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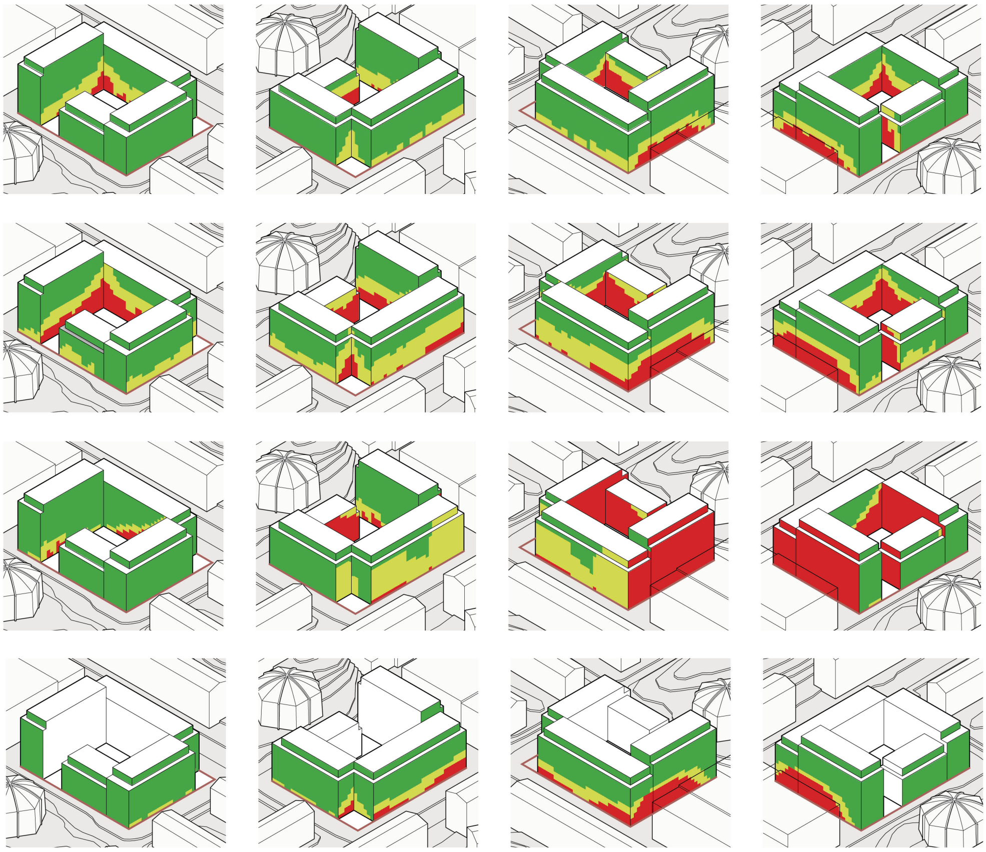

Multi-Objective Building Performance Simulation

Integrating Building Performance with Architectural Modelling in Early Stage Design

Master's thesis in the Master's Programme Structural Engineering and Building Technology

LINDA WÄPPLING

Department of Architecture and Civil Engineering
Division of Building Technology
Research Group Building Physics Modelling
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Master's Thesis ACEX30-19-85
Gothenburg, Sweden 2019

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Cover:
Building performance mesh results collage from case study, explained in Chapter 5.
Department of Architecture and Civil Engineering.
Gothenburg, Sweden, 2019

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ABSTRACT

Building performance simulation (BPS) is generally not included in early stages of the building design process. That often results in difficulties meeting the increasing demands rather than optimising for building performance. In Sweden, the responsibility for reaching the demands on building performance lies on the engineer.

There are studies made on integration of building performance within the design methodology of the architect, thus shifting the responsibility into the role of the architect. However, the author proposes an interdisciplinary integration; to keep the responsibility for BPS to the engineer and integrate BPS in early stages.

Choices for development of the proposed integration are made based on a theoretical background from a literature review and ten interviews, providing insight on the issue from a practical point of view. Barriers are identified as project budget, distribution of responsibilities, no common praxis and the usability of BPS tools.

The two last mentioned barriers are addressed. In the lack of a common praxis, a process definition is proposed, following an iterative and collaborative methodology. Furthermore, a tool for BPS is proposed and evaluated through a case study performed together with Ona Forss, writing her Master's Thesis in Architecture. The tool is an integration of the energy simulation tool 'BeDOT' with multiple analyses and connects results to a visualisation interface.

By agreement with Ona Forss, a selection of indicators is chosen as the most relevant for early stage design in the context of the case study, delimiting the proposal to indicators regarding energy and daylight, sunlight, thermal comfort, area indicators, access to solar energy and desired views. The proposed integration is one solution out of many, and an evaluation of the case study collaboration showed that it fulfils the purpose of facilitating decision-making for both architects and engineers.

Visualising results in a common interface by projecting indicator result meshes over the 3D geometry is considered valuable to the architect's design process, however the architect do not find the numerical indicators as informative as the graphical ones, and furthermore the time for simulations proves to be longer than desired.

As a result of those observations, and the conclusion that the architect's massing studies are already limited to the detailed development plan, it is suggested as future research to investigate integration of BPS in the detailed development planning process and to continue developing the tool.

Key words: Building performance simulation, interdisciplinary collaboration, integrated building performance, BeDOT, multi-objective analysis

Simulering och visualisering av indikatorer för byggnadsprestanda

Integrering med arkitektonisk modellering i tidiga skeden av byggprocessen

Examensarbete inom mastersprogrammet Konstruktionsteknik och Byggnadsteknologi

LINDA WÄPPLING

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SAMMANFATTNING

Simulering för byggnadsprestanda (BPS) är generellt sett inte inkluderat i de tidiga skedena av byggprocessen. Det resulterar ofta i svårigheter att nå ökade myndighetskrav, snarare än att optimera byggnadens prestanda. I Sverige är det ingenjören som generellt har ansvar för detta.

Det finns tidigare studier på temat integrering av byggnadsprestanda i arkitektens designmetodik som fokuserar på ett skifte av ansvar till arkitekten. Den här studien föreslår istället en interdisciplinär integration; att behålla ingenjörens ansvar för BPS och integrera med arkitektens designprocess.

Utvecklingsarbetet som föregått förslaget är baserat på en litteraturstudie och tio intervjuer. Studien identifierar fyra barriärer; projektbudget, ansvarsfördelning, att det saknas en gemensam praxis samt användbarheten hos existerande BPS-verktyg.

De två sistnämnda barriärerna bedöms ha störst potential att påverkas och är därför adresserade i denna studie. I bristen av en gemensam praxis föreslås en iterativ och kollaborativ metodik. Vidare föreslås ett verktyg för simulering och visualisering av data för BPS. Detta utvärderas genom en fallstudie genomförd i samarbete med Ona Forss som skriver sitt examensarbete i arkitektur. I studien integreras energisimuleringsverktyget 'BeDOT' med fler analyser och kopplar samman resultat till ett visualiserings-gränssnitt.

Tillsammans med Ona Forss väljs ett antal indikatorer ut kopplat till byggnadsfysik och inneklimat som anses vara mest relevanta för tidiga skeden i allmänhet och fallstudien i synnerhet; energi, dagsljus, solljus, termisk komfort, area, tillgång till solenergi och utblick. Den föreslagna integrationen är en möjlig lösning av många, och en utvärdering av fallstudien visar att förslaget uppfyller syftet med att underlätta beslutsfattande för både arkitekter och ingenjörer.

Visualisering av resultat i ett gemensamt gränssnitt genom projicering av resultat över 3D-geometrin bedöms vara värdefullt för arkitektens designprocess, men arkitekten fann inte de numeriska indikatorerna lika informativa och baserade därför kommande design till större del på de indikatorer som visualiserats i 3D-modellen.

Vidare tar simuleringarna mer tid än önskat. Som ett resultat av dessa observationer och slutsatsen att arkitektens volymstudier redan är begränsade av detaljplanen föreslås fortsatta studier för att avgöra om integrering redan i detaljplanens framtagning kan förbättra förutsättningarna för en hög arkitektonisk kvalitet i kombination med en hög byggnadsprestanda.

Nyckelord: Simulering för byggnadsprestanda, interdisciplinärt samarbete, integrerad byggnadsprestanda, BeDOT, analys med flera indikatorer

Contents

Preface

This Master's thesis was initiated with a vision of facilitating creative & qualitative workflows of building design, including the architect in making performance-driven design and simultaneously including the building performance engineer in the iterative early-stage design process of the architect. The vision of the author, Linda Wäppling, was shared with the architecture student Ona Forss, whom simultaneously worked on a Master's Thesis in Architecture.

Both authors of the respective theses have got a B.Sc in Architecture and Engineering and experience from internships at architecture and engineering firms in Sweden, the UK and Germany, providing inspiration to the vision. The two Master's theses shared a close interdisciplinary collaboration aiming to enhance the perspective on early-stage building design, gaining insight from both the architect's and the engineer's point of view – towards a common goal.

The thesis was conducted in collaboration with Bengt Dahlgren AB (BDAB) and Chalmers University of Technology department of Architecture and Civil Engineering. The study's starting point is combining work from previous Master's Theses at Chalmers in collaboration with BDAB, called "Evaluation of Sun- and Daylight Availability in Early Stages of Building Development" and "Energy Performance Modelling".

Furthermore, this thesis was supervised by Angela Sasic Kalagasidis, who provided valuable insight and helpful guidance along the way. Max Tillberg provided supervision from BDAB which helped making decisions in crossroads of the development and supported with a large portion of commitment. I am very thankful for the advice from both of you.

I want to express my sincere gratitude to Ona Forss for supporting with a holistic understanding of architecture in collaboration with building performance, and mostly for being a friend, making the spring of 2019 into a very enjoyable time. Also, I want to express my gratitude to the people that have been supporting during the process: Carl Molander, Giovana Fantin and Martin Adolfsson at BDAB, Martina Svantesson, Toivo Säwén, Carl von Rosen Johansson and Joaquim Tarraso, Chalmers University of Technology. Thanks to all interviewees and people that were spending time to spread your knowledge and support.

Gothenburg, June 2019

Linda Wäppling

Notations

Roman upper case letters

DF	Daylight factor	[-]
EP_{pet}	Primary energy number	[kWh/m^2, year]
$I_{sol,diff}$	Diffuse solar radiation	[W/m^2]
$I_{sol,dir}$	Direct solar radiation	[W/m^2]
LT	Light transmittance	[-]
PE	Primary energy factor	[-]
R	Thermal resistance	[m^{2}K/W]
U	U-value, thermal transmittance	[W/m^{2}K]

Roman lower case letters

g	g-value	[-]

Greek lower case letters

λ	Thermal conductance	[W/mK]
ρ	Reflectance	[-]
τ_{diff}	Transmission of diffuse solar radiation	[-]
τ_{dir}	Transmission of direct solar radiation	[-]

List of Terms and Abbreviations

BDAB	Abbreviation of the company Bengt Dahlgren AB.
BPS	Building Performance Simulation.
CLT	Cross-Laminated Timber
Dash	Cloud-based Python framework that can be used for building applications for data visualisation and analytics
ESBD	Early Stage Building Design
gbXML	Green Building eXtensible Markup Language
IDM	Integrated Dynamic Model
IDP	Integrated Design Process
IFC	Industry Foundation Classes
LOD	Level Of Detail
Rhino	Abbreviation for the McNeel 3D modelling software Rhinoceros
PBL	The Planning and Building Act in Sweden

1 Introduction

This introduction provides the reader with an overview of this Master's Thesis project. It is divided into background, a purpose formulation, objective and delimitations of the project and finally the hypothesis and research questions.

1.1 Background

By each year, regulations further sharpen the demands on building design regarding performance (The Swedish National Board of Housing Building and Planning, 2011). In the Swedish context, a common practice during the planning process of buildings is to include the architect in early design stages but usually excluding other professions such as building performance engineers, reserving performance analysis to later design stages where important design decisions are already made.

It is commonly known, illustrated as in Figure 1.1 by the MacLeamy curve (The American Institute of Architects, 2007), that cost of building design changes become larger at later stages in the process. Therefore, there is a need for providing early stages of building design decisions with sufficient information. This is important to fully meet the requirements and high ambitions for integrated building performance design. The possible benefits of improving decision-making in these stages are a high architectural quality and a good building performance at a lower total project cost.

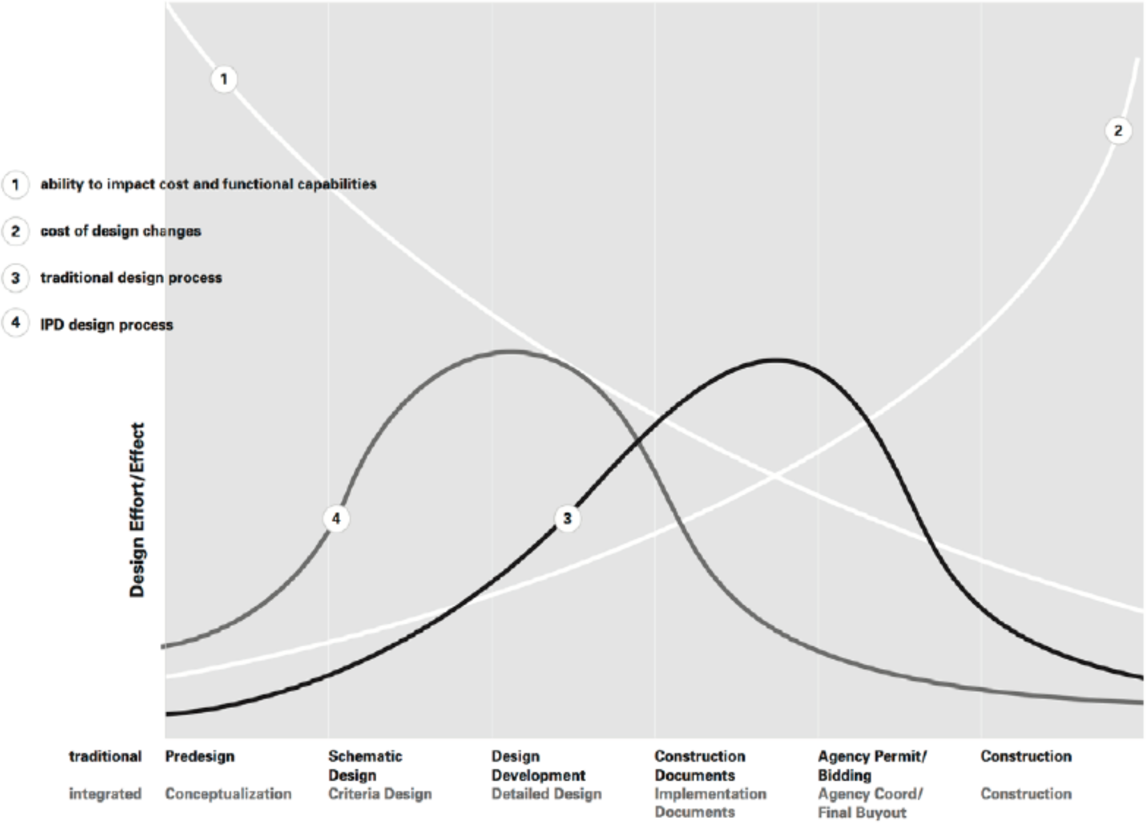


Figure 1.1 *The MacLeamy Curve, illustrating correlations between cost and process of design stages. It displays the ability to impact cost and functional capabilities and the cost of design changes in relation to the design process over time. Reprinted from American Institute of Architects, Integrated Project Delivery: A Guide, 2007, Retrieved March 03, 2019, from http://info.aia.org/siteobjects/files/ipd_guide_2007.pdf.*

To solve this issue in practice, numerous tools are available for building performance simulation. However, they are mainly used by specialists and often outside of the architect's toolbox, thus rarely used in early stage building design. Studies in academia point toward an integration of building performance simulation and design tools, but the implementation of such integration in practice is still not a reality in a larger scale (Negendahl, 2015; Soebarto, Hopfe, Crawley, & Rawal, 2015).

In 2018, a simulation tool called "BeDOT" was developed in a MSc project at Chalmers and in a collaboration with Bengt Dahlgren AB, aiming to indicate energy performance of building projects in early stages (Fantin do Amaral Silva & Bergel Gómez, 2018). The tool performs well to fulfil that purpose, but BeDOT is still not integrated within the architect's design process.

Traditionally, there are distinct borders between architect and engineer, design tool and calculation tool, design model and calculation model. Since there is a separation of responsibilities belonging to the roles, architects have traditionally worked with the design tools building a geometric design model, and respectively engineers have worked with a calculation model within a BPS environment. Implementing a means to diffuse these borders might be a solution to start integration of building performance design and simulation, for making well-informed decisions in early stages of building design.

1.2 Purpose

The overall purpose is to enable support for architects and building performance engineers in early stages with relevant information for making facilitated and well-informed design decisions regarding building performance. Specifically, the purpose is to facilitate filtration of good or bad design options regarding selected building performance indicators.

1.3 Objective and delimitations

This Master's thesis objective is to evaluate integration of building performance simulation in the early stage design process. Furthermore, the objective is to develop and, within the current design process, test a result visualisation and analysis user interface for building performance simulation. It is carried out by developing a digital tool, which is tested on a design project of a Master's thesis in Architecture.

Starting from the already built functionality of BeDOT, the objective is to investigate what additional calculations are relevant for early stage building performance, and conduct simulations for assessing necessary data within a reasonable timeframe. Additionally, the objective is to develop a user interface to analyse and visualise the result data from the developed BPS tool. The interface is intended as a complement in the design dialogue between architect and engineer, displaying design together with performance.

The intention is for the digital tool to be applicable and scalable to various projects in industry, such as housing, offices and public buildings. The development choices are based on interviews, literature studies, feedback from supervisors at Chalmers and at Bengt Dahlgren

AB and testing on one Master's Thesis project in Architecture. Therefore, the conclusions apply to the chosen context and may not be applicable outside of Sweden or other engineering professions.

One of the more complex issues covered in this thesis is how to present and compare architectural qualities (qualitative indicators like spatial planning and ambience) to quantitative indicators such as energy demand, mean U-value, daylight factor among others. These indicators are closely related to the different roles, where the architect delivers design solutions based to some extent on qualitative indicators and the building performance engineer respectively based on quantitative indicators.

The thesis scope is delimited to early stages of the building design process in Sweden, for the professions of architects and building performance engineers. Furthermore, the thesis covers only a selection of what was assumed to be the most important building performance simulations for early stage building design. Energy demand, daylight and sunlight, and view analysis are chosen in favour of acoustic, wind and structural analysis. Also, detailed economical calculations or life-cycle assessments are not within the thesis scope.

1.4 Hypothesis and research questions

This thesis relies on the hypothesis that in order to make qualified decisions in early design stages of building design, there is a need to facilitate understanding of the complex relationships of building performance indicators and design decisions.

The idea is that a shared interface between architect and building performance engineer throughout the early stage building design process may be a solution. In order to provide an interface that assist both architect and engineer, the interface needs to diffuse the border between the design and calculation tool.

Research questions

1. What is the knowledge of and attitude towards building performance simulation in early-stage building design?
    a. In practice
    b. In contemporary research
2. What is required for BPS tool integration in early-stage building design?
    a. In terms of functionality
    b. In terms of practical implementation

2 Methods

The thesis was carried out in four parts. There are chapters in the report for each of these parts; the first two being information assessment stages, the third is a development stage and the case study is testing the developed proposal, as illustrated in Figure 2.1. The case study provided input for iterative development of the interdisciplinary design method. This Master's thesis was written in collaboration with Ona Forss's Master's Thesis in Architecture, collaborating in all four parts. Results were the same for the two theses, and general conclusions are shared, meaning that there is a close correlation in some of the texts of the two theses.

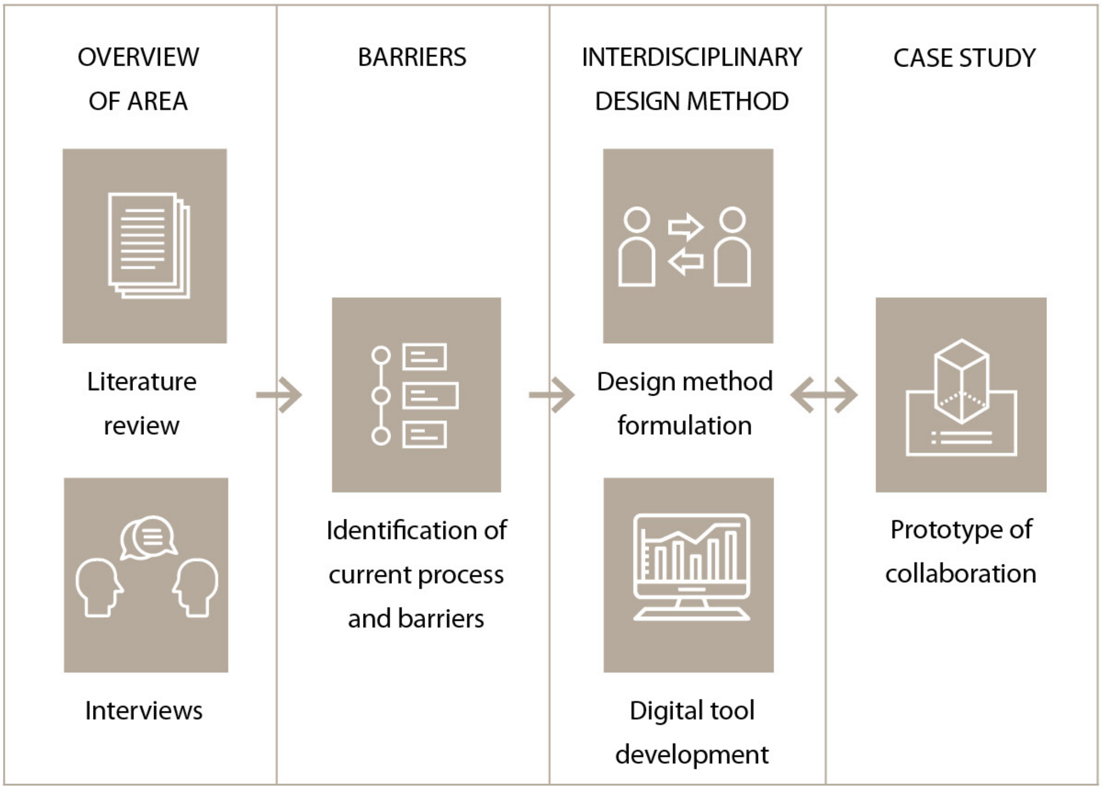


Figure 2.1 Illustration of methodology of the thesis.

2.1 Overview of area

Overview of area consisted of a literature review and several interviews with stakeholders from the industry and academia. This range of methodologies aimed to provide a basis of knowledge on the scientific area within building performance simulation (BPS) tools and visualisation, and furthermore to understand how the design process is carried out in the industry.

2.1.1 Literature review

The literature review was conducted by searching for relevant keywords at Google Scholar and the library databases of Chalmers University of Technology. Examples of keywords were 'Building performance simulation, 'Software tool for early stage building design' and 'Integration of BPS'. Both technical and research articles were included, the literature review ranging from MSc and PhD theses to conference proceedings and journal articles.

The aim of the literature study was to provide insight in contemporary research and practice in early stage building design (ESBD). More specifically to define the reference ESBD process: what actors are involved, what is a typical workflow and information flow, and what indicators are important to analyse the design with. The aim was also to gather knowledge to suggest a facilitated ESBD process. The results can be read about in Chapter 3.

2.1.2 Interviews

A total of ten interviews with architects, engineers, researchers and a property owner were conducted, aiming to gain insight in current praxis and early-stage analyses made in the industry. Another aim was to understand the general perspective on early-stage building performance modelling in both academia and in real projects. The interviews were semi-structured to allow for alternative input and effectively get a holistic understanding of the topic. The results from interviews were processed to form a summary of the answers from the interviewees in their respective professional fields, where the answers were further grouped by the respective question. The results from interviews are presented in Section 3.8.

Interviewees: Carl-Johan Martinius, developer at HSB, Emil Poulsen, computational design engineer at Thornton Tomasetti, Hussein Chith and Kajsa Crona, architects at Sweco Architects, Jenna Ernestrand, architect at Case Studio, John Helmfridsson, architect at Wingårdhs, Kristin Magnusson, city planner at Urban Minds, Liv Andersson, BuroHappold Engineering, Shea Hagy, project leader of HSB Living Lab at Chalmers and one person who wish to participate anonymously.

2.2 Identification of barriers

Development projects require a solid knowledge base as starting point. Following the two previous parts, potential barriers were identified as a synthesising of results; see Section 3.10 and Section 3.11. The synthesising of information was made in close collaboration with the parallel thesis project of Ona Forss, by a workshop discussing the findings. This was finally used to formulate the proposal and guide the development in Chapter 4.

2.3 Interdisciplinary design method

The interdisciplinary design method was formulated, split in a design method and a digital tool development. This was an iterative process that resulted in a proposal of how to integrate BPS in early stage building design. The thesis project proposed solutions for two of the four identified barriers, namely the lack of a common praxis and the usability of tools, which can all be read in Chapter 4. A reason for doing so was to put focus not only on a specific solution but also to point out that the solution needs to be implemented in a suitable context for maximal effect.

2.3.1 Design method formulation

Knowledge of the traditional workflow was assessed from the literature studies and presented in Section 3.7. Combining that knowledge with insights from the company Bengt Dahlgren AB, and in dialogue with Ona Forss performing her Master's thesis project in Architecture; a suggestion was formed for when and where in the process to implement the interface in practice. The design method formulation consists of several parts, connecting both to theory and practice in order to bridge the barrier that is the lack of a common praxis.

A suggestion of the user integration was proposed in Section 4.1. This can be seen as a high-level formulation of the design method, aiming to integrate BPS in the user domain. Section 4.3 proposed the design method related to the level of detail of the geometric input data. The aim was to provide a practical approach to how and when to implement BPS. The proposed analyses depending on the level of detail was a result from a workshop done at BDAB with Ona Forss and Max Tillberg.

2.3.2 Digital tool development

Respectively, a connection to theory and practice from the previous chapters formed the basis and motivation of choices for the tool and model integration in Section 4.2. Back-end simulation proposals were made in Grasshopper. Grasshopper is a plug-in within the environment of Rhinoceros, which is a CAD tool. Additional functionality of the simulation back-end BeDOT had to be implemented, such as handling of input data and geometry, and calculation of some geometric indicators. A feasible data structure was developed from the presumptions of the interface data visualisation and analytics. The continuation of development of additional functionality to the already existing tool BeDOT was motivated in Section 4.7. Indicators were listed and motivated for use in the proposal in Section 4.8. Chosen indicators for the study were a result of a workshop at BDAB with Ona Forss and Max Tillberg.

There was also a need of mapping a way to transfer data between users, the back-end simulation and analysis engines and the front-end interface. By studying the possibilities of BeDOT and the coding environment for the visualisation tool, those requirements were assessed into the system architecture scheme in Section 4.4. The advantage of sketching a scheme was to get an overview of the transfer of data, to target necessary data structures and file formats for the workflow. Furthermore, the BPS tool functionality was discussed and proposed in Section 0.

Finally, the tool interface was motivated and proposed in Section 4.6. The user interface proposal was the result of a qualitative assessment of interview conclusions and continuous evaluation. The interface was developed from scripting in Dash. Dash is a cloud-based Python framework that can be used for building applications for data visualisation and analytics. Dash was chosen for its advantages in data analytics, and because the code may be written only in Python, in comparison with other frameworks that might require competence in coding languages such as JavaScript, HTML and CSS. The 3D meshes and the parallel coordinates plot were used in communication of the case study with the parallel Master's thesis in Architecture.

2.4 Case study

To evaluate the functionality and relevance of the proposed methodology and BPS tool, it was tested on a case study project at Gibraltarvallen, Gothenburg. The architectural design of the case study project was developed within the parallel Master's thesis in Architecture.

The case study was performed to resemble a real collaboration between architect and building performance engineer, starting with an initial meeting where the architect informed the engineer about the most important features of the project design. It continued with back-and-forth communication through meetings and information transferring of model and result files, imitating the functionality of the proposed interface. A reason for including an architect to test the tool integration was to give valuable evaluations not only from a building performance engineer's perspective, but also from an architect's perspective. The results and conclusions from the case study can be read about in Chapter 5.

Figure 2.2 illustrates the iterative process in the case study. At first, the architectural design was simulated in relation to the chosen building performance indicators, and then evaluated by the architect and engineer together via the proposed user interface. The both actors decided whether the design was satisfactory. If not, the design was to be changed by the architect using the information from the previous iteration. The engineer could change other input data, and then perform a new iteration round of simulations. Then the design was evaluated again until a satisfactory design was achieved, resulting in a final design proposal. The final design was illustrated in the last iteration of Chapter 5. The case study gave input on how to further develop the proposals of the interdisciplinary design method in Chapter 4.

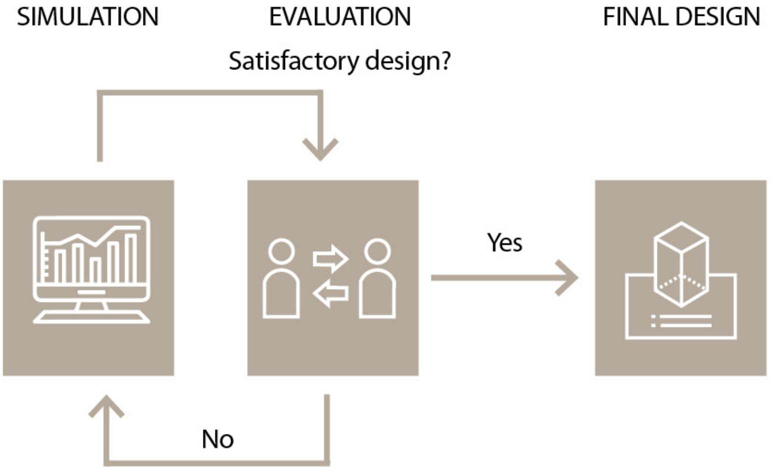


Figure 2.2 *Illustration of the iterative process in the case study. The design is simulated and evaluated until design is satisfactory.*

3 Overview of Area

This chapter is a result of the literature review and interviews in the pre-study phase. The literature review covers previous research, relevant definitions, a brief on the building design process and previously developed software for early stage building performance simulations. Interviews provide an overview of the industry and academic perspective on the topic.

3.1 Demands and regulations

Professionals in the field must fulfil regulatory demands and recommendations in order to achieve an approved building design. In Sweden, Boverket's mandatory provisions and general recommendations (BBR) provide the foundation for the demands (The Swedish National Board of Housing Building and Planning, 2011). These are in turn based on the collection of Swedish Standard regarding building design.

Section 6 in BBR cover building performance demands regarding e.g. daylight, thermal comfort and indoor air quality. Section 9 in BBR covers energy performance. Furthermore, a standard for how to assess building performance regarding energy is found in Boverket's mandatory provisions and general recommendations for assessing energy demand of normal usage and during a normalised year, BEN (Boverket, 2016).

Part from these demands, additional ones may be set by either the municipality, the property owner or other actors involved in a specific building project. It is common to use certification methods to prove the design has reached a certain level of performance. Certifications that cover building performance with regard to energy, thermal comfort and daylight are e.g. Miljöbyggnad (Sweden Green Building Council, 2017), Svanen (Nordic Ecolabelling, 2018), BREEAM (Sweden Green Building Council & BRE Global, 2018), LEED (U.S Green Building Council, 2019) and WELL (International WELL Building Institute, 2019).

3.2 Performance-based and performance-driven building design

For the sake of clarity, it is necessary to distinguish between performance-based and performance-driven design. The meaning of the more commonly adapted performance-based design is a balance of evaluating the traditional aesthetics and form with quantifiable aspects such as building performance throughout design. This became possible in the late 20th century from development of computer-aided simulation technology (Shi, 2010).

According to Shi (2010), performance-driven design makes use of specified performance criteria in a computational optimisation algorithm to drive the design towards optimisation of the chosen criteria. This is possible in a current context due to the advances in computational power. To enable the industry to move towards performance-driven design there is a need of good knowledge of simulation software, modelling and data analytics (Shi, 2010).

3.3 Building performance simulation

As explained in Section 3.2, simulating building performance has been possible for decades, and it is commonly used in praxis both in Swedish industry and in other countries. Furthermore, it is even demanded by regulations to conduct building performance simulations (BPS) for some quantitative building performance indicators, for example the regulations for daylight in BBR 25 (The Swedish National Board of Housing Building and Planning, 2011).

BPS has not yet become commonly integrated within early stages of building design, and a lot of international studies are focused on how to make this possible. According to (Soebarto et al., 2015), there has long been attempts for including BPS in early stage building design and most of them has not been adopted to a large scale in praxis. However, they suggest that one solution might be to include BPS within the modelling environment of the architect (Soebarto et al., 2015). They argue that architectural models in the 3D modelling software Rhinoceros can for instance make use of BPS through the embedded plug-in Grasshopper where it is possible to use DIVA and EnergyPlus as calculation engine, and respectively DAYSIM for daylight studies. (Soebarto et al., 2015) questions the approach of conducting research to generate “wish-lists” on BPS tools rather than understanding if there are other barriers than the specific tools that might be substantial to the issue. Through a small survey, it was concluded that architects view on the BPS tool is that performing those simulations is not the architect’s responsibility although most architects in the study express a desire to include BPS in their work. Suggested solutions were to give more responsibility by proficiency certification and more knowledge in BPS from education and training (Soebarto et al., 2015).

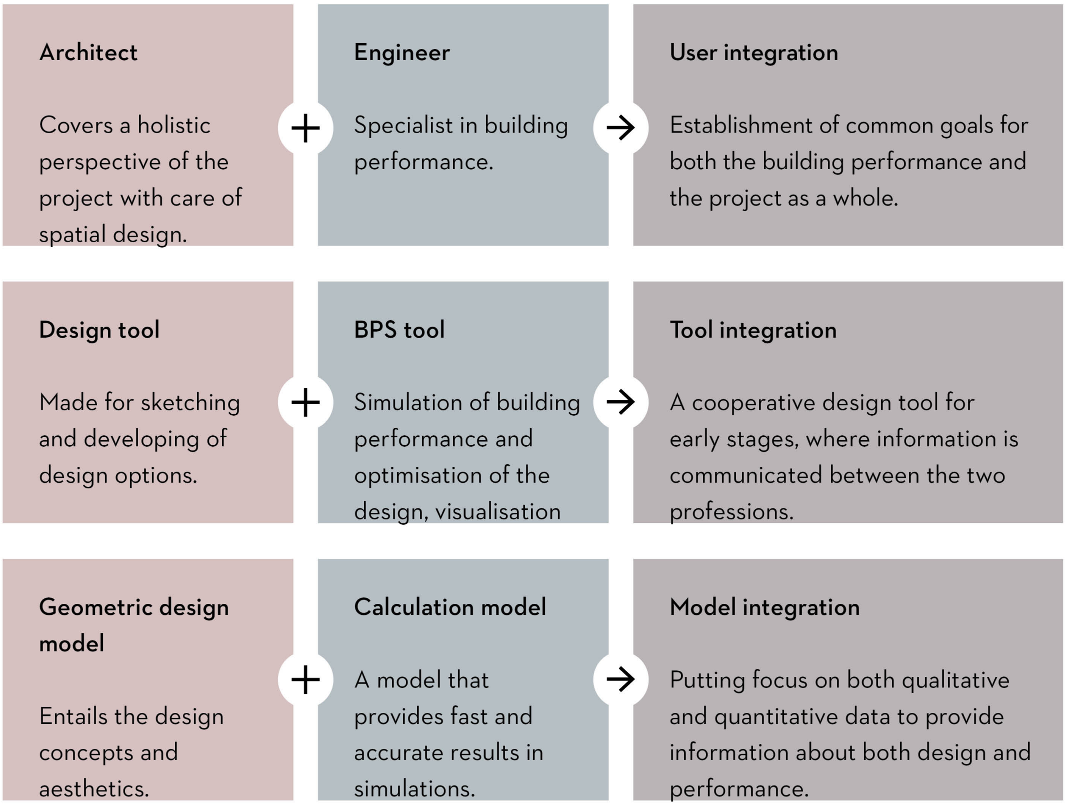
3.4 Building performance design integration

Building performance is closely related to spatial design. This is stated by Negendahl (2015), who in his study suggest that the conflict between architect and engineer is a result of the relationship between building performance and spatial design in combination with the divided responsibilities between architect and engineer. Architects, with responsibility for spatial design and engineers respectively for building performance assessment. The author also points out that architects and engineers value different objectives of building design, which may be a result of the traditional role disposition of the architect being involved in early-stage design whereas the engineer is involved in later stages (Negendahl, 2015).

For early stage design, Negendahl (2015) argues that rather than going in the direction of developing building information modelling file type methods such as IFC or gbXML, designers should go for integrated dynamic models which combines a design tool, a visual programming language and building performance simulation (BPS) (Negendahl, 2015).

Negendahl (2015) argues that development of integrating the design tool with the BPS tool has now been on-going for a couple of years, and it enables changes to the workflow of the building design, making it more focused on performance and more flexible and fast-paced.

Negendahl’s (2015) study describes how the design process can be separated into three domains, see Figure 3.1, firstly the model domain which covers the geometric design model and the calculation model, secondly the tool domain where the design tool and the BPS tool is included and lastly the human or user domain which covers the interaction between the users or project actors.



