MASTER

Supporting design decisions in early design phases using energy performance analysis for building design

van der Aa, Paul A.

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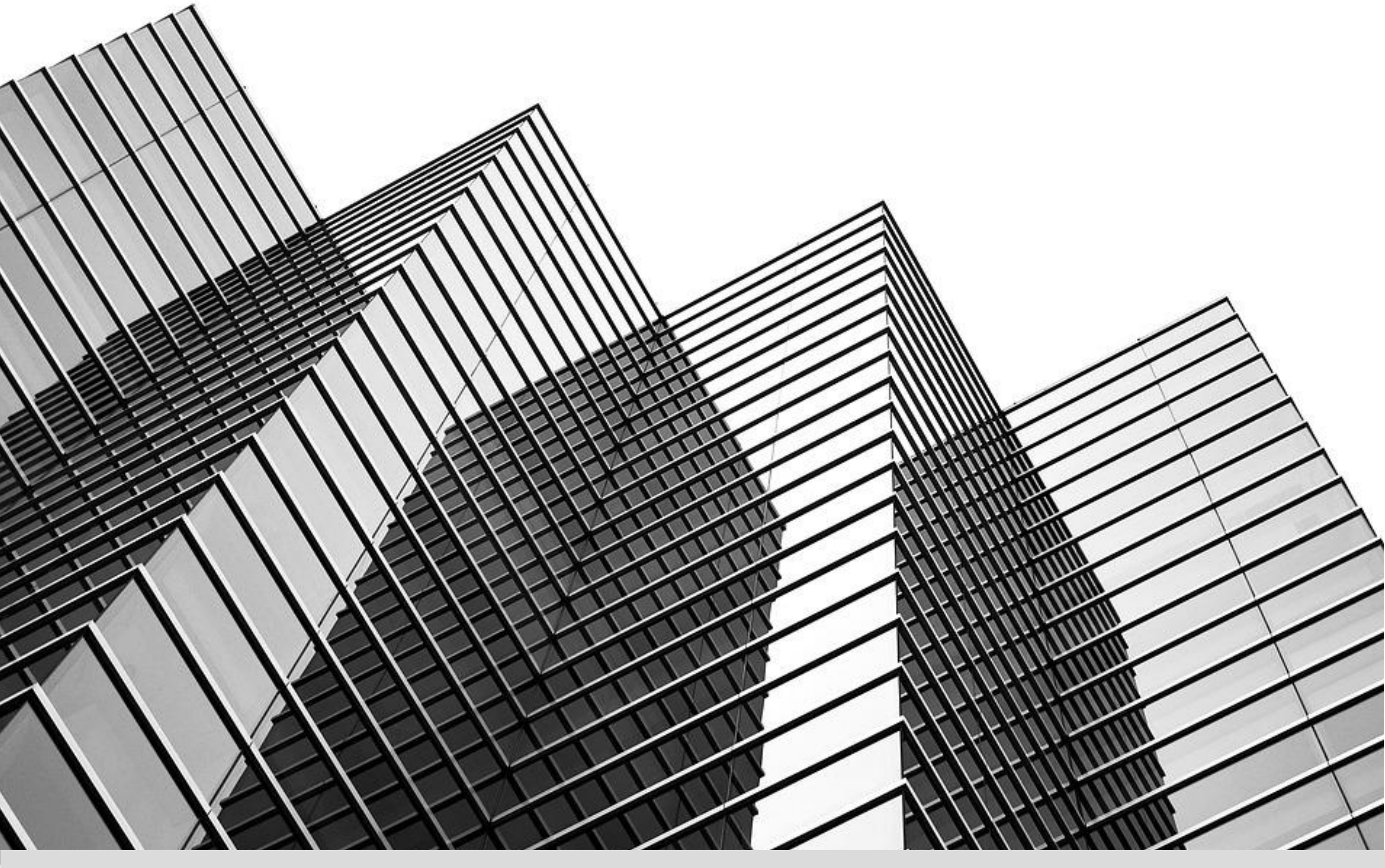

Supporting design decisions in early design phases using energy performance analyses for building design

Graduation thesis for Building Physics and Services Master of Science by:
P.A. (Paul) van der Aa

TU/e

Master graduation thesis for

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by

P.A. (Paul) van der Aa

Eindhoven, The Netherlands

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Name:	P.A. (Paul) van der Aa
Student number:	0847894
Email:	p.a.v.d.aa@student.tue.nl

University:	Eindhoven University of Technology
Department:	Built Environment
Master Program:	Architecture, Building and Planning
Master Track:	Building Physics and Services
Chair:	Building Performance

Company name:	DigiBase, VolkerWessels
Location:	Ravenswade 2, Nieuwegein, The Netherlands

Chairman:	prof.dr.ir. J.L.M. (Jan) Hensen
Faculty Supervisor:	dr.ir. P. (Pieter-Jan) Hoes
Company Supervisor:	ir. W. (Wouter) Notenbomer

Abstract

In the current trend of being willing to improve the energy performance of buildings, suitable methods need to be offered to designers to support them in making their design decisions. This research focusses on investigating possible methods, and providing a final method for giving designers insight in the energy performance of their created design.

From conducted interviews it became clear that design experts are interested in gaining a straightforward insight in the expected performance of their design in early design phases, together with the certainty of these indications. Next to this, focus points for improving the design need to be offered, together with an overview of possible design decisions in order to reach a certain established design target.

Literature research shows that very important decisions concerning the energy performance of a building are already made in the earliest design phases. This makes it important to investigate what information is known in these phases, and how this can be used to give designers insight in the level of performance of their design. This low amount of established information in the earliest design phases results in a large amount of uncertainty of performance indications. To gain an energy performance indication, building performance simulations can be conducted. Using a Monte Carlo uncertainty analysis, insight in the uncertainty of performance indications can be obtained, while a Morris sensitivity analysis is used to gain an insight in which building design parameters are most sensitive to adjustments within a certain chosen range.

In order to gain a more building-specific insight in the sensitivities of input parameters and uncertainties of results, and to have results to use as example in consult with designers, a case study of an office building has been performed. The results of this study are only relevant for this individual building. Uncertainty and sensitivity analyses are performed for three design phases using EnergyPlus and Grasshopper, allowing for parametric modelling of large variants of building designs. Using boxplots, the results of these analyses gave a clear overview of the decreasing uncertainty through the design process, mainly caused by the larger amount of established information, and so a smaller input range for the different design parameters in later design phases. This means that the high influence of the input range on the results is a very important aspect to consider during the design process. Next to this, the case study clearly shows that sensitivities of input parameters can be different for each design phase. Therefore it is important to have a constant insight in the ranking of parameter sensitivities to gain an overview in what parameters to focus on in order to improve the performance of the design.

Creating an actual tool providing the coupling of models created by the architect with the parametric simulation tool is a complex operation. Coupling of architectural models to simulation engines and parametric tools very commonly results in errors. Therefore in this research, a mock-up has been created showing a methodology for providing relevant information to the designer. Since this mock-up is completely created according the demands of the design-experts, it gives a very useful, straightforward and effective method for providing energy performance information to the designers in order to improve the building design in early design phases.

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Glossary

3D	Three-Dimensional
ACH	Air Changes per Hour
AEC	Architecture, Engineering and Construction
BEP	Building Energy Performance
BIM	Building Information Modelling
BPS	Building Performance Simulation
CAD	Computer-Aided Design
CD	Conceptual Design
CSV	Comma-Separated Values
DD	Detailed Design
DSA	Differential Sensitivity Analysis
EE	Elementary Effects
EP	EnergyPlus
EPC	Energy Performance Coefficient
EPW	EnergyPlus Weather file
gbXML	green building eXtensible Markup Language
GH	GrassHopper
HB	HoneyBee
HVAC	Heating, Ventilation, and Air-Conditioning
IDP	Integrated Design Process
IFC	Industry Foundation Classes
LB	LadyBug
LOD	Level Of Development
MCA	Monte Carlo Analysis
OAT	One-At-a-Time

PCP	Parallel Coordinate Plot
RBE	Responsive Building Element
SD	Schematic or Structure Design
TMY	Typical Meteorological Year
PV	Photo-Voltaic
VPL	Visual Programming Language
WWR	Window-to-Wall Ratio
μ	Mean of elementary effects
μ^*	Mean of absolute elementary effects
σ	Standard deviation of EE

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1. Introduction

1.1 Background

In recent years, awareness of the importance of sustainable performance of buildings has grown, resulting in a demand for sustainable building facilities with minimal environmental impact. (Zanni, 2013) (Azhar, 2011). This realization is essential, since buildings stocks are responsible for 40% of energy consumption in the European Union and for 36% of greenhouse gas emissions (EC, 2019) (Gourlis, 2017). Established building regulations force AEC (Architecture, Engineering and Construction) professionals to consider the effects of their design decisions on the building's energy consumption and environmental impact. To allow designers to consider these effects, an innovative design approach is required.

The most important design decisions influencing the sustainability of a building have to be made in early design stages. However, many critical design decisions concerning energy performance are made in design development, or even later (Bazjanac, 2011). The early design stages are often characterized by the significantly high uncertainty (Reazee, 2014), resulting in an inefficient design process in which the architect continually has to modify the design to obtain details on the building's energy performance (Azhar, 2011).

The use of simulation tools and measurements are two very important methods for obtaining the information about the energy performance of buildings. Limitation of Building Performance Simulation (BPS) tools is that they are not devised for optimization of buildings, but to quantitively justify design decisions (Bazjanac, 2011) and support decision making for energy efficient buildings

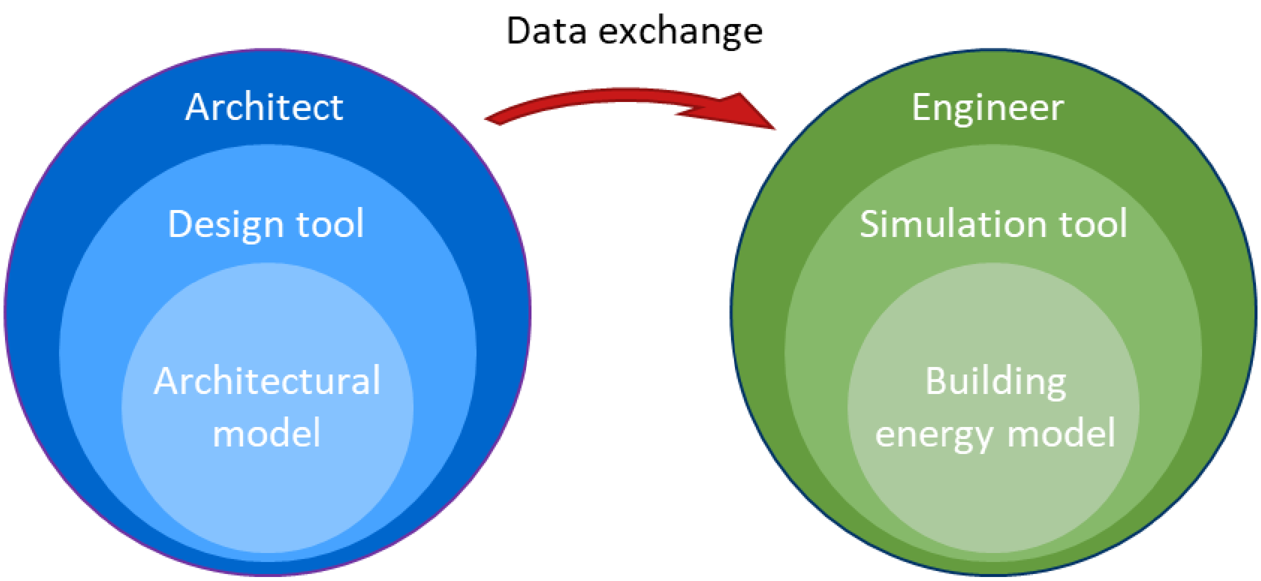


Figure 1: Data exchange between the architect and the energy simulation expert in traditional design process

(Hensen, 2011). In a traditional design process, like visible in *Figure 1*, an energy simulation is performed only after the initial architectural design, and is performed by an energy simulation expert who then introduces the information and creates the building energy model based on drawings, reports and data sheets (Maile, 2013) (Andriamamonjy, 2019). Especially for sustainable building design with high complexity, design mistakes are very commonly made, and serious disparities exist between the actual building performance and the predicted performance.

An improved design approach, for instance for early design phases, requires modelling, analysis and optimization of complex systems, for which powerful computational tools are needed (Gourlis, 2017). A platform for such full life-cycle modelling and management of buildings is offered by Building Information Modelling (BIM) (BuildingSmartAllicance, 2007). Unfortunately, because of a lack of integration that prevents collaborative relationships among team members throughout the project lifecycle, the full potential of BPS in BIM is currently not achieved (Arayici, 2018). Performance based design in early design phases is therefore often lacking.

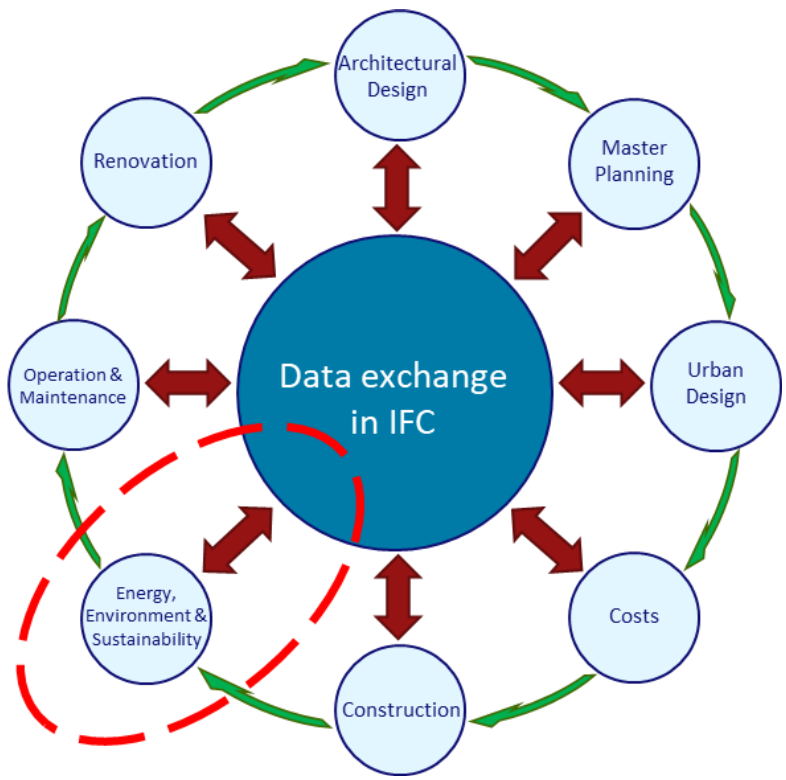


Figure 2: Information available in a BIM model and research focus

The concept of BIM originates from the idea of improving collaboration and information exchange between the AEC professionals. An universal definition of what BIM is does not exist, but generally the term BIM is used to describe a digital representation of functional or physical, three-dimensional (3D) geometry, properties of a facility, or a shared knowledge resource for information about a facility, forming a reliable basis for decisions during its life cycle, from earliest conception to demolition (Barosan, 2017). All this information is stored in one universal BIM-model, as visualized in *Figure 2.* BIM provides a wide range of benefits to the design process, including technical, standardization, diversity management, integration and economic benefits. (Ghaffarianhoseini, 2017). The improved collaboration of AEC team members shifts the workload to early design phases, as can be seen in *Figure 3*. This shift results in an advanced amount of information for each team member in all, but especially early design phases, offering an earlier insight in possible errors in the design process. This earlier notification of errors using this design process should also results in a lower amount of costs needed to be made for correcting design errors. Furthermore, an improved collaboration would ensure that geometric information will not be lost, and energy simulation experts can use the models created by architects for their simulations. This also means that simulation results would be accessible for the architect. The use of BIM for performance simulations in early design phases would therefore be very useful.

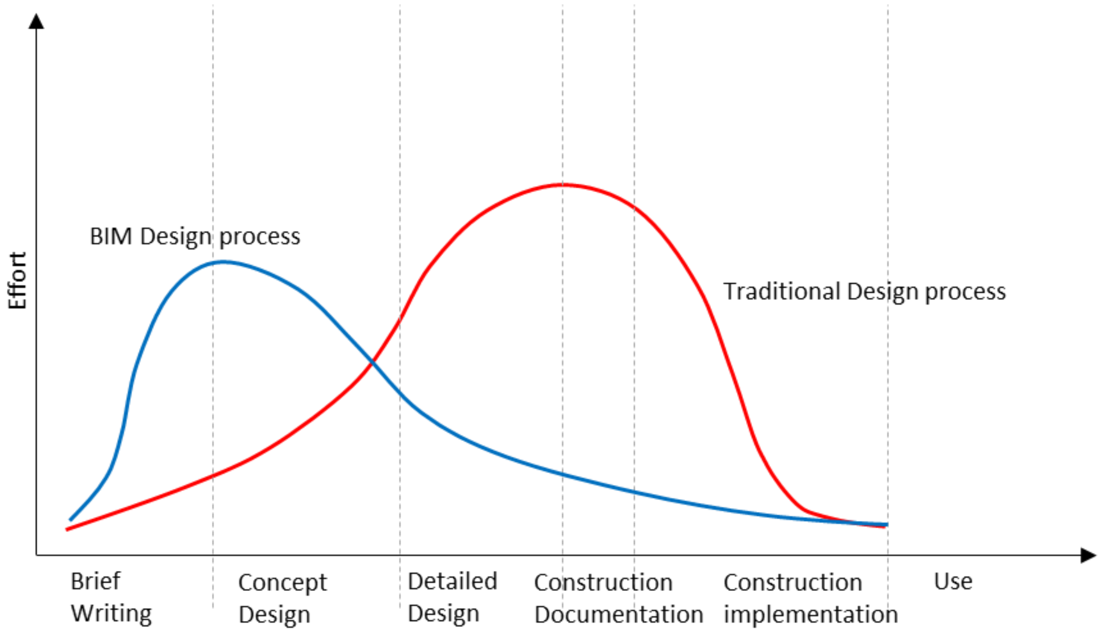


Figure 3: Influence of the BIM Design process on the effort in the designing phases

Earlier researches prove that tools allowing for building performance simulations using building information obtained from BIM do already exist (Zanni, 2013) (Prada-Hernández, 2015) (Jeong, 2016) (Habibi, 2017) (Andriamamonjy, 2019). The design loop used in these researches can be found in *Figure 4*. To perform an energy simulation, the architect exports his architectural model to an Industry Foundation Classes (IFC) file which allows for quick collaboration between the different AEC professionals, and is then imported into an energy simulation tool to be used by the energy simulation expert. The simulation expert provides feedback to the architect who is then able to adjust and optimize the architectural design. A major drawback is that this process is very time-intensive, regularly resulting in a design process where design options are explored without performance analyses.

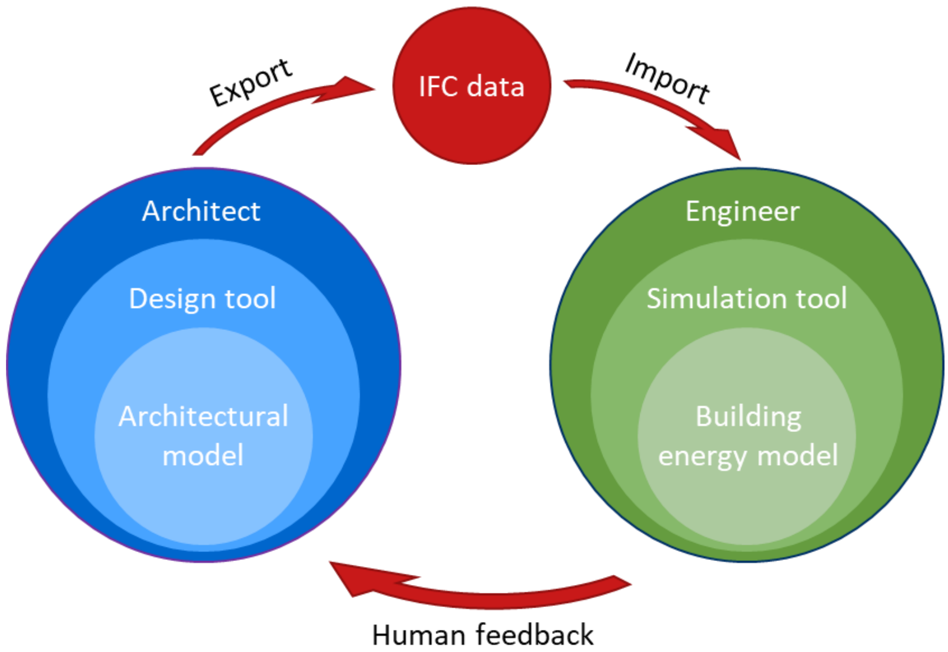


Figure 4: Data exchange between architect and engineer or energy simulation expert in reference literature

In the current trend of being willing to improve the design reliability of energy efficiency and passive design, architects and designers are excited for using effective BPS tools in early design phases. The design loop in the previously mentioned researches is missing direct feedback from the simulation tool to the architectural design. By directly displaying the effect of a design decision to the designer, this flaw may be overcome. This proposed improved design loop can be seen in *Figure 5*. The role of the engineer in the early design phase would definitely not disappear, but will be reduced, and time for decision-making in these phases would significantly decrease.

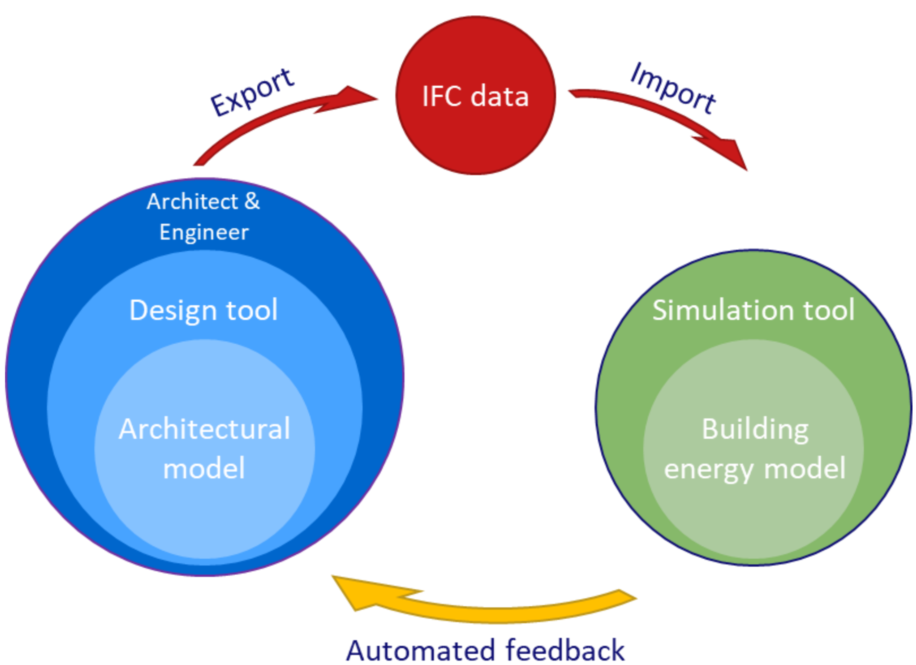


Figure 5: Proposed design loop

However, to allow architects to use BPS tools, they have to be made "Architect Friendly" (Attia, 2009). To make the information offered by these tools valuable for designers in early design phases, it should be offered so it can be used quickly and be adapted to the limited knowledge of designers about sustainable design. This information transfer is currently not sufficiently available. To bridge the gap displayed in *Figure 6*, it is important to clarify the parameters that have, in early design, the highest influence on the energy performance. To make it all useful for designers, the result of this parameter study has to be displayed in the sense that the designer understands how to adjust the design in order to improve the its energetic performance.

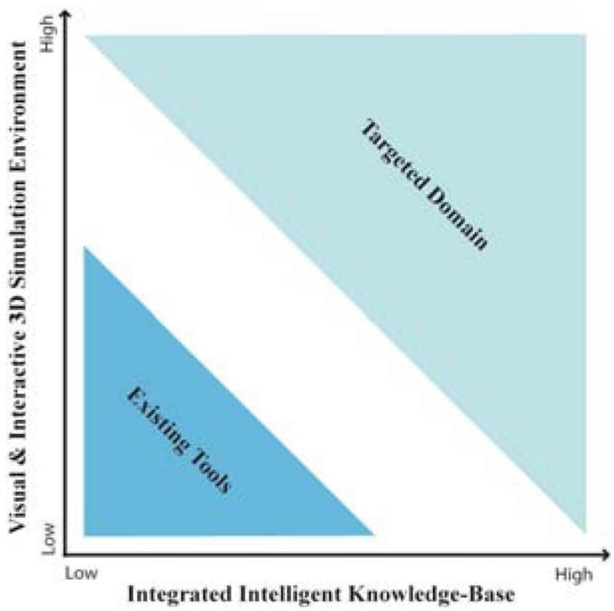


Figure 6: The gap between wishes and existing tools (Attia, 2009)

This research will be executed to gain insight in (1) if it is actually useful at all to offer performance data to a designer to improve sustainability of the design, and (2) to determine if the design loop as described in *Figure 5* is beneficial in order to assist the designer to consider the energy performance data in early design phases. To be able to gain this insight, a mock-up of an actual automated feedback tool will be created and framed to the demands of the designers using the tool. This mock-up consists of an actual parametric design tool and a description of the import and export possibilities to and into this model. This research consists of a theoretical part to investigate the design phases, uncertainties, parameters and demands and a practical part where the mock-up is created and analyzed.

1.2 Uncertainty and Sensitivity

The focus of the research will be on the earliest design phases. Important to realize is that an exact insight in the final building design cannot be given in the earliest phases, since a large amount of information is still not known at this point. To get an understanding of this uncertainty in early design phases, literature to this topic will be performed, which is further elaborated in *2. Literature research*. The overview of the different building phases should tell that the amount of settled information and so the knowledge about the final building design in the early phases significantly changes. For the earliest phases, these aspects are much lower than in later design phases. The amount of uncertainty that is occurring during each design phase is an important element for the designer to consider, since it is acting as an indicator of the usefulness and reliability of the simulated results. These uncertainties will therefore have to be determined and offered to the designer.

A schematic overview of the uncertainty occurring during the design process can be seen in *Figure 7*. The figure shows that as a result of the low amount of settled information, the opportunities to change design parameters is still relatively large in the first stages of the typical Dutch design process. The extent to which information is known determines the amount of certainty in that phase. Therefore it will be very useful to give the designer insight in the amount of uncertainty occurring in the earliest phases. The exact information that is known in each building phase will be elaborated in the literature research. Nevertheless, it can already be mentioned that at the beginning of the Detailed Design phase and consecutive phases, the amount of building parameters that can still be changed has significantly decreased, meaning that the amount of uncertainty has also significantly decreased. The amount of adjustable building parameters, and so the uncertainty in the feasibility phase is considerably high. For this reason, the main focus in this research is on the Schematic Design phase and Conceptual Design phase while also the Detailed Design phase is investigated to gain a broader insight in the changing uncertainty during the design process.

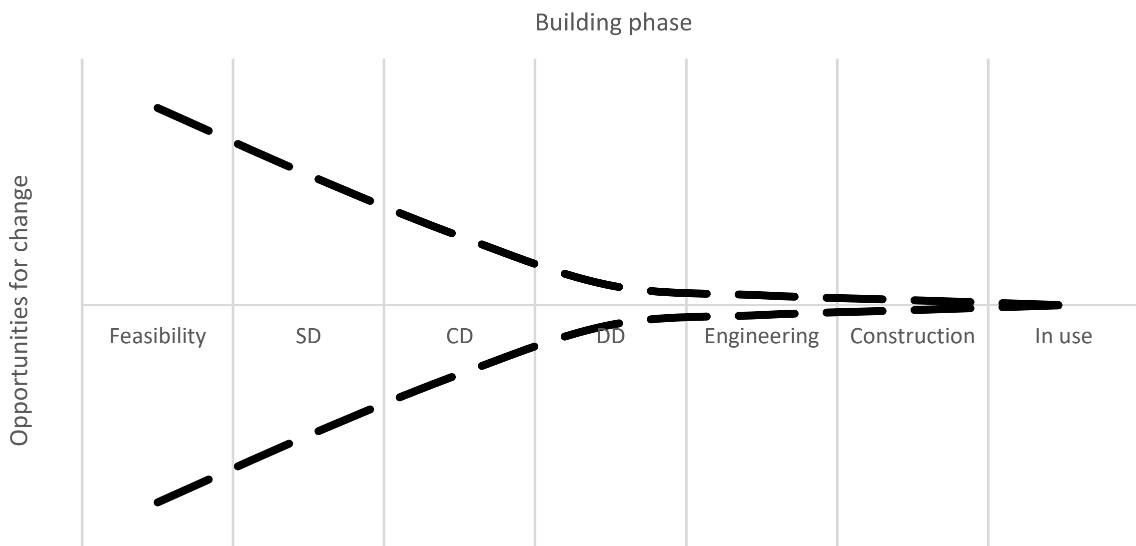


Figure 7: Schematic overview of the opportunities for change and amount of uncertainty for different Dutch building phases

The total energy use of a building is depending on multiple factors. These factors are seen as parameters in this research. For each individual building, another parameter is more of influence on the total energy performance. The size of the influence of this parameter relative to the other parameters is equal to the total sensitivity of the parameter. To give designers insight in which parameters have the highest influence, a sensitivity analysis will be performed after which the designer is able to modify the design in order to improve the energy performance of the building. Changing a design parameter with a large sensitivity has a large effect on the total energy performance of the design. It is therefore important to at least display the parameters with the highest sensitivity to designers. In *2.2.2 Overview of Sensitivity and Uncertainty analyses*, different analysis techniques have been investigated, while in *3.2.2 Choice for Morris sensitivity analysis* and *3.2.3 Choice for Monte Carlo uncertainty analysis* the consideration to choose one technique for this research is explained.

During the design process, the designer has a certain energy performance target in mind which is already determined in the first phase, visible in *Figure 8*. Because the design parameters all have an influence on reaching this target, they should be displayed to the designers so the target can still be reached. The figure shows an example this influence of one parameter in red color. This is a range of values that can be used as input in a certain phase. To still be able to reach the determined target, this parameter value has to stay within the possible input values range, displayed as the black striped lines. By aligning multiple parameters, the final target can in the end be achieved.

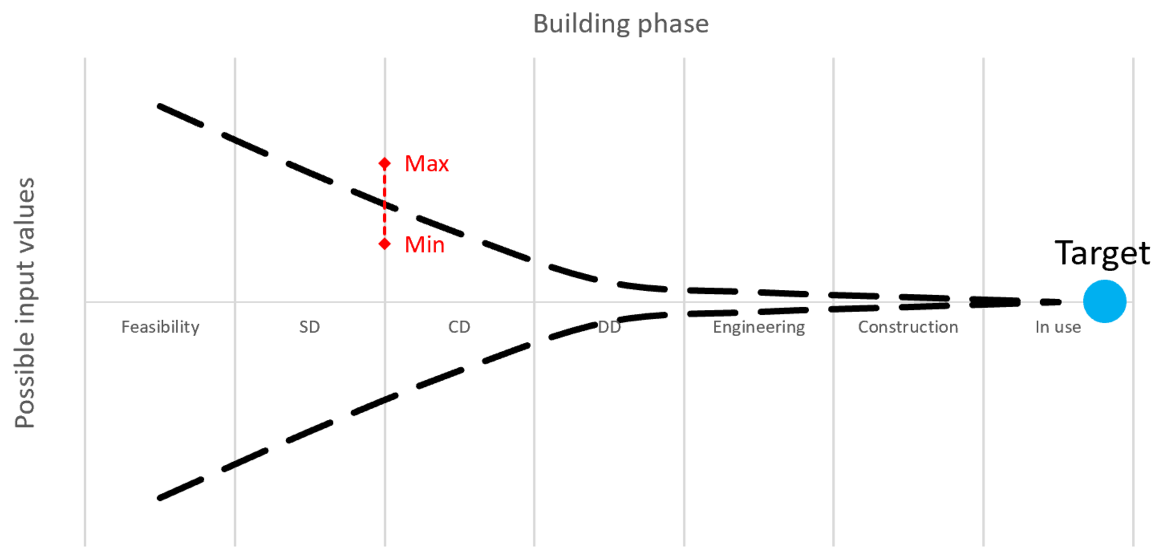


Figure 8: Schematic overview of the possible input values for each design phase

When aligning these parameters, information about the sensitivity is important. For example: a designer has, in a simplified situation, a design depending on parameter A and parameter B. Parameter A hereby has a larger influence within his range of input values then parameter B. If the designer wants to improve the energy performance of this design, it would be more beneficial to focus on parameter A, since this would clearly have a larger effect.

1.3 Problem statement

The problem in this research is focusing on a deficient or lack of utilization of energy performance data in early design phases, resulting in buildings inadequately designed regarding sustainability. This problem will be encountered by offering a revised design approach where a designer is quickly and conveniently confronted with the effect of decisions in a design process on the building's energy performance. To make this study not too comprehensive, a mock-up of a tool that develops the existing design process by providing automated feedback to the designer's BIM-model in an early design phase will be created and analyzed.

1.3.1 Problem definition

How can offering energy performance data in early design phases to the designer improve sustainability of a building design?

1.3.2 Research objectives

According the definition of the problem two research objectives have been defined:

1. *Determine which information is relevant to the designer in early design phases in order to improve the overall energy performance of a design.*
2. *Provide a method in which energy performance data can be used by the designer in early design phases, for instance an automated feedback link between a BIM-model and a simulation engine, or performance based design guidelines.*

1.3.3 Research questions

In order to achieve the objective several research questions are specified:

Design phases:

1.1 How are design phases characterized in a traditional design process, in BIM-designing, and for *Building Energy Performance (BEP)* designing?

1.2 What are their similarities and differences?

Design parameters:

2.1 What is the influence various design parameters on the energy performance in early phases of the design process of a building? To what extend can these parameters be changed or influenced?

2.2 What is the influence of assumptions and uncertainties that are taken for each design phase?

2.3 Which performance data are essential for the designer in his BIM-model in the chosen early design phase?

Mock-up:

3.1 What are the current possibilities and flaws of using BIM-models to determine energy needs in an early phase of the design process?

3.2 How can energy simulation results be visualized, to make them applicable to the designer?

1.4 Expected results

As visible in *1.3 Problem statement*, this project consists of a three parts. Information about the first part, investigating the different design phases, is obtained mostly from literature, and checked during the interviews with design experts. Expected is that this explanation will be sufficient in offering information for the creation of several mock-ups. This information will be used to support the second part, in which the different design parameters, together with their uncertainties, will be investigated.

The majority of the workload will be on this second part of the research. Creation of a model providing parametric research is most probably very time consuming. Having multiple software collaborating in order to gain simulation results may result in complications, especially in the link between BIM-models and simulation engines.

In the third part, a final mock-up of an actual automated feedback tool will be created. This mock-up will be analyzed to get an insight into the actual possibilities of a tool that connects a BIM-model and a simulation engine in order to provide a designer with feedback about the energy performance of the created physical, 3D-geometry design. This analysis is an answer to the problem definition.

It is important to realize that the final product of this research will not be an actual tool providing the automated feedback. The final result will be a mock-up of such a tool in order to analyze if the use of this tool could be beneficial to a designer. The analysis may conclude that a different solution, for instance certain designing guidelines, could better help to improve the design in early design phases.

2. Literature research

2.1 Building design phases

In the following part of this report, the results of a literature research to the different building design phases will be elaborated. First of all it is important to consider that a typical building process is divided into two separate segments: the building design and design development. The focus of this research is on the building design part. Like already clearly mentioned in the *Introduction*, this research is focused on the early design phases during a typical, traditional Dutch design process.

The literature research is performed to obtain an overview of the separate design phases, the various milestones, available information and influence on design parameters for each design phase. Division into design phases allows the client to get a grip on the design process, instead of only being able to have an opportunity for input in the initial stage, and losing all control during the following development of the design. It is therefore important to get an understanding of the various design stages.

2.1.1 Dutch building design phases

The Dutch design process commonly starts with two encompassing stages: the Initiation and the Design stage. In a traditional design, the Initiation stage consists typically of an Initiative, Feasibility analysis and Project definition phase, here combined as the Feasibility analysis (NEN2574, 1993) (NEN2634, 2002). This phase often starts with a research to the spatial requirements. The following Structure, or Schematic Design (SD) phase is often characterized as the first actual design phase, but may also be classified as a late Initiation phase.

The actual Design stage then consists of the Conceptual Design (CD) and Detailed Design (DD) phases. In these phases the designer will, according the program of requirements, frame the demands for the design. An overview of the design stages is visible in *Figure 9.* These first four phases will be further elaborated, mainly, but not only, focusing on information relevant for this research.

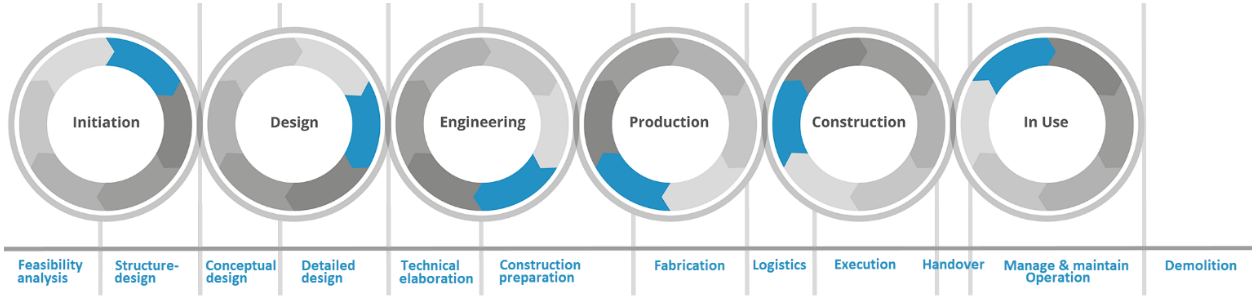


Figure 9: Building design and development phases typically used in the Dutch design process (VolkerWessels, 2019)

Feasibility analysis

In the feasibility phase, ideas about the building will first be concretized, before an analysis about to the problems and goals takes place. All matter (not) belonging to the undertaking is demarcated, and an analysis is performed to investigate whether the program of requirements is feasible. During this phase, the outcome of the design is established (Morssinkhof, 2007).

Also, the working structure of the project is determined, a tender plan is drafted, and contracts are organized with participants. Reports guarding the budget, an estimation of the operating costs, and an assessment of the financing and subsidy options are investigated.

Research is done to the building- and location-type to be able to offer decent advice about these aspects. It coincides with an urban development and landscape advice. This also contains a contribution of the expertise building physics and building acoustics (BNA, 2014).

The goal of this phase is to inventory and analyze the housing requirements or market demands, and doing research of the feasibility of a project in order to meet that market demands. Next to this, the ambitions, demands, wishes and expectations will be recorded, in such a way that the design process can be started on that basis (ONRI, 2009).

According NEN 2634, the main focus in this phase is on the complete building structure or spatial parts, while during the project definition, investigation at element cluster level is often also performed. Established information in this phase is mainly about the location of the building.

Structure design (SD)

According the formulated program of requirements, different variants and prototypes of building designs will in this phase be developed. These variants are analyzed, in order to obtain the most suitable design for further realization. A concept of this design is created containing information about the building shape and structure, which is also applicable for urban integration.

First ideas will often be visualized using handmade drawings, although appropriate software allows for a growing use of 3D-models in this phase. These models contribute in the conversation between the designer and client. Using these models, already settled information is evaluated and adjusted where needed. The model variants can later be developed and become the eventual conceptual design (Bax, 1992).

The location, which has already been widely established in the previous phase, is made definitive. Orientation of the design is also to a large extend determined. In this phase, the vision, demands and requirements regarding urban (1:1000/1:500), landscape (1:1000/1:500) and architectural integration (1:500/1:200) are further developed. An impression of the architectonical appearance, interior and exterior space is given. A main shape and mapping of the design by functions and zoning, together with relation schemes between user activities, including routing of people and equipment is also elaborated.

Demands and requirements regarding room conditions (light, air, temperature), acoustics, fire safety, installation concepts, and energy use using an Energy Performance Coefficient (EPC) are also determined. On top of the cost estimation in the previous phase, a first estimation of the investment, exploitation, construction, lifetime, and labor costs are given. Regarding the construction, a risk assessment and evaluation is performed to prevent safety and health risks as a result of the structure design, and early measures may already be taken. (BNA, 2014).

The goal of this phase is the development of a global representation of the project, in order to gain an image of the solutions in urban scale and of the main shape and main mapping of the building (ONRI, 2009).

Conceptual design (CD)

In the conceptual design stage, the designer further investigates the building design variants created in the previous design, and choses one design which is then further developed according to the schedule of requirements and destination plan. During this stage, 3D models, floor plans, façade views and section images of the building design will be created, mostly at scale 1:200, 1:100 and 1:50 (Baldwin, 2010).

The spatial and functional design of the building is in this stage settled. Further developed are the main mapping, structural planning, structural design and architectural layout. The use of materials in this phase are also mostly determined. This leads to a definitive estimation of the final investment and exploitation costs and income (Jellema, 2004).

The goal of this phase is to develop a global representation of a building, in order to obtain an image of the positioning, the functional spatial structure, destination, user facilities, the architectural appearance and the integration of structural and installation-technical aspects (ONRI, 2009).

All drawings for existing buildings will be digitalized. For new buildings, rough drawings will be created, mostly for presentations and communication with the client. Often 3D CAD-paintings, together with video- or digital animations and virtual reality presentations are made. A more elaborate vision on the interior is given, using situation sketches, floor plans, sections and scale models (mostly at scale 1:100/1:50) to gain insight in the spatial relations, routing, user functions and installation-determining functions. These drawings will also be created for the conceptual design of atria and inner gardens.

The impact of building physics advice is significantly more present than in the previous phase. Visions are given on the design assignment with a reaction on the first drawings in this phase. Advices will be given regarding heating, moisture, climate, ventilation, daylighting, outdoor view, and spatialization of the integral quality of the workplace. This last aspect means that the building related health and safety aspects, comfort criteria in different seasons, and energy saving options should be seriously investigated. A first tentative EPC-calculation will be performed, together with a clear outline of the used principles, calculation methodology, calculated values, conclusions and advices. A design justification containing all integrated advices and conclusions should then be drafted.

The conceptual assumptions regarding the acoustics of the design should also be outlined, containing advices as a reaction on the conceptual design on intern sound insulation, façade design, positioning relative to sound sources, installation sound, and room acoustics. Next to this, a first reporting on wind nuisance, urban physics, shadowing, fire safety, and vibrations, has to be supplied, containing research questions, research methodology and applicable standards and regulations. Conceptual assumptions for installations, focused on energy-, environmental- and quality-aspects should also be drafted. This also contains a comparison of installation systems regarding sustainability, efficiency and economic maintenance relative to the building design. The conceptual design of these installations, also visualizing the minimal space requirements and routing of conduits and shafts, is mostly done by floor plans and sections at scale 1:200/1:100 (BNA, 2014).

According to NEN2634, the focus in this design stage is mostly on building elements and a start of the technical solutions. These technical solutions will be much further elaborated in the next, detailed design phase.

Detailed design (DD)

In the detailed design phase, no actual new design is created, but the conceptual design is further developed. The design is made definitive, meaning that a complete and detailed image of the project is given, resulting in hardly any opportunity for adjustments left at the end of this phase. The focus in this phase is on the practicability of the conceptual design, and creation of more detailed drawings than in the previous design phase (Strumpf, 2011).

Also, the use of materials is recorded, together with the structure, shape, location and dimensions of constructions and mechanical and electrical installations. The estimation of the investments and operating plan are adjusted based on this detailed design. During this phase, no new important questions should arise. The designer should be able to test the detailed design against the program of requirements (Jellema, 2004).

The goal of this phase is to develop a detailed representation of the building, resulting in a clear image of the appearance, the internal and external structure, the use of materials, the finishing and detailing, the structural build-up and nature and capacity of the installations (ONRI, 2009).

During the phase, policy assumptions of the project are evaluated and adjusted if still needed. This contains for instance the project objectives, housing policy, project results, budget and the milestones. Definitive drawings are settled, for instance for the urban integration using situation drawings (1:500), the functional and spatial mapping using floor plans, sections and façade views (1:200/1:100), together with drawings for materialization (1:50) and principle details (1:5), all containing exact dimensions, to be used for global imaging of the architectural layout, the interior and exterior spaces and building physical and installation-technical calculations. Scale models, rendered 3D-drawings, videos- or digital animations and virtual reality presentations can all support the imaging of the definitive building design.

The building physics advice, mentioned in the previous phase, is further elaborated. More specific calculations regarding the acoustics are done, a definitive EPC-calculation is done, and building specific fire safety advices are given, for instance about the escape routing. Construction materials are made definitive, together with an advice on the future demolishing of the building. Also, an overview of the applied installations is given, with drawings mostly at scale 1:100, but also at 1:50 for shaft stands, and 1:20/1:10 for shaft layouts and engine room layout (BNA, 2014).

Overview

Table 1 summarizes the design focus and levels of design for the design stages according to NEN 2634. Visible is the overlap of levels during various design stages, resulting in a certain vagueness about the information needing to be established at the end of each design stage.

Table 1: Levels and design focus of early design phases (NEN2634, 2002)

Design phase	**Complete structure or spatial parts**	**Element clusters**	**Elements**	**Technical solutions**
Feasibility analysis	X	X		
Structure design		X	X	
Conceptual design			X	X
Detailed design				X

2.1.2 Building Performance Integrated Design Process

A state-of-the-art design process, in which the building performance is the key element, is researched in IEA-ECBCS Annex 44 (IEA-ECBCS, n.d.). The objective of this Annex 44 is to collect information about the performance of buildings that utilize responsive building systems, and improve and optimize such systems. A guide summarizing Annex 44, and offering design principles and concepts is described in the IEA ECBCS Expert Guide – Part 1, which has been used for the information gathering in this part (Heiselberg, 2010).

In Annex 44, research has been done to the design process for integrated building concepts with Responsive Building Elements (RBE). RBE are building components or subsystems which are actively used for transfer and storage of heat, light, water and air. This means that construction elements are logically and rationally combined and integrated with building service functions such as heating, cooling ventilation and lighting (Perino, n.d.).

In the expert guide, an overview of an Integrated Design Process (IDP) is given. The design strategy described in this guide, which is based on the method of the Trias Energetica by E. Lysen, ensures that different knowledge of specialists is introduced at an early project phase, so that architects, engineers and other stakeholders are already collaborating in the beginning of the process. This process is also divided into different repetitive phases, in order to improve the overview of goals, activities and products, and to be able to switch between them. An overview of the main phases according to the Annex 44 is visible in *Figure 10*. A full explanation of these phases can be found in *Appendix I.* The following phases can be distinguished:

- *Phase 1: Where to build – What to build*
- *Phase 2: Development of design concept*
- *Phase 3: System design and preliminary performance evaluation*
- *Phase 4: Component design*

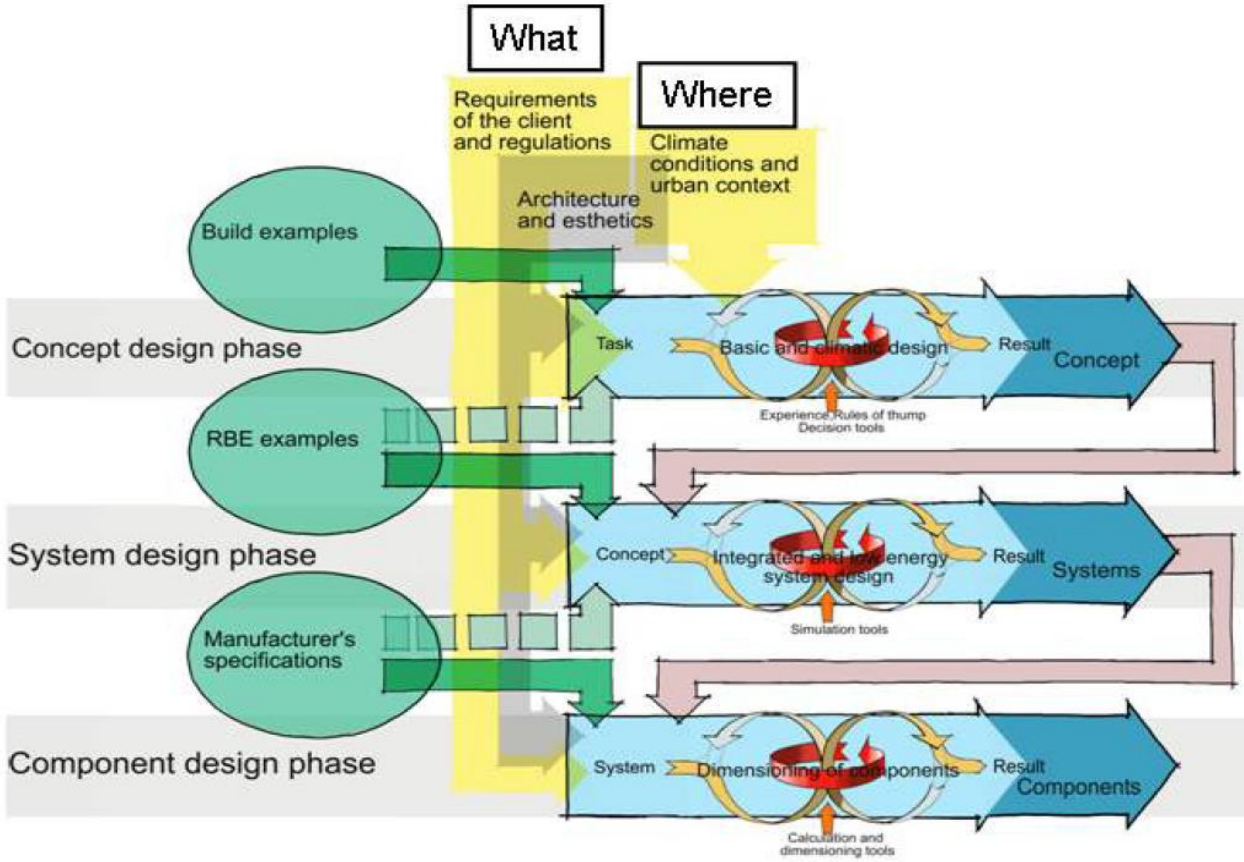


Figure 10: Design Process in Responsive Building Design (Heiselberg, 2010)

2.1.3 Levels of Development

Like mentioned before, the use of BIM causes an increase of project design efficiencies, an integrated design workflow, and reduces errors during the design process. For an efficient use of this design strategy, agreements need to be made to determine to which level of detail the stakeholders are elaborating their design in different design stages. Therefore, in BIM designing, the term Level Of Development (LOD) has been introduced.

