building. The framework of the tool is presented in Figure 3.1. Building information stored in BIM software Revit is conveyed to Rhino and Grasshopper through Rhino.Inside, the calculations are conducted following the principles in NTA 8800, which also provides necessary supplementary data. The tool returns the results of energy calculations as well as feedback on how to improve energy performance for the building.

3.1.2. Dutch Energy Norm NTA 8800

NTA 8800 is a recent Dutch technical agreement that has been developed as a determination method to calculate the NZEB requirements. With NTA 8800, not only the energy performance of new buildings can be calculated, but also the energy performance of existing buildings can be calculated. The determination method is in agreement with the market on Building Decree, energy performance of buildings, and the Energy Labels. NTA 8800 concerns both residential and non-residential construction. The goal

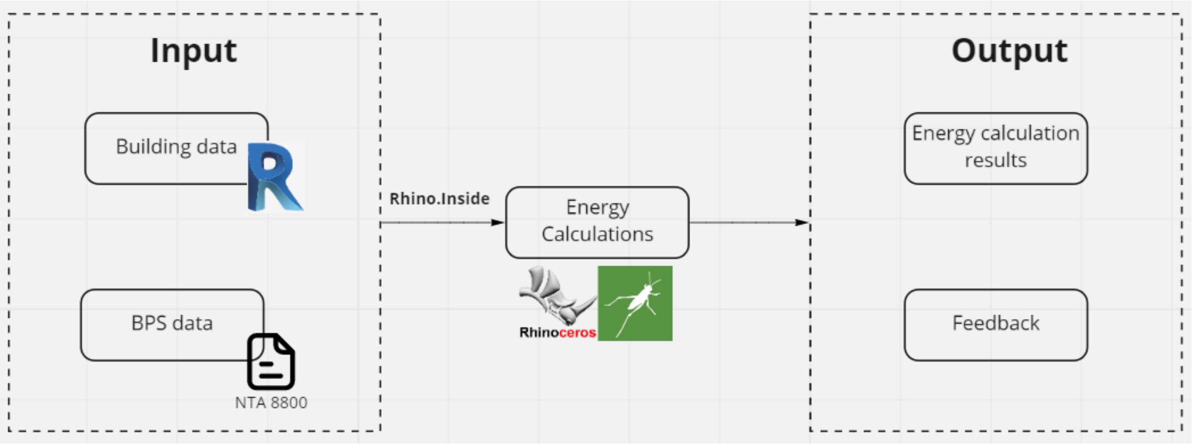


Figure 3.1: BIM-BEM tool framework

of NTA 8800 is to be a transparent and unambiguous determination method, based on the EPBD. NTA 8800 provides a method to determine whether the requirements for the energy performance of buildings are met, and it can be applied to the determination of the Energy Label or the Energy Performance Fee (EPF).

With the method provided in NTA 8800, the numerical value of the energy performance and indicators for a building can be determined. The application of NTA 8800 covers both new and existing buildings with all user functions. Building-related energy use is considered, as stated in EPBD, the item lighting is not included either. The determination method is based on the monthly calculation method in response to EPBD. Should the situation not apply, additional explanations and cases can be found in recording protocols ISSO 82.1 for residential buildings, and ISSO 75.1 for non-residential buildings.

NTA 8800 requires certain accuracy for a number of input data. NTA 8800 provides the most conservative fixed value to be applied if the needed data is absent. The recording protocols ISSO 82.1 and ISSO 75.1 describe which parameters are involved, and when a specific data is missing, which values can be used in different cases. Three energy performance indicators can be determined through NTA 8800, the energy demand indicator, the primary fossil energy indicator, and the share of renewable energy.

3.1.3. Tool Functions

There are several target functions for the proposed tool to be implemented to achieve the goal. First, the building information from the BIM software Revit needs to be collected. The information is transformed via Rhino.Inside plug-in to Rhino and Grasshopper, thus there is no format exchange involved. The energy calculations are conducted within the tool based on the energy norm NTA 8800 in Grasshopper, which is implemented by inputting formulas and conditions utilizing Python scripting. Then the results of the energy analysis shall be generated and displayed. Additionally, the tool provides feedback based on the results.

This chapter aims to introduce the principles of the proposed tool. The tool calculates the building energy performance employing the BIM API-based method and the determination method in NTA 8800.

3.2. Data input

The energy assessment has a minimum requirement for the data input. The input generally includes the geometric data of the tested building and the thermal properties.

3.2.1. Collecting Building Data

From the Dutch norm NTA 8800, it is essential to determine the building or the part of the building relevant to the energy calculation. There are four steps to have a clear insight into the investigated spaces.

Step one is name usage functions. The energy performance of a building is distinguished by its function, for example, residential function or office function. In terms of energy labeling, it has to distinguish between different types of residential functions. This thesis studies a residential space for the development of the tool.

Step two, determine building boundaries. It is possible to determine the energy performance of a whole building or individual units of it. The boundaries are therefore separating the desired calculation zone and the adjacent areas. The building being studied here is considered one unit. Thus, the envelope should be defined as the boundaries of the building.

Step three is the division into thermal zones. Thermal zones are divided based on their air-conditioning systems. Each thermal zone can have at most one heating or cooling system. As mentioned above, the building is considered as one thermal zone against the outside thermal conditions.

Step four is the division into calculation zones. A thermal zone can be divided into one or more calculation zones, usually based on certain similarities in use.

Building data input needed for energy calculation based on NTA 8800 from the BIM software side is sorted out by Radwan (2021) in Figure 3.2. It adopted the IFC-based method, thus some of the data is not necessary for this thesis, e.g. the Global Id. The input data required by this method is summarized in Table 3.2.

Walls	Roofs	Windows	Doors	Floors	Rooms
Area	Area	Area	Area	Area	Area
Rc-value	Rc-value	Sill height	Rc-value	Perimeter	N living
If exterior		Glazing type	If transparent	Rc-value	N people
Orientation		If fixed	Orientation		
		U-value			
		Orientation			
		Shading reduction factor			

Table 3.1: Input parameters

Collecting building data from BIM software Revit works through its API to read building information in Rhino. Here is an example of conveying BIM data. The sample model of Autodesk Revit (Figure 3.3) is used for demonstration. The transformation workflow contains a few steps. First is to collect the geometric elements in Revit by category. Next, after assigning layers by their category to the elements, the material data is gathered and assigned to each element. Lastly, the thermal information of the building is collected.

First, the building geometry in Revit is collected via Rhino.Inside plug-in. With Query Category component, it can read the categories defined in Revit, as shown in Value Picker in Figure 3.5. The Rhino perspective view of the Revit sample model is shown in Figure 3.4, correspondingly, the geometry reflects on the Revit model, including hidden elements.

The materials are expected in BIM models defined by architects. Via Rhino.Inside, materials are collected in Grasshopper and baked in Rhino for intuitive presentation in Figure 3.7, which is important information that is required for building energy calculation.

3.2.2. Building Energy Input

The energy input for the energy assessment according to NTA 8800 includes the following objects to calculate the energy demand indicator:

- Heat loss through transmission
- Heat loss through ventilation

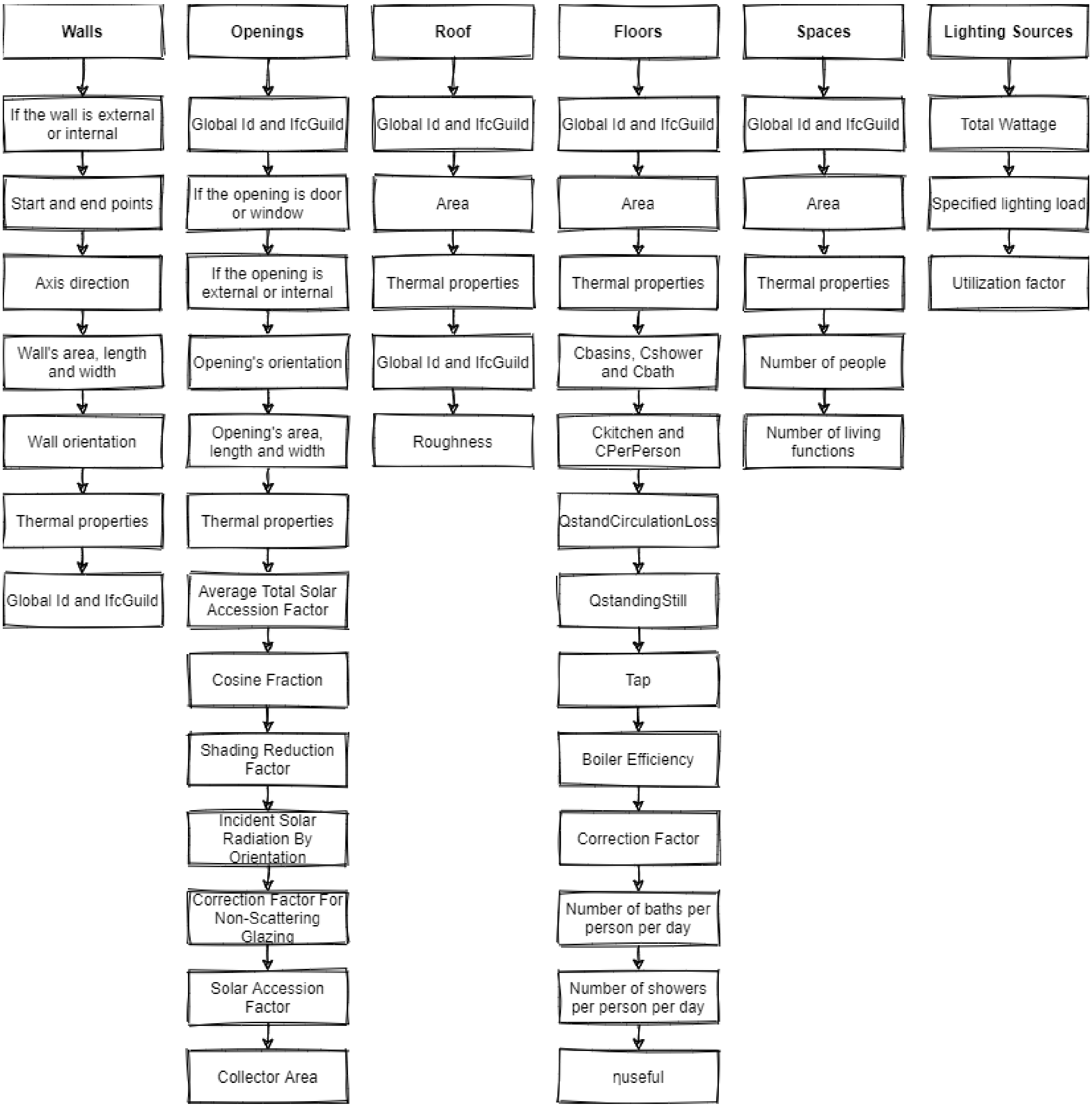


Figure 3.2: The required building data for energy calculation (Radwan 2021)

- Internal Heat gain
- Heat gain by solar radiation

Figure 3.8 shows the calculation method using the IFC-based method. In accordance to the research scope, the calculation is limited to BENG 1, and the objects above are considered in this thesis.

NTA 8800 provides fixed values for certain ventilation systems and internal heat gain due to lighting and tap water. Besides, the thermal properties can be retrieved from the BIM model defined by the user and the element family, or if they do not exist, NTA 8800 provides tables of values for common types.

3.3. Energy Calculation

The Energy Index can be determined based on the determination method provided by NTA 8800, which provides three energy indicators. This thesis studies the first indicator, the energy demand indicator

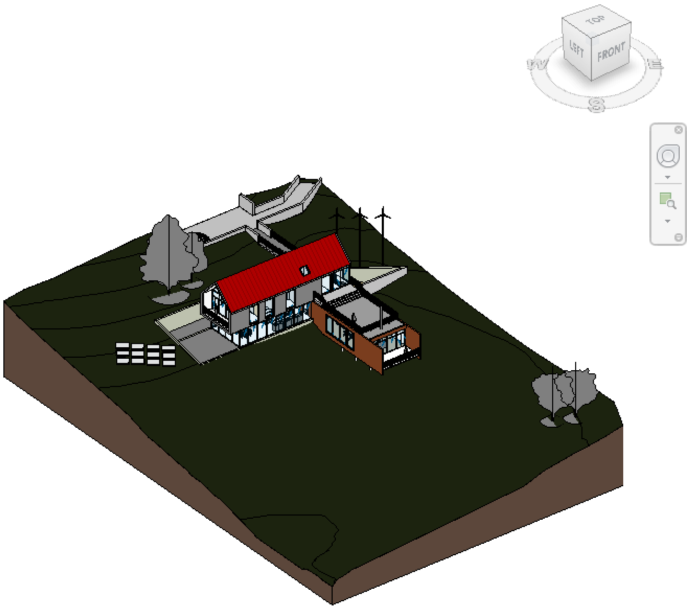


Figure 3.3: Revit sample model

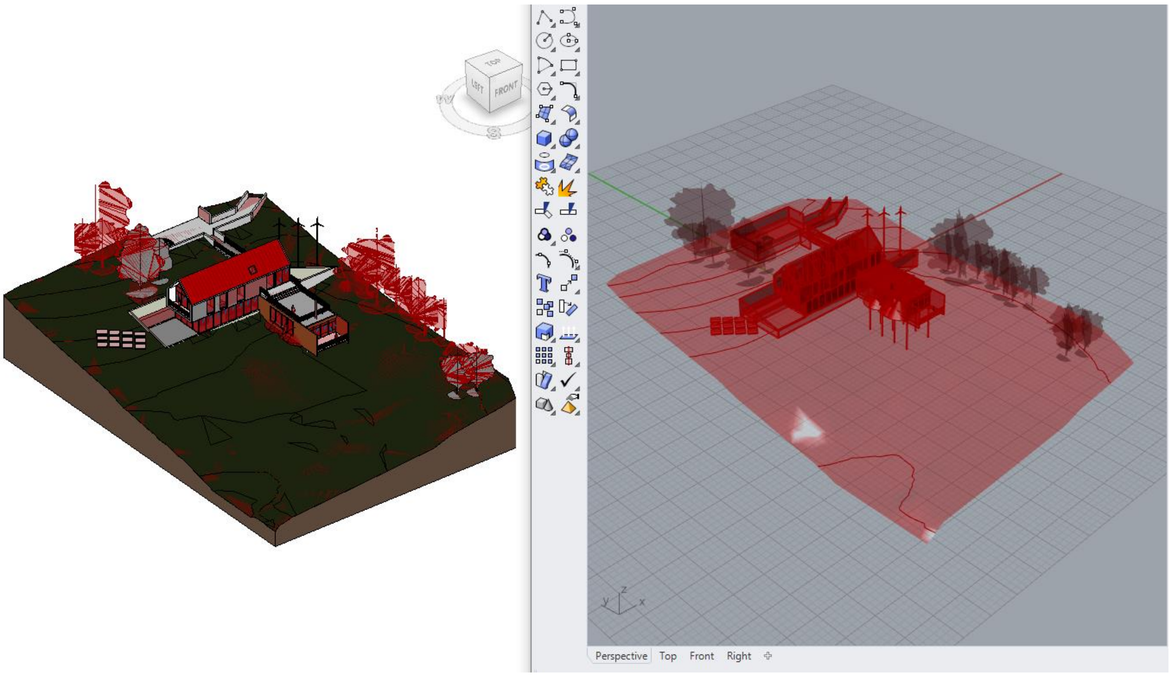


Figure 3.4: Rhino view of extracted Revit sample model

$Ewe_{H+C;nd;ventsys=C1}$, which is corresponding to the content of BENG 1.