Architect

Covers a holistic perspective of the project with care of spatial design.

\+

Engineer

Specialist in building performance.

→

User integration

Establishment of common goals for both the building performance and the project as a whole.

Design tool

Made for sketching and developing of design options.

\+

BPS tool

Simulation of building performance and optimisation of the design, visualisation

→

Tool integration

A cooperative design tool for early stages, where information is communicated between the two professions.

Geometric design model

Entails the design concepts and aesthetics.

\+

Calculation model

A model that provides fast and accurate results in simulations.

→

Model integration

Putting focus on both qualitative and quantitative data to provide information about both design and performance.

Figure 3.1 Illustration of integration of the model, tool and user.

Within each domain there is today commonly a distinct border between the two actors, their tools and their models, as to the left in Figure 3.2. Since there is a separation of responsibilities belonging to the roles, architects have traditionally worked with the design tools building a geometric design model, and respectively engineers have worked with a calculation model within a BPS environment (Negendahl, 2015).

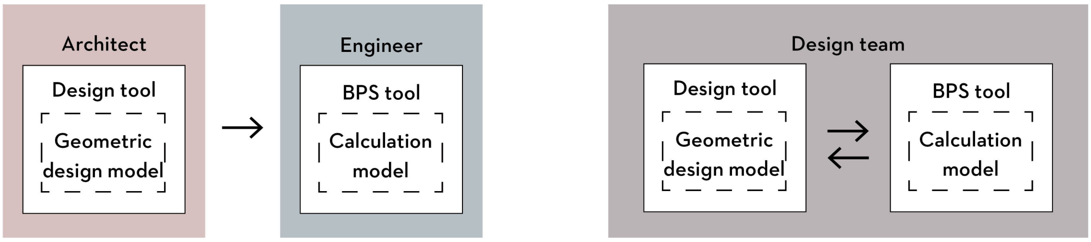


Figure 3.2 Traditional linear user integration (left), design team user integration called IDP (right). The illustration is inspired from illustrations in Negendahl (2015).

Negendahl's (2015) study examines how BPS is integrated in the early building design stage by covering two out of three aspects: the user or operator integration and the model integration. The user integration is in Negendahl's (2015) study examined from three common constellations of the collaboration between architect and engineer:

1 - The engineer as assistant to the architect
2 - The hybrid practitioner acting as both engineer and architect
3 - The engineer as partner to the architect (p.41)

Collaboration form 1 is a traditional role distribution where information flows linearly from architect to engineer. Assisting in this context is to not interfere in the creational process but rather analyse the outcome of the design. Communication take place mostly in the human domain and the tools as well as models are kept separate as the design model is exported or translated to the calculation model. This form provides no direct feedback option for design iterations (Negendahl, 2015).

Collaboration form 2 is according to (Negendahl, 2015) emerging in the architect role, where the hybrid practitioner is one actor that possess expertise and takes the role of both the designer and the analyst. The third form of collaboration is called the Integrated Design Process (IDP). Integrating the two workflows of the three domains, as to the right-hand side in Figure 3.3, requires an understanding of the most important aspects and the most suitable format of user, tool and model integration (Negendahl, 2015).

Negendahl (2015) further refers to the work of (Löhnert, Dalkowski, & Sutter, 2003) to point out that there is an economical advantage of this type of user integration, specifically that changes in design come to a lower cost in early stages. Furthermore, the advantage of mixed design teams is that they seem to provide relatively good performance results (Negendahl, 2015).

For the model integration is the Integrated Dynamic Model (IDM) presented as a feasible way forward, because it provides good feedback potential and is flexible. The IDM consist of a BPS tool in combination with a design tool and a visual programming language. IDM's can be coupled with optimisation techniques for providing fast results (Negendahl, 2015).

Furthermore, Negendahl (2015) emphasise the discrepancy in the architect's design model and the engineer's calculation model, as illustrated in Figure 3.3. The architect is likely to define the geometry of the building model to resemble an intended appearance of the building and their related functions, whereas the engineer is more likely to use a simplified geometrical representation for the calculation model (Negendahl, 2015).

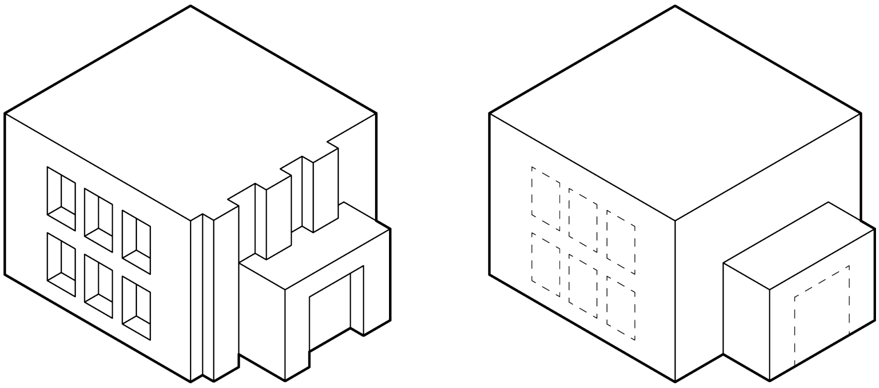


Figure 3.3 The architect's design model (left) and the engineer's calculation model (right). Courtesy of Ona Forss.

3.5 Simulation modelling methods

According to Afram & Janabi-Sharifi (2015), a **white box** model is where the simulation is modelled according to physical equations and with detailed information on input data. This makes the simulation results reliable, but the process is time-consuming (Afram & Janabi-Sharifi, 2015). For building performance, IDA-ICE and EnergyPlus are common white box methods.

A **black box** is a statistical model. This type of model gathers existing statistical data and uses it for drawing conclusions in a new setting, or in future scenarios. Examples of the black box method are genetic algorithms or artificial neural networks. The black box model has a high accuracy, but the drawbacks are that there is a need for a large dataset in order to get accurate results (Afram & Janabi-Sharifi, 2015).

The **gray box** is a model that combines the two mentioned models: with basis in the physical equations but with higher accuracy compared to white box models. Although the gray box methods may take time to develop, they are recommended for building performance simulation by (Afram & Janabi-Sharifi, 2015).

3.6 Multi-objective optimisation

A key issue in the current complexity of building designing is how to solve non-trivial problems with multi-objective design criteria. Currently, certification and regulations provide some answers but in general they do not examine the indicators relationships to each other. This commonly requires an experienced designer or analyst.

A study of the Sustainability team at BuroHappold Engineering Ltd. points out that the teams are more commonly in a process of reaching the objectives of the design rather than optimising the design (Ramsden, Keeling, Shepherd, Shea, & Sharma, 2015). The study mentions Pareto optimisation, which solves a multi-objective problem with genetic algorithms (GA) to find the set of optimum designs. However, the studied design team do not generate a sufficient amount of data for that method (Ramsden et al., 2015).

As an alternative to multi-objective optimisation, understanding and finding the optimal design which is subject to multi-objective criteria can be done with visualisations of multiple input parameters and output indicators. An example of this visualisation is the tool Design Explorer, developed by Thornton Tommasetti CORE Studio, see Figure 3.4, where the black vertical lines are input parameters and the light blue vertical lines are output indicators. Each horizontal line represents one design alternative.

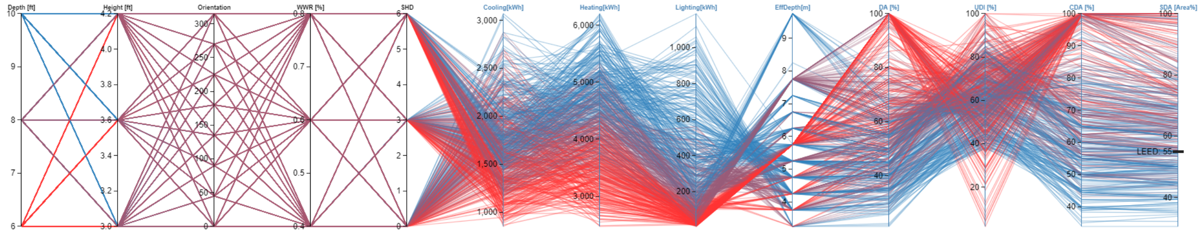


Figure 3.4 *The parallel indicators plot in Design Explorer by Thornton Tomasetti CORE Studio.*

3.7 Building design process

To understand the decisions and key issues in a building design project when it comes to architect and engineer interaction, one needs to delve into the complex and varying nature of the building design process. Here follows a brief simplification of the most relevant parts of the process in a Swedish context.

3.7.1 Building design process in Sweden

Although this study is delimited to the early stages of a building project, the detailed development plan is mentioned because it defines the spatial and economical constraints for a building project. Following the brief introduction we continue with an overview of the generalised view of a building project process.

Detailed development plan
The detailed development planning process acts as legal regulation made by the municipality and regulates the built environment, construction, and the use of land and water within a certain geographic area. The detailed development plan consists of a map and an extensive documentation of analyses made in the area. It is regulated by the Planning and Building Act (PBL). The information in the plan regarding buildings is the extent of the building above and below ground, the intent of usage and the size and proportions of apartments. This is commonly the building outline, floor space index, and building maximum height (Swedish National Board of Housing, 2018).

As the detailed development plan regulates what may or may not be built, analyses are made to determine a suitable building layout. At occasions, property owners are involved during this stage to give their perspective on building use and layout.

A building project may gain validity when the necessary documentation of the project is supplied to the municipality and compared with the regulations in the detailed development plan.

Building project
There is no exact description of the building project process, but there are generalisations of common procedures. As Eringstam & Sandahl (2018) describes, the building project starts with a pre-study, is followed by a project phase, production phase and finally the administration phase. The pre-study's main objective is to investigate whether it is feasible in economical and functional terms to move forward with a certain building project (Eringstam & Sandahl, 2018). Therefore, the pre-study is outside of the scope of this thesis. The building project design is defined during the project phase, where drawings and analyses are made, and further on, bids are made during procurement.

Figure 3.5 highlights the stages of building design where the developer or property owner commonly assigns an architect, engineers and other relevant actors. As this study is delimited to early stages of building design and architects and building performance engineers, only the initial planning phase is considered, thus the highest levels of detailing are the proposal drawings and a building program.

According to Eringstam & Sandahl (2018) the investigations are documented in a building program, setting the standards, visions and ambitions for project design and performance. Proposal drawings are a brief of the building design with regard to the given building program demands and usually they are comprised of a site plan, floor plan, section and façade drawings, perspective views and illustrations. They usually also include a brief project plan and a preliminary estimation of costs (Eringstam & Sandahl, 2018).

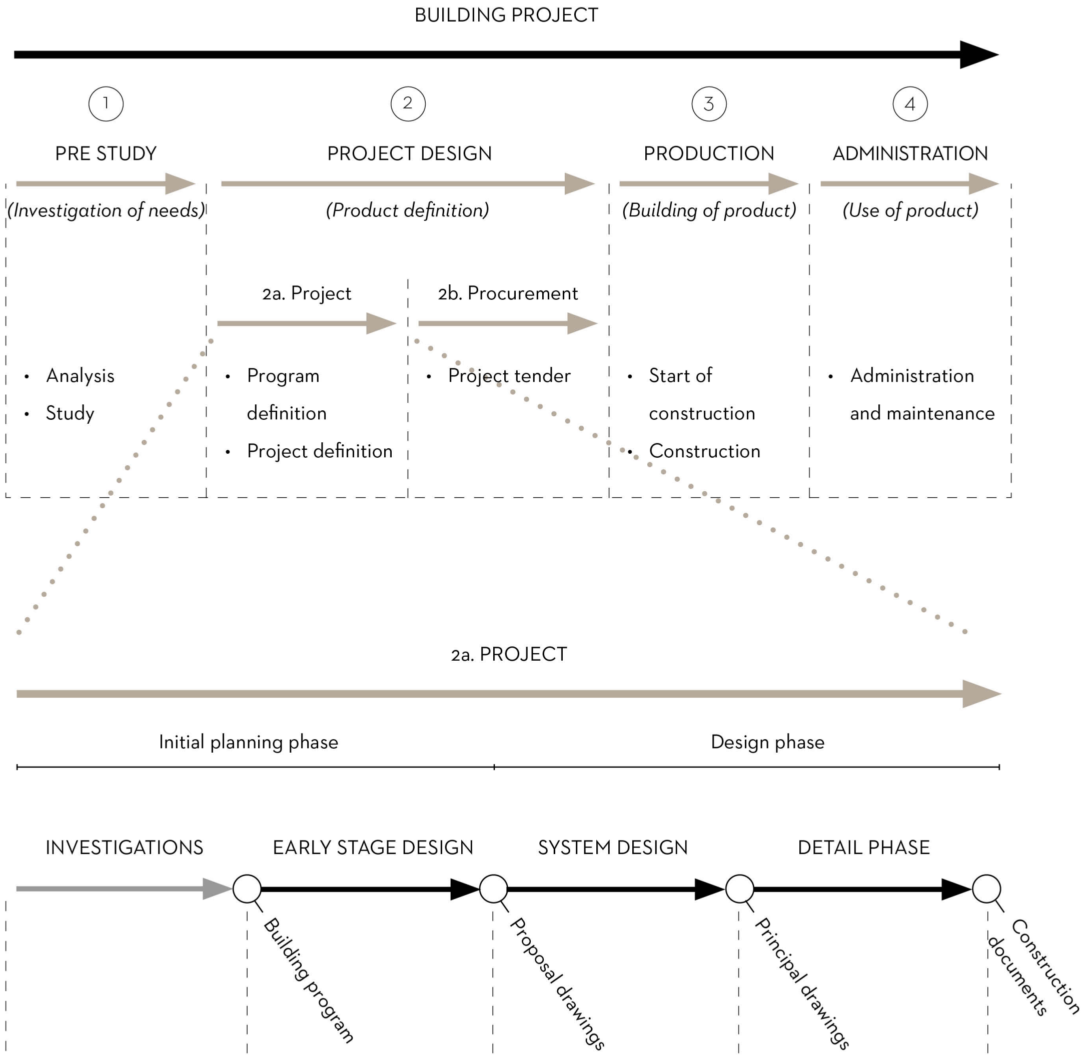


Figure 3.5 Shows a generalisation of the building design process in Sweden, as presented in (Eringstam & Sandahl, 2018). Courtesy of Ona Forss.

3.7.2 Example process from industry

A rough estimation made by employees at Bengt Dahlgren AB (BDAB) show that the estimated workload differs between projects with and without energy and environmental assessment, which are a selection of the company consultancy services. Figure 3.6 and Figure 3.7 show a process with respectively without energy and environmental assessment, where the first is considered as desired workload. Figure 3.8 show an ideal scenario from the company's perspective where BDAB are involved in early stages of building design. The scenario is ideal for BDAB because the early stage integration provides opportunities to give valuable input before important design decisions are set, and it is possible to add services that may benefit the purpose of the project. This results in a better performing product and according to the BDAB employee Martin Adolfsson, an increase in services provided from BDAB, which is a beneficial situation for all actors.

The required services are daylight calculations for BBR, energy calculations for building permits and starting clearances, some verifications and follow-ups. They argue that questions might arise regarding system boundaries, responsibilities and prerequisites that increase the work load. Furthermore, there is a risk that the planned building does not meet the regulations at the first iteration, meaning even more work in later stages, where they say they have little influence on the design, and the building is designed to fulfil the demands of the regulations rather than designed for good performance. In the end, the property owner might not be pleased with the final result and that is the reason why BDAB want to become involved in early stages, to ensure a good building performance and maintain good relations in their collaborations. The reference employee at BDAB who made the workload estimations is Martin Adolfsson.

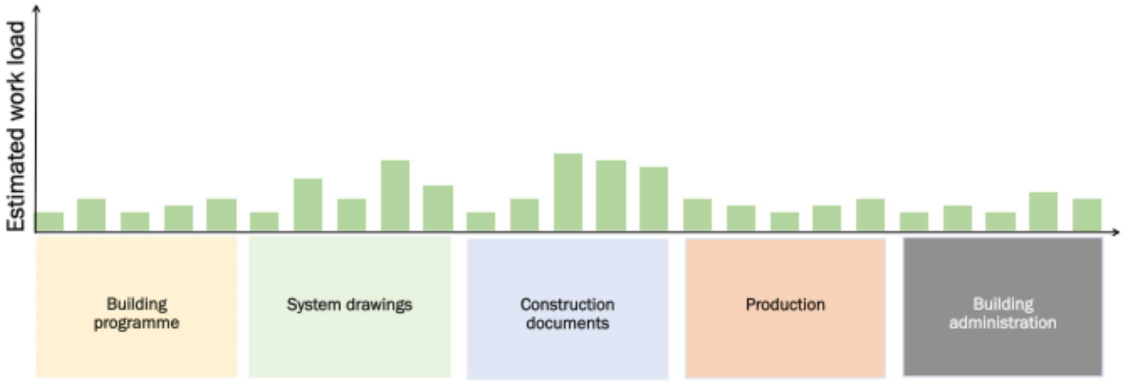


Figure 3.6 *Project with energy and environmental assessment according to employees at BDAB.*

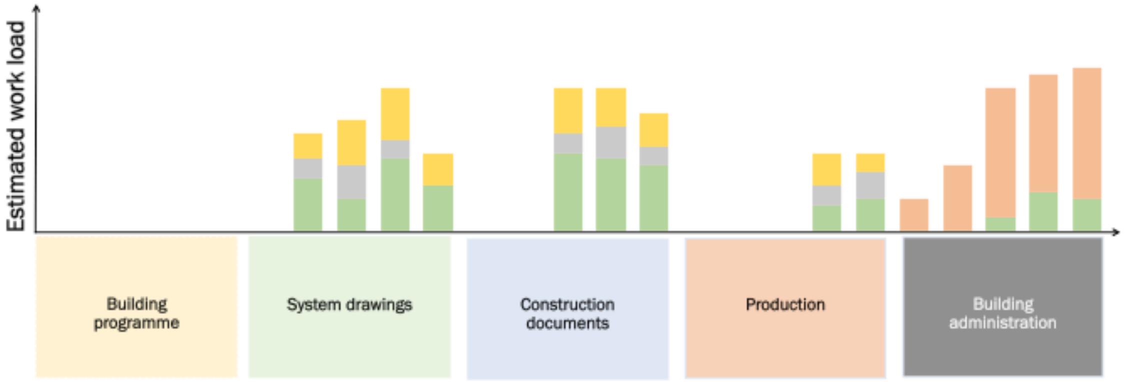


Figure 3.7 *Project without energy and environmental assessment according to employees at BDAB. The gray, yellow and red colours represent the increasing levels of additional work being required in order to reach the demands.*

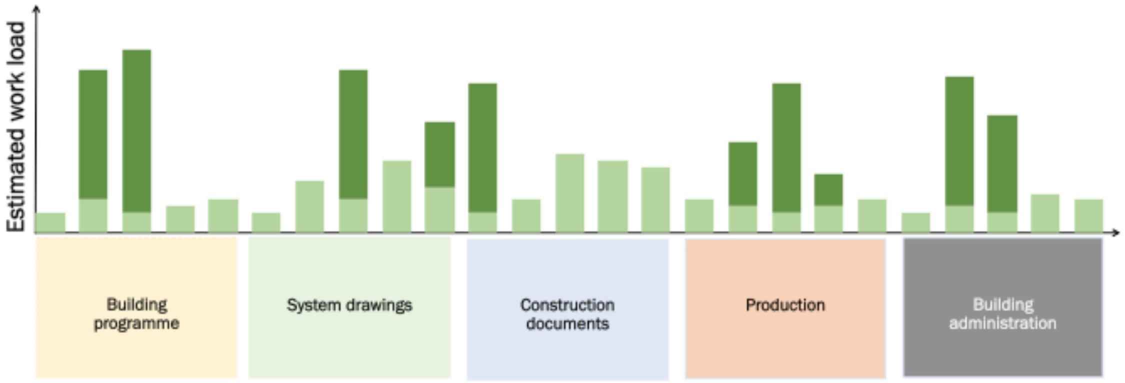


Figure 3.8 *Project with energy and environmental assessment and possible additional services according to employees at BDAB. The dark green coloured bars represent the possible additional services, e.g. early-stage simulations or analyses for higher demands than the demands by regulations.*

3.8 Interviews with stakeholders

The following questions were generally included for industry actors:

- *How does the early stage building design collaboration work in the current context between architects and building performance engineers?*
    - *Have you got an example of a building project where the early-stage collaboration has led to a successful building design from a sustainability-standpoint?*
    - *What is working well, and what is not working, today in the process related to achieving building-performance requirements?*
- *What kinds of analyses are made in early-stage building design? Which indicators do you perform analysis to attain?*
- *How do you think that the process should be developed to fulfil higher requirements for energy and indoor environment in our cities?*

These questions were discussed with a representative within academia:

- *What are your key findings in the integration of performance analysis and simulation within early stages of architectural design?*
    - *As a user of such a simulation tool, what do you consider to be important aspects of functionality in this context?*

Sections following this text describe a summary of the expressed opinions of the selected interviewees.

3.8.1 Engineers

Early stage building design collaboration between architects and building performance engineers depend highly on the property owner's and the architect's ambition. There is a common view among the interviewed engineers that a successful collaboration needs both architect and property owner to ensure that the workflow, the time- and budget-frames will include analyses in early stages of building design.

There are successful examples where the engineer was included in early stages of building design. According to L. Andersson (interview in January 14, 2019), one important part of a specific project was a workshop including architect, property owner and building performance engineer, where a multi-parameter analysis was made on different designs of housing modules. In particular, they made calculations beforehand on multiple orientations, window placement and layout configuration of the apartment modules and presented overheating and daylight indicators for each design. During the workshop, the engineers could use the calculations as a visual database in order to make informed decisions regarding the given parameters. The workshop resulted in a common understanding of the project constraints and opportunities, and the architect could return from the workshop with a number of drawings feasible from both overheating and daylight perspective to continue developing at the drawing desk. This specific project had both a positive attitude from the property owner and the architect to include building performance analysis, and the budget for doing so. This was a project in England. In Sweden, according to the interviewees, it is not as common to include engineering analysis in early stage design as in other European countries as for instance in England.

At occasions were analyses were made, the examples are:

- Acoustics, in the detailed development planning stage
- Pollution, to determine delimitations for natural ventilation
- The required analyses to follow regulations and certifications like BREEAM
- Wellbeing and social interaction
- Parameter elaborations with apartment modules in early stages: how they work from different cardinal directions, window size and type
- Overheating and thermal comfort
- Solar panel utilisation and optimisation
- Wind analysis

Even though no numbers were presented, there is a common opinion among the interviewees that including the engineer's expertise in early stages will reduce long-term costs and improve the quality of the product in aspects that are simulated and sometimes optimised for.

3.8.2 Architects

Early stage collaboration in the current context is described from the situation at larger companies. The required engineering competence can be acquired in-house. This is however highly dependent on the property owner requirements, if there is budget and no framework agreement with external consultants. Thus, the extent of collaboration with engineers in early stages is varying between each project. In general, the architect's work is according to the interviewees highly experience-based, meaning there is no systematic analytical integration in the design process, and it is rather relying on the experience and preferences of the architect.

What is currently not working is that in Swedish construction industry it exists an avoidance of cost and time expenditures in early stages and a difficulty to see the actual economical advantage of including more competences by more extensive analysis in the early stages of building design. This results in the architect being generally the only actor in early stages of a project.

Analyses or calculations mentioned as important for early stage design:

- Daylight analysis
- Parametric studies of the design
- Heat balance analysis and energy demand
- Solar study of the site
- “Qualitative life”; light and density
- Geometrical indicators such as floor space index and shape coefficient
- Window-wall ratio
- Overheating
- Life cycle analysis
- Mass storage
- Contextual architectural analysis
- Experience-based ideation, no analysis
- Ecosystem services ideas, not actual analysis

Demands that generally are designed for in the current context:

- Material choice
- Indoor environment, to build spaces that people thrive in by:
  - Attracting customers to buy apartments brings economy to the project
  - Increasing productivity at work
  - Layouts where interaction and privacy respectively are optimised for at different places within the building
  - Thermal comfort
  - Daylight autonomy, making maximal use of daylight indoors

The project “Slå Rot” at Gibraltarvallen, Gothenburg, is mentioned as an innovative project in terms of sustainability and indoor environment according to K. Crona (interview in February 6th, 2019). Innovations included in the project:

- Photovoltaics and batteries storing energy within the building
- Individual control of indoor environment, application for habitants
- Re-use of tap water
- Culvert heating of inlet air

The building K21 in Mölndal, is an example of a building design being optimised from different cardinal directions. Also, there are some natural ventilation projects that two of the architects highlight as successful innovations on the topic.

Figure 3.9 *Image of K21 building in Mölndal (57°40'09.4"N 12°00'37.3"E). On one side a double-skin façade, on the other side an ordinary glazed façade. Retrieved June 13th, 2019 from http://www.acc-glas.se/projekt/krokslatts-fabriker-k21/.*

The process could be developed to fulfil higher requirements by including simulations in the conceptual phase to support the architect's ideas. Furthermore, using tools that make it easy to find and evaluate key performance indicators for the design would also improve the process. The general point of view is to collaborate more with actors in early stages. Actual meetings and workshops are important. One idea of additional analysis to be made that could benefit projects is to connect form factor to glazing ratio.

3.8.3 Property owners

The property owner and the architect are in general the actors involved during the programme period, and later during the project planning phase other consultants, such as building performance engineers, are included. At occasions, recommendations on a specific type of certification could be included already in the detailed development plan, where a building performance engineer might be a part of that work.

In the detailed development planning process, the property or landowner sets the demands for specific projects. The sustainable city development method 'CityLab Guide' by SGBC is brought up as an example of an attempt to facilitate communication of the project vision, goals and additionally to put focus on possible synergy effects and target conflicts throughout the city development project.

An example of interest is the project "OSMOS" at Gibraltarvallen, Gothenburg. At Gibraltarvallen, the site is split in two projects (where "Slå Rot" is the other part), and it seems to have been planned in two different ways by the two property owners that won the competition for a land allocation. Both assigned architects but only the actors at OSMOS additionally assigned building performance consultants, according to C-J. Martinius (interview in January 30th, 2019). The building performance consultant supported the drawings with experience-based assumptions for the design decisions, thus no analyses made in this early stage.

What is not working well in this process is the complexity of meeting multiple conflicting demands. There are many aspects that need to be considered that it is difficult to get a holistic overview.

For specific projects, the analysis made is depending on requirements from the property owner. Some examples are:
- Noise from infrastructure (transport and communications)
- Environmental factors such as ecological consequence analysis
- Volume studies, massing, specifically area calculations
- Solar radiation study, for each project
- Daylight
- Energy demand
- Renewable energy
- Floor Space Index

The demands are communicated through:
- Detailed development plan drawings and documentation
- The land allocation competition brief
- Possibly an agreement between actors on the demands
- The property owner's demands, usually expressed in terms of common certification methods.

The critique on the process according to the interviewee is that although the economy has been good for business the recent years, the quality of building design and performance has not increased. It is suggested to start earlier with daylight and shading analysis. Furthermore, it is also suggested to work with more attractive tools from a user perspective. One wish is to be able to balance conflicting demands such as daylight and solar heat load from early stages.

There is also a wish to co-operate with multiple actors such as engineers and contractors in earlier stages, in the form of brainstorming different designs and discussing project goals before starting the drawing process. Although, in a competition there might be risks with high expenditures of competition submissions. The reason is that the proposal might not win the competition and get the land allocation. The responsibility of including more time for this lies on the property owner, according to the interviewed property owner.

3.8.4 Academia

Some of the key findings of integration of building performance analysis and simulation tools for early stage design is presented hereafter. Architects usually operate with one digital tool throughout the design process. An important point is that the usual workflow is performance-based, meaning that there is one design, which is in the end analysed by performance. On the contrary, performance-driven design is to use the analysis and simulations to change the parameters of multiple design alternatives so that the building performs better.

The downsides found with current simulation technology are that there is a high requirement of computational power to perform fast analysis. As the simulations take time, there is currently not much room for including those in early stages.

Architects are usually aware of building performance issues, but the analyses required to facilitate the design towards the desired targets are often implemented too late.

Important analyses in early-stage design:

- Daylight, in particular daylight factor
- Shading analysis of the site
- Glare analysis
- Solar radiation analysis, solar energy potential

Possible improvements for the future are to work with performance-driven design, to be able to make fast and reliable simulations, and to support working with non-standard geometry. Furthermore the interviewee mentions improvements such as to work with usability of the simulation and visualisation tool, and to implement recommendations for adjustments based on the simulation results, thus working with relationships between input parameters and the target indicators. Also, an improvement would be to include checkpoints to re-make the analysis again to make sure good results sustain throughout the project design iterations. To include weighted input by the actors is important if including parameter optimisation in the iteration phase, because it means the design is optimised from the specific project ambitions.

3.8.5 Conclusions from interviews

From interviews with several actors at different companies and in academia, it is evident that the amount of analysis for BPS is vastly varying between companies and even within companies between projects, usually depending on project budget. Projects are evaluated on the indicators that are demanded by regulations, but all interviewees express the desire to work in a way that supports optimisation of the design with regard to building performance and sustainable building in general.

The common analyses in early stage building design are connected to daylight and how the building masses and their surrounding are affected by sunlight, externally for shading and internally for solar heat load and daylight, two conflicting indicators. Economical aspects such as Floor Space Index and other area indicators are common to be analysed for in early stages. There is no common praxis found in interviews for when to include analysis in the design process.

The two projects at Gibraltarvallen, OSMOS and Slå Rot, have both won the competition but none performed quantitative analysis in the competition stage, although one project had a building performance engineer involved for qualitative studies. How the actual buildings perform is a matter for the future, as they are now entering the next design phase. It seems that currently there is a varying inclusion of building performance engineers, even in a competition aiming high from a building performance perspective.

Interviews confirmed the hypothesis that there is a need to integrate engineering analysis in early stage design. The idea of a software tool is supported, and there are demands on usability, transparency, fast calculations supporting the iterative design, and also to understand synergies or conflicts between indicators and the input parameter relationship to the indicators. Usability of a software tool is mentioned several times and seems important.

Although a tool can improve a lot, actual meetings and workshops discussing the design are of great use. Reasons for BPS not being integrated in the early stages of building design are project budget, distribution of responsibilities, no common praxis and the usability of BPS tools.

3.9 Description of BeDOT

BeDOT was developed during 2018 as Giovana Fantin do Amaral Silva and Ramón Bergel Gómez was conducting their Master's Thesis at BDAB. BeDOT is a simulation tool for early-stage energy performance modelling (Fantin do Amaral Silva & Bergel Gómez, 2018) based on the ISO standard SS-EN 13790:2008 (Swedish Standards Institute, 2008). The standard was adapted with an additional resistance in the thermal network, further explained in section 3.9.2. BeDOT was aimed to function as a simplified white box model, explained in contrast to other methods in Section 3.5.

The authors (Fantin do Amaral Silva & Bergel Gómez, 2018) stated a number of goals with their work, and two of these goals are cited below:

> *"2. To have this tool used by students, engineers and architects as an initial step in the pursuit of more effective buildings."*
>
> *"6. To provide a user-friendly, intuitive interface, which does not require from the user a deep knowledge on BES tools."* (p.1)

Another goal which was made clear by the authors and developers, was for BeDOT not only to function as an energy performance modelling tool, but also to include a number of analyses related to early stage design (Fantin do Amaral Silva & Bergel Gómez, 2018).

BeDOT is developed according to a logic that is suitable for energy performance modelling. The geometry and parameters are defined from outside-to-inside. As the energy model zoning does not include wall depth, this means that the full representation of the building is defined from the outside, where also the border between the outdoor air and the façade is located. The authors suggest using representative rooms for detailed analysis on daylight and thermal comfort (Fantin do Amaral Silva & Bergel Gómez, 2018).

One of BeDOT's idealised features is the possibility for collaboration between architect and engineer, meaning that working collaboratively in the same environment for early stage design will be beneficial to any project (Fantin do Amaral Silva & Bergel Gómez, 2018).

3.9.1 Modelling environment

BeDOT is embedded within Rhinoceros (Rhino), which is a 3D modelling environment. The geometry that is to be simulated is drawn or imported into Rhino, and the pre-processing, simulation and post-processing takes part in the Rhino plug-in called Grasshopper. Grasshopper has consequently additional plug-ins for data handling, geometry identification and API connections to external simulation engines such as DAYSIM. The embedded plug-in functionality is shown in Figure 3.10.

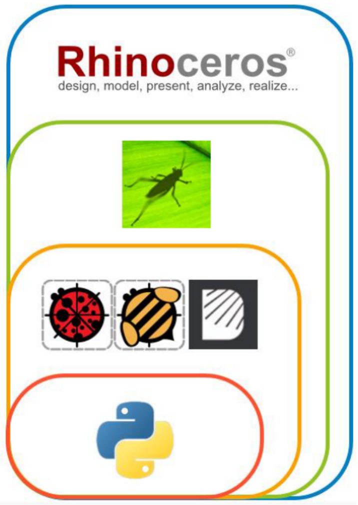


Figure 3.10 The modelling environment in which BeDOT is embedded (Fantin do Amaral Silva & Bergel Gómez, 2018).

Ladybug is used for handling and extracting weather data for use in the simulations. Honeybee manages the mass modelling and geometry identification. DAYSIM is a computation engine for daylight analysis using RADIANCE, which is validated for use. Furthermore, RADIANCE is a backward ray-tracing software commonly used in sunlight or daylight analysis (Jakubiec & Reinhart, 2011).

BeDOT consist of several Grasshopper components written in Python, it may be suitable to call it a module for energy performance simulation. For running the module BeDOT, it needs to be combined with components that are necessary for data import, data formatting, API calls, geometry identification and post-processing of data.

The components of BeDOT are 'AHU: Hygienic airflow', 'Heat balance' and 'Heating and cooling power (AHU & local)'. After the thesis where BeDOT was initially developed, the definition has been further developed by BDAB to include also some features which were delimited in the previous thesis: Heat transfer to ground, a solar shading control system and input data import from Excel.

Figure 3.11 describes how BeDOT definition is embedded in the Grasshopper environment. It is structured from left to right, as information flows downstream. The leftmost part import input data from the Excel file. Here, the data structure related to each zone is established. Further on comes the weather file and geometry import and interpreter, mainly using HoneyBee components to create HoneyBee zones and identify exterior and interior walls, roof, floor slabs etc. The next part is the sun calculation that performs a ray-tracing on the model. The resulting irradiance files are afterwards converted to data in the correct data structure. The data is then sent to the air handling units, the heat balance and the heating and cooling power components of BeDOT. Those results may be connected to a result export of directly visualised in the Rhinoceros interface.

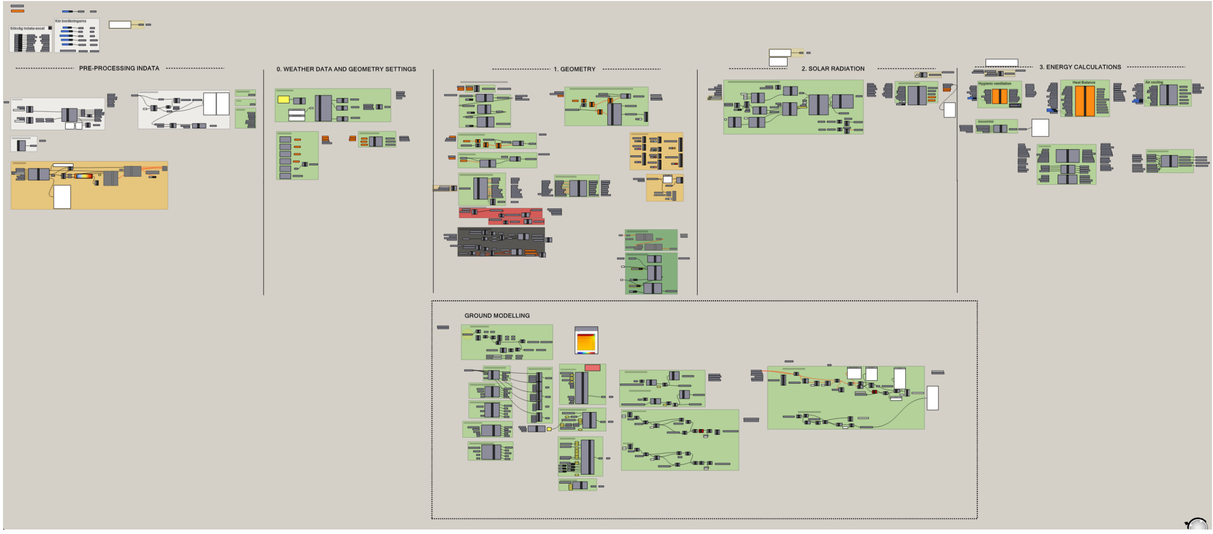


Figure 3.11 *BeDOT definition seen from the Grasshopper interface. Showing the different sections: pre-processing indata, weather data and geometry import, geometry processing, ground modelling, solar calculations and energy calculations.*

3.9.2 The choice of standard for energy simulation

A way of calculating heat balance for a building is presented in the standard SS-EN ISO 13790:2008 (Swedish Standards Institute, 2008), called the simplified hourly method or 5R1C model. This is one out of three suggested methods, and it was chosen for its time-efficient calculations, which are considered important for early stages. Another common terminology is the “lumped model”.