This term may be somewhat confusing, since it may also be referred to as Level Of Detail. In both cases the term is referring to the amount of available information and data in a design object or model, and not the graphic complexity (Kensek, 2014). The term relevant in this research, the Level Of Development, can be defined as a specific component used in project design, which includes different levels of information during the design process, such as specifications and dimensions (Latiffi, 2015). The American Institute of Architecture (AIA, 2013), mentions that the LOD's describe the minimum dimensional, spatial, quantitative, qualitative, and other data included in Model Elements to support the Authorized Uses associated with such LOD.

The exact definition of LOD's has changed since the definition in the standard release of AIA in 2008. The definitions and available information of each LOD for the earliest design phases as commonly used, and summarized by different references (NationaalBIMPlatform, 2019) (Smelt, 2017) will be further elaborated:

LOD 000

Spatial objects, like spaces and volumes, related to the user functions with global dimensions and mutual relations. Non-geometric information can be coupled to the spatial objects, like user functions and accessory functional spatial specifications.

LOD 100

Graphical representation in the model may be worked out using symbols or any other generic representation, but this does not satisfy the requirements for the LOD 200. Information related to the model, for instance costs per square meter, or the tonnage of HVAC systems, can be derived from other model elements.

LOD 200

A graphical representation within the model as a generic system, object or assembly with approximate quantities, size, shape, location, and orientation. Non-graphic information may also be attached to the model.

LOD 300

The model is graphically represented within the model as a specific system, an object or assembly in terms of quantity, size, shape, location, and orientation. Non-graphic information may also be attached to the model element.

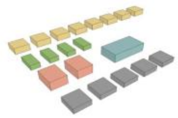
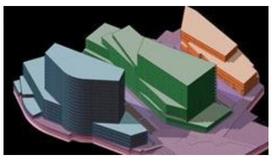
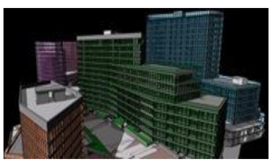
LOD 400

A graphical representation of the model element within the model as a specific system, object or assembly in terms of size, shape, location, quantity, and orientation with detailing, fabrication, assembly, and installation information. Non-graphic information may also be attached to the model element.

2.1.4 Overview of design phases

An overview of the relations of the traditional design process, the integrated design process, and the LOD-levels is visible in *Table 2*.

Table 2: Overview of typical design process phases. Figures retrieved from BIM register (Spekkink, 2012).

Typical 3D image	Traditional design process	Integrated design process	LOD-level
	Feasibility Phase	Phase 1	LOD 000
	Structure Design	Phase 1 – Phase 2	LOD 100
	Conceptual Design	Phase 2 – Phase 3	LOD 200
	Detailed Design	Phase 4	LOD 300

2.2 Changing sensitivity and uncertainty during the design process

2.2.1 Investigation of parameters

As a result of the available data as described in the previous section, decisions can be made about certain design parameters. *Appendix I* shows a roadmap which is an overview of the sequence of design considerations and parameters when designing with RBE's. Such a roadmap is an example for designers when designing using performance information. Parameters as mentioned in *Table 3* may need more clarification. For this more elaborate definition is referred to the IEA ECBCS Expert Guide – Part 1 (Heiselberg, 2010).

According to the literature (Hopfe, 2009) (Struck, 2012), it is already clear that the influence of parameters during the design process can be different for each type of building, like residential or utility buildings, and even for each individual building. It is therefore difficult to establish one overarching overview of the most important design parameters for all buildings in each design phase.

This means that to gain insight in the influences and sensitivities of parameters and uncertainties during design phases, an individual analyses will need to be performed for each individual building. These analyses will also be performed in this research using a case study in order to gain a more project-specific insight into the different parameters through the early design phases.

An investigation to the influence of all noticed parameters during the design process would be very complex and time consuming. Therefore, some of the parameters from step 1 and 2, the basic and climatic design, have been selected for further analysis. The overview of the selection is visible in *3.4.3 Case building in Grasshopper*.

2.2.2 Overview of Sensitivity and Uncertainty analyses

A possible definition of sensitivity analysis is the following: *The study of how uncertainty in the output of a model (numerical or otherwise) can be apportioned to different sources of uncertainty in the model input* (Saltelli, 2008). Sensitivity and uncertainty analysis are commonly ran following each other.

The sensitivity and uncertainty analyses are often used in model development, and also used for this research, is because they have the ability to for instance (Østergärd, 2017):

- Simplify the design problem by identifying non-influential inputs (screening);
- Help the modeler to understand and calibrate the model;
- Highlight inputs that deserve most attention in a multi-actor design process;
- Identify regions of design space that meet design criteria;
- Create reliable, fast metamodels.

Various methods for determining the sensitivity and uncertainty for each building phase are compared. The outline of the different methodologies is important, since each analysis method has its own characteristics and outputs. An elaboration of each analysis method can be found in *Appendix II,* while a short overview of the methods is here given. The analysis method most suitable for this research is applied and will be further explained. A more project specific application will be elaborated in *3. Methodology*.

- *Differential Sensitivity Analysis:* A One-At-a-Time (OAT) method, relatively easy to use, allowing for very quick exploration of output results. This method only provides information about each individual parameter, so it does not tell anything about the relation between parameters, and so the cumulative parameter impact.
- *Monte Carlo Analysis*: The uncertainty is obtained by giving all uncertain parameters a probability distribution. Using this method, a large set of values for each individual parameter can be obtained. The sensitivities of the output predictions cannot be made visible using this method.
- *Morris Analysis:* This method provides information about the uncertainty of the model output as a result of the different changing input parameters. It is relatively easy to identify and fixate insignificant inputs that have no or negligible influence on the energy performance of the building using this method.

Table 3: Typical design considerations according the design strategy proposed in Annex 44 (Heiselberg, 2010)

	Heating	Cooling	Lighting	Ventilation
Step 1: Basic Design	**Conservation** ❖ Surface to volume ratio ❖ Zoning ❖ Insulation ❖ Infiltration	**Heat Avoidance** ❖ Façade design ❖ Solar shading ❖ Insulation ❖ Internal heat gain control ❖ Thermal mass	**Day lighting** ❖ Room height and shape ❖ Zoning ❖ Orientation	**Source Control** ❖ Surface material emission ❖ Zoning ❖ Local exhaust ❖ Location of air intake
Step 2: Climatic Design	**Passive Heating** ❖ Direct solar heat gain ❖ Thermal storage wall ❖ Sunspace	**Passive Cooling** ❖ Free cooling ❖ Night cooling ❖ Earth cooling	**Daylight Optimization** ❖ Windows (type and location) ❖ Glazing ❖ Skylights, light-wells ❖ Light shelves	**Natural Ventilation** ❖ Windows and openings ❖ Atria, stacks ❖ Air distribution
Step 3: Integrated System Design	**Application of Responsive Building Elements** ❖ Intelligent façade ❖ Thermal mass activation ❖ Earth coupling ❖ Control strategy	**Application of Responsive Building Elements** ❖ Intelligent façade ❖ Thermal mass activation ❖ Earth coupling ❖ Control strategy	**Daylight Responsive Lighting Systems** ❖ Intelligent façade ❖ Interior finishes ❖ Daylight control strategy	**Hybrid Ventilation** ❖ Building integrated ducts ❖ Overflow between rooms ❖ Control strategy
Step 4: Design of Low Exergy Mechanical Systems	**Low Temperature Heating System** ❖ Application of renewable energy ❖ Floor/wall heating	**High Temperature Cooling System** ❖ Application of renewable energy ❖ Floor/wall cooling	**High Efficiency Artificial Light** ❖ LED	**Low Pressure Mechanical Ventilation** ❖ Efficient air distribution ❖ Low pressure ductwork, filtration and heat recovery ❖ Low pressure fan
Step 5: Design of Conventional Mechanical Systems	**Heating System** ❖ Radiators ❖ Radiant panels ❖ Warm air system	**Cooling System** ❖ Cooled ceiling ❖ Cold air system	**Artificial Lighting** ❖ Lamps ❖ Fixtures ❖ Lighting control	**Mechanical Ventilation** ❖ Efficient air distribution ❖ Mechanical exhaust ❖ Mechanical ventilation
Step 6: Intelligent Control	❖ Advanced sensor techniques, model based and adaptable control algorithms, user interface, …			

3. Methodology

3.1 Context

As mentioned, the research has been divided into three parts. In the first part the first research objective “*Determine which information is relevant to the designer in early design phases in order to improve the overall energy performance of a design*”, is investigated. This is initiated by doing research to the information that is known in different building design phases, in which the focus is on the Dutch design process. Typically in practice, the distinction between consecutive building phases can be relatively vague. So in order to improve the overall design, or improve decision making time during early design stages, the different design stages have to be clearly specified.

This insight in information is gained in two ways. The first is by doing literature research which has been presented before in *2.1 Building design phases* . The advantage of this method is that it should give a very distinct overview of the different phases. This literature consists of scientific papers, as well as information obtained from building standards and regulations. Drawback of this approach is that this overview may be very theoretical, instead of giving a clear, operative insight.

Therefore, interviews with design experts, mostly project developers of VolkerWessels companies, are also conducted. Primarily, the aim of these interviews is to gain insight in how the design experts distinguish the building phases during their early design processes. Alongside of this main purpose, these interviews also aim to find out about the issues that these experts encounter during the early phases, and how they think that these could be tackled. In order to give the experts as many freedom as possible in describing their own main concerns, and how they generally apply different building phases, *unstructured interviews* will be conducted. This interview method typically requires larger preparation time, but is considered more in-depth, and provides results with more insight in the interviewees experiences and perspective (Wildemuth, 2017).

An overview of the important outcomes of these interviews will be offered at the different sections of this report. These interviews serve as a guideline for the sequel of this research, since they offer the principal focus points. They do not only give practical information about the information in the building phases, but also later on inform what design parameters should be focused on in each building phase. These design parameters are a crucial element of the second part of this research.

In this second part, the influence of each changing parameter on the energy performance of a design is investigated. This serves to show the designer which parameter should be focused on when trying to reach a certain sustainability goal. The need for both this sensitivity analysis and analysis of the total uncertainty for each building phase was already explained in *1.2 Uncertainty and Sensitivity*. To perform this analyses, a parametric simulation model is created. The decision to choose certain types of analysis methods can be found in both *3.2.2 Choice for Morris* sensitivity analysis and *3.2.3 Choice for Monte Carlo* uncertainty analysis, while the elaboration of the used parametric model can be found in *3.3 Parametric simulation* tool.

The sensitivity and uncertainty of design parameters in each building phase can be different for each individual building, since they all have their own characteristics. For this reason, these analyses have been performed for one specific building. Next to that, this implementation of the building will also give an insight in the possibilities and shortcomings of using a coupling of BIM models and Building Energy Performance (BEP) tools. The characteristics of this building, together with the method of implementation in the parametric simulation tool will be described in *3.4 Case study building*.

To be able to answer the problem definition, "*How can offering energy performance data in early design phases to the designer improve sustainability of a building design?*", the final mock-up is created in the third part of the research. As mentioned, the interviews that are taken at the first part serve to identify the encountered issues during early design, but also to point out the demands of the designers for a mock-up of the earlier described automated feedback tool. For instance, the designers are able to give input in the way they would like to get feedback on their design decisions in order to be able to quickly improve their design. In this way, the interviews again serve as a guideline for the development of the tool mock-up. Eventually, the final mock-up of an actual tool is created and presented according to the interests of the design expert.

The previously mentioned build-up of this report has been visualized in the report flowchart in *Figure 11*.

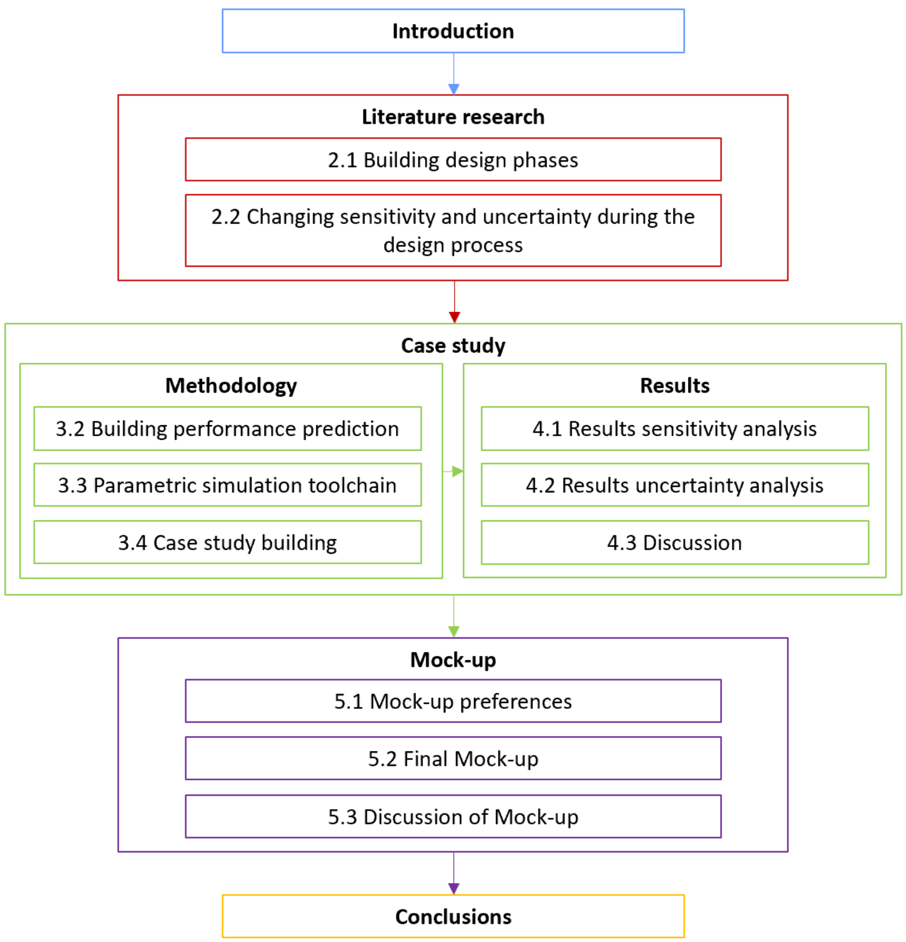


Figure 11: Report Flowchart

3.2 Building performance prediction

3.2.1 Building Performance Simulation

Building performance simulation (BPS) can facilitate analysis of the interrelated effects of building shape, construction type, materials, energy systems, weather influences and occupant behavior on building performance (Loonen, de Klijn, & Hensen, 2019). BPS tools can be used to justify design decisions and support decision making for energy efficient buildings. In order to predict the energy performance of the created designs in this research, the energy simulation engine EnergyPlus (EP) (EnergyPlus, 2019) is used. This simulation engine is able to calculate the thermal energy demand for heating and cooling, which will be the two mainly used performance indicators in this research, Next to this, it would also be able to give an indication of the electricity consumption for equipment, lighting and fans for the created designs.

This simulation engine uses an EnergyPlus Weather file (EPW), which includes all relevant weather information about a Typical Meteorological Year (TMY) at a certain chosen location. This file can be downloaded for free from the EnergyPlus website. The import of an .epw weather file and the use of EnergyPlus results in a very accurate simulation output.The collaboration of EnergyPlus with the other software used in this research can be found in *3.3 Parametric simulation toolchain*.

3.2.2 Choice for Morris sensitivity analysis

An outline of different sensitivity and uncertainty analyses has been given in *2.2.2 Overview of Sensitivity and Uncertainty analyses.* In this paragraph, the decision to choose for two types of analyses will be elaborated. For the sensitivity analysis, a Morris analysis will be performed.

Like mentioned, a Morris analysis will provide a relatively quick way of obtaining an overview of the most important parameters during the earliest design stages. This is very favorable, since the time for obtaining results about these most influential parameters is very important to the designers. In this method, the time is reduced by only having to import a limited number of inputs to still obtain a relatively reliable results.

Next to this, the Morris analysis provides information about the dependency of input parameters on other parameters, which is also very useful information for the designer when trying to improve the design.

For this research the Morris analysis is therefore very suitable. The quick results in sensitivity can also be very easily processed, and therefore be used as an input for the following uncertainty analysis.

3.2.3 Choice for Monte Carlo uncertainty analysis

For the determination of the uncertainty of the energy performance indication of the design in the early phases, a Monte Carlo analysis will be performed. The actual input values used in this analysis can be found in *3.4.3 Case building in Grasshopper*. Giving all parameters a range of input values would result in an analysis with too many combinations of parameters, too many simulations, and would therefore be too time-consuming. A Monte Carlo analysis provides a method to gain quick insight into the uncertainty, while keeping the amount of simulations to perform relatively low.

As a result of the Morris sensitivity analysis, an overview can be obtained of the most sensitive parameters for a building design. For each investigated building phase in this research, six of the most sensitive parameters resulting from the sensitivity analysis will be given a value range for the uncertainty analysis, while the other parameters will be given a constant value. The same parameters will get a range for all three investigated phases, except for when a parameter is settled in a phase, and can therefore only have a constant value. The simulations will then be performed using the MCA method as described in *2.2 Changing sensitivity and uncertainty during the design process*, meaning that prediction results of simulations will be saved, new input values for the chosen parameters will be used, after which the simulations will again be performed until all combinations have been made.

3.3 Parametric simulation toolchain

The various software that will be collaborating to provide the parametric modeling, and obtain energy performance simulation results, are visible in the flowchart in *Figure 12*.

Grasshopper will be used as a platform for parametric modeling. The use and comparison of different parametric tools is further elaborated in *Appendix III*. The Grasshopper tool provides creation of complex 3D geometries by using components or blocks that can be dragged into a canvas. By connecting these components they can collaborate to be able to for instance perform analyses about lighting or building energy performance. The possibilities of using IFC-files as input for the Grasshopper tool is investigated in this research.

In collaboration with Grasshopper, Rhinoceros is used as a tool to visualize the design created in Grasshopper. Rhinoceros is compatible with a large amount of software. Another advantage of Rhinoceros is the opportunity to give a very precise representation of the designed model created in Grasshopper, and give immediate feedback.

Grasshopper will be connected to a validated simulation engine using Honeybee (Honeybee, 2019) and Ladybug (Ladybug, 2019). Ladybug is here used for the determination of energy generation by Photo-Voltaic-panels, while Honeybee is used to determine the energy loads of the created model. Honeybee and Ladybug serve as a connection between Grasshopper and the thermal simulation engine EnergyPlus, of which the functioning has been explained before.

An alternative to EnergyPlus would be OpenStudio (OpenStudio, 2019). The largest difference between these two engines, considering this research, is the complexity of Heating, Ventilation and Air-Conditioning (HVAC) systems. Since this research is focused on early design phases, and only an Ideal Air Loads situation is considered, EnergyPlus is sufficient for these simulations.

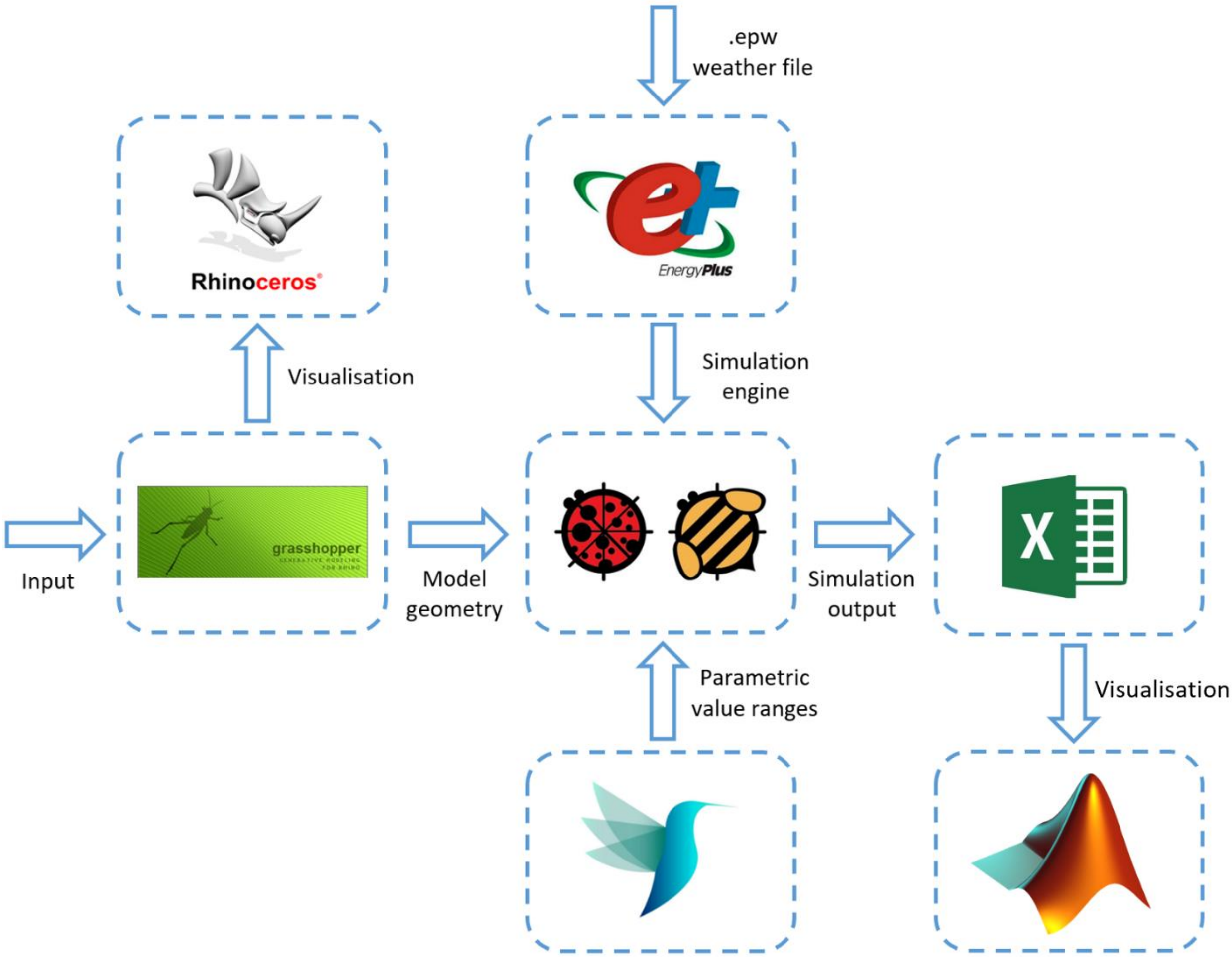


Figure 12: Flowchart of collaborating software providing parametric design

To be able to input multiple parameter value ranges, and so provide the parametric modeling, Colibri (Colibri, 2019) will be used. Colibri, element of the TT Toolbox (Colibri, 2019), allows for an option to very quickly combine input parameters for the parametric designing using an iterator, and for an overview of Grasshopper input and output values in Design Explorer (DesignExplorer, 2019). It is therefore a very strong and useful tool to gain quick access to an overview of the simulation outcomes as a result of different input values.

The simulation results are offered in a Comma-Separated Values (CSV) file, which can be opened in Excel for postprocessing. The postprocessing of these results consists mostly of combining them into one table. The graphical visualization of these results can be done using Excel, or by using MATLAB (Matlab, 2019).

More detailed information on the workflow of the Grasshopper model can be found in *Appendix IV*. A verification study has also been performed to test the collaboration between the different simulation software. The verification has been performed according the BESTEST 600 case, but is not further elaborated in this research.

3.4 Case study building

Figure 13: Architectural view of design of case study building in CD-phase

3.4.1 Case building characteristics

To gain more insight in building specific influence of parameters a case study will be performed. It is already mentioned that the influence of parameters during the design process can be very different for each type of building, and it would not really be possible to establish one overarching overview of the importance of parameters for all buildings or building types.

The case study that will be performed to gain this more project-specific insight is of the design of an office building at the Pieter Vreedeplein in Tilburg, the Netherlands. Models of this building design were offered by *Van de Ven Bouw en Ontwikkeling BV* (Van de Ven, 2019). The decision to select this building design was mostly based on the fact that during the early design stages of this building, models were already designed in Revit and SketchUp. These models were also already exported to IFC, which is currently not very often done in early design phases. Also, the geometry of this building is not very complex, but relatively straightforward compared to other available models, making it very suitable for this research. Next to this, different variants of building designs created during the design process were available, showing a fine overview of the current design development of a building. Examples of building variants in the SD phase are visible in *Figure 14*.

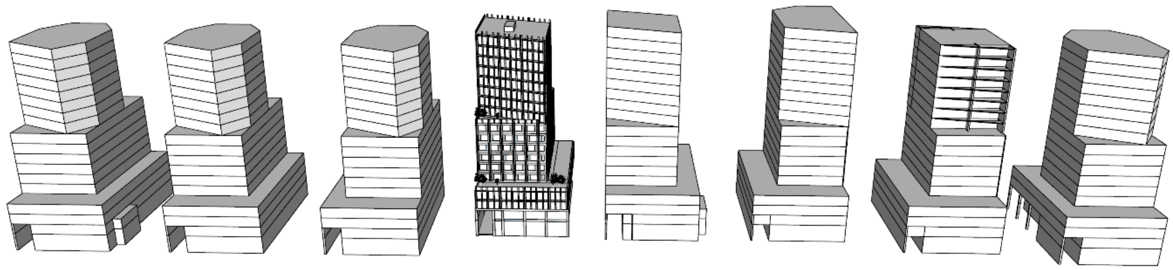


Figure 14: Design variants of the case study building created during the SD-phase

For the different analyses that are performed in this study, a base case design has to be established. The characteristics of this base case can be found in *Table 4*. The known parameters that are mentioned in this table are based on the latest available design of this building. Some of the parameters are unknown, and therefore constant input values that are generally used for typical Dutch office buildings are presumed. The geometry has been divided into parts A, B and C. Explanation for this division can be found in *3.4.3 Case building in Grasshopper*.

Table 4: Case building characteristics

Known Parameter	**Value**	**Presumed Parameter**	**Value**
Maximum outer dimensions	26,5 x 42,2 x 53,0 m	HVAC system	Ideal Air Load
Volume A	15750 m^3	Heating setpoint	20 °C
Volume B	13300 m^3	Cooling setpoint	27 °C
Volume C	12650 m^3	Equipment load	11 W/m^2
		Infiltration	0,0003 m^3/s-m^2
Length ratio A	26,5 m	Lighting	10 W/m^2
Depth ratio A	42,2 m	People per area	0,25 ppl/m^2
Height ratio A	14,0 m		
Length ratio B	21,0 m		
Depth ratio B	34,8 m		
Height ratio B	17,9 m		
Length ratio C	20,3 m		
Depth ratio C	29,5 m		
Height ratio C	27,9 m		
Floor height	3,0 m		
North Glazing Percentage	75 %		
West Glazing Percentage	75 %		
South Glazing Percentage	75 %		
East Glazing Percentage	75 %		
Location	Tilburg, The Netherlands		
Orientation	0°		

It is visible that for the HVAC system, an Ideal Air Load System is applied. This system supplies heating and cooling to a zone to meet any heating or cooling demand of the zone at all times with 100% efficiency (Al-janabi, 2019). This type of system is often chosen in situations where the performance of a building is investigated, without modeling the full HVAC system. It is therefore very useful for building investigations in early design phases to study and test complex building materials as well as to optimize building envelope performance.

The infiltration is expressed with the unit m^3/s-m^2, but could also be expressed in ACH. Grasshopper and Honeybee contain a component that allows for the conversion between two units, visible in

Appendix IV part I1. The difference between these two units is that the definition in $m^3/s\text{-}m^2$ also considers a different room volume, floor area and airflow time. This means that the conversion from ACH to $m^3/s\text{-}m^2$ can only be done if the zone geometry is known.

3.4.2 Architectural model coupling to simulation tool

A goal of this research if to find a method of using models created by architects in order to provide an indication of the energy performance of the building. As earlier mentioned, in the current trend of designing with quick collaboration between different AEC professionals, IFC models are created in order to provide rapid exchange of building information. Different than just lines in traditional CAD tools, BIM-models also contain benefits of visualization, built-in intelligence and simulation, intelligent objects of a structure, and structured data (Strumpf, 2011). Therefore, the possibility of coupling these IFC-models to the used simulation tool has been investigated in this research.

Different tools allowing the coupling between IFC and Grasshopper are already available, but the most commonly used Grasshopper add-on for importing IFC models is GEOMGYM by GeometryGym (GeometryGym, 2019). This tool works with green building eXtensible Markup Language (gbXML) (gbXML, 2019), which was specially developed for exchange of energy related information.

When working with this collaborating software, it was quickly visible that it does contain flaws and limitations. The software does not contain the option of checking the model correctness and completeness. Especially in the earliest design stages, it is often seen that the models created by the architects are lacking crucial information needed to perform an actual energy simulation. Incompleteness of models for instance includes the incomplete definition of building elements, of which an example is visible in *Figure 15*. In this example, floors are not visualized in Rhinoceros, since in the IFC model information has been defined in a different matter then readable for the GeometryGym add-on.

The example in *Figure 15* contains a model in which a building element, the floors, are not correctly imported into Grasshopper. In many cases, especially in the early design phases, an entire IFC model cannot be imported into Grasshopper, often caused by the incompleteness of the IFC, or different, often difficult to understand misfunctioning of the IFC/Grasshopper collaboration. This error also occurs for the models created for the Pieter Vreedeplein.

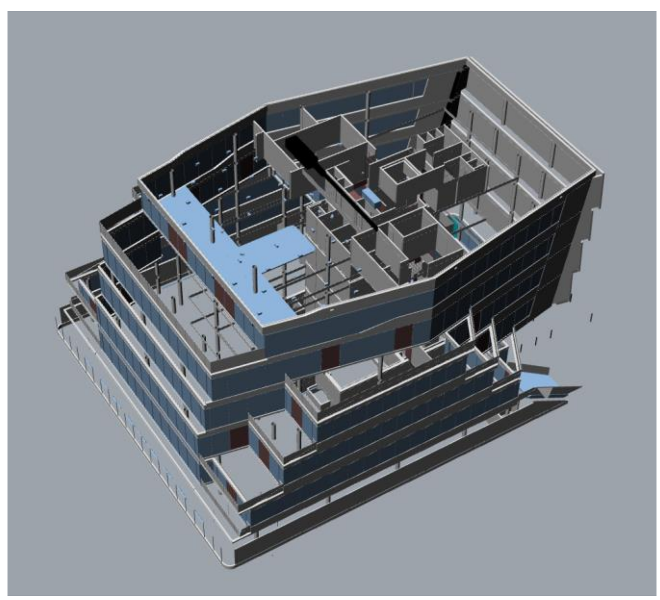


Figure 15: Common error in the Grasshopper/IFC coupling: building elements not being visualized

As a first step to improve the well-functioning of the collaboration between IFC and simulation engine, the IFC models should be defined according specially defined guidelines so that these models contain enough well-defined information to perform an energy simulation. An actual elaboration of such an improved design method and workflow will not be further elaborated in this research, but has been further investigated in reference literature (Strumpf, 2011) (Jariç, 2015) (Rinheiro, 2018).

Since the import of the IFC models of the Pieter Vreedeplein could not be correctly made, a different method has to be found for analyzing these models in order to get a project specific insight of the different parameters during the design process. In *3.4.3 Case building in Grasshopper* is explained how a representation of these models has been created in Grasshopper in order to allow for a parametric research to the energy performance of the design. Next to this, creating an actual tool providing the insight of all simulation results that could immediately be used by the designers is found out to require large expertise and knowledge of programming, which is also very time-consuming. Also, this is not essential to answer the stated problem definition and research objectives, since these were only about the methodology of offering the indication of the energy performance. For these reasons, it is chosen to create a mock-up of an actual tool, showing a well-considered method for offering this energy performance indication.

As mentioned, the main focus of this research is on the SD and CD phases, but also contains the parameter results for the DD phase. The largest uncertainty is actually visible in the phase before the SD phase, the feasibility phase. For instance research to the influence of global building masses can be performed in this phase, and could also be very interesting. This phase is actually not investigated in this research. In the first place since this phase is sometimes even skipped, but also because information in building models created by architects in this phase is, if ever made, too limited to use for energy performance analysis. For the case study building used in this research, no IFC models were created that could imported into Grasshopper either, so this phase has been left out. Studies to for instance the global building shape which could already be done in the feasibility phase can be very interesting, but are not the focus of this research (Asadi, Amiri, & Mottahedi, 2014).

3.4.3 Case building in Grasshopper

Table 5 shows the parameters that have been used for both the sensitivity and uncertainty analyses. The decision to opt for these exact parameters was based on the preferences resulting from the interviews with the design experts, the literature study in *2.1 Building design phases* , and overviews of most influential parameters of office buildings in other reference literature (Struck, 2012) (Lomas & Eppel, 1992) (Zha, 2019).

Visualization of a variant of the case building representation in Rhinoceros can be seen in *Figure 16*. The geometry of this model has been created using the Grasshopper workflow structure described in section 1 of *Appendix IV*, while the method for selection of various (physical) parameters with their ranges is explained in section 2.

It can be seen that the geometry of the case study building can be represented by choosing the option to use three separate rectangular elements topping each other, of which the dimensions and volume can all separately be selected. This option has been made available to represent the case study building as close as possible, since this building also seems to be build up with three in size differing volumes as could for instance be seen in *Figure 14*. Using this division into bottom part A, middle part B, and top part C, also makes it possible to investigate the influence of all three volumes separately.

The input of the value range of the different geometries during each design phase is based on the available different models for that specific phase. This means that the input range selected in each phase is largely determined by the range found in the different models created by the designers, in order to choose parameter ranges that are realistic and based on expert knowledge. The range obviously is getting narrower during the phases, as the opportunity to make large changes is getting smaller.

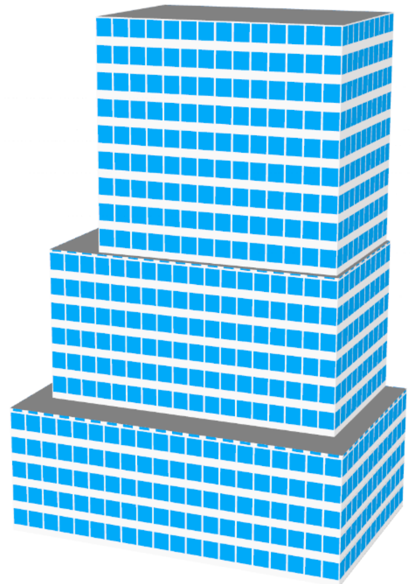


Figure 16: Visualization of variant of case study building in Rhinoceros/Grasshopper

The input values for the sensitivity analysis for all three investigated phases can be seen in *Table 5*. It is visible that the unit for the R-value is [m²K/W], while the unit for the U-value of the windows is [W/m²K]. The explanation of this sensitivity analysis can be found in *Appendix II*, and *3.2.2 Choice for*

Table 5: Sensitivity analysis input values in SD-, CD- and DD-phase:

Parameter	**Structure design**		**Conceptual design**		**Detailed design**	
	Base case value	**Value ranges**	**Base case value**	**Value ranges**	**Base case value**	**Value ranges**
Volume A	16500	15500-17500	16000	15500-16500	15750	15650-15850
Volume B	14000	13000-15000	14500	14000-15000	14600	14500-14700
Volume C	13000	11000-13000	12000	11000-12000	11500	11300-11500
Length ratio A	29	25-33	25	23-27	26,5	26-27
Depth ratio A	38	37-45	40	39-43	42,2	42-43
Height ratio A	16	10-18	15	12-16	14	13-14
Length ratio B	23	16-24	20	17-21	21	20-21
Depth ratio B	34	30-38	35	33-37	34,8	34,3-35,3
Height ratio B	19	16-24	18	16-20	17,9	17,5-18,5
Length ratio C	18	18-22	20	20-22	20,3	20-21
Depth ratio C	29	26-30	30	28-30	29,5	28,5-29,5
Height ratio C	30	26-30	28	26-28	27,9	27-28
Location	Beek	Amsterdam, Groningen, Beek	Beek	Beek	Beek	Beek
Orientation	0	-90-90	0	-10-10	0	0
North Glazing Ratio	0,4	0,2-0,8	0,7	0,6-0,8	0,75	0,7-0,8
West Glazing Ratio	0,3	0,2-0,8	0,6	0,6-0,8	0,75	0,7-0,8
South Glazing Ratio	0,2	0,2-0,8	0,6	0,6-0,8	0,75	0,7-0,8
East Glazing Ratio	0,5	0,2-0,8	0,7	0,6-0,8	0,75	0,7-0,8
R-value Wall [m²K/W]	8	3-9	6	4-6	4,5	4-5
U-value Window [W/m²K]	2	1-2	1,7	1,3-1,7	1,65	1,45-1,65
R-value Roof [m²K/W]	6	3-7	6	4-6	6	5-6
R-value Floor [m²K/W]	7	3-7	5	3-5	5	4-5

Morris sensitivity analysis. The grid that is chosen in this research is also scaled from 0 to 1, and the step size Δ is 0.5. The changes for each parameter during the sensitivity analysis following from these step changes can be seen in the tables in *Appendix V*. These tables, show the first trajectories in the different phases. In each trajectory, the order in which parameters are changed is different. For this research, a total of four trajectories for each design phase is used.

The explanation of a Monte Carlo uncertainty analysis has already been given in *3.2.3 Choice for Monte Carlo* uncertainty analysi*s*. *Table 6* shows the input values for the uncertainty analysis, in which mostly the same parameters have been used for each building phase. The parameters that have been given an value range in the SD phase have been marked in this table, for the other parameters the value is constant, and so the base case value is used. The input values for the other phases are visible in *Appendix VI*. It is visible that the base case value may have changed compared to the sensitivity analysis.

Table 6: Base case values and input value ranges for uncertainty analysis in SD phase

Structure Design Phase			
Parameter	**Base case value**	**Value ranges**	**Remarks**
Volume A	17500	15500-17500	*
Volume B	13000	13000-15000	*
Volume C	10500	10500-12500	*
Length ratio A	25	25-33	
Depth ratio A	**37**	**37-45**	
Height ratio A	10	10-18	*
Length ratio B	**16**	**16-24**	
Depth ratio B	30	30-38	*
Height ratio B	24	16-24	*
Length ratio C	19	18-22	*
Depth ratio C	28	26-30	*
Height ratio C	30	26-30	
Location	Beek	Amsterdam, Groningen, Beek	
Orientation	**0**	**-90-90**	
North Glazing Ratio	0,4	0,2-0,8	
West Glazing Ratio	**0,3**	**0,2-0,8**	
South Glazing Ratio	0,2	0,2-0,8	
East Glazing Ratio	**0,2**	**0,2-0,8**	*****
R-value Wall	**9**	**3-9**	*****
U-value Window	2	1-2	
R-value Roof	6	3-7	
R-value Floor	7	3-7	
* = Base case value is different from the sensitivity analysis			

Different other characteristics can also be used to gain further insight in the design decisions taken by the designer. The actual application of these characteristics can be found in *5.1 Mock-up preferences*. Some characteristics that can be visualized in order to understand the results are:

- *Window/Wall surface ratio*, or the Window-to-Wall Ratio (WWR), which has been mentioned before, is the measure of the percentage area determined by dividing the building's total glazed area by its exterior envelope wall area.
- *Exterior surfaces/Volume ratio*, which is the measure for the Compactness Ratio, and can very well addresses the energy efficiency of a building. Without considering insulation levels, orientation, or building system, the compactness ratio can in early design tell about how efficient the building is going to be.
- *Wall surface/Floor surface ratio*, which is a measure for the plan efficiency. It is an indication of the proportion of external wall required to enclose a given floor area. This measure is mostly related to building construction costs.

- *Skin load dominated vs. Internal load dominated*. Skin-load, or External-load dominant buildings are those whose energy use is determined by heat loss or gain through the exterior envelope, while for Internal load dominant buildings, the energy use is driven by high heat gain from occupants, lighting and equipment. This also gives the designer an overview of the design parameters to focus during the design process.

The characteristics, that will be used in combination with the value input ranges for each phase can be seen in *Table 7*.

Table 7: Mean building characteristics of the building designs in each phase

	Schematic Design	Conceptual Design	Detailed Design
Window/Wall surface ratio	0.49	0.70	0.76
Exterior surfaces/Volume ratio	0.22	0.20	0.19
Wall surface/Floor surface ratio	0.45	0.46	0.45
Skin load dominated vs. Internal load dominated	*Internal load dominated*	*Internal load dominated*	*Internal load dominated*

3.5 Mock-up creation

As mentioned, a mock-up of a tool is created in order to give the designers insight in the opportunities of using an building energy performance indication for making design decisions. The preferences for the final mock-up will mainly be based on the interviews with the different design experts. As mentioned before, in order to gain as many as possible input from the designers and give them as many as possible freedom in describing their own preferences, unstructured interviews will be conducted. This type of interview would also allow them to describe the level of difficulty that a mock-up is allowed to have, in order to make the tool workable.

From these interviews three main attributes for the creation of the mock-up became clear. The mock-up should contain:

1. an indication of the energy performance of the design in early design phases and its reliability;
2. an insight in focus points in order to improve the energy performance of the design.
3. an overview of all design possibilities in order to reach the desired energy performance target;

To address these attributes, different solutions are investigated in literature (Pianosi & Beven, 2016) (Struck, 2012) (Østergärd, 2017), or with actual input of the designers themselves. The decision to choose for certain solutions is based on the applicability for this specific research, and after consultation with the design experts, after which they are implemented in the final mock-up.

The application of these attributes can be found in *5. Mock-up of tool*.

4. Case study

4.1 Results sensitivity analysis

The different sensitivity ranking diagrams in *Figure 17* shows the results for the case study for the SD-phase. The results for the other phases can be found in *Appendix VIII.* The rankings of sensitivities for the heating and cooling load in kWh/m^2 are visualized, while the rankings for the PV generation in kWh can also be found in *Appendix VIII*. In this appendix all sensitivity results are arranged per phase, while in this chapter the parameter rankings in successive phases are also visualized side by side to be able to show changes within these different phases.

Schematic Design Phase Results

Figure 17 shows the ranking of parameters for the SD-phase. It is clearly visible that glazing ratios on the east, south and west façades are relatively high, all having a value of -2. In (c) is also visible that the Standard Deviation of these parameters is relatively low, since the sensitivity of this parameters is apparently relatively independent from other parameters. For the heating load, also the R-value of the wall and the U-value of the windows appear to have a relatively high sensitivity. It is also visible that the sensitivity of these two parameters is very much influenced by the other parameters.

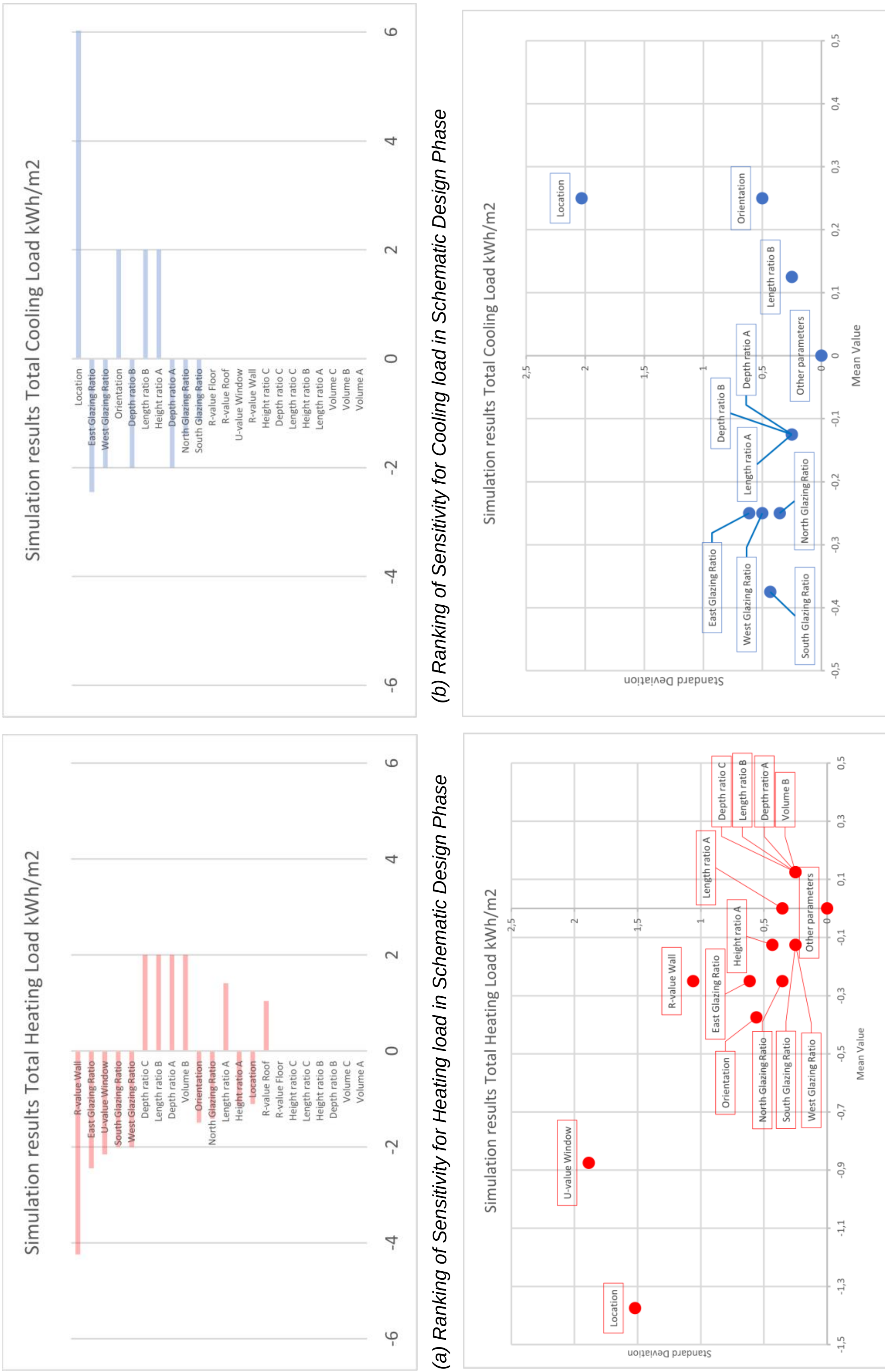
As earlier mentioned, the parameter location is also taken into account in this first investigated phase. As mentioned, for this research, this parameter represents different locations in the Netherlands. For the cooling load it is visible that the sensitivity of this parameter has a large sensitivity, since it is for both the cooling and heating load relatively much depending on the other parameters.

For the cooling load, the glazing ratios also have a relatively large sensitivity. A clear difference between heating and cooling load are the low sensitivities for the R-value of the wall and U-value of the windows.

Sensitivity in design phases

The differences between the successive phases can for each parameter be better visualized when placed side by side. This way, the changing sensitivity of single parameters can be more clearly offered to the designer. Two examples, one for the heating load, and one for the cooling load are visible in *Figure 18* and *Figure 19*.

The overview visible in *Figure 18* highlights the shifting rank of the U-value of the windows for the heating load during the design process. It is clearly visible that for the SD-phase, the U-value has a relatively high sensitivity, but decreases significantly for the following phases. When looking at the overall overview, it is visible that the largest amount of sensitive parameters can be seen in the CD-phase.



(a) Ranking of Sensitivity for Heating load in Schematic Design Phase

(b) Ranking of Sensitivity for Cooling load in Schematic Design Phase

(c) Interdependency of parameters for Heating load

(d) Interdependency of parameters for Cooling load

Figure 17: Sensitivity ranking and Interdependency of the input parameters for the Schematic Design Phase

Figure 19 shows an overview of the changing parameter sensitivity for the cooling load, while here also the parameter sensitivity of the U-value of the window is highlighted. Using this presentation method it can for instance be seen that the ranking of the sensitivity of this parameter is relatively high in especially the CD- and DD-phases, which is remarkably different then the ranking of the parameter for heating load, even though the actual sensitivity is relatively equal in these phases.

The geometry related parameters have for both the heating and cooling load significantly smaller sensitivities in the DD-phase. The amount of opportunities to change these parameters, and therefore the input range of these parameters is relatively small, resulting in a very low sensitivity compared to the other parameters.