The energy demand consists of the heating and cooling requirement of buildings with fixed ventilation system C1, which represents natural supply and mechanical discharge. NTA 8800 provides fixed values

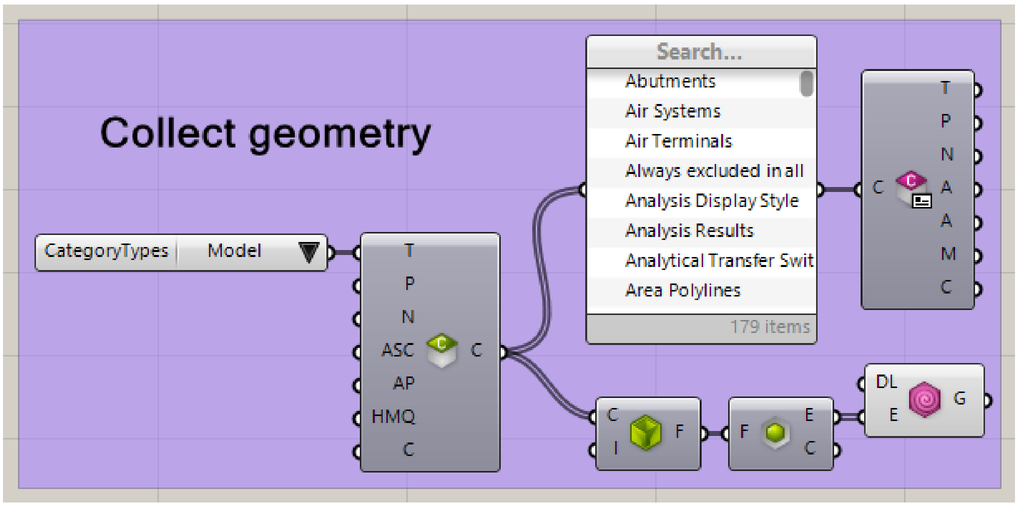
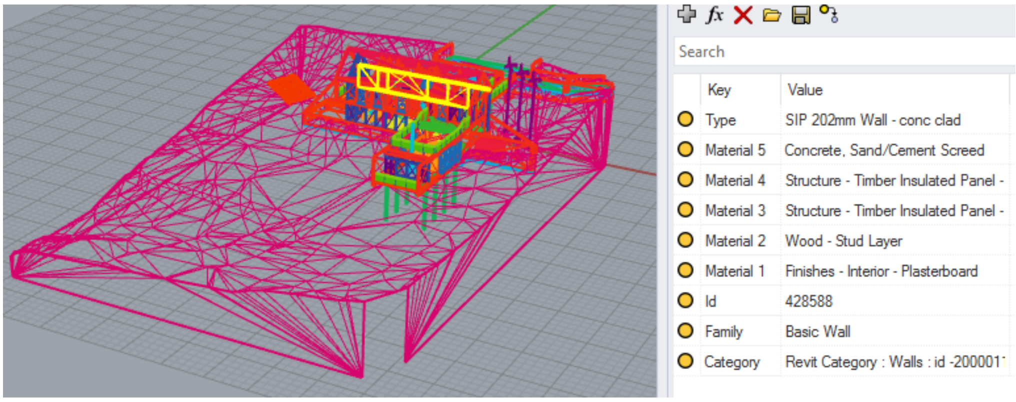


Figure 3.5: Collect geometry from Revit



	Key	Value
○	Type	SIP 202mm Wall - conc clad
○	Material 5	Concrete, Sand/Cement Screed
○	Material 4	Structure - Timber Insulated Panel -
○	Material 3	Structure - Timber Insulated Panel -
○	Material 2	Wood - Stud Layer
○	Material 1	Finishes - Interior - Plasterboard
○	Id	428588
○	Family	Basic Wall
○	Category	Revit Category : Walls : id -200001

Figure 3.6: The property of a wall element in Rhino

for certain ventilation systems for the calculation, as well as the internal heat load of tap water and lighting.

$$Ewe_{H+C;nd;ventsys=C1} = \frac{Q_{H+C;nd;ventsys=C1}}{A_{g;tot}} \tag{3.1}$$

where,

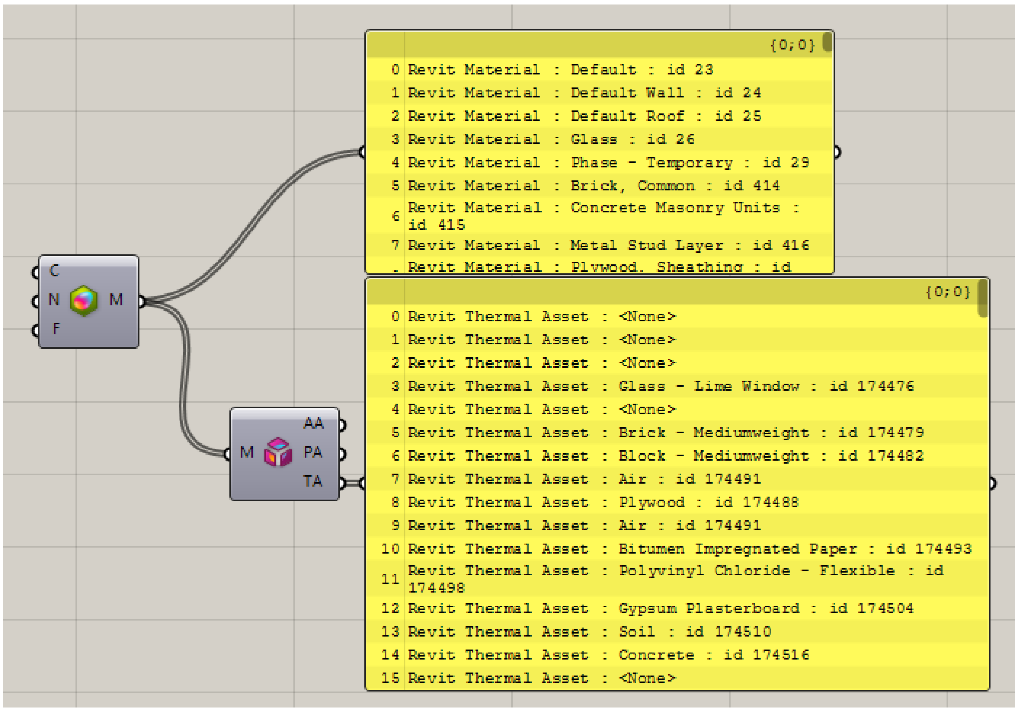
$Ewe_{H+C;nd;ventsys=C1}$	energy demand indicator	kWh/m^2
$Q_{H+C;nd;ventsys=C1}$	annual energy demand	kWh
$A_{g;tot}$	usable area of the total calculation zones	m^2

3.3.1. Heat demand

The annual heating and cooling energy demand composes the total annual energy demand, as in the following equation:

$$Q_{H+C;nd;ventsys=C1} = Q_{H;nd;ventsys=C1} + Q_{C;nd;ventsys=C1} \tag{3.2}$$

Where,



```
{0;0}
 0 Revit Material : Default : id 23
 1 Revit Material : Default Wall : id 24
 2 Revit Material : Default Roof : id 25
 3 Revit Material : Glass : id 26
 4 Revit Material : Phase - Temporary : id 29
 5 Revit Material : Brick, Common : id 414
 6 Revit Material : Concrete Masonry Units :
   id 415
 7 Revit Material : Metal Stud Layer : id 416
   Revit Material : Plywood, Sheathing : id
```

```
{0;0}
 0 Revit Thermal Asset : <None>
 1 Revit Thermal Asset : <None>
 2 Revit Thermal Asset : <None>
 3 Revit Thermal Asset : Glass - Lime Window : id 174476
 4 Revit Thermal Asset : <None>
 5 Revit Thermal Asset : Brick - Mediumweight : id 174479
 6 Revit Thermal Asset : Block - Mediumweight : id 174482
 7 Revit Thermal Asset : Air : id 174491
 8 Revit Thermal Asset : Plywood : id 174488
 9 Revit Thermal Asset : Air : id 174491
10 Revit Thermal Asset : Bitumen Impregnated Paper : id 174493
11 Revit Thermal Asset : Polyvinyl Chloride - Flexible : id
   174498
12 Revit Thermal Asset : Gypsum Plasterboard : id 174504
13 Revit Thermal Asset : Soil : id 174510
14 Revit Thermal Asset : Concrete : id 174516
15 Revit Thermal Asset : <None>
```

Figure 3.7: The list of materials and their thermal properties of the sample model

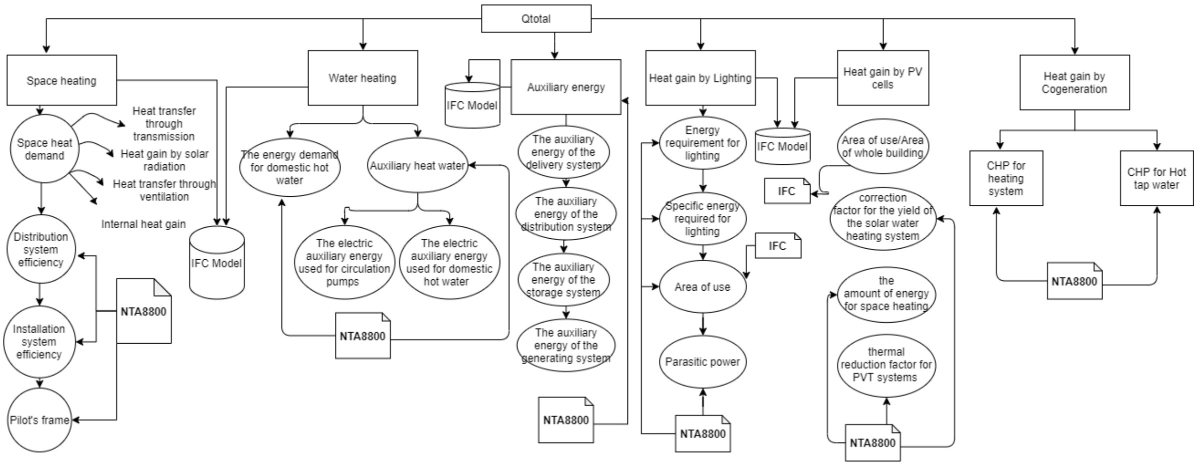


Figure 3.8: Schematic overview of the Energy Index calculations steps (Radwan 2021)

$Q_{H;nd;ventsys=C1}$	annual heating demand	kWh
$Q_{C;nd;ventsys=C1}$	annual cooling demand	kWh

The total annual heating demand is the summation of which for each month and each calculation zone.

$$Q_{H;nd;ventsys=C1} = \sum_{zi;mi} Q_{H;nd;zi;mi} \tag{3.3}$$

$$Q_{H;nd;zi;mi} = Q_{H;ht;zi;mi} - \eta_{H;gn;zi;mi} \times Q_{H;gn;zi;mi} \tag{3.4}$$

Where,

$Q_{H;nd;zi;mi}$	monthly heating demand per calculation zone	kWh
$Q_{H;ht;zi;mi}$	total heat transfer per month per calculation zone	kWh
$\eta_{H;gn;zi;mi}$	dimensionless utilization factor for the heat gain	$dimensionless$
$Q_{H;gn;zi;mi}$	total heat gain for heating	kWh

According to Chapter 7 of NTA 8800, the total heating and cooling demand regarding four aspects: heat transfer through transmission, heat transfer through ventilation, internal heat gain, and solar heat gain. For each calculation space and each month, the formula can be expressed as:

$$Q_{H;ht;zi;mi} = Q_{H;tr;zi;mi} + Q_{H;ve;zi;mi} \tag{3.5}$$

Where,

$Q_{H;tr;zi;mi}$	total heat transfer through transmission for heating	kWh
$Q_{H;ve;zi;mi}$	total heat transfer through ventilation for heating	kWh

Heat transfer through transmission

Heat transfer through transmission can be calculated as the following equation:

$$\begin{aligned} Q_{H;tr;zi;mi} =& (H_{H;tr(excl);zi;mi}(\theta_{int;calc;H;zi;mi} - \theta_{e;ave;mi}) \\ &+ H_{g;an;zi;mi}(\theta_{int;calc;H;zi;mi} - \theta_{e;ave;an}))0.001t_{mi} \end{aligned} \tag{3.6}$$

in which,

$$H_{H;tr(excl);zi;mi} = H_{H;D;zi;mi} + H_{H;U;zi;mi} + H_{H;A;zi;mi} + H_{H;P;zi} \tag{3.7}$$

Where,

$H_{H;tr(excl);zi;mi}$	heat transfer coefficient excluding the ground floor	W/K
$H_{H;D;zi;mi}$	heat transfer coefficient between the heated space and the outside air	W/K
$H_{H;U;zi;mi}$	heat transfer coefficient through adjacent unheated spaces	W/K
$H_{H;A;zi;mi}$	heat transfer coefficient through adjacent heated spaces	W/K
$H_{H;P;zi}$	heat transfer coefficient via vertical pipes passing through the envelope	W/K
$\theta_{int;calc;H;zi;mi}$	calculation temperature of the calculation zone for heating	$^{\circ}C$
$\theta_{e;ave;mi}$	average outside temperature in month mi	$^{\circ}C$
$H_{g;an;zi;mi}$	heat transfer coefficient for elements regarding the ground floor	W/K
$\theta_{e;ave;an}$	average outdoor temperature for the entire year	$^{\circ}C$
t_{mi}	calculation value for the length of the considered month	h

The heat transfer coefficients through transmission take thermal bridges into consideration, for simplification, since thermal bridges contribute marginally to the total heat transfer, it is decided to neglect them in the calculations. Thus, the direct heat transfer coefficient of the envelope can be calculated as the following equation:

$$H_{H;D;zi;mi} = \sum_{i}(A_{T;i} \cdot U_{C;i}) \tag{3.8}$$

$A_{T;i}$	projected area of the flat element i of the external partition	m^2
$U_{C;i}$	heat transfer coefficient of the flat element i of the external partition	$W/(m^2 \cdot K)$

For a one-storey residential building, if it is unknown that whether a vertical pipe passes through the thermal envelope and directly connects to the outside air, one uninsulated fictitious vertical pipe per usage function is assumed. $H_{H;P;zi} = 1.8W/K$ is used for the study case based on the assumption and the table provided in the norm.

For floors above crawling spaces, or unheated basements, the heat loss coefficient can be calculated with a flat-rate settlement of the linear thermal bridges:

$$H_g = A_{fl} \times U_{fl} + 0.5P \tag{3.9}$$

Where,

A_{fl}	projected floor area	m^2
U_{fl}	heat transfer coefficient of the floor	$W/(m^2 \cdot K$
P	length of the perimeter	m

Heat transfer through ventilation

Heat transfer through ventilation can be calculated as the following equation:

$$Q_{H;ve;zi;mi} = H_{ve;zi;mi} \times (\theta_{int;calc;zi} - \theta_{e;avg;mi})0.001t_{mi} \tag{3.10}$$

Where,

$Q_{H;ve;zi;mi}$	total heat transfer through ventilation for heating	kWh
$H_{ve;zi;mi}$	total heat transfer coefficient through ventilation for heating	W/k

$$H_{ve;zi;mi} = \rho_a \cdot c_a \cdot \sum q_{v;k;H:zi;mi} \cdot b_{v;k;H;zi;mi} \cdot f_{v;dyn;k;zi;mi}/3600 \tag{3.11}$$

ρ_a	density of air	$1.205kg/m^3$
a	specific heat capacity of air	$1005J/kgK$
$b_{v;k;H;zi;mi}$	supply temperature correction factor for air volume flow k	$dimensionless$
$f_{v;dyn;k;zi;mi}$	dynamic correction factor for air volume flow k	$dimensionless$
$q_{v;k;H:zi;mi}$	air volume flow k	m^3/h

For natural supply system, the supply temperature correction factor equals 1. In the same way, the effective incoming airflow equals to the required airflow of outside air, as in equation below:

$$q_{v;eff;in;zi;mi} = \sum_{path;i;zi} C_{path;i} \times |\Delta P_{path;i;mi}|^n \tag{3.12}$$

Where,

$q_{v;eff;in;k;zi;mi}$	effective incoming airflow k	m^3/h
$C_{path;i}$	air permeability coefficient of opening i	$m^3/h(Pa)^n$
$\Delta P_{path;i;mi}$	pressure difference across opening i	Pa
n	flow exponent of opening i	$dimensionless$

$$\Delta P_{path;i;mi} = P_{e;path;i;zi;mi} - P_{z;path;i;zi;mi} \tag{3.13}$$

$$P_{e;path;i;zi;mi} = \rho_{a;ref} \cdot \frac{T_{e;ref}}{\theta_{e;avg;mi} + 273} \cdot (0.5 \cdot C_{p;,i} \cdot u^2_{site;mi} - H_{path;i} \cdot g) \tag{3.14}$$

$$P_{z;path;i;zi;mi} = P_{z;ref;mi} - \rho_{a;ref} \cdot H_{path;i} \cdot g \cdot \frac{T_{e;ref}}{T_{int;set;zi}} \tag{3.15}$$

$$P_{z;ref} = P_{z;path;gem;zi;mi} + \rho_{a;z} \times H_{path;lea} \times g \tag{3.16}$$

$$T_{int;set;zi} = \theta_{int;set;stc} + 273 \tag{3.17}$$

Where,

$P_{e;path;i;zi;mi}$	external pressure at air volume flow i	Pa
$P_{z;path;i;zi;mi}$	internal pressure at air volume flow i	Pa
$P_{z;ref;mi}$	internal reference pressure in month mi	Pa
$\rho_{a;ref}$	density of air at sea level, at 293 K and dry air	$1.205 kg/m^3$
$C_{p;i}$	wind pressure coefficient	$dimensionless$
$u_{site;mi}$	wind speed at the height of the calculation zone	m/s
$H_{path;i}$	height of the opening	m
g	acceleration of gravity	$9.81 m/s^2$
$T_{e;ref}$	reference outdoor temperature	$293K$
$T_{int;set;zi}$	normal heating temperature set point	K
$\theta_{int;set;stc}$	setpoint temperature for heating	$^\circ C$

For accommodation functions, the setpoint temperatures for thermally conditioned zones for heating and cooling are 21 $^\circ C$ and 24 $^\circ C$ respectively.