5R1C assumptions that enables time-efficient calculations (Swedish Standards Institute, 2008):

- That internal gains are evenly distributed at the internal surfaces
- That air temperature is uniform within the zone

For an extensive insights of the assumptions and equations of 5R1C, read ISO 13790:2008 (Swedish Standards Institute, 2008). The most important equations of the heat balance model that was used for BeDOT will be presented later in this section.

The authors of BeDOT chose to adapt the 5R1C model into the 6R1C model. The choice is justified with a study on a theoretical room where energy demand of heating and cooling is simulated over a year. The study showed that there were large inconsistencies of the named indicators between 5R1C and 6R1C model, and their study pointed towards the adjustment factor having a dominant unwanted effect on the energy estimation results.

$$b_{ek} = (T_{set,HC} - T_{supply})/(T_{set,HC} - T_{outside}) \tag{1}$$

The adjustment factor in equation 1 was supposed to compensate for the simplification of combining ventilation and infiltration losses into one resistance. To clarify, ventilation and infiltration flux operate with different temperatures. Ventilation flux occur with a controlled supply temperature while air infiltration need to account for temperature of the outdoor air. Furthermore, it occurs because the adjustment factor assumes the air temperature being equal to one of the room set points, which is not true for all hours of the year. The errors are assumed to occur when the air temperature is free-ranging between the heating and cooling setpoint.

In summary, the authors of BeDOT chose to adapt the 5R1C model into the 6R1C model by excluding the adjustment factor and instead including another resistance in the thermal network that includes an additional ventilation loss part: infiltration losses. This has been done before by (Węglarz & Narowski, 2011). A thermal network of 6R1C model is shown in Figure 3.12.

A detailed explanation on the assumptions and the functionality behind BeDOT is found in the referenced Master's Thesis (Fantin do Amaral Silva & Bergel Gómez, 2018).

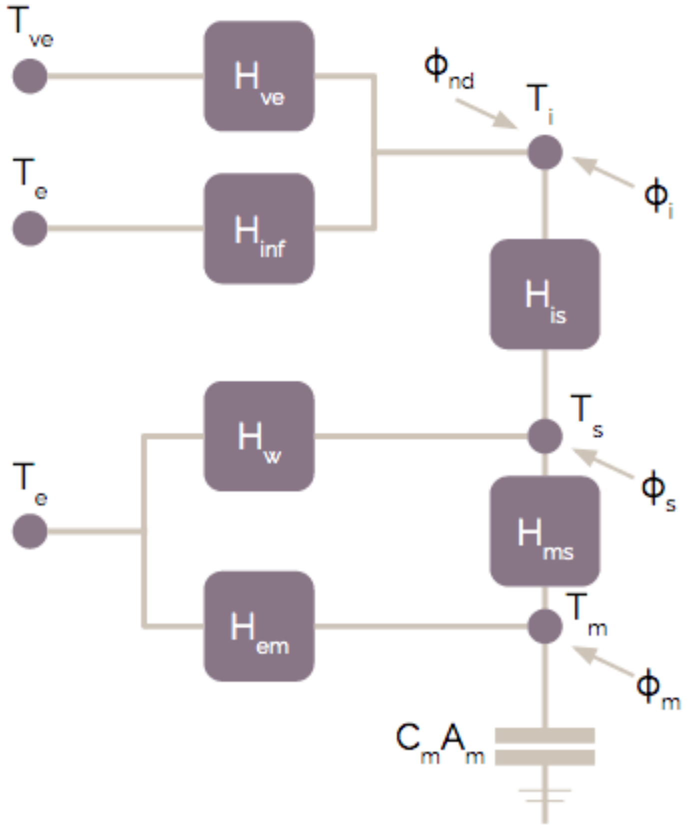


Figure 3.12 Thermal network of heat balance in an insulated space, the 6R1C method.

3.10 Concluding the findings

Information from literature review and the interviews has been assessed to get a holistic view of the issue. This chapter summarise the findings from the previous chapter and point out the identified barriers that needs to be addressed to fulfil the thesis objectives.

The previous sections of Chapter 3 provide a holistic perspective of the thesis scope from an academic and a practical point of view. Specifically, Section 3.1 gives an overview of the demands and regulations that are relevant for early stage building design. Then Section 3.2 clarifies what performance-based and performance-driven design are, two general representations of techniques that are different mainly in the sense that performance-driven design is driven by an algorithm evaluating performance whereas performance-based design is driven by user evaluation.

Section 3.3 gives relevance to why building performance simulation is required, and problematise the fact that it is not yet integrated within early stages of building design and within the scope of the architect's responsibility. One important point that they are making is that we must understand if there are other things than the specific tools that may be a solution for including BPS in early stage design. From their survey results it was concluded that the architects do see the benefit of including BPS in early stage design, however, the architects to not see it as their role's responsibility to perform the BPS simulations. The main suggestion for how to integrate BPS in building design is focused on increasing the architect's expertise to include BPS tools and simulations. Negendahl (2015) also acknowledge the potential of cost reductions by the highlighted user integration.

(Soebarto et al., 2015) suggests including BPS within the modelling environment of the architect. On the other hand, in Section 3.4 presents Negendahl (2015) a versatile discussion of the user and the model integration and suggests a mixed design team as user integration, and the Integrated Dynamic Model (IDM) as model integration. In summary, Negendahl's (2015) study point toward combining a BPS tool, a design tool and a visual programming language into what is called an Integrated Dynamic Model (IDM). Furthermore, the user integration, which seems most likely to achieve good building performance results, is the mixed design team. Also, Negendahl's (2015) study highlights the differences in the architect's design model and the engineer's calculation model.

Furthermore, Section 3.5 defines different simulation models which are useful when interpreting the work on BeDOT in Section 3.9, which may be regarded as a white box model, with future possibilities of integrating with additional white or black box methods.

In Section 3.6, multi-objective optimisation techniques are presented, one which requires a large data set for a machine learning algorithm, and one which makes use of visualisation techniques and may be integrated with fast simulation tools to present design options and their multiple criteria so that the user may make a qualified decision.

Section 3.7 summarise a generalised view on the building design process in Sweden. Section 3.7.2 provides an example from BDAB who works partly with building performance simulations. It highlights the process related to workload and the ambitions of improving both building performance and workload.

Section 3.8.5 concludes as a result from interviews that there is an ambition of integrating BPS tools in early stages, but there are some barriers such as limited project budget and the lack of a common praxis around the issue.

3.11 Summary of identified barriers

Interviews that are described in Section 3.8 confirm most of the sources in the literature study. Section 3.10 concludes the reasons for BPS not being integrated in the early stages of building design, which are summarised here:

A. Project budget; because it does not always allow engineer integration in early stages of building design
B. Distribution of responsibilities; because building performance engineers are ultimately responsible for BPS
C. No common praxis; because there is no common ‘when’ or ‘how’ to use BPS
D. Usability of BPS tools; because BPS tools require specialist expertise, commercial licenses and many of the available tools lack in usability

Figure 3.13 Key reasons for BPS not being integrated in early stage design.

4 Interdisciplinary Design Method

This chapter outlines a proposal of an interdisciplinary design method that may be integrated in early stages of building design (ESBD). The chapter starts with two sections describing a high-level proposal with justifications that are tied to the previous chapter results, and then delves into more detailed explanations of the proposed methodology.

This thesis focus is not on project budget, which is presented as an issue in Section 3.8.5, nor on changing the roles or responsibility distribution of the involved actors. These are factors that are of a more institutional matter and are therefore outside the scope of the thesis. Instead, the thesis proposal makes use of the current distribution of responsibilities between architects and engineers. Furthermore, it suggests an integrated design method because there is no common praxis today and also suggests a building performance simulation (BPS) tool for multi-objective design, as illustrated in Figure 4.1.

Figure 4.1 *Illustration of which of the potential gaps are targeted in this thesis (the two highlighted icons).*

4.1 User integration

Section 3.7.1 presented the traditional design process, a linear workflow between architect and engineer, aligning with the theory presented in Section 3.4. As concluded in Section 3.10, this involves a barrier that obstruct traditional projects from integrating BPS tools in ESBD. The general impression from the interviews in Section 3.8, that the responsibility of the building performance relies on the building performance engineer in a Swedish context, does not align with the main suggestion in Section 3.3; that the architect should bear the responsibility for the BPS. As stated above, the thesis focus is not on changing the responsibility distribution.

Therefore, this thesis will provide a proposal of an alternative design process where architect and engineer are both involved in early stages so that the feedback loop between design iterations may be closed. This aims to target the lack of a common praxis of integrating BPS tools in ESBD. Furthermore, this proposal means in theory to provide a form of user integration according to the integrated design process (IDP) where the building performance engineer is integrated starting as early as the initial planning phase, see *Figure 4.2*. The aimed process in the figure describes the estimated simplification of main project involvement and responsibility over time divided over the roles.

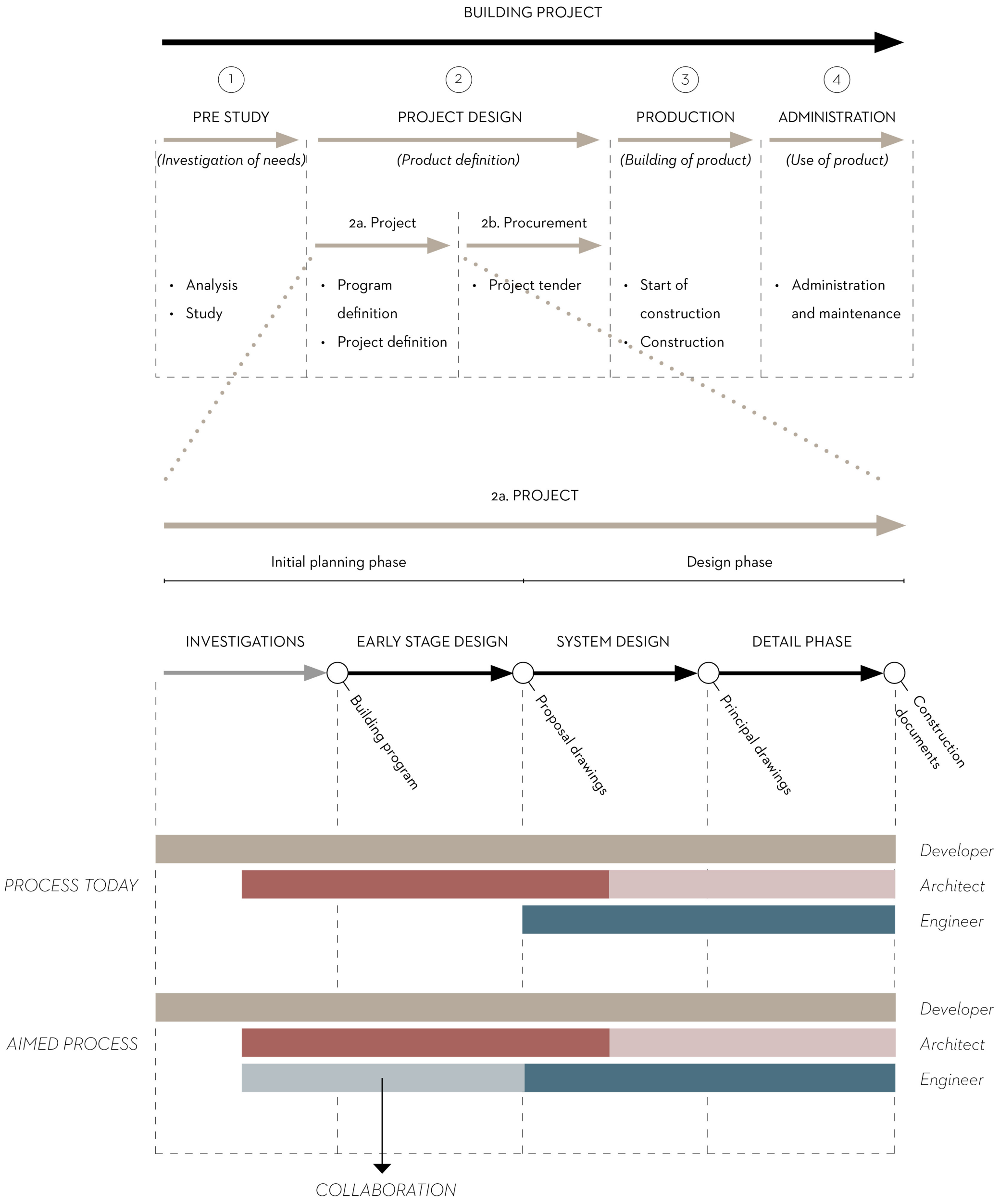


Figure 4.2 *Proposal of building design process user integration as a design team.*

This user integration is done to ensure that common ambitions among architect and building performance engineer is set from the very beginning, and to ensure that the project constraints are investigated also with building performance simulation tools. This collaboration aims to close the feedback loop of each design iteration as presented in Figure 4.3.

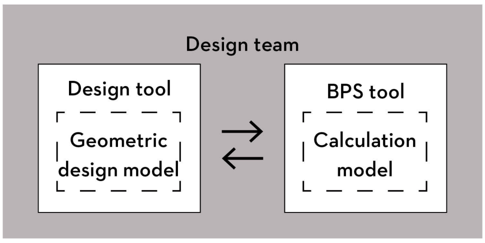


Figure 4.3 *The design team integration of the user domain, closing the feedback loop.*

4.2 Tool and model integration

The complexity of the barriers obstructing BPS from being integrated in early stages is presented in Section 3.10 and Section 3.11, indicating that a tool might not be the only barrier or solution for this integration. It might also be a lack of common praxis, the traditional responsibility distribution and a limited project budget. As explained in Section 4.1, that is why this thesis also put focus on the user integration.

However, because of the need of practical implementation of BPS tools, the author of this thesis argues that there is a need of investigating the technical possibilities and barriers with integrating a BPS tool within an ESBD context. This is examined in the following case study, and the findings of the barriers are handled by the development of the tool and a gathered list of "best practice" in Appendix J.

This thesis will focus on developing a tool for engineers to use in a design team with the architect, as illustrated in Figure 4.3. The tool will consist of a visual scripting back-end, that may translate the design model of the architect, enable the engineer to make simulations and calculations, analyse the data, and furthermore to visualise the results in a web-based front-end. The system architecture of this IDM is further explained in Section 4.4.

The choice of the IDM enables the user to make qualitative input in the design process between the iterations. This is emphasised as an important aspect by architects interviewed in Section 3.8.2 and seems relevant for the industry as performance-based design is already commonly practiced. Therefore, this thesis will investigate and develop a method for performance-based design, allowing for qualitative user input that is integrated in early stage building design.

This thesis delimits the study to use simple simulation techniques, instead of applying closed optimisation feedback loops with the use of genetic algorithms. Multi-objective simulations are proposed with design performance feedback loops driven by users. The simulations will be used in combination with visualisation techniques such as the one presented in Figure 3.4.

4.3 Proposed analyses depending on level of detail

The type of analysis that is possible is highly dependent on the input data level of detail. Therefore, a workshop was conducted in order to suggest a suitable workflow for early stage building design, see Section 2.3.1. The result is a workflow fragmented in five analysis levels as a result from the workshop: 0. Site Study, 1. Building Envelope Study, 2. Massing Study, 3. Façade Study, 4. Interior Study. The named levels allow for multiple iterations or tested with varying input data.

The analysis levels correspond to Lantmäteriet's definitions on level of detail (LOD) and can be read about in (Lantmäteriet, 2018), although some parts are adjusted to fit the purpose of the thesis. In general, Lantmäteriet's LOD 0 correspond to '0. Site Study', LOD 1 correspond to '1. Building Envelope' and so on. Images and texts explaining the different LOD are presented in the sections below.

4.3.1 Site study

Site study is a first analysis of the site and context. The geometric input consists of what is known about the site at a pre-study stage, e.g. the site outline, existing and planned surrounding buildings, and other objects in surrounding. Other data considered is geographic conditions such as weather data, or noise data.

Possible analyses are shading, noise or wind analyses. It can be useful for understanding important exterior conditions on the site. The illustration in Figure 4.4 describes the geometrical level of detail.

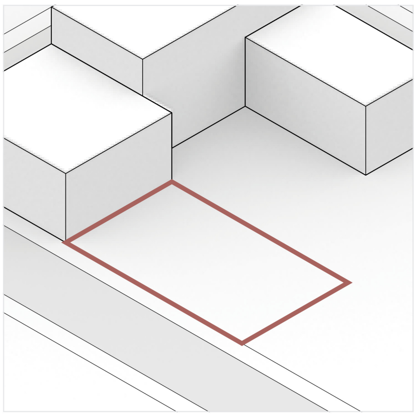


Figure 4.4 Site study level of detail. Courtesy of Ona Forss.

4.3.2 Building envelope study

The Building envelope study use coarse approximations of a building to give a first indication on the site and building constraints in relation to demands by regulations. This can be regarded as an integration of BPS where input data is highly approximate. Integration can take place during the start of the early stage design phase of a building project as illustrated in Figure 4.2.

A detailed development plan contains geometrical data at LOD 1, which describe the maximum building outline and maximum height, together with the surrounding context, as in Figure 4.5. The Building envelope study use this data together with weather data, information of surrounding views and usually approximate values for elevation count, window/wall ratio, and envelope U-values.

Suitable indicators connected to the building envelope are for example:

- Daylight Factor [%] on facade, correlation with a theoretical room
- Sunlight hours [h] on façade
- Solar heat load [W/m2], for estimation of thermal comfort
- View [%], access to desired views from the building
- Single thermal zone energy demand [kWh/m2, year]

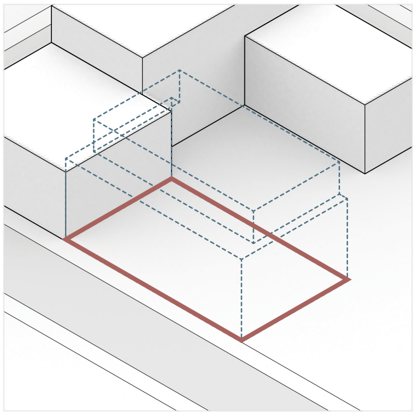


Figure 4.5 Building envelope study level of detail. Courtesy of Ona Forss.

4.3.3 Massing study

Architects are familiar with exploring multiple massing options for design decision-making. Therefore, it is suitable to integrate BPS at this LOD. Massing study analyses require a detailing level defined as LOD 2, with the addition of data on floor height, see Figure 4.6.

Thus, the geometric inputs are the same as in the Building envelope study, however, now the geometry is split in elevations and the building volumes are input from the architect, not from the detailed development plan. Other input information may be on an equally approximate level as the previous study, or more precise as the architect or property owner forms a vision of e.g. materiality that may affect U-value of the envelope.

Suitable analyses are the same as the previous study, part from a more detailed thermal zoning for energy demand simulations. The analyses enable comparisons of multiple massing options both from an architectural perspective and a building performance perspective, and indicate e.g. suitable placement of windows and balconies for the coming façade studies. The analyses also provide indications for critical areas with regard to the indicators and target values for those.

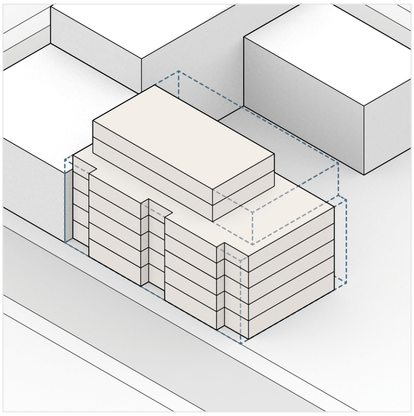


Figure 4.6 Massing study level of detail. Courtesy of Ona Forss.

4.3.4 Façade study

The Façade study is modelled with LOD 3, where the exterior geometrical data is detailed but there is little information on the interior side of the building. The data inputs added from the previous Massing study are placement and size of windows, balcony geometry, and approximate data on the interior such as virtual room size and reflectance values on surfaces. Figure 4.7 illustrate the geometrical LOD.

The proposed analyses are the same as in the Massing study. Except that the results may be used to indicate building performance with regard to demands and ambitions, it is also a detailed façade that may be evaluated from an architectural perspective. Façade studies may indicate suitable window and balcony configurations, which will have an impact on the floor plan design in the next detailing level.

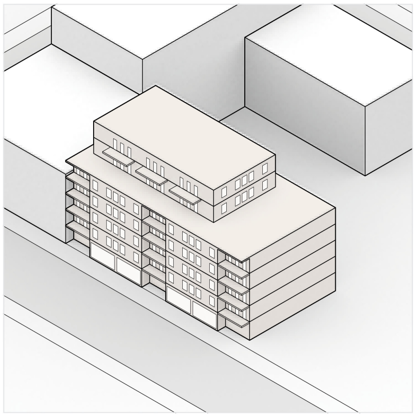


Figure 4.7 Façade study level of detail. Courtesy of Ona Forss.

4.3.5 Interior study

The interior study requires geometrical data on LOD 4. This is the highest level of detailing with regard to the geometrical input, see Figure 4.8. It is expected that also the input data on e.g. U-values are more precise than earlier studies, and therefore this study is suitable at a stage in design where this information is present.

Detailed simulation results are possible to assess from this method, which is suitable for later design stages such as the design phase as illustrated in *Figure 4.2*.

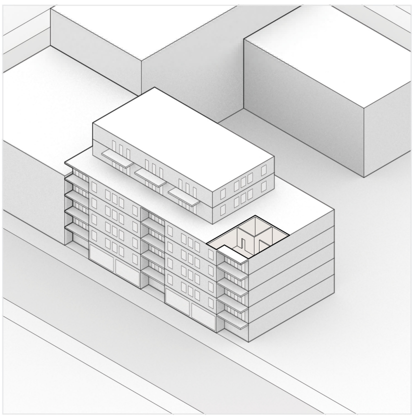


Figure 4.8 Interior study level of detail. Courtesy of Ona Forss.

4.3.6 Proposed analyses in context of the building process

The previously mentioned BPS studies are proposed to be integrated as illustrated in Figure 4.9. The site study is proposed for the investigations phase, the interior study is proposed as the last of the proposed studies and suggested to follow the given order. However, if an intended project may benefit from another order it is up to the user to integrate BPS as wished.

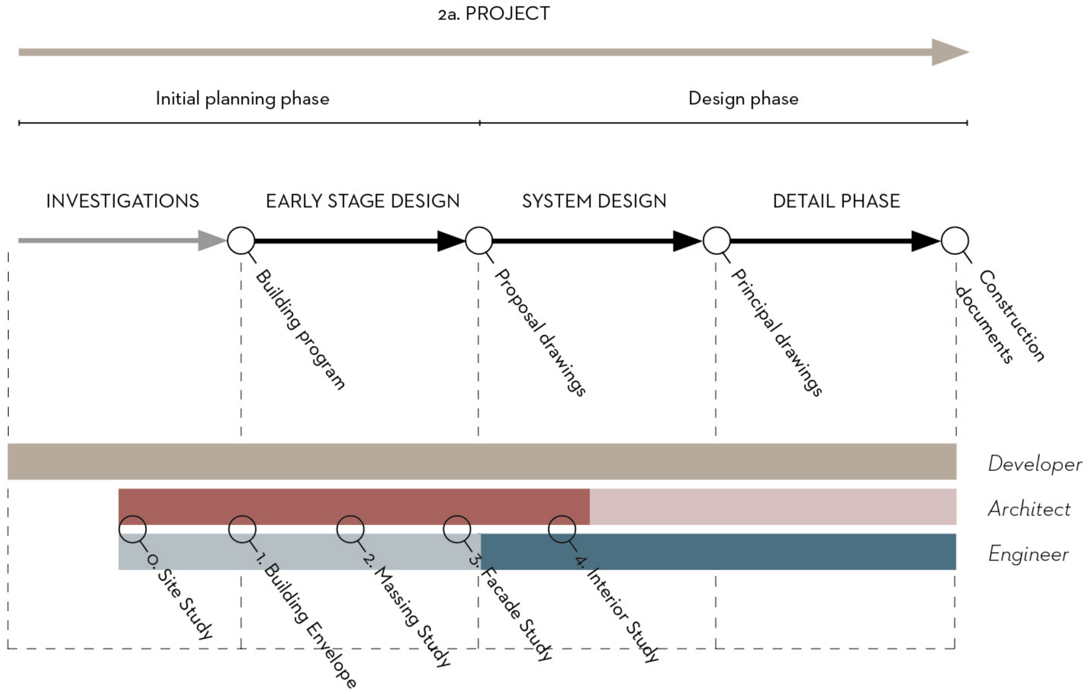


Figure 4.9 Illustration of BPS integration in ESBD.

4.4 Proposed system architecture and user story

Apart from providing the calculations with input data and assumptions to give as realistic results as possible, there is also a need of providing a good system architecture and supporting data structure.

Goals concerning system architecture:

A. Data transfer between parts of the system architecture should work seamlessly and without requiring user action, when it is possible
B. Ability to add analyses in back-end and visualisations in front-end code
C. Possibility to save and load user input data from the interface

The choice of developing a simulation back-end in Grasshopper is justified because it enables the use of previously developed work (BeDOT) to be included when developing a tool for multiple building performance analyses. The front-end is written in Dash. Dash is a cloud-based Python framework that was chosen because it is simplifying the coding required to achieve the thesis ambitions of data visualisation and analytics. Another reason for choosing

Dash is that it enables hosting a web-application for visualising the results. This means that the actors only need a stable Internet connection and a browser to see the results, in comparison to downloading or buying commercial software. It is considered as likely that the backend definition in Grasshopper will be re-defined in a non-visual programming language in the future. Therefore, the development considers this in order to enable a simple future transition.

The proposed system architecture is illustrated in Figure 4.10. The workflow represents the events of one iteration, with red arrow representing architect input information, blue arrows represent the engineer's input data and the grey arrows represent steps which are automatically run by the system. The purple arrow represents the user-driven feedback loop for the current iteration.

The architect provides geometrical data in the format of their choice, although it is beneficial because of file conversion reasons to submit the 3D geometrical data in Rhino's format .3dm. In the same time, the engineer in dialog with the architect set the initial input data for BeDOT in an Excel file .xlsx, along with other input data in the Grasshopper definition.

By the initiation of the engineer, simulations are run in Grasshopper for the chosen modular analyses. This is called the simulation backend because it provides raw data by simulations and calculations, saved to the database in .obj and .csv.

Following the simulation, a python backend is run performing data analysis on the raw data, performing mathematical operations and filtering for the visualisation in the frontend Dash python script. There is built-in functionality for saving user input data from the interface. However, loading input data and running the Grasshopper script from the web browser is considered suboptimal and therefore omitted in this study.

Dash provides flexible options for data visualisation and can be customised for multiple purposes. The proposed interface prototype is presented in Section 4.6.

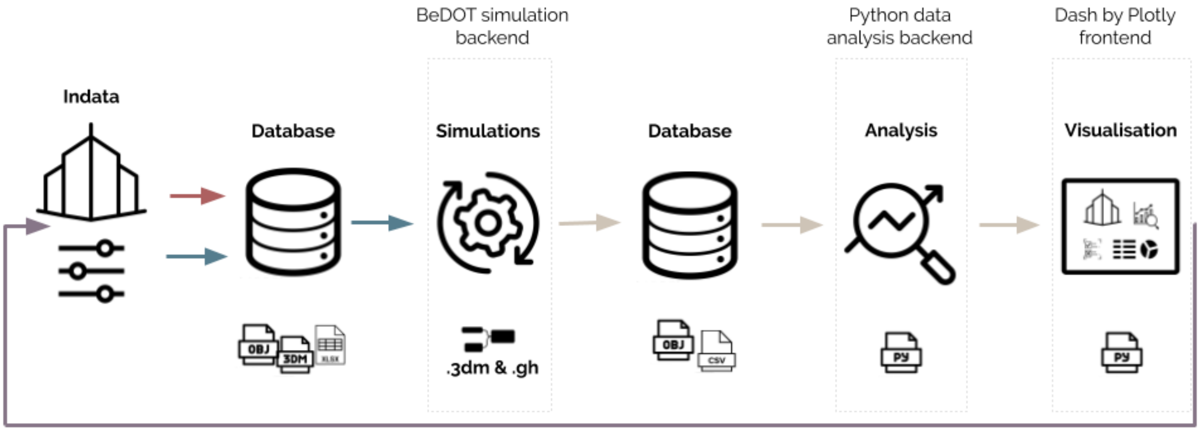


Figure 4.10 *Illustration of system architecture.*

4.5 BPS tool functionality

As described in Section 3.9, BeDOT is primarily a building energy performance tool and thus needs extension of its functionality for fulfilment of the current thesis aim. This section explains development choices for the BPS tool general functionality and interoperability. For an additional explanation of "best practice" when using the tool, see Appendix J.

4.5.1 Importing data functionality

The thesis was situated within the Rhinoceros environment, but there is no guarantee that Rhinoceros is the modelling environment of the architect. There is exporting functionality of various 3D modelling programs that is compatible with Rhinoceros, but it was not tested in this thesis, and is thus only commented.

4.5.2 Exporting data functionality

Results from BeDOT are saved in .csv files that are loaded into the interface for visualisation in BeDOT Interface. The .csv files describe mesh coordinates, orientation and values, and indicator results.

The 3D geometry that is used for visualisation of the design is exported into .obj files. This is done manually by the engineer, making sure that the export does not wrap long lines or map Rhino Z to Obj Y. This is important because the code in the interface requires that from the resulting .obj-file.

4.5.3 Virtual rooms

In some of the methods for calculating indicators, the term "virtual rooms" is used. Virtual rooms are in this thesis defined as fictive representations of rooms, meaning that the 3D geometry is not explicitly drawn in the modelling interface. For early-stage design, it might not always be suitable or even possible to draw multiple rooms inside a building. The reason might be that there is limited time, thus reducing modelling time by not having to draw actual rooms is beneficial, or another reason might be that there is not enough information in the project about the room geometry.

A virtual room is therefore built upon a statistical correlation used on real rooms, modelled and simulated or actually built rooms. For this thesis, the statistical correlation is derived through linear regression analyses. The correlation relates a factor on the inside (the room) with a factor on the outside (the façade). An example of that is to measure access to daylight on a façade and correlate it with the simulated daylight in a test room, something that has been tested in this thesis in Section 4.8.2. When finding a correlation, it is possible to perform external simulations over a façade mesh to find the corresponding value inside a virtual room, anywhere on the mesh.

4.5.4 Perimeter zoning

Single-zoning is the use of one thermal zone for one building. When there is need of a higher resolution for thermal zoning, one may either draw all zones by hand according to the floor plan, or draw or generate perimeter zones. As Figure 4.11 illustrate, the perimeter zones are around the core zone. This type of zoning is more detailed than single-zoning because it is representing perimeter zones, which are more affected by the climate outside through the windows, and a core zone which is not in contact with the envelope. This method was used in the thesis where BeDOT was developed (Fantin do Amaral Silva & Bergel Gómez, 2018).

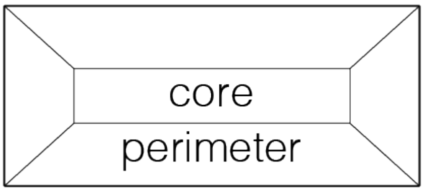


Figure 4.11 Top view diagram of a floor plan with perimeter and core zones used for energy simulation.

In the model integration of this project are HoneyBee's components 'splitBuildingMass' and 'splitFloor2ThermalZones' automatically generating thermal zones from the input geometry from the architect. However, in order for the zoning to work optimally, a checklist has been documented in Appendix J.

4.5.5 Calculation of model translation from architectural model

One important difference which is highlighted in Section 3.4 is that the calculation model for thermal balance simulations is defined as thermal zones and usually from the inside of the walls, floors and ceilings. This has an importance when translating the architect's model for calculations, meaning that there is a need to set a geometrical definition for the translation. Specifically, the floor area and room volume is depending on the wall depth, which in turn is dependent on the chosen U-value of the wall and the slab height. These factors have influence on the energy demand as the zone volume is needed for ventilation transmission calculations and the floor area is used in many indicators for calculating the specific values, e.g. specific energy demand.

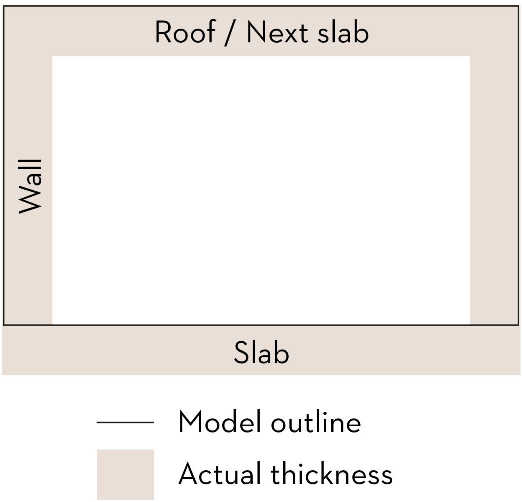


Figure 4.12 Section of architectural model geometry definition.

The black lines in Figure 4.12 represent the architect's model geometry definition. The beige lines represent the actual wall, ceiling and floor thickness that needs to be taken into account for a more accurate estimation of thermal zone size and floor area.

Calculating wall depth, d_{wall}

As the U-value of the wall is iterated over a range of values, e.g. in a sensitivity analysis, one can expect that the wall depth (d_{wall}) also change. Furthermore, d_{wall} has got influence of a number of resulting indicators as it affects the area within the buildings, such as floors area and A_{temp}.

Rewriting the formula for calculating thermal conductance over multi-layered objects (1), it is easy to extract the wall depth as all values are given except from the insulation depth.

$$U_{wall} = \frac{1}{R_{si} + \sum_{i=0}^{n} R_i + R_{se}} \qquad [W/m^2K] \qquad (1)$$

Where,

R_{si} = 0.13 [m^2K/W] is the internal surface resistance

R_{se} = 0.04 [m^2K/W] is the external surface resistance

$$R_i = \frac{\lambda_i}{d_i} \qquad [m^2K/W] \qquad (2)$$

Where,

R_i is the resistance of envelope wall layer i

The formulas and assumptions above are assessed from Hagentoft (2001). Assuming that the layers between the indoor and to the outdoors create the total wall resistance, the thermal conductivities are known and all material layer depths are known except for the insulation layer. Thus, the depth of the insulation layer is assumed to change as U_{wall} is changed, and d_{wall} can be derived from the equations above. An example used for calculations in the case study is provided in Appendix H. The reader should note that thermal bridges are not accounted for in this method, and calculating U-value of the wall is suitable for layered walls e.g. CLT walls, wood walls or brick walls.

Calculating remaining floor area

As concluded in Section 3.10, the floor area plays a part in estimating energy demand. As the author has not found many examples of the connection between the architectural model and the calculation model, efforts has been made to estimate the floor area as a function of the wall depth. As the wall depth is a function of the U-value of the wall, the definition for floor areas needs to be parametric and change as the U-value of the wall changes.

For very coarse models, such as a single-zone model, the floor area is calculated by using the zone floor outline per elevation and offsetting it by the given wall depth

When using the 5-zone model, the area estimation due to the wall thickness grows more complicated. The wall thickness only occurs at the perimeter (envelope) walls, and as the geometry of the massing increases in complexity, so does the area calculation. This is further motivated and explained for how it was solved for the case study in Appendix I.

4.5.6 Sensitivity analysis

A sensitivity analysis may help determining input data for the next iteration step. Performing iterative analysis means that the analysis will run in sequences with a range of varying input data. As the geometrical input in these types of calculations are rather complex and difficult and maybe also redundant to keep parameterised, there are alternative sorts of input data that might be interesting to iterate over.

The iterations are done with the Grasshopper plugin TT Toolbox Colibri. The iterator creates all possible combinations of the iterations, called the genome. The iterator is then connected per input data where the input is used for calculations, so they will change in all necessary calculations. The parameters to analyse for are multiple different output from relevant studies that are affected by the change of input data. An example of the sensitivity analysis is illustrated in the case study in Section 5.3.3.

The parameters are input to the 'Aggregator' component in Colibri and is called the 'Phenome'. Other input to the 'Aggregator' is a file path to a folder where the results will be saved. Also, a Boolean toggle needs to be set to True for results to be written. Then the user may let Colibri "Fly" and perform the specified number of iterations. Results are saved in a .csv file and the intention is to display the data with a parallel indicators plot such as the one described in Section 3.6.

4.6 Result visualisation interface

An interface where actors of a building project may communicate around building design and performance is suggested as a solution and developed during this thesis as a prototype.

4.6.1 Interface structure

One of the benefits of hosting a web page with project information is that there is no need of having any kind of software installed locally on the machine part from a web browser. However, a stable Internet connection is needed to use the interface. A proposal of the interface front-end is written in Python, using the framework Dash by Plotly.

The interface consists of a number of parts:

- A header, describing the actual project.
- Tabs, for alternative studies and for detailed studies
- A 3D viewport, where the user may explore the project geometry and calculation meshes.
- Complementary graphs presenting indicators

Development is done up to the point where to an interactive interface with some implemented intelligence simplifying communication for early stage building design. As seen in Figure 4.13, the prototype of the interface is hosted locally from a computer, something that would for a real project be run from a server and hosted on a public web address, thus enabling remote communication. A prototype of the interface is shown in Figure 4.13 and in Figure 4.14.