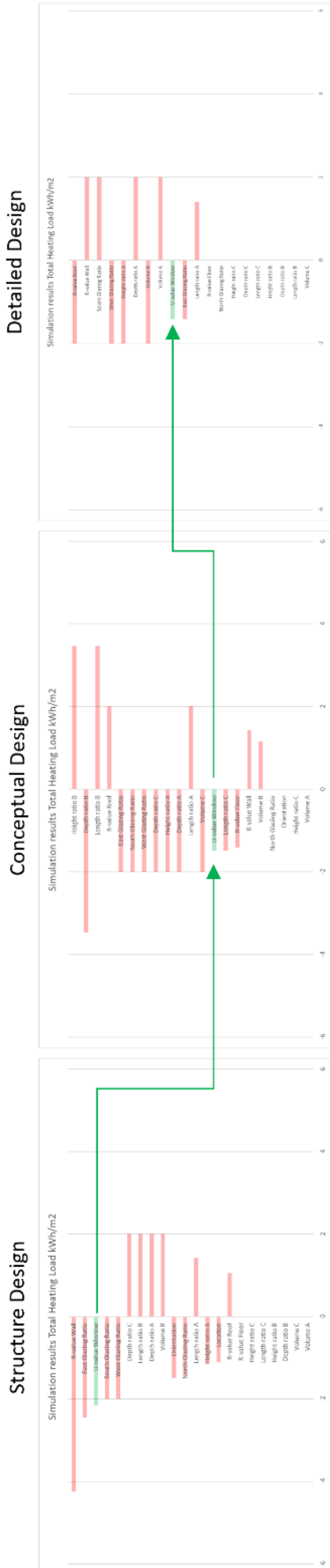


Figure 18: Different Heating load sensitivity ranking for a parameter through the design process

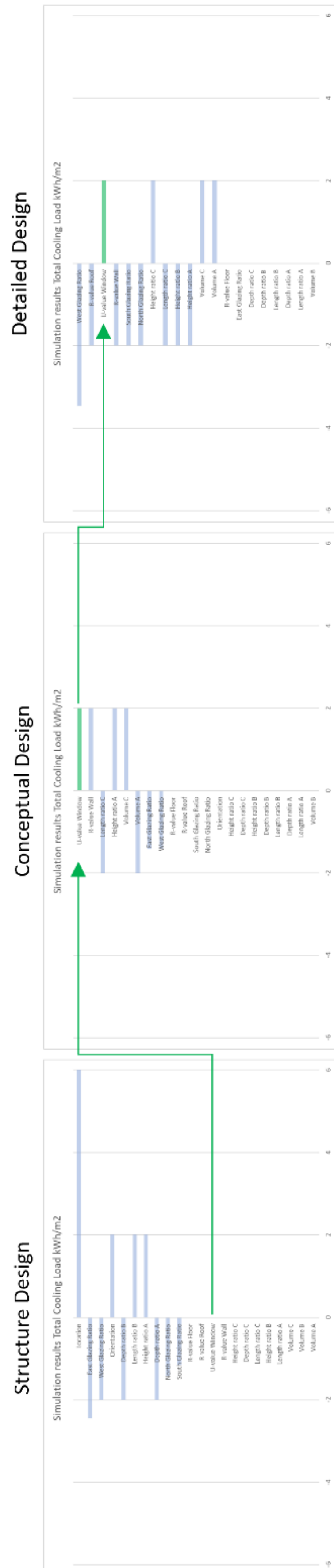


Figure 19: Different Cooling load sensitivity ranking for a parameter through the design process

4.2 Results uncertainty analysis

The mean indications of the heating and cooling loads resulting of the 64 simulations for each individual phase can be seen in *Figure 20*. When looking at the total mean expected energy load, an addition of the heating and cooling load, it is visible that for the case study in the SD- and CD-phase, it is indicated as 40,5 kWh/m^2, and increases to 41,5 kWh/m^2 in the DD-phase, which is only a 2% increase. It is visible that for the SD-phase, the heating load is indicated as 28,5 kWh/m^2 (70,5% of total load), while the indication of the cooling load shows 12 kWh/m^2 (29,5% of total load). These mean indications do not change in the CD-phase, and only the cooling load indication slightly increases to 13 kWh/m^2 (31,3% of new total load), which is an 8% increase in cooling load.

When comparing this indication to the reference building, it is visible that the total mean indication is relatively equal, since this building has a total energy load for cooling and heating of 41 kWh/m^2. The distribution of cooling and heating within this total load is in fact noticeably different, with 18 kWh/m^2 (43,9% of total load) for the heating load, and 23 kWh/m^2 (56,1% of total load) for the cooling load.

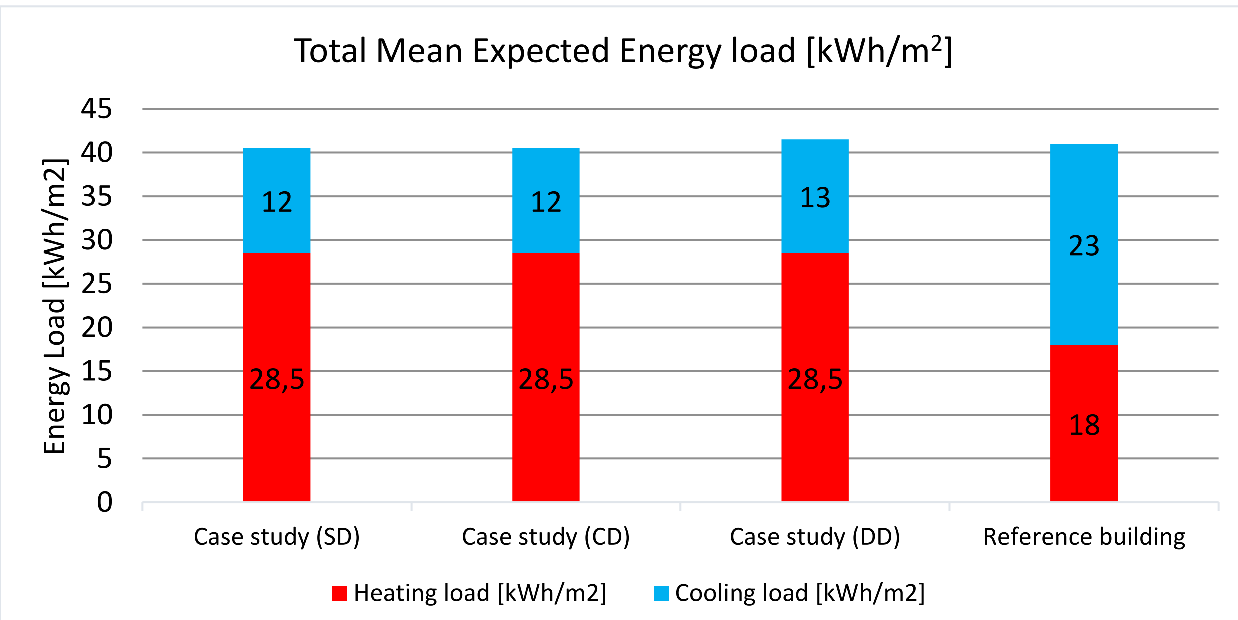


Figure 20: Expected heating and cooling load in kWh/m2 for the SD-, CD- and DD- phase of the case study and the reference building

The overview in *Figure 20* only shows an overview of the mean of the indication of the total energy load. To tell something about the reliability of these results, the total uncertainty is visualized in box plots as can be seen in *Figure 21*.

The red line in this figure shows the expected mean energy load per phase. The boxes in this figure above and under this red line show the Interquartile Range, which indicates the 25% to 75% of all results. The highest and smallest expected values are visualized by the horizontal outer horizontal lines, called the whiskers, as for instance visible in the heating and cooling load for the SD-phase. So called outliers, visualized as a red plus sign as visible in the DD-phase for the heating load, show a values that are only very occasionally observed.

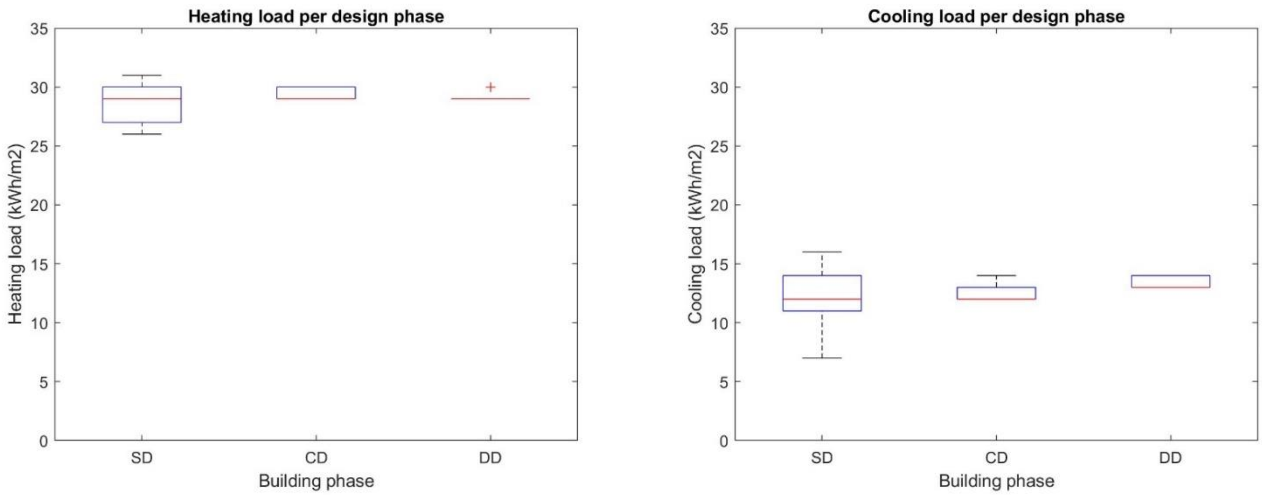


Figure 21: Heating and Cooling load indication with uncertainties for SD-, CD- and DD-phases

For the heating load in the SD-phase it is visible that results can be expected between 26 and 31 kWh/m^2. The range of results for the cooling load is larger, this range shows results between 7 to 16 kWh/m^2. The Interquartile Range is for both phases relatively equal, with a range of 27 to 30 kWh/m^2 for the heating load, and a range of 11 to 14 kWh/m^2 for the cooling load. This means that the larger total range for the cooling load can be assigned to the larger whiskers in this phase.

The amount of uncertainty has significantly decreased in the CD-phase. For the heating load, only results between 29 kWh/m^2 and 30 kWh/m^2 can be expected, while for the cooling load results between 12 to 14 kWh/m^2 are visible. In the DD-phase, the heating load range decreases even to a single value of 28,5 kWh/m^2, with an outliner for 29 kWh/m^2, while the cooling load range decreases to 13 to 14 kWh/m^2.

4.3 Discussion

Sensitivity analysis - Schematic Design Phase Results

The ranking of parameters for the SD-phase were shown in *Figure 17*. The very large sensitivity of the glazing ratios on the east, south and west façades for the heating load can be related to the relatively large range of input values (0,2-0,8) in this phase. In relatively low Standard Deviation of parameters visible in (c) can be explained by the fact that the sensitivity of this parameters is apparently relatively independent from other parameters. The relatively high sensitivity of the R-value of the wall and the U-value of the windows for the heating load could be explained by their own relatively large range of input, but also by the dependency of the range of actual glazing and exterior wall surface, of which was already mentioned that their input range is also large.

The high sensitivity for the cooling load of the location parameter can be explained with *Figure IV.2* in *Appendix IV*. During winter months, hardly any difference between the temperature characteristics of the weather file is visible. Therefore, the sensitivity of the heating load is low. During the warm summer days, relatively large differences for longer periods of time between especially Beek and Amsterdam are clearly visible. Therefore, the input range is relatively high, resulting in a large sensitivity for the cooling load.

The large sensitivity of the glazing ratios for the cooling load are also caused by the relatively large input range. A clear difference between heating and cooling load are the low sensitivities for the R-value of the wall and U-value of the windows. For the used locations in The Netherlands, the amount of cooling load is often less depending on the amount of insulation, since summertime heat gain is not so high that it investing in blocking this heat gain is of the highest relevance. Therefore for the cooling load, the relatively large range of geometry related input parameters, especially for the large volumes A and B, have a higher sensitivity in this phase.

Sensitivity analysis - Sensitivity in design phases

In the results it is visible that in the SD-phase, the U-value has a relatively high sensitivity, but decreases significantly for the following phases. This can, like earlier mentioned, be explained by the large input range in the SD-phase compared to the input range in the other two phases. The largest amount of sensitive parameters was found in the CD-phase. This means that within the possible range of input values for these parameters, there is a wide range of possibilities for the designer to choose from when improving the energy performance.

As visible, many of the remarkable parameter sensitivities can be explained by looking at the input ranges and building characteristics. It can be concluded that the input range of the parameters is a very important aspect to consider in the making of design decisions and the use of the tool. Therefore, this information will be coupled to the results in the mock-up of the tool, as can be seen in the next chapter.

Uncertainty analysis

The essence of the comparison to the reference building is to give the designer an insight of the level of performance of the design. Hardly any differences between the different total expected energy loads were visible for the building phases, and neither when comparing these results to the reference building. When comparing the heating and cooling loads to the reference building, large differences were actually clearly visible. Large differences can especially be explained by the different location of the two buildings and relatively large differences in input parameters such as the glazing ratios and insulation values.

For the results in the box plot diagrams can be said that they are less uncertain if the range of the boxplot is narrower. It is clearly visible that during the phases, the box plots for both the heating and cooling load are getting narrower, which means that the results are getting more reliable. This can be explained by the decreasing range of parameter input values. The results in the different phases are relatively in line with each other, make the results relatively reliable.

It is clearly visible that the range for all phases is narrower for the heating load indication than for the cooling load indication, meaning that there is less uncertainty in the results for the heating load. Visualizing these results in combination with insight in the characters of the design variants that lead to these results can inform the designer about how this uncertainty is established, which will be visible in the Mock-up.

The results of this analysis have been rounded off to values of 0,5. In the boxplot for the heating in *Figure 21* is visible that for the SD-phase, a full box with outliners is used to visualize the indication together with the uncertainty. For the CD-phase, no whiskers are visible, but only a box together with the red line showing the expected mean energy load. The whiskers, as mentioned earlier, represent the 25% highest and lowest results. Rounding off at halve values resulted in resulted in the CD-phase only in two results: 29 kWh/m^2 and 30 kWh/m^2. Since these were the only two observed values, no boxplot with whiskers could be created. Rounding the results off at 0,1 would lead to more detailed results. This effect is also visible for the cooling load results in the DD-phase. For the cooling load in the CD-phase, one whisker is visible, describing the top 25% of the results. Also here, there is no bottom whisker visible visualizing the lowest 25% of results.

For the DD-phase, only the red line showing the expected mean energy load, together with one outliner is visible. This means that only one value, of 28,5 kWh/m^2 is obtained. The outliner showing the result of 29 kWh/m^2 is a result that is more than can normally be expected. Also here, to gain more detailed insight, the results should be rounded at 0.1 kWh/m^2.

5. Mock-up of tool

5.1 Mock-up preferences

The relevant performance indicators that were for now used in this research are the total annual heating load in kWh/m^2, which is the amount of heat energy that would need to be added to a space to maintain the temperature in an acceptable range, and also cooling load in kWh/m^2, which is the amount of heat energy that would need to be removed from a space to maintain the temperature in an acceptable range. It has to be mentioned that the energy needed for ventilation, lighting and equipment have here not been taken into account. To be able to offer the designers an indication of the grade of their design, these indicators will be expressed in kWh/m^2, and compared to a reference office building, which is for this study a building used in IEA SHC Task 56, located in Stuttgart (D'Antoni, Bonato, & Loonen, 2017). The relevant characteristics of this reference building and energy load results can be found in *Appendix VII*. This use of a reference building serves to give the designers insight in the reason in the actual meaning of their obtained performance indicators.

Visualization of certain building characteristics can be used to help in the interpretation of the rankings. A large advantage if making use of the coupling with IFC models is that this geometry related information is already stored in the models, resulting in no more need for manual determination of these values. A list of geometric building characteristics has already been mentioned in *3.4.3 Case building in Grasshopper*.

Relevant building characteristics can be visualized for each individual building variant that has been parametrically designed, but a mean of all building design characteristics can be used to link to the sensitivity ranking, and to make these results better interpretable for the designer. The mean building characteristics that are used for the interpretation of the parameter rankings of the case study are visible in *Table 7*. In this table can be seen that the building is considered as Internal load dominated. This is mainly caused by the fact that typical office parameters have been presumed for the equipment load (11 W/m^2), Lighting (10 W/m^2), and People per area (0,25 ppl/m^2) in each phase, as mentioned before in *Table 4*.

As a result of this investigation of different solutions, the following methods of results presentation, in combination with the building characteristics and comparison to a standard building, were chosen:

1.1 *Stacked bar diagram*

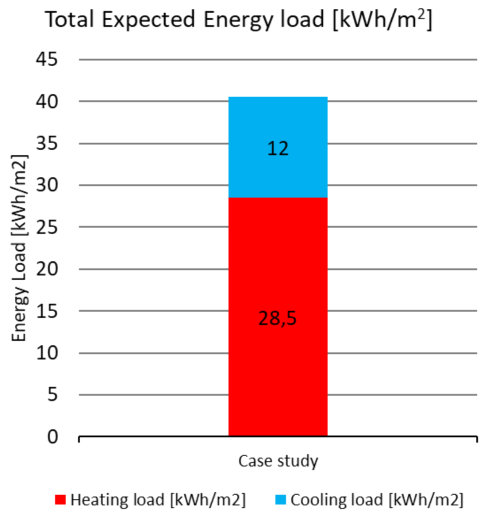


Figure 22: Stacked bar diagram used for showing a total energy load indication of the design

To tackle the first previously mentioned mock-up preference of the designers, a stacked bar diagram is used. A stacked bar diagram is showing a relatively straight-forward overview of the expected total energy load of the building design. It also shows a clear overview of the share of the cooling and heating load in the total energy expected energy load. Next to this, it also very useful for comparison to the reference results. It does not give an insight in the uncertainty of results, and is therefore combined with a box plot.

1.2 Box plot

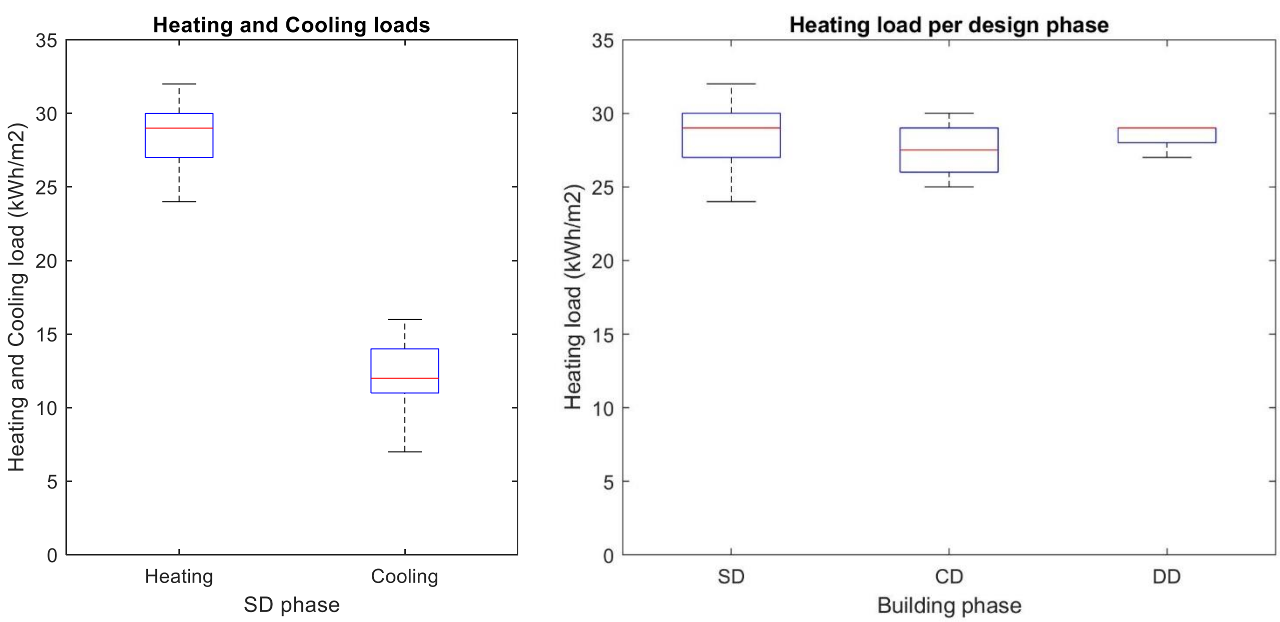


Figure 23: Box plots showing an indication of the Heating and Cooling load for a single design phase, and of the Heating load for consecutive phases

The total uncertainty of results that have been showed in the stacked bar chart diagram can be made visible in a box plot diagram. This could in the first place be done for individual phases, but the growing certainty through the different phases can be better visualized in an overview of box plots in one figure.

2.1 *Parameter sensitivity ranking*

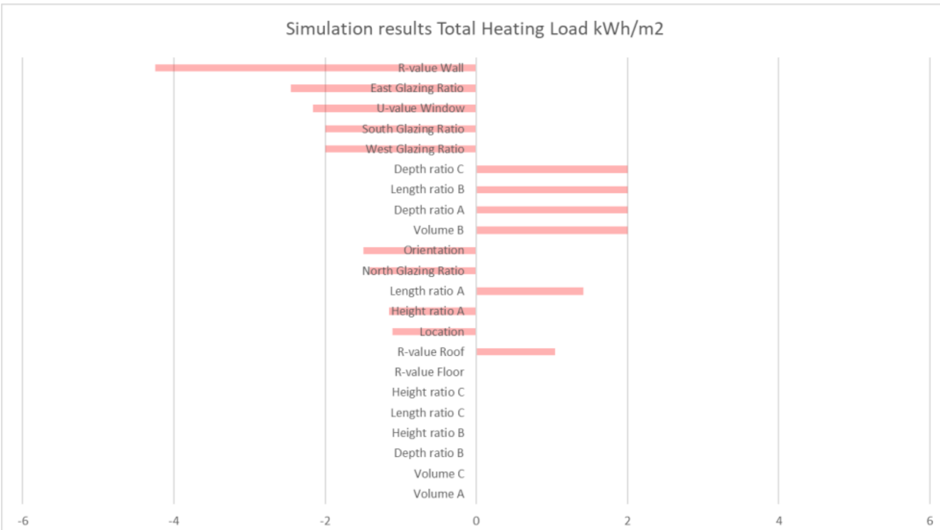


Figure 24: Ranking of the sensitivity of parameters on the total Heating load

The second attribute will be addressed by showing a ranking of the sensitivity of the different input parameters on the total heating load. This information was not only used for determining the input parameters in the uncertainty analysis, but can also offer the designers a focus point when striving to improve the design.

2.2 *Parameter interdependency overview*

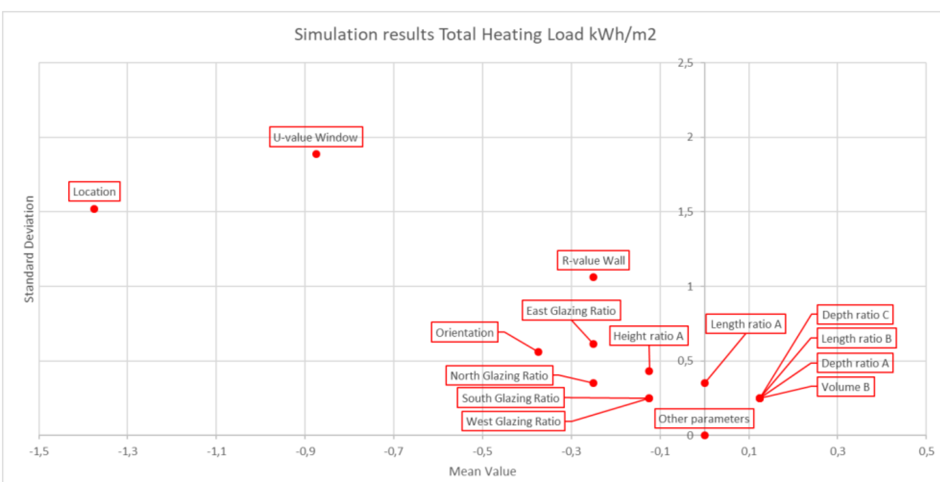


Figure 25: Overview of the interdependency of parameters for the total Heating load

A large advantage of using the Morris method for the sensitivity is the possibility to gain information about the standard deviation, which is an measure for the dependency of a certain parameter on other parameters. It is therefore here named as the interdependency. This overview is used in combination with the sensitivity ranking to inform the designer of the parameters that can best be focused on in order to improve the energy performance.

3.1 Parallel Coordinate Plot (PCC)

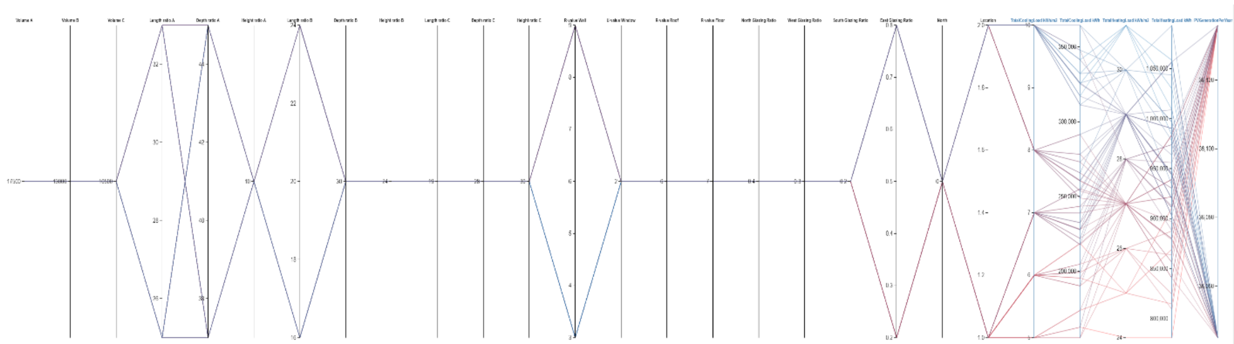


Figure 26: Parallel Coordinate Plot

To be able to explore design options that result in a desired energy performance, a Parallel Coordinate Plot (PCC) can be used. A CSV file containing all results of the uncertainty analysis, obtained from the Grasshopper tool, can be used as input file for online tools, such as the mentioned Design Explorer tool. The PCC provides an overview of not only the input ranges and constants, but also the full range of result outputs. By selecting only a desired range of result outputs in the tool, the PCC tool shows all combinations of design input parameters leading to this desired output. The results of a Monte Carlo analysis are commonly used in combination with a PCC (Østergärd, 2017). Therefore this method is very desirable for this research.

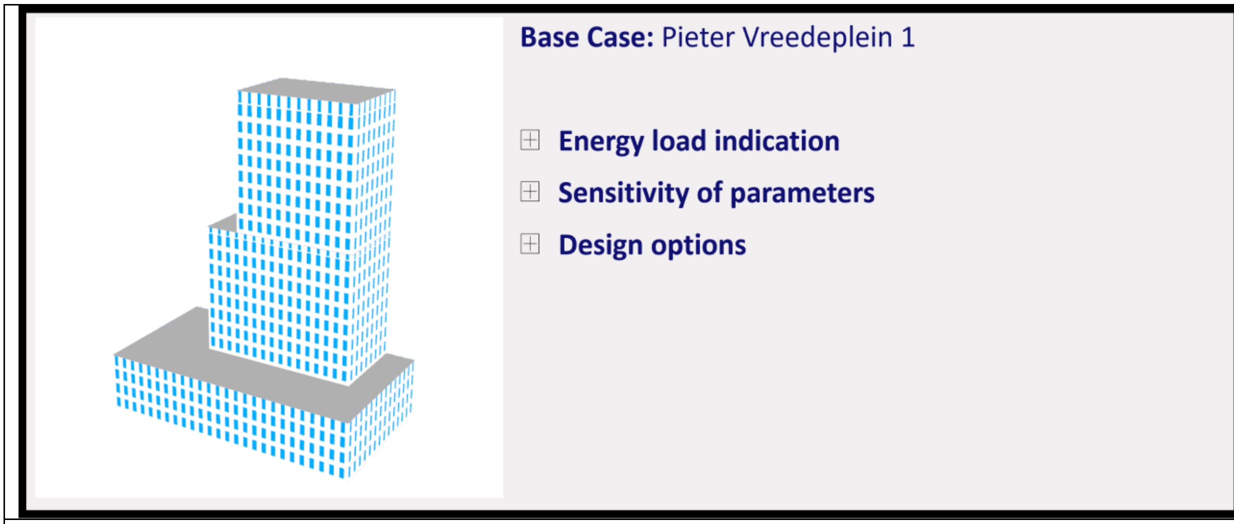
To show the functioning of the tool with the mentioned ways of presenting results, a method needs to be pitched up which serves as accessible mock-up of the actual tool. A very effective method for this accessible mock-up turns out to be an interactive, clickable presentation, to allow the designers to explore the opportunities of the tool themselves. Different versions of these presentations were created, of which one is used in the final mock-up.

5.2 Final Mock-up

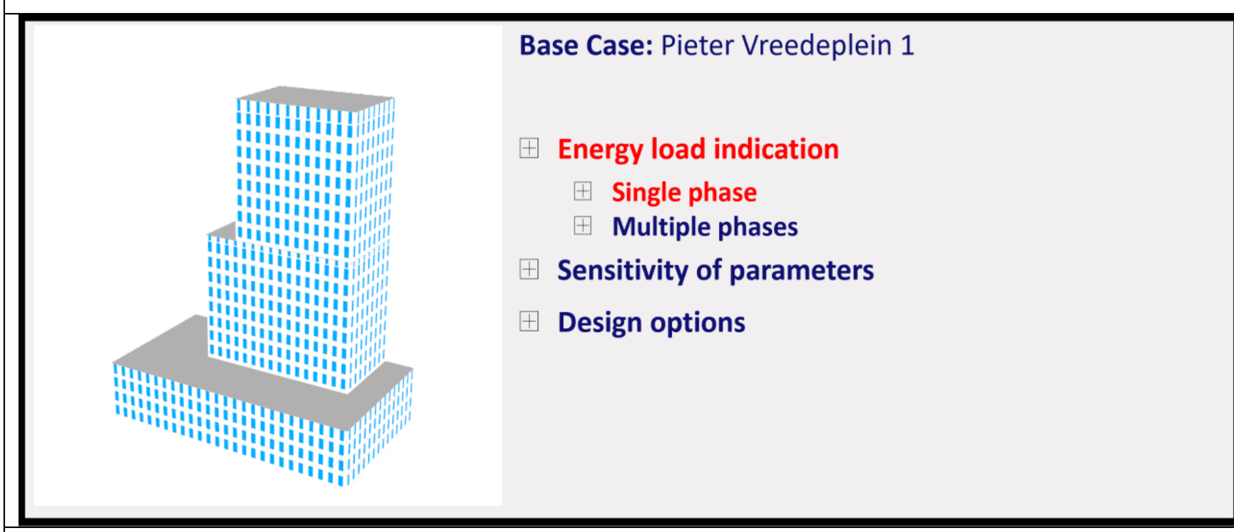
The final mock-up is visualized using the following series of figures in *Table 8*. Each figure contains a short explanation or instructions of the use of the tool.

In the ideal situation, a coupling with the models created by the designer would be used as input file for the parametric modelling. Using that model, maximum allowed parameter ranges would be chosen by the designer after which automatic sensitivity analysis takes place, on which the automatic uncertainty analysis is based. Results of these automatic simulations together with feedback will be offered to the designer in a straightforward way as will be showed, in order to help the designer improving the design in the early design phase.

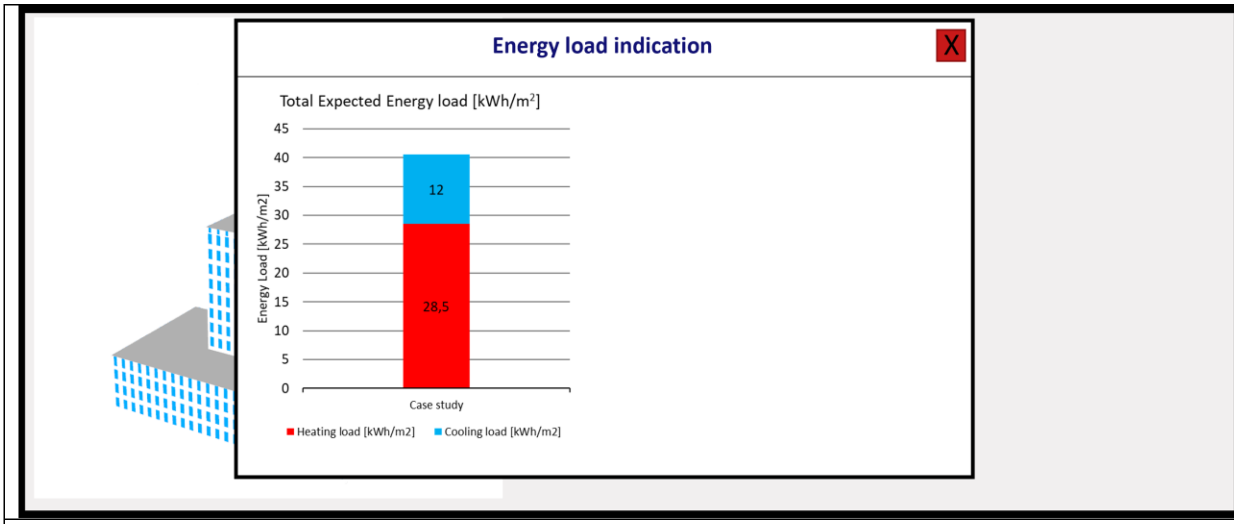
Table 8: Visualization of final mock-up



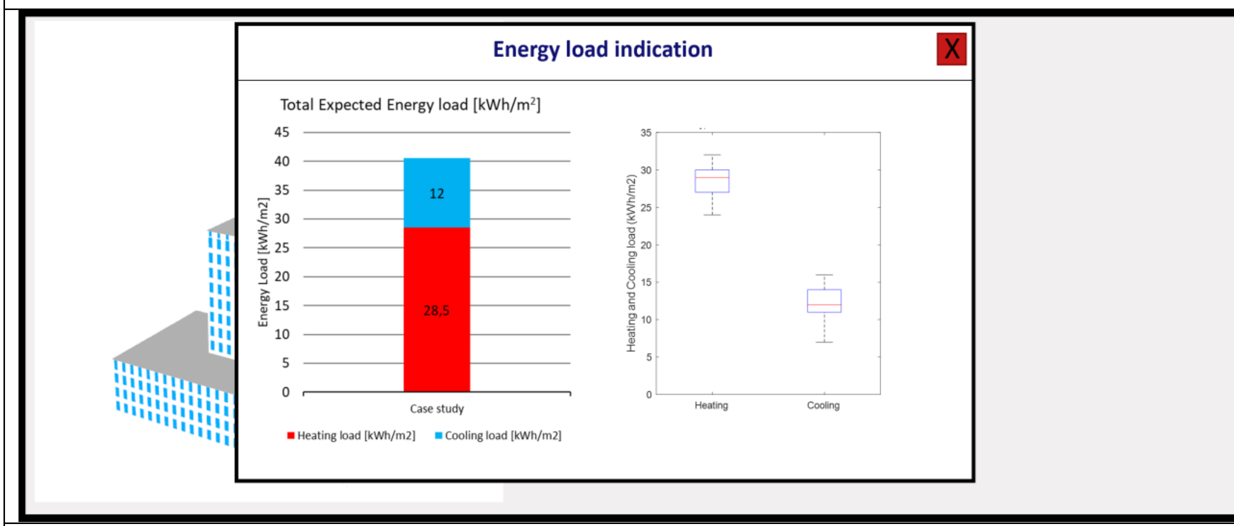
The tool shows a visualization of the base case geometric model that has been input, in this case of the Pieter Vreedeplein 1. It is visible that three options are available: an indication of the energy load, the sensitivity of parameters and the overview of different design options.



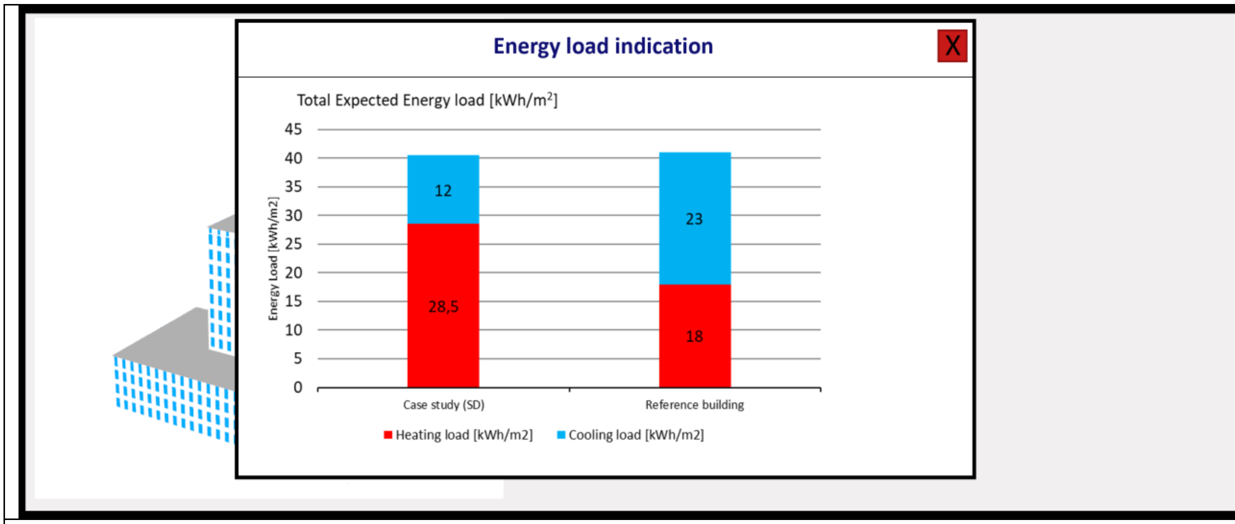
The energy load indication can be given for a single phase.



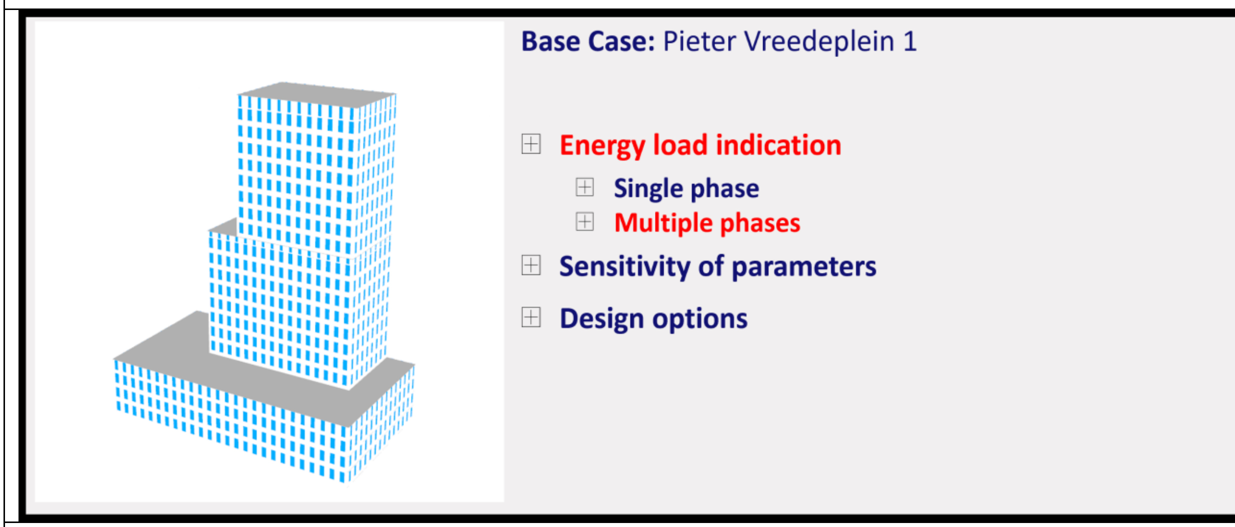
This first offers an stacked bar diagram giving an indication of the heating and cooling load in kWh/m² for this phase.



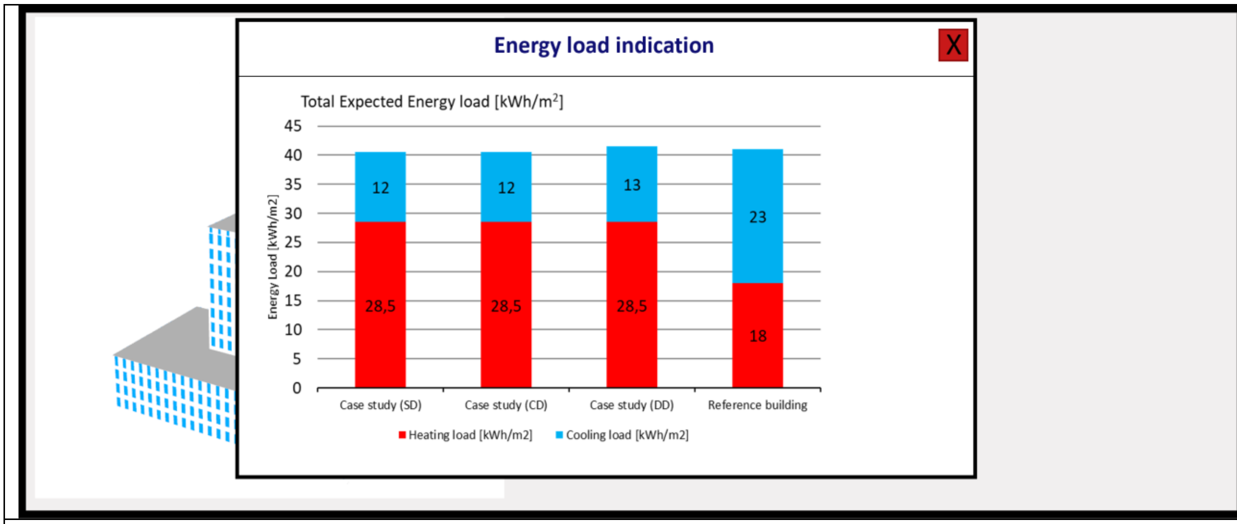
To gain information about the certainty and reliability of these results, an additional diagram can be shown offering the total range of simulation results in a box plot. This gives an overview of all results that have been received from the simulations, and so the results that can be expected.



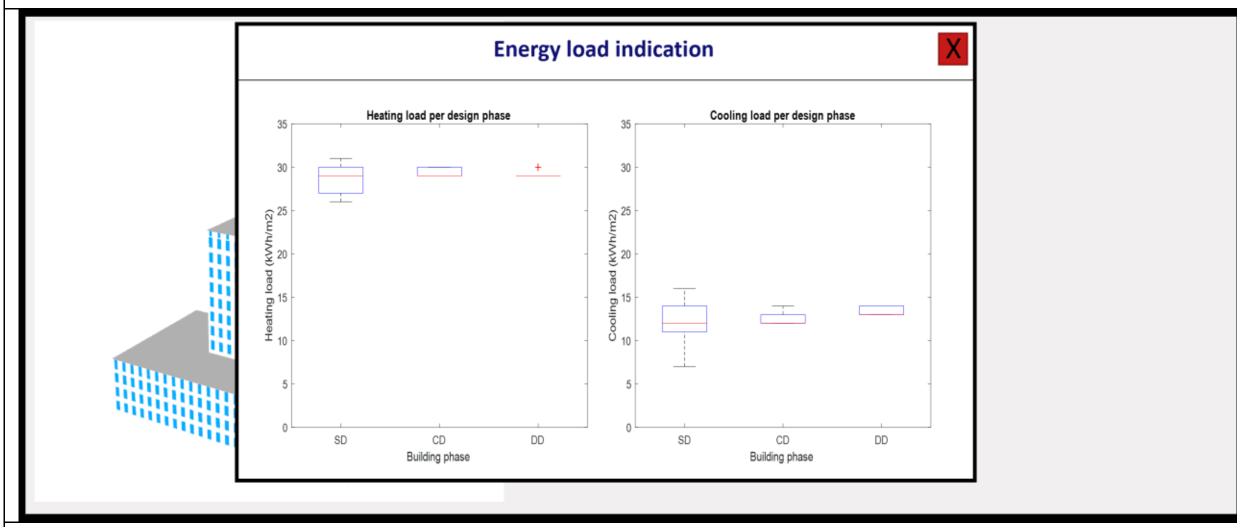
In order to give the designer insight in the level of performance of the design, the results are compared the energy loads of a reference building.



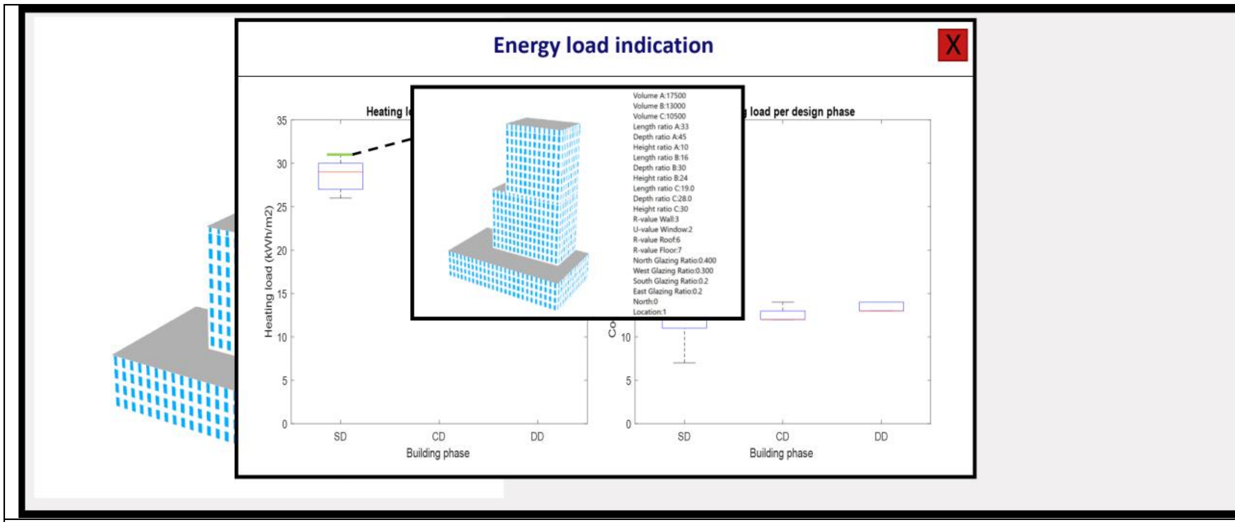
Next to the energy load indication of a single phase, the designer can also gain insight in the changing energy load and uncertainties in the building phases.



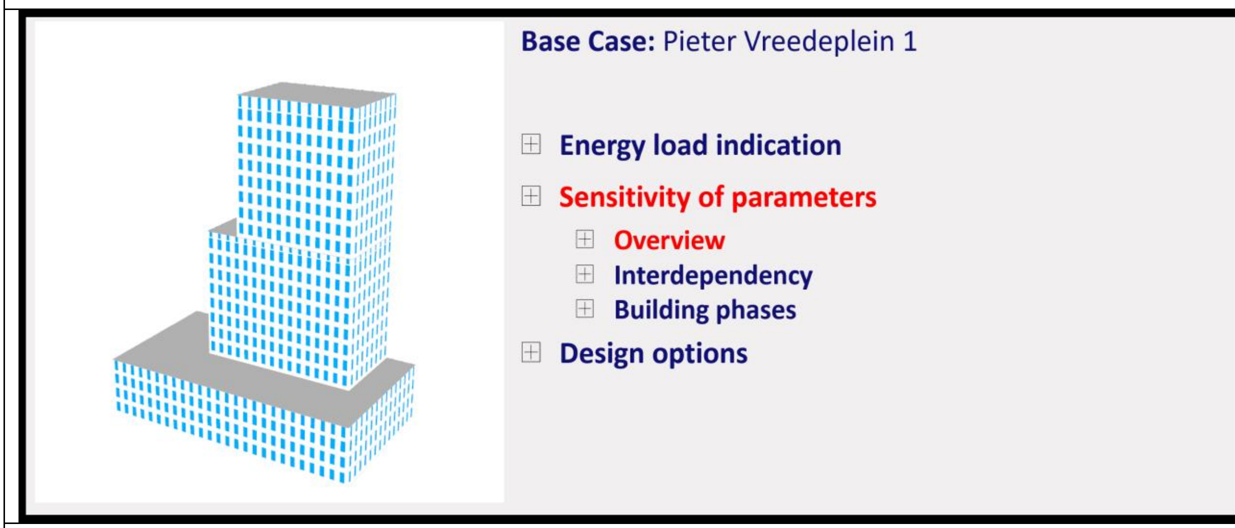
This insight can be given by again using a stacked bar diagram showing the results for the successive phases, compared to the reference building.



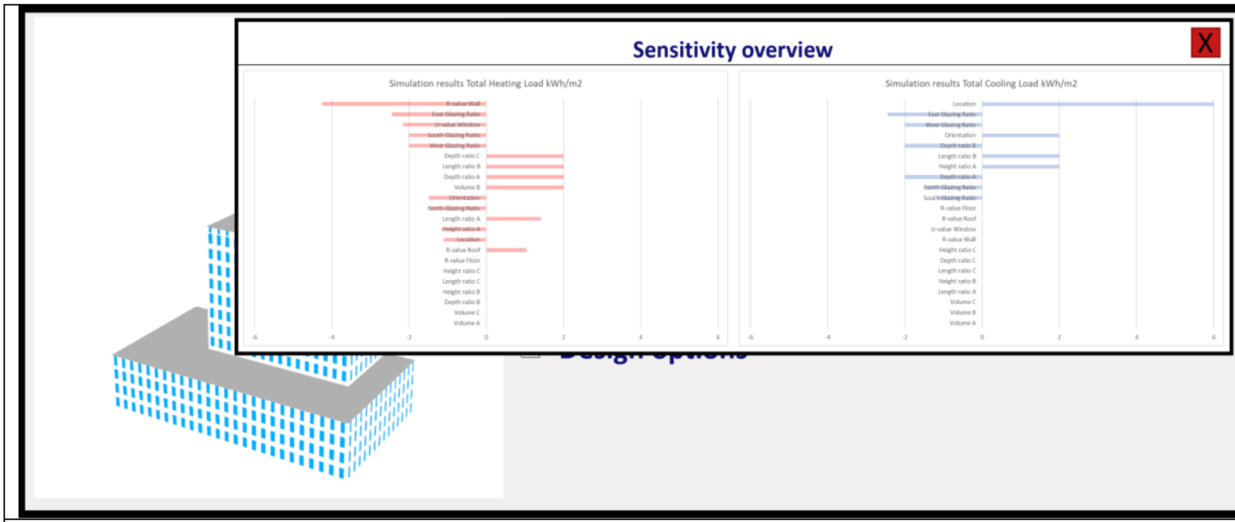
The bar diagrams can be supported by using a collaboration with box plots to offer an overview of the changing uncertainty through the successive phases.