3.3.2. Heat gain

The total heat gain for heating can be calculated as:

$$Q_{H;gn;zi;mi} = Q_{H;int;zi;mi} + Q_{H;sol;zi;mi} \tag{3.18}$$

Where,

$Q_{H;int;zi;mi}$	total internal heat gain for heating	kWh
$Q_{H;sol;zi;mi}$	total solar gain for heating	kWh

Internal heat gain

Internal heat gain can be calculated as the following formula:

$$Q_{H;int;dir;zi;mi} = 180 \cdot N_{living;zi} \cdot N_{p;living;zi} \cdot 0.001 \cdot t_{mi} \tag{3.19}$$

In which,

$$A_g/N_{living;zi} <= 30m^2 : N_{p;living;zi} = 1 \tag{3.20}$$

$$30 < A_g/N_{living} <= 100m^2 : N_{p;living;zi} = 2.28 - \frac{1.28}{70} \times (100 - A_g/N_{living;zi}) \tag{3.21}$$

$$A_g/N_{living} > 100m^2 : N_{p;living;zi} = 1.28 + 0.01 \times A_g/N_{living} \quad (3.22)$$

Where,

$Q_{H;int;dir;zi;mi}$	internal heat gain for heating	kWh
$N_{living;zi}$	number of residential functions in calculation zone	NA
$N_{p;living;zi}$	average number of residences per	NA
A_g	usable area of the considered calculation zone	m^2

Solar heat gain

Solar heat gain from transparent part and non-transparent part is respectively calculated as below:

$$Q_{H;sol;zi;mi} = \sum Q_{H;sol;wi;k;mi} + \sum Q_{H;sol;op;k;mi} \quad (3.23)$$

Where,

$Q_{H;sol;zi;mi}$	monthly solar gain of the calculation zone	kWh
$Q_{H;sol;wi;k;mi}$	monthly solar heat gain by transparent element	kWh
$Q_{H;sol;op;k;mi}$	monthly solar gain by non-transparent element	kWh

The solar incidence through transparent and non-transparent elements is respectively calculated as below:

$$Q_{H;sol;wi;k;mi} = g_{gl;wi;k;H;mi} \cdot A_{wi;k} \cdot (1 - F_{fr;wi;k}) \cdot F_{sh;obst;wi;k;mi} \cdot I_{sol;wi;k;mi} \cdot 0.001 \cdot t_{mi} - Q_{sky;wi;k;mi} \quad (3.24)$$

Where,

$g_{gl;wi;k;H;mi}$	average effective total solar gain factor	$dimensionless$
$A_{wi;k}$	area of window	m^2
$F_{fr;wi;k}$	frame fraction of window	$dimensionless$
$F_{sh;obst;wi;k;mi}$	shading reduction factor for external obstacles	$dimensionless$
$I_{sol;wi;k;mi}$	monthly average total solar radiation per area of the window	W/m^2
$Q_{sky;wi;k;mi}$	monthly extra heat flow due to heat radiation to the sky	kWh

The total solar gain factor (corrected for the angle of incidence) is determined as:

$$g_{gl;wi} = F_w \cdot g_{gl;n;wi} \quad (3.25)$$

Where,

F_w	correction factor for non-diffusing glazing	$dimensionless$
$g_{gl;n;wi}$	sun exposure factor at perpendicular incidence of solar radiation	$dimensionless$

The correction factor of 0.90 is applied based on NTA 8800, and the sun exposure factor is determined according to Table 3.2 from the norm.

$$Q_{H;sol;op;k;mi} = \alpha_{sol} \cdot R_{se} \cdot U_{c;op;k} \cdot A_{c;op;k} \cdot F_{sh;obst;op;k;mi} \cdot I_{sol;op;k;mi} \cdot 0.001 \cdot t_{mi} - Q_{sky;op;k;mi} \quad (3.26)$$

Type	$g_{gl;n}$
Single glass	0.85
Double glass	0.75
Double glazing with spectrally (low) selective and low-emissivity coating (HR++)	0.60
Triple glass without or with one spectrally (low) selective and low-emmisivity coatings	0.50
Triple glass with two spectrally (low) selective and low-emissivity coatings	0.40
Single glass with single glass front window or rear window without coating	0.75

Table 3.2: Fixed values for the total solar ingress factor at perpendicular incidence, $g_{gl;n}$, for common types of glazing

Where,

α_{sol}	absorption coefficient for solar radiation	$dimensionless$
R_{se}	heat transfer resistance on the outside	m^2K/W
$U_{c;op;k}$	heat transfer coefficient of non-transparent element	$W/(m^2K)$
$A_{c;op;k}$	projected area of non-transparent element	m^2

4

Tool Development

A tool is developed as said in section Deliverable to testify the method based on NTA 8800.The tool is built within a limited scope, and applies for residential buildings. The aim of the method is to support the sustainability-related decision-making in early design stage by on-the-fly energy calculation.

This chapter will demonstrate how the tool is developed. The basic workflow of the tool will be explained. Then the energy calculation equations used in the tool will be shown. Besides the functions, the tool's user interface will also be displayed. The Grasshopper script is attached in the Annex A. Lastly, the limitations and future improvements of the tool will be given.

4.1. Workflow

The tool is developed in Rhino/Grasshopper, aided with GHPython, which is the Python interpreter component for Grasshopper. The tool operates three main activities for the user: first, it receives elements from Revit to Rhino/Grasshopper; secondly, it calculates the energy based on equations in NTA 8800, and wraps the results into a report; thirdly, it provides the possibilities to analyze the results and adjust the geometry in Revit.

The iterative workflow is demonstrated in a flowchart as shown in Figure 4.1. The yellow shapes represent the actions or files by the user, while the blue shapes represent the developed tool and terminators. Designers start from creating a 3D model for their building, then open the designed tool inside Revit and Rhino/Grasshopper to import the Revit model. In the Figure 4.1, the rounded box on the left zoomed in the functions of the designed tool. The tool receives the 3D model, calculates energy demand for the building based on NTA 8800, and gives the results, namely the energy demand indicator. Having received the results, the designer can evaluate the energy performance by themselves, and decide if the desired requirements are satisfied. If not, the designer can modify the model and repeat the operations above to improve the energy performance.

Compared to the IFC-based method, where the designer needs to set IFC export options, export the IFC file, and import the IFC into the calculating software, the manual procedure is simplified by skipping these steps.

4.1.1. Preliminary Requirements

The developed Grasshopper tool requires preliminary preparation from the Revit model, apart from the input data needed. Designer might need to have basic knowledge about Revit or have a well-built Revit model to obtain useful results. To be specific, first, designer needs to create Rooms in Revit to define calculation zones. The developed tool can generate a report including the results and the input parameters so that designers is allowed to inspect if the parameters are correct and reasonable.

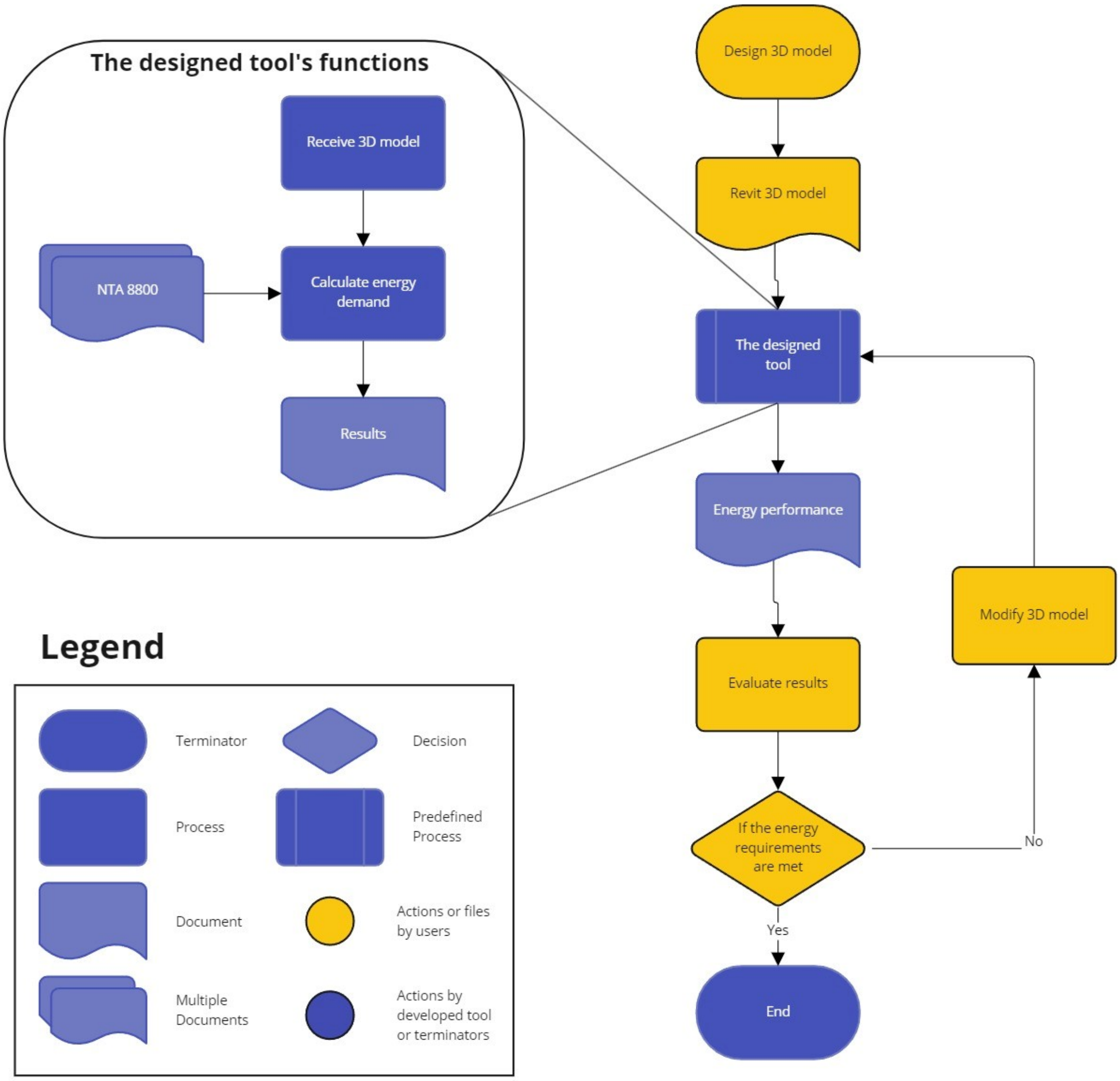


Figure 4.1: Workflow of the designed tool’s functionality

4.1.2. Scope Limitations

The developed tool is designed to analyze energy use for buildings with limited conditions. Firstly, the tool considers residential buildings, as it is a common building type. The typical Dutch houses built directly on the ground will be focused on. For the sake of simplicity, a single calculation zone of each building is considered. Besides, the linear and point thermal bridges are neglected both in the developed script and Uniec 3, by minimizing the length of thermal bridges to 0.01m in Uniec 3.

NTA 8800 is a comprehensive document which is designed for extreme accuracy in energy use. The developed tool makes assumptions when calculating the temperature and air volume in order to balance the accuracy and complexity.

4.1.3. Tool Script

The energy calculation based on the Dutch norm document NTA 8800 is divided into several parts according to Figure 3.8. This section will elaborate on the scripting process in Grasshopper.

The Grasshopper script is presented in 4.2. From the Grasshopper script, it is divided into five main groups to derive the final energy demand indicator Ewe. The groups will be introduced from left to right and from top to bottom, starting form the categories. Each group has a scribble text besides it to indicate its functions.

The categories sort out all elements by their family in Revit. NTA 8800 provides fixed values for temperatures and month lengths, which are designed into look-up tables in the script using GHPython. In the block of element properties, various parameters including dimensions, thermal transmittance values, and specific factors are retrieved from the elements by categories and are used for the subsequent computations. The next group is in charge of executing the calculation based on the equations from the Dutch norm, which is split into four clusters responsible for transmission, ventilation, internal heat gain, and solar radiation. The final step is to obtain the indicator Ewe by processing the results of energy demand. Apart from the energy calculations, the script also has a button on the left top for users. By clicking the button after the calculation, it pops up an Excel report listing the parameters and the final results. The Grasshopper components are clustered for a clear overview, and a more detailed explanation of the script and the codes can be found in the Annex A.

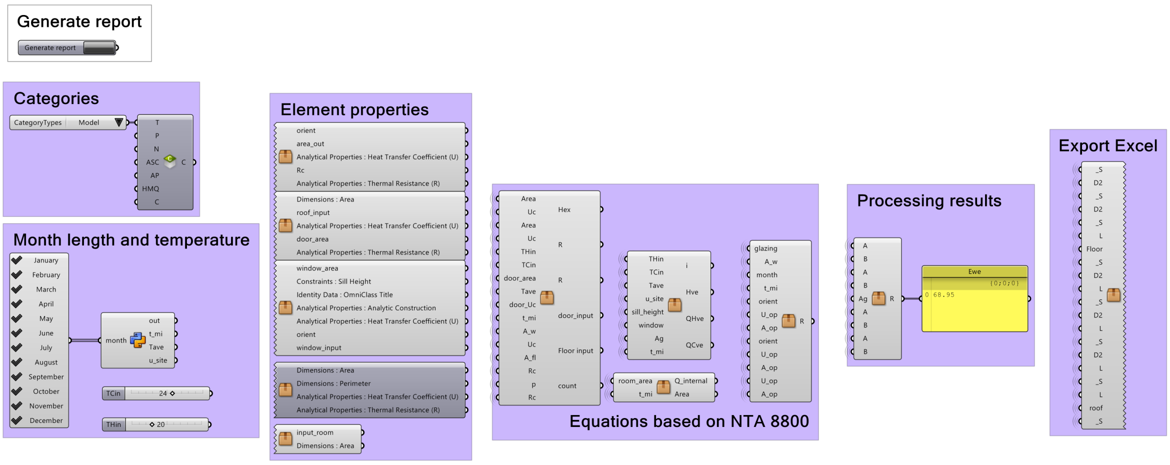


Figure 4.2: Grasshopper script of the developed tool

4.2. Implementation

The implementation of the developed tool needs to be based and tested on a Revit model. According to the scope limitation of the tool, a tiny timber house inspired by the IKEA house has been used to develop and verify the framework, as shown in Figure 4.3. The tiny house serves as a residential building located in the Netherlands.

First, the model has been built in Revit, and the required parameters, including geometric and energy-related parameters have been defined. The total area is 15 m^2, and the measurements of the floor plan are shown in Figure 4.6 to 4.8. The front door and the back side of the tiny house in 3D views are presented below, in Figure 4.4 and 4.5. The envelope including the roof and the floor of the tiny house are mainly made of timber material for lightweight. The tiny house is in contact with the ground directly. The door in the front is facing north, together with two large windows. Another two windows are facing south and one facing east. The thermal properties are assumed for the envelope, including the U-value of the windows and the door, and the Rc-Value for the opaque elements. The input data is listed in the table 4.1 below.

4.2.1. Uniec 3

To test if the developed tool is generating meaningful data, the result needs to be validated. The validation of the energy assessment model has various methods, including analytical solutions, empirical data, and peer models (Ryan & Sanquist 2012). The energy use of the tiny timber house has been used for validation by means of comparing it with a certificated energy calculation tool, Uniec 3.