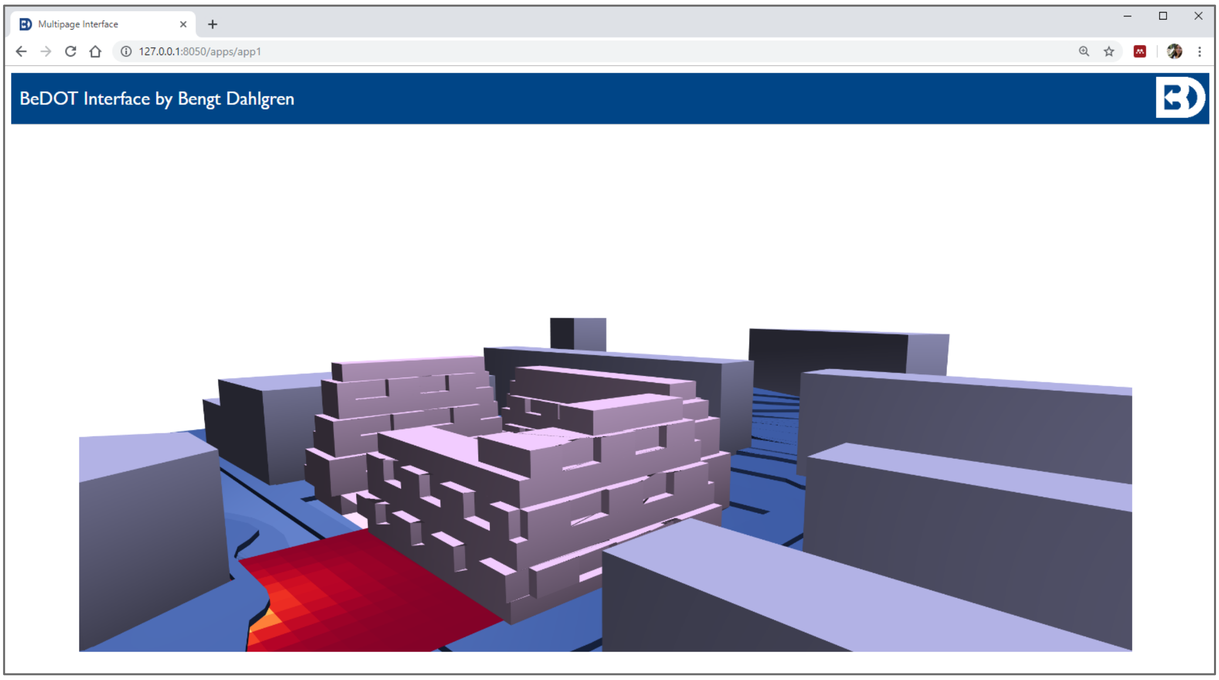
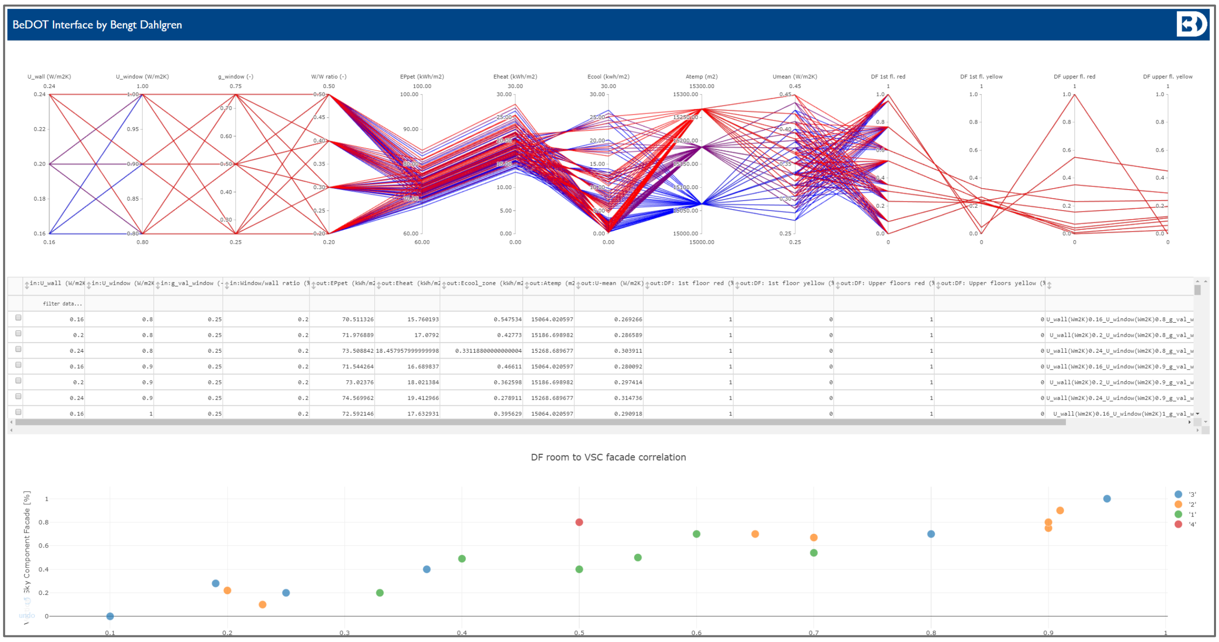


Figure 4.13 Interface prototype 3D visualisation tab, written in Python with Dash.



	in:U_wall (W/m2K	in:U_window (W/m2K	in:g_val_window (-	in:Window/wall ratio (%	out:EPpet (kWh/m2	out:Eheat (kWh/m2	out:Ecool_zone (kWh/m2	out:Atemp (m2	out:U-mean (W/m2K)	out:DF: 1st floor red (%	out:DF: 1st floor yellow (%	out:DF: Upper floors red (%	out:DF: Upper floors yellow (%	
	filter data...													
☐	0.16	0.8	0.25	0.2	70.511326	15.760193	0.547534	15064.020597	0.269266	1	0	1	0	U_wall(Wm2K)0.16_U_window(Wm2K)0.8_g_val_w
☐	0.2	0.8	0.25	0.2	71.976889	17.0792	0.42773	15186.698982	0.286589	1	0	1	0	U_wall(Wm2K)0.2_U_window(Wm2K)0.8_g_val_w
☐	0.24	0.8	0.25	0.2	73.508842	18.457957999999998	0.33118800000000004	15268.689677	0.303911	1	0	1	0	U_wall(Wm2K)0.24_U_window(Wm2K)0.8_g_val_w
☐	0.16	0.9	0.25	0.2	71.544264	16.689837	0.46611	15064.020597	0.280092	1	0	1	0	U_wall(Wm2K)0.16_U_window(Wm2K)0.9_g_val_w
☐	0.2	0.9	0.25	0.2	73.02376	18.021384	0.362598	15186.698982	0.297414	1	0	1	0	U_wall(Wm2K)0.2_U_window(Wm2K)0.9_g_val_w
☐	0.24	0.9	0.25	0.2	74.569962	19.412966	0.278911	15268.689677	0.314736	1	0	1	0	U_wall(Wm2K)0.24_U_window(Wm2K)0.9_g_val_w
☐	0.16	1	0.25	0.2	72.592146	17.632931	0.395629	15064.020597	0.290918	1	0	1	0	U_wall(Wm2K)0.16_U_window(Wm2K)1_g_val_w

Figure 4.14 Interface prototype data analysis tab, written in Python with Dash.

4.6.2 Data visualisations

The 3D viewport requires access to .obj files for geometry visualisation and .csv files for calculation mesh and other data visualisation. To visualise the .obj geometries, we need to translate vertices and faces of the obj file into geometrical data that the plotly.graph_objs may handle. Aid on how to write the code for this purpose was found in the Plotly community where lines of code was received and implemented in the Dash BeDOT Interface. Meshes are visualised by extracting the values from calculation mesh results and colouring these in a triangulated or squared mesh. An example of the 3D visualisation in Dash is shown in Figure 4.15, showing buildings and ground which are .obj-files imported to Dash, and a 2D mesh from an analysis. As seen in the figure, the graphics is not translated correctly in some of the convex parts of the geometry, unveiling that there is still development work to be done for achieving a good 3D representation. The figure also shows that the code developed for this thesis currently support 2D meshes, meaning that a façade mesh in 3D requires development work. The 2D mesh from the resulting simulation is remapped into a rectangular meshgrid along the x- and y-axis in the Dash 3D viewport.

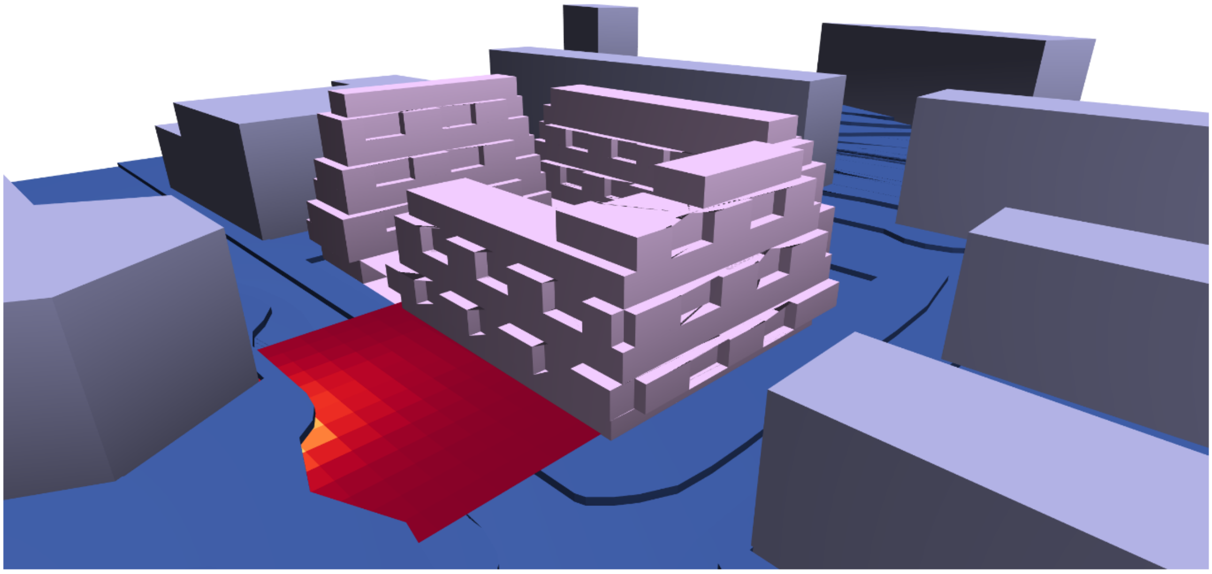
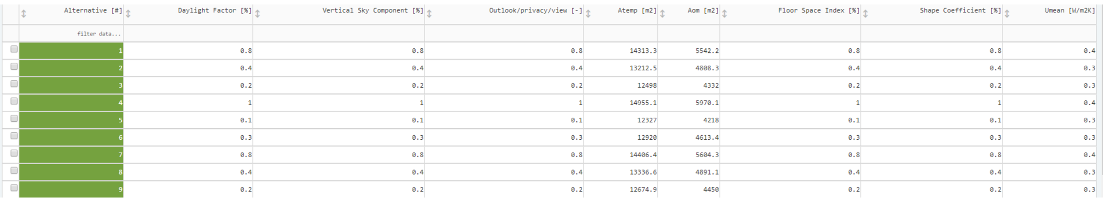


Figure 4.15 *Screenshot of the 3D figure in the interface, showing buildings, ground and a 2D analysis mesh.*

A traffic light legend is set to represent the data in the 3D viewport. Green represents that the mesh point data is above the target demand and the chosen safety margin (for the case study of this thesis being 20 %), yellow represents results that are within the safety margin above and below the target demand and red represents results that are below the target demand by 20 %. Examples of this can be seen in the case study in Chapter 5.

The vast majority of the data can efficiently be visualised in tables. Dash supply with tables that enables filtering and may be linked to other graphs for the user to display what is of interest to the user, an example described in Figure 4.16.



	Alternative [#]	Daylight Factor [%]	Vertical Sky Component [%]	Outlook/privacy/view [-]	Atemp [m2]	Aom [m2]	Floor Space Index [%]	Shape Coefficient [%]	Umean [W/m2K]
	filter data...								
☐	1	0.8	0.8	0.8	14313.3	5542.2	0.8	0.8	0.4
☐	2	0.4	0.4	0.4	13212.5	4808.3	0.4	0.4	0.3
☐	3	0.2	0.2	0.2	12498	4332	0.2	0.2	0.3
☐	4	1	1	1	14955.1	5970.1	1	1	0.4
☐	5	0.1	0.1	0.1	12327	4218	0.1	0.1	0.3
☐	6	0.3	0.3	0.3	12920	4613.4	0.3	0.3	0.3
☐	7	0.8	0.8	0.8	14406.4	5604.3	0.8	0.8	0.4
☐	8	0.4	0.4	0.4	13336.6	4891.1	0.4	0.4	0.3
☐	9	0.2	0.2	0.2	12674.9	4450	0.2	0.2	0.3

Figure 4.16 *Screenshot of the Dash Datatable with filtering and selection capabilities.*

The parallel coordinates plot is chosen for its ability to display multiple parameters and multiple resulting indicators in the same plot. Each design alternative is represented by one line in the plot, allowing for the user to discover correlations or conflicts among indicators. The screenshot in Figure 4.17 show an example of how multiple alternatives may be displayed to compare multiple indicators (the nine vertical lines to the right) to multiple input data (the four leftmost vertical lines). The lines are coloured by the values of one of the input parameters, allowing the user to see direct correlations between input and output where the colours are sorted in the indicators.

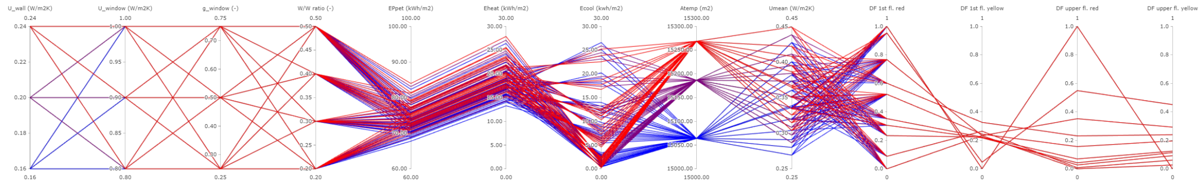


Figure 4.17 *Parallel coordinates plot.*

4.6.3 System boundary

Data on energy demand can be exported without system boundaries, meaning that hourly data on energy demand as raw data is available to be exported into the interface for more sophisticated data analytics. However, for the prototype interface, the energy demand included a number of system delimitations in order to export only the data that is of interest in this case study, which is aggregated over a year and aggregated to each building. This was motivated when hosting the interface on a local machine, however in a real project with data stored in a cloud, it might not be an issue.

4.7 BeDOT simulation backend

It was clear from the thesis developing BeDOT that the authors achieved many of the goals with their work, such as providing a building energy model performing in a simplified white box model. Results are obtained by fast simulations and verified as a feasible substitute to classic white box models that require more time.

This thesis uses BeDOT as a starting point, and therefore the author of this thesis wishes to highlight the user-centred goals cited in Section 3.9. The impression is that there is still room for developing these goals further. BeDOT is introduced up to this point as a white box model (which is described in Section 3.5) with potential of adding other simulation methods. This is what is intended with this thesis; to implement additional relevant functionality to accompany BeDOT's energy simulation functionality.

A brainstorming session with Ona Forss resulted in a list of indicators that are relevant for building performance simulation in the context of housing projects in Sweden. The reader should bear in mind that the development of the backend was from this point delimited towards the test environment of the case study in Chapter 5. The chosen additional analyses are explained in the following Section 4.8.

4.8 Indicators for BPS

In this section follows and explanation of the indicators that are relevant for this thesis, their definitions and the methods for assessing them.

By an evaluation of the most important indicators for an early stage design project, specifically targeted for the following case study, the following indicators was decided to be assessed. The decision was made together with Ona Forss, conducting her Master's Thesis in Architecture. Table 5.1 describe each indicator briefly and in short how it is assessed in the four last analysis stages which are proposed in Section 4.3.

Table 5.1 Indicator summary. The term f() should be read as "function of".

Indicator	**Analysis 1: Building Envelope**	**Analysis 2: Massing study**	**Analysis 3: Façade study**	**Analysis 4: Interior study**
Daylight	Grid f(room geometry, LT(g))	Grid f(room geometry, LT(g))	Grid f(virtual room)	Grid f(real room)
Energy demand EP_{pet} [kWh/m^2]	Single-zone modelling	Perimeter-zone	Perimeter-zone	Zones drawn to match layout
View	Grid f(façade srf, view srf)	Grid f(façade srf, view srf)	Grid f(façade srf, view srf)	Grid f(real room)
Thermal comfort	Grid f(solar heat load), Cooling demand	Grid f(solar heat load), Cooling demand	Grid f(solar heat load), Cooling demand	Grid f(real room, PPD)
Sunlight	Grid f(sunlight hours)	Grid f(sunlight hours)	Grid f(sunlight hours)	Grid f(sunlight hours)
U_{mean} [W/m^2K]	f() very simplified assumptions	f() very simplified assumptions	f() simplified assumptions	ISO calculation
Solar energy [kWh/m^2]	f(irradiance, area of facade)	f(irradiance, area of facade)	f(irradiance, area of facade)	f(irradiance, modelled PV's)
Floor space index	f(BTA/real estate area)	f(BTA/real estate area)	f(BTA/real estate area)	f(BTA/real estate area)
Window/wall ratio	Input data	Input data	Result of drawn windows	Result
Shape coeff.	f(Aom/Atemp)	f(Aom/Atemp)	f(Aom/Atemp)	f(Aom/Atemp)

Emphasis was put on the following indicators illustrated in Figure 4.18, which are motivated in the sub-sections of Section 4.8.

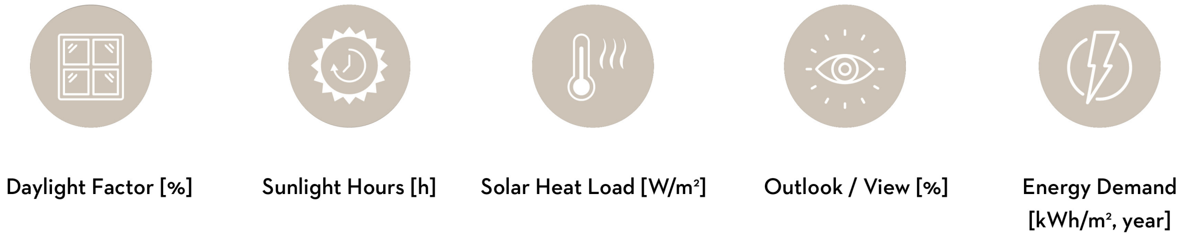


Figure 4.18 Additional analyses (left) to accompany the existing functionality of BeDOT (right).

4.8.1 Daylight

Daylight Factor (DF) is a common indicator for estimating daylight, especially in Sweden. Other ways of estimating daylight are by calculating daylight autonomy or the useful daylight illuminance (UDI). Furthermore, sky view factor and vertical sky component are also mentioned as simplified metrics of daylight on facades. A comparison between daylight factor (DF), sky view factor (SVF) and vertical sky component (VSC) is shown in Appendix A.

DF is chosen for representation of daylight for this study. However, the limitations of DF as an indicator must be known; it does not consider weather, glare, overheating nor orientation. The indicator DF is relevant because it is one of the demands set by regulations. For housing, DF must be at a minimum of 1 % (The Swedish National Board of Housing Building and Planning, 2011). It is demanded that there must be "adequate access" in rooms that are used more than occasionally.

Daylight factor is defined as the ratio of illuminance between indoors and outdoors (Swedish Standards Institute, 2018). It is defined under an overcast sky, and consist of three parts; the sky component, the exterior and the interior reflected component. Illuminance inside is measured at a point 1 m from the darkest side wall, 0.8 m above the floor.

Sky View Factor (SVF) is defined in the same way as in the thesis of (Jacobsson & Eriksson, 2017), using the HoneyBee component 'viewAnalysis', therefore this definition is referenced from the source code of the component: "The percentage of the sky that is visible from the surface geometry." Sky View weights the sky patches by "their area projected into the plane of the surface being evaluated".

Vertical Sky Component (VSC) is defined as "the ratio of direct sky illuminance falling of a vertical wall at a reference point, to the simultaneous horizontal illuminance under an unobstructed sky" by BRE (UK Building Research Establishment). Honeybee has got an already-built component for VSC; 'runDaylightAnalysis' which is used. VSC is simulated with CIE overcast sky and cosinus weighting and without reflections from the ambience.

See Appendix A for a comparison between the daylight indicators.

As the logic of BeDOT is built from an outside-to-inside perspective, there is no connection to the indoor environment, something that is necessary to investigate when estimating the Daylight Factor inside. This is a motivation of the two following methods.

4.8.2 Approximated Daylight Factor simulation methods

This thesis use and evaluate two methods for daylight factor approximation.

Daylight Factor method from statistical correlation – "Method 1"

For fast analyses, the simplified daylight factor method is presented below. This method was derived from work in two previous theses at Chalmers in collaboration with BDAB; "Daylight in existing buildings" (Eriksson & Waldenström, 2016) and "Evaluation of sun-and daylight availability in early stages of building development" (Jacobsson & Eriksson, 2017). The method was for the purpose of this thesis adapted with a correlation between window g-value and LT-value to provide relevant approximations on daylight factor (DF) for the iterative sensitivity analysis in section 4.5.6.

This method combines the daylight factor indoors with a sky view factor (SVF) on the façade. Jakobsson & Eriksson (2017) found in their thesis a correlation between DF and SVF together with room geometry. It was found by evaluating DF from a database with 25000 rooms simulated in the thesis of Eriksson & Waldenström (2016), plotting (SVF x A_{glass} / $A_{room,floor}$) against DF_{median} in a scatterplot and finding a linear relationship with the correlation factor of 0.26. The light transmittance used in windows was constant through all simulations: LT = 0.7 [-]. The formula for the relationship is presented in equation 3:

$$DF_{median} = 0.26 \times SVF \times \frac{A_{glass}}{A_{room,floor}} \quad [-] \tag{3}$$

Where,

DF_{median}	is the median daylight factor in a room [-]
SVF	is the sky view factor [-] which represent the amount of daylight available outside the room at overcast sky
A_{glass}	is the area of glazing towards the outside of the room [m^2]
$A_{room,floor}$	is the area of the floor in the room [m^2]

In this thesis, the recently mentioned method will be used to give an initial impression of the daylight availability on a specific project site. Furthermore, it will be adapted to also give relevant data for the sensitivity analysis. One of the parameters that serve as input to that analysis is g-value, which affects energy but also have some correlation with light transmittance values. By studying g-value and LT-value correlation from a number of windows from one established window producer, the g-value iterations will also have an impact on the DF. Assuming an overcast sky with only diffuse radiation, and that all parameters are constant in the previous formula except from g-value, we are able to find a correlation between g-value and DF.

A full description of assumptions made to find the correlation between the g-value and the DF is presented in Appendix B. The derived equation 4 is:

$$DF_{median} = g_{window} \times \frac{x_{corr}}{LT_{old}} \times 0.26 \times SVF \times \frac{A_{glass}}{A_{room,floor}} \quad [-] \tag{4}$$

Where,

g_{window}	is the g-value of the window [-]
x_{corr}	= 1.7732 , as derived in Appendix B

Jakobsson & Eriksson (2017) also defined a geometry relation of the virtual rooms:

$$\frac{A_{glass}}{A_{wall}} = \frac{A_{glass}}{A_{room,floor}} \times \frac{d}{H_{floor}} \quad [-] \tag{5}$$

Where,

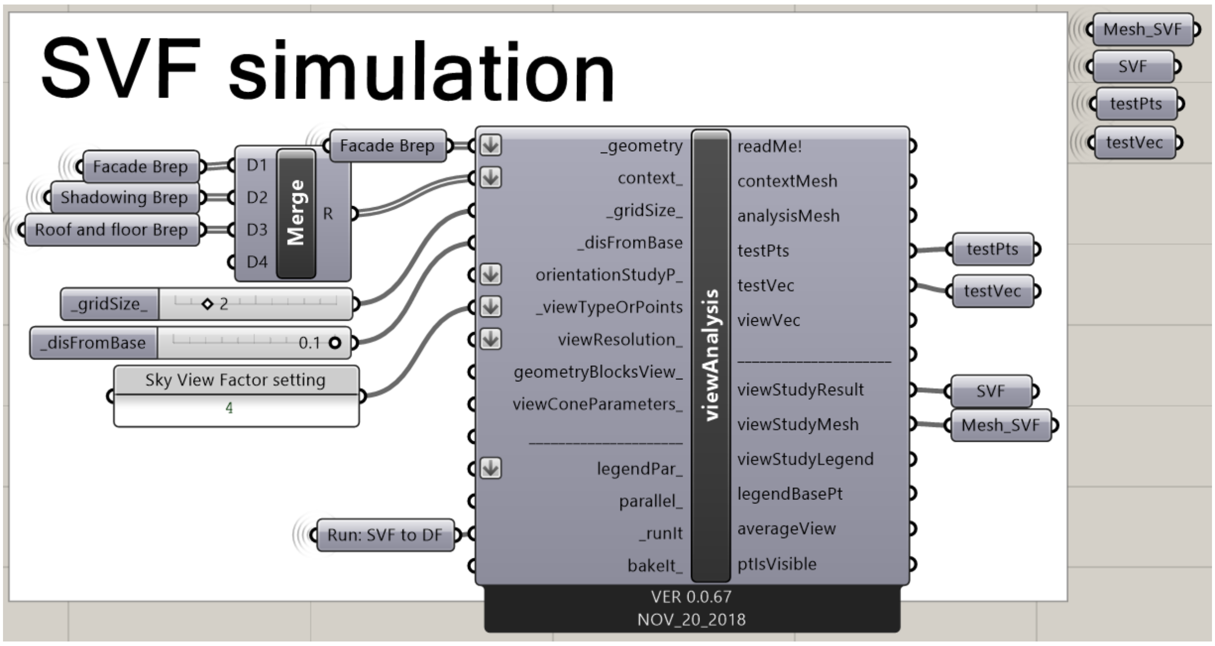
A_{wall}	is the area of the external wall [m^2]
d	is the virtual room depth [m]
H_{floor}	is the height per floor [m]

The geometry relation can be used to find $A_{glass}/A_{room,floor}$ for calculating DFmedian:

$$\frac{A_{glass}}{A_{room,floor}} = \frac{A_{glass}}{A_{wall}} \times \frac{H_{floor}}{d} \qquad [-] \qquad (6)$$

The simulations are illustrated in figures and explained step-by-step below.

1. Simulate SVF in 'viewAnalysis', Figure 4.19
2. Calculate window/floor ratio with the geometry relation, Figure 4.20 & equation 6.
3. Use the equation 4 to calculate DFmedian, Figure 4.21

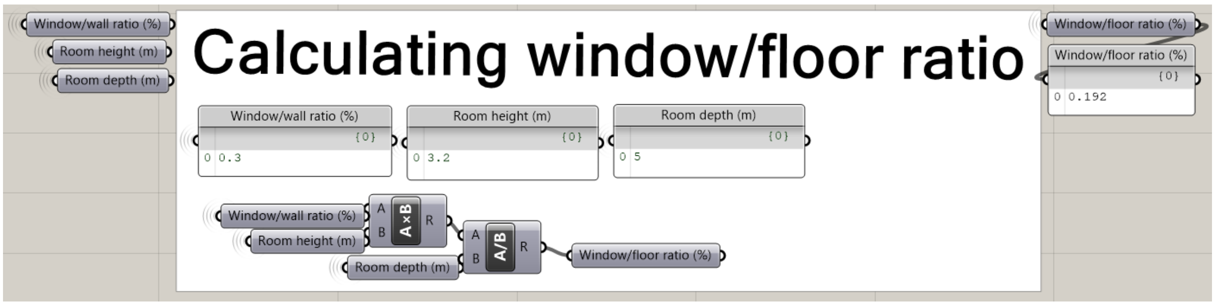


gridSize 2

_disFromBase 0.1

Sky View Factor setting 4

Figure 4.19 Simulation of SVF in Grasshopper, using the LadyBug component 'viewAnalysis'.



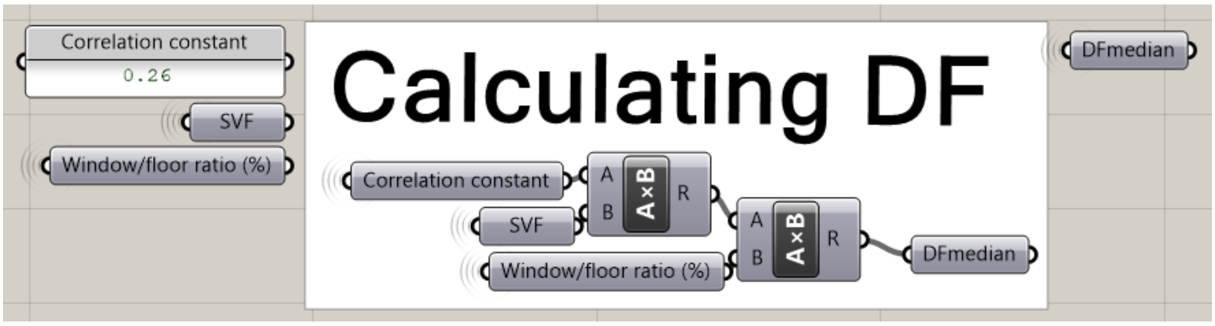
Window/wall ratio (%) {0} 0 0.3

Room height (m) {0} 0 3.2

Room depth (m) {0} 0 5

Window/floor ratio (%) {0} 0 0.192

Figure 4.20 Calculation of window/floor ratio, example room.



Correlation constant 0.26

Figure 4.21 Calculation of DF_{median} according to equation above.

Moving into the façade design stage, it is relevant to supply a daylight factor methodology that is both quick and provides project-specific results. The project-specific method is described further below.

Daylight Factor from Project-Specific Correlation – "Method 2"

The following method is suitable for façade analysis stages, where quick results are desired, but the decisions require project specific data such as window or balcony placement. The method was developed by an employee at BDAB and has been adapted in this thesis for a broader range of analyses. The method characteristic is the generation of parametric test rooms connected to the façade and finding a linear correlation between the exterior and interior. Instead of using an already derived correlation, as in equation 4, the internal DF is correlated with the external VSC to get a project-specific correlation through linear regression analysis of a number of test rooms. With the correlation, the user is able to approximate DF inside the building on each mesh point of the façade by only calculating VSC. The vertical sky component simulation can be done in seconds, when the traditional DF simulation may take minutes to hours for just one room. This means shortening the simulation time to get an approximation for DF. The equation below describes the correlation.

$$DF = x_{corr,2} \times VSC \quad [-]$$

Where,

$x_{corr,2}$	is the correlation factor of method 2 derived from linear regression [-]
VSC	is the vertical sky component [-]

This is a step-by-step methodology for Method 2:

1. Make a VSC analysis for fast input on good daylight availability outside of façade, Figure 4.23. Figure 4.22 illustrates an example from the case study.
2. Test rooms are parametrically generated by the input of a baseline curve. The curve is placed over a range of different values of VSC to provide a diverse range of results to connect to DF inside the rooms, Figure 4.24. The generation of test rooms is based on a definition developed at BDAB, however it was adapted for rooms with more than one window for application in a wider scale, see Appendix C.
3. Simulate DF inside the test rooms. The component 'runDaylightAnalysis' is used, Figure 4.25, calculating DF according to the definition in this chapter.
4. Find the VSC result that is in a mesh point closest to the respective window of calculated DF inside the room. Plot the found VSC results and the corresponding DF results in a scatter plot to find a linear correlation. For details of the case study example, see Appendix D.
5. From all simulated mesh points of VSC it is now possible to find DF inside a virtual room, see Figure 4.26.

An example of Method 2 was used in the case study façade analysis in Section 5.9 and 5.10. Furthermore, a linear regression analysis can be read about in Appendix D, which explains the case study application of the method and the project-specific correlations.

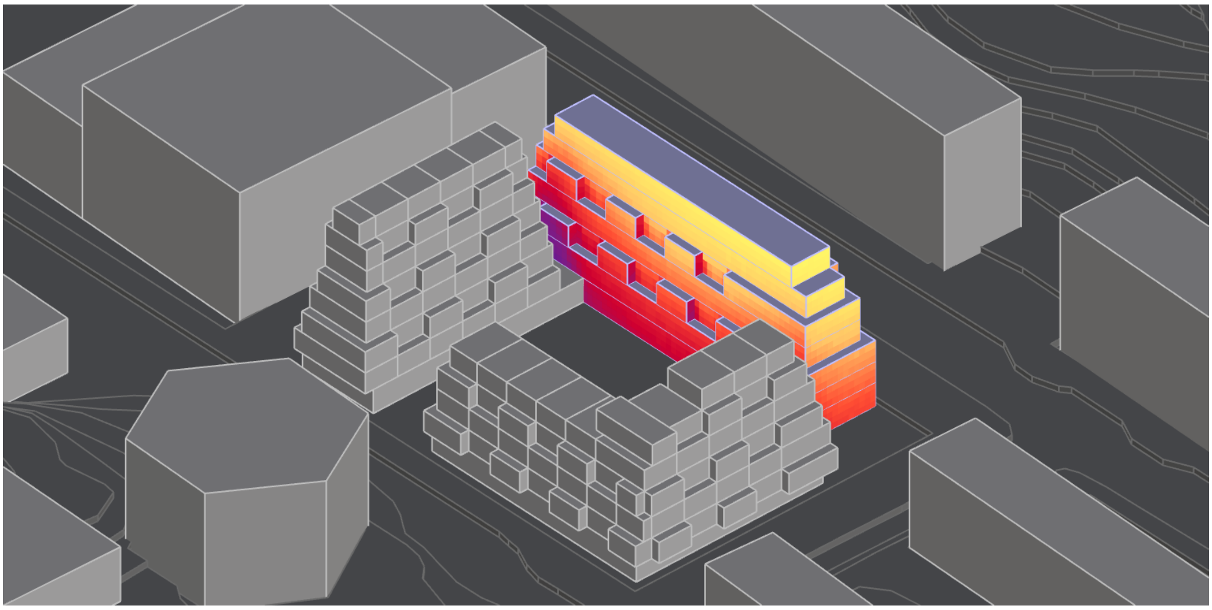


Figure 4.22 *Vertical Sky Component on façade to guide where to place the test rooms, view from southwest.*

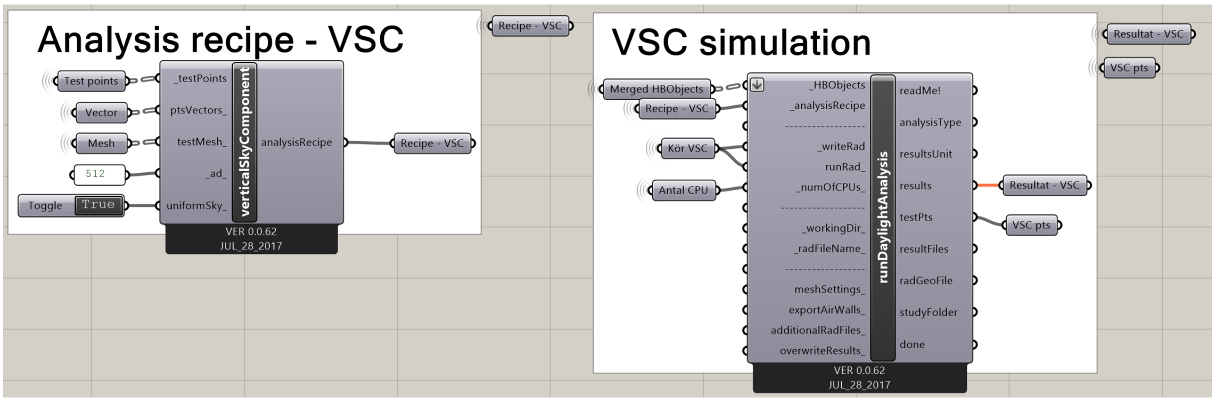


Figure 4.23 *Simulation of VSC in Grasshopper.*

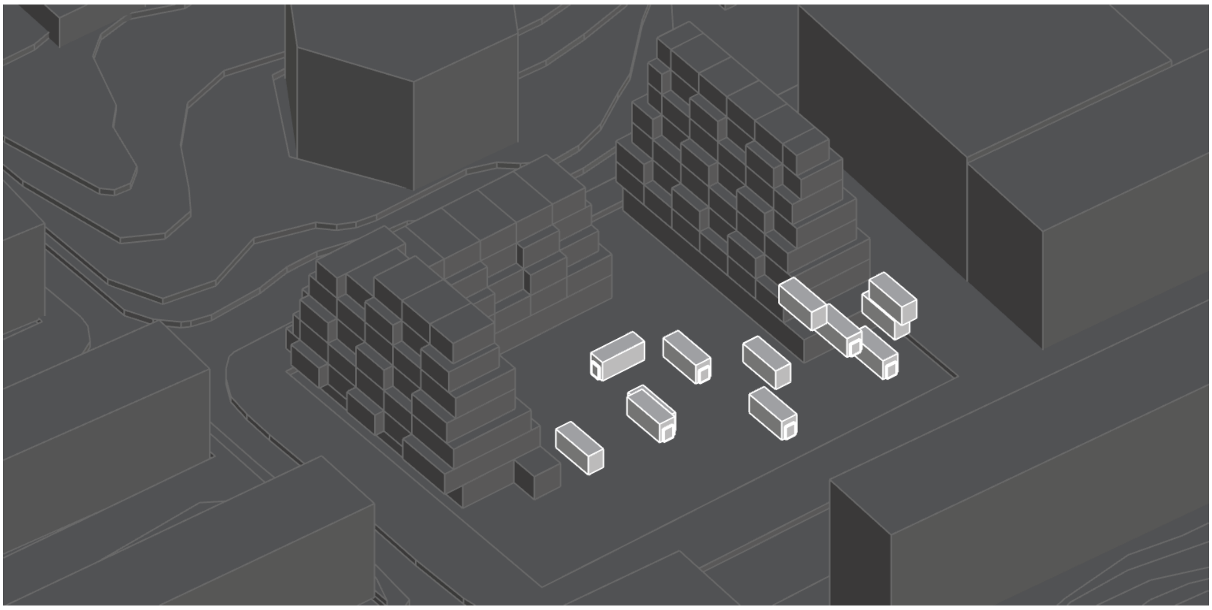


Figure 4.24 *Placement of the test rooms, view from southeast. Example from case study.*

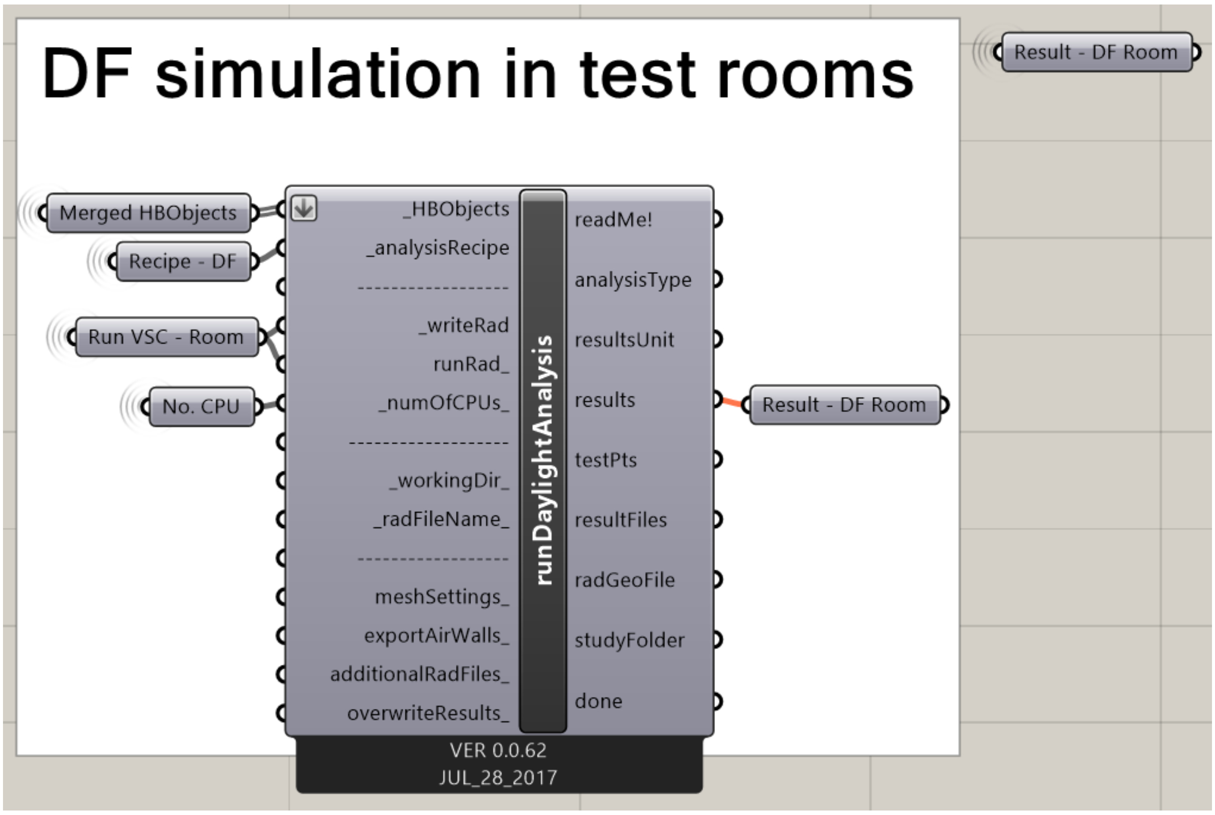


Figure 4.25 Simulation of DF in test rooms with the HoneyBee component 'runDaylightAnalysis'.