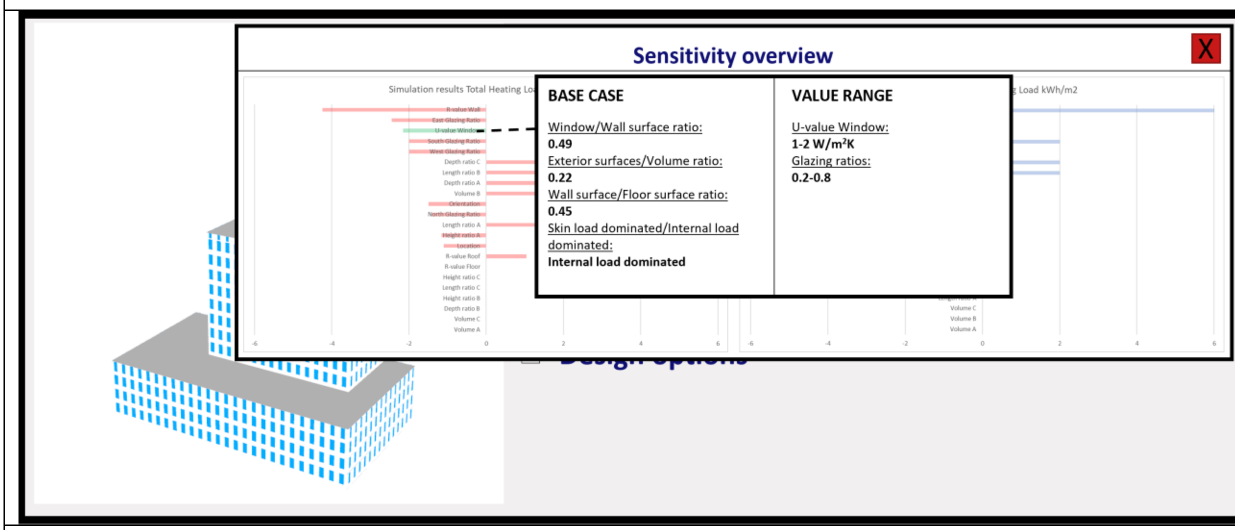
By offering the option to select results, for instance the result determining the highest simulated value, and allowing the designer to see the combination of parameters that lead to this result, the designer will be able to detect the cause of the actual uncertainty in a phase. It is next to this possible to offer the designer insight in the which parameters are significant input values, that could be the reason for this noticeable result.



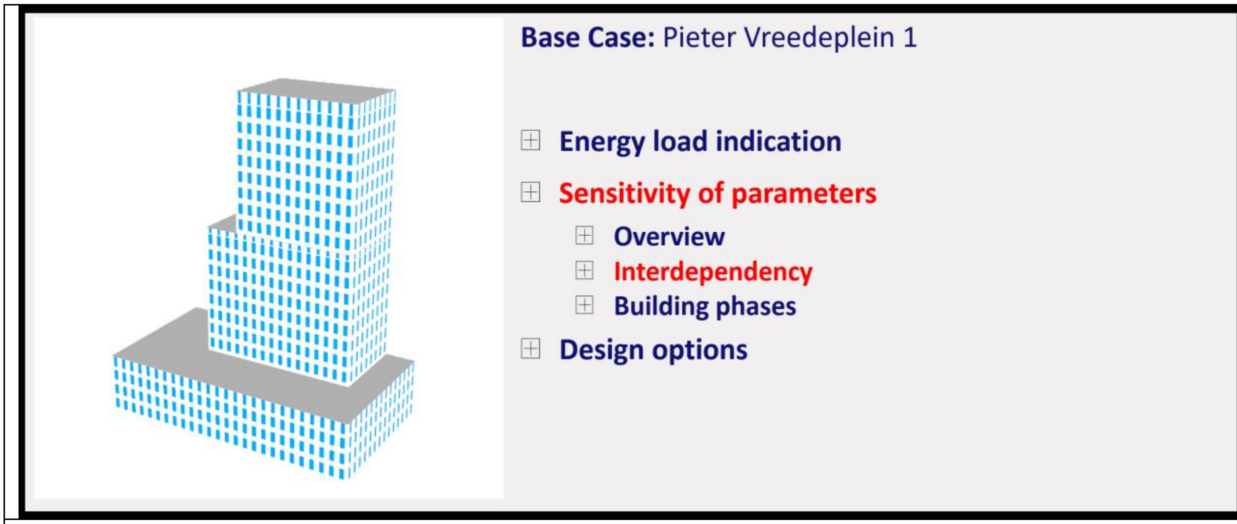
Next to the energy load indication, the designer can also gain insight in the different sensitivities of input parameters.



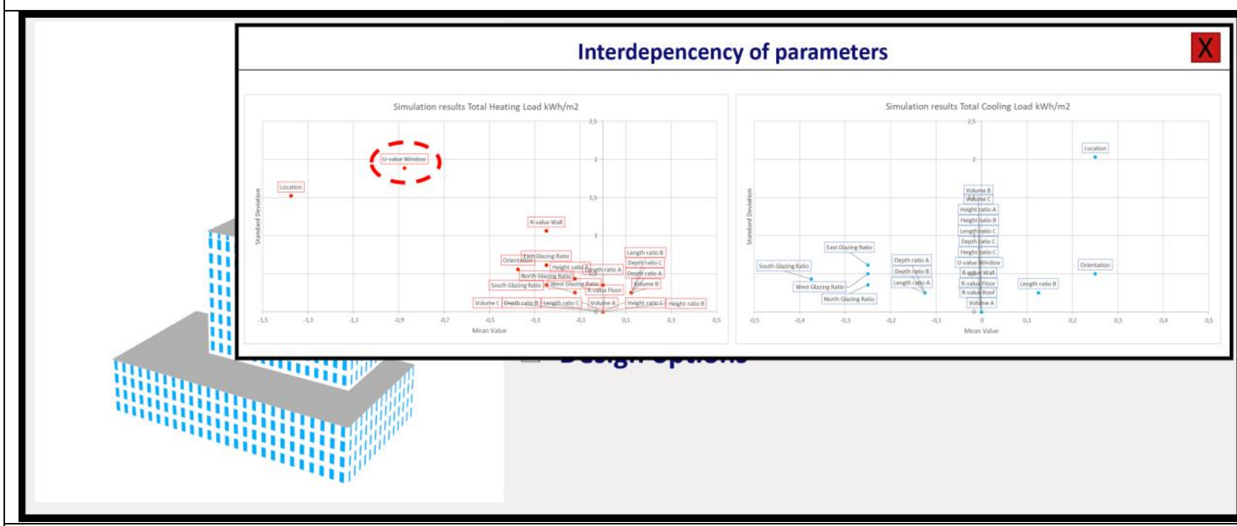
This sensitivity overview per design phase could give the designer information about parameters to focus on in order to improve energy performance of the design.



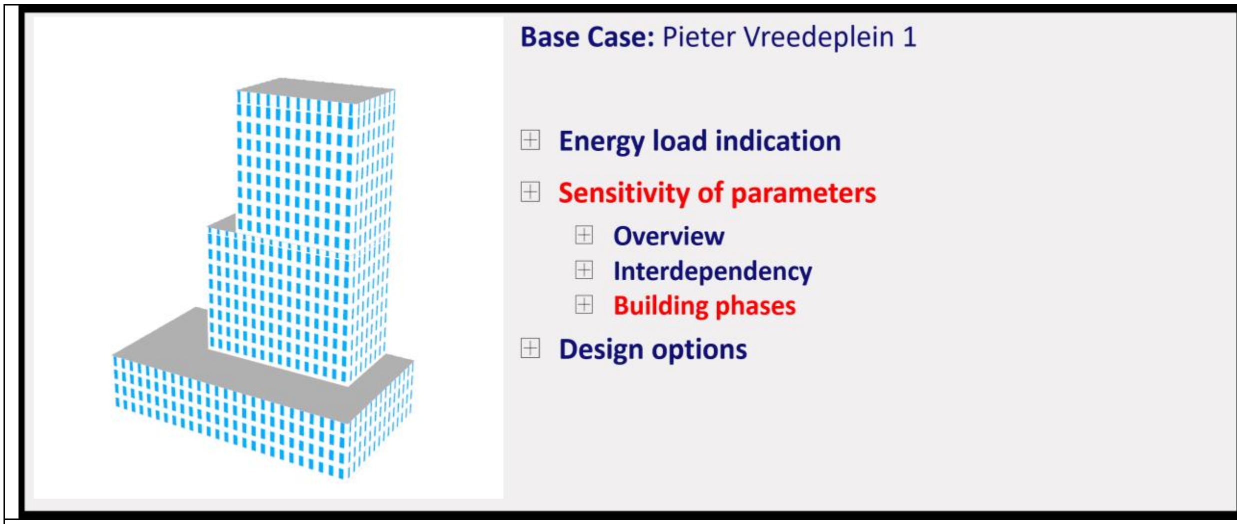
The designer also get the option to select a parameter, and find out about the reason for the specific ranking of this parameter. This shows an overview of certain typical building characteristics, together with noteworthy parameter ranges, that may have had an influence on the sensitivity of this parameter.



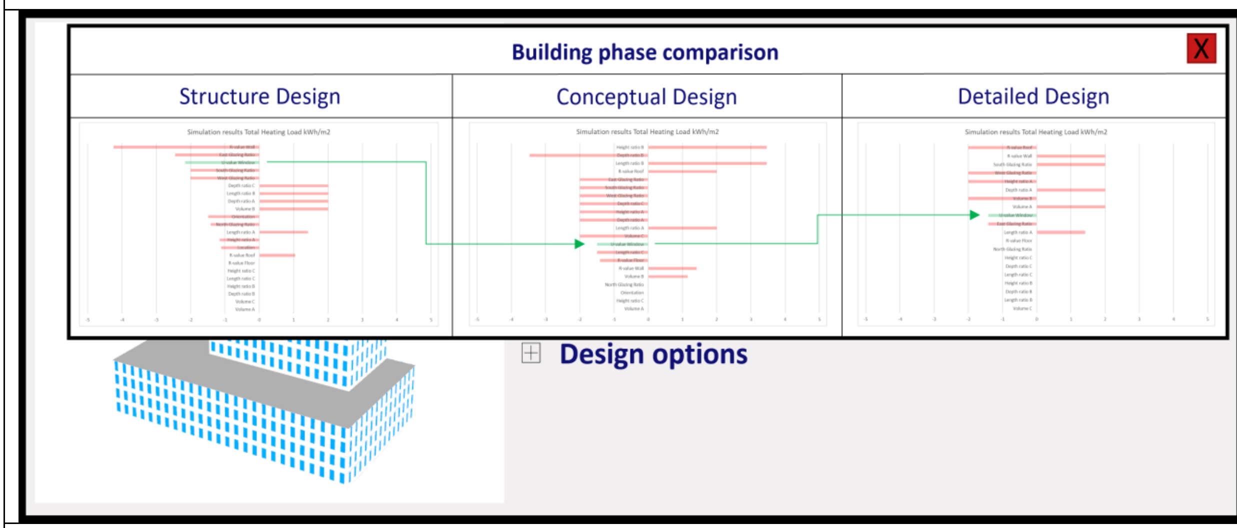
Sensitivity of parameters can also be depending of other parameters. This "interdependency" of parameters can also be visualized to the designers.



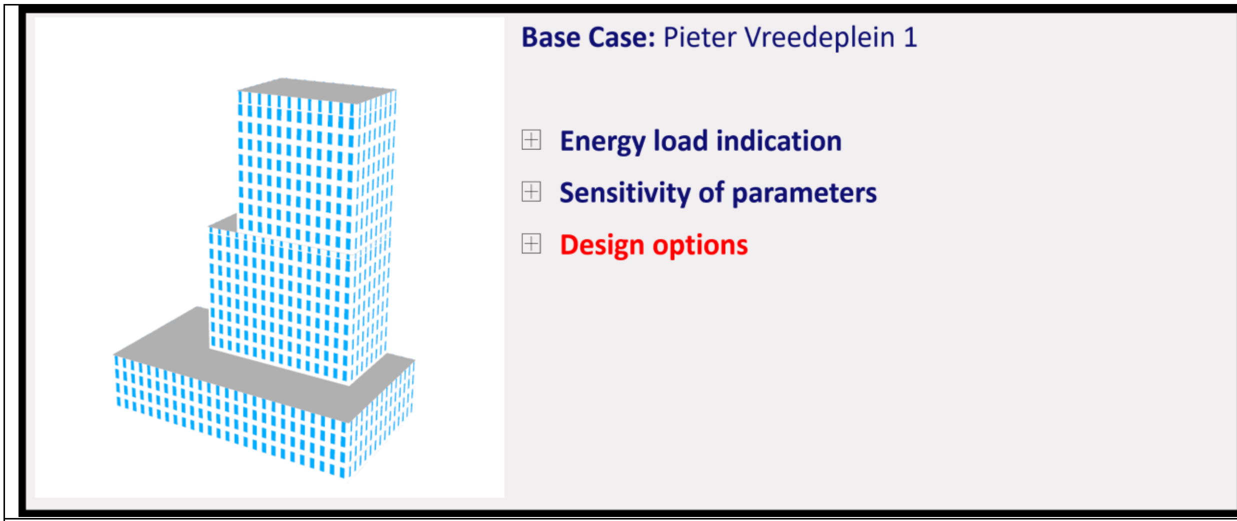
The interdependency tells how much the sensitivity of a parameter is influenced by other parameters. It is therefore important for the designer to consider when trying to improve the design while focusing on certain sensitive parameters.



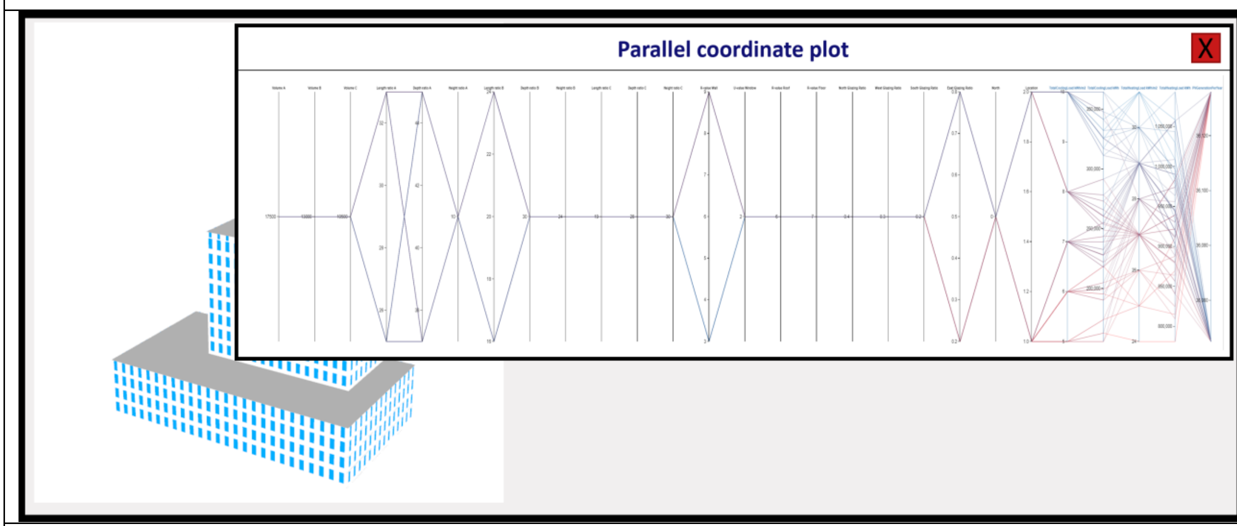
The ranking of parameters may change during the design phases, which means that the parameters to focus on in the early design change. An overview of this change is also visualized.



In the overview of the sensitivity rankings is made by offering the results of the successive phases side by side. By selecting one of the parameters, the changes in sensitivity ranking become clearly visible.



The designer can also be informed with information about which of combinations of input parameters result in a certain desired outcome of energy performance.



The design options that result in a desired energy performance can be explored by using a Parallel Coordinate Plot. Using this method, a desired range of performance results can be selected, showing all input parameters that lead to this result. The designer can use this information to be able to exclude certain parameters, and to obtain a narrowed range of design options.

5.3 Discussion of Mock-up

The mock-up currently only is a representation of an actual tool providing automatic insight of the expected energy performance. The information provided to the designer is attempted to be as easy, straightforward, and usable way as possible. There are still thing that can be added to the model to increase reliability and usability.

A current limitation of the model is that for instance only a certain selection of parameters has been investigated. Influencing parameters such as the infiltration rate, different sun shading systems or HVAC systems can still be investigated, to gain insight in their influence, also even in the earliest design phases.

Next to this, by offering information about for instance the costs related to design decisions, or a coupling to energy labeling, the designer could get a broader insight in the effect of his taken decisions.

Showing different choices during the creation of the mock-up of the designers, and giving them the opportunity to provide feedback on the final mock-up proves that the tool has an high usability, and also makes the outcome of the mock-up relatively reliable.

6. Conclusions

6.1 Main conclusions

Many AEC-experts are willing to use energy performance data, even already in early design, in order to improve their design or speed up the time for making design decisions. This research focused on finding a method for designers to gain a quick and understandable insight in the energy performance of their created building design.

The amount of information provided to the designer can very easily be complex or extensive. In order to provide the designer a relatively quick and straightforward insight in the expected building energy performance, only the heating and cooling load in kWh/m^2 were provided and compared to a "standard reference building". The way of providing this information as showed in the final mock-up is a very convenient method for giving the first insight, on which certain design decisions can be based in order to improve the design. This mock-up is actually the best method to give answer on the problem definition, since it shows an uncomplicated method for the designer to use energy performance data in early design phases to improve the sustainability of the building design. The use of this method could definitely positively change the design process.

The coupling of the IFC-models created by the designers with the Grasshopper tool points out to be a very complex procedure, which is very prone to errors. Very basic models, of which building element have been accurately defined, can often be imported relatively flawless, but complexity in models very often results in errors. Before creating an actual feedback tool, this coupling, or the setup of the building models, has to be further investigated to create a more effortless collaboration between the different software.

Simulations often take a large amount of time to run, sometimes even up to 10 minutes each. Also the amount of possible simulations to run is relatively low, determined by the internal memory of the Grasshopper tool. More parameters could be investigated simultaneously if the tool had allowed this. The Grasshopper tool used Colibri for the automatic Monte Carlo uncertainty analysis, but lacked the opportunity to provide an automatic Morris sensitivity analysis, which would also speed up the process significantly. Total time for providing the designer with results could therefore be significantly reduced. In the current state, in which large time is needed to perform all the simulations, it can seriously be doubted if the use of energy performance information in early design phases actually speeds up the design process.

The case study showed that parameters with relatively high sensitivities, and so the parameters to focus on in order to improve the design can significantly diverge for each phase. It is therefore important to make an overview for all phases to investigate what the effect of a parameter change could yield. The amount of uncertainty through the building process is indeed decreasing, as was also mentioned in the literature research, most often caused by the lower value input ranges, and so the smaller opportunities to change parameters.

The results of the case study are specific for this individual project. They do not provide information about the uncertainty of other comparable types of buildings, since different parameters may have different influences on uncertainties for each individual building. For building design in general can be said that the chosen range of input parameters has an considerably large influence on the sensitivity of parameters, but also to the total uncertainty of results. For this research, literature and advice from design experts was used to determine the input ranges. It is highly advised that input value ranges should be considered very thoroughly before being used.

Using this, or any comparable mock-up does not mean that the role of the engineer in early design disappears. The suggested tool only gives first insight in results that could be expected on which design decisions can be based, while the role of the engineer is much more far-reaching than that. An improved collaboration of AEC-professionals, for instance by using these tools, could actually shift the build-up of building phases. Using these tools that provide an indication of the energy load of the design, as a handhold for decision making, could not only speed up the designing process and therefore decrease costs, but also decrease the need to make up for limitations of a design which are found in later phases. This sounds very promising, but at this point in time, making an actual tool providing this collaboration seems hardly possible, and a lot of research is still needed to make this collaboration available. Creating this collaboration that would give a very straightforward insight in performance information proves to be a very complex activity also needing far more investigation.

6.2 Future work

This research provides a mock-up for an actual tool supporting the designer in making energy performance based design decisions in early design phases. A next step could be to actually implement this mock-up by creating an actual tool. Therefore, certain steps will still need to be taken first.

For instance, the collaboration between IFC-models and the parametric simulation tool has to be improved. This can be started by further investigating the most common errors in the import of a model into the simulation tool. Also a large step forward could be made by composing a set of properties that a geometric model should at least have, in order to make it suitable for the export into the parametric tool. An addition to this is the use of tools like SimpleBIM, in which geometric IFC models can be simplified allowing for easier parametric modeling, and import to the simulation tool with just the information that is needed for an energy simulation

The current research has only investigated a certain amount of parameters, which were based on mostly literature and preferences of the interviewed design experts. Future work could contain the investigation of different parameters that have not been investigated in this research, but may also have a relatively large sensitivity or influence on the energy load.

In this research, only the heating and cooling load have been used as performance indicators. To develop a tool even further, information of for instance the solar gains, internal gains, ventilation losses and infiltration losses would also be very useful information for the designer. Also here, an appropriate method has to be provided in order to make the offering of this information useful. Next to this, coupling to for instance energy labeling, or coupling to actual costs could be very useful design indicators as well.

The results of this study are case building specific. A larger investigation to multiple buildings could result in statistical results of the same building types. These results could also be used by designers in early phases to give an insight in the parameters to focus on in order to improve their building design.

7. Bibliography

AIA. (2013). Building Information Modeling Protocol Form. The American Institute of Architects.

Al-janabi, A. (2019). Comparison of EnergyPlus and IES to model a complex university building using three scenarios: Free-floating, ideal air load system, and detailed. *Journal of Building Engineering 22*, 262-280.

Andriamamonjy, A. (2019). A combined scientometric and conventional literature review to grasp the entire BIM knowledge and its integration with energy simulation. *Journal of Building Engineering 22*, 513-527.

Arayici, Y. (2018). Interoperability specification development for integrated BIM use inperformance based design. *Automation in Construction 85*, 167-181.

Asadi, S., Amiri, S., & Mottahedi, M. (2014). On the development of multi-linear regression analysis to assessenergy consumption in the early stages of building design. *Energy and Buildings 85*, 246-255.

Attia, S. (2009). "Architect Friendly": A Comparison Of Ten Different Building Performance Simulation Tools. *Eleventh International IBPSA Conference*, (pp. 204-211). Glasgow, Scotland.

Azhar, S. (2011). Building information modeling for sustainable design and LEED® rating analysis. *Automation in Construction 20*, 217-224.

Baldwin, A. (2010). Modelling information flow during the conceptual and schematic stages of building design. In *Construction Management & Economics* (pp. 155-167). Routledge Taylor & Francis Group.

Barosan, I. (2017, November). Intro to SysML. *Lecture slides of the course Fundamentals of Building Information Modeling*. Eindhoven: Eindhoven University of Technology.

Bax, M. (1992). *Concepten van de bouwkunde.* Eindhoven: Eindhoven University of Technology, Faculteit Bouwkunde.

Bazjanac, V. (2011). An Assessment Of The Use Of Building Energy Performance Simulation In Early Design. *12th Conference of International Building Performance Simulation Association*, (pp. 1579-1585). Sydney.

BNA. (2014, May). *Standaardtaakbeschrijving (STB).* Retrieved from BNA, Branchevereniging Nederlandse Architectenbureaus: http://www.bna.nl/standaardtaakbeschrijving-stb

BuildingSmartAllicance. (2007). *National Building Information Modeling Standard.* National Institute of BUILDING SCIENCES.

Cheung, F. (2012). Early stage multi-level cost estimation for schematic BIM models. *Automation in Construction 27*, 67-77.

Colibri. (2019). *TT Toolbox, Food4Rhino, Apps for Rhino and Grasshopper*. Retrieved from https://www.food4rhino.com/app/tt-toolbox

D'Antoni, M., Bonato, P., & Loonen, R. (2017). *IEA SHC T56 - System Simulation Models - Office Reference Building - Part C.* Solar Heating & Cooling Programme, International Energy Agency.

DesignExplorer. (2019, September). *DesignExplorer Github*. Retrieved from http://tt-acm.github.io/DesignExplorer/

Dynamo. (2019, May). *Dynamo, Open source graphical programming for design*. Retrieved from https://dynamobim.org/

EC. (2019, May). *Energy performance of buildings*. Retrieved from European Commission: https://ec.europa.eu/energy/en/topics/energy-efficiency/energy-performance-of-buildings

EnergyPlus. (2019, May). *EnergyPlusTM*. Retrieved from https://energyplus.net/

Ferreira, G. (2016). *An Enhanced Programming Environment for Generative Design.* Lisboa: Universidade de Lisboa.

gbXML. (2019). Retrieved from Green Building XML: https://www.gbxml.org/

GeometryGym. (2019, May). *GeometryGym, openBIM Interoperability tools for BIM and Structural Analysis*. Retrieved from https://geometrygym.wordpress.com/

Ghaffarianhoseini, A. (2017). Building Information Modelling (BIM) uptake: Clear benefits, understanding its implementation, risks and challenges. *Renewable and Sustainable Energy Reviews 75*, 1046-1053.

Gourlis, G. (2017). Building Information Modelling for analysis of energy efficient industrial buildings – A case study. *Renewable and Sustainable Energy Reviews 68*, 953-963.

Grasshopper. (2019, May). *Grasshopper, Algoritmic Modeling for Rhino*. Retrieved from https://www.grasshopper3d.com/

Habibi, S. (2017). The promise of BIM for improving building pereformance. *Energy and Buildings 153*, 525-548.

Heiselberg, P. (2010). *Integrating Environmentally Responsive Elements in Buildings, Expert Guide - Part 1 Responsive Building Concepts.* Aalborg, Denmark: Aalborg Universitiy.

Hensen, J. L. (2011). Building performance simulation for sustainable building design and operation. *60th Anniversary Environmental Engineering Department*, 1-8.

Honeybee. (2019, May). *Food4Rhino, Apps for Rhino and Grasshopper*. Retrieved from https://www.food4rhino.com/app/ladybug-tools

Hopfe, C. (2009). *Uncertainty and sensitivity analysis in building performance simulation for decision support and design optimization.* Eindhoven: Eindhoven University of Technology.

IEA-ECBCS. (n.d.). *Energy in Buildings and Communities Programme.* Retrieved from https://ecbcs.org/

Jariç, M. (2015). PREPARING BIM MODEL FOR ENERGY CONSUMPTION SIMULATION. *6th International Symposium on Industrial Engineering.*

Jellema. (2004). *Inleiding, 1 Bouwnijverheid.* Urecht/Zutphen: ThiemeMeulenhoff.

Jeong, W. (2016). A framework to integrate object-oriented physical modelling with building information modelling for building thermal simulation. *Journal of Building Performance Simulation*, 50-69.

Kensek, K. (2014). *BIM in Current and Future Practice.* Hoboken, New Jersey, United States: John Wiley & Sons.

Ladybug. (2019, May). *Food4Rhino, Apps for Rhino and Grasshopper*. Retrieved from https://www.food4rhino.com/app/ladybug-tools

Latiffi, A. (2015). Building Information Modeling (BIM): Exploring Level of Development (LOD) in Construction Projects. *Applied Mechanics and Materials*, 933-937.

Lomas, K., & Eppel, H. (1992). Sensitivity analysis techniques for building thermal simulation programs. *Energy and Buildings, 19*, 21-44.

Loonen, R., de Klijn, M., & Hensen, J. (2019). Opportunities and pitfalls of using building performance simulation in explorative R&D contexts. *Journal of Building Performance Simulation, 12(3),*, 272-288.

Maile, T. (2013). BIM - Geometry Modelling Guidelines for energy performance simulation. *13th Conference of International Building Performance Simulation Association*, (pp. 3242-3249). Chambéry.

Matlab. (2019). *MathWorks, Matlab*. Retrieved from https://www.mathworks.com/products/matlab.html

Morris, M. (1991). Factorial Sampling Plans for Preliminary Computational Experiments. *Technometrics, Vol. 33, No. 2.*, 161-174.

Morssinkhof, G. (2007). *Procesmapping in bouwprocessen.* Twente: Universiteit Twente.

NationaalBIMPlatform. (2019). *Levels of Detail*. Retrieved from Het Nationaal BIM Platform: https://hetnationaalbimplatform.nl/levels-of-detail.php

NEN2574. (1993). *Nederlandse Norm, Tekeningen in de bouw - Indeling van gegevens op tekeningen voor gebouwen.* NEN 2574:1993 nl.

NEN2634. (2002). *Nederlandse Norm, Termen, definities en regels voor het overdragen van gegevens over kosten- en kwaliteitsaspecten voor bouwprojecten.* NEN 2634:2002 nl.

ONRI, B. (2009). *Standaardtaakbeschrijving, Toelichting en takenoverzicht.* Amsterdam: DNR-STB.

OpenStudio. (2019, May). *OpenStudio R*. Retrieved from https://www.openstudio.net/

Østergärd, T. (2017). Early Building Design: Informed decision-making by exploring multidimensional design space using sensitivity analysis. *Energy and Buildings 142*, 8-22.

Perino, M. (n.d.). *Responsive Building Elements - Actual Development and Trends Within IEA.* Retrieved from https://www.aee-intec.at/0uploads/dateien323.pdf

Pianosi, F., & Beven, K. (2016). Sensitivity analysis of environmental models: A systematic review with practical workflow. *Environmental Modelling & Software 79*, 214-232.

Prada-Hernández, A. V. (2015). Interoperability of Building Energy Modeling (BEM) with Building Information Modeling (BIM). *Sibragec Elagec*, 519-526.

Reazee, R. (2014). A new approach to the integration of energy assessment tools in CAD for early stage of design decision-making considering uncertainty. *Georgia institute of technology.* Atlanta, USA.

Rhinoceros3D. (2019, May). *Rhinoceros, NURBS modeling for Windows*. Retrieved from http://www.rhino3d.nl/

Rinheiro, S. (2018). MVD based information exchange between BIM and building energy performance simulation. *Automation in Construction*, 91-103.

Saltelli, A. (2008). Global Sensitivity Analysis: The Primer. In A. Saltelli, *Global Sensitivity Analysis: The Primer.* Chichester, England: John Wily & Sons, Ltd.

Seghier, T. (2017). Building Envelope Thermal Performance Assessment Using Visual Programming and BIM, based on ETTV requirement of Green Mark and GreenRE. *INTERNATIONAL JOURNAL OF BUILT ENVIRONMENT AND SUSTAINABILITY*, 227-235.

Smelt, K. (2017). *Thermal performance simulation in BIM applying systems engineering to the IPD process, using an IFC model.* Eindhoven: Eindhoven University of Technology.

Spekkink, D. (2012, February). *IPC voor Architecten - Collectief Project BIM.* Retrieved from BIM register: https://www.bimregister.nl/actueel/documentatie/425-ipc-voor-architecten-collectief-project-bim

Struck, C. (2012). *Uncertainty propagation and sensitivity analysis techniques in building performance simulation to support conceptual building and system design.* Eindhoven: Eindhoven University of Technology Library.

Strumpf, A. (2011). *Early Design Energy Analysis Using Building Information Modeling Technology.* Newmark: US Army Engineer Research and Development Center.

Van de Ven. (2019). *Van de Ven Bouw en Ontwikkeling Tilburg*. Retrieved from https://www.vandevenbv.nl/

VolkerWessels. (2019, May). Nieuwegein, The Netherlands.

Wildemuth, B. (2017). In *Applications of Social Research Methods to Questions in Information and Library Science* (pp. 240-246). Santa Barbara, California: Libraries Unlimited.

Zanni, M. A. (2013). Exploring The Potential Of BIM-Integrated Sustainability Assessment In AEC. *Proceedings of the Sustainable Building and Construction Conference* (pp. 186-195). Coventry: Coventry University.

Zha, C. (2019). Lunch reading Computational Solutions. Delft University of Technology.

8. Appendix

Appendix I: Integrated Design Process

Phases in Integrated design process

A description of these main phases, characteristics and design methods in the integrated design is given (Heiselberg, 2010):

Phase 1: Where to build – What to build

For responsive building design, it is essential to understand the climate characteristics of the building site. Not only is climate data useful for estimation of the heating and cooling load of a building, but also for the creation of passive design concepts. This contains analysis of the environmental potential by surveys. This includes analysis of wind, sun, landscape, urban development plans, creation of a roadmap of energy system principles, indoor environment and analysis of the profile of the client. Next to this, also the effectiveness of passive design solutions are demonstrated, for instant Photo-Voltaic (PV), wind generation and geothermal energy.

For each phase, different types of design methods and tools can be used to allow for selecting the most suitable technical solutions for a building design. In this phase, climate data consists of three scales: macro-, meso- and micro climate data. The macro-climate data is obtained from the nearest weather station, but the micro-climate data can often be obtained by individual measurements on site.

For this phase, decision instruments in the form of design process methods are required. This means that certain rating systems have been developed which result in an indication of the targets for the design performance, which go beyond the requirements of building regulations and codes.

Phase 2: Development of design concept

During this second phase, sketches, architectural ideas, concepts, functional demands and construction principles can be linked to building energy concepts by applying the proposed design strategy. The variations in conceptual design solutions are developed, and their expected qualities are constantly evaluated against the goals in the building design brief. The result of this analysis is an integrated building concept, which can be further elaborated in the next phase.

The architect, client, engineer and other stakeholders will all have their influence on the design decision making during this phase, and on the selection of the final design. The different background, both scientific and cultural, makes this collaboration in this phase very important to obtain the best possible design. This design may depend on the following characteristics:

- Social- and physical environmental conditions of building surroundings
- Building type and its operating (management) system
- Lifestyle of the occupants
- The individual identity of the corporate concerning environmental principles of the company
- Private preference of a sense of values of the client
- Aesthetics

Phase 3: System design and preliminary performance evaluation

The systems design phase is used for development of specific architectural and technical solutions and systems through sketches, additional calculations and adjustments. In this phase, the assemblance of architectural, spatial and functional qualities, together with the construction and energy consumption demands takes place. The site location, together with the basic building form are determined. This is done after a series of functional analyses, corresponding with design strategy step 1, which will be further explained in the next chapter of this appenix. By also applying step 2, 3 and 4, various ideas regarding the integration of passive and active systems can be used in the consideration of design decisions, with a special focus on for instance renewable energy technologies.

The performance of the building should be inspected after the system design is completed. There are many indicators of the building performance. Two ways of predicting and evaluating this building performance in this phase are the use of design guidelines, and the use of design tools.

Design guidelines are a simplified method for evaluation of the building performance in early design phases. If the performance of the design is not acceptable, the design will be adjusted until satisfactory. The use of simulation tools is favorable to determine the performance later in the system design. These tools allow to consider all issues regarding energy, climatic and surrounding conditions. If the performance, as specified in the previous concept design phase cannot be achieved, the integrated responsive building elements should be reconsidered by returning to this phase.

Phase 4: Component design

The final design in this phase is finished, after the performance of the system design is confirmed. During this phase, the technical solutions are refined while also the creation of design documents is done. Next to this, specification in cooperation with building companies, suppliers and product manufacturers is created.

The simulation tools required in this phase are very detailed, but are similar to the simulation tools in the previous phase. Detailed sizing of the responsive building elements is in this stage of the design process considered, together with the integration of all building systems. All these improved design considerations should result in an improved buildings, since they are less expensive, more comfortable, and more responsive to the occupant.

Overview

The summation of Annex 44 describes one more, fifth phase: the *Operation and Management Phase*. This phase cannot be seen as an actual early design phase, and is therefore, like in the traditional design phases assessment where only the earliest design phases are investigated, not much further elaborated. The main focus in this phase is to trace conflicts between building services. An integrated design strategy by use of the previously mentioned phases should prevent these conflicts.

The previously proposed design method gives a global overview of building performance focused design. This means that the use of this methodology and the influence of each design parameter can be different for each type of building. It is therefore important to reconsider each parameter during each individual building design project and design phase. More about the design parameters is elaborated in *2.2.1 Investigation of parameters.*

Roadmap of Integrated design process

As a result of the available data as described in *2.1 Building design phases* , decisions can be made about certain design parameters. The integrated design process, as described in Annex 44, offers a roadmap for the application of the Trias Politica based design strategy. This roadmap, consisting of six design steps, identifies different design parameters for heating, cooling, lighting and ventilation design of buildings (Heiselberg, 2010).

Important to realize is that the six design steps in this roadmap do not one-on-one comply the design stages as overviewed in *2.1.4 Overview of design phases*. This roadmap gives an overview of an example of an order in which the investigation of design parameters can be applied in the design process. A short description of these steps is given, while an overview of the typical design considerations for each step can be found in *Table 3*.

Step 1: Basic design focusing on reduction of energy demands

Reduction of the demands for heating, cooling, lighting and ventilation is the main focus in the first step of the design, which is achieved by reducing the internal heat loads, optimization of day lighting and reducing the heating, cooling and ventilation energy.

Here, the priority is the reduction of internal and external heat loads. Secondly, an optimum in reducing the heating and cooling gains by an optimal surface to volume ratio, zoning, shading, insulation level and demand controlled ventilation level should be found. In this stage of the design, it should still be able to modify the design in order to reduce the capacity, size and complexity of the building services, which can reduce the capital cost of the services without having to remove features from the design.

Step 2: Climatic design through optimization of passive technologies

In this step, optimization of natural gains from sun, wind, and thermal storage takes place by applying direct solar gains, free cooling, thermal mass and natural ventilation measures. These measures, mostly already created in the previous step, could significantly reduce the loads since they often lead to reduction of the complexity and size of building services.

Step 3: Integrated system design and application of responsive building elements

RBE's, as described before, are introduced in this step with the design of integrated systems. Building components are here further employed by the activation of building elements, for instance by using intelligent facades, thermal mass activation and earth coupling, as visible in *Table 3*.

Step 4: Design of low exergy mechanical systems

The required comfort conditions can be realized by applying mechanical systems for heating, cooling, lighting and ventilation. These handle the remaining loads that remain from the combined effect of the previous steps. Like visible in the *Table 3*, a large focus is on the application of renewable energy sources using low exergy mechanical systems.

Step 5: Efficient design of conventional mechanical systems

In the fifth step, conventional building services are designed, like for instance radiators, cooled ceilings and regular lamps. An energy efficient design strategy should avoid conflicts between different building services, to make sure these conflicts are eliminated, and prevented is to carry a flawed design forward.

Step 6: Design of intelligent control for optimized operation

In order to receive an efficient operation of the building, and reach optimal energy efficiency, an intelligent control of the energy transport is very important. For instance advanced sensor techniques can care to tune to different external and internal climate conditions, and adapt to the comfort requirements of the building occupants.

Appendix II: Overview of sensitivity and uncertainty analyses

A possible definition of sensitivity analysis is the following: *The study of how uncertainty in the output of a model (numerical or otherwise) can be apportioned to different sources of uncertainty in the model input* (Saltelli, 2008). Sensitivity and uncertainty analysis are commonly ran following each other.

The sensitivity and uncertainty analyses are often used in model development, and also used for this research, is because they have the ability to for instance (Østergärd, 2017):

- Simplify the design problem by identifying non-influential inputs (screening);
- Help the modeler to understand and calibrate the model;
- Highlight inputs that deserve most attention in a multi-actor design process;
- Identify regions of design space that meet design criteria;
- Create reliable, fast metamodels.

Various methods for determining the sensitivity and uncertainty for each building phase are compared. The outline of the different methodologies is important, since each analysis method has its own characteristics and outputs. The analysis method most suitable for this research is applied and will be further explained. A more project specific application will be elaborated in *3. Methodology*.

Differential Sensitivity Analysis

A very commonly used technique for determining the sensitivity is the Differential Sensitivity Analysis (DSA). This technique allows for very quick exploration of output results, and is relatively easy to use. Next to the sensitivity, it also gives a result of the total uncertainty, by making changes in the many possible inputs (Lomas & Eppel, 1992).

This analysis is known as a One-At-a-Time (OAT) method, since all simulation input parameters stay fixed at the base case value except for one, which varies for each simulation. By repeating these simulations, the individual effects (Δp_i) of each parameter can be determined by:

$$\Delta p_i = p_i - p_B \qquad (1)$$

where p_i is the predicted modified value of the input, and p_B is the predicted base-case input value.

The influence coefficients, $\frac{\Delta p_i}{\Delta i}$, are an estimation of the differential sensitivities for a certain output p. The effect on a prediction, dp_i, can be found by making relatively small changes, di, and as a result of these outputs, make an actual statement about the sensitivities of the input parameter changes. This effect could also, more safely, be calculated using:

$$dp_i = di\frac{\Delta p_i}{\Delta i} \qquad (2)$$

When all input parameters are varying by the same amount, the total influence on the predicted parameter $\Delta \mathrm{p}_{tot}$ can be estimated by using:

$$\Delta \mathrm{p}_{tot} = \sqrt{\sum_{i=1}^{I} \Delta {p_i}^2} \qquad (3)$$

The DSA method does only provide information about each individual parameters, so it does not tell anything about the relation between parameters, and so the cumulative parameter impact.

The amount of simulations N is depending on the number of simulations C, and the number of considered parameters n (Struck, 2012):

$$N = 1 + (n * C) \quad (4)$$

Using this method is repetitive, since it contains selecting an input, adjusting it, creating a new input file, performing the simulation, gather the results, calculating the individual and total uncertainties, and repeating the complete process again.

Monte Carlo Analysis

In a Monte Carlo Analysis (MCA), all uncertain parameters are given a probability distribution. According this distribution, a value is selected for each input parameter. For parameters that are not very influential, it is more likely that base case values are used than for parameters that have a large influence. The prediction results will be saved, after the simulations are again performed with a new set of input values.

After all simulations have been done, a large set of values has been obtained for each individual parameter. Since the amount of parameters is large, the values predicted for each particular parameter (p), are probably normally distributed. This means that the total uncertainty can be expressed by the standard deviation (s):

$$s = \sqrt{\frac{1}{N-1}\sum_{n=1}^{N}\left({p_n}^2 - N{_ṕ}^2\right)} \quad (5)$$

where N = *total number of simulations*, n = simulation number, and ṕ = mean value of output parameter p.

Different than with the DSA, the accuracy of s when using MCA does only depend on the number of simulations N, and not on the number of uncertain input parameters I. Also for the MCA, problems with non-linearities of input or outputs do will not occur. The drawback of this method relative to the DCA is that because of the simultaneous changing of input values, the sensitivities of the output predictions are not being made visible.

Morris Analysis

The Morris method (Morris, 1991) is often seen as the most interesting method for sensitivity analysis in sustainable building design. This method is useful, since (Heiselberg, 2010):

- It is able to handle large numbers of parameters;
- It is economical – the number of simulations are few compared to the number of parameters;
- It is not dependent on assumptions regarding linearity and/or correlations between parameter and model output;
- Parameters are varied globally within the limits;

- Results are easily interpreted and visualized graphically;
- Indicates if parameter variation is non-linear of mutually correlated.

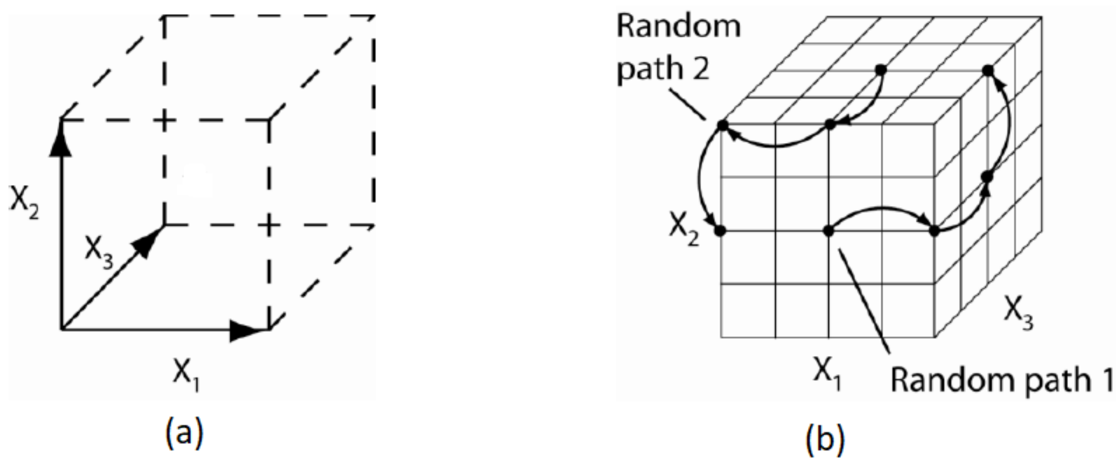


Figure II.1: Morris analysis. (a) Region of experimentation defined by three parameters. (b) Representation of a five-level grid with three parameters and two trajectories (Struck, 2012).

The method provides information about the uncertainty of the model output as a result of the different changing input parameters. This does not include an indication of the output uncertainty. Using this method, it is relatively easy to identify and fixate insignificant inputs that have no or negligible influence on the energy performance of the building (Østergärd, 2017).

In this method, the following sensitivity measures are important:

- EE = Elementary Effect
- μ = Mean of elementary effects
- μ* = Mean of absolute elementary effects
- σ = Standard deviation of EE

Using this method, different paths, also named trajectories, are created within a *N*-dimensional design space. *Figure II.1* gives an overview of (a) a three-dimensional design space, meaning it investigates three different design parameters, and (b) two different trajectories through this space. Regularly, each design space is scaled from 0 to 1, which is divided into sections creating a level grid as visible in (b). During the analysis, for each calculation, only one parameter changes with an equally large step size Δ, while the other parameters remain the same as in the previous calculation.

Using this, the Elementary Effect (EE) can be calculated, which expresses the output change measured at r different places within the design space. This means that for a certain input i, the EE can be described by (6). Δ here is the predetermined multiple of $1/p$-1.

$$EE_i = \frac{Y(X_1, X_2, \ldots, X_{i-1}, X_i + \Delta, \ldots, X_N) - Y(x)}{\Delta} \qquad (6)$$

As a result of this Elementary Effect, the other three earlier mentioned sensitivity measures can be determined using:

$$\mu_i = \frac{1}{r}\sum_{j=1}^{r} EE_i^j \qquad (7)$$

$$\mu_i^* = \frac{1}{r}\sum_{j=1}^{r} |EE_i^j| \qquad (8)$$

$$\sigma_i^2 = \frac{1}{r}\sum_{j=1}^{r} (EE_i^j)^2 \qquad (9)$$

The influence of an input is high when the mean of the absolute values, μ_i^*, is large. When an input value has a large standard deviation, the influence of this value depends on the values of other inputs, or the model is non-linear.

The number of model runs N, depending on the amount of input parameters n and amount of trajectories r can be calculated by using:

$$N = r(n+1) \qquad (10)$$

Appendix III: Parametric tools

To perform the sensitivity and uncertainty analyses, a parametric design model has been created. To gain immediate insight in decisions made, tools providing Visual Programming Language (VPL) are investigated. VPL allows designers to create flexible and powerful form-generating algorithms without having to first learn how to write code (Seghier, 2017). It is therefore a different, more user-friendly parametric design approach for programming. Several flexible tools allowing for this type of parametric modeling are available, although the opportunities of two of the leading Visual Programming tools, Grasshopper (GH) (Grasshopper, 2019) and Dynamo (Dynamo, 2019), are investigated.

Grasshopper is an established community-driven open source tool. This tool is linked to Rhinoceros (Rhinoceros3D, 2019), a Computer-aided design (CAD) tool, immediately visualizing the results of the created workflow. Such a workflow, as visible in *Figure III.1* is formed out of boxes which receive an input value, process this information, and return an output value. Grasshopper is a very powerful tool allowing for both digitally fabricated smaller project and complex geometries. The connection of Grasshopper to BIM has only recently been made by using the GeometryGym plug-in (GeometryGym, 2019) for Rhino/Grasshopper.

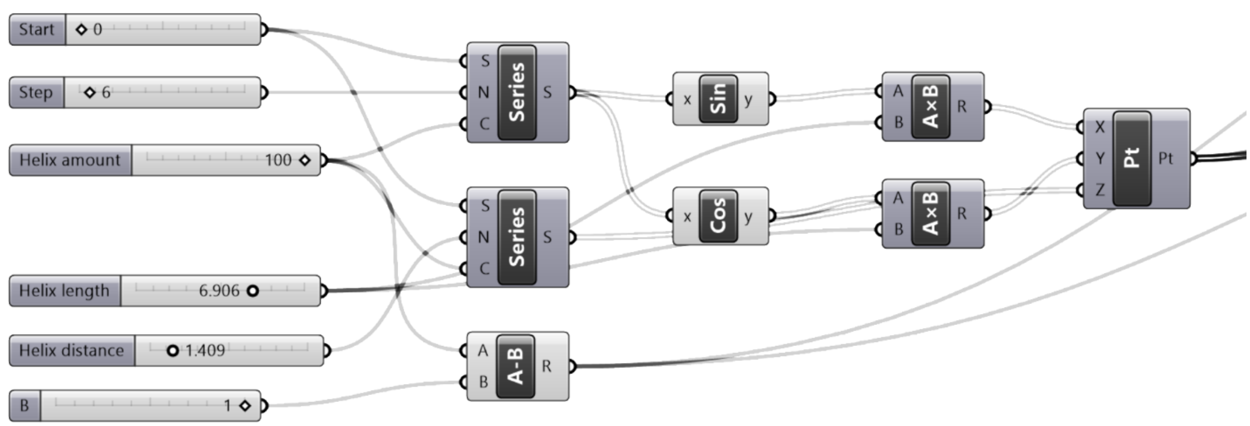


Figure III.1: Workflow in Grasshopper creating the coordinates of an helix shape

Grasshopper is a highly developed tool providing a very effective method for designing building models. The usefulness is a result of the following design principles (Ferreira, 2016):

- Receiving immediate feedback on the created workflow. As mentioned before, for the designer to be able to make quick decisions, immediate feedback on the changes made in building geometry or performance parameters should be provided. Grasshopper provides this method of instantly visualizing this results in the CAD model.
- Grasshopper facilitates the input of various values. Like visible in *Figure III.1*, different sliders can be used as input, involving different value ranges. This allows for a quick method for design exploration. Each new value within the range of the slider generates a new model which can immediately be simulated.
- Interaction of the program with the created elements. After the creation of an element in Grasshopper and selecting this element, it will be highlighted in the Rhino canvas. The design

tool is therefore very user-friendly and allows designers to understand the effect of each design decision.