Figure 4.3: IKEA tiny home

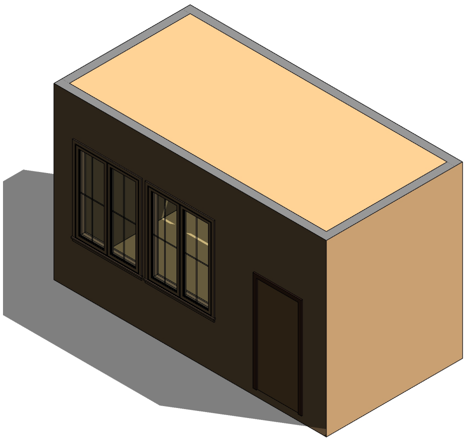


Figure 4.4: Front door of the tiny house

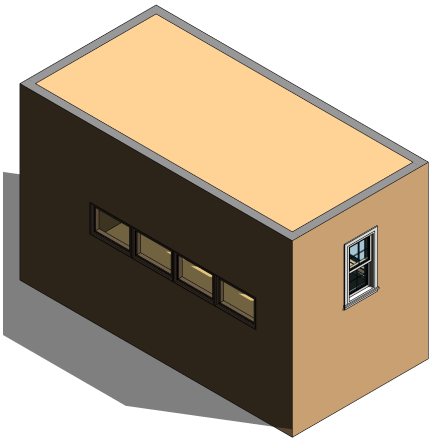


Figure 4.5: Back side of the tiny house

Uniec 3 is a cloud-analyzing software based on the norm NTA 8800 that calculates the energy performance of buildings. The functions of Uniec 3 regarding the validation include: creating a calculation zone for the house; filling out the architectural library, defining building envelop; adding installations; and calculating the energy demand.

First, the building type needs to be defined, the user may choose from land-bound houses, apartment buildings, individual apartments, vacation houses, caravans, and houseboats. The timber house is designed as a land-bound timber building, so the first option is taken. Besides, the basic input approach instead of the detailed input approach is determined to keep it consistent with the designed framework. The main difference between the two approaches is if the thermal bridges are defined precisely or the fixed value is used. The thermal bridges have been neglected in both the Grasshopper script and Uniec 3.

The architectural library of all building elements used in the project is built. First, the opaque area is defined, specifically the roof, the exterior walls, and the ground floor. Windows, panels, and doors are sorted in transparent construction, and the U-values, solar gain factors, and areas are required for each element.

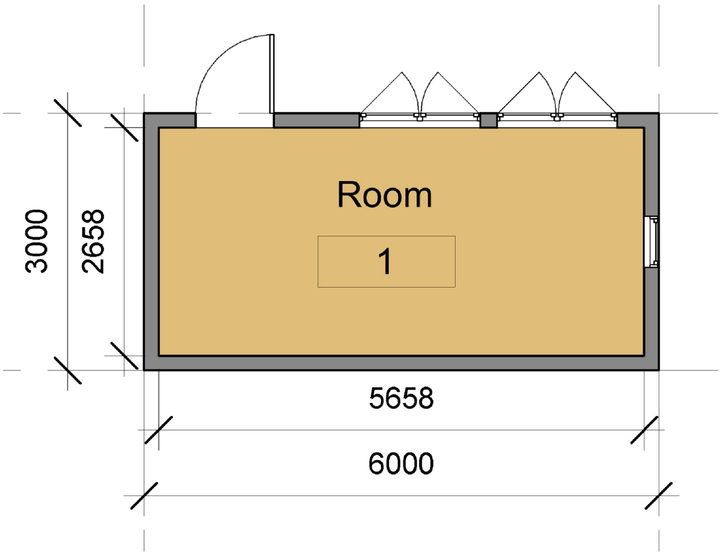


Figure 4.6: Measurements of the floor plan

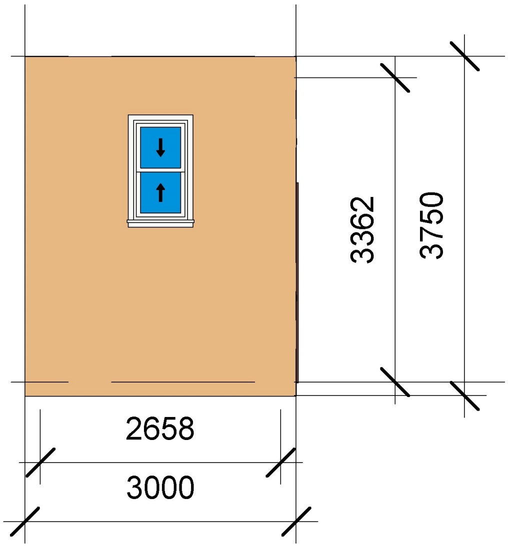


Figure 4.7: Measurements of the east facade

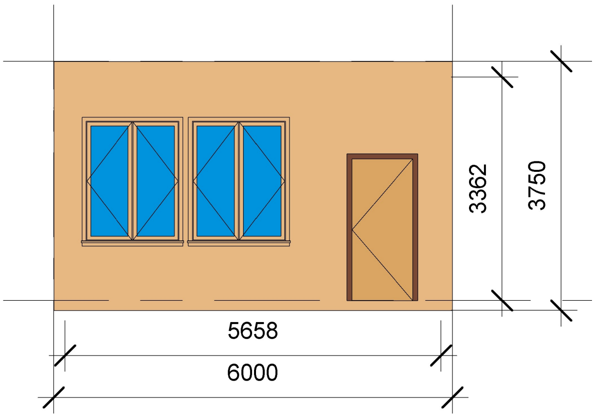


Figure 4.8: Measurements of the north facade

Element	Parameter	Value	Unit
Calculation zone	Total area	15.04	m^2
Floor	Area	15.04	m^2
	Perimeter	16.63	m
	Rc	4.91	m^2K/W
	U	0.20	$W/(m^2K)$
Wall	Area (N)	22.50	m^2
	Opaque area (N)	15.51	m^2
	Area (S)	22.50	m^2
	Opaque area (S)	20.27	m^2
	Area (E)	9.97	m^2
	Opaque area (E)	9.31	m^2
	Area (W)	9.97	m^2
	Opaque area (W)	9.97	m^2
	Rc	4.12	m^2K/W
	U	0.24	$W/(m^2K)$
Door	Area	1.95	m^2
	Rc	0.59	m^2K/W
	U	1.70	$W/(m^2K)$
Window (N)	Area	2.52	m^2
	Sill height	0.90	m
	g_{gl}	0.75	-
	U	3.10	$W/(m^2K)$
Window (S)	Area	0.56	m^2
	Sill height	1.50	m
	g_{gl}	0.75	-
	U	3.70	$W/(m^2K)$
Window (E)	Area	0.66	m^2
	Sill height	1.80	m
	g_{gl}	0.75	-
	U	3.10	$W/(m^2K)$
Roof	Area	15.04	m^2
	Rc	5.58	m^2K/W
	U	0.18	$W/(m^2K)$

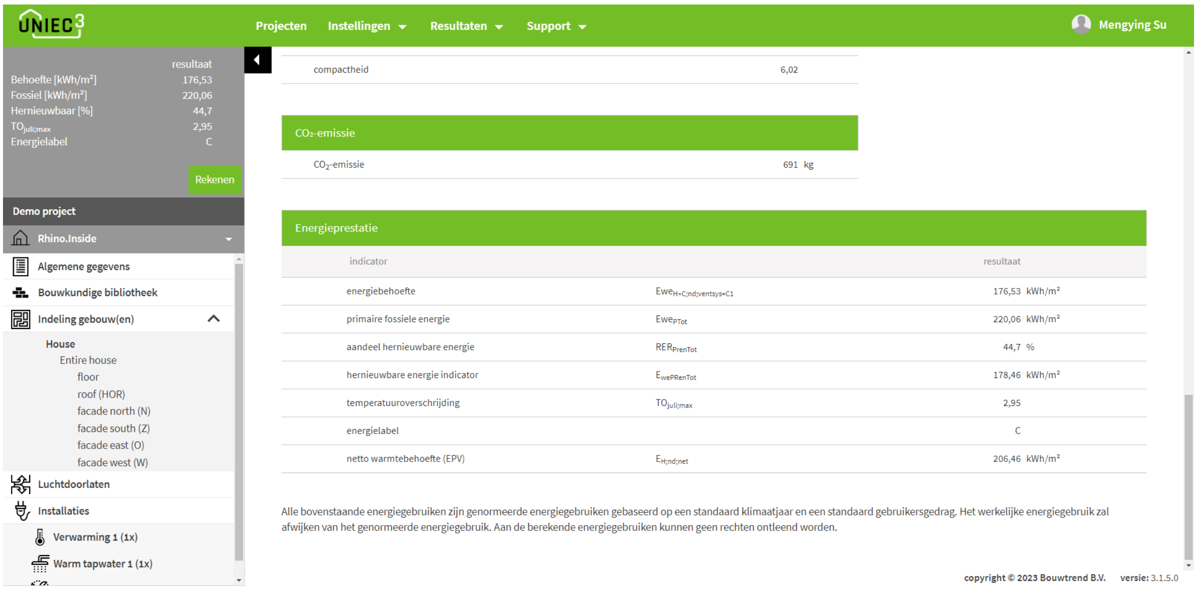
Table 4.1: Input data used in the case study

Defining the building envelope, or defining the building layout, is to assemble the elements stored in the architectural library that have been built earlier. In other words, the windows and the doors created in the architectural library need to be placed on the envelope. In general, the tiny house is a timber frame structure with a timber floor and an individual flat roof, differing from townhouses with continuous roofs which has adjacent areas. The assembling of the elements is operated surface by surface. Minimum shading is applied to all the windows.

Another important parameter is ventilation. It involves infiltration and vertical pipes in direct connection with outside air. Default values are taken for both parameters since in most cases at an early stage, these values are assumed.

The final step before it comes into calculation is applying the installations. At least one heating system, warm tap water, and one ventilation system for the entire house are required, as the tiny house is mechanically discharged. After tests over different data inputs, it is noted that, although the information about the installations must be filled in to continue computing, it does not have an impact on the energy demand indicator, which is the main indicator for this paper, and only influences fossil fuels and renewable energy, referring to BENG 2 and BENG 3.

Having followed the steps above, Uniec 3 can start computing. The results include energy performance



	resultaat
Behoefte [kWh/m²]	176,53
Fossiel [kWh/m²]	220,06
Hernieuwbaar [%]	44,7
$TO_{juli;max}$	2,95
Energielabel	C

compactheid	6,02

CO_2-emissie

CO_2-emissie	691 kg

Energieprestatie

indicator		resultaat
energiebehoefte	$Ewe_{H+C;nd;ventsys=C1}$	176,53 kWh/m²
primaire fossiele energie	Ewe_{PTot}	220,06 kWh/m²
aandeel hernieuwbare energie	$RER_{PrenTot}$	44,7 %
hernieuwbare energie indicator	$E_{wePRenTot}$	178,46 kWh/m²
temperatuuroverschrijding	$TO_{juli;max}$	2,95
energielabel		C
netto warmtebehoefte (EPV)	$E_{H;nd;net}$	206,46 kWh/m²

Alle bovenstaande energiegebruiken zijn genormeerde energiegebruiken gebaseerd op een standaard klimaatjaar en een standaard gebruikersgedrag. Het werkelijke energiegebruik zal afwijken van het genormeerde energiegebruik. Aan de berekende energiegebruiken kunnen geen rechten ontleend worden.

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Figure 4.9: The results page of Uniec 3

	$Ewe[kWh/m^2]$	$H_H; vent[W/K]$	$H_H; trans[W/K]$
GH script	171.19	43.71	45.28
Uniec 3	176.53	41.39	44.56

Table 4.2: The energy demand indicator, heat transfer coefficients of the tiny timber house

regarding BENG regulations and TOjuly regarding overheating in summer. As stated before, the energy demand indicator Ewe will be compared to the result from the developed framework.

4.2.2. Results

The results are shown in forms of numbers from a panel in Grasshopper script and can be exported as Excel file with parameters, as displayed in Figure 4.2 and Figure 4.10. The outcome of Uniec 3 is presented in Figure 4.9. Key factors of both tools have been listed in Table 4.2 for comparison.

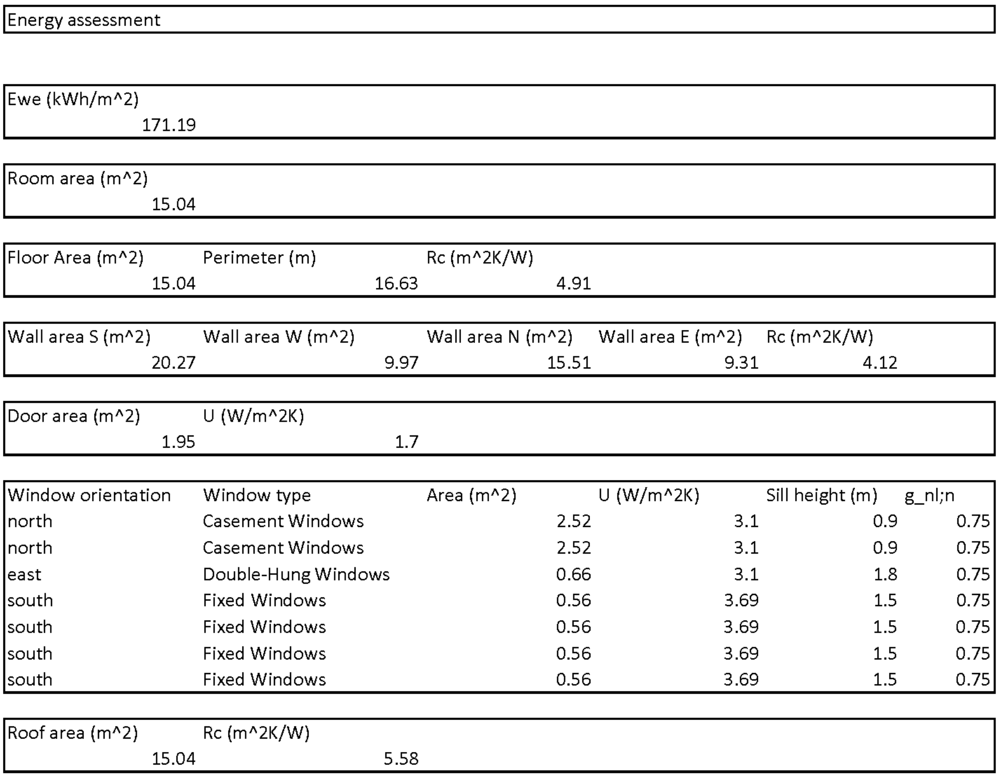
The difference between the results from Uniec 3 and the developed framework is 3%, which is a good outcome. Besides, the table lists the heat transfer coefficient calculated for transmission and ventilation for heating, as the heating demand is dominant and representative.

Figure 4.11 plots the heat loss through transmission for each month over a year, in which the blue line stands for Uniec 3 results, and the yellow line stands for the Grasshopper script results, the same also applies for the following graphs. The heat losses through transmission converge in July and August and diverge in January. Figure 4.12 plots the heat loss through ventilation. It is noted that in February it shows a different trend. In other months, the heat losses are almost the same.

Figure 4.13 plots the internal heat gain of the tiny house. The results are identical as it involves less complex parameters. Another heat gain source is plotted in Figure 4.14, which shows a relatively large difference compared to other heat transfer means. The Grasshopper script gets larger solar radiation energy each month.

Apart from four heat calculation sections, the temperature used for computing heating demand is worth paying attention to due to the adoption of simplified methods, which is plotted in Figure 4.15. The temperature participates the computation of transmission and ventilation part. From the figure, it can be seen that the average temperatures are close, though the curve of Grasshopper script is more flat.