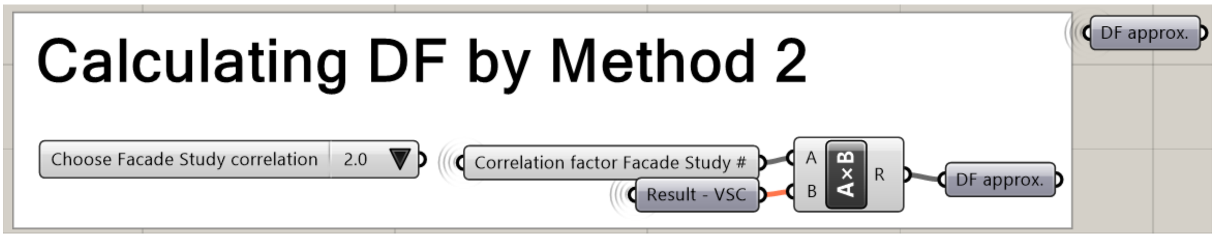


Figure 4.26 Calculating DF by the linear correlation derived from a linear regression over DF and VSC.

4.8.3 Energy demand

The buildings specific energy use is a commonly used indicator for estimating a building's energy demand. This section cites the current definitions for relevant parameters needed for calculating specific energy use after the simulations of BeDOT.

The buildings energy use is defined by The Swedish National Board of Housing Building and Planning (SNBHBP) (2011) as

> *"The energy which, in normal use during a reference year, needs to be supplied to a building (often referred to as "purchased energy") for heating (Euppv), comfort cooling (Ekyl), hot tap water (Etvv) and the building's property energy (Ef). If underfloor heating, towel dryers or other devices for heating are installed, their energy use is also included. The building's energy use is calculated using the equation below,*

$E_{bea} = E_{uppv} + E_{kyl} + E_{tvv} + E_f$ " (The Swedish National Board of Housing Building and Planning, 2011). (p. 141)

A_{temp} is defined by SNBHBP (2011) as

> *"The area enclosed by the inside of the building envelope of all storeys including cellars and attics for temperature-controlled spaces are intended to be heated to more than 10 ºC. The area occupied by interior walls, openings for stairs, shafts, etc., are included. The area for garages, within residential buildings or other building premises other than garages, are not included."* (p. 141)

The buildings specific energy use is defined by SNBHBP (2011) as

> *"The building's energy use divided by Atemp expressed in kWh/m2 and year. Domestic energy is not included. Neither is occupancy operational energy used in addition to the building's occupancy basic operation adapted requirements for heat, hot water and ventilation. The building's specific energy use ($E_{beaspec}$) is calculated using the equation below,*
>
> $E_{beaspec} = E_{bea} / A_{temp}$ *"* (p. 142)

Energy for heating E_{heat} is defined as the energy required for heating the thermal zone air temperature to be above the heating set point (The Swedish National Board of Housing Building and Planning, 2011).

E_{air} is an addition to E_{heat} for recovery of lost heat from airing (The Swedish National Board of Housing Building and Planning, 2011).

Energy for cooling E_{cool} is defined as energy required for cooling the thermal zone air temperature to be below the cooling set point (The Swedish National Board of Housing Building and Planning, 2011).

Energy for hot tap water E_{tvv} is commonly a large part of the building energy use, a general recommendation in BEN if not calculated is to assume 25 [kWh/m^2] (Boverket, 2016).

The buildings property energy E_f is in BBR 25 defined as:

> *"The part of the building electricity consumption that is related to the building's needs, where the electricity consuming appliance is located in, under or affixed to the exterior of the building. This includes permanently installed lighting of common spaces and utility rooms. It also includes energy used in heating cables, pumps, fans, motors, control and monitoring equipment and the like. Externally locally placed devices that supply the building, such as pumps and fans for free cooling, are also included. Appliances intended for use other than for the building, such as engine and compartment heaters for vehicles, battery chargers for external users, lighting in gardens and walkways, are not included."*
> (The Swedish National Board of Housing Building and Planning, 2011).

E_f can be calculated or estimated in detailed design stages. For early stage design, the users are proposed to use a constant value E_f = 15 [kWh/m^2], recommended by BEN (Boverket, 2016).

The buildings primary energy indicator EP_{pet} is a common indicator for energy demand, weighted by energy source and geographical location. The formula for calculating EP_{pet} is described in Section 4.8.4. In BBR 25, the highest allowed EP_{pet} is described in table 9:2a, for housing being 85 kWh/m^2 (The Swedish National Board of Housing Building and Planning, 2011).

4.8.4 Specific energy demand simulation

Simulation of the energy demand is done using BeDOT, which is explained in Section 3.9. The input data is set through an Excel interface, one example of the vast amount of input data being shown in Appendix E. Furthermore, the input geometry is derived directly from the architect's design model, translated into a calculation model as Section 4.5.5 describe.

This thesis explores two simplified methods of thermal zones for which the simulations are run. The first, being called "single-zone model" is used for the Building envelope study using one thermal zone for one building, is a very coarse method giving a first indication of the energy demand of the design. The second method is called "perimeter-zones model" and is a commonly used method in praxis for creating thermal zones. For each floor, five zones are created; one for each cardinal direction with a given perimeter depth, and one core zone which is not as affected by the envelope wall transmissions or direct incoming solar radiation.

The formula used for assessing EP_{pet} is explained in equation 7:

$$EP_{pet} = \frac{\sum_{i=1}^{6}\left(\frac{E_{heat,i}}{F_{geo}} + E_{cool,i} + E_{tvv,i} + E_{f,i}\right) \times PE_i}{A_{temp}} \text{ [kWh/m}^2\text{, year]} \tag{7}$$

Where,

F_{geo}	is the geographical adjustment factor [-]
PE_i	is the primary energy factor per energy source [-]

Both F_{geo} and PE_i can be found in BBR 25 (The Swedish National Board of Housing Building and Planning, 2011). E_{heat} and E_{cool} and is extracted as raw data from BeDOT, E_{tvv} is recommended by BEN to be assumed as 25 [kWh/m^2], E_f assumed as 15 [kWh/m^2] and E_{air} = 4 [kWh/m^2], thus a large part of the energy demand calculated is actually constant values (Boverket, 2016).

4.8.5 View from building

The indicator was defined in co-operation with Ona Forss as a result of a workshop on the topic, see Section 2.3. The purpose was to find an indicator that was of interest to architects working in early stages of building design. There are regulations for view stated in (The Swedish National Board of Housing Building and Planning, 2011) section 6.33:

> *"At least one window in rooms or separable parts of a room where people are present other than occasionally should be situated to ensure the view provides the opportunity to follow the seasonal variations day and night. In dwellings, skylights should not be the only source of daylight in rooms, where people are present other than occasionally."*

Access to view with regard to the citation above was in the workshop considered a quality of building important for housing projects in the cityscape. Although the study found no common praxis for calculating view, it exists a simple calculation method that is proposed by this thesis and tested in the case study.

The indicator was defined the percentage of how many points in the mesh of the view surfaces are directly visible from each point of the façade [%]. The desired views are decided by the architect for each specific project and may consist of sky patches, landmarks or landscape views. The workshop estimations resulted in choosing 25 % as target value for desired views. Figure 4.27 show contextual buildings (white), the building façade where view is to be simulated (grey with green borders) and the selected desired views (green transparent).

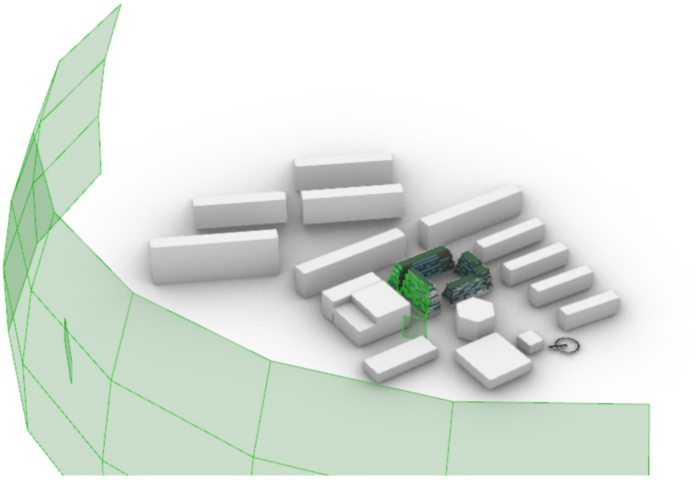


Figure 4.27 Example of the view from façade. Green areas on the façade represent the areas analysed for view, and green areas in the 3D landscape is sky patches, landmark and greenery views.

4.8.6 View simulation method

The indicator View was defined in Section 4.8.5. This section explains methodology of achieving the indicator to meet regulations and investigate view from the building.

The script was inspired by an open-source Grasshopper definition from Hydrashare that determines areas of a building façade with quality views (Chris Mackey, 2017).

To build the definition for the script, one needs to follow the steps below:

1. Use the component “viewAnalysis”, with input described by the following parts and illustrated in Figure 4.28.
2. Add the geometry of the building facade. These surfaces serve as “_geometry” input. It is recommended to make four simulations, one for each cardinal or façade direction.
3. Set the parameters “_gridSize” and “_disFromBase” that determines settings for the test points that is generated on the building envelope from the input “_geometry”.
4. Add contextual objects that may block the view as “context_” input.
5. Set the “_viewTypeOrPoints” to the mesh of the desired view surfaces.
6. Run the analysis

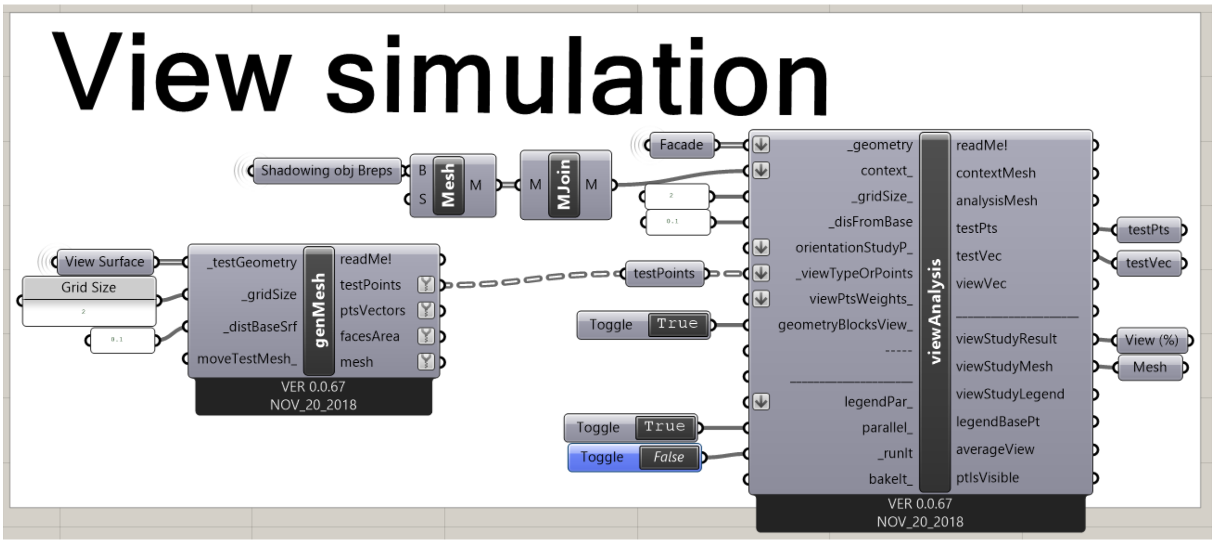


Figure 4.28 Definition used for the indicator "View from building".

The 'viewAnalysis' component generates a mesh and resulting view. It describes the percentage of how many points in the mesh of the view surfaces are directly visible from each point of the façade.

4.8.7 Thermal comfort

BBR (The Swedish National Board of Housing Building and Planning, 2011) reads:

> *"Buildings and their installations shall be designed in such a way that thermal comfort adapted to a space's intended use can be achieved under normal operating conditions."* (section 6:42)

Recommendations are stated in BBR for the lowest acceptable operative temperature in residential buildings to 18 °C, accompanied by recommendations on temperature differences over the thermal zones, surface temperatures and air velocity. However, all the mentioned factors of thermal comfort need a high level of detailing in design of rooms and technical systems, as well as detailed simulation methods. As BeDOT calculates the air temperature, and the thermal mass temperature is in reality closer to the operative temperature than the air temperature, it is possible to get the detailed answers that the standard requires. However, achieving the general recommendations in BBR for thermal comfort, by the common method of estimating PPD index, is considered as an option for later stage simulations.

On the other hand, something which may serve as a early stage indicator of thermal comfort is the solar heat load [W/m^2] (Section 4.8.8) and the cooling demand of zones [kWh/m^2] (Section 4.8.9) which is a result of the heat balance of BeDOT. It is recommended to plot the solar heat load [W/m^2] to the cooling power [W/m^2] to find a correlation that can be used to define target values for thermal comfort.

4.8.8 Solar heat load simulation as help-indicator to thermal comfort

The indication for solar heat load (SHL) is connected to the geometry of the façade by an irradiance simulation on the building façade. Connecting solar heat load results to the geometry may help the user to discover potential critical areas for overheating and thus indicate a low thermal comfort.

Solar head load is a well-known indicator in Sweden and is defined in SGBC's Miljöbyggnad 3.0 (Sweden Green Building Council, 2017) and is when performing simulations calculated for rooms with windows toward one direction according to equation 8:

$$SHL = I_{sol} \times g_{syst} \times \frac{A_{glass}}{A_{room,floor}} \qquad [\text{W/m}^2 \text{ floor area}] \tag{8}$$

Where,

I_{sol} is the simulated incoming solar irradiance on a window [W/m^2]

g_{syst} is the g-value of the window and the shading multiplied together [-]

The simulation of incoming irradiance is illustrated in Figure 4.29. Reflectance is set for all geometry in the model, which are converted to HoneyBee surfaces as input to the 'runDaylightAnalysis' component. Gridpoint settings, EPW file, RADIANCE and Daysim parameters are set to the 'annualDaylightSimulation' component. The analysis is run over a year using Daysim and recorded in .ill-files, containing the irradiance results. The files may be read through another component that converts the file results into a data tree of irradiance per grid point with a branch for each hour of the year.

Figure 4.30 describes the assumptions made for assessing a feasible value for the maximum irradiance over a year, meaning the data tree will decrease into one value per gridpoint. The simulation often return a number of values which are far too large to count as accurate, therefore those values are extracted before the ten largest remaining irradiance numbers are used to calculate a mean per grid point.

Finally, SHL is calculated according to equation 8 and Figure 4.31.

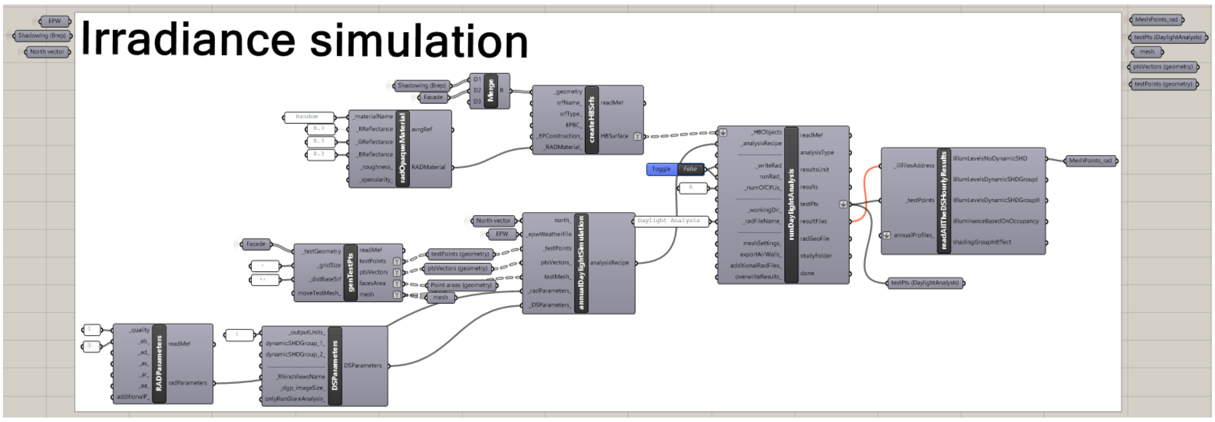


Figure 4.29 Screenshot of the Grasshopper definition for the irradiance simulation.

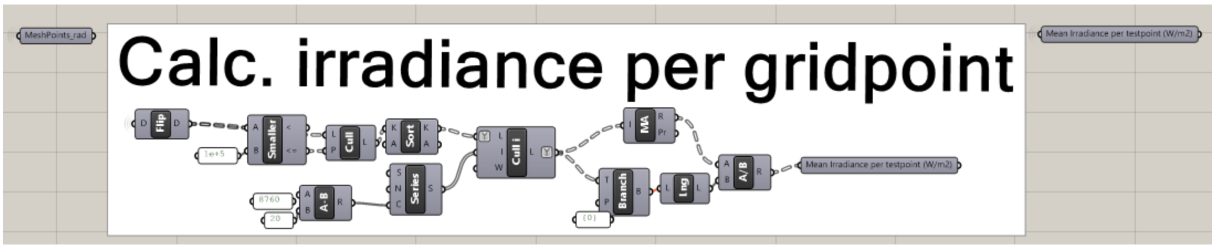


Figure 4.30 Screenshot of definition calculating irradiance per grid point.

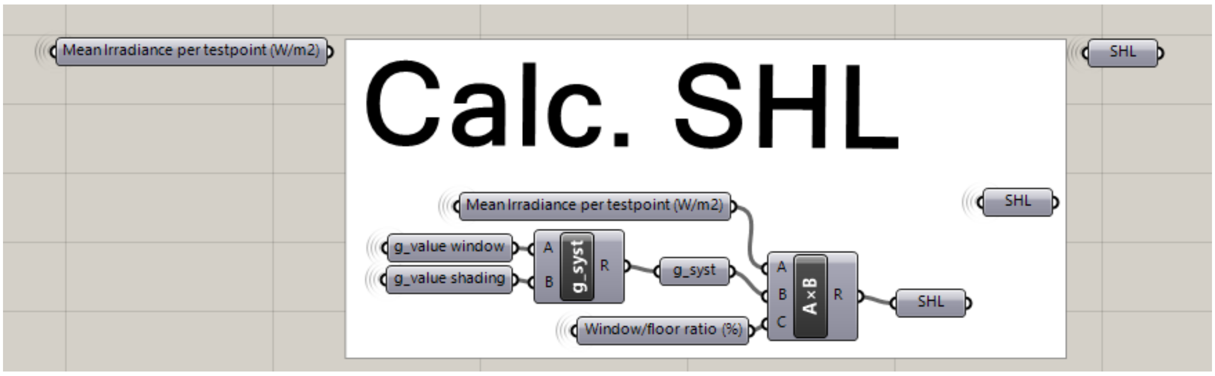


Figure 4.31 Calculation definition for solar heat load (SHL).

4.8.9 Cooling demand of zones as help-indicator to thermal comfort

The cooling demand of the thermal zones may indirect indicate thermal comfort because it is an indicator of overheating. Cooling demand is calculated for each hour in BeDOT and is then assessed over the year in [kWh/m^2, year], adding up for each hour when the zone temperature is above the cooling set point. The results can be presented as a numerical value against a target value that is defined by the user.

4.8.10 Sunlight

Sunlight is defined as the part of direct visible solar radiation. (The Swedish National Board of Housing Building and Planning, 2011) states that at least one habitable room must have access to direct sunlight and recommends access to observer seasonal variations from the room. The demands do not give further information on how much sunlight is feasible, however, the new standard on daylight in buildings also specify recommended hours of exposure to sunlight in at least one of the habitual rooms in Table 5.2 (Swedish Standards Institute, 2018). Further, the standard recommends assessment of the indicator during an arbitrary date between February 1st and March 21st, with shadowing objects included in the calculation.

Table 5.2 Recommendations for sunlight hours by the Swedish National Board of Housing and Planning (2011).

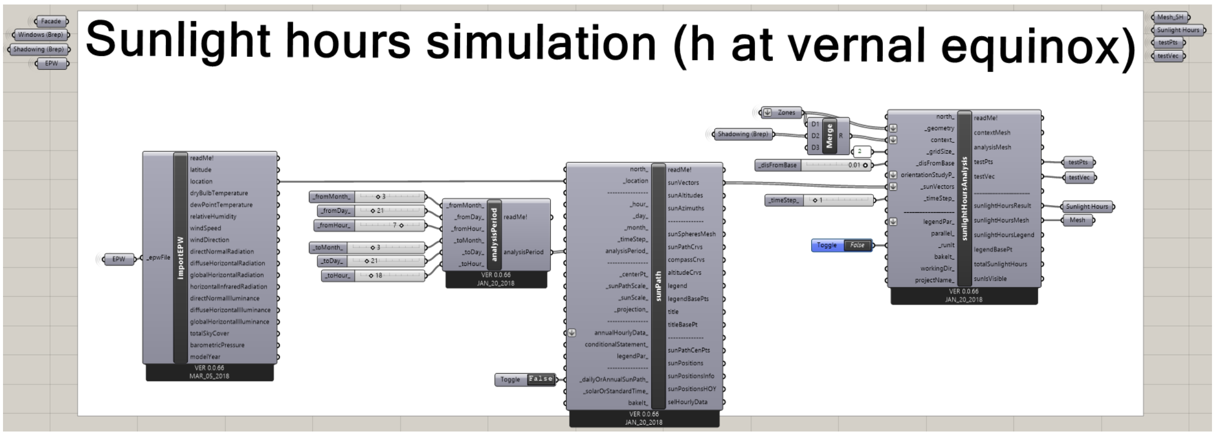
Level of recommendation for exposure to sunlight	Sunlight exposure
Minimum	1.5 h
Medium	3.0 h
High	4.0 h

Recommended exposure to sunlight in at least one of the habitual room according to the table above. In the current densification of cities, it is unrealistic to achieve unlimited amount of sunlight. It might not even be beneficial because of the solar heat load it entails. However, access to sunlight is undoubtedly a quality in housing, and therefore it is nonetheless included as an indicator in this thesis.

4.8.11 Sunlight hours simulation method

This thesis propose simulation of the amount of direct sunlight hours on the façade during vernal equinox, according to the steps below and Figure 4.32:

1. Use the EPW file for extracting the project-specific location.
2. Create an analysis period, recommended is one day at vernal equinox.
3. Generate a sun path for the chosen analysis period and location.
4. Connect the geometry to be simulated and the surrounding shadowing objects to the ‘sunlightHoursAnalysis’ component.
5. Choose settings for analysis mesh and time step (default is 0.5 h).
6. Run the analysis.



fromMonth 3
fromDay 21
fromHour 7
toMonth 3
toDay 21
toHour 18
Toggle False
gridSize 2
_disFromBase 0.01
timeStep 1
Toggle False

Figure 4.32 Simulation of sunlight hours using the LadyBug component ‘sunlightHoursAnalysis’.

4.8.12 U_{mean}

U_{mean} is chosen as an indicator because of the general recommendations in BBR and the indicator’s close connection to surface areas. The method chosen for calculation of U_{mean} is developed at BDAB and is not yet verified, however it is a progressing development work.

In general, Boverket (2011) defines the **average thermal transmittance $\mathbf{U_m}$** (U_{mean}) as:

> *“The average thermal transmittance for structural elements and thermal bridges (W/m^{2}K) as determined by SS-EN ISO 13789:2007 and SS 24230 (2) and calculated using the formula below”* (p.142)

$$U_m = \frac{\left(\sum_{i=1}^{n} U_i A_i + \sum_{k=1}^{n} l_k \psi_k + \sum_{j=1}^{n} \chi_j\right)}{A_{om}}$$

The full description of all parameters involved is available in BBR 25 (Boverket, 2011). In summary, the mean U-value is the sum of the envelope UA-value, the linear and the point shaped thermal bridges over the area A_{om}.

The calculation of U_{mean} is a simplification tailored for early stages because only when windows, balconies and inner walls are designed, it is possible to get a good estimation of all the linear and point shaped thermal bridges. In the component, A_{om} is calculated as the sum of all areas encapsulating the indoor environment from the outside, which is the same as in BBR 25. When it comes to the nominator parts of the equation above, the solution does not follow the definition. Instead, BeDOT require a U_{bridge} value as input data, describing the amount of thermal bridges estimated in the project. Multiplying U_{bridge} with A_{om} gives the contribution conductance of the thermal bridges as seen in equation 9.

$$U_m = \frac{\left(\sum_{i=1}^{n} U_i A_i + \sum_{i=1}^{n} U_{bridge} A_{om}\right)}{A_{om}} \qquad [W/m^2K] \qquad (9)$$

4.8.13 Estimation of available solar energy

Using a simple estimation of roof area, simulating the incoming irradiation to the roof areas as in Figure 4.33, and assuming that the solar panels can make use of 10-20% of the total incident solar radiation per year (Lund University; LU Innovation System; Applied Geomatics International, 2019), will provide a first indication of the available solar energy accumulated over a year. The reader should bear in mind that this is a very coarse indicator, and should not be used directly to reduce energy demand, because the hourly solar energy available must be compared to the hourly energy demand over a year. There are studies of solar energy storage in residential buildings (Brf Viva project in Gothenburg being one example), but it has not been implemented yet on a large scale. According to Solcellskollen.se, this is due to current economic disadvantages (Solcellskollen, 2019).

The purpose of estimating available solar energy is that the specific energy use may be reduced with the available solar energy when there is such a need, as stated in BBR 25 (The Swedish National Board of Housing Building and Planning, 2011). The irradiation per gridpoint [W/m^2] of the roof is calculated according to Figure 4.33.

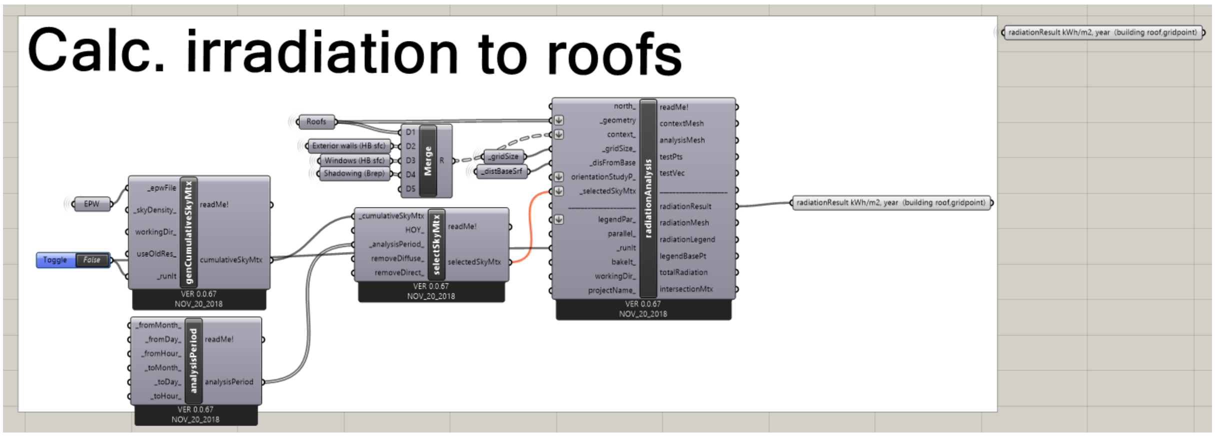


Figure 4.33 Calculation of incoming irradiation to roofs.

4.8.14 Floor space index

The floor space index (FSI) is a simple indication of the economy of the project that might be regulated in the detailed development plan. It is calculated according to equation 10 (Boverket, 2011):

$$FSI = \frac{BTA}{A_{site}} \qquad [-] \qquad (10)$$

Where,

BTA is the building gross total area [m^2], defined in (Eringstam & Sandahl, 2018)
A_{site} is the area of the site [m^2]

Figure 4.34 illustrates a building site outline marked by a purple line, and the BTA, which is the building gross total area. As visible in the illustration, a building with multiple floors will have a higher FSI than a single-floor building.

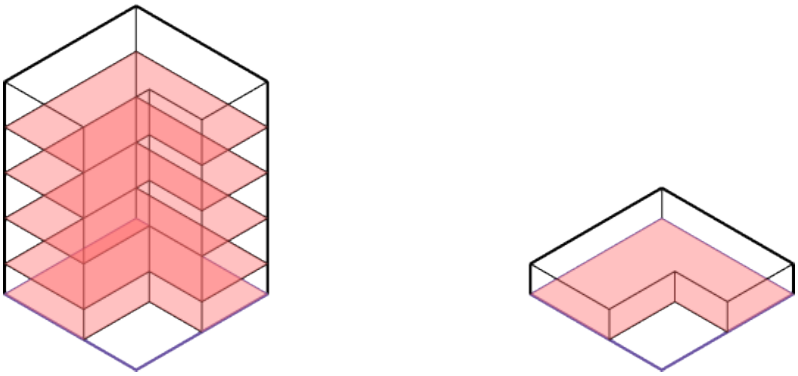


Figure 4.34 Illustration of the floor space index of two buildings.

4.8.15 Shape coefficient

The building shape coefficient (SC) is a geometric indicator that is assumed to have a correlation to energy demand. The parameters of the indicator are areas, more specifically the encapsulating area A_{om} and the heated floor area A_{temp}. A high shape coefficient indicates that there is a lot of envelope area causing transmission losses to the ambience. It is important to note that the shape coefficient has a large effect on the building layout, indicating that square block buildings are optimal (Energilyftet, 2019). It is calculated according to equation 11:

$$SC = \frac{A_{om}}{A_{temp}} \; [-] \tag{11}$$

Where,
A_{om} is the enclosing area of the building volume [m^2]

Figure 4.35 illustrates the parts of the shape coefficient, A_{om} and A_{temp}.

Figure 4.35 Illustration of the shape coefficient parts; A_{om} (left) and A_{temp} (right)

5 Case Study

The case study aims to test the proposed tool on a housing project at Gibraltarvallen, Gothenburg. It presents the project requirements, which are stated by the competition brief, and then presents the intentions and results of analysis stages that are adapted from the Interdisciplinary Design Method. It is the result of the collaboration between Ona Forss and the author, Linda Wäppling.

5.1 Project competition brief

A land allocation agreement competition for building housing at Gibraltarvallen, Johanneberg, has been announced by the municipality of Gothenburg during 2017. The site is shown in Figure 5.1. The thesis building design is benchmarked to the project competition brief, and here follows a summary of the most relevant facts for the thesis, which is seen in full version in "Trähusbebyggelse vid Gibraltarvallen - Tävlingsprogram" (Fastighetskontoret Göteborgs Stad, 2016). The detailed development plan allows for 14000 m^2 BTA. It also states that there will be public premises in the bottom floor of the façade towards the street, see Figure 5.2.

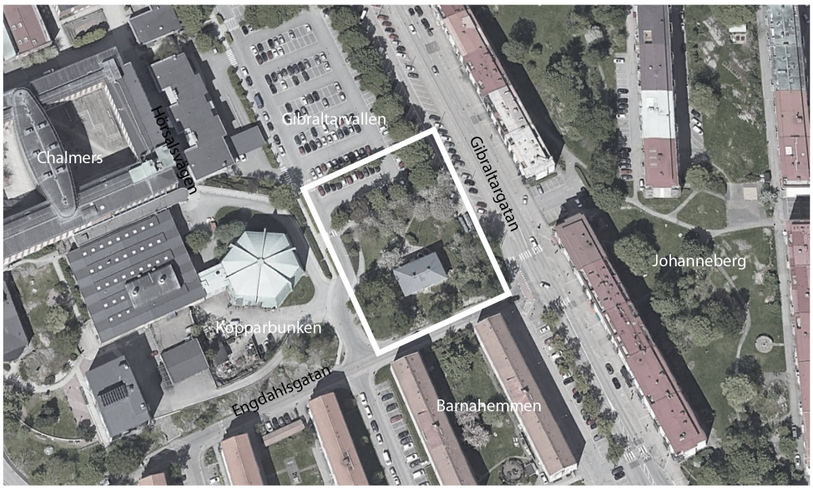


Figure 5.1 Site of the project and contextual relations.