- Visualizing the differences between created models. The output of each block in the Grasshopper workflow serves as the input of the next block. Grasshopper contains the effective feature to replicate the geometry of the first block into the following block. This interaction is very effective for design exploration, since it maintains the old, unchanged geometry. Therefore the designer is able to see the effect of the change made in the design.

Dynamo, just like Grasshopper, offers a state of the art method of programming. Dynamo, alternatively to Grasshopper, is implemented on top of Revit, a BIM-based product by Autodesk. This is also the most important reason for choosing Dynamo over Grasshopper, since the collaboration between the BIM-model and the parametric design tool seems to be more stable. Add-ons for combining BIM-models with Grasshopper/Rhino will always be needed, possibly resulting in compilations.

On the other hand, the development of the Grasshopper/Rhino software is always faster since the Rhino team only has to maintain one product, where the Autodesk team has to maintain many. Dynamo is more constrained, and less flexible than the open-source Grasshopper/Rhino software, which is more established, has more tutorials and has many more plug-ins used for simulations and other applications. Simulation add-ins like Ladybug and Honeybee have been available for Grasshopper for a while now, while the it has only recently become available for Dynamo, possibly resulting in still unknown flaws. Also, Grasshopper offers the option to write own codes in Python, which is still relatively underdeveloped in Dynamo.

The objective of this research is to create a mock-up of a tool that will be used for energy performance based designing. Since the collaboration between Grasshopper and validated performance simulation engines seems more reliable, together with the previously mentioned arguments, the Grasshopper/Rhino collaboration will be used in this research.

BIM tools have widely been used for specific designing. For instance, for architectural design, exist tools such as Revit and ArchiCad, for structural design there are tools such as Tekla and Structuralworks, and for cost estimation there are DesignEst Pro and Vico. The collaboration between all these tools is still often criticized, since the building models created are often focused on the needs of the individual company (Cheung, 2012). An evolving standard such as IFC is used to improve interoperability, but even these often lack uniformity between the object schemas. Therefore, the possibilities for a collaboration between these IFC models and the used parametric design tool Grasshopper is also investigated in this research.

Appendix IV: Grasshopper Model

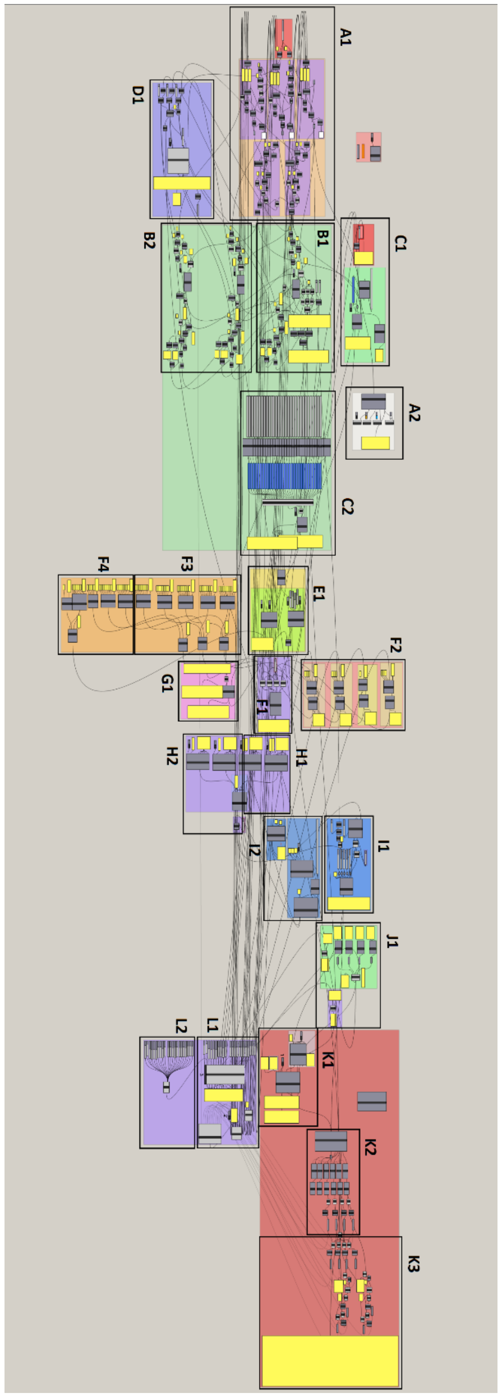


Figure IV.1: Overview Grasshopper model providing parametric designing

Grasshopper model workflow

Figure IV.1 shows an overview of the model created in Grasshopper which is used to for the parametric designing of different configurations of buildings. A workflow in three sections for the creation and simulation of the parametric model is further elaborated.

The versions of the different software used in this research are:

- Rhinoceros 6
- Grasshopper 0.9.0076
- Ladybug 0.0.64 & Honeybee 0.0.67
- TT Toolbox 1.9

Section 1: Geometry creation

In this first section of the model, consisting of part A and B, the geometry is created within Grasshopper, which is directly visualized in Rhinoceros. This allows for the creation of one rectangular shape with any desired dimensions and volume, or multiple shapes which will be stacked on top of, or next to each other.

The advantage of creating this geometry within Grasshopper is the very straightforward opportunity to pull apart the created geometry, and define for instance the dimensions and volume of the different created shapes as parameters using value sliders (*Figure III.1*) for the different later analyses. The current absence of the coupling with IFC models in this Grasshopper model is justified in *3.4.2 Architectural model coupling to simulation tool*.

Section 2: Parameter selection

In the second section of the model, part C until J, the parameters inserted for the simulations are selected.

In part C, the created geometries can be divided into floors, after which zone functions can be determined. These zone functions contain information about the infiltration rate, the equipment load per area, the lighting density per area, the number of people per area, and the ventilation rate per area. This information can all be overwritten in part H and I.

Using a Ladybug tool, the area of PV panels can be determined. For this model, the panels have only been placed on the roof of the top shape created in section 1. Furthermore, the glazing percentages for the different façade orientations can be selected. This percentage can be selected manually, for instance useful for the verification study, but also with the later elaborated Colibri tool. This effects the Window-to-Wall ratio (WWR) since this is the measure of the percentage area determined by dividing the building's total glazed area by its exterior envelope wall area.

For the construction build-up, some predefined information is selected for the verification study, but this can also be determined using the Colibri combination.

Part J offers the option to select the orientation and location. This is not the location within one building site, but different global locations using different EnergyPlus Weather files. The three weather files that will for this research be used, only to gain some insight in the SD-phase, are from Amsterdam, Beek and Groningen. The air temperature characteristics of these files for one year can be seen in *Figure IV.2*.

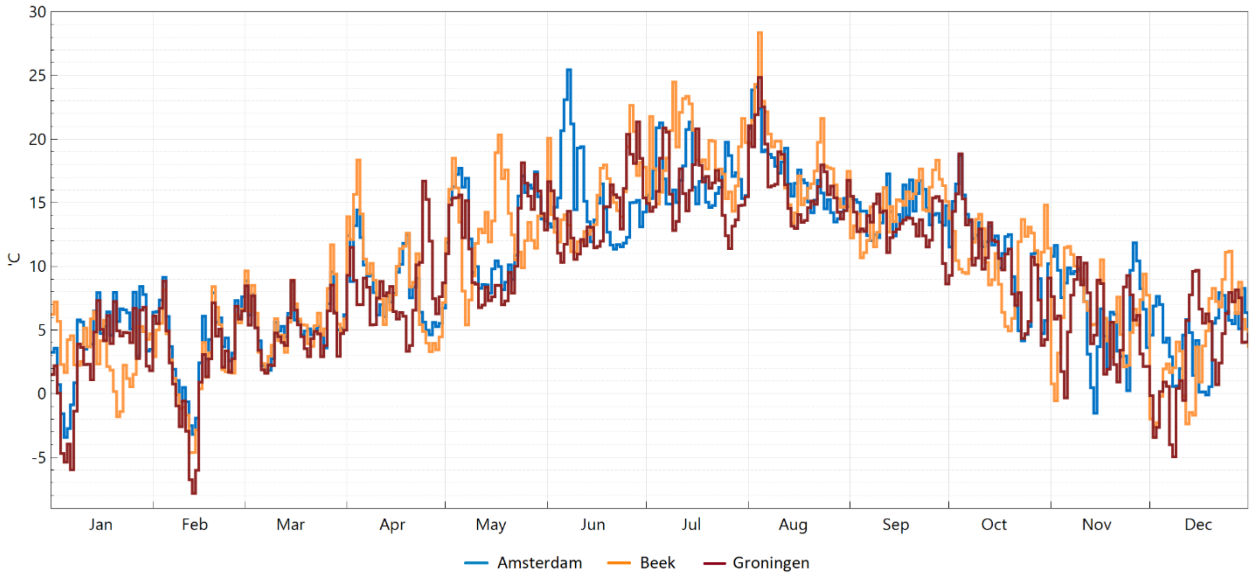


Figure IV.2: Air temperature characteristics of .epw files for Amsterdam, Beek and Groningen

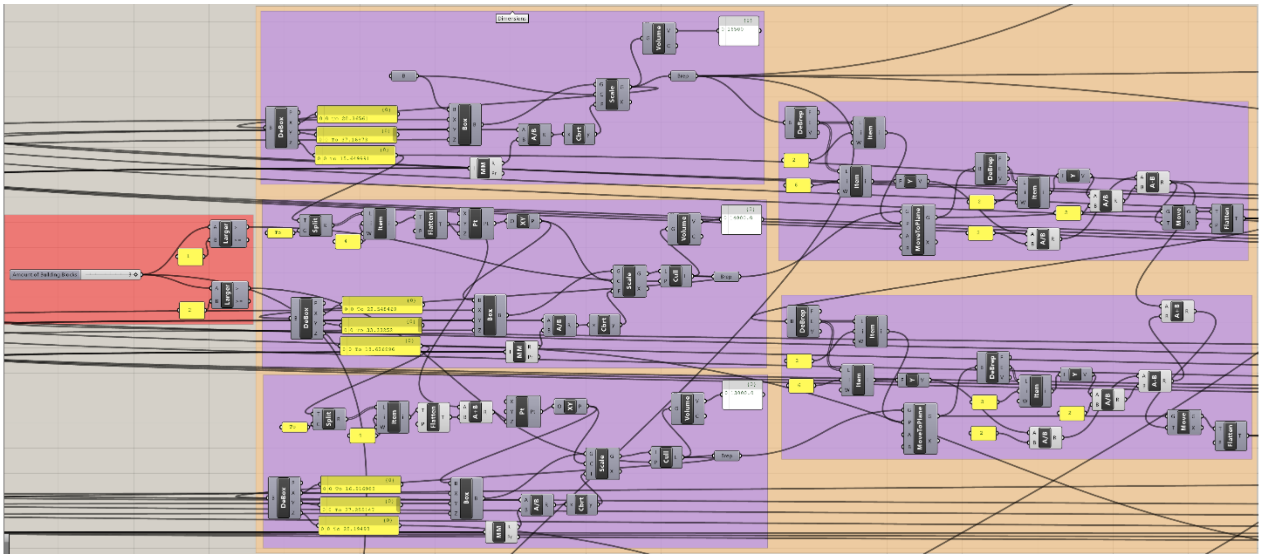
Section 3: Parametric simulation

In this third section, containing of part K and L, the simulation can be run using the Honeybee simulation engine using EnergyPlus. Simulation outputs can here be selected, together with the desired simulation timestep. Visible in part K2 and K3, the results are simulated for the heating and cooling loads in kWh and kWh/m^2, and the peak loads in W/m^2. Also an indication of the total electric light and equipment load are simulated in kWh, but these will not be further elaborated in this research.

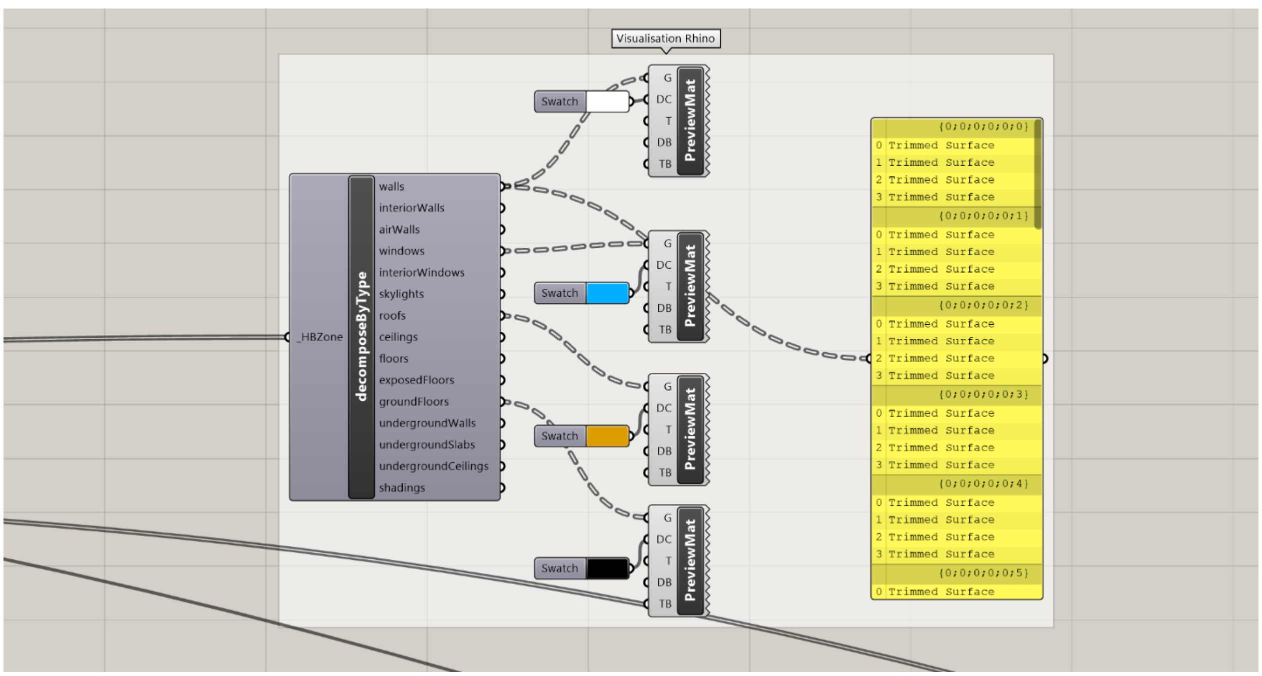
In part L the Colibri tool, part of the TT Toolbox, is used allow very quick combining of the different parameter range inputs for this research. After selecting a folder to save the simulated data, and selecting the desired input ranges, multiple simulations can be performed by first once running the Honeybee interface, and then running the Colibri iteration tool. Depending on the model complexity, each simulation takes between one to eight minutes to run. Simulation results, together with images of each building variant, should now be stored in the selected folder.

A. Geometry creation

A1: Base geometry creation

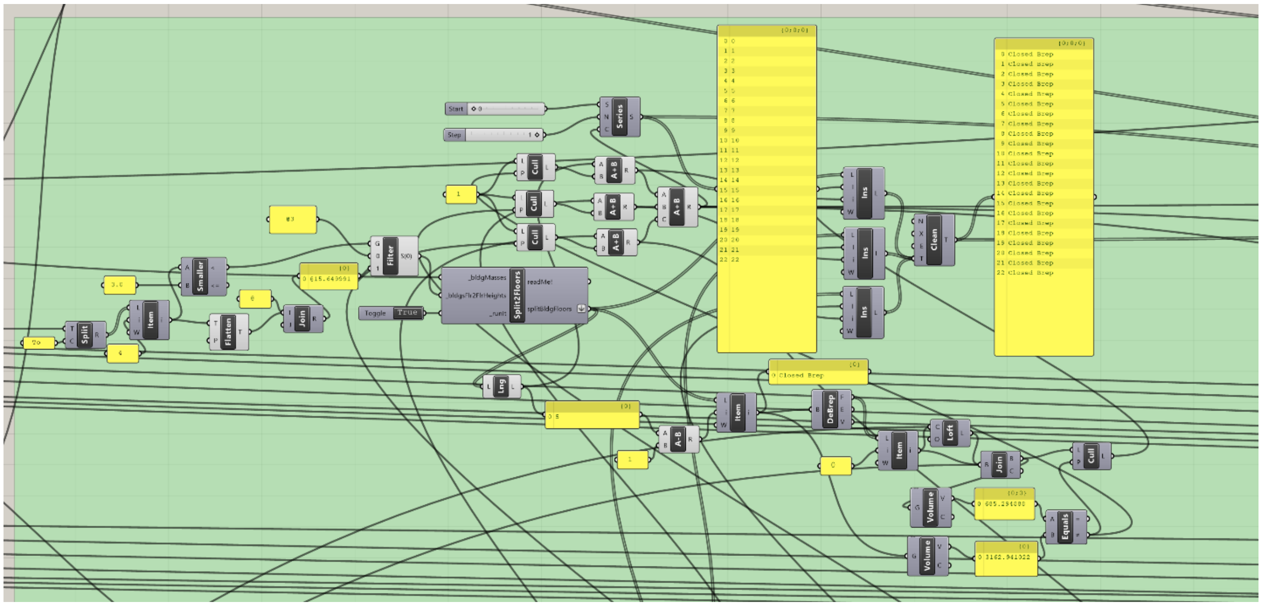


A2: Geometry coloring in Rhinoceros

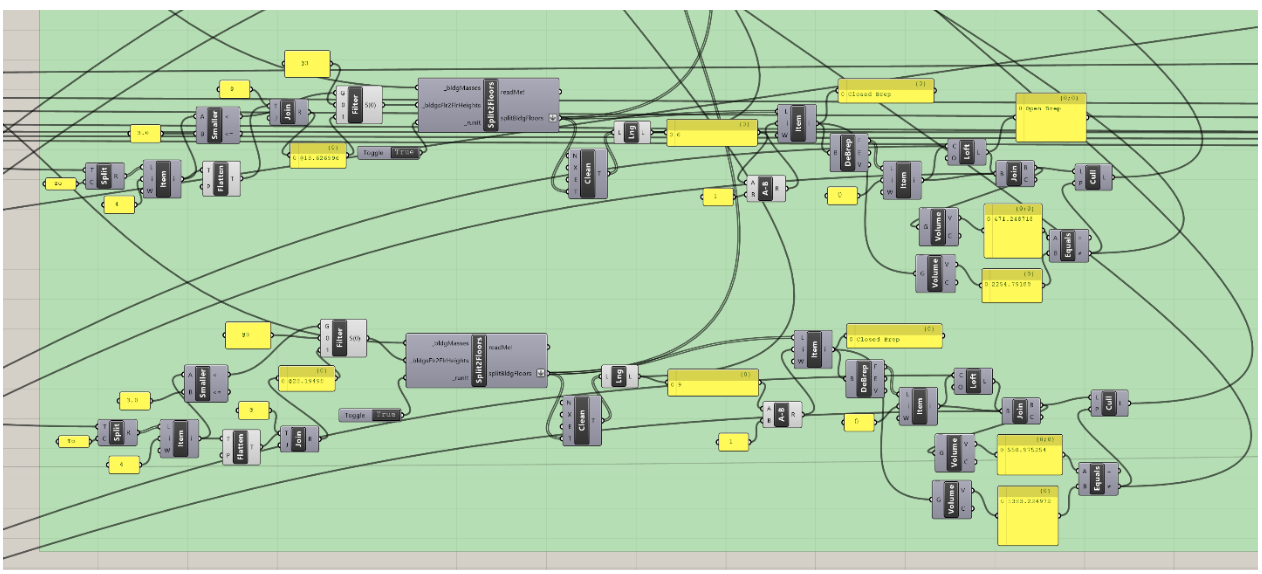


B. Geometry Corrections

B1: Corrections and creation of top floor (1)

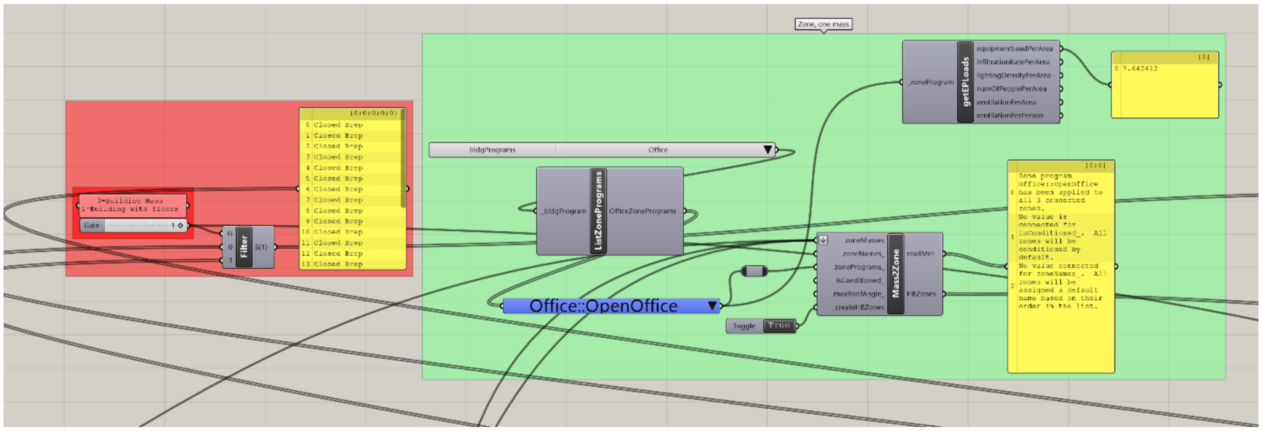


B2: Corrections and creation of top floor (2)

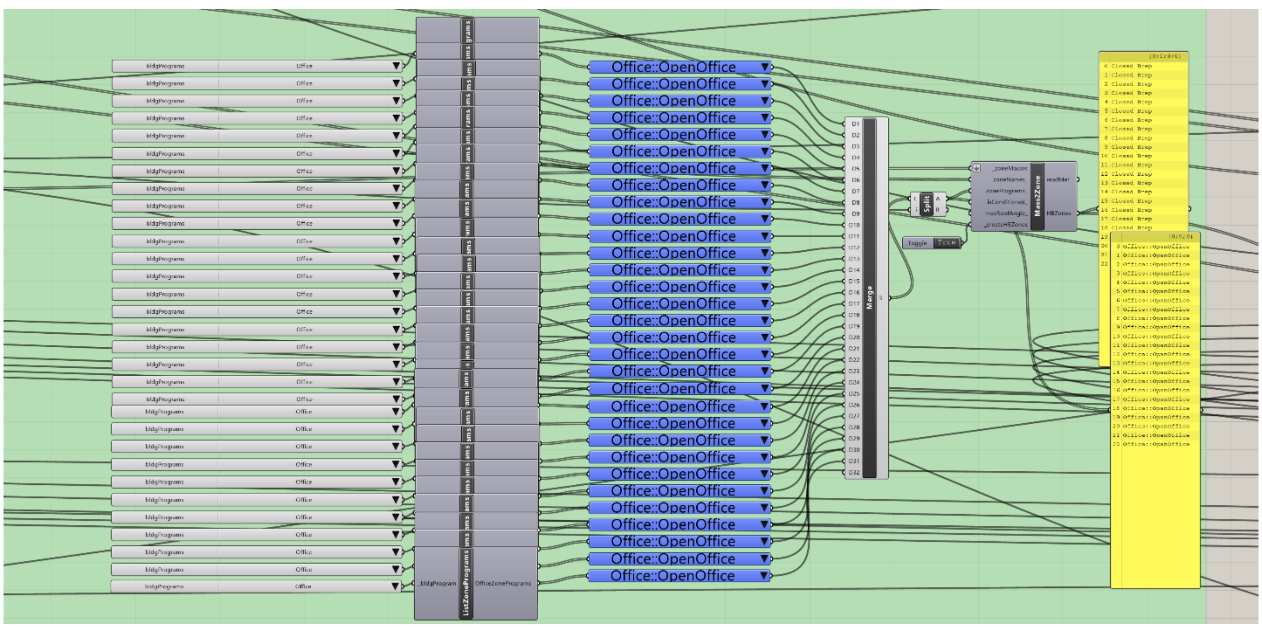


C. Floor Division

C1: Selection division in floors and Selection with one zone

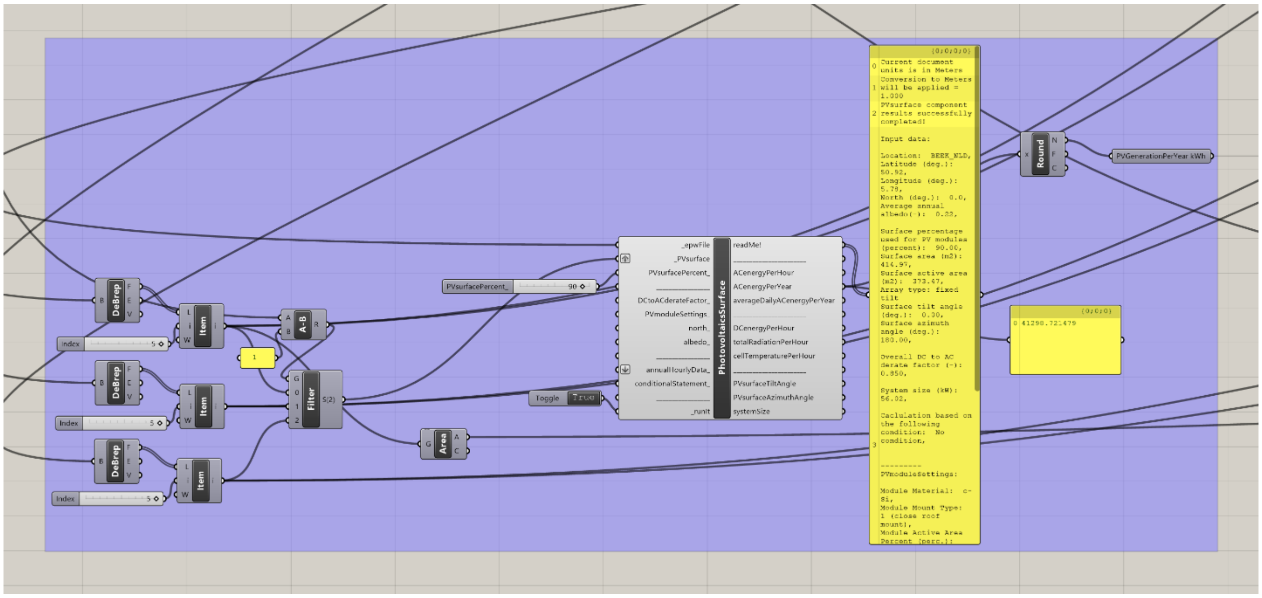


C2: Selection of multiple zones



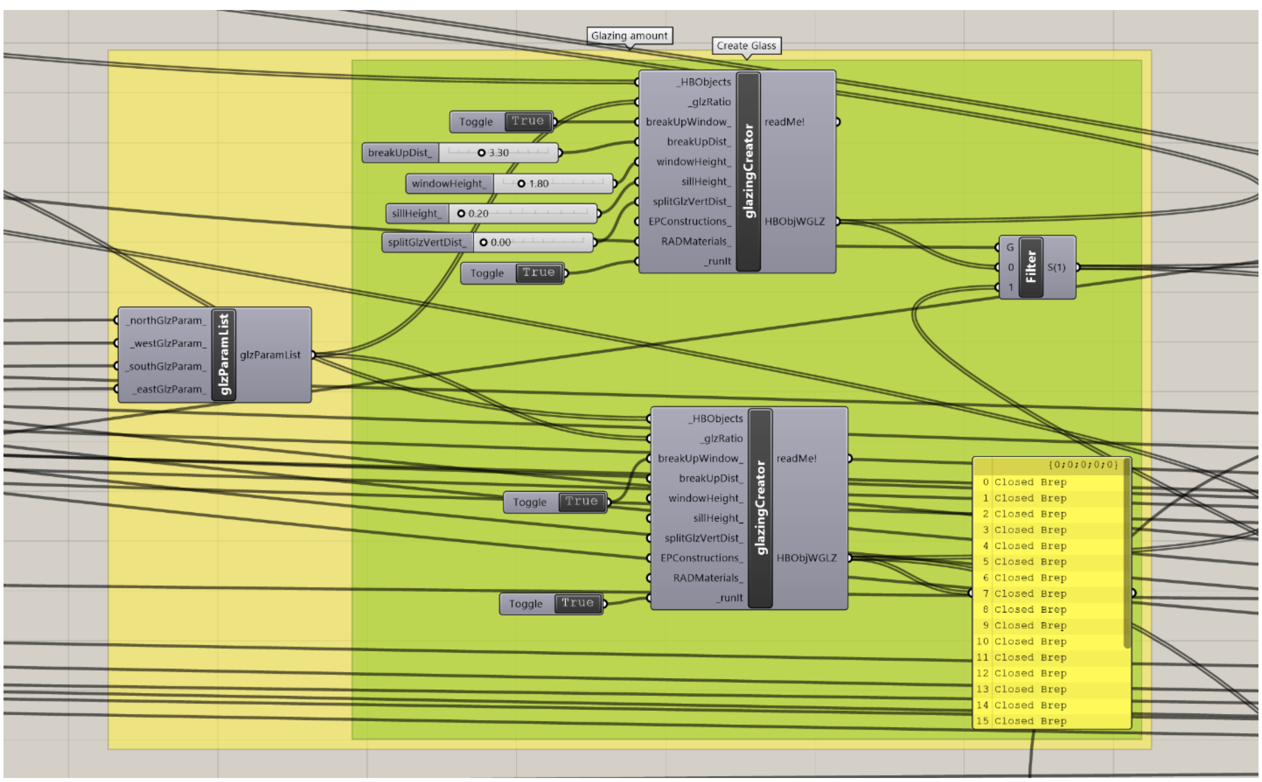
D. PV Generation

D1: Generation by PV-panels



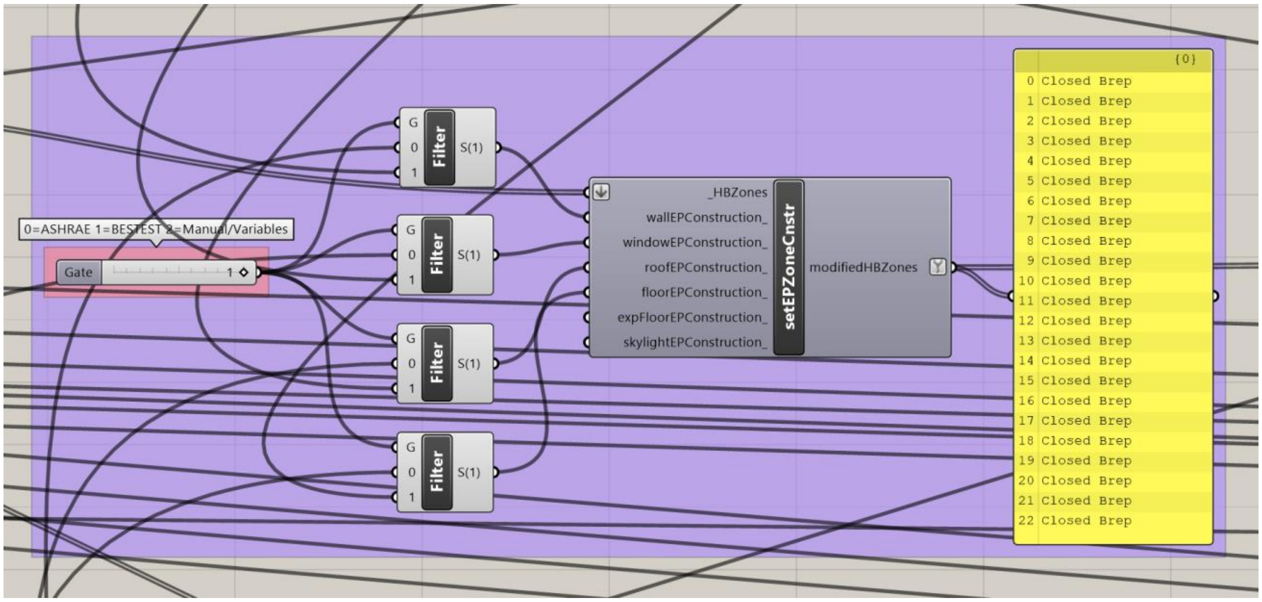
E. Glazing percentage

E1: Glazing percentage

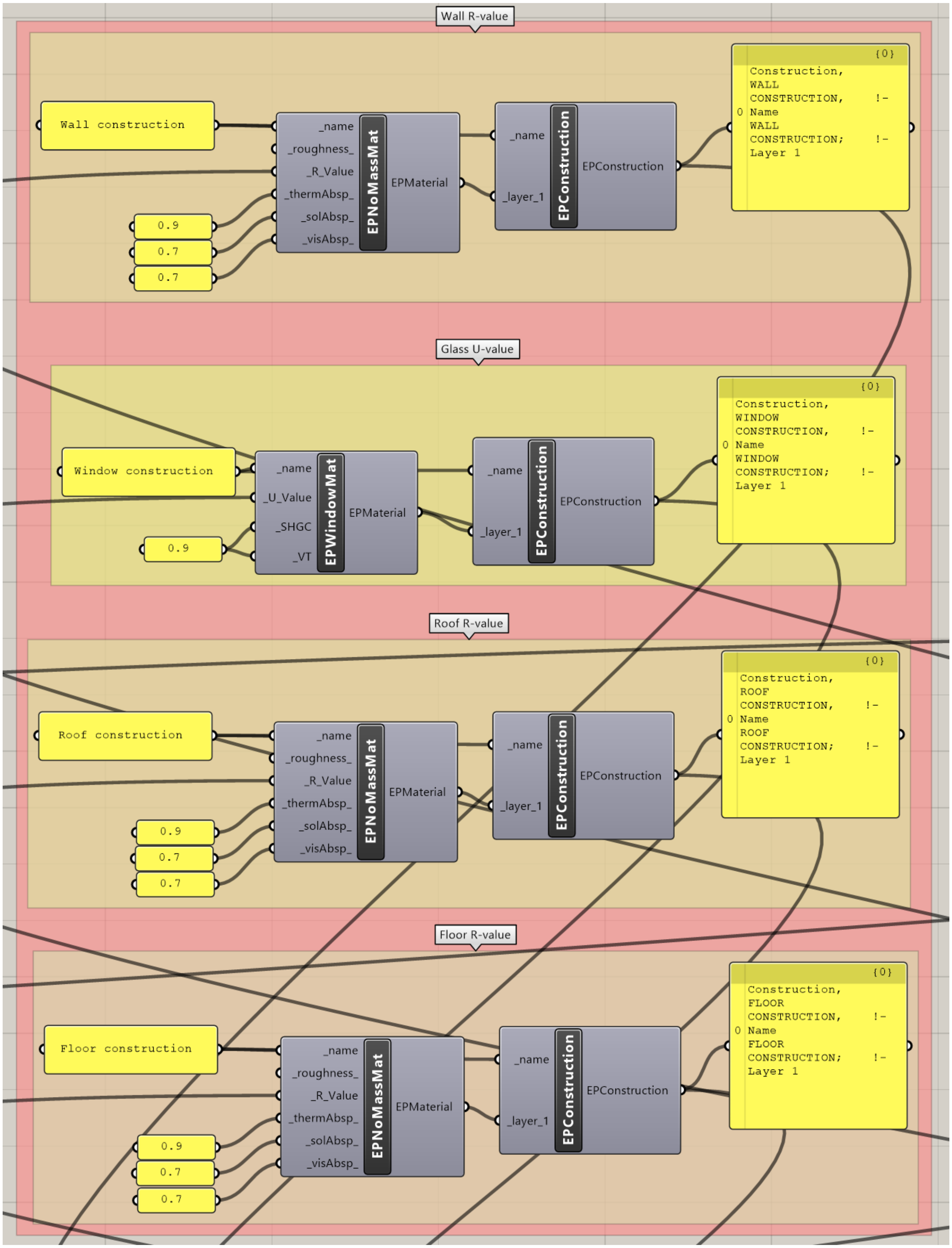


F. Construction

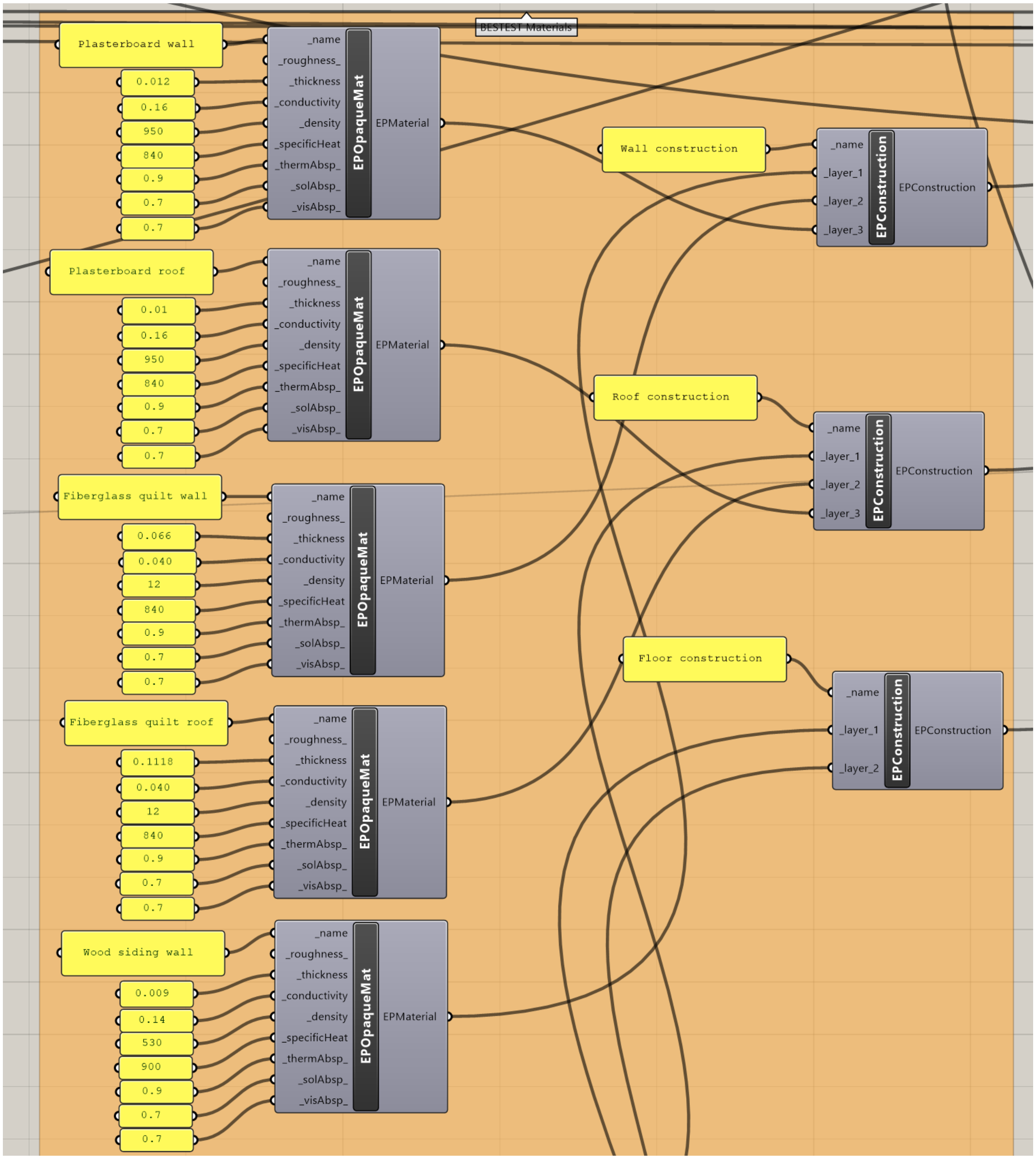
F1: Selection of type of construction build-up



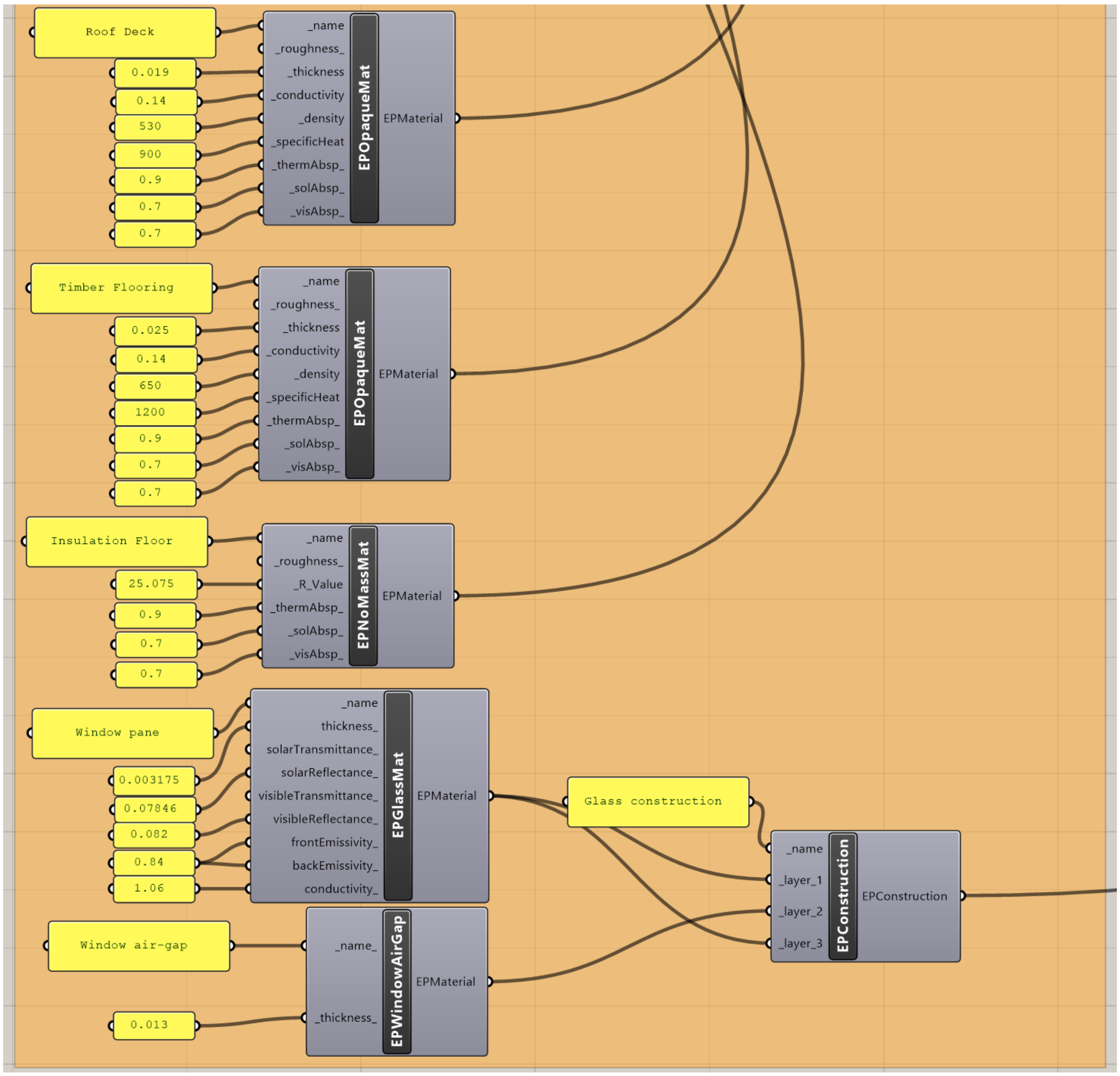
F2: Construction build-up for parametric research



F3: Build-up of construction for BESTEST case 600 (1)

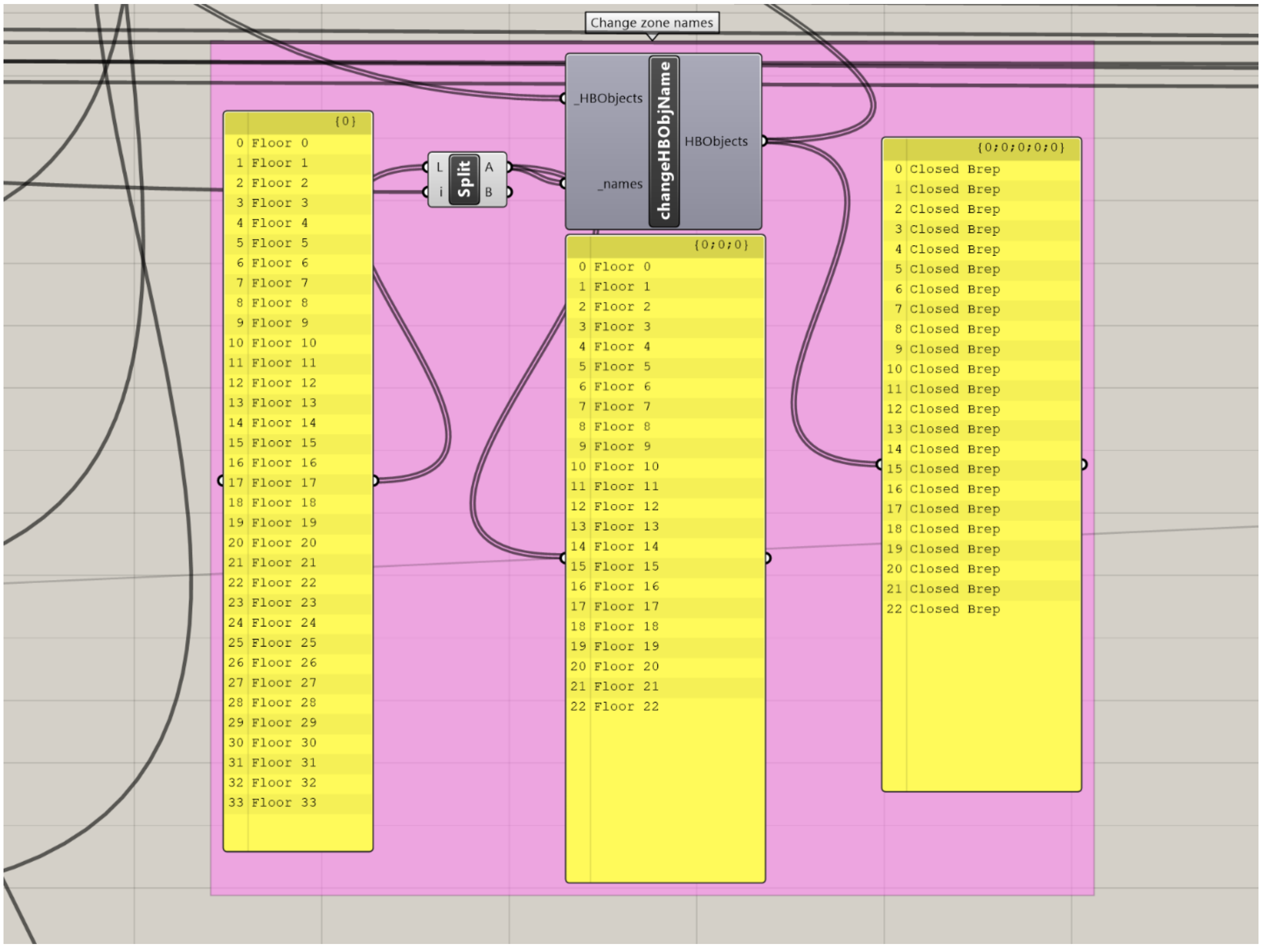


F4: Build-up of construction for BESTEST case 600 (2)