In general, the results of the Grasshopper script are quite similar to Uniec 3 in each aspect. Despite the



Energy assessment

Ewe (kWh/m^2)
171.19

Room area (m^2)
15.04

Floor Area (m^2)	Perimeter (m)	Rc (m^2K/W)
15.04	16.63	4.91

Wall area S (m^2)	Wall area W (m^2)	Wall area N (m^2)	Wall area E (m^2)	Rc (m^2K/W)
20.27	9.97	15.51	9.31	4.12

Door area (m^2)	U (W/m^2K)
1.95	1.7

Window orientation	Window type	Area (m^2)	U (W/m^2K)	Sill height (m)	g_nl;n
north	Casement Windows	2.52	3.1	0.9	0.75
north	Casement Windows	2.52	3.1	0.9	0.75
east	Double-Hung Windows	0.66	3.1	1.8	0.75
south	Fixed Windows	0.56	3.69	1.5	0.75
south	Fixed Windows	0.56	3.69	1.5	0.75
south	Fixed Windows	0.56	3.69	1.5	0.75
south	Fixed Windows	0.56	3.69	1.5	0.75

Roof area (m^2)	Rc (m^2K/W)
15.04	5.58

Figure 4.10: The Excel report of the results and parameters by the developed tool

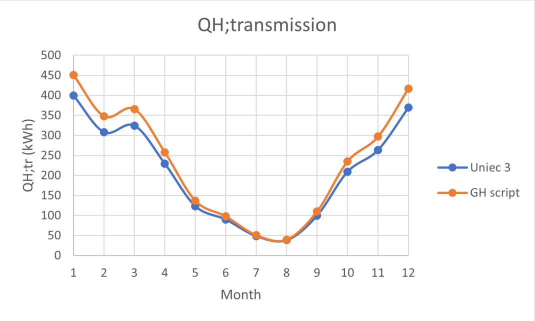


Figure 4.11: Comparison of heat transfer through transmission

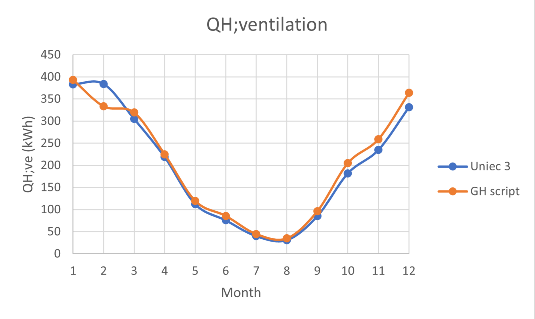


Figure 4.12: Comparison of heat transfer through ventilation

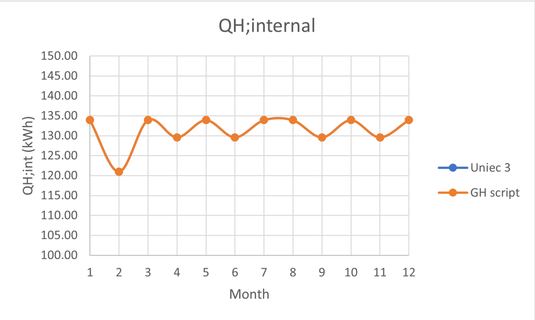


Figure 4.13: Comparison of heat transfer through internal heat gain

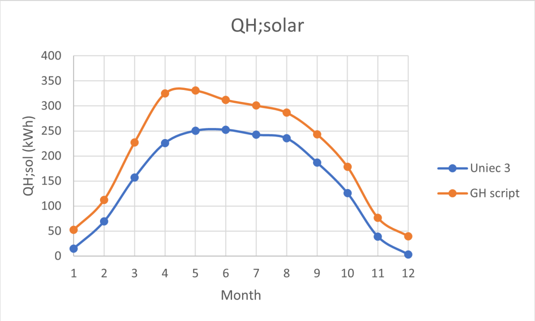


Figure 4.14: Comparison of heat transfer through solar radiation

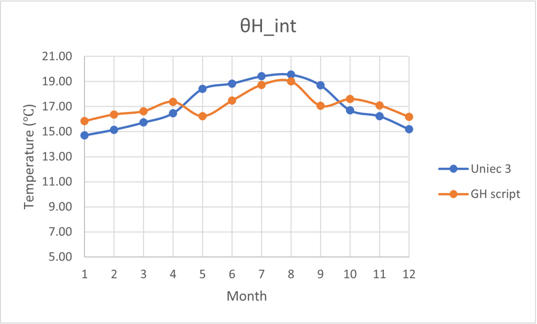


Figure 4.15: Comparison of heat calculation temperature

several difference mentioned above, the developed tool produces results that follows the same logic of Uniec 3. Therefore, the tiny timber house as a preliminary case study has validated the developed tool based on NTA 8800 produces meaningful results compared to Uniec 3.

5

Validation

Two case studies have been conducted to validate the developed tool and answer the following questions:

1. Does the developed tool provide meaningful results of data for the designers?
2. Is the adoption of the developed tool superior in terms of time-saving and simplicity?

The case studies consider both horizontal and vertical contrast to verify if the developed script produces robust (case study 1) and logical (case study 2) results. Case study 1 considers horizontally the geometric parameters while the materials of the envelope remain the same. Case study 2 considers vertically the connection of how the window-to-wall ratio and the window U value influence energy use.

This chapter include two case studies, and each case study will commence by presenting the introduction to the variants of the case studies to understand the configuration of the variants. Next, the energy use of the variants will be examined by both the developed tool and Uniec 3. The results will be presented and analyzed in contrast to the tiny timber house.

5.1. Case Study 1

Two variants are randomly generated in Revit, aiming to verify if the developed tool produces reliable energy results while magnifying the sizes of the building. Figure 5.1 and 5.2 present the geometry of the two variants.

5.1.1. Configurations

In addition to the geometric parameters of the envelope, the variants adopt identical materials and thermal properties. The location of the windows and doors is randomized on the buildings. The dominant factor of case study 1 is the size of the building, which is compared in Table 5.1.

Variants	Ag $[m^2]$	Total wall area $[m^2]$
Tiny house	15.04	75.08
Variant 1	242.44	329.16
Variant 2	168.83	258.01

Table 5.1: Geometric data of the variants of case study 1

5.1.2. Results

The energy use of the two variants have been assessed by the developed tool and Uniec 3, in Table 5.2. The difference of variant 1 is 1.14%, and the difference of variant 2 is 2.29%, and both are smaller than the tiny house. In terms of question 1, the developed tool is able to produce meaningful results

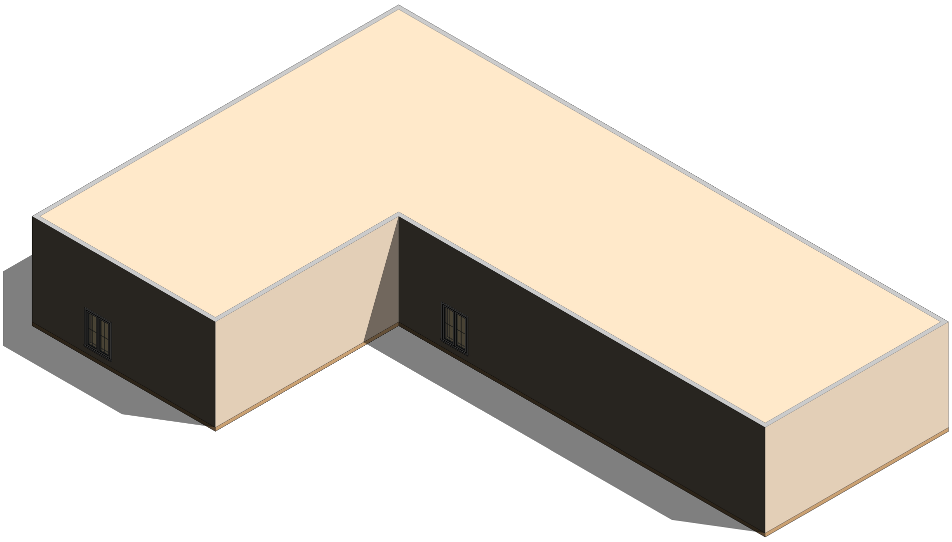


Figure 5.1: Geometric 3D view of variant 1

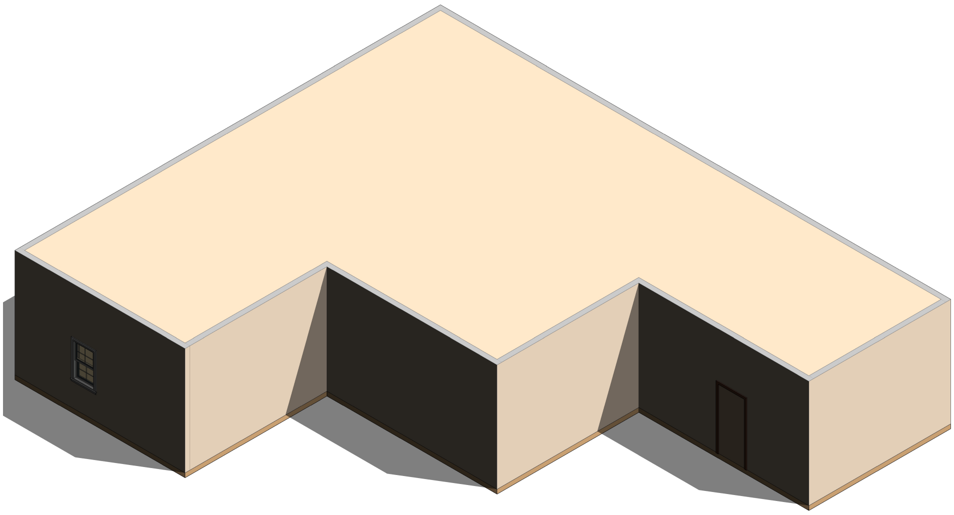


Figure 5.2: Geometric 3D view of variant 2

with various dimensions.

Variants	Tool result	Uniec 3 result	Comparison
Tiny house	171.19 kWh/m^2	176.53 kWh/m^2	-3.02%
Variant 1	68.95 kWh/m^2	68.17 kWh/m^2	1.14%
Variant 2	66.27 kWh/m^2	67.82 kWh/m^2	-2.29%

Table 5.2: Energy use indicator of the variants of case study 1

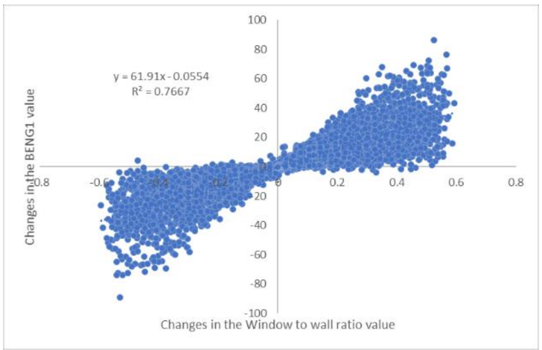


Figure 5.3: Changes in the BENG1 value from changes in the value of window to wall ratio (Kafaei 2021)

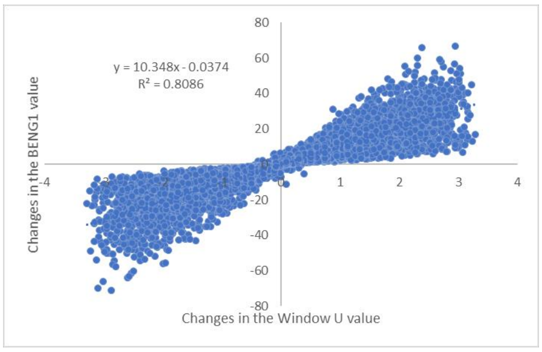


Figure 5.4: Changes in the BENG1 value from changes in the value of window U (Kafaei 2021)

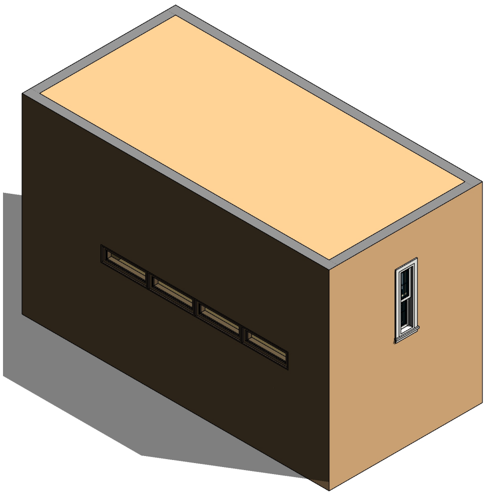


Figure 5.5: Geometric 3D view of variant 3

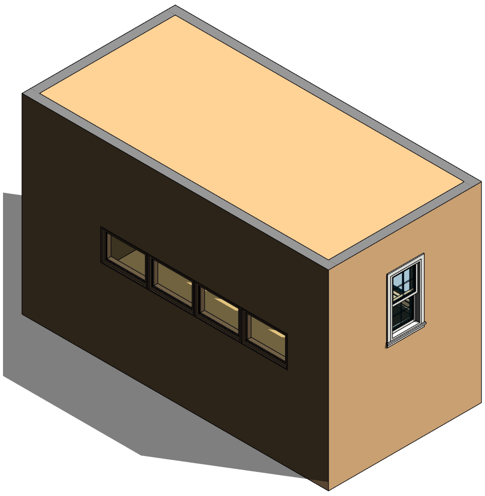


Figure 5.6: Geometric 3D view of variant 4

5.2. Case Study 2

Various scenarios are considered to validate the developed tool's robustness. According to the sensitivity analysis by Kafaei (2021), the first level of priority which influences the energy performance the most includes ”Compactness (Als/Ag)”, ”Window to wall ratio”, ”Window U”, and the ”Infiltration rate”. The changes in Ewe value from changes in the value of window-to-wall ratio and window U value are shown in Figure 5.3 and 5.4, and they are both positively associated. This indicates that, by decreasing the window size or window U value will result in lower Ewe value. Since the tiny house has windows on three walls, the compactness can not be verified without changing the window-to-wall ratio. In addition, the infiltration rate is unknown and the fixed value is used. So the window-to-wall ratio and the window U-value are decided to use for the validation.

5.2.1. Configurations

Based on the tiny house, two scenarios are considered: first, the window sizes are reduced to 0.5 times the original ratio; second, the window U-values are reduced to 0.5 times the original U-values. The 3D views of variant 3 and 4 are presented in Figure 5.5 and 5.6.

5.2.2. Results

The tiny house and the two variants are tested both in the developed tool and Uniec 3, and the results are shown in Table 5.3. The difference of variant 3 is 5.50%, and the difference of variant 4 is 4.20%. Although the changes of variant 3 and 4 are slightly larger than the changes of variant 1 and 2, the results can be considered effective for following the logic according to the sensitivity study.

Ewe Results	Developed tool	Uniec 3	Difference	Notes
Case study	171.19 kWh/m^2	176.53 kWh/m^2	-3.02%	
Variant 3	134.20 kWh/m^2	127.20 kWh/m^2	5.50%	Window size / 2
Variant 4	153.03 kWh/m^2	159.80 kWh/m^2	-4.20%	Window U / 2

Table 5.3: Results of variants and comparison (kWh/m^2)

According to case study 2, the developed tool provides designers with meaningful data in terms of the rule of physics or energy. In addition, the adoption of the developed tool takes a few seconds to produce results, while Uniec 3 requires minutes to hours to manually fill in the project in detail. In conclusion, the two questions of the case studies have been answered.

6

Discussion

This thesis aims to develop a framework for BIM model to energy assessment to optimize the energy performance of buildings. Thus, the thesis has developed a tool in order to improve the efficiency of energy assessment, aided with a visual programming tool. The calculation method of the developed tool is based on NTA 8800, the Dutch energy determination document. Although there are various energy assessing software on the market, the design process can hardly take good advantage of them. With the developed tool, it is convenient and efficient to combine energy analysis with building design to cut out unnecessary or repetitive work.

Two case studies combined with a preliminary study have been conducted to validate the developed framework and its demonstration tool. The results are in good shape, by having averagely less than 5% difference compared to Uniec 3. The application of the developed Grasshopper script shortens the time, making the process more efficient.

The preliminary case study adopted a tiny timber house model from IKEA, to implement the Grasshopper script. The results are presented and compared part by part. In addition to the internal heat gain, other energy calculations slightly offset. There are possible reasons behind it. First, the temperature for heating is calculated with simplified steps, as a result, the temperature differs from that of Uniec 3 in each month, but in general, the average temperature remains quite similar, which shows little influence on the annual energy demand indicator. Another difference comes from the solar heat gain. In Uniec 3, it is assumed that every window has a minimum shading, while it is not included in the Grasshopper script. Besides, the monthly extra heat flow due to heat radiation to the sky from the window, which should be taken off from the total solar radiation, is also neglected in the Grasshopper script. Other errors might be caused by simplification of the calculation methods or human error.