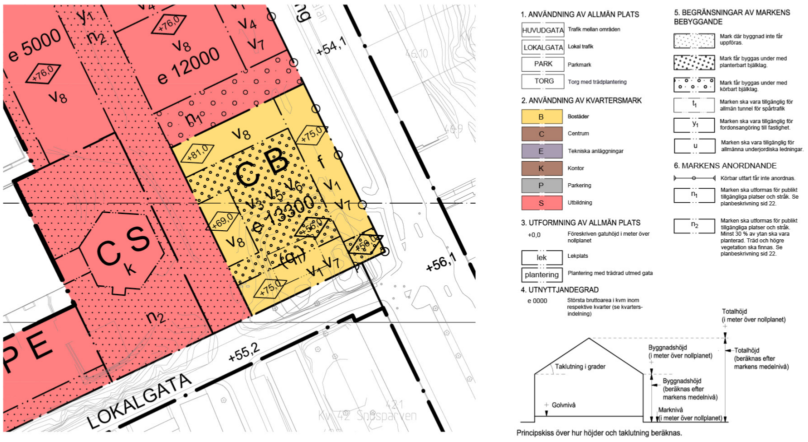


Figure 5.2 Detailed development plan.

The municipality of Gothenburg is explicitly stating that the project aims to provide qualitative, energy efficient and innovative housing. It is made clear that construction wood will be used for the structure, furthermore wood is intended to be the main material and it aims to inspire the use of wood generally in the building industry.

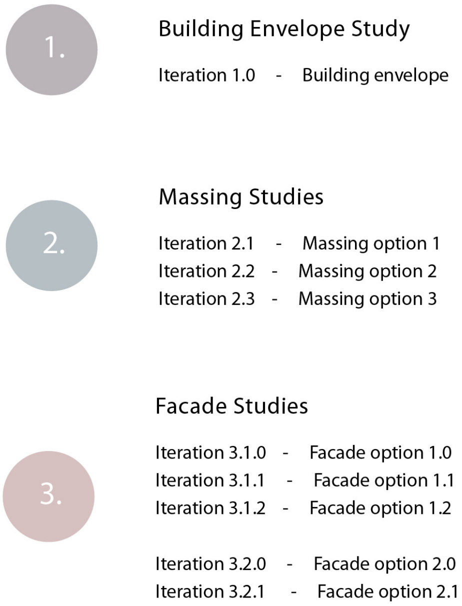
It is emphasised for the building to be energy efficient and maintain a good indoor environment. Furthermore, a demand in the competition is for the design to follow a local sustainability program "Göteborgs stads program för miljöanpassat byggande" (Fastighetskontoret Göteborgs Stad, 2017). In the scope of the program, relevant indicators for the case study to benchmark is E1.

- E1: Nettoenergibehov, Energy demand (Sveby), 60 kWh/m2 Atemp / år

Generally, the competition brief focus on innovative sustainable energy, material and holistic system solutions, and on the individual's opportunities to live more ecologically sustainable. Ecological sustainability, which is weighted 40% of the total competition score, involves energy efficiency of the envelope and technical systems, among others. It is stated that integrated energy design is beneficial to win the competition.

5.2 Iteration setup

The analysis stages that were chosen for the case study were 1. Building Envelope Study, 2. Massing Study and 3. Façade Study. The amount of iterations were discussed with Ona Forss and decided according to Figure 5.3. The buildings are numbered according to Figure 5.4.



Building Envelope Study

Iteration 1.0 - Building envelope

Massing Studies

Iteration 2.1 - Massing option 1
Iteration 2.2 - Massing option 2
Iteration 2.3 - Massing option 3

Facade Studies

Iteration 3.1.0 - Facade option 1.0
Iteration 3.1.1 - Facade option 1.1
Iteration 3.1.2 - Facade option 1.2

Iteration 3.2.0 - Facade option 2.0
Iteration 3.2.1 - Facade option 2.1

Figure 5.3 Chosen studies and iteration numbering. Courtesy of Ona Forss.

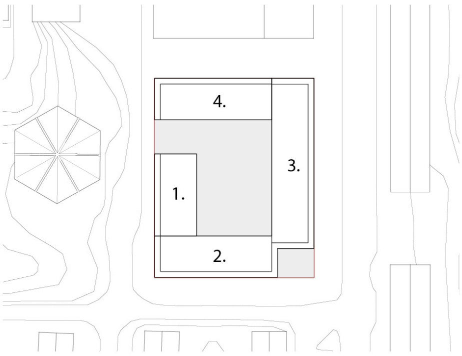


Figure 5.4 Building numbering. Courtesy of Ona Forss

The result mesh legends are set from the demands in each indicator with a safety margin of 20 %. The demands can be altered to fit the user's needs, however for this case study they are set as shown in Table 5.3.

Table 5.3 Summary of mesh legend threshold values.

Indicator [unit]	Demand/recommendation	Red (-20 %)	Green (+20 %)
Daylight Factor [%]	1 (According to BBR)	0.8	1.2
Sunlight Hours [h]	(According to SS-EN ISO 17037:2018)	1.5*	4.0*
Solar Heat Load [W/m²]	18	14.4	21.6
View [%]	25	20	30

*Sunlight hours do not include a safety margin but use the SS-EN ISO 17037:2018 recommendations for minimum, medium and high amount of sunlight hours.

5.3 Building envelope study

The building envelope study was made according to the proposed methodology in Section 4.3.2, with one thermal zone for each building and one for the garage. The purpose was to get an indication of critical parts of the building project with regard to the chosen indicators.

The geometrical level of detail does not include floor levels. However, it is required for calculating total floor areas in the current iteration step. As the area is important for instance when determining specific energy demand, it was necessary to make a good enough estimation already at this stage. The estimation of floor area was based on the following assumptions: a thickness of external walls depending on the U-value of the wall and a ceiling centre height of 3.5m, which indicated the number of floors.

A first meeting with the architect resulted in the ambition of building with CLT modules.

5.3.1 Building design and input data

The geometry input was the geometrical boundaries described in the detailed development plan, as Figure 5.5 illustrate.

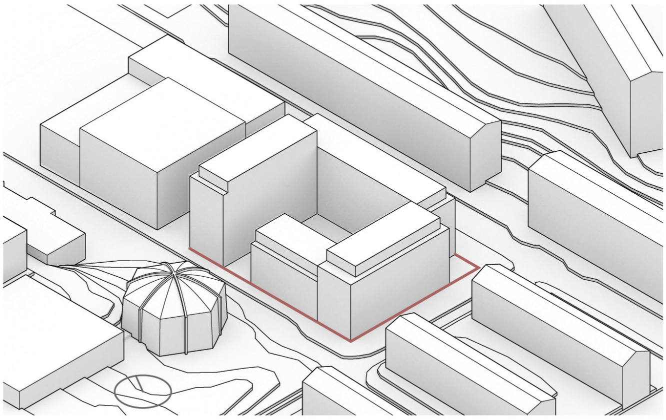


Figure 5.5 Geometry input of building envelope, illustration courtesy of Ona Forss.

Envelope wall
A CLT wall construction was assumed for the case study as a result of the first meeting with the architect. Appendix H describes the chosen construction of the wall, which defines both the architectural appearance of the building and some of the input data for calculations. Specifically, it determines wall thickness for different U-values of the wall, and the thermal capacity which is approximated as a lightweight structure because of the choice of wood.

Input data and other assumptions
The input data for BeDOT are: U-values, thermal bridges, heat capacity, g-values, solar shading, air flow rates, set points and more are stated in Appendix E. When simulating DF, the room depth was chosen at 5m and at 7m, to investigate deep and shallow apartment types.

As this study LOD has no information on window size and placement, simply a window/wall ratio was assumed after the architect's recommendation. Assumed window/wall ratio was 30 % on all buildings and facades. Furthermore, the floor height was also approximated by the architect as 3.5 m center-to center, with a 0.3 m thick slab.

For calculation of EP_{pet}, assumptions were made based on Sveby "Brukarindata för bostäder" according to Table 5.4 (Sveby, 2012).

Table 5.4 Sveby recommended values for energy assessment.

Parameter [unit]	**Value**	**Comment**
Geographic adjustment factor for E_{heat} [-]	0.9	Gothenburg
Tap water [kWh/m2]	25	PE_{factor} = 1
Real estate electricity demand [kWh/m2]	15	PE_{factor} = 1.6. Consist of electricity for pumps, fans, real estate operation and light, rainwater pipe heating,
Airing, E_{air} [kWh/m2]	4	Added to E_{heat}

5.3.2 Simulation and analysis results

The mesh results for Building envelope study are presented in Figure 5.6.

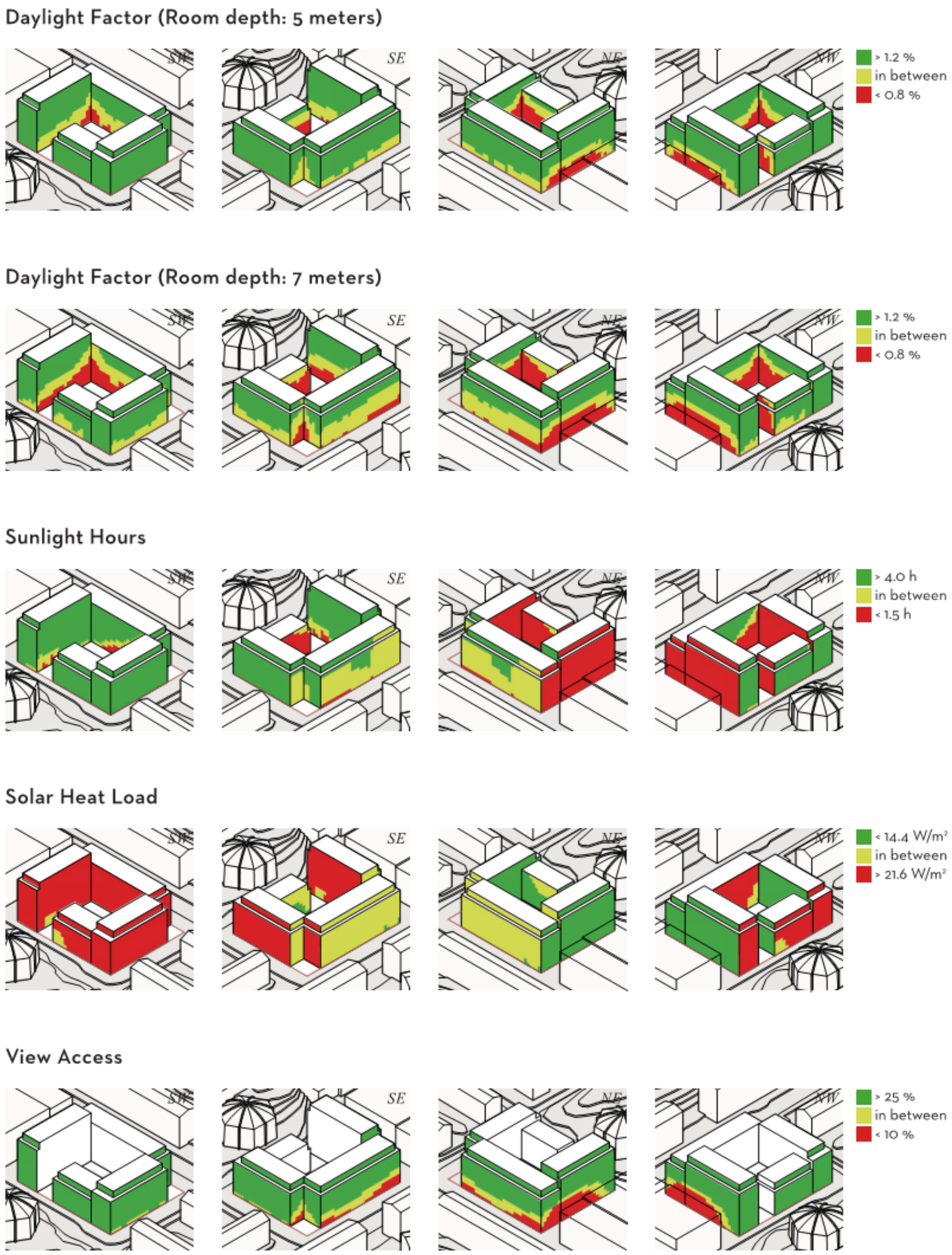


Figure 5.6 Mesh results for Building envelope study.

Daylight Factor
The results show where demands for daylight factor (DF) are achievable with safety margin (green), within the safety margin (yellow) and areas with bad conditions (red).

Connecting the results to the geometry, it shows that bad conditions for DF exist at places where there is high building density, i.e. on the lower parts of the façade, within courtyard corners and at locations where the building is close to other buildings.

Sunlight hours

The north facades do not get sufficient amounts of sunlight hours. The surrounding buildings along Gibraltargatan decrease the amount on the eastern façade. Also the building itself cast shadows on the courtyard facades which therefore get insuffiecent amount of sunlight hours.

Solar heat load

The facades turned toward the west have, not surprisingly, the largest solar heat load. There is a lot of red and yellow areas, indicating that the solar heat load is too large on many parts of the façade compared to the demand.

View

The southeast corner of the geometry is cut-out which leaves the view from the façade lower than on other parts. Also, the north façade view is obstructed by the opposite building.

Energy demand

The energy demand was calculated as EP_{pet} to 73.7 kWh/m2, year. E_{heat} is the only part of the energy demand that may be altered and on the current study the result for E_{heat} is 18.7 kWh/m2, year.

5.3.3 Sensitivity analysis

A sensitivity analysis was made on some of the input data with the assumed largest influence on E_{heat} and plotted in a parallel coordinates plot, see Figure 5.7. For an enhancement of figure size, see Appendix G. The input parameters that was iterated is shown in Table 5.5. A total of 108 iterations were made based on all possible combinations below.

Table 5.5 Indata for the sensitivity analysis.

U_{wall} [W/m^{2}K]	U_{window} [W/m^{2}K]	g_{window} [-]	Window/wall ratio [%]
0.24	1.00	0.75	50
0.20	0.90	0.50	40
0.16	0.80	0.25	30
			20

U_{wall} and U_{window}

It is evident from Figure 5.8 that these input parameters affect energy demand in terms of heating and (to some extent) cooling because of transmission losses.

g_{window}

The g-value affect the amount of energy transmitted from the solar radiation outside through the windows. It also affects the daylight factor because of the correlation between LT and g-value. A low g-value means a window that lets through a small amount of energy that will become solar gains.

Window/wall ratio

It can be seen from the results that this parameter affects both DF results and energy demand with regard to cooling and heating.

Resulting indicators

The resulting indicators were EP_{pet} [kWh/m^2], E_{heat} [kWh/m^2], cooling demand [kWh/m^2], A_{temp} [m^2], U_{mean} [W/m^{2}K] and the calculated amount of areas (%) that are red or yellow, split between the bottom floor and the upper floors.

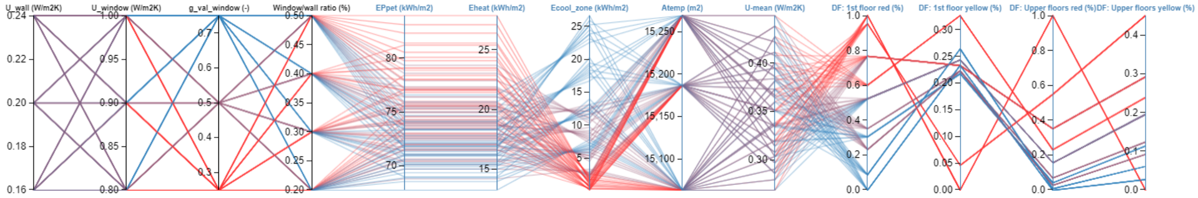


Figure 5.7 Parallel coordinates plot.

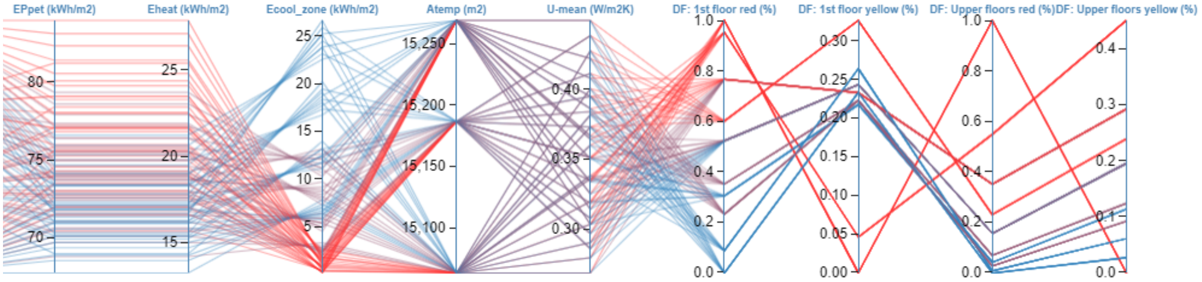


Figure 5.8 Zoom-in on the resulting indicators.

EP_{pet}

This indicator is relevant because that it is demanded by regulations.

E_{heat}

The Figure 5.8 confirms that E_{heat} is the only energy factor in this study that affects the total EP_{pet}. The other part of EP_{pet} consist of standard constant values added as recommendations.

Cooling demand

As this study only cover the housing part of this project, it is not included in the energy demand, but it is chosen as an indicator for overheating, and therefore it is included. The alternatives with a high cooling demand have varying U-values but a high window/wall ratio in combination with a high g-value of windows. The g-value seems to be the dominating parameter for cooling demand.

A_{temp}

The heated area changes as the U-value of the wall changes, because a variety of U-values must mean a variety of wall configurations, and furthermore wall depths. The wall depth has an influence on this indicator and is therefore included in the sensitivity analysis. Figure 5.8 shows that around 150m2 are lost in the total housing project due to thicker walls because of lower U-value.

U_{mean}

Is included because it is a demand by regulations. Most of the alternatives have a sufficient U_{mean}.

Daylight factor

The sensitivity study calculated DF in rooms at 5m, with the first daylight factor calculation method. The results show that the bottom floor in general has a lower DF than the upper floors. This indicates that the bottom floor may be used to other purposes than housing, e.g. laundry room, storage rooms or commercial premises.

How the indicators and input data correlate

- A low U-value results in decrease of A_{temp}, a high U-value increase A_{temp}
- A low g-value decrease the cooling demand, indicating a higher thermal comfort
- Low window/wall ratio decrease the DF and a high one increases DF
- It is preferred to use lower U-values on windows and relatively high U-values on walls to optimise the energy demand. Windows have a larger effect on transmission losses but of course the window/wall ratio multiplies the effect. This means economical optimisation is possible in terms of a maximal A_{temp}. The area is made larger when using thinner walls (higher U-value). The mean U-value is also increased with this configuration. However, it makes no difference in cooling demand.
- High window/wall ratio is affecting energy demand, i.e. the space heating and cooling as well as U_{mean} by increasing them. It is of interest to keep all as low as possible.

5.3.4 Conclusions from building envelope analysis

It was concluded that the building volumes needs modifications to achieve a satisfying DF. It might not be possible to build on the whole intended plot because of insufficient DF. Apartments that have two opposite external walls may be a solution. Furthermore, splitting up the building volumes in the corners, decreasing the building depth or lowering the height of the buildings may increase DF.

In conclusion, there is in general a sufficient amount of sunlight hours, and the distribution over the facades may indicate where to place windows and balconies.

The red and yellow areas of the solar heat load indicate that there might be problems with overheating because there is no cooling system for traditional housing in Sweden. However, the demand for solar heat load was set according to Miljöbyggnad Guld, meaning that the demand was high from the start.

The north façade and outer environment require thoughtful planning in order to weigh the limited access to desired views.

A sensitivity analysis shows that influence of room geometry, window placement, form and wall thickness play a more important role for DF, however it is not information that exists at this early stage.

Ona Forss considered the building envelope study to provide informative indications for where there might be issues with the given building site with regard to the chosen indicators, and the insights were used for designing the following massing studies.

5.4 Massing study 1

The second iteration is a first massing draft from the architect, based on the insight from the building envelope study.

5.4.1 Building design and input data

Ona Forss highlight that building 3 is a separate volume, detached from the corners connecting to the other buildings, enabling more daylight to enter through the openings. The stepping shapes are intended to function also as terraces to the apartments, see Figure 5.9 and Figure 5.10.

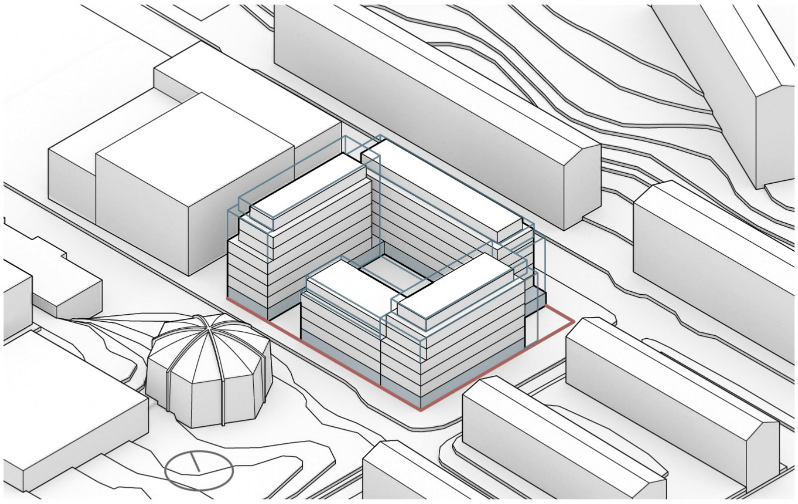


Figure 5.9 Geometry input of massing 1, illustration courtesy of Ona Forss.

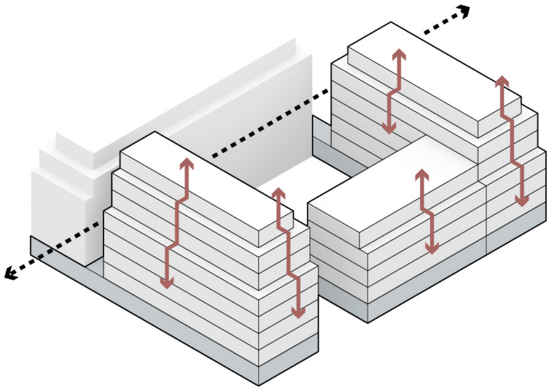


Figure 5.10 Architectural diagram of massing 1, illustration courtesy of Ona Forss.

The input data to BeDOT is presented in Appendix F.

5.4.2 Simulation and analysis results

The mesh results for massing study 1 are presented in Figure 5.11.

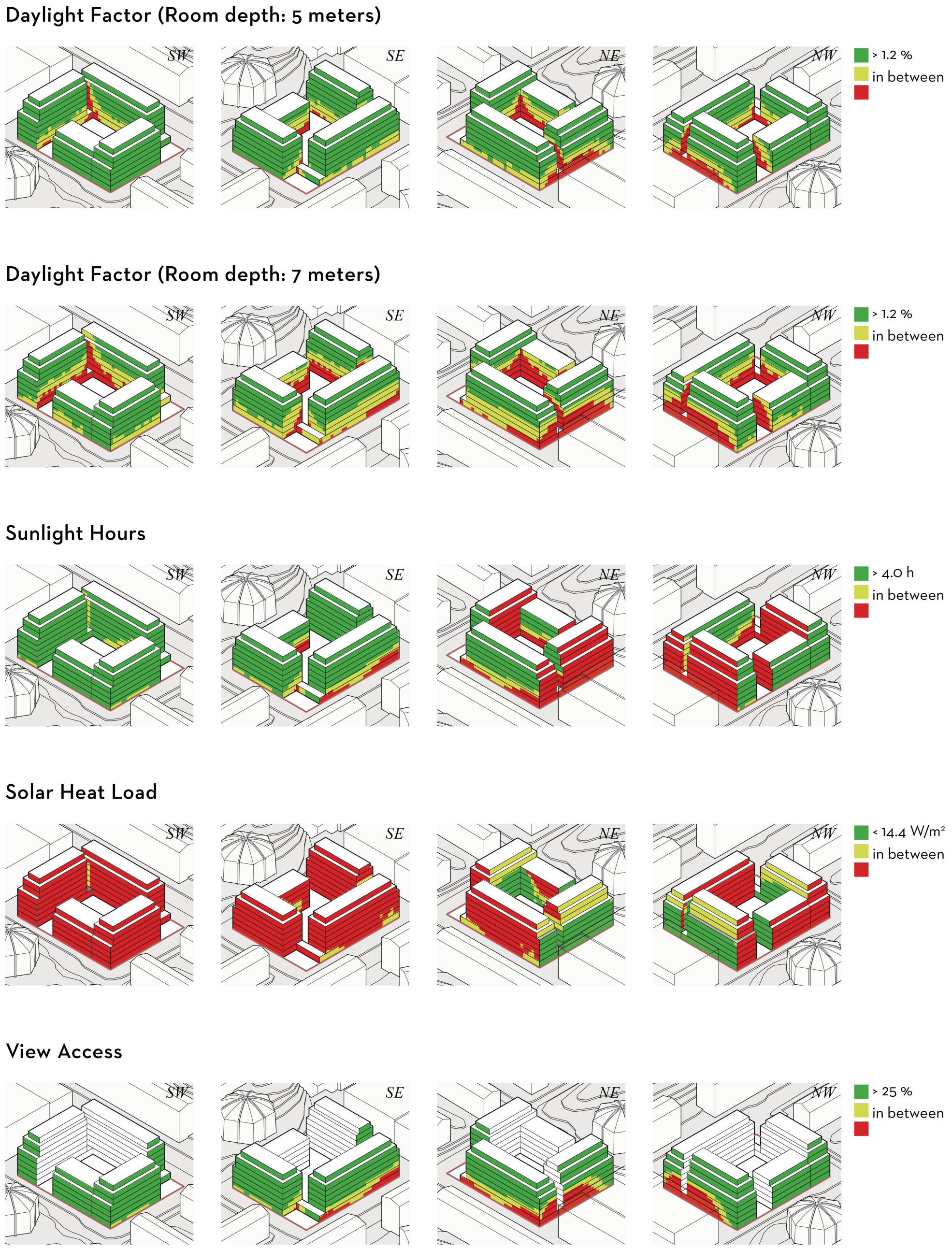


Figure 5.11 Mesh results massing 1.

Daylight factor

Massing 1 prove to have more daylight access than the building envelope study, as a result of the partitioning of buildings. However, the stepping did not have the intended effect on DF, possibly because the spaces with insufficient DF were at the ground level. The most critical area for daylight factor is between building 3 and building 4, see Figure 5.4. Daylight factor 7m indicates DF in deep apartments at 7 m room depth.

Sunlight hours
The stepping of the building results in more sunlight let past to the courtyard, as it is not shading itself. The amount of sunlight hours is improved because of the openings between buildings.

Solar heat load
Results indicate a too high value on solar heat load.

View
View from the building is slightly better in massing 1 than in building envelope, meaning that the massing provides equal or better views in the south-east corner of the building site.

5.5 Massing study 2

The intention with massing 2 was to increase daylight access by fragmenting the building in more vertical partitions. The partitions provide a more aesthetical street view according to Ona Forss. The intention is also to investigate solar heat load, sunlight hours and view results as a result from the vertical partitioning.

5.5.1 Building design and input data

Figure 5.12 and Figure 5.13 illustrate the geometrical input of massing 2.

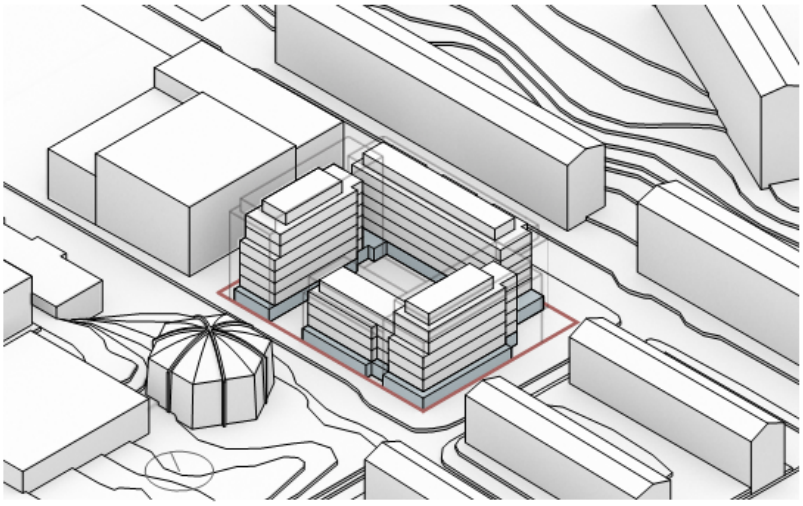


Figure 5.12 Geometry input of massing 2, illustration courtesy of Ona Forss.

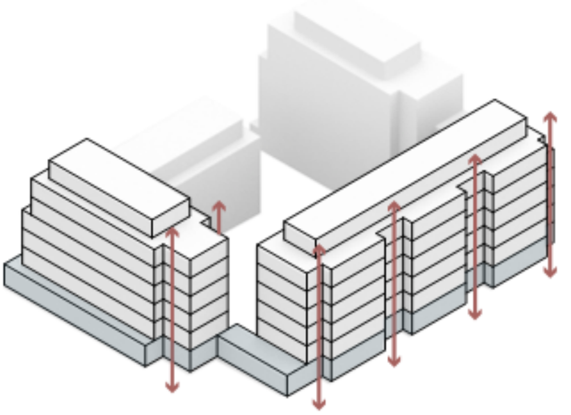
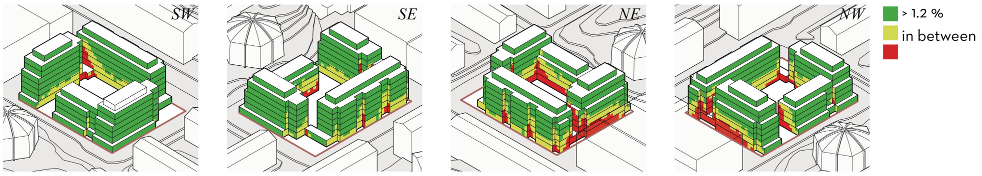


Figure 5.13 Architectural diagram of massing 2, illustration courtesy of Ona Forss.

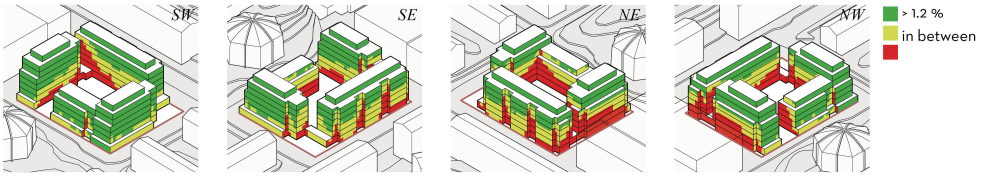
5.5.2 Simulation and analysis results

The mesh results for Massing study 2 are presented in Figure 5.14.

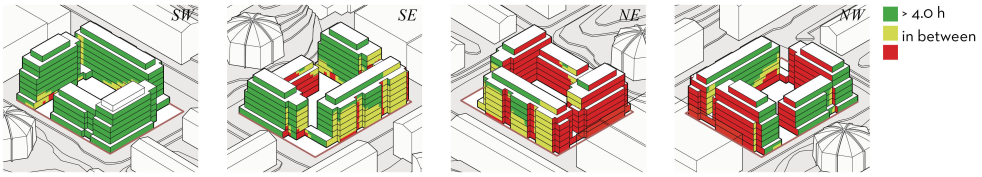
Daylight Factor (Room depth: 5 meters)



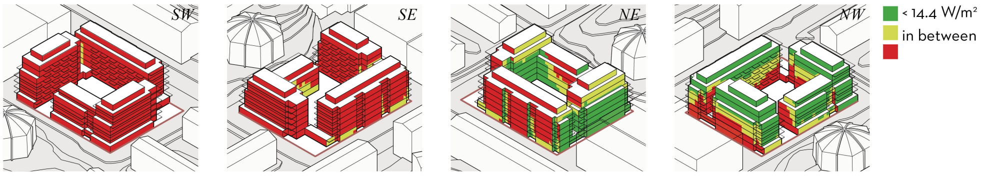
Daylight Factor (Room depth: 7 meters)



Sunlight Hours



Solar Heat Load



View Access

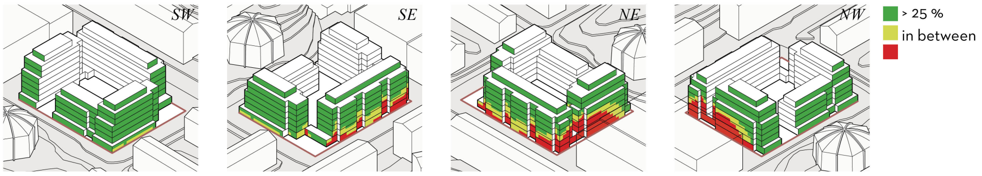


Figure 5.14 *Mesh results massing 2.*

Daylight factor
The vertical partitioning decreases the DF. The building shadow itself.

Sunlight hours
The access to sunlight hours is decreased by the vertical partitioning.

Solar heat load
The solar heat load is very high on the east, south and west facades.

View
The eastern façade view access is decreased by the current definition of view.

5.6 Massing study 3

A third massing option was analysed. The intention was to provide opportunities for terraces and views to multiple directions from each apartment. The concave niches provide privacy according to Ona Forss. The geometry consists of more vertical partitioning and niches in the façade.

5.6.1 Building design and input data

Massing 3 geometrical data is presented in Figure 5.15 and Figure 5.16.

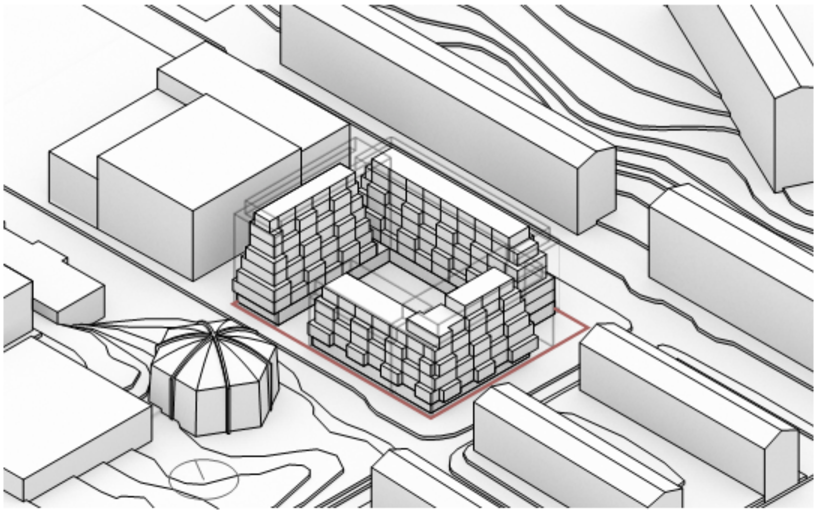


Figure 5.15 Geometry input of massing 3, illustration courtesy of Ona Forss.

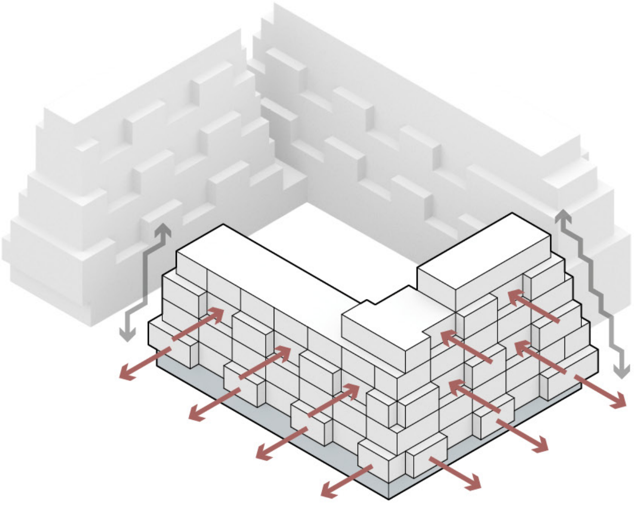


Figure 5.16 Architectural diagram of massing 3, illustration courtesy of Ona Forss.

5.6.2 Simulation and analysis results

Figure 5.17 illustrates the mesh results from massing 3.