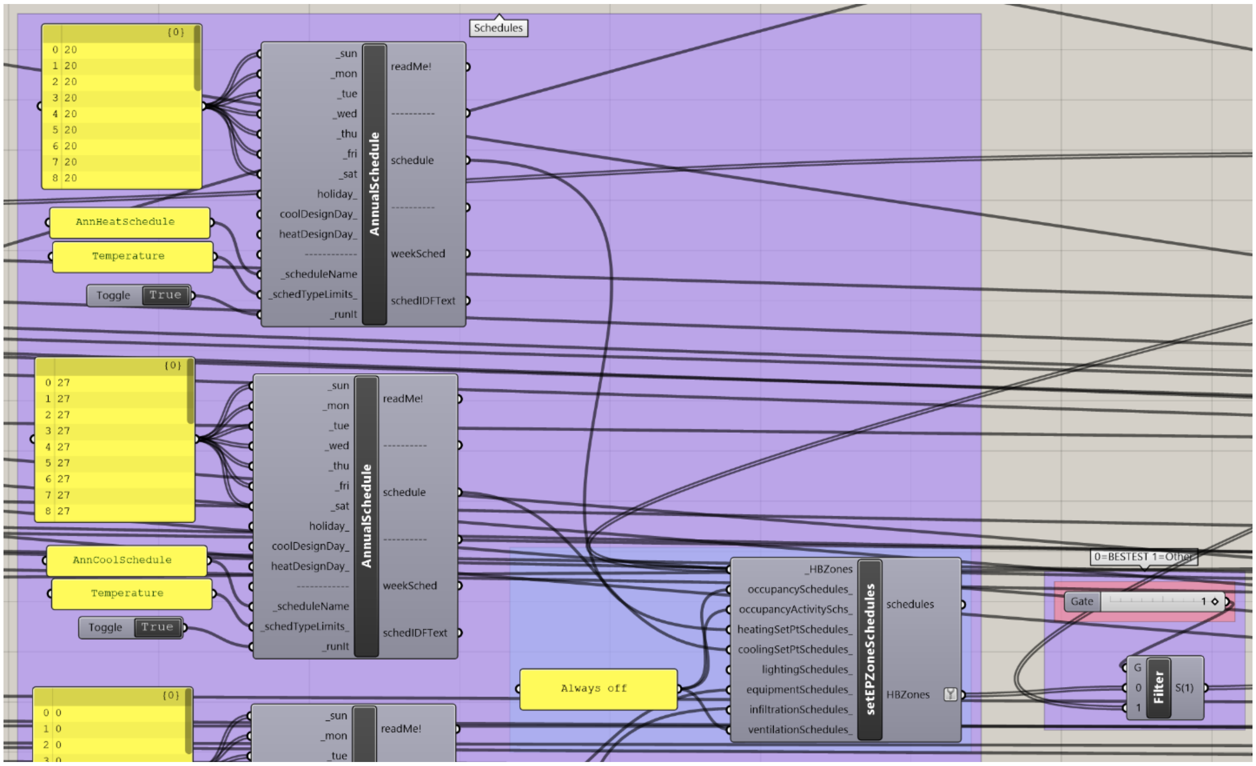
G. Zone naming

G1: Naming of individual zones

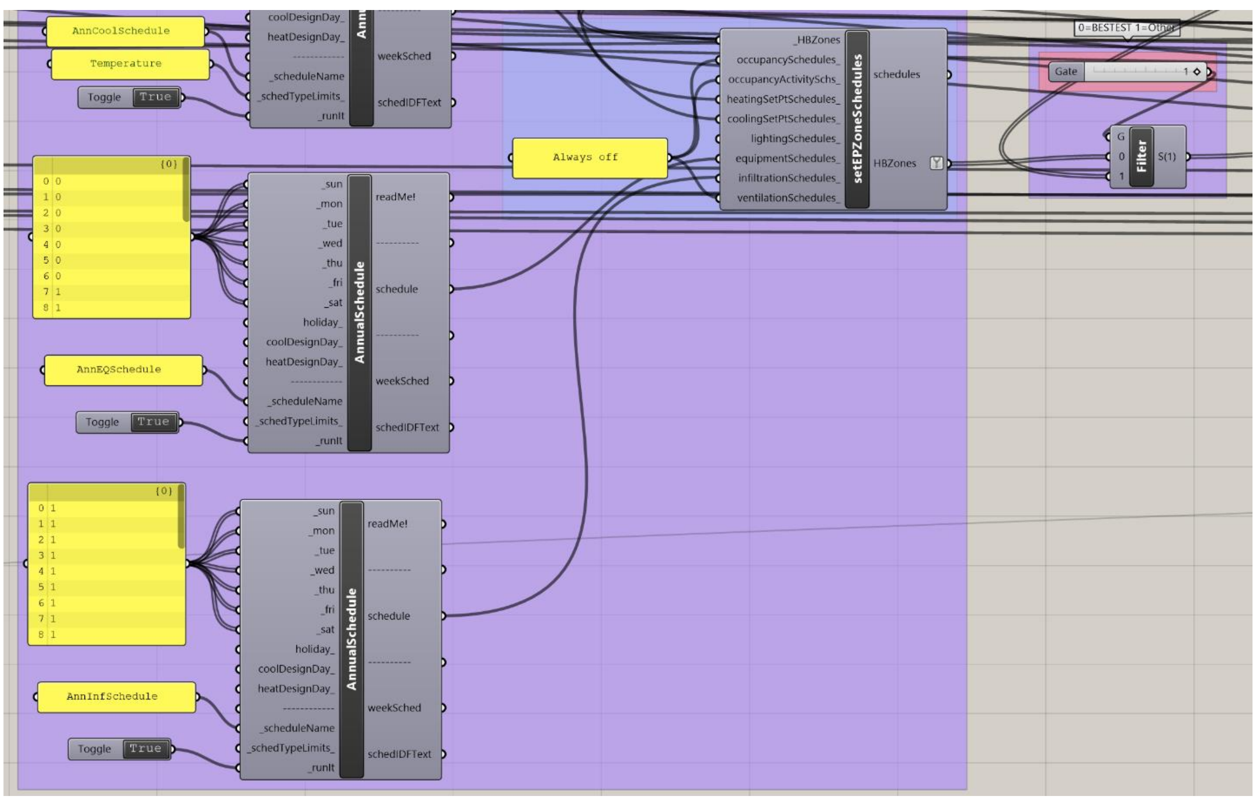


H. Zone Schedules

H1: Zone Schedules for BESTEST case 600 (1)

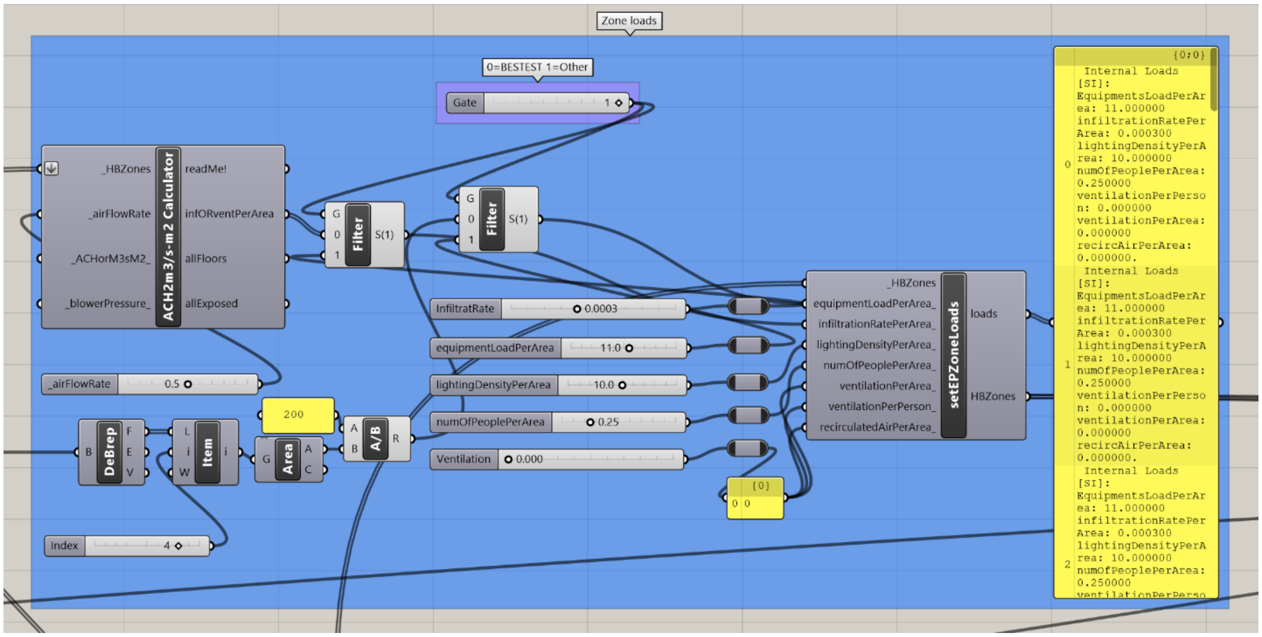


H2: Zone Schedules for BESTEST case 600 (2)

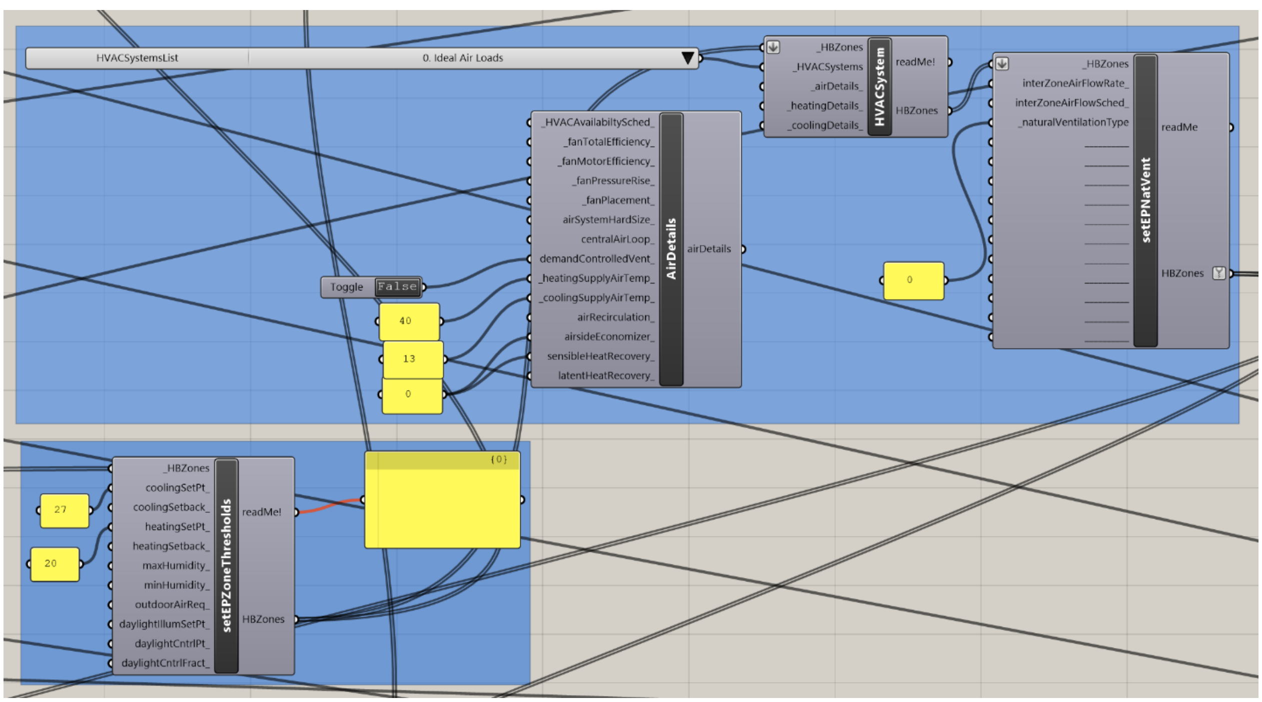


I. Zone Loads

I1: Zone loads selection

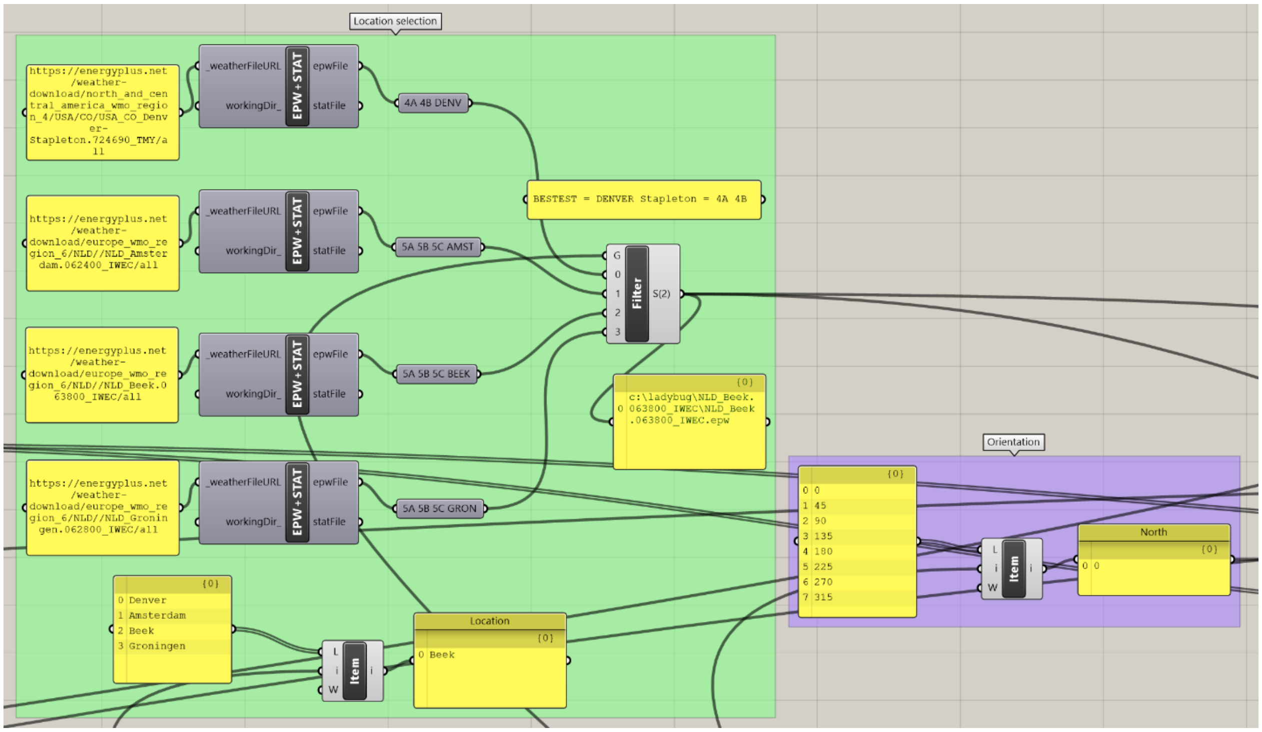


I2: HVAC system details



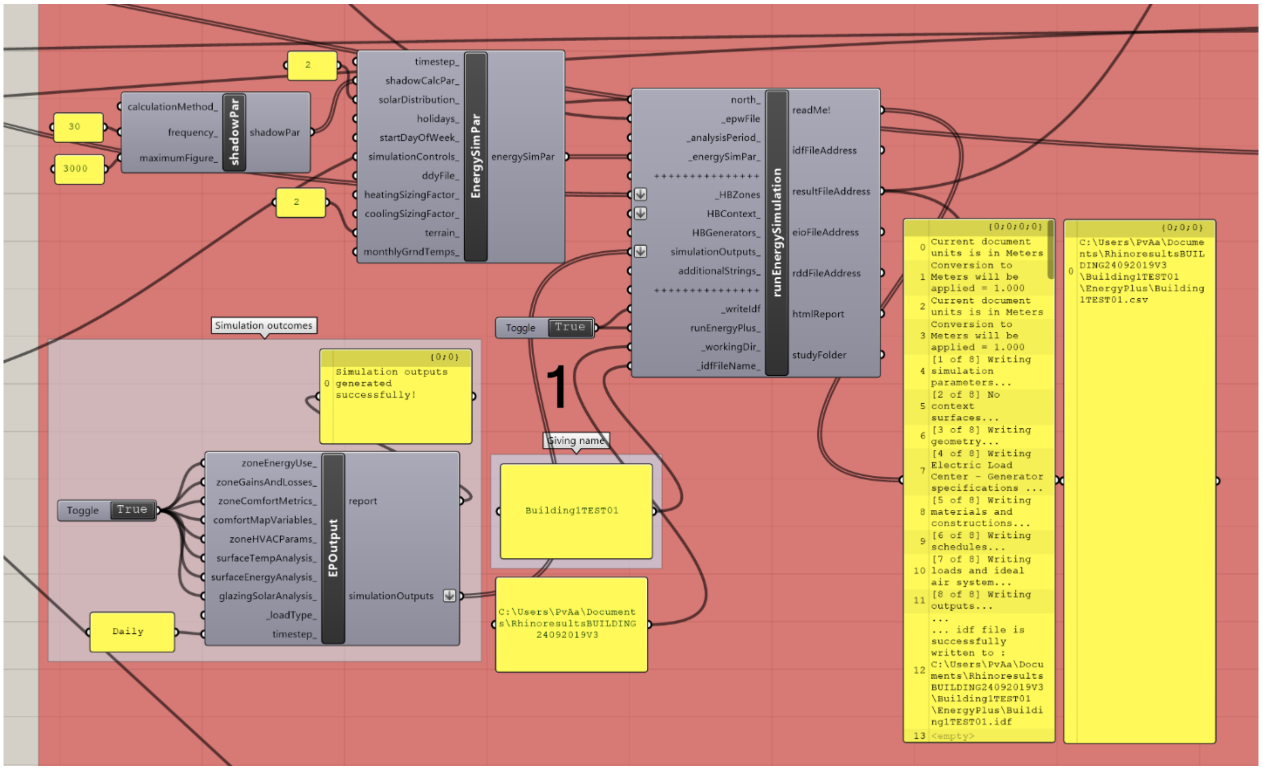
J. Location Selection and Orientation

J1: .epw file input and Orientation

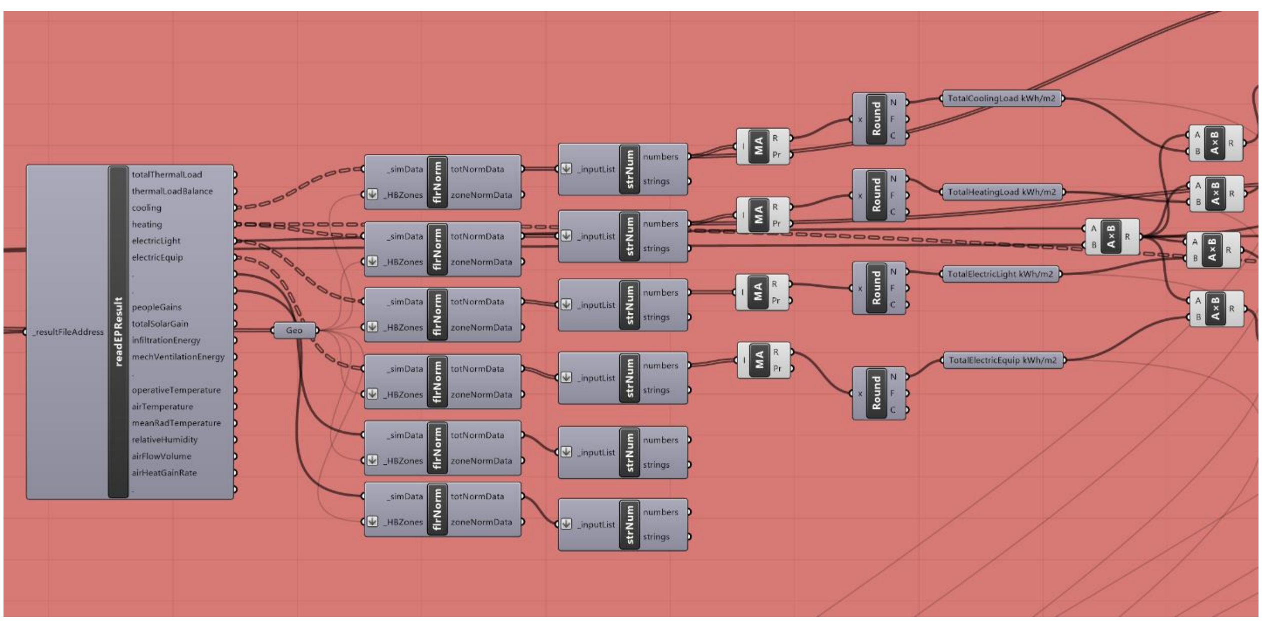


K. Simulation Engine

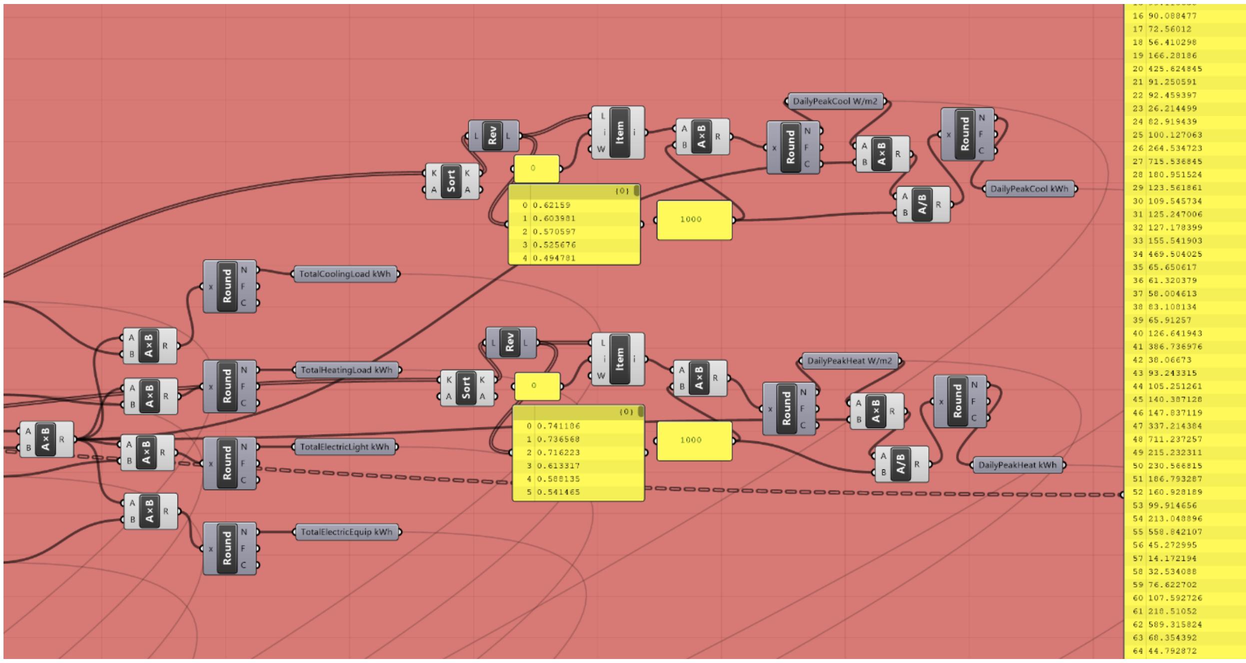
K1: EnergyPlus simulation engine



K2: Results processing (1)

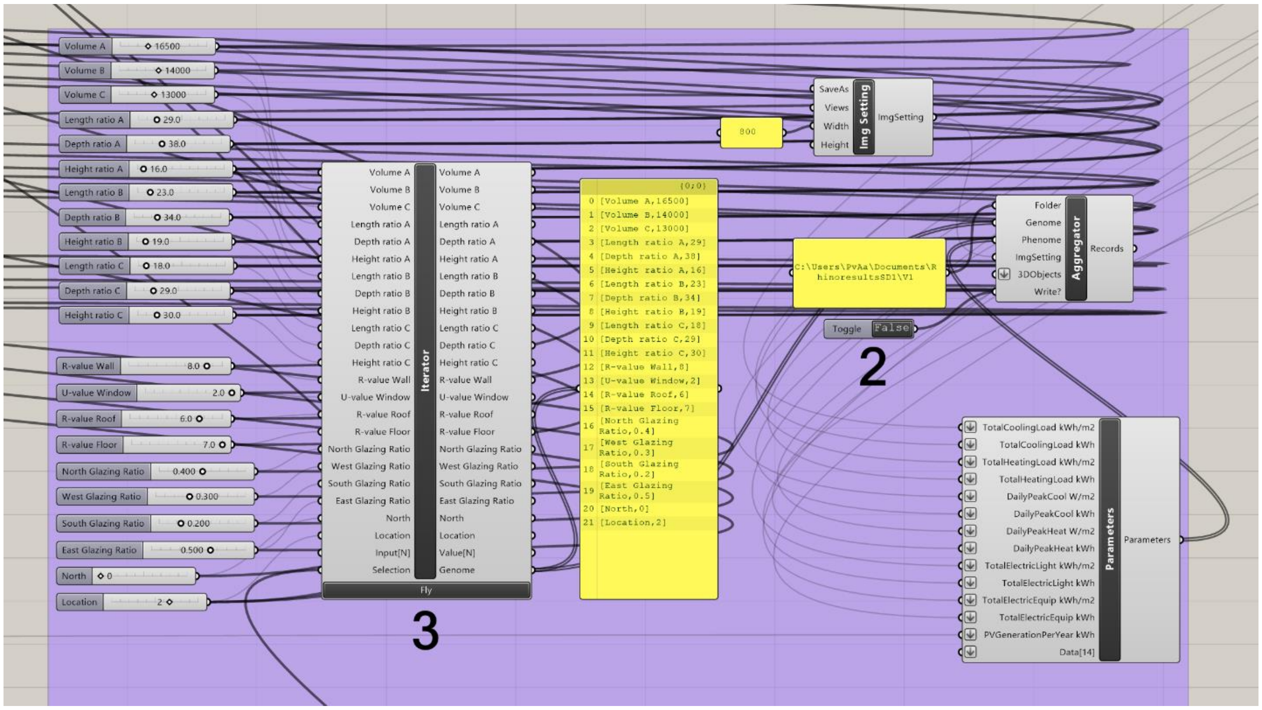


K3: Results processing (2)

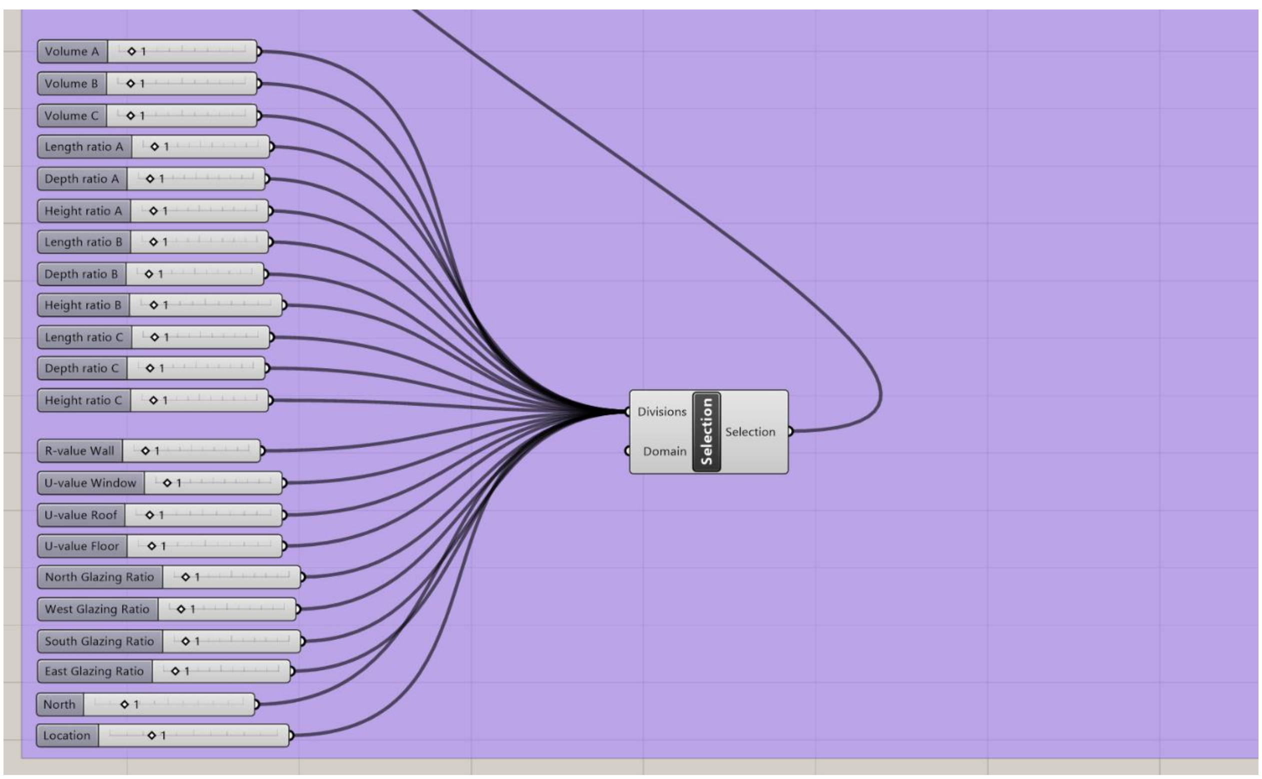


L. Colibri

L1: Selecting value ranges



L2: Selecting division of value ranges



Appendix V: Morris sensitivity analysis input values

Structure design phase

Parameter	Base case value	Value ranges
Volume A	16500	15500-17500
Volume B	14000	13000-15000
Volume C	13000	11000-13000
Length ratio A	29	25-33
Depth ratio A	38	37-45
Height ratio A	16	10-18
Length ratio B	23	16-24
Depth ratio B	34	30-38
Height ratio B	19	16-24
Length ratio C	18	18-22
Depth ratio C	29	26-30
Height ratio C	30	26-30
Location	Beek	Amsterdam, Groningen, Beek
Orientation	0	-90-90
North Glazing Ratio	0,4	0,2-0,8
West Glazing Ratio	0,3	0,2-0,8
South Glazing Ratio	0,2	0,2-0,8
East Glazing Ratio	0,5	0,2-0,8
R-value Wall	8	3-9
U-value Window	2	1-2
R-value Roof	6	3-7
R-value Floor	7	3-7

	Number	Parameter name	Parameter change	Step size
	1	/	/	/
	2	Volume A	-1000	-0,5
	3	Volume B	-1000	-0,5
	4	Volume C	-1000	-0,5
	5	Length ratio A	-4	-0,5
	6	Depth ratio A	4	0,5
	7	Height ratio A	-4	-0,5
	8	Length ratio B	-4	-0,5
	9	Depth ratio B	-4	-0,5
	10	Height ratio B	4	0,5
	11	Length ratio C	2	0,5
Trajectory 1	12	Depth ratio C	-2	-0,5
	13	Height ratio C	-2	-0,5
	14	Location	1	0,5
	15	Orientation	-90	-0,5
	16	North Glazing Ratio	0,3	0,5
	17	West Glazing Ratio	0,3	0,5
	18	South Glazing Ratio	0,3	0,5
	19	East Glazing Ratio	0,3	0,5
	20	R-value Wall	-3	-0,5
	21	U-value Window	-0,5	-0,5
	22	R-value Roof	-2	-0,5
	23	R-value Floor	-2	-0,5
	24	/	/	/
	25	U-value Window	1	0,5
	26	R-value Wall	3	0,5
	27	R-value Floor	-2	-0,5
	28	R-value Roof	2	0,5
	29	Orientation	90	0,5
	30	Location	1	0,5
	31	East Glazing Ratio	-0,3	-0,5
	32	South Glazing Ratio	-0,3	-0,5
	33	West Glazing Ratio	-0,3	-0,5
	34	North Glazing Ratio	-0,3	-0,5
Trajectory 2	35	Length ratio C	2	-0,5
	36	Depth ratio C	2	0,5
	37	Height ratio C	-2	-0,5
	38	Length ratio A	4	0,5
	39	Depth ratio A	-4	-0,5
	40	Height ratio A	4	0,5
	41	Length ratio B	4	0,5
	42	Depth ratio B	4	0,5
	43	Height ratio B	-4	-0,5

	44	Volume A	1000	0,5
	45	Volume B	1000	0,5
	46	Volume C	1000	0,5
Trajectory 3	47	/	/	/
	48	West Glazing Ratio	0,3	0,5
	49	South Glazing Ratio	0,3	0,5
	50	Location	-1	-0,5
	51	R-value Floor	3	0,5
	52	R-value Roof	-3	-0,5
	53	Length ratio A	-4	-0,5
	54	Depth ratio A	4	0,5
	55	Height ratio A	4	0,5
	56	Volume A	-1000	-0,5
	57	Volume B	-1000	-0,5
	58	Volume C	-1000	-0,5
	59	R-value Wall	3	0,5
	60	U-value Window	0,3	0,5
	61	Length ratio C	2	0,5
	62	Depth ratio C	-2	-0,5
	63	Height ratio C	2	0,5
	64	Length ratio B	-4	-0,5
	65	Depth ratio B	-4	-0,5
	66	Height ratio B	-4	-0,5
	67	Orientation	90	0,5
	68	North Glazing Ratio	-0,3	-0,5
	69	East Glazing Ratio	-0,3	-0,5
Trajectory 4	70	/	/	/
	71	Orientation	-90	-0,5
	72	R-value Roof	2	0,5
	73	Length ratio B	4	0,5
	74	Depth ratio B	4	0,5
	75	Height ratio B	4	0,5
	76	Length ratio C	-2	-0,5
	77	Depth ratio C	-2	-0,5
	78	Height ratio C	2	0,5
	79	R-value Floor	2	0,5
	80	U-value Window	-0,5	-0,5
	81	South Glazing Ratio	-0,3	-0,5
	82	East Glazing Ratio	-0,3	-0,5
	83	North Glazing Ratio	0,3	0,5
	84	West Glazing Ratio	0,3	0,5
	85	Volume A	-1000	-0,5
	86	Volume B	-1000	-0,5
	87	Volume C	-1000	-0,5

88	R-value Wall	-3	-0,5
89	Location	-2	-0,5
90	Height ratio A	-4	-0,5
91	Depth ratio A	-4	-0,5
92	Lenght ratio A	4	0,5

Parameter	Number	Volume A 15500-17500	Volume B 13000-15000	Volume C 11000-13000	Length ratio A 25-33	Depth ratio A 37-45	Height ratio A 10-18	Length ratio B 16-24	Depth ratio B 30-38	Height ratio B 16-24	Length ratio C 18-22	Depth ratio C 26-30	Height ratio C 26-30	Location 1-3	Orientation -90-90	North Glazing Ratio 0,2-0,8	West Glazing Ratio 0,2-0,8	South Glazing Ratio 0,2-0,8	East Glazing Ratio 0,2-0,8	R-value Wall 3-9	U-value Window 1-2	R-value Roof 3-7	R-value Floor 3-7
	1	**16500**	**14000**	**13000**	**29**	**38**	**16**	**23**	**34**	**19**	**18**	**29**	**30**	**2**	**0**	**0,4**	**0,3**	**0,2**	**0,5**	**8**	**2**	**6**	**7**
	2	15500	14000	13000	29	38	16	23	34	19	18	29	30	2	0	0,4	0,3	0,2	0,5	8	2	6	7
	3	15500	13000	13000	29	38	16	23	34	19	18	29	30	2	0	0,4	0,3	0,2	0,5	8	2	6	7
	4	15500	13000	12000	29	38	16	23	34	19	18	29	30	2	0	0,4	0,3	0,2	0,5	8	2	6	7
	5	15500	13000	12000	25	38	16	23	34	19	18	29	30	2	0	0,4	0,3	0,2	0,5	8	2	6	7
	6	15500	13000	12000	25	42	16	23	34	19	18	29	30	2	0	0,4	0,3	0,2	0,5	8	2	6	7
	7	15500	13000	12000	25	42	12	23	34	19	18	29	30	2	0	0,4	0,3	0,2	0,5	8	2	6	7
	8	15500	13000	12000	25	42	12	19	34	19	18	29	30	2	0	0,4	0,3	0,2	0,5	8	2	6	7
	9	15500	13000	12000	25	42	12	19	30	19	18	29	30	2	0	0,4	0,3	0,2	0,5	8	2	6	7
	10	15500	13000	12000	25	42	12	19	30	23	18	29	30	2	0	0,4	0,3	0,2	0,5	8	2	6	7
	11	15500	13000	12000	25	42	12	19	30	23	20	29	30	2	0	0,4	0,3	0,2	0,5	8	2	6	7
Trajectory 1	12	15500	13000	12000	25	42	12	19	30	23	20	27	30	2	0	0,4	0,3	0,2	0,5	8	2	6	7
	13	15500	13000	12000	25	42	12	19	30	23	20	27	28	2	0	0,4	0,3	0,2	0,5	8	2	6	7
	14	15500	13000	12000	25	42	12	19	30	23	20	27	28	3	0	0,4	0,3	0,2	0,5	8	2	6	7
	15	15500	13000	12000	25	42	12	19	30	23	20	27	28	3	-90	0,4	0,3	0,2	0,5	8	2	6	7
	16	15500	13000	12000	25	42	12	19	30	23	20	27	28	3	-90	0,7	0,3	0,2	0,5	8	2	6	7
	17	15500	13000	12000	25	42	12	19	30	23	20	27	28	3	-90	0,7	0,6	0,2	0,5	8	2	6	7
	18	15500	13000	12000	25	42	12	19	30	23	20	27	28	3	-90	0,7	0,6	0,5	0,5	8	2	6	7
	19	15500	13000	12000	25	42	12	19	30	23	20	27	28	3	-90	0,7	0,6	0,5	0,8	8	2	6	7
	20	15500	13000	12000	25	42	12	19	30	23	20	27	28	3	-90	0,7	0,6	0,5	0,8	5	2	6	7
	21	15500	13000	12000	25	42	12	19	30	23	20	27	28	3	-90	0,7	0,6	0,5	0,8	5	1,5	6	7
	22	15500	13000	12000	25	42	12	19	30	23	20	27	28	3	-90	0,7	0,6	0,5	0,8	5	1,5	4	7
	23	15500	13000	12000	25	42	12	19	30	23	20	27	28	3	-90	0,7	0,6	0,5	0,8	5	1,5	4	5

Parameter	Number	Volume A	Volume B	Volume C	Length ratio A	Depth ratio A	Height ratio A	Length ratio B	Depth ratio B	Height ratio B	Length ratio C	Depth ratio C	Height ratio C	Location	Orientation	North Glazing Ratio	West Glazing Ratio	South Glazing Ratio	East Glazing Ratio	R-value Wall	U-value Window	R-value Roof	R-value Floor
	24	**16500**	**13500**	**11000**	**26**	**44**	**13**	**20**	**31**	**22**	**21**	**26**	**29**	**1**	**0**	**0,6**	**0,5**	**0,8**	**0,7**	**3**	**1**	**3**	**6**
	25	16500	13500	11000	26	44	13	20	31	22	21	26	29	1	0	0,6	0,5	0,8	0,7	3	1,5	3	6
	26	16500	13500	11000	26	44	13	20	31	22	21	26	29	1	0	0,6	0,5	0,8	0,7	6	1,5	3	6
	27	16500	13500	11000	26	44	13	20	31	22	21	26	29	1	0	0,6	0,5	0,8	0,7	6	1,5	3	4
	28	16500	13500	11000	26	44	13	20	31	22	21	26	29	1	0	0,6	0,5	0,8	0,7	6	1,5	5	4
	29	16500	13500	11000	26	44	13	20	31	22	21	26	29	1	90	0,6	0,5	0,8	0,7	6	1,5	5	4
	30	16500	13500	11000	26	44	13	20	31	22	21	26	29	2	90	0,6	0,5	0,8	0,7	6	1,5	5	4
	31	16500	13500	11000	26	44	13	20	31	22	21	26	29	2	90	0,6	0,5	0,8	0,4	6	1,5	5	4
	32	16500	13500	11000	26	44	13	20	31	22	21	26	29	2	90	0,6	0,5	0,5	0,4	6	1,5	5	4
	33	16500	13500	11000	26	44	13	20	31	22	21	26	29	2	90	0,6	0,2	0,5	0,4	6	1,5	5	4
	34	16500	13500	11000	26	44	13	20	31	22	21	26	29	2	90	0,3	0,2	0,5	0,4	6	1,5	5	4
Trajectory 2	35	16500	13500	11000	26	44	13	20	31	22	19	26	29	2	90	0,3	0,2	0,5	0,4	6	1,5	5	4
	36	16500	13500	11000	26	44	13	20	31	22	19	28	29	2	90	0,3	0,2	0,5	0,4	6	1,5	5	4
	37	16500	13500	11000	26	44	13	20	31	22	19	28	27	2	90	0,3	0,2	0,5	0,4	6	1,5	5	4
	38	16500	13500	11000	30	44	13	20	31	22	19	28	27	2	90	0,3	0,2	0,5	0,4	6	1,5	5	4
	39	16500	13500	11000	30	40	13	20	31	22	19	28	27	2	90	0,3	0,2	0,5	0,4	6	1,5	5	4
	40	16500	13500	11000	30	40	17	20	31	22	19	28	27	2	90	0,3	0,2	0,5	0,4	6	1,5	5	4
	41	16500	13500	11000	30	40	17	24	31	22	19	28	27	2	90	0,3	0,2	0,5	0,4	6	1,5	5	4
	42	16500	13500	11000	30	40	17	24	35	22	19	28	27	2	90	0,3	0,2	0,5	0,4	6	1,5	5	4
	43	16500	13500	11000	30	40	17	24	35	18	19	28	27	2	90	0,3	0,2	0,5	0,4	6	1,5	5	4
	44	17500	13500	11000	30	40	17	24	35	18	19	28	27	2	90	0,3	0,2	0,5	0,4	6	1,5	5	4
	45	17500	14500	11000	30	40	17	24	35	18	19	28	27	2	90	0,3	0,2	0,5	0,4	6	1,5	5	4
	46	17500	14500	12000	30	40	17	24	35	18	19	28	27	2	90	0,3	0,2	0,5	0,4	6	1,5	5	4

Parameter	Number	Volume A	Volume B	Volume C	Length ratio A	Depth ratio A	Height ratio A	Length ratio B	Depth ratio B	Height ratio B	Length ratio C	Depth ratio C	Height ratio C	Location	Orientation	North Glazing Ratio	West Glazing Ratio	South Glazing Ratio	East Glazing Ratio	R-value Wall	U-value Window	R-value Roof	R-value Floor
	47	**17500**	**15000**	**12500**	**32**	**41**	**10**	**24**	**38**	**24**	**19**	**28**	**26**	**3**	**-90**	**0,8**	**0,2**	**0,4**	**0,6**	**4**	**1,5**	**7**	**3**
	48	17500	15000	12500	32	41	10	24	38	24	19	28	26	3	-90	0,8	0,5	0,4	0,6	4	1,5	7	3
	49	17500	15000	12500	32	41	10	24	38	24	19	28	26	3	-90	0,8	0,5	0,7	0,6	4	1,5	7	3
	50	17500	15000	12500	32	41	10	24	38	24	19	28	26	2	-90	0,8	0,5	0,7	0,6	4	1,5	7	3
	51	17500	15000	12500	32	41	10	24	38	24	19	28	26	2	-90	0,8	0,5	0,7	0,6	4	1,5	7	5
	52	17500	15000	12500	32	41	10	24	38	24	19	28	26	2	-90	0,8	0,5	0,7	0,6	4	1,5	5	5
	53	17500	15000	12500	28	41	10	24	38	24	19	28	26	2	-90	0,8	0,5	0,7	0,6	4	1,5	5	5
	54	17500	15000	12500	28	45	10	24	38	24	19	28	26	2	-90	0,8	0,5	0,7	0,6	4	1,5	5	5
	55	17500	15000	12500	28	45	14	24	38	24	19	28	26	2	-90	0,8	0,5	0,7	0,6	4	1,5	5	5
	56	16500	15000	12500	28	45	14	24	38	24	19	28	26	2	-90	0,8	0,5	0,7	0,6	4	1,5	5	5
	57	16500	14000	12500	28	45	14	24	38	24	19	28	26	2	-90	0,8	0,5	0,7	0,6	4	1,5	5	5
Trajectory 3	58	16500	14000	11500	28	45	14	24	38	24	19	28	26	2	-90	0,8	0,5	0,7	0,6	4	1,5	5	5
	59	16500	14000	11500	28	45	14	24	38	24	19	28	26	2	-90	0,8	0,5	0,7	0,6	7	1,5	5	5
	60	16500	14000	11500	28	45	14	24	38	24	19	28	26	2	-90	0,8	0,5	0,7	0,6	7	2	5	5
	61	16500	14000	11500	28	45	14	24	38	24	21	28	26	2	-90	0,8	0,5	0,7	0,6	7	2	5	5
	62	16500	14000	11500	28	45	14	24	38	24	21	26	26	2	-90	0,8	0,5	0,7	0,6	7	2	5	5
	63	16500	14000	11500	28	45	14	24	38	24	21	26	28	2	-90	0,8	0,5	0,7	0,6	7	2	5	5
	64	16500	14000	11500	28	45	14	20	38	24	21	26	28	2	-90	0,8	0,5	0,7	0,6	7	2	5	5
	65	16500	14000	11500	28	45	14	20	34	24	21	26	28	2	-90	0,8	0,5	0,7	0,6	7	2	5	5
	66	16500	14000	11500	28	45	14	20	34	20	21	26	28	2	-90	0,8	0,5	0,7	0,6	7	2	5	5
	67	16500	14000	11500	28	45	14	20	34	20	21	26	28	2	0	0,8	0,5	0,7	0,6	7	2	5	5
	68	16500	14000	11500	28	45	14	20	34	20	21	26	28	2	0	0,5	0,5	0,7	0,6	7	2	5	5
	69	16500	14000	11500	28	45	14	20	34	20	21	26	28	2	0	0,5	0,5	0,7	0,3	7	2	5	5

Parameter	Number	Volume A	Volume B	Volume C	Length ratio A	Depth ratio A	Height ratio A	Length ratio B	Depth ratio B	Height ratio B	Length ratio C	Depth ratio C	Height ratio C	Location	Orientation	North Glazing Ratio	West Glazing Ratio	South Glazing Ratio	East Glazing Ratio	R-value Wall	U-value Window	R-value Roof	R-value Floor
	70	**17000**	**14000**	**12000**	**27**	**43**	**15**	**17**	**32**	**17**	**22**	**30**	**28**	**2**	**90**	**0,2**	**0,8**	**0,6**	**0,2**	**9**	**1,5**	**4**	**5**
	71	17000	14000	12000	27	43	15	17	32	17	22	30	28	2	0	0,2	0,8	0,6	0,2	9	1,5	4	5
	72	17000	14000	12000	27	43	15	17	32	17	22	30	28	2	0	0,2	0,8	0,6	0,2	9	1,5	6	5
	73	17000	14000	12000	27	43	15	21	32	17	22	30	28	2	0	0,2	0,8	0,6	0,2	9	1,5	6	5
	74	17000	14000	12000	27	43	15	21	36	17	22	30	28	2	0	0,2	0,8	0,6	0,2	9	1,5	6	5
	75	17000	14000	12000	27	43	15	21	36	21	22	30	28	2	0	0,2	0,8	0,6	0,2	9	1,5	6	5
	76	17000	14000	12000	27	43	15	21	36	21	20	30	28	2	0	0,2	0,8	0,6	0,2	9	1,5	6	5
	77	17000	14000	12000	27	43	15	21	36	21	20	28	28	2	0	0,2	0,8	0,6	0,2	9	1,5	6	5
	78	17000	14000	12000	27	43	15	21	36	21	20	28	30	2	0	0,2	0,8	0,6	0,2	9	1,5	6	5
	79	17000	14000	12000	27	43	15	21	36	21	20	28	30	2	0	0,2	0,8	0,6	0,2	9	1,5	6	7
	80	17000	14000	12000	27	43	15	21	36	21	20	28	30	2	0	0,2	0,8	0,6	0,2	9	1	6	7
Trajectory 4	81	17000	14000	12000	27	43	15	21	36	21	20	28	30	2	0	0,2	0,8	0,3	0,2	9	1	6	7
	82	17000	14000	12000	27	43	15	21	36	21	20	28	30	2	0	0,2	0,8	0,3	0,5	9	1	6	7
	83	17000	14000	12000	27	43	15	21	36	21	20	28	30	2	0	0,5	0,8	0,3	0,5	9	1	6	7
	84	17000	14000	12000	27	43	15	21	36	21	20	28	30	2	0	0,5	0,5	0,3	0,5	9	1	6	7
	85	16000	14000	12000	27	43	15	21	36	21	20	28	30	2	0	0,5	0,5	0,3	0,5	9	1	6	7
	86	16000	13000	12000	27	43	15	21	36	21	20	28	30	2	0	0,5	0,5	0,3	0,5	9	1	6	7
	87	16000	13000	11000	27	43	15	21	36	21	20	28	30	2	0	0,5	0,5	0,3	0,5	9	1	6	7
	88	16000	13000	11000	27	43	15	21	36	21	20	28	30	2	0	0,5	0,5	0,3	0,5	6	1	6	7
	89	16000	13000	11000	27	43	15	21	36	21	20	28	30	1	0	0,5	0,5	0,3	0,5	6	1	6	7
	90	16000	13000	11000	27	43	11	21	36	21	20	28	30	1	0	0,5	0,5	0,3	0,5	6	1	6	7
	91	16000	13000	11000	27	39	11	21	36	21	20	28	30	1	0	0,5	0,5	0,3	0,5	6	1	6	7
	92	16000	13000	11000	31	39	11	21	36	21	20	28	30	1	0	0,5	0,5	0,3	0,5	6	1	6	7

Conceptual design phase

Parameter	Base case value	Value ranges
Volume A	16000	15500-16500
Volume B	14500	14000-15000
Volume C	12000	11000-12000
Length ratio A	25	23-27
Depth ratio A	40	39-43
Height ratio A	15	12-16
Length ratio B	20	17-21
Depth ratio B	35	33-37
Height ratio B	18	16-20
Length ratio C	20	20-22
Depth ratio C	30	28-30
Height ratio C	28	26-28
Location	Beek	Beek
Orientation	0	-10-10
North Glazing Ratio	0,7	0,6-0,8
West Glazing Ratio	0,6	0,6-0,8
South Glazing Ratio	0,6	0,6-0,8
East Glazing Ratio	0,7	0,6-0,8
R-value Wall	6	4-6
U-value Window	1,7	1,3-1,7
R-value Roof	6	4-6
R-value Floor	5	3-5

	Number	Parameter name	Parameter change	Step size
Trajectory 1	1	/	/	/
	2	Volume A	-500	-0,5
	3	Volume B	-500	-0,5
	4	Volume C	-500	-0,5
	5	Length ratio A	-2	-0,5
	6	Depth ratio A	2	0,5
	7	Height ratio A	-2	-0,5
	8	Length ratio B	-2	-0,5
	9	Depth ratio B	-2	-0,5
	10	Height ratio B	2	0,5
	11	Length ratio C	1	0,5
	12	Depth ratio C	-1	-0,5
	13	Height ratio C	-1	-0,5
	14	Orientation	-10	-0,5
	15	North Glazing Ratio	0,1	0,5
	16	West Glazing Ratio	0,1	0,5
	17	South Glazing Ratio	0,1	0,5
	18	East Glazing Ratio	0,1	0,5
	19	R-value Wall	-1	-0,5
	20	U-value Window	-0,2	-0,5
	21	R-value Roof	-1	-0,5
	22	R-value Floor	-1	-0,5
Trajectory 2	23	/	/	/
	24	U-value Window	0,2	0,5
	25	R-value Wall	1	0,5
	26	R-value Floor	-1	-0,5
	27	R-value Roof	1	0,5
	28	Orientation	10	0,5
	29	East Glazing Ratio	-0,1	-0,5
	30	South Glazing Ratio	-0,1	-0,5
	31	West Glazing Ratio	-0,1	-0,5
	32	North Glazing Ratio	-0,1	-0,5
	33	Length ratio C	-1	-0,5
	34	Depth ratio C	1	0,5
	35	Height ratio C	-1	-0,5
	36	Length ratio A	2	0,5
	37	Depth ratio A	-2	-0,5
	38	Height ratio A	2	0,5
	39	Length ratio B	2	0,5
	40	Depth ratio B	2	0,5
	41	Height ratio B	-2	-0,5
	42	Volume A	500	0,5
	43	Volume B	500	0,5
	44	Volume C	500	0,5
	45	/	/	/