The case study 1 and 2 are designed to further validate the robustness and accuracy of the tool. In case study 1, two variants with larger dimensions compared to the tiny house are tested in the script. The results of both variants are close to Uniec 3 results, and are even smaller than the tiny house. This could be due to the relatively small window-to-wall ratio, which has been tested to have an positive relation with Ewe value according to Kafaei (2021). The case study 2 is designed to verify the script in a logical way. The window sizes and window U values are reduced respectively for variant 3 and 4. In contrast to case study 1, it presents a bit more difference than the preliminary case. Although the results are corresponding to the sensitivity study and the rule of thumb, the increase of difference suggests there could be optimized to improve the accuracy.

Above that, the decrease in energy demand indicates that by using the developed tool and modifying the model, the energy efficiency is optimized. Both studies presented the efficiency using the developed script for saving time and workload. By removing the step of manual modifications, it increases productivity and avoids human errors as much as possible. The improvement in the aspect of efficiency is significant. By testing, it has found that filling out the necessary data required by Uniec 3, mentioned in Section 4.2.1, needs minutes to hours, let alone the double checks and the modifications. While the developed tool requires nearly zero manual input or adaptations, which allows it to take less than seconds to assess the energy demand. In Uniec 3, only if the user has all the required values and fills out all data following the steps, can the user view the final results. While using the designed framework, the user may see the results in real-time.

As stated before, the framework and its tool have scope limitations that allow them to be applied under certain circumstances in current stage. The framework is designed to link the BIM software and the energy assessment tool, and help designers on energy optimization in the early design stages. The framework integrates Revit models and Grasshopper script to realize on-the-fly energy assessment by virtue of Rhino.Inside. The plug-in limits the choice on the BIM software and the energy assessment tool. In addition, the proposed framework works best with steady-state energy analysis in the early stage. Because the dynamic analysis requires much more parameters from the BIM model, it will significantly increase the workload of preparing the BIM model, and this will result in inefficiency in reverse.

According to Kheiri (2018), the criteria to evaluate energy assessment tools include robustness, accuracy, and efficiency. The robustness refers to that the methods should perform reasonably well for the acceptable range of values. The definition of accuracy is that the optimization method should be able to optimize the problem within the desired accuracy. The efficiency lays in computational time and the memory required for the problem

The robustness and the accuracy of the developed tool can be guaranteed according to the results of the case studies. Opposite to the manual input in Uniec 3, the tool adopted Grasshopper to acquire information directly from the Revit model and reduced data error caused by manual record. Besides, the difference between the two assessment tools holds mostly within 5%, which is adequate for the early design stage.

The developed tool as a demonstration for the framework, has its limitations as well. Other than the overall constraints of the framework, the developed tool is limited to residential building type and works best for land-bound houses. The tool is focusing on BENG 1, based on the Dutch norm NTA 8800, and adopts a simplified equations. However, the simplification of the equations may result in inaccuracy of the outcome. This can be a trade-off between accuracy and simplicity for future development.

There are improvements can be made to the developed tool. Firstly, the visualization of the model in Uniec 3 will make it more user-friendly. A dashboard with input data or a preview of the model allows users to quickly check the parameters, and have intuitive impressions of the model. In general, this thesis only responds to BENG 1 based on the Dutch norm NTA 8800, specifically the energy demand indicator Ewe. It might be developed to include the whole NTA 8800, or to include more indicators and various criteria or regulations in the future.

Challenges in performing energy calculations reflect in several aspects. First, the data transfer from Revit to Grasshopper can be more complicated in case of a large project with complex buildings. Therefore, a report is generated after the assessment to verify the energy demand indicator and the input parameters. What's more, the norm NTA 8800 is a comprehensive document, and it is complex to develop an energy analyzing tool based on it during the thesis project. Thus, the developed tool has simplified the calculating process in several equations. These have made the difference of the results between the developed tool and Uniec 3.

Above all, the developed tool is so far aimed at early-stage designs. The on-the-fly energy assessment for the late design stages is still a challenge. It requires more considerations and a large amount of workload to accommodate the increased information. Future work can be done for exploring the boundary of energy designs to better serve the goal of energy efficiency.

7

Conclusions

This chapter will conclude the thesis by summarizing the key research achievements in relation to the research aim and research questions, together with the added value and contribution thereof.

This thesis aimed to develop an on-the-fly energy calculation method while repetitively modifying the building is allowed, in order to enhance energy efficiency. The results from the case studies indicate that the framework can help with the design process on energy assessment. The demonstration tool provides efficient and accurate results to the designers.

The thesis has proposed a BIM-API-Grasshopper framework for early-stage energy optimization, and developed a demonstration script for validation. The application of the framework allows architects to involve energy design in an early stage, with less limitations of time, workload, and expertise. It helps to solve the problem where energy optimization often come into play after the most architectural design work has been done due to the low collaboration with energy consultants. With the assistance of the developed tool, architects may easily check the energy performance while modifying the building model in the conceptual phase. Based on the framework, a thorough tool can be made to aid energy designs by architects in the industry.

7.1. Conclusions to Sub-Research Questions

1. What framework can be used to make the energy assessment on-the-fly?

   The BIM-API-based method integrated with visual programming software proved to be effective in terms of energy assessment in real-time. The developed tool from this thesis also provides insight into how energy calculations are responding to the modifications of the 3D model. Rhino.Inside provides possibilities to integrate Grasshopper with Revit, allowing immediate response to the changes of the model. Employing Grasshopper also allows customized script, which represents its potential in different areas.

2. What is the added value of the on-the-fly simulation method?

   The on-the-fly simulation method significantly enhances the efficiency of involving sustainability in the early design stage. The method allows designers to observe the real-time impact on energy use by modifying the model. The integration of sustainable design and architectural design becomes more feasible and natural with the help of on-the-fly simulation. The investigated cases validates the effectiveness of the tool, and indicates the potential usage scenarios.

3. How can validated assessments be made in an early design stage?

   The common validation methods include analytical solutions, empirical data, and peer solutions.

To verify the results grounded on the Dutch norm NTA 8800, a peer software Uniec 3 which is based on NTA 8800 was used for validating the energy indicator Ewe. Besides, an analytical method can also be used in case of plain geometries.

7.2. Conclusions to Main Research Question

The main research question is:

”How can energy performance be assessed, in compliance with Dutch building law, in a very early design stage based on a preliminary BIM-model while modifications to the design can be made on-the-fly?”

The thesis has developed a BIM-to-BEM tool for real-time energy calculations of buildings in the early design stage. The tool is based on the Dutch energy norm NTA 8800 and implemented with Rhino/-Grasshopper and Rhino.Inside. The tool has a Grasshopper script associated with Python, in which the energy equations are included. Throughout the case study, the developed tool produced logical results validated by Uniec 3, and showed its potential in optimizing energy efficiency.

8

Recommendations

This thesis presented a framework that allows an efficient and on-the-fly energy analysis of BIM models. The framework benefits designers who desire sustainable design in a very early stage. Nevertheless, some improvements can be made for a better version and to suit future requirements.

For practice, the approach can be modified to adopt various analyses. The prototype can be implemented for more complex BIM models and be in use. There are criteria that need to be considered when selecting methods for energy assessment, and efficiency, accuracy, and robustness are principal (Kheiri 2018). In terms of efficiency, the developed script is able to produce results fast, though a user-friendly interface could be helpful for designers to double-check the input data. As stated earlier, the accuracy can be improved by taking thermal bridges and infiltration into consideration. The script has been modestly simplified based on the sample model, a residential building, and a tiny timber house. To increase the robustness of it, further development can be made to include more and complex conditions.

The valued can be added by introducing a user interface of the developed tool. A Revit BIM model is rarely perfect for energy assessment, should a designer would like to modify the building data or schedules, a proper user interface allows manual modifications.

From the validation, it is noted that the developed tool has not yet covered the norm NTA 8800 completely, which results in the difference with the peer software. It can be improved by implementing in details. For instance, the thermal bridges and infiltration could be taken into consideration in further development. Besides, in the case of tilted roofs, the situation can be more complex, and the script needs to be modified to accommodate.

For future research, the following research directions can be investigated based on this thesis:

- Research on the development of the automation of energy optimization in the whole process.
- Sensitivity research on different energy calculation norms and methods using on-the-fly assessment tool.
- Research on developing interoperable software in different specializations.

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A

Script and Codes

In Appendix A, the Grasshopper script and the codes are demonstrated and explained. The overview of the script is explained in Figure 4.2 in Chapter 4. The following is an explanation of the components and the codes used, including 5 main groups: the categories, the month length and temperatures, the element properties, the equations, and the results.

Categories

Categories are the highest-level built-in groups to organize the elements by their functions. Revit models contain multiple category types: model categories, analytical categories, annotation categories, and internal categories. Model categories are suitable for selecting elements by their functions, e.g. walls, roofs, floors, etc. for the subsequent energy calculations. There are 179 categories in this Revit model, but essential ones are only: Walls, Roofs, Doors, Windows, Floors, and Rooms.

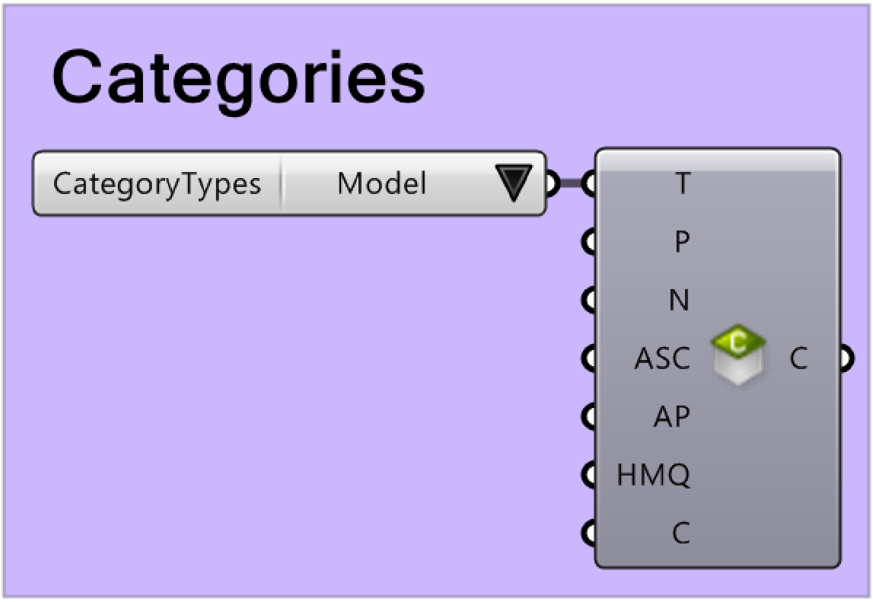


Figure A.1: The categories of elements

Month Length and Temperature

NTA 8800 provides fixed values for month-related factors: month length t_{mi}, monthly average outdoor air temperature $\theta_{e;avg;mi}$, and the monthly average wind speed $u_{site;mi}$. The GHPython component allows users to practice customized functions. Since the values vary from each month, a look-up table is used. The input parameter is a single month or multiple months, and the output parameters are the corresponding factors. Besides, the sliders below represent the calculation temperatures of the calculation zone for heating and cooling.

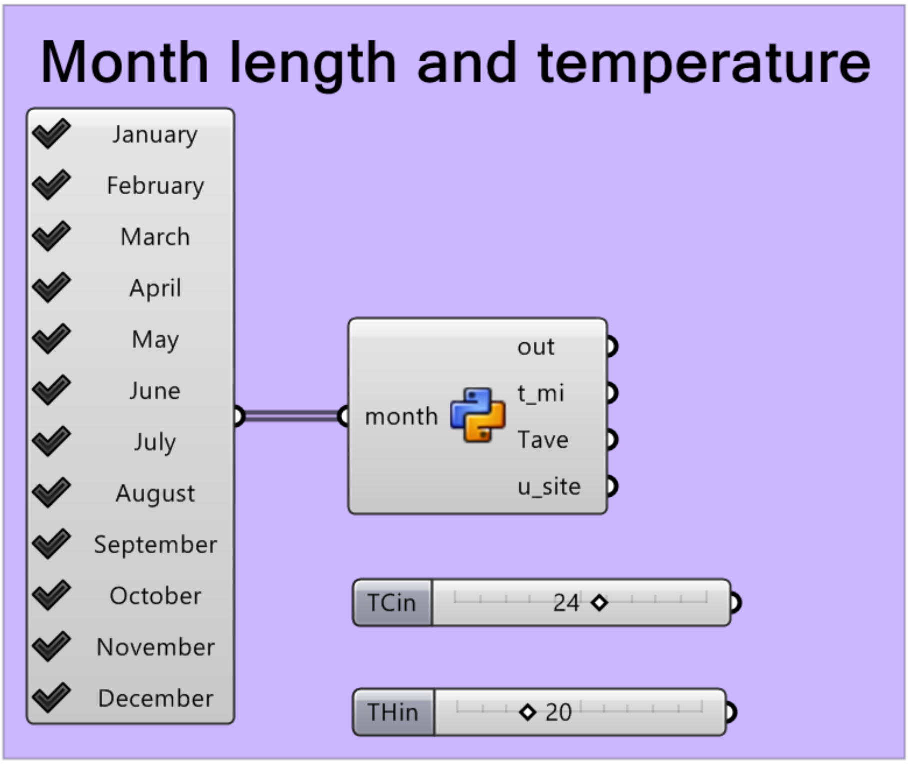


Figure A.2: The month length and temperature

The codes in the GHPython components are:

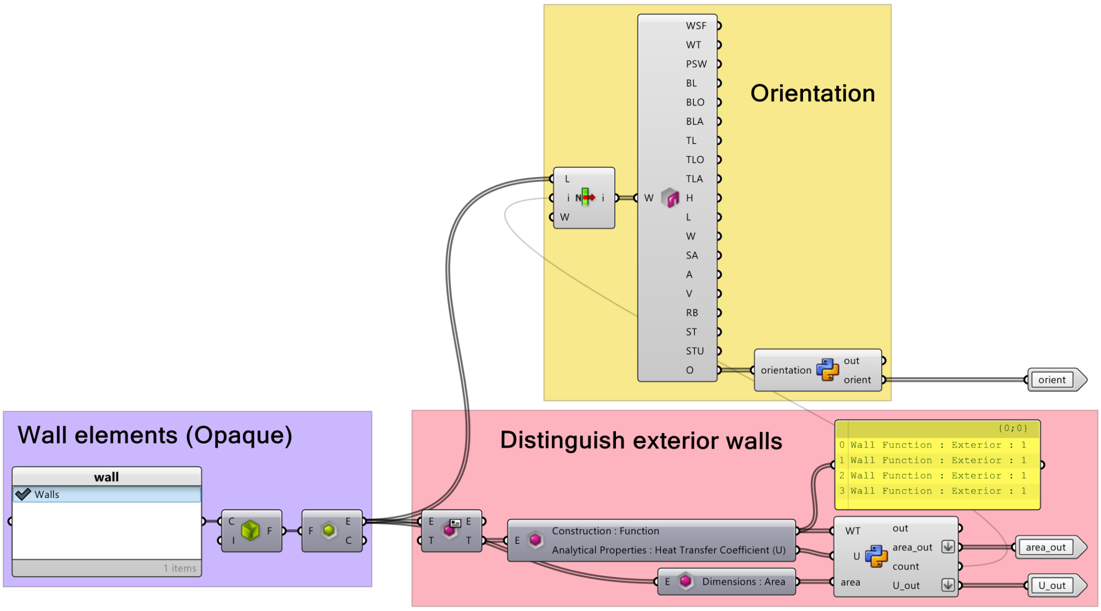
```
import rhinoscriptsyntax as rs

tdict = {
    'January': [744, 2.61, 3.04],
    'February': [672, 4.82, 4.15],
    'March': [744, 5.91, 2.99],
    'April': [720, 9.32, 3.06],
    'May': [744, 14.73, 2.97],
    'June': [720, 16.12, 2.78],
    'July': [744, 18.05, 2.63],
    'August': [744, 18.48, 2.51],
    'September': [720, 15.63, 2.71],
    'October': [744, 10.4, 2.78],
    'November': [720, 7.99, 2.83],
    'December': [744, 4.00, 2.83]
    }

t_mi = tdict[month][0]
Tave = tdict[month][1]
u_site = tdict[month][2]
```

Element Properties

The elements are sorted and processed respectively by categories in this step for further calculations. In general, there are 5 groups, as shown in Figure A.3, to deal with elements of Walls, Roofs, Doors, Windows, Floors, and Rooms respectively.