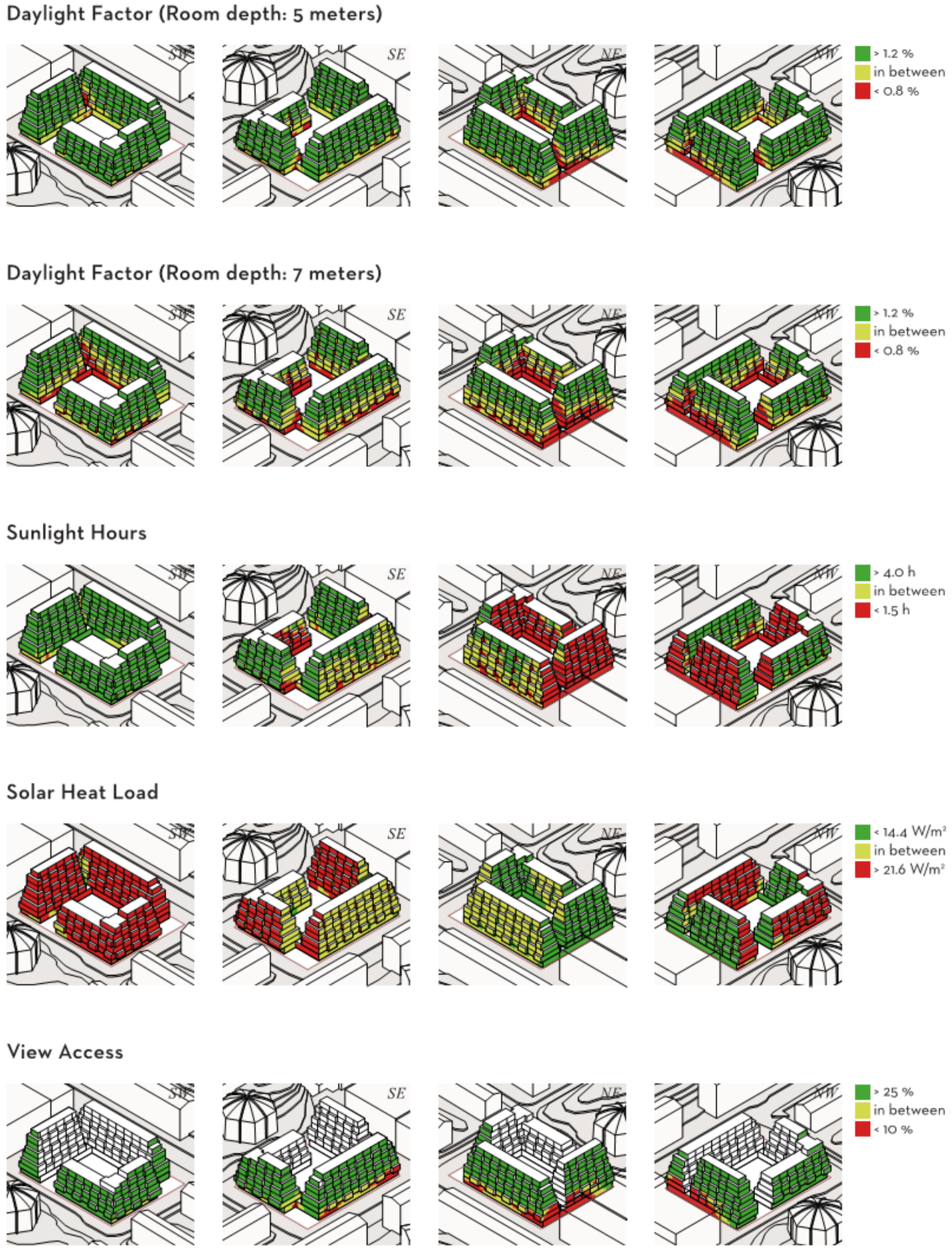


Figure 5.17 Mesh results massing 3.

Daylight
Daylight factor results are improving with the even more fragmented building volume.

Sunlight hours
The sunlight hours results are in general same as previous massing, with the exception that there are now more niches not getting enough direct sunlight.

Solar heat load
The solar heat load results show that south and west facades have too high values.

View
The view from the building is in general good and needs care in the areas near other buildings.

5.7 Massing studies numerical indicators

Table 5.6 summarise the numerical results of the three massings.

Table 5.6 Numerical indicator result summary.

Building 1	Massing 1	Massing 2	Massing 3
EP_{pet} [kWh/m^2]	87.3	93.5	99.1
E_{heat} [kWh/m^2]	30.8	36.5	41.5
E_{cool} [kWh/m^2]	6.1	6.3	5.0
E_{sol} [kWh/m^2 roof]	128.9	128.9	134.6
U_{mean} [W/m^{2}K]	0.332	0.332	0.340
A_{temp} [m^2]	1911.4	1542.5	1546.0
A_{om} [m^2]	2470.1	2259.0	2438.9
SC [-]	1.29	1.46	1.57
Mean Solar Heat Load [W/m^2]	18.4	25.4	43.9

Building 2	Massing 1	Massing 2	Massing 3
EP_{pet} [kWh/m^2]	86.3	88.6	94.0
E_{heat} [kWh/m^2]	30.0	32.1	36.9
E_{cool} [kWh/m^2]	7.4	7.1	6.3
E_{sol} [kWh/m^2 roof]	196.7	196.7	196.7
U_{mean} [W/m^{2}K]	0.365	0.353	0.352
A_{temp} [m^2]	3317.4	2538.1	2274.8
A_{om} [m^2]	4042.8	3383.5	3407.7
SC [-]	1.22	1.33	1.50
Mean Solar Heat Load [W/m^2]	30.7	29.6	58.0

Building 3	Massing 1	Massing 2	Massing 3
EP_{pet} [kWh/m^2]	84.4	88.3	94.6
E_{heat} [kWh/m^2]	28.2	31.8	37.4
E_{cool} [kWh/m^2]	6.9	6.6	6.3
E_{sol} [kWh/m^2 roof]	192.4	196.1	196.1
U_{mean} [W/m^{2}K]	0.360	0.364	0.363
A_{temp} [m^2]	4503.0	4068.9	4215.8
A_{om} [m^2]	5419.2	4927.3	5184.5
SC [-]	1.20	1.21	1.23
Mean Solar Heat Load [W/m^2]	29.3	43.3	58.4

Building 4	Massing 1	Massing 2	Massing 3
EP_{pet} [kWh/m^2]	85.8	89.1	100.2
E_{heat} [kWh/m^2]	29.6	32.5	42.5
E_{cool} [kWh/m^2]	7.7	7.1	6.4
E_{sol} [kWh/m^2 roof]	196.7	196.7	196.7
U_{mean} [W/m^{2}K]	0.367	0.362	0.366
A_{temp} [m^2]	3691.1	3155.9	2666.2
A_{om} [m^2]	4563.0	3797.5	3839.0
SC [-]	1.24	1.20	1.44
Mean Solar Heat Load [W/m^2]	30.6	32.1	56.4

All buildings	Massing 1	Massing 2	Massing 3
BTA [m^2]	14 426	12 183	11 286
A_{site} [m^2]	2448.4	2448.4	2448.4
FSI [-]	5.9	5.0	4.6

5.8 Summary and conclusions from massing studies

Regarding daylight, the different massing options did not provide the intended answers for what massing provide the best daylight factor. More shallow buildings obviously result in increase of DF, but the trade-off is the floor area, which is used for terraces instead. The floor area could have been sold or rented instead, which probably is important for the property owner. Possibly a study for daylight access on the courtyard could have given more information on the performance of the three massing options.

Likewise, the sunlight hours in general do not provide the intended answers; to indicate the massing option with the best access to sunlight hours. Although, the sunlight hours were affected in a positive sense by the apertures between the buildings compared to the building envelope geometry. A conclusion from the massing is that the sunlight hours are mainly an indication of the access to sun in the site with the given contextual shadowing buildings. A difference in the massing does not provide satisfyingly diverse results to help choose between different massing options, according to Ona Forss.

Results for solar heat load are difficult to compare because they seem inconsistent with the results from building envelope. It can be seen in the solar heat load mesh in massing 3 that the results are again more similar to building envelope study than the previous massing studies. The calculations have been run again and a possible source for the error is rounding error. Furthermore, as it has been stated, the solar heat load demand is set very low, according to Miljöbyggnad Guld, meaning there is room for altering the threshold value for this indicator.

Furthermore, the solar heat load does not differ much between massings, although the partitioning makes the building is shading itself and thus decreases the solar heat load in the vertical partitioning. The results, however, do indicate where there might be a need of shading the façade, perhaps with balconies.

Even though the view is decreased due to the vertical partitions are there aesthetical benefits with them according to Ona Forss. This means there are aspects that the architect value that are not covered by this calculation tool.

In the tables of Section 5.7 numerical indicators are aggregated per building for the housing zones. A trend is that EP_{pet} increase as E_{heat} increase for each massing option. This is a result of the increased building envelope area. Although the thermal bridge calculations are simplified, one may assume that in reality, the effects from those change with each massing option. This is however omitted from the study. E_{cool} indicate the thermal comfort of a building, showing that most buildings decrease the cooling demand in the zones for each massing option, where massing 3 has the lowest cooling demand and thus the best opportunity for thermal comfort.

E_{sol} indicate that there is solar energy access on all the building roofs, however the solar energy is not a constant source and varies vastly for each hour. A more detailed analysis of solar energy access in combination with the hourly energy demand will give a better indication of the possibility to harvest the energy on the rooftops.

Indications of A_{temp} facilitate the understanding of the economy of the project on a simplified level. The mean solar heat load is also aggregated per building and increase with each massing option. A trend is that shape coefficient (SC) increase per massing iteration, meaning that envelope area increases in relation to the floor area. The floor space index (FSI) decrease per massing iteration.

In summary, the methodology provided clear indications on building performance with regard to the given indicators. However, none of the mesh results managed to provide a sufficient decision basis for how to change the massing options to achieve the best building performance. There were also aspects, e.g. aesthetical, that was not taken into account as a quantifiable indicator.

One aspect that was made clear from the massing study were the conditions outside the façade. That could facilitate the decision making of how to layout the floor plan, e.g. if the façade indicate a high daylight factor on one side of the building and a low on the other, there might be a need of having a façade-to-façade apartment with access to both the facades.

Furthermore, the methodology gave insight in that the detailed development plan governs a lot of the project geometrical constraints, and deviating too much from it would decrease economical aspects of the projects.

5.9 Façade study 1

Moving forward to the façade study, massing 3 of building 3 is chosen for further analysis. Solar heat load on the facade will not be studied in the façade study.

5.9.1 Building design and input data

The intention with the different window and balcony configurations is optimisation of the façade design with regard to the chosen building performance indicators. One window placement and size with an overall 25 % window/wall ratio was tested in three versions: without balcony (1.0), with balcony (1.1) and with small balcony (1.2), see Figure 5.18. The balconies are 1.5 meters deep. The test rooms are 5m deep, 2.5 m wide and have a height of 3.2 m between floor to ceiling. There are two windows measuring 0.8 x 1.5 m. Surface recfletances are stated in Appendix D.

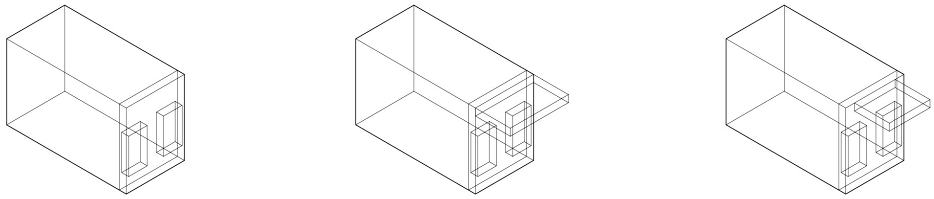


Figure 5.18 *Room configurations of façade study 1.0 (left) 1.1 (mid) and 1.2 (right).*

5.9.2 Simulation and analysis results

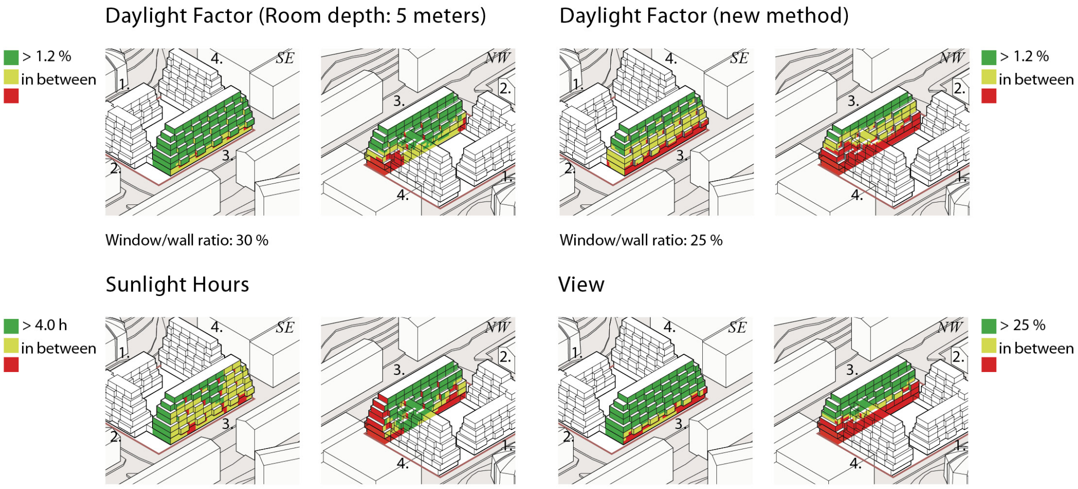


Figure 5.19 *Mesh results of façade option 1.0.*

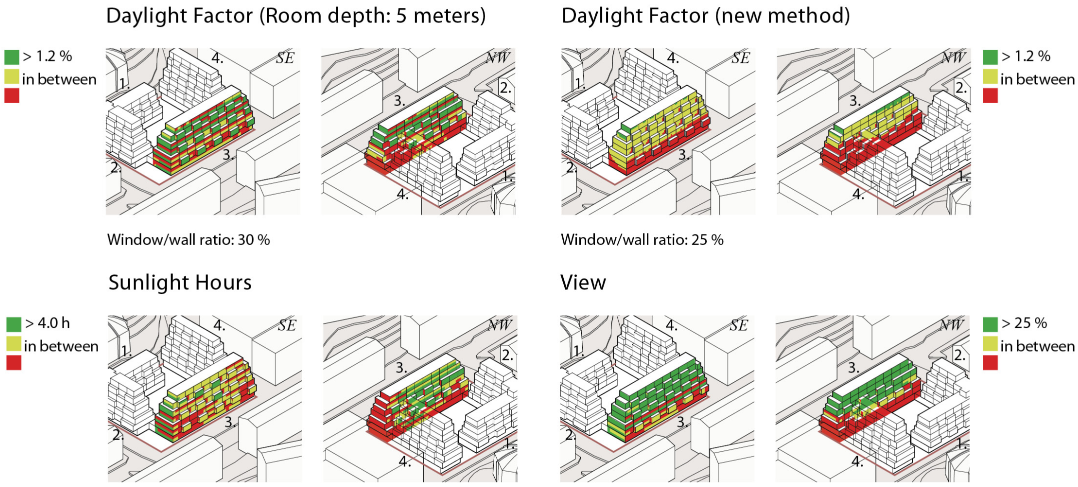


Figure 5.20 *Mesh results of façade option 1.1.*

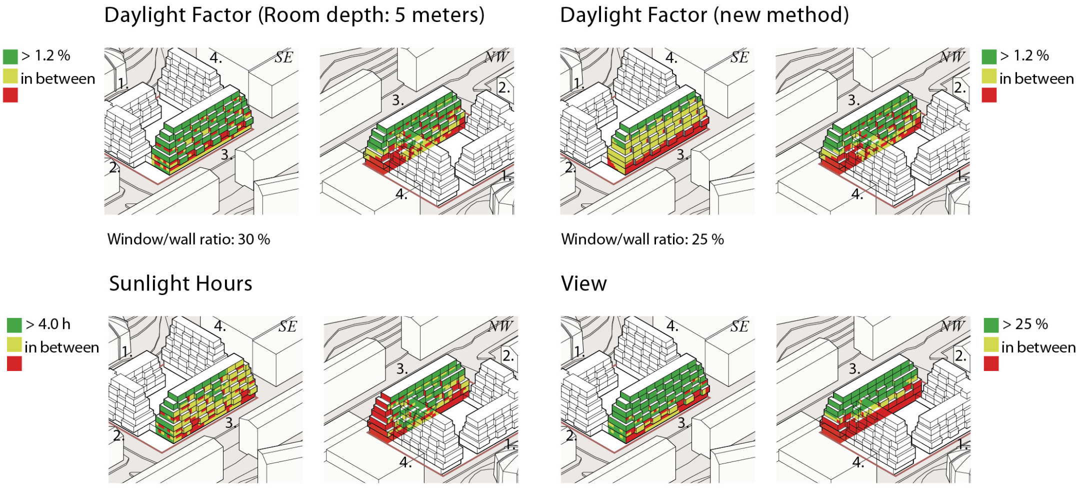


Figure 5.21 *Mesh results of façade option 1.2.*

Daylight Factor

Daylight factor was calculated first with the method that was used in the building envelope and the massing studies. Then daylight factor was calculated with the second method, using site-specific correlations.

It was clear that method 1 shows more optimistic results for DF than method 2. The balconies affected the DF to a large extent, where façade option 1.2 shows a higher total DF over the façade than 1.1.

Smaller balconies let through some daylight to the windows and therefore option 1.2 had a higher DF than 1.1. As expected, the option without a balcony provided the highest DF.

Sunlight hours

Adding balconies, some of the green parts of the façade fell within the safety margin and turns into yellow. The results were better on the north-west façade because of the evening sun. The morning sun was obscured by surrounding buildings and landscape.

View

The balconies do change the view from the façade, however to a small extent if the balconies are not too deep.

5.10 Façade study 2

Facade study 2 cover an alternative of façade design to make possible a comparative study between the window sizes and placements.

5.10.1 Building design and input data

Increasing the window wall ratio to 33%, a new window size and placement was tested in façade study 2. The alternatives were the same configurations as 1.0 and 1.1, thus without and with balcony. Figure 5.22 illustrates their differences. The room size is equal to façade study 1, and the two windows are 0.8 x 1.5 m. Surface recfletances are stated in Appendix D.

Figure 5.22 Configurations of façade 2.0 (left) and 2.1 (right).

5.10.2 Simulation and analysis results

The mesh results shown here are ultimately daylight factor, because the sunlight hours and the view results do not differ from façade study 1.

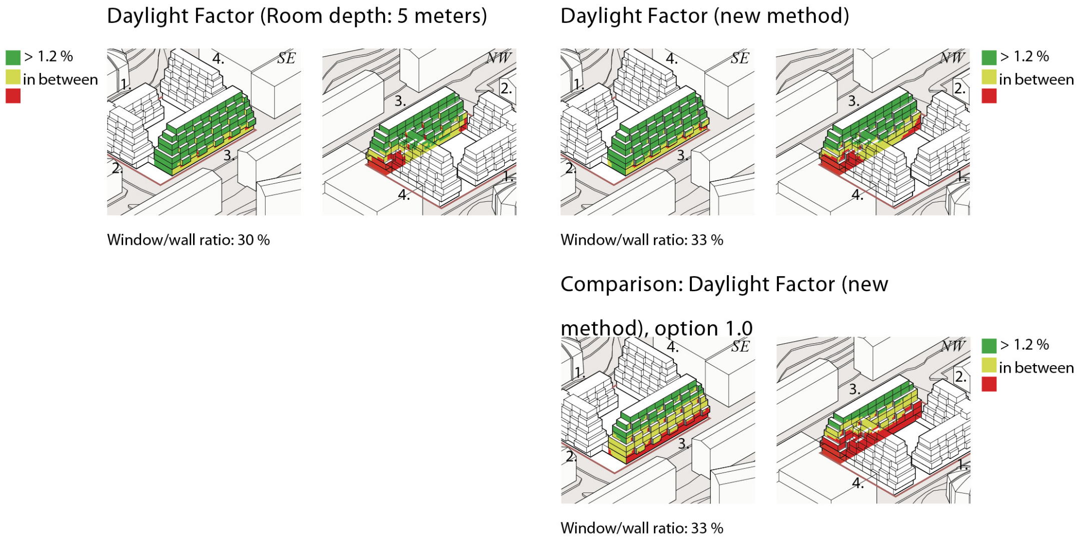
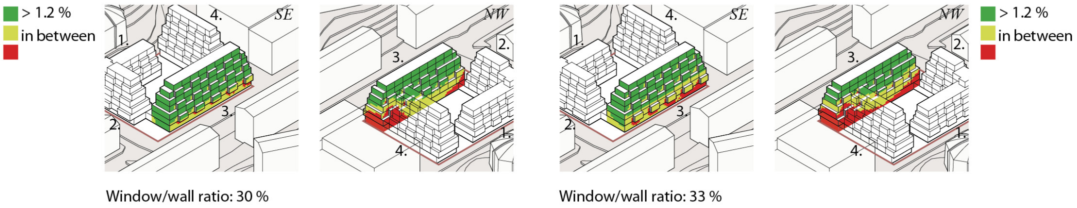


Figure 5.23 Mesh results of DF for façade option 2.0.

Daylight Factor (Room depth: 5 meters)

Daylight Factor (new method)



Comparison: Daylight Factor (new method), option 1.1

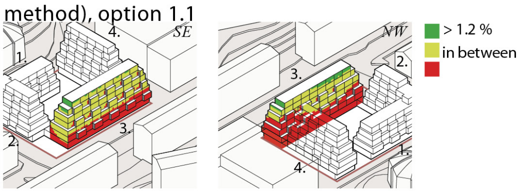


Figure 5.24 Mesh results of DF for façade option 2.1.

Daylight factor

As in façade study 1, method 1 showed more optimistic results than method 2. However, the large windows enable the building to achieve a sufficient DF in all areas except where it is close to connections to the neighbouring buildings. Comparing with façade option 1.0, as in Figure 5.23 and Figure 5.24, it is clear that façade options 2.0 and 2.1 result in higher DF for more parts of the building than façade option 1.0, which is the best option out of 1.0, 1.1 and 1.2.

5.11 Summary and conclusions from facade studies

Table 5.7 Results summary of numerical indicators for the façade study.

Building 3	1.0	1.1	1.2	2.0	2.1
EP_{pet} [kWh/m^2]	96.7	97.7	97.2	98.4	99.3
E_{heat} [kWh/m^2]	39.4	40.3	39.7	40.9	41.6
E_{cool} [kWh/m^2]	4.3	2.9	3.5	5.8	4.1
U_{mean} [W/m^{2}K]	0.379	0.379	0.379	0.401	0.402
A_{temp} [m^2]	3914.2	3914.2	3914.2	3914.2	3914.2
A_{temp} Housing [m^2]	2746.2	2746.2	2746.2	2746.2	2746.2
A_{temp} Lokal [m^2]	571.5	571.5	571.5	571.5	571.5
Mean Solar Heat Load [W/m^2]	59.7	59.9	59.7	71.7	71.6
PV mean per building roof	196.1	196.1	196.1	196.1	196.1

Numerical indicators

The second façade option has a larger energy demand than the first corresponding option, e.g. 2.0 has a larger EP_{pet} than 1.0. The values for E_{heat} share the same pattern.

It seems that the U_{mean} value is just over the demand on 0.4 [W/m^{2}K]. Mean solar heat load is higher at façade options 2.0 and 2.1 in comparison to 1.0-1.2. It is also indicated that there is solar energy access on the roof of building 3.

Conclusions
1.0, 1.1 and 1.2 provided insight about sunlight hours and view, and that it differs little between alternatives. With this analysis setup, the daylight factor varied sufficiently enough between the design alternatives for the users to make a quantitative comparison form the mesh visualisations.

The window/wall ratio differed from DF method 1 where the automated windows had a total of 30 % window/wall ratio in comparison with the 25 % of method 2, which should be known when comparing the methods.

The option that provided the best DF value was as expected without balconies. Ona Forss evaluated the balcony option 1.1 and 2.1 as the most visually appealing, to the contrary of the building performance results. Comparing the two in DF, 2.1 had the largest amount of area with sufficient DF. The difference between the DF methods might be because they share target demand, but as the methods are different they might actually be evaluated differently.

There are better sunlight hour conditions form the south and west, as there are obstructing buildings when the sun is low in the morning to the east.

View from façade did not provide the expected decision information basis and one suggestion is to develop the methodology to instead for the façade study use view from inside a fictive room. It can be solved by using the same component as before, but with a surface inside the room that describes standing or seated position of a person. And from that surface calculate the access to desired views.

5.12 Time requirement

The time elapsed for making BPS was measured during two of the iterations in the case study. The raw data is presented in Appendix K, and the results are visualised in tree charts where a larger area represent a larger amount of time requirement per component of the tool. Figure 5.25 show the results for Massing 3.3 and Figure 5.26 show the results for Façade study 2.0.

It is evident that the components 'Solar radiation per zone', 'SHL meshing' and 'runDaylightAnalysis' consume a lot of time compared to other components. Also 'View meshing' may require more time because of that the study needs to be run four times in all cardinal directions. However, the daylight factor and the sunlight hour calculation require only seconds. SHL meshing is used for simulation of the solar heat load indicator, and View meshing is used for simulation of view. The total time elapsed for the included components in the massing iteration was 57.2 minutes and for the façade study the respective elapsed time was 118.5 minutes.

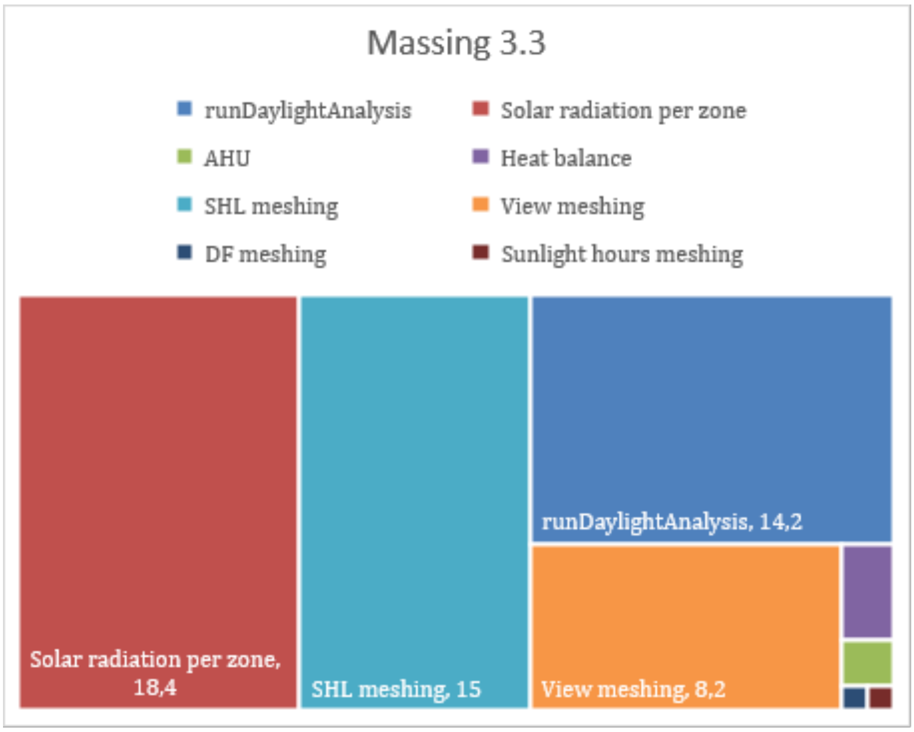


Figure 5.25 Tree chart of time requirement for Massing 3.3.

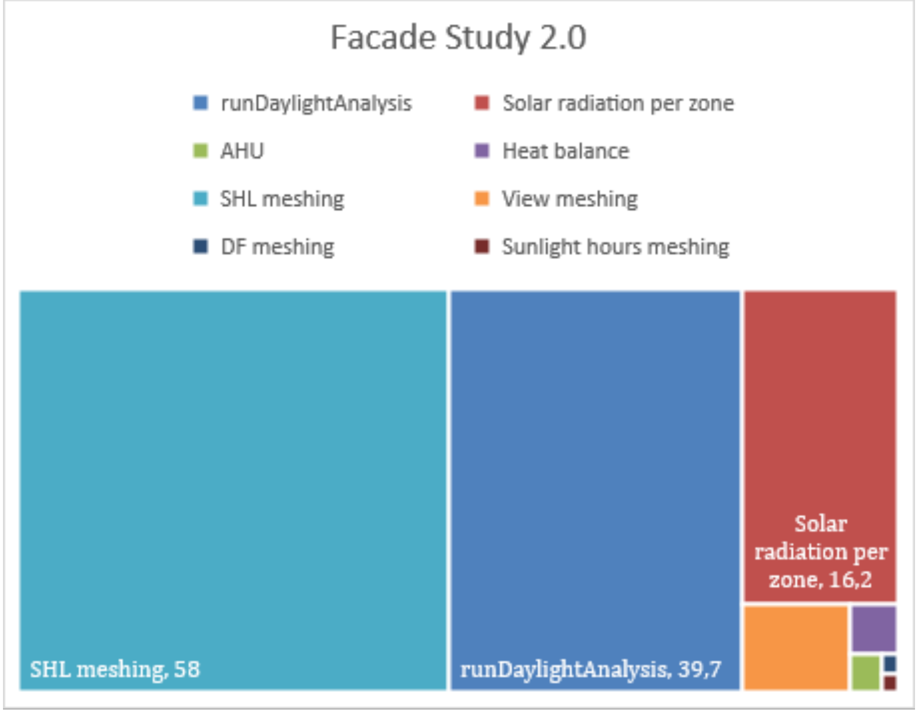


Figure 5.26 Tree chart of time requirement for Façade Study 2.0.

5.13 Qualitative evaluation of the methodology and tool

Evaluation of the case study showed that the BPS tool facilitated decision-making in the architect's design process. Furthermore, it was confirmed that the proposal gave the engineer an opportunity to integrate building performance within early stage design by the communicative interface, and it was considered to give the project actors a deeper understanding of the given indicators and their relation to design. However, the results were based solely on the described case study with Ona Forss as acting architect and the author as acting engineer. There might be other conclusions to draw if the tool and process was tested on a larger scale.

Integration of the architectural model into the calculation model was considered as an important key to decreasing time for each iteration. Approximations had to be included in order to speed up the process, avoiding that the engineer needed to re-draw the model. This is further described in Appendix I. It was concluded that it was a good idea of keeping the engineer responsible of the model integration to ensure correct input geometry.

Results visualised in 3D were considered as communicative and easier to connect to the design than solely numerical indicators. The legend with three colours on the mesh helped the users to identify critical areas of the design option in relation to project demands. The possibility to alter the legend threshold values was evaluated as good. However, it was suggested to visualise the results in a 3D mesh weighed by the considered relevance of each indicator. Results that were displayed in the parallel coordinates plot provided an interactive and informative multi-objective evaluation, but mostly for the engineer due to the chosen input parameters. However, the sensitivity study would have made more sense if also included in the façade study, where the level of detail on the building design was higher. Finally, the numerical indicators were compared with the demands giving a clear indication on the results aggregated for each building. Showing results in more detailed aggregation levels such as public premises compared to housing is possible but was omitted because it was not of interest for the architect in the case study. The most relevant numerical indicators were energy demand, however, the connection to the design was not clear.

The results on time requirements were too high to be regarded as acceptable for a BPS tool used in an early stage, which is a matter that needs to be resolved before implementation in actual projects. The positive side of it is that the bottlenecks were exposed and something for further work to improve. Best practice was documented in Appendix J. The proposed workflow in general was considered as feasible in the three tested levels of detail; building envelope, massing and façade analysis. However, the geometrical restrictions in the detailed development plan was considered obstructing in the massing design, as a change in massing would conflict with the economic incentive. Furthermore, the façade study and the interior study do not have to follow a linear process but can be iterated over to reach a feasible design.

As a result of the named observations, and the conclusion that the architect's massing studies are already limited to the detailed development plan, it was suggested as further work to include the proposed BPS even in the detailed development planning process. The case study indicated that the framework of the detailed development plan had an influence on indicators such as daylight factor and floor space index, meaning that these might be subject to optimisation even in the detailed development planning process.

Finally, integrating BPS in early stage design by addressing potential gaps increased the overall collaboration and understanding of design correlation to building performance. An important learning was that the detailing level of the input data have a direct relation to the approximation level of the results. This is important to keep in mind when integrating BPS in early stages.

6 Discussion

In the long run, it is easy to stare blindly at the demands or high set goals that architects and engineers need to achieve. The focus of this thesis has been on facilitating the design process of the architect and including the building performance engineer to support decision-making with quantitative data made from simulations. The most important case study results are not the actual figures or if the building design reached any of the goals; it is the user experience of the architect and engineer in collaboration, what input the process gives to them, and finally how it is translated into a new iteration of the design. This thesis put focus on visualising the quantitative aspects and allowing for qualitative input, however that means qualitative input in the design process is highly dependent on the actors in the project.

Depending on detailing level in the input geometry, the method will give a varied approximation as results, which is important to keep in mind when integrating BPS in early-stage building design.

The simulation time proves to be longer than expected, especially for simulations connected to RADIANCE, and the solar gains calculation for each zone. This results in less time available for design decision-making, highlights the importance of fast simulations. However, the methodology in general has been welcomed by Ona Forss being the test person and does fulfil the purpose of facilitating design decision-making for integrated building performance design.

Light transmittance (LT) is often the same in housing projects in Sweden as a result of very few windows on the market; therefore the sensitivity analysis with parametric LT that changes with g-value is rather redundant for housing projects. However, for e.g. office buildings it can be useful to include the correlation because those buildings often have a wider spectrum of glazing. Sunlight hours have been calculated in the case study with the time resolution of 1h, however the recommended time resolution should be 0.5h because of the demand resolution of sunlight hours.

This study adds a pragmatic approach to the research area on the integration of BPS in early stage building design. This study indicates that a multi-objective approach is required in design and suggest a feasible way forward. The study does not weigh the indicators but visualise multiple indicators altogether. However, the results that are not visualised in meshes might be in need of visual emphasis to gain the same amount of attention as the other visuals.

As this project cannot provide simulation techniques for all possible aspects of building performance, it has been delimited to what is considered most relevant for the case study project design iterations. As an example, heating and cooling power of the building has been omitted because it is considered outside the scope of the housing project. However, power supply to our built environment is important and from that perspective the named indicators should be considered in future application of this proposal. On that note, future research on cooling power and the correlation to the solar heat load is recommended. This may provide indications on thermal comfort target values.

The tool and methodology development are the results of one architect and one engineer collaborating. A suggestion is to scale the collaboration for future case studies, allowing the software to be tested on more projects and by more architects and engineers.

7 Conclusion

This thesis has been evaluating the possibilities and barriers with integrating building performance simulation in early stage design. An initial information assessment phase has consisted of ten interviews and a literature review. The possibilities and barriers have been identified in Section 3.10 and Section 3.11 and addressed in Chapter 4. Finally, the proposed method has been tested on a case study housing project in Gothenburg, Sweden. Testing and evaluation of the method in the case study has been made in collaboration with Ona Forss, writing her Master's thesis in Architecture.

It has been found from the overview of area that integration of BPS is encouraged, but the potential barriers are the project budget, the traditional responsibility distribution, that no common praxis seem to occur and that BPS tools lack in usability. The project budget and role distribution are outside the scope of the thesis, but the interdisciplinary design method address both the lack of a common praxis and the usability of BPS tools. The first has been addressed by proposing user integration through a process where architect and engineer work in a design team. The process consists of five parts, each depending on the level of detail of the building design. A BPS tool has been developed by proposing system architecture, the workflow of using the tool, and an implementation by using BeDOT together with additional building performance simulations. Those simulations has been made to assess a selection of the most relevant indicators for early stage design; demands by regulations regarding energy and daylight, recommendations for sunlight, thermal comfort, area indicators, access to solar energy and desired views. The tool interface has been proposed as a web interface written in the Python framework Dash.

Development of the proposed process and BPS tool has been made through continuous evaluation and collaboration with Ona Forss. The BPS tool has been delimited to target the case study project. The knowledge base does allow for alternative conclusions as the development project has been partly based on qualitative decision-making throughout the thesis.

The qualitative evaluation of the case study show that the BPS tool facilitated decision-making in the architect's design process and the engineer's enhanced ability to communicate building performance of the design. An important key for decreasing time between each iteration is the integration of the architectural model into the calculation model, and that the engineer keeps the responsibility for translating the geometry.

Evaluations confirm that the result visualisations of correlating indicators as meshes projected on the 3D geometry and the parallel coordinates plot do provide information for multiple indicators and thus facilitate the design process decision-making in early stages. However, simulation time prove to be longer than expected, which is a barrier. Looking at the bigger picture, including more experience in programming and data science into the field of civil engineering and architecture would probably increase usability and decrease computation time, but possibly also provide innovative solutions in general.

The proposed user integration is considered to be feasible with the current common praxis among architects and building performance engineers.

Even if reliable, fast and user-friendly methodologies and tools are made available, there is still a need of fostering a positive culture about integrating building performance simulation in early stage design. If the working culture among architects and building performance engineers does not align with the ambitions of this thesis, there is no point in supplying these tools. It is only when the early adopters include the vast majority that this type of tools might actually make a difference and start fulfilling the purpose on a larger scale.

Although this study has covered a range of perspectives on this subject, the outcome is the result of iterative research and development of a tool in dialogue with both academia and the industry. Therefore, other results might have been found or developed with the same basis of knowledge. The author welcomes further research to cover potential gaps, and especially as this work put focus on communication as an enabler, please reach out if you have any questions or comments and the knowledge in this field can be developed together.

7.1 Future work

Integration of building performance simulation with architectural modelling in early stage building design requires further research. Suggestions for future work is to:

- Investigate the possibilities of direct feedback options in the modelling interface when modelling the design model for it to be translatable into the calculation model.
- Enable automated steps between back-end and front-end.
- Implement optimisation algorithms to automate the feedback loop of each iteration.
- Investigate the memory requirements for running analyses in order to provide even faster simulation steps.
- User other daylight indicators than approximations of daylight factor, e.g. Useful Daylight Illuminance.
- Include heating and cooling power as indicators because of their increasing importance in buildings. Furthermore, cooling power in combination with solar heat load is suggested to be investigated further as indicators of thermal comfort.
- Speed up the Solar Gains component in BeDOT by improving the Python code.
- Development of the visualisation interface to include more visualisations, 3D meshes in particular.
- Test the proposed methodology on several projects; get input from architects and engineers in the field.
- Validate the case study results to results of the competition entries in the real project at Gibraltarvallen.