Trajectory 3	46	West Glazing Ratio	0,1	0,5
	47	North Glazing Ratio	0,1	0,5
	48	East Glazing Ratio	0,1	0,5
	49	South Glazing Ratio	-0,1	-0,5
	50	R-value Floor	-1	-0,5
	51	R-value Roof	1	0,5
	52	Length ratio A	2	0,5
	53	Depth ratio A	-2	-0,5
	54	Height ratio A	-2	-0,5
	55	Volume A	-500	-0,5
	56	Volume B	500	0,5
	57	Volume C	500	0,5
	58	R-value Wall	1	0,5
	59	U-value Window	-0,2	-0,5
	60	Length ratio C	1	0,5
	61	Depth ratio C	-1	-0,5
	62	Height ratio C	-1	-0,5
	63	Length ratio B	-2	-0,5
	64	Depth ratio B	2	0,5
	65	Height ratio B	-2	-0,5
	66	Orientation	-10	-0,5
Trajectory 4	67	/	/	/
	68	Orientation	-10	-0,5
	69	R-value Roof	1	0,5
	70	Length ratio B	2	0,5
	71	Depth ratio B	2	0,5
	72	Height ratio B	2	0,5
	73	Length ratio C	-1	-0,5
	74	Depth ratio C	-1	-0,5
	75	Height ratio C	1	0,5
	76	R-value Floor	1	0,5
	77	U-value Window	-0,2	-0,5
	78	South Glazing Ratio	-0,1	-0,5
	79	East Glazing Ratio	-0,1	-0,5
	80	North Glazing Ratio	0,1	0,5
	81	West Glazing Ratio	0,1	0,5
	82	Volume A	-500	-0,5
	83	Volume B	-500	-0,5
	84	Volume C	-500	-0,5
	85	R-value Wall	-1	-0,5
	86	Height ratio A	-2	-0,5
	87	Depth ratio A	-2	-0,5
	88	Lenght ratio A	2	0,5

Parameter	Number	Volume A 15500-16500	Volume B 14000-15000	Volume C 11000-12000	Length ratio A 23-27	Depth ratio A 39-43	Height ratio A 12-16	Length ratio B 17-21	Depth ratio B 33-37	Height ratio B 16-20	Length ratio C 20-22	Depth ratio C 28-30	Height ratio C 26-28	Orientation -10-10	North Glazing Ratio 0,6-0,8	West Glazing Ratio 0,6-0,8	South Glazing Ratio 0,6-0,8	East Glazing Ratio 0,6-0,8	R-value Wall 4-6	U-value Window 1,3-1,7	R-value Roof 4-6	R-value Floor 3-5
	1	**16000**	**14500**	**12000**	**25**	**40**	**15**	**20**	**35**	**18**	**20**	**30**	**28**	**0**	**0,7**	**0,6**	**0,6**	**0,7**	**6**	**1,7**	**6**	**5**
	2	15500	14500	12000	25	40	15	20	35	18	20	30	28	0	0,7	0,6	0,6	0,7	6	1,7	6	5
	3	15500	15000	12000	25	40	15	20	35	18	20	30	28	0	0,7	0,6	0,6	0,7	6	1,7	6	5
	4	15500	15000	11500	25	40	15	20	35	18	20	30	28	0	0,7	0,6	0,6	0,7	6	1,7	6	5
	5	15500	15000	11500	23	40	15	20	35	18	20	30	28	0	0,7	0,6	0,6	0,7	6	1,7	6	5
	6	15500	15000	11500	23	42	15	20	35	18	20	30	28	0	0,7	0,6	0,6	0,7	6	1,7	6	5
	7	15500	15000	11500	23	42	13	20	35	18	20	30	28	0	0,7	0,6	0,6	0,7	6	1,7	6	5
	8	15500	15000	11500	23	42	13	18	35	18	20	30	28	0	0,7	0,6	0,6	0,7	6	1,7	6	5
	9	15500	15000	11500	23	42	13	18	33	18	20	30	28	0	0,7	0,6	0,6	0,7	6	1,7	6	5
	10	15500	15000	11500	23	42	13	18	33	20	20	30	28	0	0,7	0,6	0,6	0,7	6	1,7	6	5
Trajectory 1	11	15500	15000	11500	23	42	13	18	33	20	21	30	28	0	0,7	0,6	0,6	0,7	6	1,7	6	5
	12	15500	15000	11500	23	42	13	18	33	20	21	29	28	0	0,7	0,6	0,6	0,7	6	1,7	6	5
	13	15500	15000	11500	23	42	13	18	33	20	21	29	27	0	0,7	0,6	0,6	0,7	6	1,7	6	5
	14	15500	15000	11500	23	42	13	18	33	20	21	29	27	-10	0,7	0,6	0,6	0,7	6	1,7	6	5
	15	15500	15000	11500	23	42	13	18	33	20	21	29	27	-10	0,8	0,6	0,6	0,7	6	1,7	6	5
	16	15500	15000	11500	23	42	13	18	33	20	21	29	27	-10	0,8	0,7	0,6	0,7	6	1,7	6	5
	17	15500	15000	11500	23	42	13	18	33	20	21	29	27	-10	0,8	0,7	0,7	0,7	6	1,7	6	5
	18	15500	15000	11500	23	42	13	18	33	20	21	29	27	-10	0,8	0,7	0,7	0,8	6	1,7	6	5
	19	15500	15000	11500	23	42	13	18	33	20	21	29	27	-10	0,8	0,7	0,7	0,8	5	1,7	6	5
	20	15500	15000	11500	23	42	13	18	33	20	21	29	27	-10	0,8	0,7	0,7	0,8	5	1,5	6	5
	21	15500	15000	11500	23	42	13	18	33	20	21	29	27	-10	0,8	0,7	0,7	0,8	5	1,5	5	5
	22	15500	15000	11500	23	42	13	18	33	20	21	29	27	-10	0,8	0,7	0,7	0,8	5	1,5	5	4

Parameter	Number	Volume A	Volume B	Volume C	Length ratio A	Depth ratio A	Height ratio A	Length ratio B	Depth ratio B	Height ratio B	Length ratio C	Depth ratio C	Height ratio C	Orientation	North Glazing Ratio	West Glazing Ratio	South Glazing Ratio	East Glazing Ratio	R-value Wall	U-value Window	R-value Roof	R-value Floor
	23	**15500**	**14250**	**11000**	**24**	**43**	**14**	**19**	**33**	**19**	**21,5**	**28**	**27,5**	**0**	**0,7**	**0,7**	**0,8**	**0,8**	**4**	**1,3**	**4**	**4**
	24	15500	14250	11000	24	43	14	19	33	19	21,5	28	27,5	0	0,7	0,7	0,8	0,8	4	1,5	4	4
	25	15500	14250	11000	24	43	14	19	33	19	21,5	28	27,5	0	0,7	0,7	0,8	0,8	5	1,5	4	4
	26	15500	14250	11000	24	43	14	19	33	19	21,5	28	27,5	0	0,7	0,7	0,8	0,8	5	1,5	4	3
	27	15500	14250	11000	24	43	14	19	33	19	21,5	28	27,5	0	0,7	0,7	0,8	0,8	5	1,5	5	3
	28	15500	14250	11000	24	43	14	19	33	19	21,5	28	27,5	10	0,7	0,7	0,8	0,8	5	1,5	5	3
	29	15500	14250	11000	24	43	14	19	33	19	21,5	28	27,5	10	0,7	0,7	0,8	0,7	5	1,5	5	3
	30	15500	14250	11000	24	43	14	19	33	19	21,5	28	27,5	10	0,7	0,7	0,7	0,7	5	1,5	5	3
	31	15500	14250	11000	24	43	14	19	33	19	21,5	28	27,5	10	0,7	0,6	0,7	0,7	5	1,5	5	3
	32	15500	14250	11000	24	43	14	19	33	19	21,5	28	27,5	10	0,6	0,6	0,7	0,7	5	1,5	5	3
Trajectory 2	33	15500	14250	11000	24	43	14	19	33	19	20,5	28	27,5	10	0,6	0,6	0,7	0,7	5	1,5	5	3
	34	15500	14250	11000	24	43	14	19	33	19	20,5	29	27,5	10	0,6	0,6	0,7	0,7	5	1,5	5	3
	35	15500	14250	11000	24	43	14	19	33	19	20,5	29	26,5	10	0,6	0,6	0,7	0,7	5	1,5	5	3
	36	15500	14250	11000	26	43	14	19	33	19	20,5	29	26,5	10	0,6	0,6	0,7	0,7	5	1,5	5	3
	37	15500	14250	11000	26	41	14	19	33	19	20,5	29	26,5	10	0,6	0,6	0,7	0,7	5	1,5	5	3
	38	15500	14250	11000	26	41	16	19	33	19	20,5	29	26,5	10	0,6	0,6	0,7	0,7	5	1,5	5	3
	39	15500	14250	11000	26	41	16	21	33	19	20,5	29	26,5	10	0,6	0,6	0,7	0,7	5	1,5	5	3
	40	15500	14250	11000	26	41	16	21	35	19	20,5	29	26,5	10	0,6	0,6	0,7	0,7	5	1,5	5	3
	41	15500	14250	11000	26	41	16	21	35	17	20,5	29	26,5	10	0,6	0,6	0,7	0,7	5	1,5	5	3
	42	16000	14250	11000	26	41	16	21	35	17	20,5	29	26,5	10	0,6	0,6	0,7	0,7	5	1,5	5	3
	43	16000	14750	11000	26	41	16	21	35	17	20,5	29	26,5	10	0,6	0,6	0,7	0,7	5	1,5	5	3
	44	16000	14750	11500	26	41	16	21	35	17	20,5	29	26,5	10	0,6	0,6	0,7	0,7	5	1,5	5	3

Parameter	Number	Volume A	Volume B	Volume C	Length ratio A	Depth ratio A	Height ratio A	Length ratio B	Depth ratio B	Height ratio B	Length ratio C	Depth ratio C	Height ratio C	Orientation	North Glazing Ratio	West Glazing Ratio	South Glazing Ratio	East Glazing Ratio	R-value Wall	U-value Window	R-value Roof	R-value Floor
	45	16500	15000	11750	26	41	12	21	37	20	20,5	29	26	-10	0,8	0,7	0,7	0,7	5	1,5	6	3
	46	16500	15000	11750	26	41	12	21	37	20	20,5	29	26	-10	0,8	0,8	0,7	0,7	5	1,5	6	3
	47	16500	15000	11750	26	41	12	21	37	20	20,5	29	26	-10	0,8	0,8	0,8	0,7	5	1,5	6	3
	48	16500	15000	11750	26	41	12	21	37	20	20,5	29	26	-10	0,8	0,8	0,8	0,7	5	1,5	6	4
	49	16500	15000	11750	26	41	12	21	37	20	20,5	29	26	-10	0,8	0,8	0,8	0,7	5	1,5	5	4
	50	16500	15000	11750	24	41	12	21	37	20	20,5	29	26	-10	0,8	0,8	0,8	0,7	5	1,5	5	4
	51	16500	15000	11750	24	43	12	21	37	20	20,5	29	26	-10	0,8	0,8	0,8	0,7	5	1,5	5	4
	52	16500	15000	11750	24	43	14	21	37	20	20,5	29	26	-10	0,8	0,8	0,8	0,7	5	1,5	5	4
	53	16000	15000	11750	24	43	14	21	37	20	20,5	29	26	-10	0,8	0,8	0,8	0,7	5	1,5	5	4
	54	16000	14500	11750	24	43	14	21	37	20	20,5	29	26	-10	0,8	0,8	0,8	0,7	5	1,5	5	4
Trajectory 3	55	16000	14500	12250	24	43	14	21	37	20	20,5	29	26	-10	0,8	0,8	0,8	0,7	5	1,5	5	4
	56	16000	14500	12250	24	43	14	21	37	20	20,5	29	26	-10	0,8	0,8	0,8	0,7	6	1,5	5	4
	57	16000	14500	12250	24	43	14	21	37	20	20,5	29	26	-10	0,8	0,8	0,8	0,7	6	1,7	5	4
	58	16000	14500	12250	24	43	14	21	37	20	21,5	29	26	-10	0,8	0,8	0,8	0,7	6	1,7	5	4
	59	16000	14500	12250	24	43	14	21	37	20	21,5	28	26	-10	0,8	0,8	0,8	0,7	6	1,7	5	4
	60	16000	14500	12250	24	43	14	21	37	20	21,5	28	27	-10	0,8	0,8	0,8	0,7	6	1,7	5	4
	61	16000	14500	12250	24	43	14	19	37	20	21,5	28	27	-10	0,8	0,8	0,8	0,7	6	1,7	5	4
	62	16000	14500	12250	24	43	14	19	35	20	21,5	28	27	-10	0,8	0,8	0,8	0,7	6	1,7	5	4
	63	16000	14500	12250	24	43	14	19	35	18	21,5	28	27	-10	0,8	0,8	0,8	0,7	6	1,7	5	4
	64	16000	14500	12250	24	43	14	19	35	18	21,5	28	27	0	0,8	0,8	0,8	0,7	6	1,7	5	4
	65	16000	14500	12250	24	43	14	19	35	18	21,5	28	27	0	0,7	0,8	0,8	0,7	6	1,7	5	4
	66	16000	14500	12250	24	43	14	19	35	18	21,5	28	27	0	0,7	0,8	0,8	0,6	6	1,7	5	4

Parameter	Number	Volume A	Volume B	Volume C	Length ratio A	Depth ratio A	Height ratio A	Length ratio B	Depth ratio B	Height ratio B	Length ratio C	Depth ratio C	Height ratio C	Orientation	North Glazing Ratio	West Glazing Ratio	South Glazing Ratio	East Glazing Ratio	R-value Wall	U-value Window	R-value Roof	R-value Floor
	67	16250	14750	11500	23	42	14	17	34	16	22	30	27	10	0,6	0,8	0,7	0,6	6	1,5	5	4
	68	16250	14750	11500	23	42	14	17	34	16	22	30	27	0	0,6	0,8	0,7	0,6	6	1,5	5	4
	69	16250	14750	11500	23	42	14	17	34	16	22	30	27	0	0,6	0,8	0,7	0,6	6	1,5	6	4
	70	16250	14750	11500	23	42	14	19	34	16	22	30	27	0	0,6	0,8	0,7	0,6	6	1,5	6	4
	71	16250	14750	11500	23	42	14	19	36	16	22	30	27	0	0,6	0,8	0,7	0,6	6	1,5	6	4
	72	16250	14750	11500	23	42	14	19	36	18	22	30	27	0	0,6	0,8	0,7	0,6	6	1,5	6	4
	73	16250	14750	11500	23	42	14	19	36	18	21	30	27	0	0,6	0,8	0,7	0,6	6	1,5	6	4
	74	16250	14750	11500	23	42	14	19	36	18	21	29	27	0	0,6	0,8	0,7	0,6	6	1,5	6	4
	75	16250	14750	11500	23	42	14	19	36	18	21	29	28	0	0,6	0,8	0,7	0,6	6	1,5	6	4
	76	16250	14750	11500	23	42	14	19	36	18	21	29	28	0	0,6	0,8	0,7	0,6	6	1,5	6	5
Trajectory 4	77	16250	14750	11500	23	42	14	19	36	18	21	29	28	0	0,6	0,8	0,7	0,6	6	1,3	6	5
	78	16250	14750	11500	23	42	14	19	36	18	21	29	28	0	0,6	0,8	0,6	0,6	6	1,3	6	5
	79	16250	14750	11500	23	42	14	19	36	18	21	29	28	0	0,6	0,8	0,6	0,7	6	1,3	6	5
	80	16250	14750	11500	23	42	14	19	36	18	21	29	28	0	0,7	0,8	0,6	0,7	6	1,3	6	5
	81	16250	14750	11500	23	42	14	19	36	18	21	29	28	0	0,7	0,7	0,6	0,7	6	1,3	6	5
	82	15750	14750	11500	23	42	14	19	36	18	21	29	28	0	0,7	0,7	0,6	0,7	6	1,3	6	5
	83	15750	14500	11500	23	42	14	19	36	18	21	29	28	0	0,7	0,7	0,6	0,7	6	1,3	6	5
	84	15750	14500	11000	23	42	14	19	36	18	21	29	28	0	0,7	0,7	0,6	0,7	6	1,3	6	5
	85	15750	14500	11000	23	42	14	19	36	18	21	29	28	0	0,7	0,7	0,6	0,7	5	1,3	6	5
	86	15750	14500	11000	23	42	12	19	36	18	21	29	28	0	0,7	0,7	0,6	0,7	5	1,3	6	5
	87	15750	14500	11000	23	40	12	19	36	18	21	29	28	0	0,7	0,7	0,6	0,7	5	1,3	6	5
	88	15750	14500	11000	25	40	12	19	36	18	21	29	28	0	0,7	0,7	0,6	0,7	5	1,3	6	5

Detailed design phase

Parameter	Base case value	Value ranges
Volume A	15750	15650-15850
Volume B	14600	14500-14700
Volume C	11500	11300-11500
Length ratio A	26,5	26-27
Depth ratio A	42,2	42-43
Height ratio A	14	13-14
Length ratio B	21	20-21
Depth ratio B	34,8	34,3-35,3
Height ratio B	17,9	17,5-18,5
Length ratio C	20,3	20-21
Depth ratio C	29,5	28,5-29,5
Height ratio C	27,9	27-28
Location	Beek	Beek
Orientation	0	0
North Glazing Ratio	0,75	0,7-0,8
West Glazing Ratio	0,75	0,7-0,8
South Glazing Ratio	0,75	0,7-0,8
East Glazing Ratio	0,75	0,7-0,8
R-value Wall	4,5	4-5
U-value Window	1,65	1,45-1,65
R-value Roof	6	5-6
R-value Floor	5	4-5

	Number	Parameter name	Parameter change	Step size
	1	/	/	/
	2	Volume A	-100	-0,5
	3	Volume B	-100	-0,5
	4	Volume C	-100	-0,5
	5	Length ratio A	-0,5	-0,5
	6	Depth ratio A	0,5	0,5
	7	Height ratio A	-0,5	-0,5
	8	Length ratio B	-0,5	-0,5
	9	Depth ratio B	-0,5	-0,5
	10	Height ratio B	0,5	0,5
	11	Length ratio C	0,5	0,5
Trajectory 1	12	Depth ratio C	-0,5	-0,5
	13	Height ratio C	-0,5	-0,5
	14	North Glazing Ratio	0,05	0,5
	15	West Glazing Ratio	0,05	0,5
	16	South Glazing Ratio	0,05	0,5
	17	East Glazing Ratio	0,05	0,5
	18	R-value Wall	-0,5	-0,5
	19	U-value Window	-0,1	-0,5
	20	R-value Roof	-0,5	-0,5
	21	R-value Floor	-0,5	-0,5
	22	/	/	/
	23	U-value Window	0,1	0,5
	24	R-value Wall	0,5	0,5
	25	R-value Floor	-0,5	-0,5
	26	R-value Roof	0,5	0,5
	27	East Glazing Ratio	-0,05	-0,5
	28	South Glazing Ratio	-0,05	-0,5
	29	West Glazing Ratio	-0,05	-0,5
	30	North Glazing Ratio	-0,05	-0,5
Trajectory 2	31	Length ratio C	-0,5	-0,5
	32	Depth ratio C	0,5	0,5
	33	Height ratio C	-0,5	-0,5
	34	Length ratio A	0,5	0,5
	35	Depth ratio A	-0,5	-0,5
	36	Height ratio A	0,5	0,5
	37	Length ratio B	0,5	0,5
	38	Depth ratio B	0,5	0,5
	39	Height ratio B	-0,5	-0,5
	40	Volume A	100	0,5
	41	Volume B	100	0,5
	42	Volume C	100	0,5
	43	/	/	/
	44	West Glazing Ratio	0,05	0,5
	45	North Glazing Ratio	0,05	0,5

Trajectory 3	46	East Glazing Ratio	0,05	0,5
	47	South Glazing Ratio	-0,05	-0,5
	48	R-value Floor	-0,5	-0,5
	49	R-value Roof	0,5	0,5
	50	Length ratio A	0,5	0,5
	51	Depth ratio A	-0,5	-0,5
	52	Height ratio A	-0,5	-0,5
	53	Volume A	-100	-0,5
	54	Volume B	100	0,5
	55	Volume C	100	0,5
	56	R-value Wall	0,5	0,5
	57	U-value Window	-0,1	-0,5
	58	Length ratio C	0,5	0,5
	59	Depth ratio C	-0,5	-0,5
	60	Height ratio C	-0,5	-0,5
	61	Length ratio B	-0,5	-0,5
	62	Depth ratio B	0,5	0,5
	63	Height ratio B	-0,5	-0,5
Trajectory 4	64	/	/	/
	65	R-value Roof	0,5	0,5
	66	Length ratio B	0,5	0,5
	67	Depth ratio B	0,5	0,5
	68	Height ratio B	0,5	0,5
	69	Length ratio C	-0,5	-0,5
	70	Depth ratio C	-0,5	-0,5
	71	Height ratio C	0,5	0,5
	72	R-value Floor	0,5	0,5
	73	U-value Window	-0,1	-0,5
	74	South Glazing Ratio	-0,05	-0,5
	75	East Glazing Ratio	-0,05	-0,5
	76	North Glazing Ratio	0,05	0,5
	77	West Glazing Ratio	0,05	0,5
	78	Volume A	-100	-0,5
	79	Volume B	-100	-0,5
	80	Volume C	-100	-0,5
	81	R-value Wall	-0,5	-0,5
	82	Height ratio A	-0,5	-0,5
	83	Depth ratio A	-0,5	-0,5
	84	Lenght ratio A	0,5	0,5

Parameter	Number	Volume A	Volume B	Volume C	Length ratio A	Depth ratio A	Height ratio A	Length ratio B	Depth ratio B	Height ratio B	Length ratio C	Depth ratio C	Height ratio C	North Glazing Ratio	West Glazing Ratio	South Glazing Ratio	East Glazing Ratio	R-value Wall	U-value Window	R-value Roof	R-value Floor
		15650 - 15850	14500 - 14700	11300 - 11500	26-27	42-43	13-14	20-21	34,3-35,3	17,5-18,5	20-21	28,5-29,5	27-28	0,7-0,8	0,7-0,8	0,7-0,8	0,7-0,8	4-5	1,45-1,65	5-6	4-5
	1	**15750**	**14600**	**11500**	**26,5**	**42,2**	**14**	**21**	**34,8**	**17,9**	**20,3**	**29,5**	**27,9**	**0,75**	**0,75**	**0,75**	**0,75**	**4,5**	**1,65**	**6**	**5**
	2	15650	14600	11500	26,5	42,2	14	21	34,8	17,9	20,3	29,5	27,9	0,75	0,75	0,75	0,75	4,5	1,65	6	5
	3	15650	14500	11500	26,5	42,2	14	21	34,8	17,9	20,3	29,5	27,9	0,75	0,75	0,75	0,75	4,5	1,65	6	5
	4	15650	14500	11400	26,5	42,2	14	21	34,8	17,9	20,3	29,5	27,9	0,75	0,75	0,75	0,75	4,5	1,65	6	5
	5	15650	14500	11400	26	42,2	14	21	34,8	17,9	20,3	29,5	27,9	0,75	0,75	0,75	0,75	4,5	1,65	6	5
	6	15650	14500	11400	26	42,7	14	21	34,8	17,9	20,3	29,5	27,9	0,75	0,75	0,75	0,75	4,5	1,65	6	5
	7	15650	14500	11400	26	42,7	13,5	21	34,8	17,9	20,3	29,5	27,9	0,75	0,75	0,75	0,75	4,5	1,65	6	5
	8	15650	14500	11400	26	42,7	13,5	20,5	34,8	17,9	20,3	29,5	27,9	0,75	0,75	0,75	0,75	4,5	1,65	6	5
	9	15650	14500	11400	26	42,7	13,5	20,5	34,3	17,9	20,3	29,5	27,9	0,75	0,75	0,75	0,75	4,5	1,65	6	5
	10	15650	14500	11400	26	42,7	13,5	20,5	34,3	18,4	20,3	29,5	27,9	0,75	0,75	0,75	0,75	4,5	1,65	6	5
Trajectory 1	11	15650	14500	11400	26	42,7	13,5	20,5	34,3	18,4	20,8	29,5	27,9	0,75	0,75	0,75	0,75	4,5	1,65	6	5
	12	15650	14500	11400	26	42,7	13,5	20,5	34,3	18,4	20,8	29	27,9	0,75	0,75	0,75	0,75	4,5	1,65	6	5
	13	15650	14500	11400	26	42,7	13,5	20,5	34,3	18,4	20,8	29	27,4	0,75	0,75	0,75	0,75	4,5	1,65	6	5
	14	15650	14500	11400	26	42,7	13,5	20,5	34,3	18,4	20,8	29	27,4	0,8	0,75	0,75	0,75	4,5	1,65	6	5
	15	15650	14500	11400	26	42,7	13,5	20,5	34,3	18,4	20,8	29	27,4	0,8	0,8	0,75	0,75	4,5	1,65	6	5
	16	15650	14500	11400	26	42,7	13,5	20,5	34,3	18,4	20,8	29	27,4	0,8	0,8	0,8	0,75	4,5	1,65	6	5
	17	15650	14500	11400	26	42,7	13,5	20,5	34,3	18,4	20,8	29	27,4	0,8	0,8	0,8	0,8	4,5	1,65	6	5
	18	15650	14500	11400	26	42,7	13,5	20,5	34,3	18,4	20,8	29	27,4	0,8	0,8	0,8	0,8	4	1,65	6	5
	19	15650	14500	11400	26	42,7	13,5	20,5	34,3	18,4	20,8	29	27,4	0,8	0,8	0,8	0,8	4	1,55	6	5
	20	15650	14500	11400	26	42,7	13,5	20,5	34,3	18,4	20,8	29	27,4	0,8	0,8	0,8	0,8	4	1,55	5,5	5
	21	15650	14500	11400	26	42,7	13,5	20,5	34,3	18,4	20,8	29	27,4	0,8	0,8	0,8	0,8	4	1,55	5,5	4,5

Parameter	Number	Volume A	Volume B	Volume C	Length ratio A	Depth ratio A	Height ratio A	Length ratio B	Depth ratio B	Height ratio B	Length ratio C	Depth ratio C	Height ratio C	North Glazing Ratio	West Glazing Ratio	South Glazing Ratio	East Glazing Ratio	R-value Wall	U-value Window	R-value Roof	R-value Floor
	22	**15650**	**14550**	**11300**	**26,25**	**43**	**13,5**	**20,5**	**34,3**	**18,25**	**20,75**	**28,5**	**27,5**	**0,75**	**0,75**	**0,8**	**0,8**	**4**	**1,45**	**5**	**4,5**
	23	15650	14550	11300	26,25	43	13,5	20,5	34,3	18,25	20,75	28,5	27,5	0,75	0,75	0,8	0,8	4	1,55	5	4,5
	24	15650	14550	11300	26,25	43	13,5	20,5	34,3	18,25	20,75	28,5	27,5	0,75	0,75	0,8	0,8	4,5	1,55	5	4,5
	25	15650	14550	11300	26,25	43	13,5	20,5	34,3	18,25	20,75	28,5	27,5	0,75	0,75	0,8	0,8	4,5	1,55	5	4
	26	15650	14550	11300	26,25	43	13,5	20,5	34,3	18,25	20,75	28,5	27,5	0,75	0,75	0,8	0,8	4,5	1,55	5,5	4
	27	15650	14550	11300	26,25	43	13,5	20,5	34,3	18,25	20,75	28,5	27,5	0,75	0,75	0,8	0,75	4,5	1,55	5,5	4
	28	15650	14550	11300	26,25	43	13,5	20,5	34,3	18,25	20,75	28,5	27,5	0,75	0,75	0,75	0,75	4,5	1,55	5,5	4
	29	15650	14550	11300	26,25	43	13,5	20,5	34,3	18,25	20,75	28,5	27,5	0,75	0,7	0,75	0,75	4,5	1,55	5,5	4
	30	15650	14550	11300	26,25	43	13,5	20,5	34,3	18,25	20,75	28,5	27,5	0,7	0,7	0,75	0,75	4,5	1,55	5,5	4
	31	15650	14550	11300	26,25	43	13,5	20,5	34,3	18,25	20,25	28,5	27,5	0,7	0,7	0,75	0,75	4,5	1,55	5,5	4
Trajectory 2	32	15650	14550	11300	26,25	43	13,5	20,5	34,3	18,25	20,25	29	27,5	0,7	0,7	0,75	0,75	4,5	1,55	5,5	4
	33	15650	14550	11300	26,25	43	13,5	20,5	34,3	18,25	20,25	29	27	0,7	0,7	0,75	0,75	4,5	1,55	5,5	4
	34	15650	14550	11300	26,75	43	13,5	20,5	34,3	18,25	20,25	29	27	0,7	0,7	0,75	0,75	4,5	1,55	5,5	4
	35	15650	14550	11300	26,75	42,5	13,5	20,5	34,3	18,25	20,25	29	27	0,7	0,7	0,75	0,75	4,5	1,55	5,5	4
	36	15650	14550	11300	26,75	42,5	14	20,5	34,3	18,25	20,25	29	27	0,7	0,7	0,75	0,75	4,5	1,55	5,5	4
	37	15650	14550	11300	26,75	42,5	14	21	34,3	18,25	20,25	29	27	0,7	0,7	0,75	0,75	4,5	1,55	5,5	4
	38	15650	14550	11300	26,75	42,5	14	21	34,8	18,25	20,25	29	27	0,7	0,7	0,75	0,75	4,5	1,55	5,5	4
	39	15650	14550	11300	26,75	42,5	14	21	34,8	17,75	20,25	29	27	0,7	0,7	0,75	0,75	4,5	1,55	5,5	4
	40	15750	14550	11300	26,75	42,5	14	21	34,8	17,75	20,25	29	27	0,7	0,7	0,75	0,75	4,5	1,55	5,5	4
	41	15750	14650	11300	26,75	42,5	14	21	34,8	17,75	20,25	29	27	0,7	0,7	0,75	0,75	4,5	1,55	5,5	4
	42	15750	14650	11400	26,75	42,5	14	21	34,8	17,75	20,25	29	27	0,7	0,7	0,75	0,75	4,5	1,55	5,5	4

Parameter	Number	Volume A	Volume B	Volume C	Length ratio A	Depth ratio A	Height ratio A	Length ratio B	Depth ratio B	Height ratio B	Length ratio C	Depth ratio C	Height ratio C	North Glazing Ratio	West Glazing Ratio	South Glazing Ratio	East Glazing Ratio	R-value Wall	U-value Window	R-value Roof	R-value Floor
	43	**15850**	**14700**	**11450**	**26,75**	**42,5**	**13**	**20,75**	**35,3**	**18,5**	**20,25**	**29**	**27**	**0,8**	**0,75**	**0,75**	**0,75**	**4,5**	**1,55**	**6**	**4**
	44	15850	14700	11450	26,75	42,5	13	20,75	35,3	18,5	20,25	29	27	0,8	0,8	0,75	0,75	4,5	1,55	6	4
	45	15850	14700	11450	26,75	42,5	13	20,75	35,3	18,5	20,25	29	27	0,8	0,8	0,8	0,75	4,5	1,55	6	4
	46	15850	14700	11450	26,75	42,5	13	20,75	35,3	18,5	20,25	29	27	0,8	0,8	0,8	0,75	4,5	1,55	6	4,5
	47	15850	14700	11450	26,75	42,5	13	20,75	35,3	18,5	20,25	29	27	0,8	0,8	0,8	0,75	4,5	1,55	5,5	4,5
	48	15850	14700	11450	26,25	42,5	13	20,75	35,3	18,5	20,25	29	27	0,8	0,8	0,8	0,75	4,5	1,55	5,5	4,5
	49	15850	14700	11450	26,25	43	13	20,75	35,3	18,5	20,25	29	27	0,8	0,8	0,8	0,75	4,5	1,55	5,5	4,5
	50	15850	14700	11450	26,25	43	13,5	20,75	35,3	18,5	20,25	29	27	0,8	0,8	0,8	0,75	4,5	1,55	5,5	4,5
	51	15750	14700	11450	26,25	43	13,5	20,75	35,3	18,5	20,25	29	27	0,8	0,8	0,8	0,75	4,5	1,55	5,5	4,5
	52	15750	14600	11450	26,25	43	13,5	20,75	35,3	18,5	20,25	29	27	0,8	0,8	0,8	0,75	4,5	1,55	5,5	4,5
Trajectory 3	53	15750	14600	13500	26,25	43	13,5	20,75	35,3	18,5	20,25	29	27	0,8	0,8	0,8	0,75	4,5	1,55	5,5	4,5
	54	15750	14600	13500	26,25	43	13,5	20,75	35,3	18,5	20,25	29	27	0,8	0,8	0,8	0,75	5	1,55	5,5	4,5
	55	15750	14600	13500	26,25	43	13,5	20,75	35,3	18,5	20,25	29	27	0,8	0,8	0,8	0,75	5	1,65	5,5	4,5
	56	15750	14600	13500	26,25	43	13,5	20,75	35,3	18,5	20,75	29	27	0,8	0,8	0,8	0,75	5	1,65	5,5	4,5
	57	15750	14600	13500	26,25	43	13,5	20,75	35,3	18,5	20,75	28,5	27	0,8	0,8	0,8	0,75	5	1,65	5,5	4,5
	58	15750	14600	13500	26,25	43	13,5	20,75	35,3	18,5	20,75	28,5	27,5	0,8	0,8	0,8	0,75	5	1,65	5,5	4,5
	59	15750	14600	13500	26,25	43	13,5	20,25	35,3	18,5	20,75	28,5	27,5	0,8	0,8	0,8	0,75	5	1,65	5,5	4,5
	60	15750	14600	13500	26,25	43	13,5	20,25	34,8	18,5	20,75	28,5	27,5	0,8	0,8	0,8	0,75	5	1,65	5,5	4,5
	61	15750	14600	13500	26,25	43	13,5	20,25	34,8	18	20,75	28,5	27,5	0,8	0,8	0,8	0,75	5	1,65	5,5	4,5
	62	15750	14600	13500	26,25	43	13,5	20,25	34,8	18	20,75	28,5	27,5	0,75	0,8	0,8	0,75	5	1,65	5,5	4,5
	63	15750	14600	13500	26,25	43	13,5	20,25	34,8	18	20,75	28,5	27,5	0,75	0,8	0,8	0,7	5	1,65	5,5	4,5

Parameter	Number	Volume A	Volume B	Volume C	Length ratio A	Depth ratio A	Height ratio A	Length ratio B	Depth ratio B	Height ratio B	Length ratio C	Depth ratio C	Height ratio C	North Glazing Ratio	West Glazing Ratio	South Glazing Ratio	East Glazing Ratio	R-value Wall	U-value Window	R-value Roof	R-value Floor
	64	**15800**	**14650**	**11400**	**26**	**42,75**	**13,5**	**20**	**34,55**	**17,5**	**21**	**29,25**	**27,5**	**0,7**	**0,8**	**0,75**	**0,7**	**5**	**1,55**	**5,5**	**4,5**
	65	15800	14650	11400	26	42,75	13,5	20	34,55	17,5	21	29,25	27,5	0,7	0,8	0,75	0,7	5	1,55	6	4,5
	66	15800	14650	11400	26	42,75	13,5	20,5	34,55	17,5	21	29,25	27,5	0,7	0,8	0,75	0,7	5	1,55	6	4,5
	67	15800	14650	11400	26	42,75	13,5	20,5	35,05	17,5	21	29,25	27,5	0,7	0,8	0,75	0,7	5	1,55	6	4,5
	68	15800	14650	11400	26	42,75	13,5	20,5	35,05	18	21	29,25	27,5	0,7	0,8	0,75	0,7	5	1,55	6	4,5
	69	15800	14650	11400	26	42,75	13,5	20,5	35,05	18	20,5	29,25	27,5	0,7	0,8	0,75	0,7	5	1,55	6	4,5
	70	15800	14650	11400	26	42,75	13,5	20,5	35,05	18	20,5	28,75	27,5	0,7	0,8	0,75	0,7	5	1,55	6	4,5
	71	15800	14650	11400	26	42,75	13,5	20,5	35,05	18	20,5	28,75	28	0,7	0,8	0,75	0,7	5	1,55	6	4,5
	72	15800	14650	11400	26	42,75	13,5	20,5	35,05	18	20,5	28,75	28	0,7	0,8	0,75	0,7	5	1,55	6	5
Trajecory 4	73	15800	14650	11400	26	42,75	13,5	20,5	35,05	18	20,5	28,75	28	0,7	0,8	0,75	0,7	5	1,45	6	5
	74	15800	14650	11400	26	42,75	13,5	20,5	35,05	18	20,5	28,75	28	0,7	0,8	0,7	0,7	5	1,45	6	5
	75	15800	14650	11400	26	42,75	13,5	20,5	35,05	18	20,5	28,75	28	0,7	0,8	0,7	0,75	5	1,45	6	5
	76	15800	14650	11400	26	42,75	13,5	20,5	35,05	18	20,5	28,75	28	0,75	0,8	0,7	0,75	5	1,45	6	5
	77	15800	14650	11400	26	42,75	13,5	20,5	35,05	18	20,5	28,75	28	0,75	0,75	0,7	0,75	5	1,45	6	5
	78	15700	14650	11400	26	42,75	13,5	20,5	35,05	18	20,5	28,75	28	0,75	0,75	0,7	0,75	5	1,45	6	5
	79	15700	14550	11400	26	42,75	13,5	20,5	35,05	18	20,5	28,75	28	0,75	0,75	0,7	0,75	5	1,45	6	5
	80	15700	14550	11300	26	42,75	13,5	20,5	35,05	18	20,5	28,75	28	0,75	0,75	0,7	0,75	5	1,45	6	5
	81	15700	14550	11300	26	42,75	13,5	20,5	35,05	18	20,5	28,75	28	0,75	0,75	0,7	0,75	4,5	1,45	6	5
	82	15700	14550	11300	26	42,75	13	20,5	35,05	18	20,5	28,75	28	0,75	0,75	0,7	0,75	4,5	1,45	6	5
	83	15700	14550	11300	26	42,25	13	20,5	35,05	18	20,5	28,75	28	0,75	0,75	0,7	0,75	4,5	1,45	6	5
	84	15700	14550	11300	26,5	42,25	13	20,5	35,05	18	20,5	28,75	28	0,75	0,75	0,7	0,75	4,5	1,45	6	5

Appendix VI: Monte Carlo uncertainty analysis input values

Structure design phase

SD			
Parameter	**Base case value**	**Value ranges**	**Remarks**
Volume A	17500	15500-17500	*
Volume B	13000	13000-15000	*
Volume C	10500	10500-12500	*
Length ratio A	25	25-33	
Depth ratio A	**37**	**37-45**	
Height ratio A	10	10-18	*
Length ratio B	**16**	**16-24**	
Depth ratio B	30	30-38	*
Height ratio B	24	16-24	*
Length ratio C	19	18-22	*
Depth ratio C	28	26-30	*
Height ratio C	30	26-30	
Location	Beek	Amsterdam, Groningen, Beek	
Orientation	**0**	**-90-90**	
North Glazing Ratio	0,4	0,2-0,8	
West Glazing Ratio	**0,3**	**0,2-0,8**	
South Glazing Ratio	0,2	0,2-0,8	
East Glazing Ratio	**0,2**	**0,2-0,8**	*
R-value Wall	**9**	**3-9**	*
U-value Window	2	1-2	
R-value Roof	6	3-7	
R-value Floor	7	3-7	
			* = Base case value is different from the sensitivity analysis

Conceptual design phase

CD			
Parameter	**Base case value**	**Value ranges**	
Volume A	16000	15500-16500	
Volume B	14500	14000-15000	
Volume C	12000	11000-12000	
Length ratio A	25	23-27	
Depth ratio A	40	39-43	
Height ratio A	15	12-16	
Length ratio B	**20**	**17-21**	
Depth ratio B	37	33-37	*
Height ratio B	18	16-20	
Length ratio C	20	20-22	
Depth ratio C	30	28-30	
Height ratio C	**28**	**26-28**	
Location	Beek	Beek	
Orientation	-10	-10-10	*
North Glazing Ratio	0,6	0,6-0,8	*
West Glazing Ratio	**0,6**	**0,6-0,8**	
South Glazing Ratio	0,6	0,6-0,8	
East Glazing Ratio	**0,7**	**0,6-0,8**	
R-value Wall	**6**	**4-6**	
U-value Window	1,7	1,3-1,7	
R-value Roof	6	4-6	
R-value Floor	5	3-5	
			* = Base case value is different from the sensitivity analysis

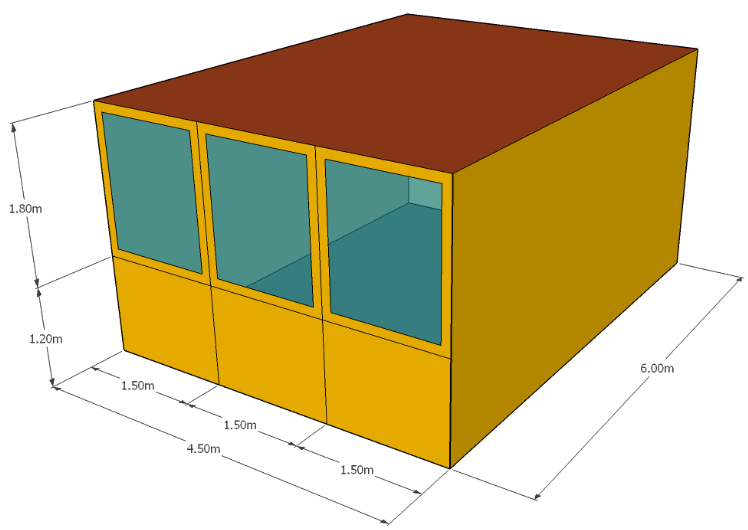
Detailed design phase

DD			
Parameter	**Base case value**	**Value ranges**	**Remarks**
Volume A	15750	15650-15850	
Volume B	14500	14500-14700	*
Volume C	11500	11300-11500	
Length ratio A	26,5	26-27	
Depth ratio A	42,2	42-43	
Height ratio A	14	13-14	
Length ratio B	**21**	**20-21**	
Depth ratio B	34,8	34,3-35,3	
Height ratio B	17,9	17,5-18,5	
Length ratio C	20	20-21	*
Depth ratio C	29,5	28,5-29,5	
Height ratio C	28	27-28	*
Location	Beek	Beek	
Orientation	0	0	
North Glazing Ratio	0,75	0,7-0,8	
West Glazing Ratio	0,7	0,7-0,8	*
South Glazing Ratio	0,7	0,7-0,8	*
East Glazing Ratio	0,7	0,7-0,8	*
R-value Wall	**4,5**	**4-5**	
U-value Window	1,65	1,45-1,65	
R-value Roof	6	5-6	
R-value Floor	5	4-5	
			* = Base case value is different from the sensitivity analysis

Appendix VII: IES SHC Task 56 Reference Building Characteristics

All information is obtained from IES SHC Task 56 (D'Antoni, Bonato, & Loonen, 2017). The tables also show the information of Stockholm and Rome, but the focus in this research is on the Stuttgart location.

Model Geometry:



Thermal transmittance and insulation thickness of external façade opaque element:

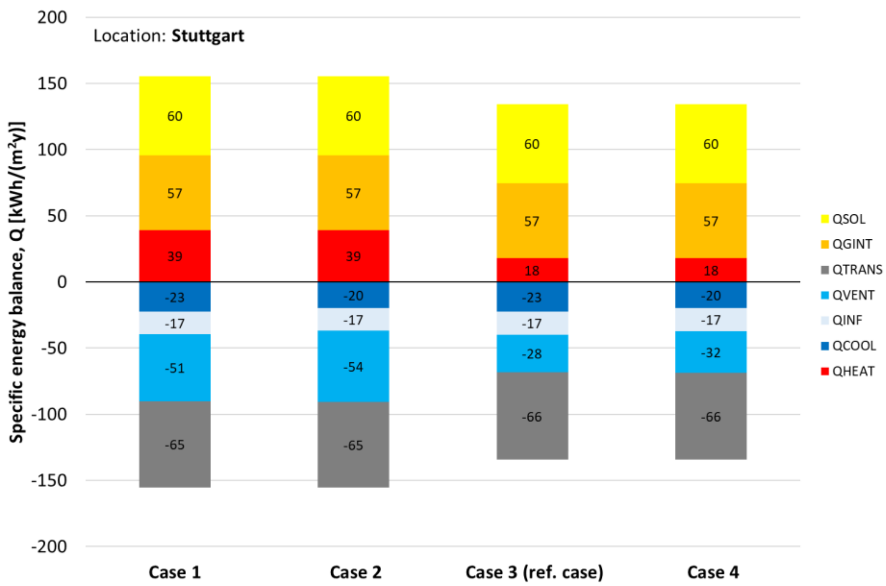
Climatic zone	U-wall [W/(m²K)]	Insulation thickness [cm]
Stockholm	0.3	12
Stuttgart	**0.4**	**9**
Rome	0.8	4

Thermal and optical characteristics of transparent structures:

Location	Description	Assembly	U-glass [W/(m²K)]	g-value [-]	T-sol [-]	Rf-sol [-]	T-vis [-]
Stockholm	Double glazing filled w. Krypton	4/16/4	0.81	0.632	0.462	0.237	0.749
Stuttgart	**Double glazing filled w. Argon**	**4/16/4**	**1.40**	**0.589**	**0.426**	**0.266**	**0.706**
Rome	Double glazing filled w. Argon	6/16/6	1.29	0.333	0.260	0.218	0.659

Specific energy balance of the reference office space for the reference location Stuttgart

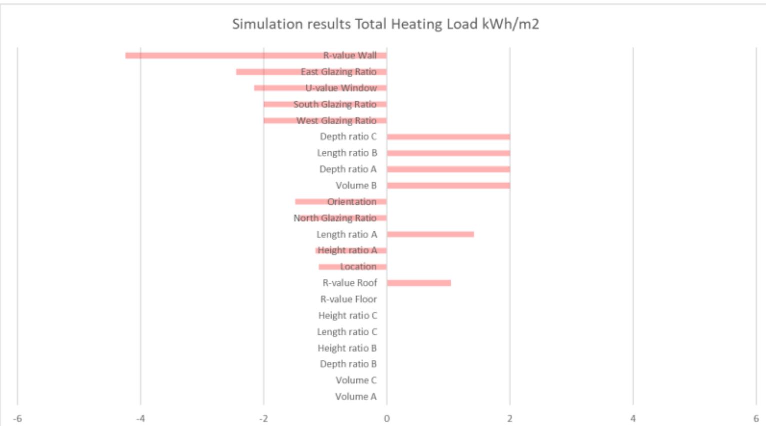
The results of case 3 are for this research used as reference case.