Figure A.3: Processing elements by categories

Wall elements are involved in energy calculations regarding transmission and solar radiation, and the required parameters include the area, orientations, and the heat transfer coefficient U. Figure A.4 presents the method of obtaining these factors. In the purple group on the left, from left to right, the components are Value Picker, to select Walls from all categories; the Category Filter, to match elements by their categories; and Query Elements, to get filtered elements. The elements of the rest categories are obtained in the same way, so the explanation will be omitted in the following sections. The pink group is to distinguish exterior walls since the interior walls take no part in heat exchange, and to get the areas and the heat transfer coefficients. Through the Inspect Element component, which is also used for the rest categories later, the element types are assessed. Under Construction Function output, the location of the walls (if exterior or interior) can be found. Then it is convenient to single out the exterior walls and their areas together with U values, using the codes below. The yellow group in the figure is to identify the orientation of each wall. The exterior walls are analyzed through Analyze Wall component, and the orientations can be found in forms of coordinates, and then transformed into text, which is done by customized GHPython component.



```
{0;0}
0 Wall Function : Exterior : 1
1 Wall Function : Exterior : 1
2 Wall Function : Exterior : 1
3 Wall Function : Exterior : 1
```

Figure A.4: Processing walls

The codes to select exterior walls are:

```
import rhinoscriptsyntax as rs

area_out = []
U_out = []
if ”Exterior” in WT:
    area_out.append(area)
    U_out.append(U)
    count = 1
```

The codes to transform orientation from coordinates into text are:

```
import rhinoscriptsyntax as rs

if orientation[0] < 0 and orientation[1] == 0 and orientation[2] == 0:
    orient = ”east”
elif orientation[0] > 0 and orientation[1] == 0 and orientation[2] == 0:
    orient = ”west”
elif orientation[1] < 0 and orientation[0] == 0 and orientation[2] == 0:
```

```
    orient = ”north”
elif orientation[1] > 0 and orientation[0] == 0 and orientation[2] == 0:
    orient = ”south”
```

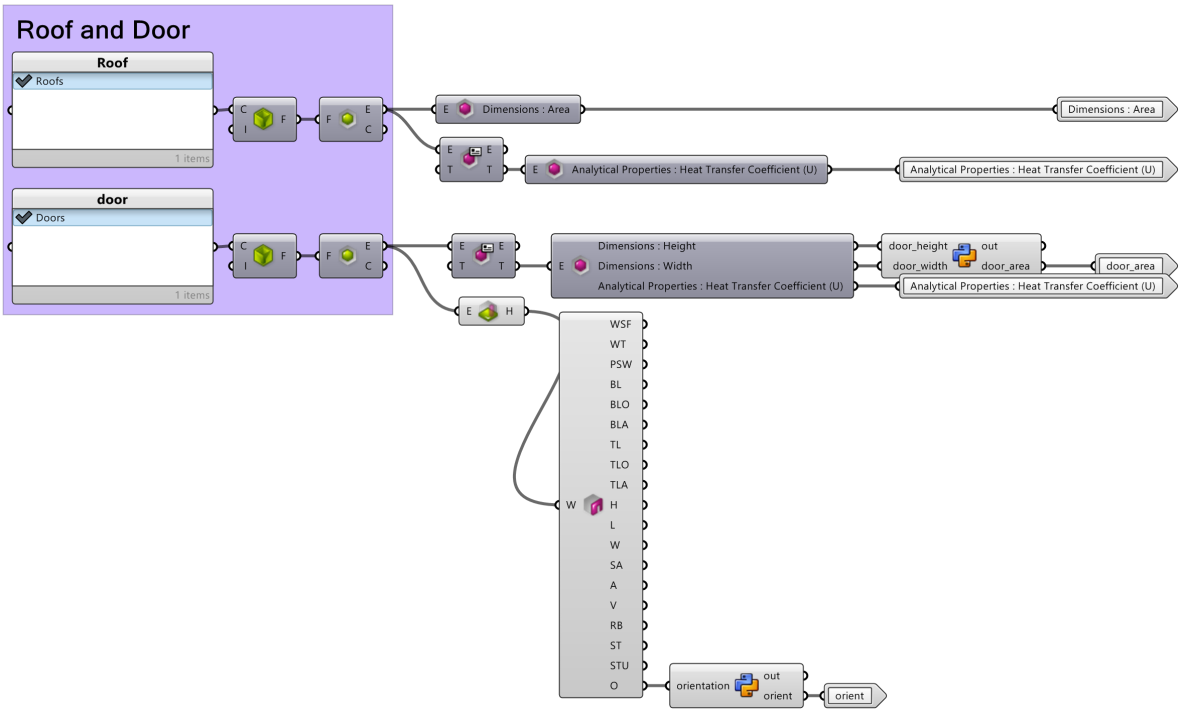


Figure A.5: Processing roofs and doors

The second group in Figure A.3 concerns doors and roofs. Following the same scheme as before, the areas and the U values are identified. The only GHPython component is applied to calculate the areas of the doors, because it is not directly provided by Revit. The codes to calculate door’s area are:

```
import rhinoscriptsyntax as rs

door_area = door_height * door_width
```

Windows are involved in multiple calculations, and regard many input data related to the calculations, including area, sill height, glazing type, if fixed, U value, orientation, and the shading reduction factor. The orientation of the windows depends on the host. A host in Revit is an element that supports other elements, which is the wall that windows located in this case. The rest components and process are explained before.

Same scheme applies for the floors and the rooms. The parameters required are the area, the perimeter, and the U value of the floors; the area of the rooms.

Energy Calculations

The energy calculations are conducted based on the equations of NTA 8800. As shown in Figure A.9, the whole process consist of four parts: heat transfer through transmission, heat transmission through ventilation, solar radiation, and internal heat gain. The equations are explained in detail in this section.

The heat loss through transmission reckons the heat flow passing through the envelope, regarding the walls, roofs, doors, windows, and the ground floor. As can be seen from Figure A.10, it concerns the

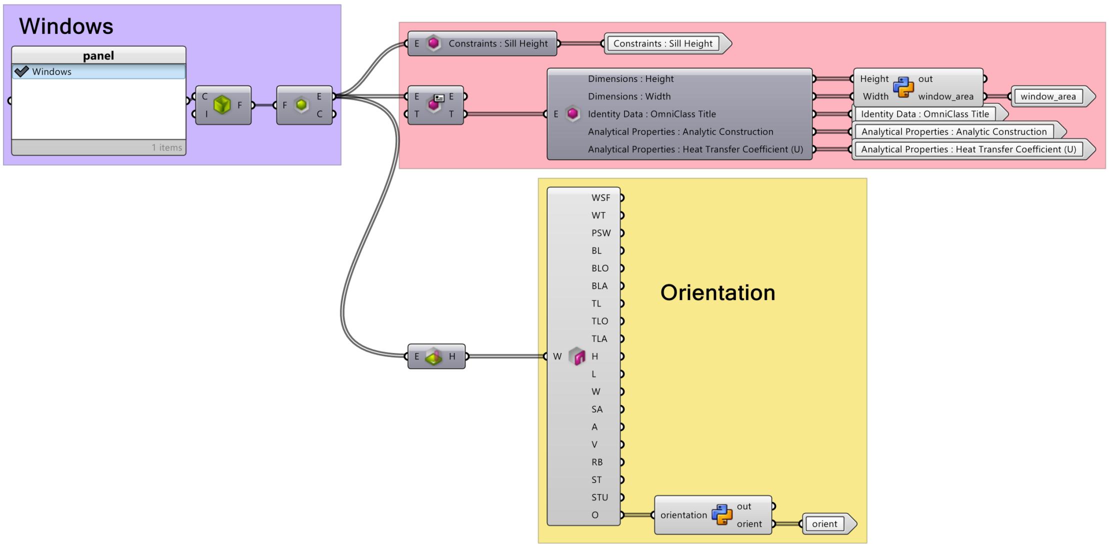


Figure A.6: Processing windows

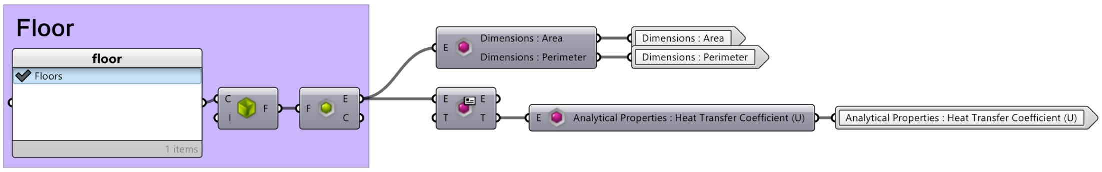


Figure A.7: Processing floors

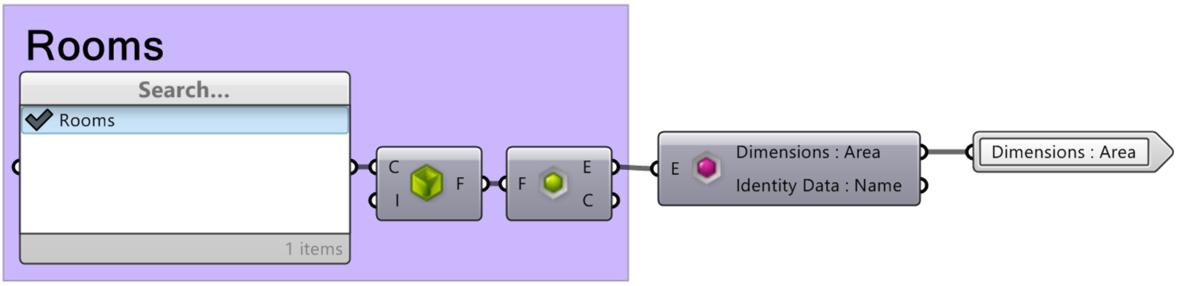


Figure A.8: Processing rooms

elements on the envelope, and has two main groups. The computing process is basically composed of two steps. First, the total heat transfer coefficient through transmission is calculated based on Equation 3.7, 3.8, and 3.9 in Chapter 3. Next, the heat loss is computed and summed up according to the Equation 3.6. It is noted that the a few parameters gathered from Revit are in Imperial units, so they are converted into metric units by the codes below.

The codes to calculate heat transfer coefficients are:

```python
import rhinoscriptsyntax as rs
import ghpythonlib.components as ghcomp
```

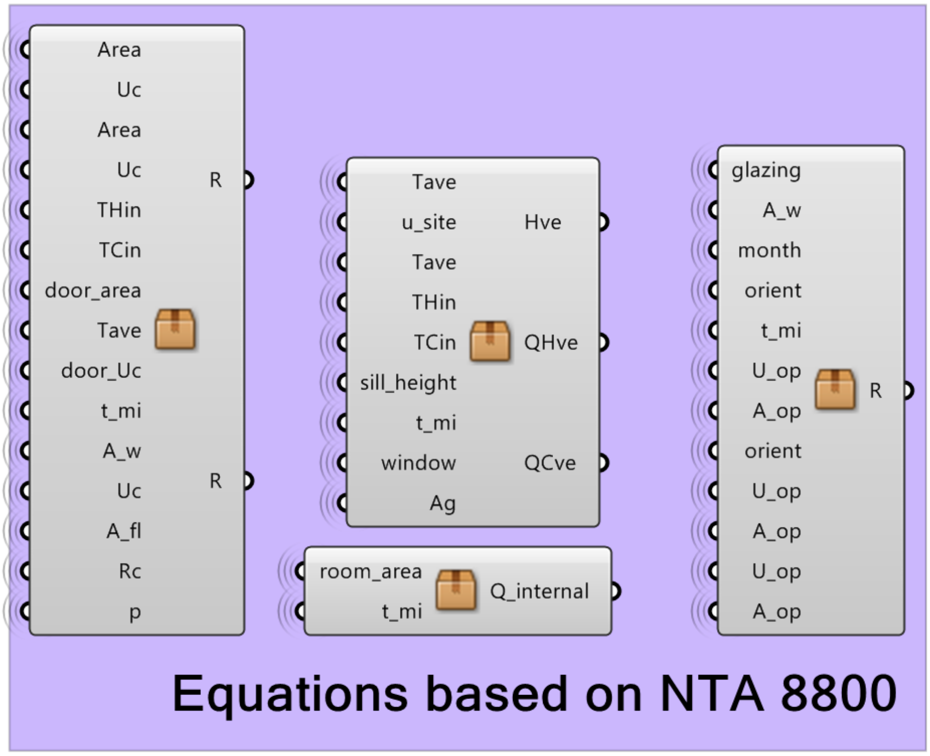


Figure A.9: Equations based on NTA 8800

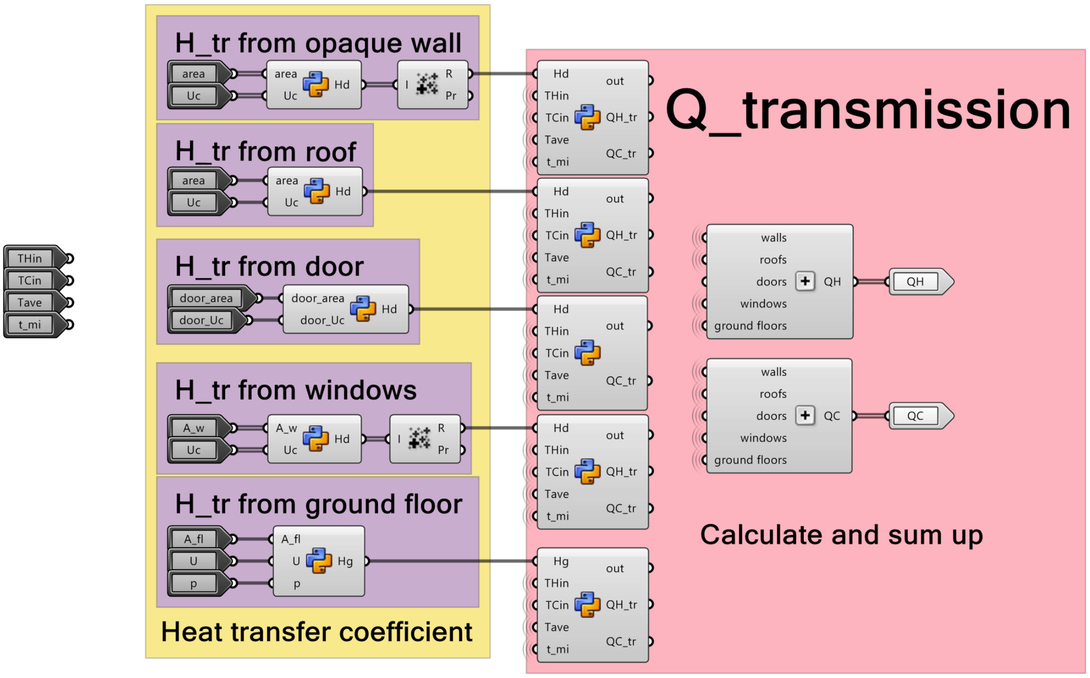


Figure A.10: Heat transfer through transmission

```
import clr
clr.AddReference('RevitAPI')
import Autodesk
from Autodesk.Revit.DB import *

Uc = UnitUtils.Convert(Uc, UnitTypeId.SquareFeet,UnitTypeId.SquareMillimeters)

Hd = (float(area)/(10**6) * Uc)
```

The codes to calculate and sum up the heat loss through transmission are:

```
import rhinoscriptsyntax as rs

QH_tr = (float(Hd) + float(Hp)) * (float(THin) - float(Tave)) * 0.001 * float(t_mi)

QC_tr = (float(Hd) + float(Hp)) * (float(TCin) - float(Tave)) * 0.001 * float(t_mi)
```

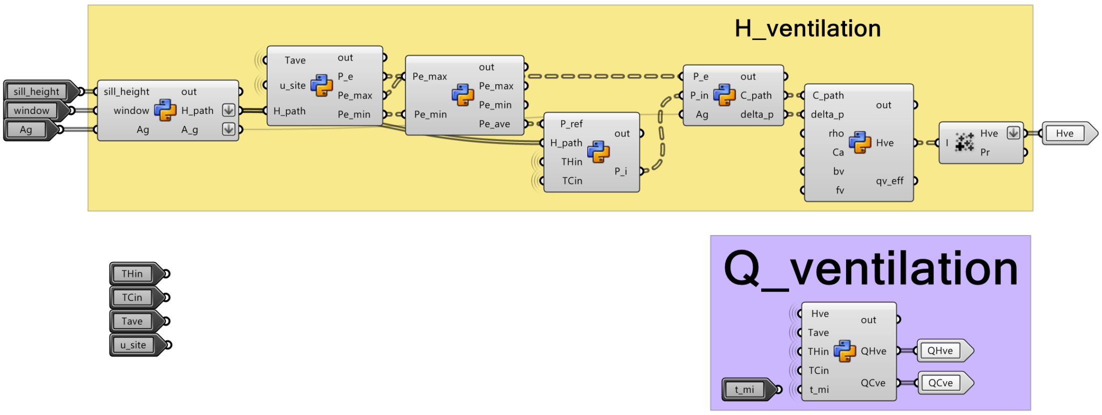


Figure A.11: Heat transfer through ventilation

Another source of heat loss is through ventilation. Likewise, as in Figure A.11, the heat transfer coefficient is calculated, and the heat loss through ventilation is obtained subsequently. The yellow group illustrates the calculation process of heat transfer coefficient, according to Equation 3.11 to 3.17; while the purple group underneath computes the amount of heat demand via ventilation. The codes in order are attached below.

```
import rhinoscriptsyntax as rs
import ghpythonlib.components as ghcomp
import clr
clr.AddReference('RevitAPI')
import Autodesk
from Autodesk.Revit.DB import *

sill_height = UnitUtils.Convert(sill_height, UnitTypeId.Millimeters,UnitTypeId.Meters)

sill_height = 0.5 * sill_height

Ag = UnitUtils.Convert(Ag, UnitTypeId.SquareMillimeters,UnitTypeId.SquareMeters)
```

```
A_g = []
H_path = []

if ”Fixed” not in window:
    H_path.append(sill_height)
    A_g.append(Ag)
```

```
import rhinoscriptsyntax as rs

T_set = 21 + 273

P_e = []
Pe_max = []
Pe_min = []

for p in H_path:
    P_e.append(1.205 * (293 / (273 + Tave)) * (0.5 * 0.25 * (u_site ** 2) - p * 9.81
    Pe_max.append(1.205 * (293 / (273 + Tave)) * (0.5 * (0.25) * (u_site ** 2) - p *
    Pe_min.append(1.205 * (293 / (273 + Tave)) * (0.5 * (-0.5) * (u_site ** 2) - p *
```

```
import rhinoscriptsyntax as rs

Pe_max = max(Pe_max)

Pe_min = max(Pe_min)

Pe_ave = (Pe_max + Pe_min)/2
```

```
import rhinoscriptsyntax as rs
g = 9.81

rho = 1.205

Te_ref = 293

TH_in = THin + 273

TC_in = TCin + 273

P_i = P_ref - rho * H_path * g * (Te_ref / TH_in)
```

```
import rhinoscriptsyntax as rs
import ghpythonlib.components as ghcomp

qv_oda = 0.8 * 0.5 * 3.6 * Ag
delta_p = P_e - P_in
n = 0.67
C_path = 0.5 * qv_oda / (delta_p ** n)
```

```
import rhinoscriptsyntax as rs

fv = 1
rho = 1.205
Ca = 1005
bv = 1
n = 0.67

if delta_p > 0:
    qv_eff = C_path * (delta_p ** n)
else:
    qv_eff = 0

Hve = rho * Ca * qv_eff * bv * fv / 3600
```

```
import rhinoscriptsyntax as rs

QHve = Hve * (THin - Tave) * 0.001 * t_mi
QCve = Hve * (float(TCin) - Tave) * 0.001 * t_mi
```

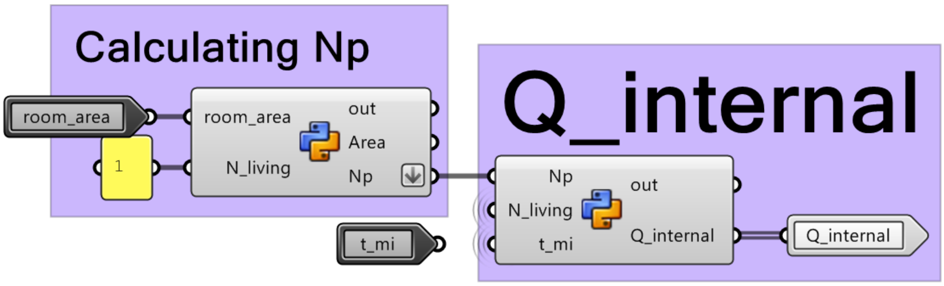


Figure A.12: Internal heat gain

The internal sources that contribute to the internal heat gain do not include spacing heating or cooling, or hot tap water either. The internal heat gain concerns the number of residents in the calculation zone. Equation 3.20 to 3.22 give the number of residents regarding different usage areas. The codes of the GHPython components in Figure A.12 are as below.

```
import rhinoscriptsyntax as rs

Area = sum(room_area)/1000000

if Area/N_living <= 30:
    Np = 1;
elif Area/N_living > 30 and Area/N_living <= 100:
    Np = round(2.28 - (1.28/70) * (100 - Area/N_living))
elif Area/N_living > 100:
    Np = round(1.28 + 0.01 * Area/N_living)
```

```
import rhinoscriptsyntax as rs

Q_internal = 180 * Np * N_living * 0.001 * t_mi
```

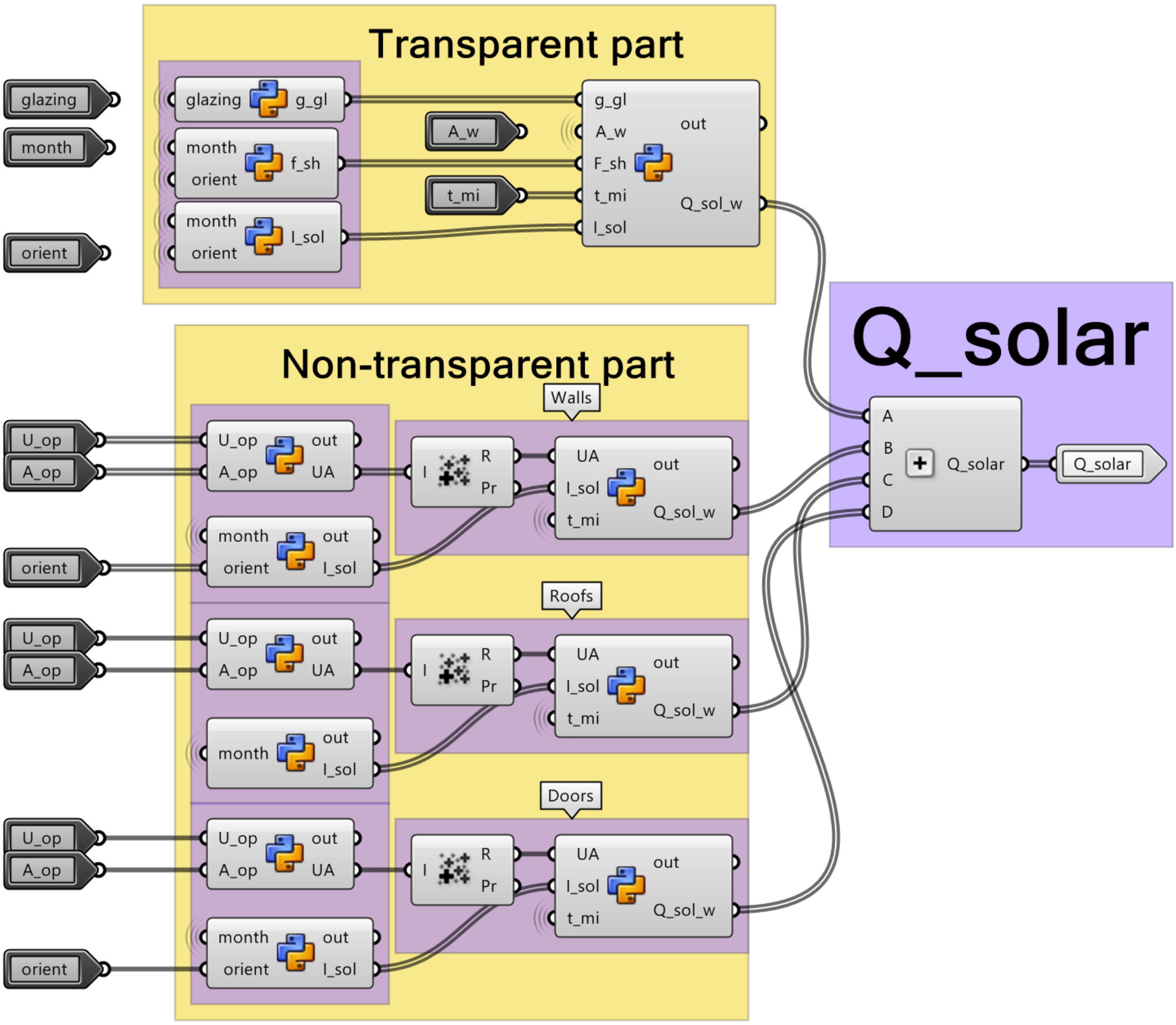


Figure A.13: Solar radiation

The heat gain through solar radiation concerns both transparent and non-transparent elements on the envelope that exposed to the sunlight. As in Figure A.13, the transparent part mainly involves the windows, and the non-transparent part mainly involves the walls, roofs, and doors. For the transparent elements, the solar radiation is calculated as Equation 3.24. Three factors related are identified separately. The solar gain factor is defined according to Table 3.2. Next, the shading reduction factor and the monthly average total solar radiation, which depend on the month, the orientation, and the angle to horizontal plane, etc., are found based on NTA 8800 in the form of look-up tables. Then, the solar radiation is found for the transparent area. The codes used are as below.

```python
import rhinoscriptsyntax as rs

if ”ouble glazing” in glazing:
    g_n = 0.85
elif ”ingle glazing” in glazing:
    g_n = 0.75
else:
    g_n = 0.75

Fw = 0.9
g_gl = Fw * g_n
```

```
import rhinoscriptsyntax as rs

fsh = {
    'January': [0.23, 0.85, 0.92, 1],
    'February': [0.91, 0.85, 0.79, 1],
    'March': [1, 0.89, 0.82, 1],
    'April': [1, 0.82, 0.91, 0.99],
    'May': [1, 0.88, 0.95, 0.97],
    'June': [1, 0.93, 0.90, 0.97],
    'July': [1, 0.92, 0.93, 0.97],
    'August': [1, 0.89, 0.94, 0.98],
    'September': [1, 0.85, 0.87, 1],
    'October': [0.97, 0.83, 0.84, 1],
    'November': [0.61, 0.90, 0.92, 1],
    'December': [0.19, 0.87, 0.86, 1]
    }

if orient == ”south”:
    f_sh = fsh[month][0]
elif orient == ”west”:
    f_sh = fsh[month][1]
elif orient == ”east”:
    f_sh = fsh[month][2]
elif orient == ”north”:
    f_sh = fsh[month][3]
```

```
import rhinoscriptsyntax as rs

Isol = {
    'January': [60.1, 23.4, 11.1, 20.2],
    'February': [66.7, 32.8, 19.5, 36.5],
    'March': [101.8, 57.3, 34.8, 70.7],
    'April': [135.1, 96.2, 49.4, 112.2],
    'May': [124.9, 107.3, 61.9, 114.6],
    'June': [112.7, 125.7, 73, 114.8],
    'July': [109.7, 112.7, 66.7, 104.9],
    'August': [128.5, 120, 55.9, 89],
    'September': [122.3, 83.9, 41.4, 73.7],
    'October': [96.2, 46.7, 26.4, 49.8],
    'November': [59.5, 22.7, 13.6, 23.9],
    'December': [46.2, 15.2, 8.9, 15.9]
    }

if orient == ”south”:
    I_sol = Isol[month][0]
elif orient == ”west”:
    I_sol = Isol[month][1]
elif orient == ”east”:
    I_sol = Isol[month][2]
elif orient == ”north”:
    I_sol = Isol[month][3]
```

```
import rhinoscriptsyntax as rs

F_fr = 0.25
A_w = A_w / (10 ** 6)
Q_sol_w = g_gl * A_w * (1 - F_fr) * F_sh * I_sol * 0.001 * t_mi
```

As for the non-transparent part, it is calculated based on Equation 3.26. First, the heat transfer factor on each surface is obtained. Besides, the monthly average total solar radiation is acquired in the same way as which for the transparent part, thus, the codes are omitted. The heat gain from solar radiation of non-transparent part is calculated, and the entire amount is summed up using the following codes.

```
import rhinoscriptsyntax as rs
import ghpythonlib.components as ghcomp
import clr
clr.AddReference('RevitAPI')
import Autodesk
from Autodesk.Revit.DB import *

U_op = UnitUtils.Convert(U_op, UnitTypeId.SquareFeet,UnitTypeId.SquareMillimeters)
A_op = UnitUtils.Convert(A_op, UnitTypeId.SquareMillimeters,UnitTypeId.SquareMeters)

UA = U_op * A_op
```

```
import rhinoscriptsyntax as rs

a_sol = 0.6
R_se = 0.04
F_sh = 1
Q_sol_w = a_sol * R_se * UA * F_sh * I_sol * 0.001 * t_mi
```

Processing Results

Having gathered the amount of the heat demand and the heat gain, finally, the results are processed to derive the energy demand indicator Ewe using Equation 3.1.

The codes to determine the Ewe value are:

```
import rhinoscriptsyntax as rs

gamma = QH_gn / QH_ht
eta = 1

if gamma <= 0 and QH_gn > 0:
    QH_nd = 0;
elif gamma > 2:
    QH_nd = 0;
else:
    QH_nd = QH_ht - eta * QH_gn

if QH_nd < 0:
    QH_nd = 0

Ewe = round(QH_nd / (Ag / 10 ** 6), 2)
```

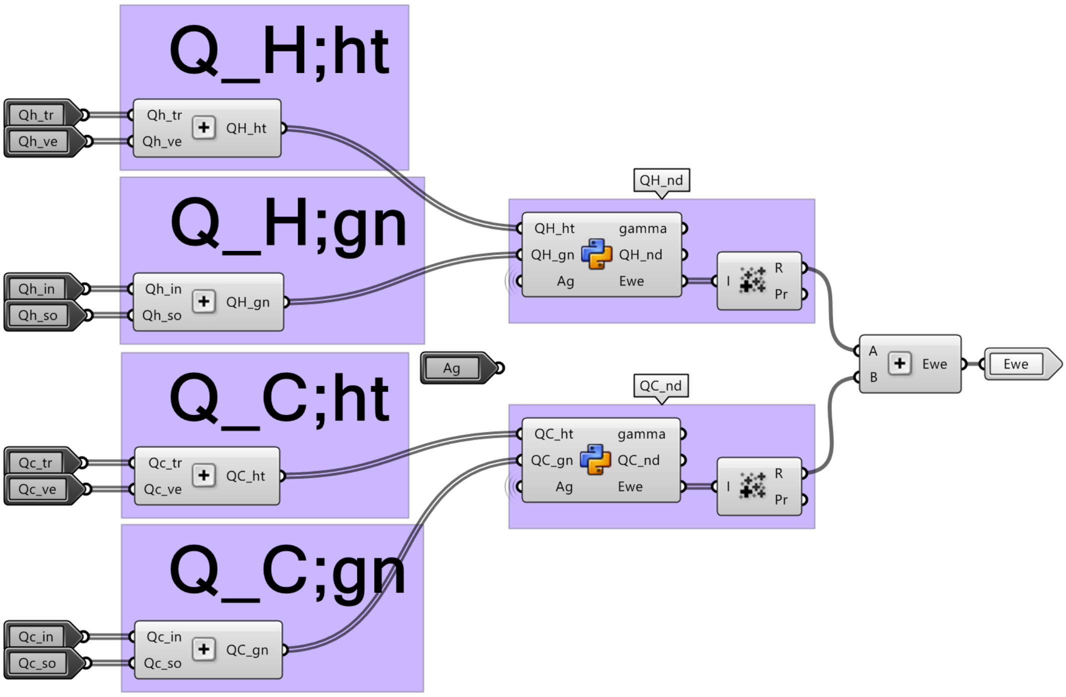


Figure A.14: Processing the results

```
import rhinoscriptsyntax as rs

gamma = QC_gn / QC_ht

print(1/gamma)
eta = 1


if 1/gamma > 2:
    QC_nd = 0;
else:
    QC_nd = QC_ht - eta * QC_gn

if QC_nd < 0:
    QC_nd = 0

Ewe = round(QC_nd / (Ag / 10 ** 6), 2)
```