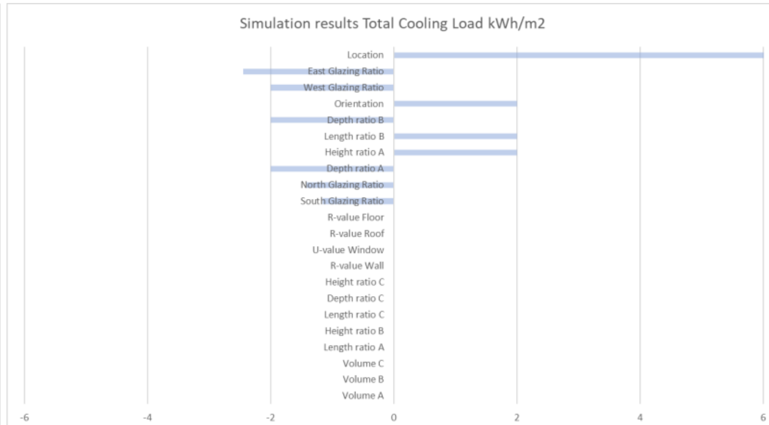


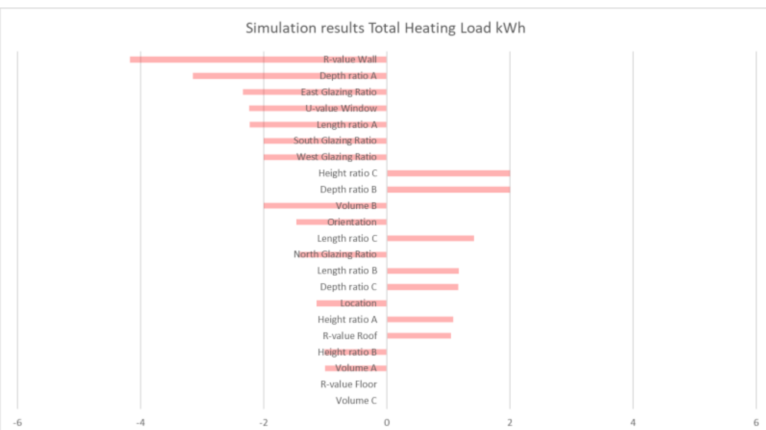
Appendix VIII: Results sensitivity & uncertainty analysis

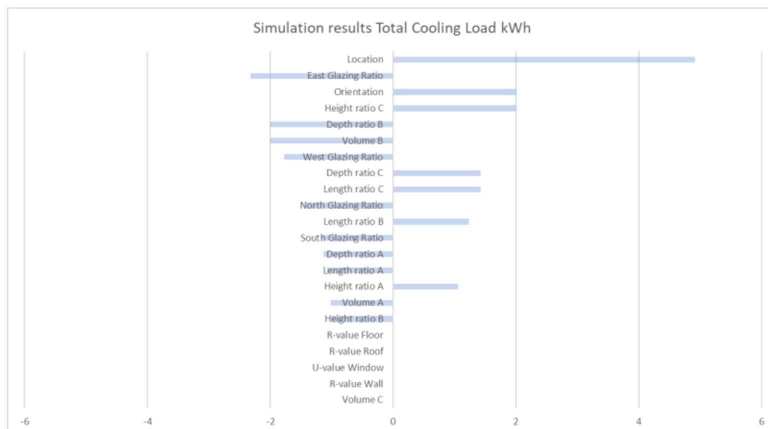
Sensitivity analysis results

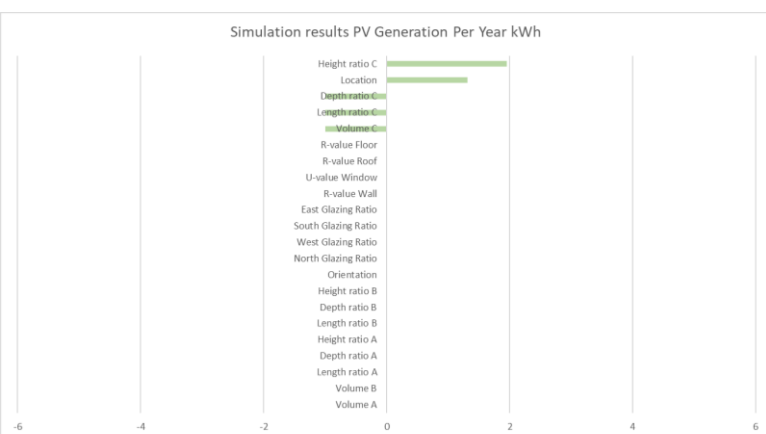
Structure design phase

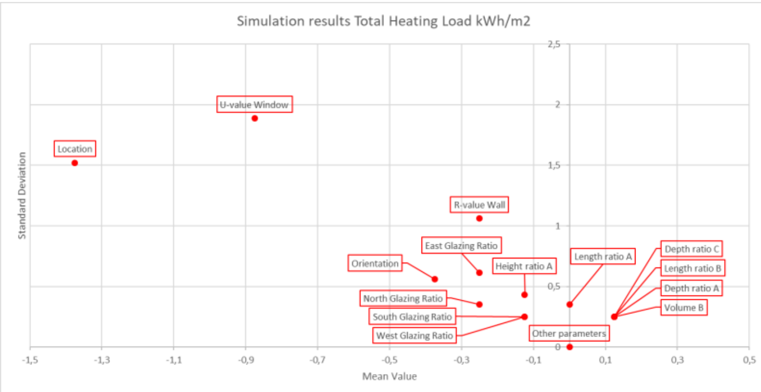


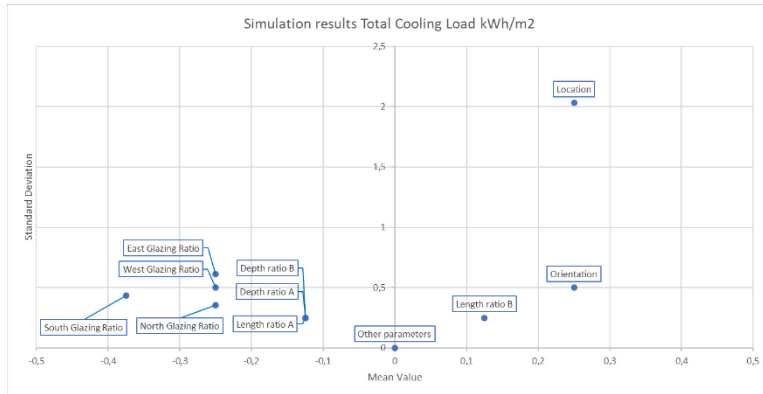


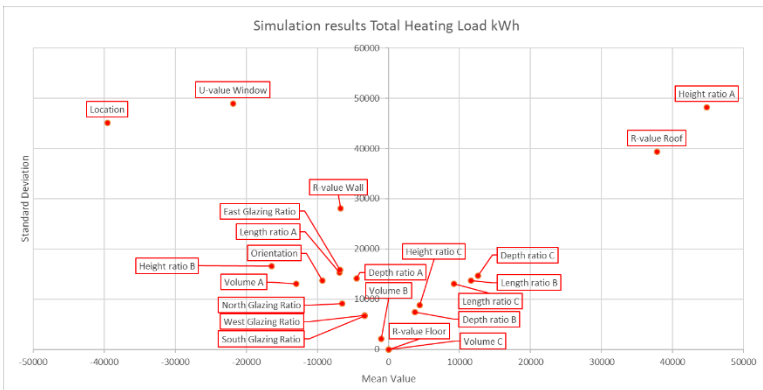


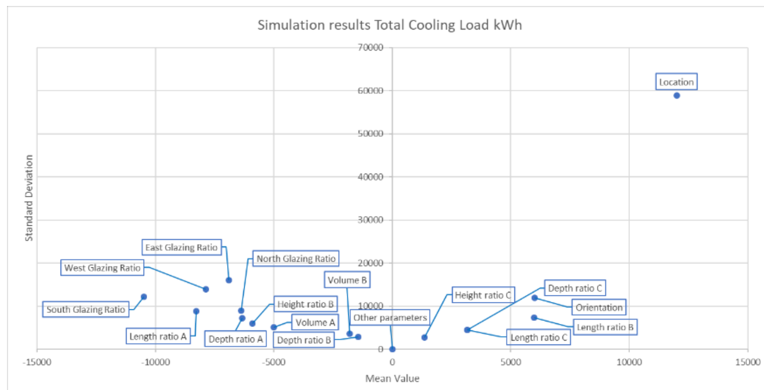


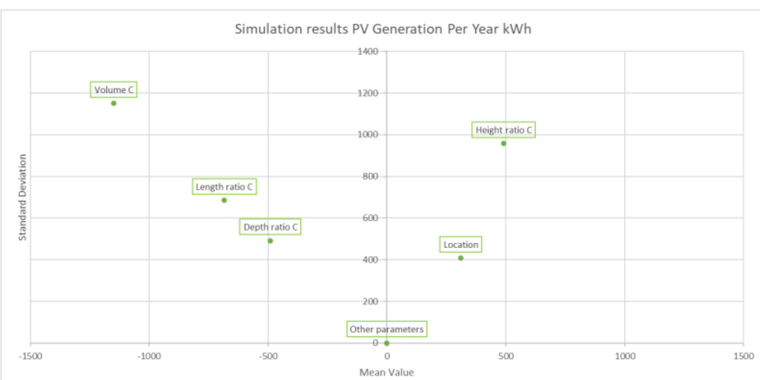



Simulation results Total Heating Load kWh/m2
Standard Deviation
Mean Value
U-value Window
Location
R-value Wall
East Glazing Ratio
Orientation
Height ratio A
Length ratio A
Depth ratio C
Length ratio B
Depth ratio A
Volume B
North Glazing Ratio
South Glazing Ratio
West Glazing Ratio
Other parameters

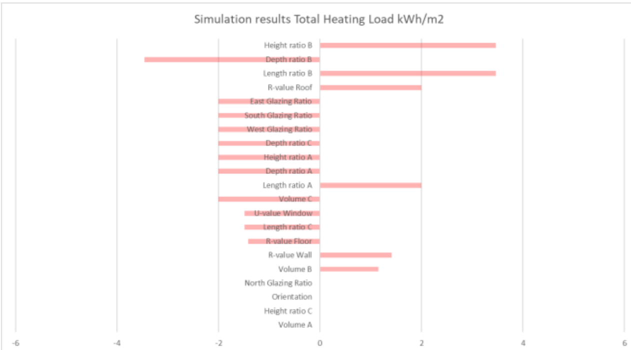

Simulation results Total Cooling Load kWh/m2
Standard Deviation
Mean Value
Location
East Glazing Ratio
West Glazing Ratio
Depth ratio B
Depth ratio A
Orientation
Length ratio B
South Glazing Ratio
North Glazing Ratio
Length ratio A
Other parameters


Simulation results Total Heating Load kWh
Standard Deviation
Mean Value
U-value Window
Location
Height ratio A
R-value Roof
R-value Wall
East Glazing Ratio
Length ratio A
Orientation
Height ratio B
Volume A
Height ratio C
Depth ratio C
Depth ratio A
Length ratio B
Volume B
Length ratio C
North Glazing Ratio
West Glazing Ratio
South Glazing Ratio
Depth ratio B
R-value Floor
Volume C

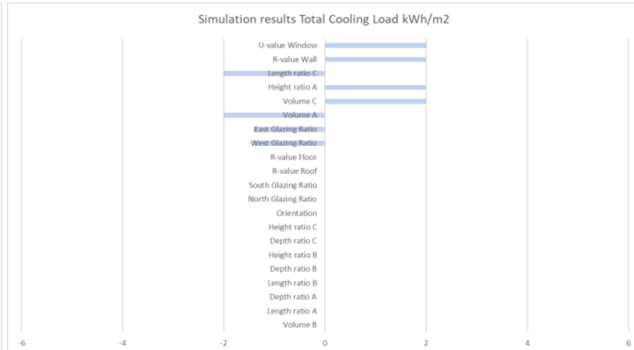

Simulation results Total Cooling Load kWh
Standard Deviation
Mean Value
Location
East Glazing Ratio
West Glazing Ratio
North Glazing Ratio
Volume B
South Glazing Ratio
Height ratio B
Volume A
Other parameters
Height ratio C
Depth ratio C
Orientation
Length ratio B
Length ratio C
Length ratio A
Depth ratio A
Depth ratio B


Simulation results PV Generation Per Year kWh
Standard Deviation
Mean Value
Volume C
Height ratio C
Length ratio C
Depth ratio C
Location
Other parameters

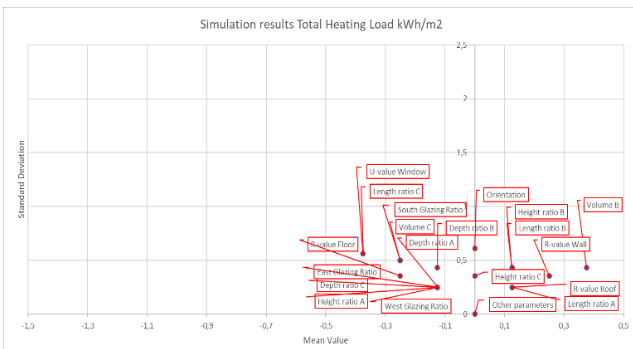
Conceptual Design Phase



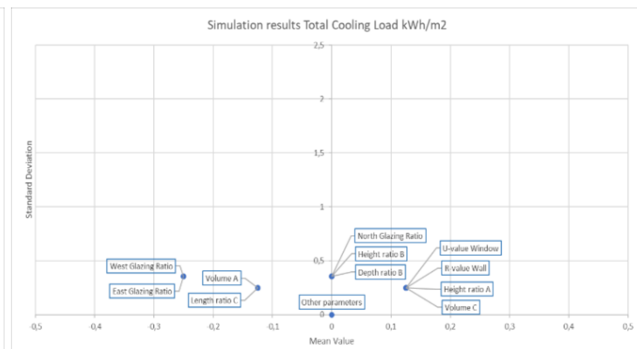
(a) Ranking of Sensitivity for Heating load in Conceptual Design Phase



(b) Ranking of Sensitivity for Cooling load in Conceptual Design Phase



(c) Interdependency of parameters for Heating load in Conceptual Design phase



(d) Interdependency of parameters for Cooling load in Conceptual Design phase

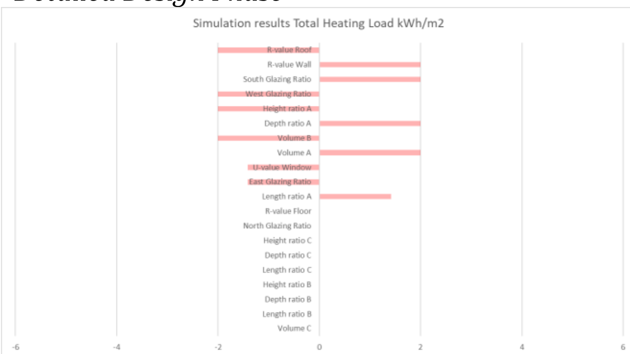
Figure VII.1: Sensitivity ranking and Interdependency of the input parameters for the Conceptual Design Phase

For the CD-phase, the sensitivity rankings and Interdependencies can be seen in. Clearly visible for the heating load is the high sensitivity of the geometric input parameters of volume B, the R-value of the Roof, followed by the East, South and West glazing ratios. The Standard Deviation of these parameters is higher than for the other parameters, but relatively low compared to the previous phase.

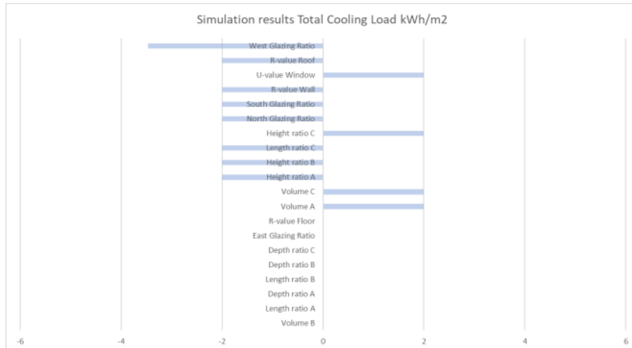
The increased relative sensitivity of the geometric input parameters can again best be explained by looking at the input ranges. The range width for the Length, Depth and Height of largest volume A has decreased to 4 meters, while also the range width of the dimensions of the smaller volume B has decreased to 4 meters. The smallest volume C even has the range width of input values decreased to 2 meters. This means that relatively to the other volumes, volume B now has the largest range of inputs, and therefore has a higher sensitivity.

Even more than in the previous phase, for the cooling load in this phase, a large amount of parameters with a relatively low sensitivity is significant, especially when compared to the relatively high amount of parameters that is sensitive for the heating load. For instance, the relatively large dimensions of volume B do not result in an increased sensitivity of these parameters for the cooling load, while they had a remarkable effect for the heating load. The large amount of low sensitivities for the cooling load can again be explained by the fact that especially for relatively cold climates, like for a Dutch climate, slight changes in parameters have only a relatively small effect on the need for cooling of a building, while the same change can have a relatively large effect on the heating load during wintertime.

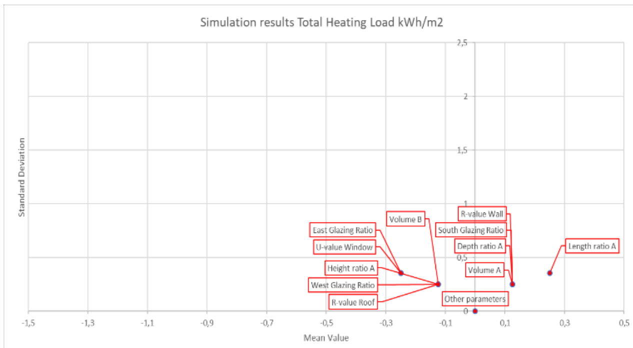
Detailed Design Phase



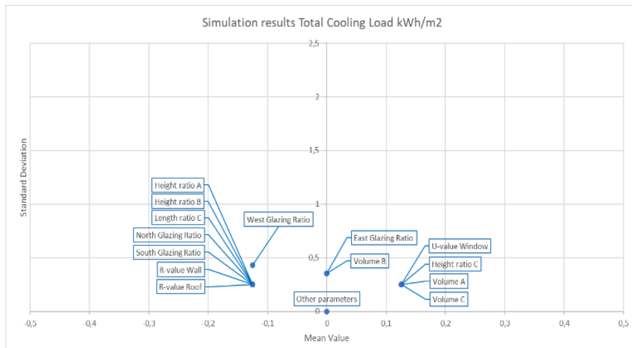
(a) Ranking of Sensitivity for Heating load in Detailed Design Phase



(b) Ranking of Sensitivity for Cooling load in Detailed Design Phase



(c) Interdependency of parameters for Heating load in Detailed Design phase



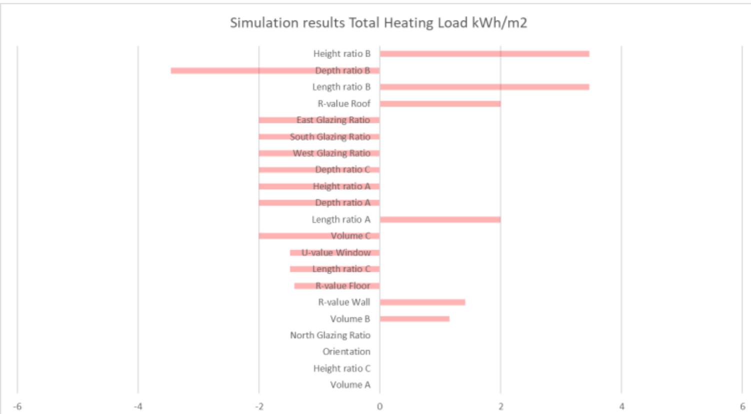
(d) Interdependency of parameters for Cooling load in Detailed Design phase

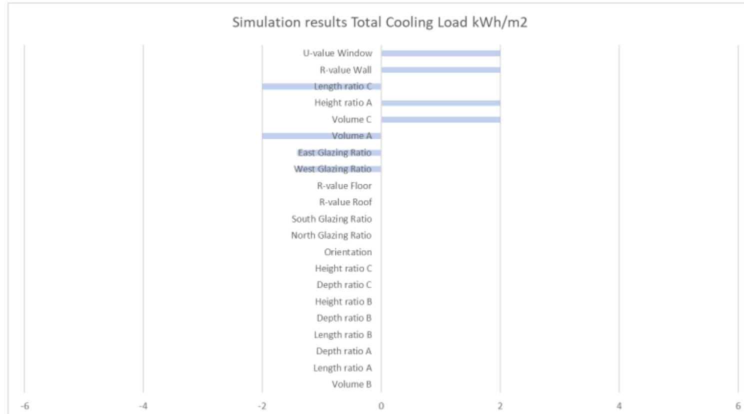
Figure VIII.2: Sensitivity ranking and Interdependency of the input parameters for the Detailed Design Phase

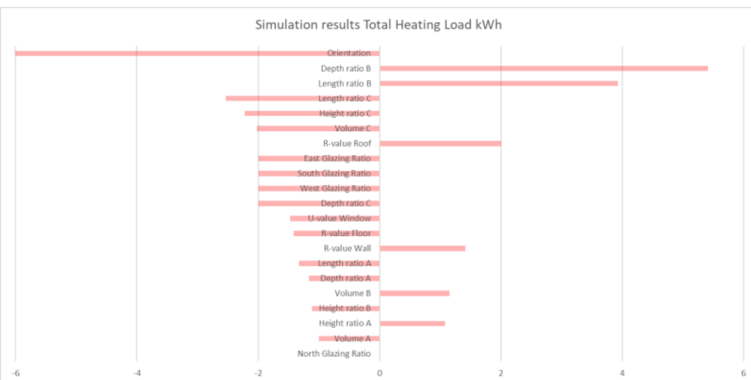
The rankings and interdependencies of the parameters in the DD-phase can be seen in *Figure VIII.2*. Many of the geometry related parameters have a very low sensitivity, especially for volumes B and C, since their range of input parameters in this phase is significantly small. The other parameters are all relatively equally sensitive, and also have a relatively equal interdependency. This is mostly caused by the fact that all parameters have a very low range of input values, which is usual, since the amount of opportunities to change parameters is relatively small. Therefore, also no exceedingly high sensitivities occur in this phase.

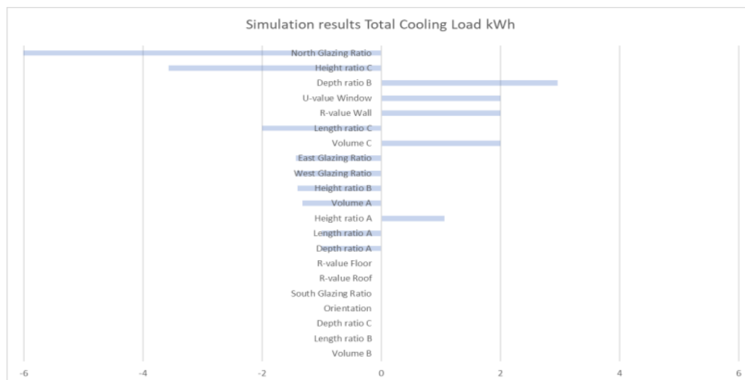
For the cooling load, it is also visible that many parameters have an equal sensitivity ranking, which can also be explained by the low range of input values in this phase. Just like for the heating load, the interdependency is also relatively small here. The only parameter that has a remarkably high sensitivity here is the West Glazing ratio.

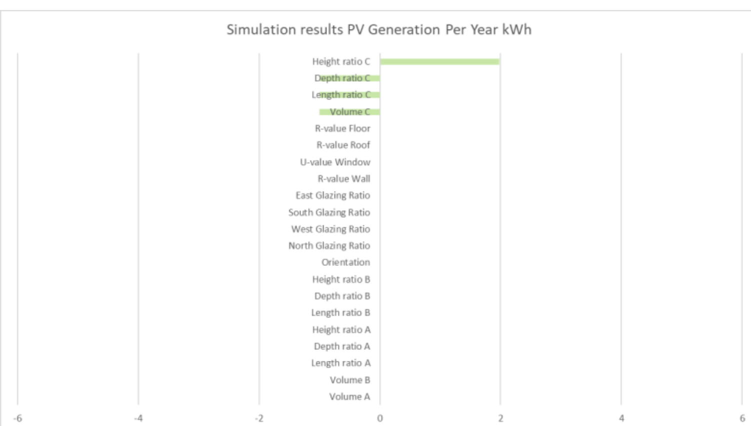
Conceptual design phase

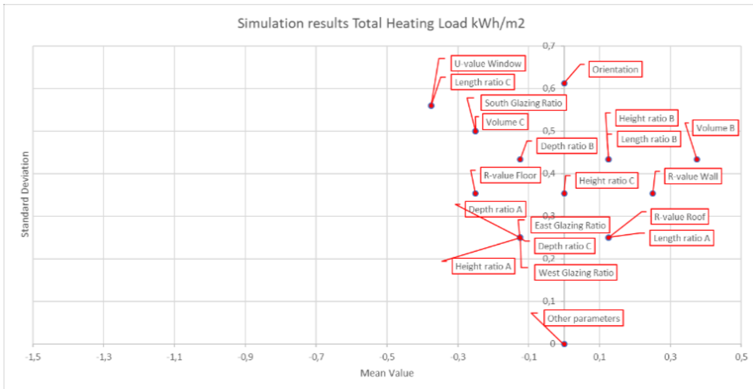


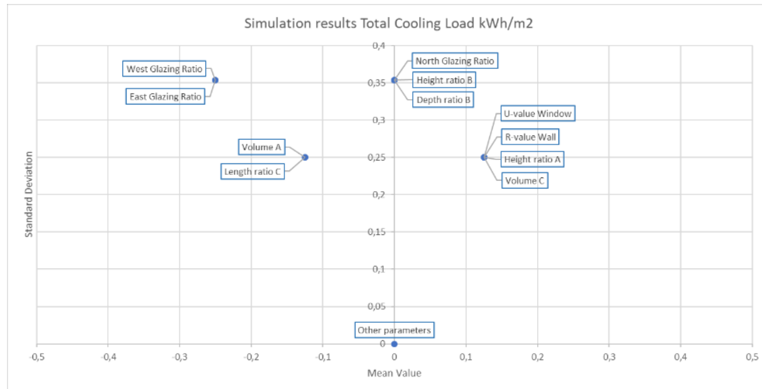


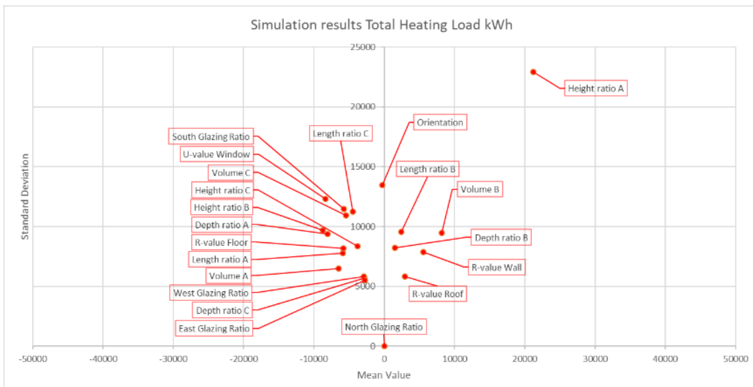


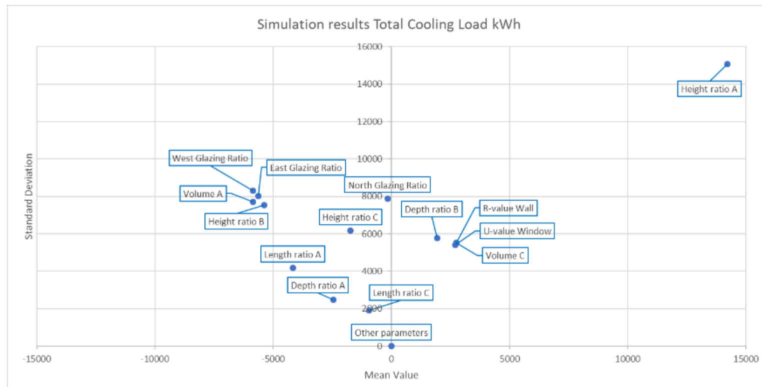


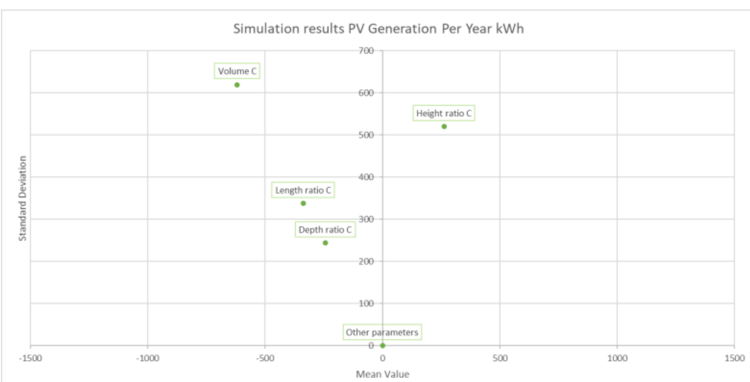



Simulation results Total Heating Load kWh/m2
U-value Window
Length ratio C
Orientation
South Glazing Ratio
Volume C
Height ratio B
Length ratio B
Volume B
Depth ratio B
R-value Floor
Height ratio C
R-value Wall
Depth ratio A
East Glazing Ratio
R-value Roof
Depth ratio C
Length ratio A
Height ratio A
West Glazing Ratio
Other parameters
Standard Deviation
Mean Value

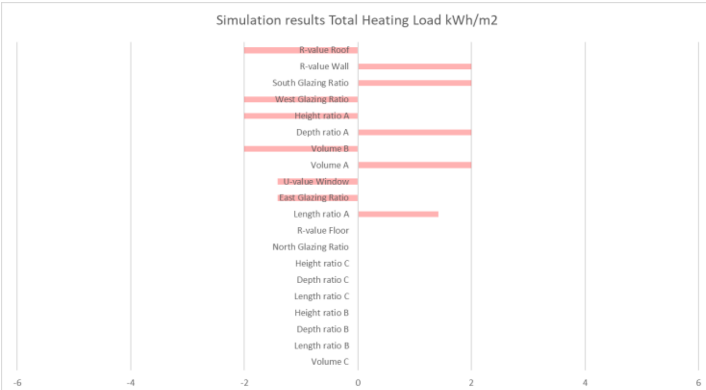

Simulation results Total Cooling Load kWh/m2
West Glazing Ratio
East Glazing Ratio
North Glazing Ratio
Height ratio B
Depth ratio B
U-value Window
R-value Wall
Volume A
Length ratio C
Height ratio A
Volume C
Other parameters
Standard Deviation
Mean Value

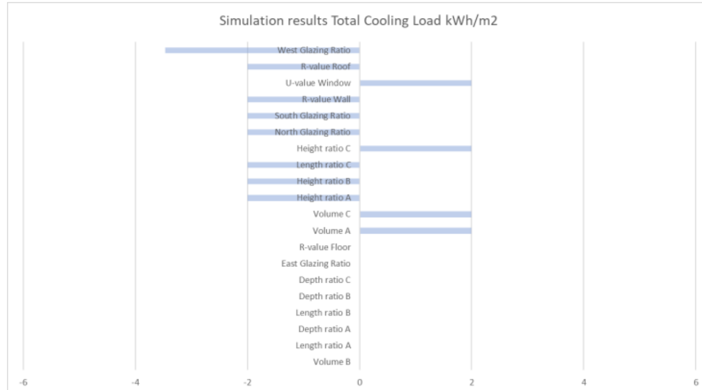

Simulation results Total Heating Load kWh
Height ratio A
Orientation
South Glazing Ratio
Length ratio C
U-value Window
Volume C
Length ratio B
Height ratio C
Volume B
Height ratio B
Depth ratio A
Depth ratio B
R-value Floor
Length ratio A
R-value Wall
Volume A
West Glazing Ratio
R-value Roof
Depth ratio C
East Glazing Ratio
North Glazing Ratio
Standard Deviation
Mean Value

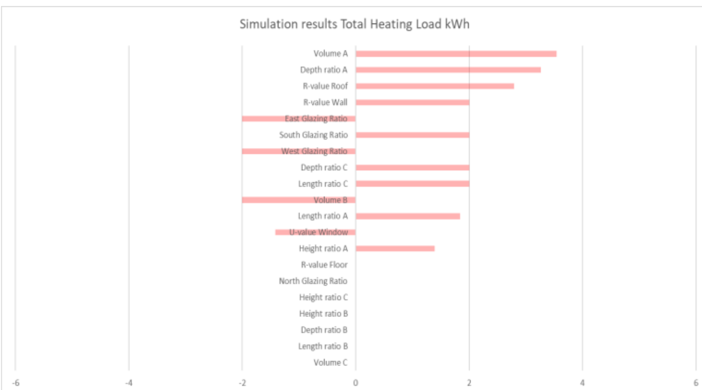

Simulation results Total Cooling Load kWh
Height ratio A
West Glazing Ratio
East Glazing Ratio
North Glazing Ratio
Volume A
Depth ratio B
R-value Wall
Height ratio B
Height ratio C
U-value Window
Volume C
Length ratio A
Depth ratio A
Length ratio C
Other parameters
Standard Deviation
Mean Value

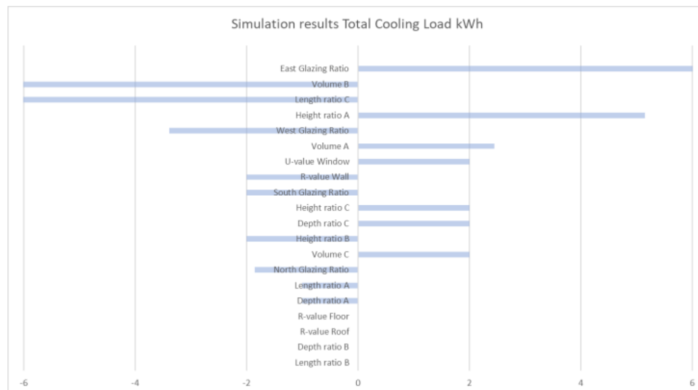

Simulation results PV Generation Per Year kWh
Volume C
Height ratio C
Length ratio C
Depth ratio C
Other parameters
Standard Deviation
Mean Value

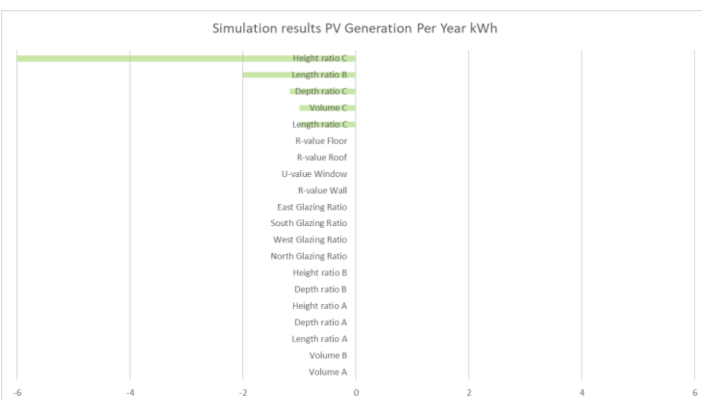
Detailed design phase

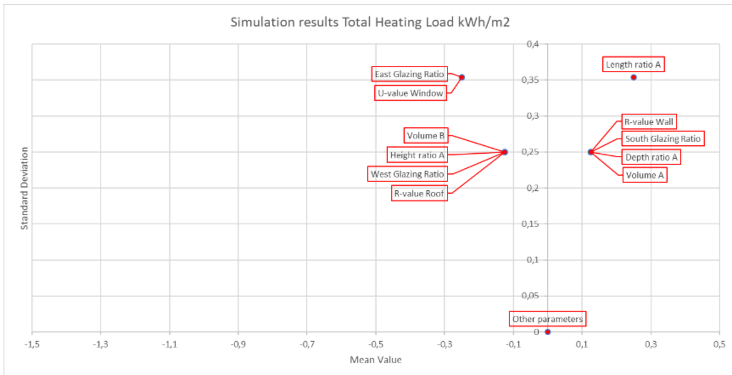


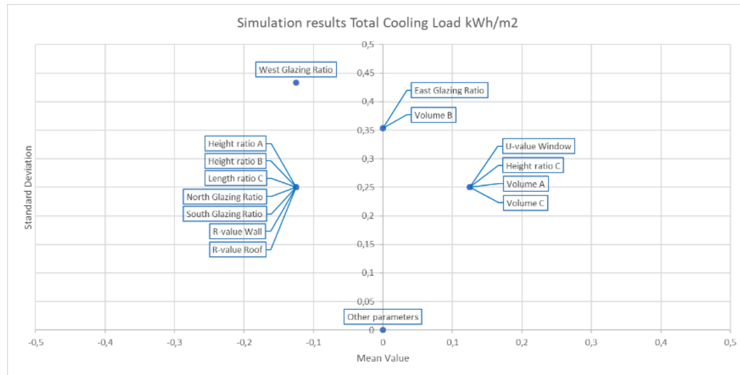


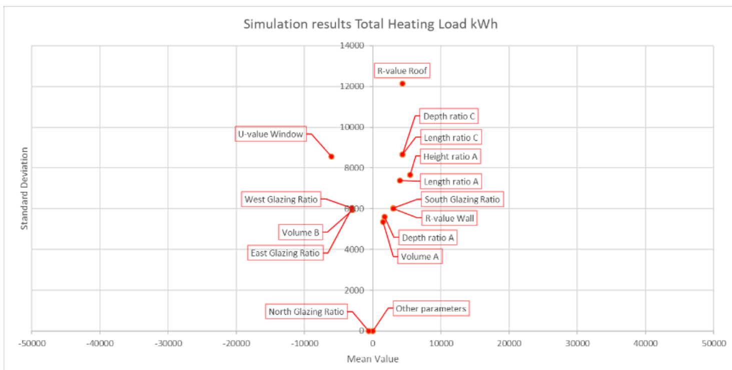


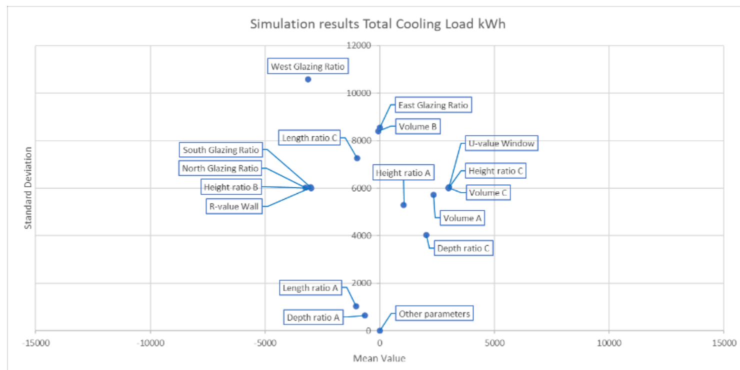


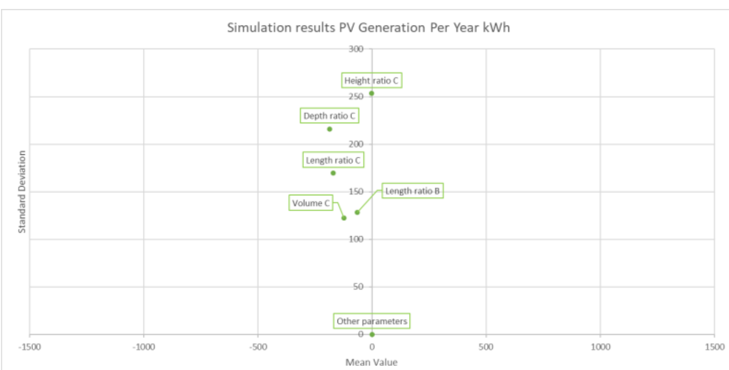



Simulation results Total Heating Load kWh/m2
Standard Deviation
Mean Value
East Glazing Ratio
U-value Window
Length ratio A
Volume B
Height ratio A
West Glazing Ratio
R-value Roof
R-value Wall
South Glazing Ratio
Depth ratio A
Volume A
Other parameters

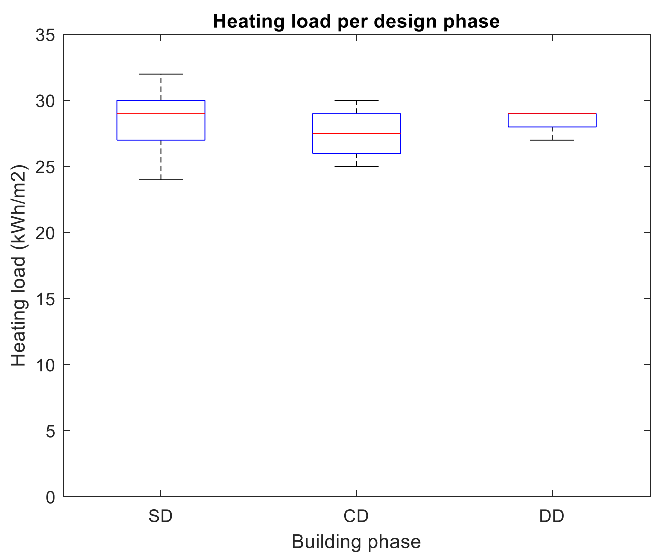

Simulation results Total Cooling Load kWh/m2
Standard Deviation
Mean Value
West Glazing Ratio
East Glazing Ratio
Volume B
Height ratio A
Height ratio B
Length ratio C
North Glazing Ratio
South Glazing Ratio
R-value Wall
R-value Roof
U-value Window
Height ratio C
Volume A
Volume C
Other parameters

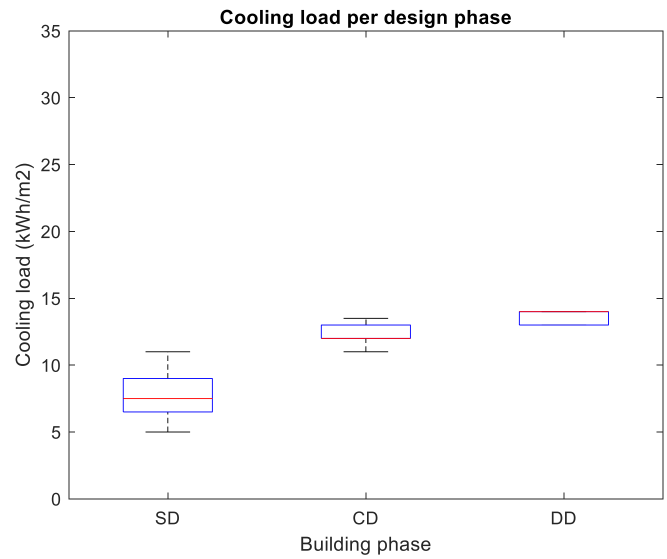

Simulation results Total Heating Load kWh
Standard Deviation
Mean Value
R-value Roof
U-value Window
Depth ratio C
Length ratio C
Height ratio A
Length ratio A
West Glazing Ratio
South Glazing Ratio
R-value Wall
Volume B
East Glazing Ratio
Depth ratio A
Volume A
North Glazing Ratio
Other parameters

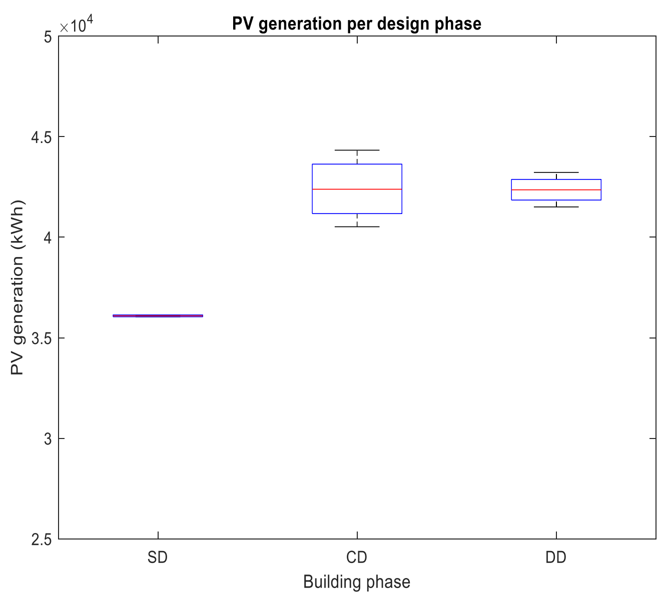

Simulation results Total Cooling Load kWh
Standard Deviation
Mean Value
West Glazing Ratio
East Glazing Ratio
Volume B
Length ratio C
U-value Window
South Glazing Ratio
North Glazing Ratio
Height ratio A
Height ratio C
Height ratio B
Volume C
R-value Wall
Volume A
Depth ratio C
Length ratio A
Depth ratio A
Other parameters


Simulation results PV Generation Per Year kWh
Standard Deviation
Mean Value
Height ratio C
Depth ratio C
Length ratio C
Length ratio B
Volume C
Other parameters

Uncertainty analysis results

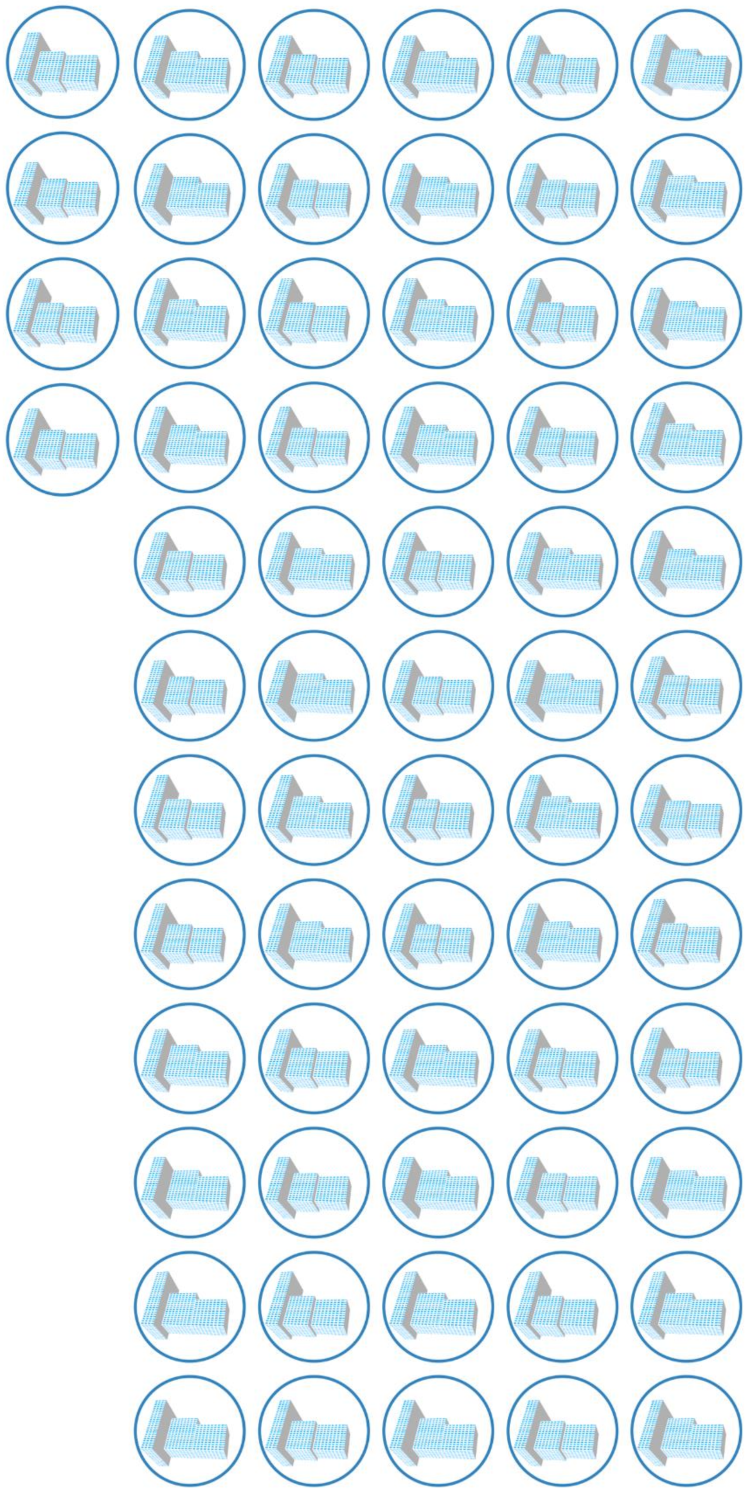




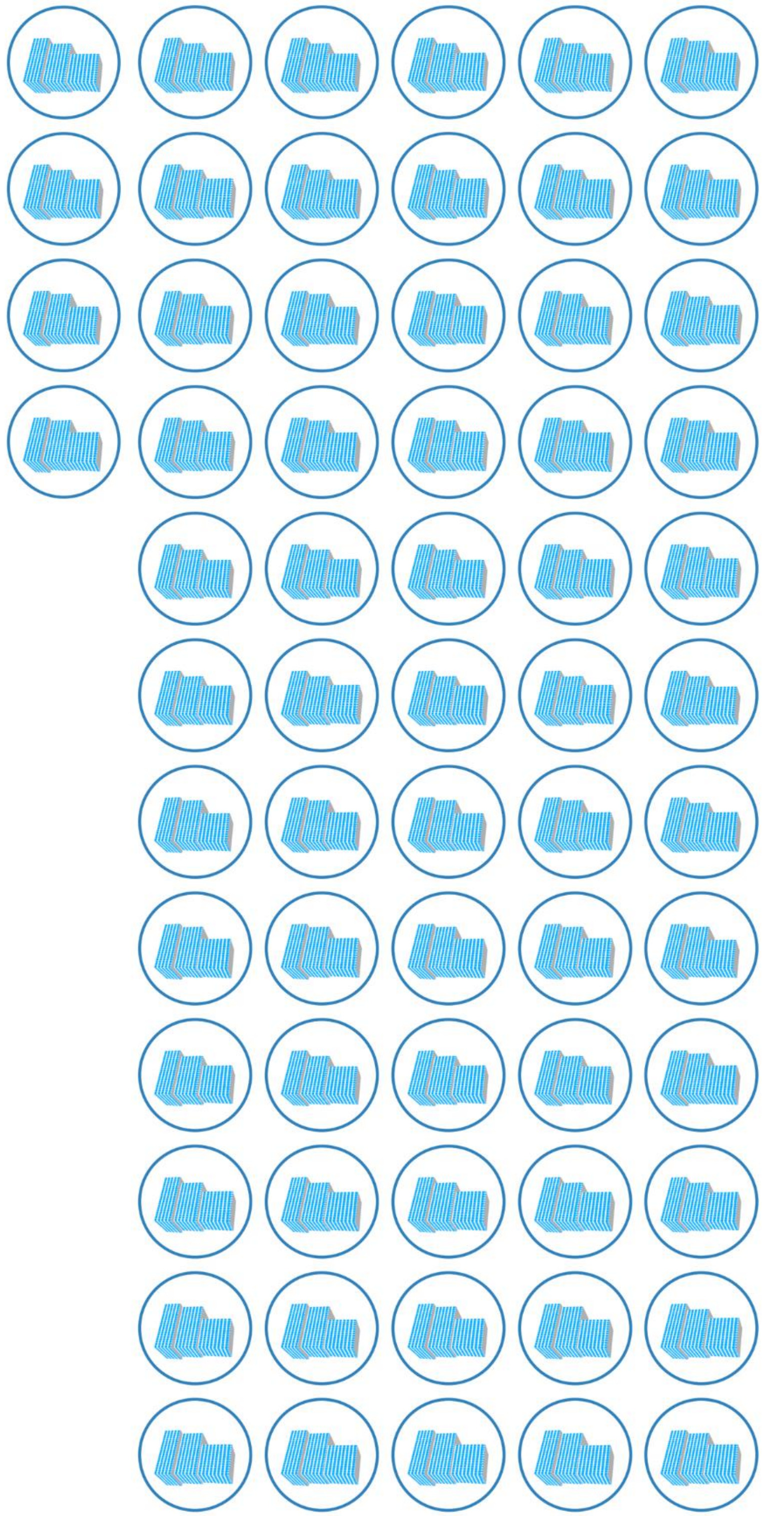


Appendix IX: Visualization of models created for uncertainty analysis

Structural design



Conceptual design



Detailed design