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Figure 1.1 *The MacLeamy Curve, illustrating correlations between cost and process of design. Reprinted from American Institute of Architects, Integrated Project Delivery: A Guide, 2007, Retrieved March 03, 2019, from http://info.aia.org/siteobjects/files/ipd_guide_2007.pdf.*

Figure 3.9 *Image of K21 building in Mölndal (57°40'09.4"N 12°00'37.3"E). On one side a double-skin façade, on the other side an ordinary glazed façade. Reprinted from ACC Glas- och fasadkonsult. Retrieved June 13th, 2019 from http://www.acc-glas.se/projekt/krokslatts-fabriker-k21/.*

APPENDICES

Appendix A **Daylight indicator comparison**

Definitions of DF, SVF and VSC can be found in Section 4.8.1. In a Master's thesis from 2016, (Eriksson & Waldenström, 2016) made a comparison between Daylight factor (DF), Sky view factor (SVF) and sky exposure factor (SEF). Also (Jacobsson & Eriksson, 2017) compared these indicators and summarised their characteristics as in Table A.1.

Table A.1 Summary of characteristics for modelling of daylight indicators (Jacobsson & Eriksson, 2017).

INDICATOR	SKY TYPE	REFLECTIONS	COSINUS WEIGHTED
DAYLIGHT FACTOR DF	CIE Overcast sky	Yes	Yes
SKY EXPOSURE FACTOR SEF	Uniform sky	No	No
SKY VIEW FACTOR SVF	Uniform sky	No	Yes

Reflections are omitted in SEF and SVF but included in DF. One may assume that in a city landscape, where buildings are placed densely, that external reflections do have an influence on the daylight. However, the ambient bounces of the reflections are computationally heavy. For quicker estimations of DF, it was therefore necessary to use other methods. That is the reason why there has been attempts to find linear relationships between SVF and DF. SVF was chosen over SEF because of the fact that it is cosinus weighted, thus weighing access to patches of sky that is closer to zenith. (Jacobsson & Eriksson, 2017) finds a linear relationship between DF_{median} and SVF when including the ratio of window-to-floor area, as shown in Figure 8.1. This relationship is used in this thesis for "Method 1". Table A.2. describe VSC, which was used in "Method 2", with regard to the same parameters as in the table above.

Table A.2 VSC characteristics.

INDICATOR	SKY TYPE	REFLECTIONS	COSINUS WEIGHTED
VERTICAL SKY COMPONENT VSC	CIE Overcast sky	No	Yes

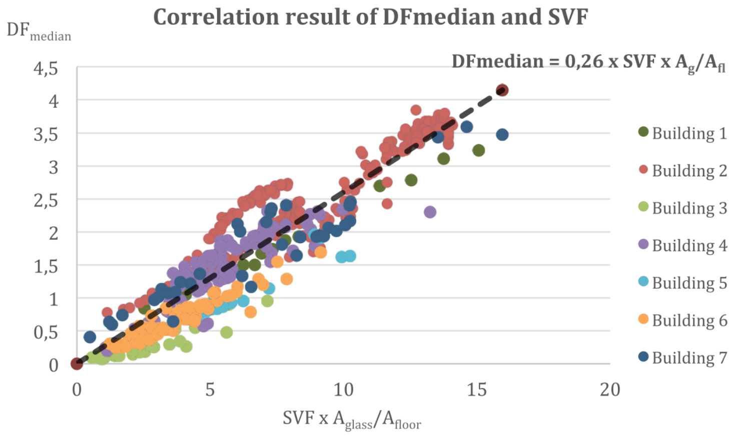


Figure 8.1 Relationship between DF inside and SVF outside including a geometrical ratio (Jacobsson & Eriksson, 2017).

Appendix B **Correlation between g-value and DF**

In order to understand how much daylight is transmitted through a window, we start from the formula of solar heat gain through windows. According to ASHRAE, there are two parts of the solar heat gain (ASHRAE, 2017):

a. The directly transmitted part, including direct and diffuse solar radiation.
b. The part that is absorbed by the fenestration/window glazing and is released to the indoor environment as heat or secondary emissions.

The directly transmitted part was relevant for this case, as the ambition was to investigate if there might be a correlation between light transmittance and daylight factor. Solar heat gain in a space is dependent on both the incoming direct and diffuse solar radiation as well as the window's ability of direct and diffuse light transmission according to the following formula (Hagentoft, 2001):

$$Solar\ heat\ gain = \tau_{\mathrm{dir}} \times \mathrm{I}_{\mathrm{sol,dir}} + \tau_{\mathrm{diff}} \times \mathrm{I}_{\mathrm{sol,diff}} \quad [\mathrm{W/m^2}] \tag{1}$$

Where,
τ_{dir} = transmission of direct solar radiation [-]
$\mathrm{I}_{\mathrm{sol,dir}}$ = direct solar radiation [W/m^2]
τ_{diff} = transmission of diffuse solar radiation [-]
$\mathrm{I}_{\mathrm{sol,diff}}$ = diffuse solar radiation [W/m^2]

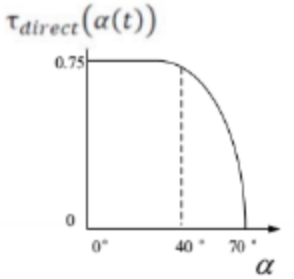


Figure 8.2 Transmission as a function of incident angle.

As seen in Figure 8.2, τ_{dir} depends on the angle of incidence, whereas τ_{diff} is constant. Transmission τ_{diff} refers to the diffuse part of solar radiation, only present at an overcast sky, which have no angle of incidence and is therefore constant. As τ_{diff} is a constant value, we may assume that there is a linear correlation between how much daylight (which is regarded as the diffuse part, alike how solar radiation is estimated in equation 1) there is outside of the room and how much daylight enter the room through the window.

(Eriksson & Waldenström, 2016) simulated daylight in 25000 rooms. The light transmittance used in windows was constant through all simulations as LT = 0.7 [-].

Formula 4 in (Jacobsson & Eriksson, 2017) was used for the first iteration calculation of Daylight Factor. It was found by evaulating DF from a database with 25000 rooms, plotting (SVF * A_{glass} / $A_{\mathrm{room,floor}}$) against $\mathrm{DF}_{\mathrm{median}}$ in a scatterplot and finding the correlation factor of 0.26. The same formula is presented below:

$$DF_{median} = 0.26 \times SVF \times \frac{A_{glass}}{A_{room,floor}} \quad [-] \qquad (2)$$

Where,
DF_{median} is the median daylight factor in a room [-]
SVF is the sky view factor [-] that represents amount of daylight available outside the room
A_{glass} is the area of glazing towards the outside of the room [m^2]
$A_{room,floor}$ is the area of the floor in the room [m^2]

Thus, if the geometry of the room (A_{glass} / $A_{room,floor}$) and the amount of daylight outside of the room (SVF) is constant, only the correlation factor of equation (2), 0.26, is subject to change as the g-value changes. As it was known that the LT assumed in the original simulations was 0.7 (Eriksson & Waldenström, 2016), it was possible to apply a factor to adjust the correlation factor with the LT-value corresponding to a certain g-value:

$$DF_{median} = LT_{factor} \times 0.26 \times SVF \times \frac{A_{glass}}{A_{room,floor}} \quad [\%] \qquad (3)$$

$$LT_{factor} = \frac{LT_{new}}{LT_{old}} \quad [-] \qquad (4)$$

Where $LT_{old} = 0.7$

Regression analysis

As an attempt to investigate linear correlation between g-value and LT-value of windows, data from Pilkington glass products was assessed and a linear regression analysis was performed. The data source was (Pilkington Floatglas AB, 2018) and the data in Table E.1 was used in a scatter plot to form Figure 8.3.

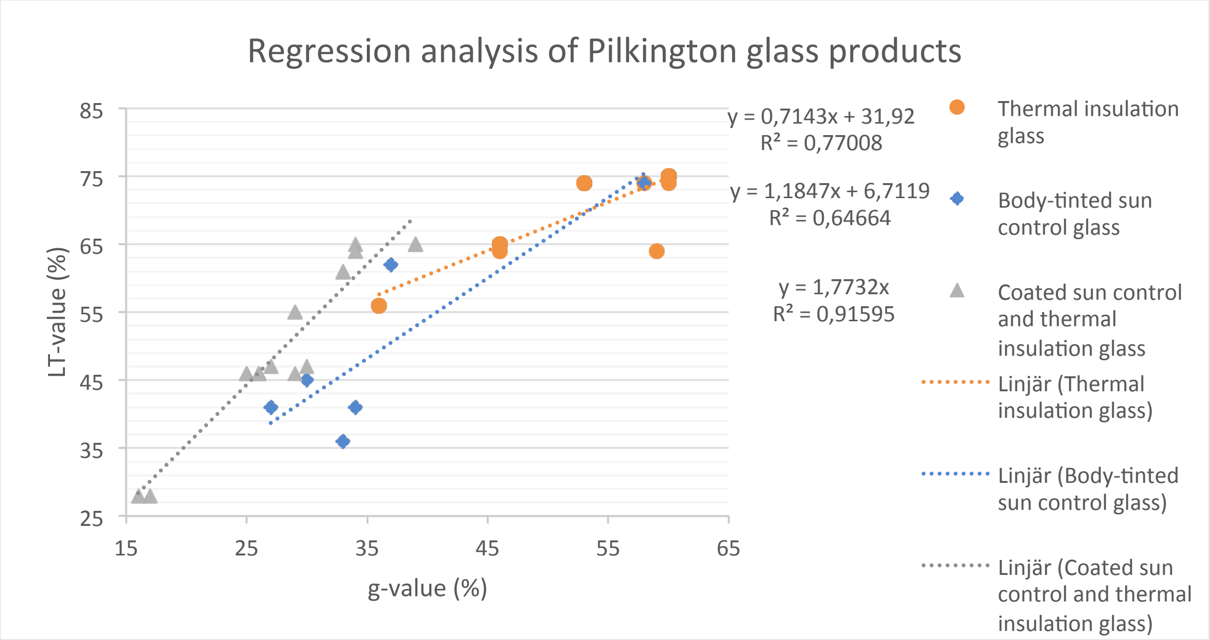


Figure 8.3 Regression analysis graph.

As found from a regression analysis of g-values and LT-values, there is a linear correlation between g and LT:

$$LT_{new} = g_{win} \times x_{corr} \qquad [-]$$

Where x_{corr} is a correlation factor that is determined from the linear regression analysis, and from Figure 8.3 it could be seen that the coated sun control and thermal insulation glass had the best linear correlation due to highest R2-value. Assuming that zero g-value gives zero light transmission, the equation can be read from Figure 8.3:

$$LT_{new} = g_{win} \times 1.7732 \qquad [-]$$

Therefore, equation 3 may be rewritten into:

$$DF_{median} = \frac{g_{win} \times 1.7732}{LT_{old}} \times 0.26 \times SVF \times \frac{A_{glass}}{A_{room,floor}} \qquad [\%] \tag{5}$$

Table E.1. Pilkington product data.

PANES	PRODUCT CODE	LT(%)	G (%)
THERMAL INSULATION GLASS			
	4-16Ar-4-16Ar-KN4	69	68
3	4KN-16Ar-4-16Ar-KN4	64	59
1+2	4+30+4-16Ar-S(3)4	75	60
3	4-12Ar-4-12Ar-S(3)4	75	60
3	4-16Ar-4-16Ar-S(3)4	75	60
3	4-9Ar-4-15Ar-S(3)4	75	60
3	4-16Ar-4-16Ar-S(3)6,4L	74	60
3	6-16Ar-4-16Ar-S(3)4	74	58
3	4S(3)-12Ar-4-12Ar-S(3)4	74	53
3	4S(3)-16Ar-4-16Ar-S(3)4	74	53
3	4S(3)-18Ar-4-18Ar-S(3)4	74	53
1+2	4+30+4-16Ar-S(1)4	65	46
3	4-12Ar-4-12Ar-S(1)4	65	46
3	4-16Ar-4-16Ar-S(1)4	65	46
3	4-16Ar-4-16Ar-S(1)6,4L	64	46
3	4S(1)-16Ar-4-16Ar-S(1)4	56	36
3	4S(1)-18Ar-4-18Ar-S(1)4	56	36
3	4-12Ar-4-12Ar-4	76	72
BODY-TINTED SUN CONTROL GLASS			
3	6gy-16Ar-4-16Ar-S(3)4	36	33
1+2	6gy+30+4-16Ar-S(3)4	36	33
3	6bz-16Ar-4-16Ar-S(3)4	41	34
1+2	6bz+30+4-16Ar-S(3)4	41	34
3	6gn-16Ar-4-16Ar-S(3)4	62	37
1+2	6gn+30+4-16Ar-S(3)4	62	37
3	6ab-16Ar-4-16Ar-S(3)4	45	30
1+2	6ab+30+4-16Ar-S(3)4	45	30
3	A6ab-16Ar-4-16Ar-S(3)4	41	27
1+2	A6ab+30+4-16Ar-S(3)4	41	27
3	6-16Ar-4-16Ar-S(3)4	74	58

COATED SUN CONTROL AND THERMAL INSULATION GLASS			
3	6C(74)-16Ar-4-16Ar-4	65	39
3	6C(74)-16Ar-4-16Ar-S(3)4	65	39
3	6C(70)-16Ar-4-16Ar-4	65	34
3	6C(70)-16Ar-4-16Ar-S(3)4	64	34
3	6C(66)-16Ar-4-16Ar-4	61	33
3	6C(66)-16Ar-4-16Ar-S(3)4	61	33
3	6C(61)-16Ar-4-16Ar-4	55	29
3	6C(61)-16Ar-4-16Ar-S(3)4	55	29
3	6C(50)-16Ar-4-16Ar-4	46	25
3	6C(50)-16Ar-4-16Ar-S(3)4	46	25
3	6C(30)-16Ar-4-16Ar-4	28	17
3	6C(30)-16Ar-4-16Ar-S(3)4	28	16
3	6Cs(50)-16Ar-4-16Ar-4	47	30
3	6Cs(50)-16Ar-4-16Ar-S(3)4	46	29
3	6Cb(50)-16Ar-4-16Ar-4	46	26
3	6Cb(50)-16Ar-4-16Ar-S(3)4	46	26
1+2	12.8CL(65)+500+4-16Ar-S(3)6	53	38
1+2	12.8LC(65)+500+4-16Ar-S(3)6	54	39
1+2	12.8CL(65)+500+6C(70)-16Ar-6	46	26
1+2	12.8LC(65)+500+6C(70)-16Ar-6	47	27
PILKINGTON SUN CONTROL AND THERMAL INSULATION GLASS			
3	6wC(74)-16Ar-4-16Ar-S(3)4	66	41
3	6wC(70)-16Ar-4-16Ar-S(3)4	66	36
1+2	4+30+4wC(70)-16Ar-4	67	37
1+2	4+30+4wC(70)-16Ar-8,8Lp	66	37
3	6wC(66)-16Ar-4-16Ar-S(3)4	62	33
3	6wC(61)-16Ar-4-16Ar-S(3)4	56	31
3	6wC(50)-16Ar-4-16Ar-S(3)4	47	26
3	6wC(30)-16Ar-4-16Ar-S(3)4	28	17
3	6wCs(50)-16Ar-4-16Ar-S(3)4	48	31
3	6wCb(50)-16Ar-4-16Ar-S(3)4	47	27
3	6-16Ar-4-16Ar-S(3)4	74	58

Appendix C Generation of test rooms for DF simulation

Figure 8.4 show a screenshot of the complex Grasshopper definition for calculation of DF according to Method 2. The definition was originally developed by an employee at BDAB, however, the rooms generated are adapted for office buildings which usually consist of cell offices with one window. Therefore, the writer of this thesis added three parts of visual scripting code for generation of rooms with more than one window (the white boxes in the figure), making it more scalable into other types of rooms. The Grasshopper definition is one out of many add-ons to the original BeDOT definition.

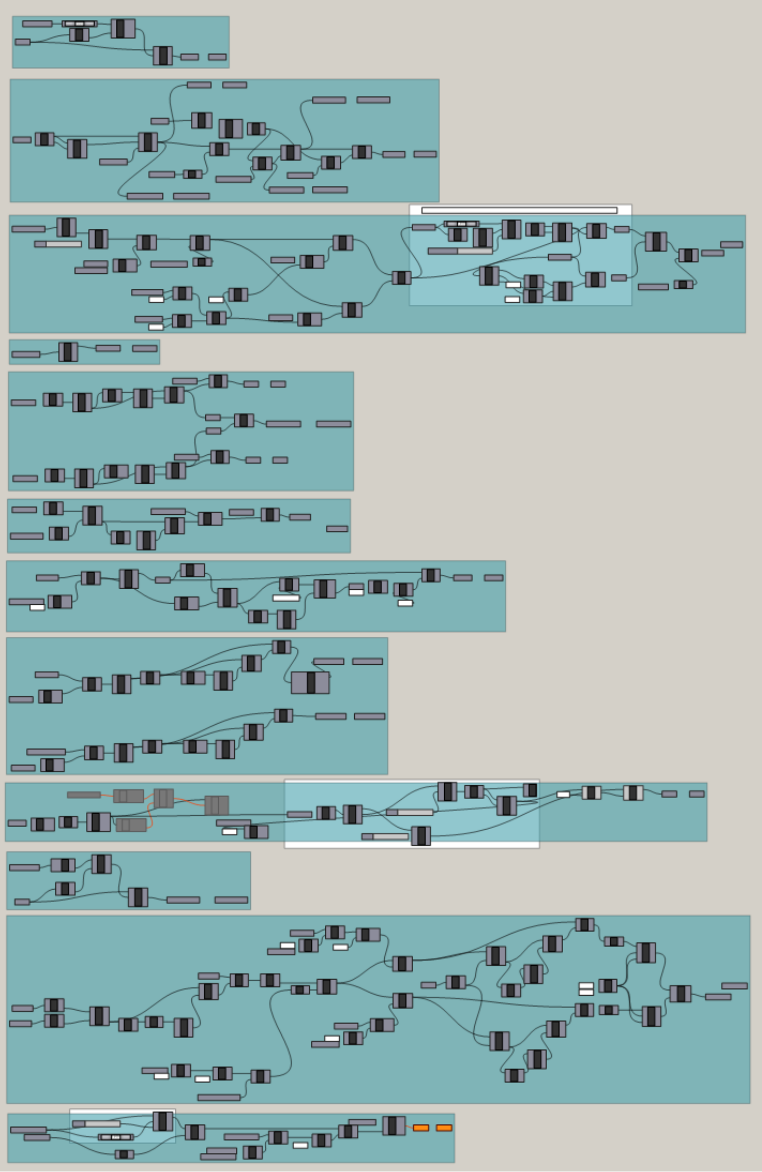


Figure 8.4 *Screenshot of Grasshopper definition for parametric generation of test rooms. The image shows the definition that was developed at BDAB (blue) and the parts that were modified by the author to be adaptable to rooms with more than one window, and for the design of balconies in the case study (white).*

Appendix D **Correlation between DF indoor and VSC**

This text describes a site-specific method, in the thesis called Method 2, determining the correlation between indoor daylight factor (DF) and façade exterior vertical sky component (VSC). A general explanation of the method is described in Section 4.8.2. Here follows the specific implementation of the façade analyses in the case study.

Simulations for DF was made for room configurations as explained in Section 5.9 and Section 5.10. The reflectance ρ used for surfaces can be seen in Table D.1.

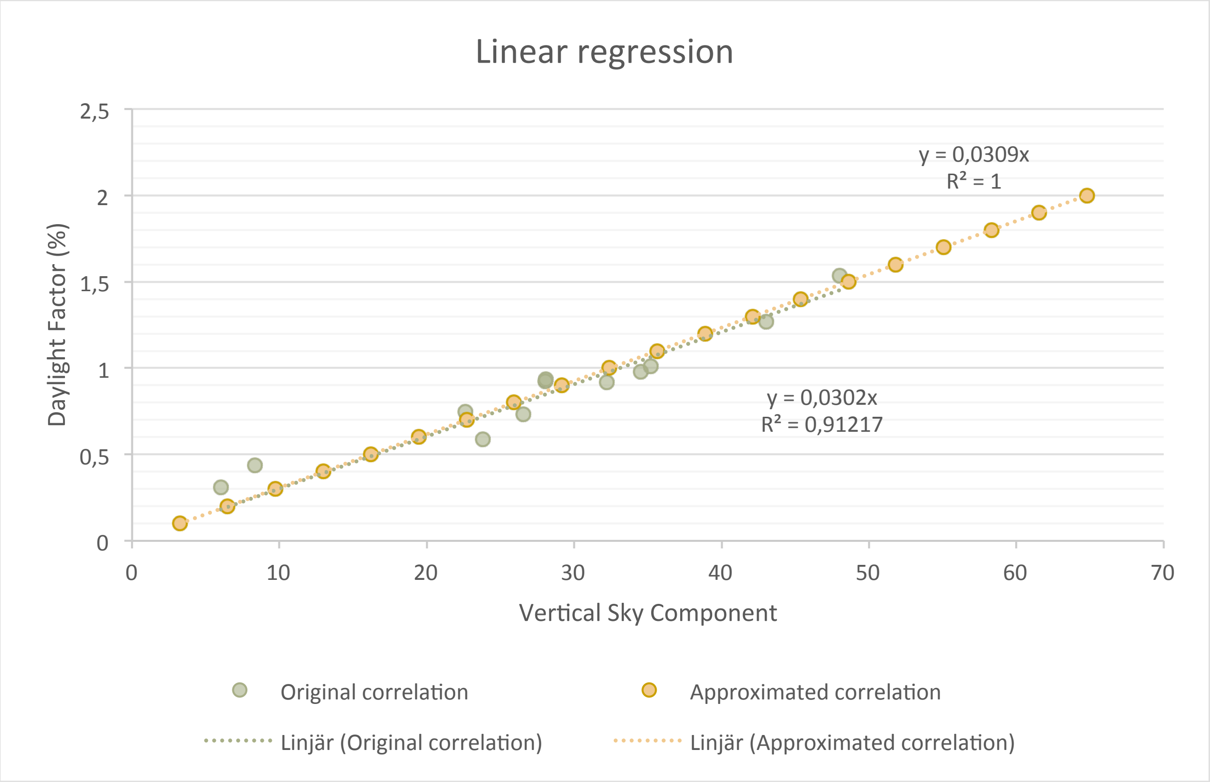
Table D.1 All reflectances used in calculation for Method 2.

$\rho_{WALL,OUT}$	ρ_{ROOF}	$\rho_{SURROUNDING}$	ρ_{GROUND}	$\rho_{WALL,IN}$	ρ_{CEIL}	ρ_{FRAME}	ρ_{FLOOR}	ρ_{GLASS}
0.3	0.3	0.3	0.2	0.8	0.9	0.6	0.4	0.6

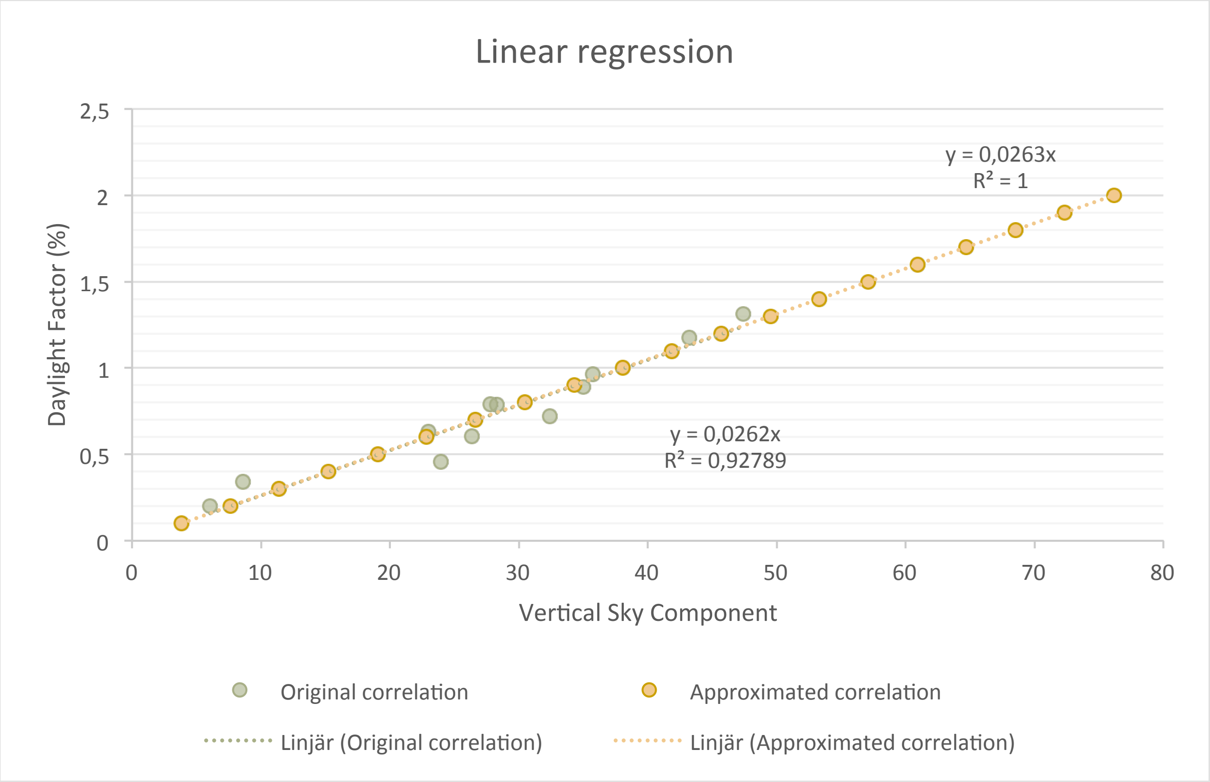
The plots were made by harvesting data from the Grasshopper simulations for DF (for the test rooms) and VSC (on the closest point to the room window on the facade), plotting the data in Excel using a scatter plot and finding the linear trend line (green, original correlation in the plot). The line was fitted through (0,0) assuming 0 VSC will result in 0 DF.

The R2-values in the figures below ranged between 0.9122-0.9493 and were considered to be sufficient for concluding a linear correlation between VSC and DF. For each façade study, a linear approximation of the green curve was fitted into the yellow (approximated correlation in the plots). Thus the correlations that were used for generation of DF values with VSC were derived:

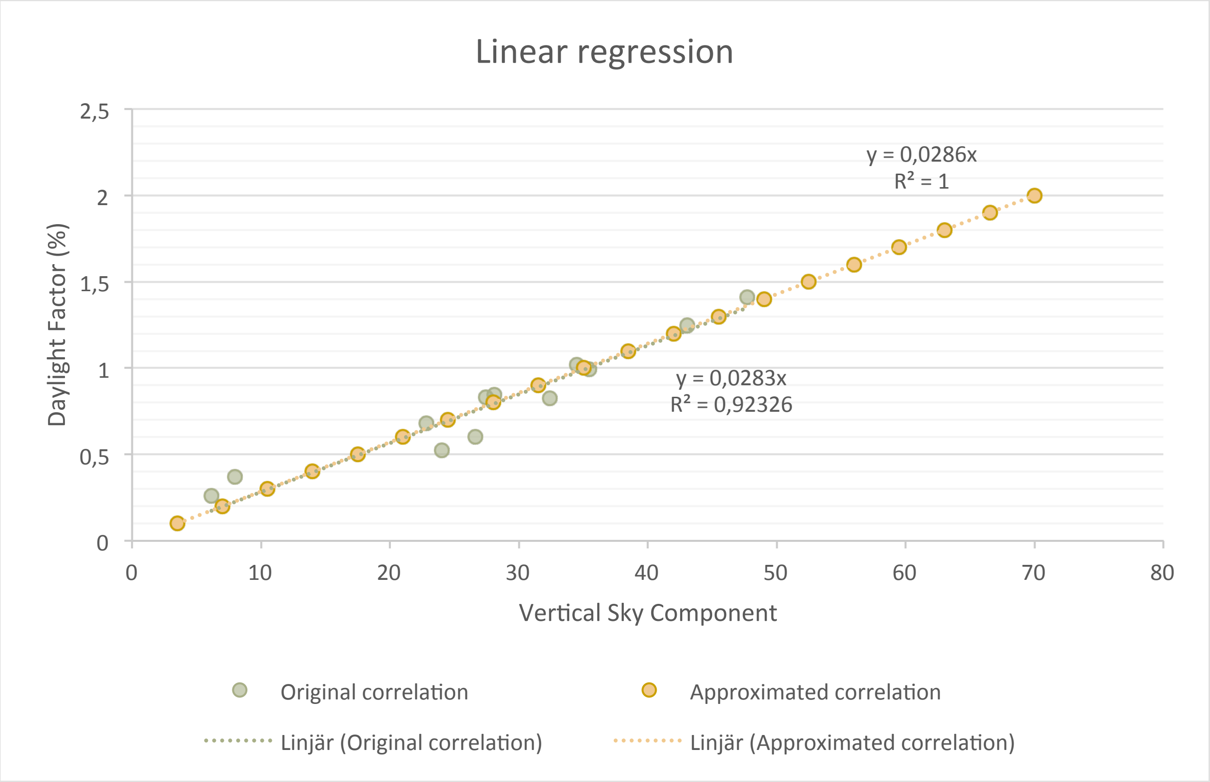
For façade study 1.0: $DF = 0.0309 \times VSC$
For façade study 1.1: $DF = 0.0263 \times VSC$
For façade study 1.2: $DF = 0.0286 \times VSC$
For façade study 2.0: $DF = 0.046 \times VSC$
For façade study 2.1: $DF = 0.0389 \times VSC$



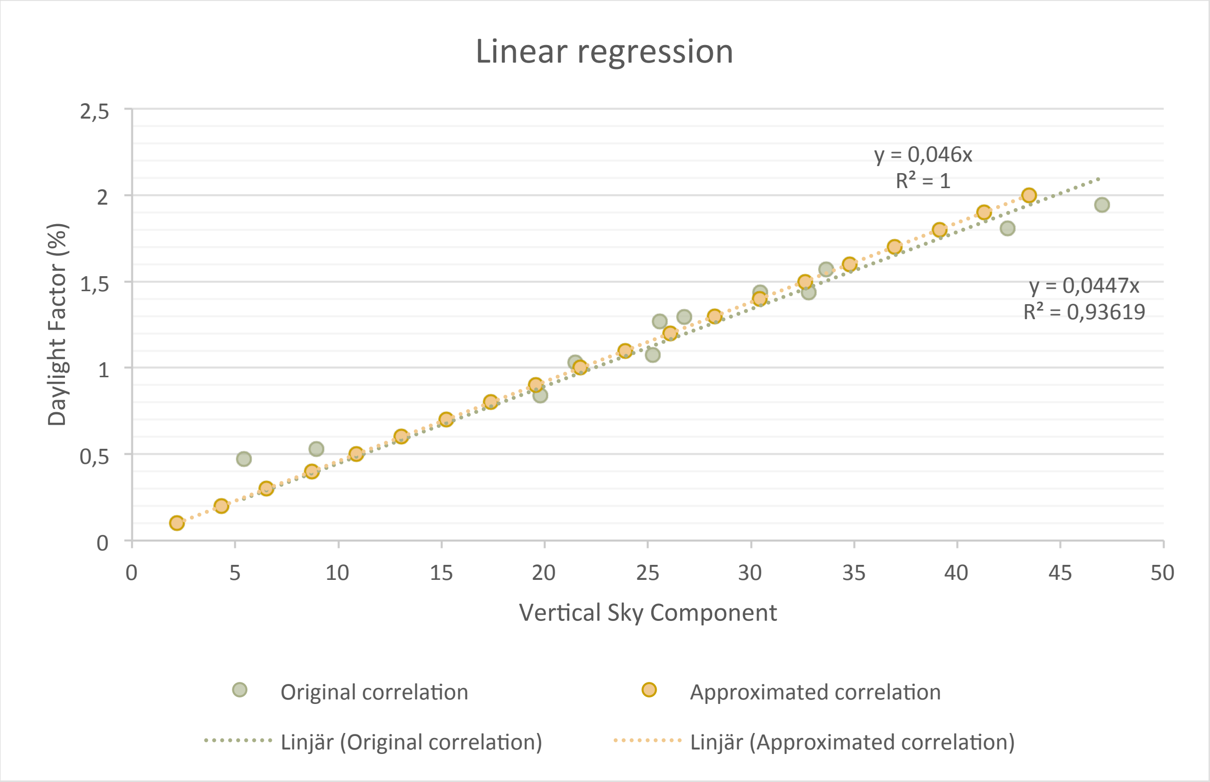
Figur 8.1 *Linear regression DF and VSC for the test rooms in façade study 1.0.*



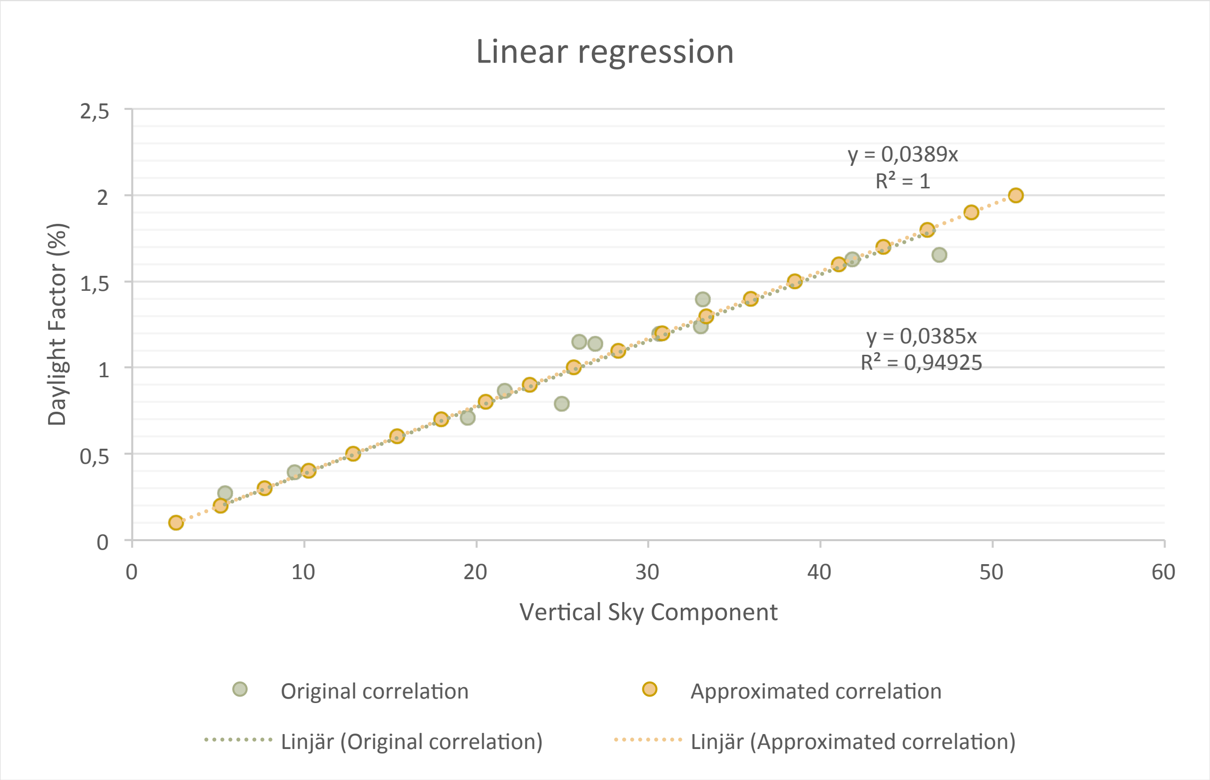
Figur 8.2 *Linear regression DF and VSC for the test rooms in façade study 1.1.*



Figur 8.3 *Linear regression DF and VSC for the test rooms in façade study 1.2.*



Figur 8.4 *Linear regression DF and VSC for the test rooms in façade study 2.0.*



Figur 8.5 *Linear regression DF and VSC for the test rooms in façade study 2.1.*

Appendix E **Building envelope study input data**

Table E.1 Input data for building envelope study. Only ‘Bostäder’ and ‘Garage’ columns are used for this iteration.

PARAMETERS	BOSTÄDER	LOKALER	BIYTOR	GARAGE
U_WALL	0.2	0.147	0.2	0.2
U_ROOF	0.12	0.1	0.12	0.12
U_BRIDGE	0.08	0.08	0.08	0.08
U_WINDOW	0.9	1.1	0.9	0.9
U_SKYLIGHT	0	0	0	0
HEAT CAPACITY	Lätt	Medel	Lätt	Medel
INTERNAL WALL AREAS	0.5	0.6	0.5	0.6
G_VALUE WINDOW	0.4	0.4	0.4	0.5
G_VALUE SKYLIGHT	0	0	0	0
SOLAR SHADING	0.7	0.7	0.7	1
SHADING CONTROL [W/M2]	100	100	100	0
HYGIENIC (L/SM2)	0.35	0.6	0.35	0.9
VENTILATIONSTIDER	Alltid-pa	Lokaler vent	Alltid-pa	Garage vent
LEAKAGE (L/SM2) VID NOMALA FÖRHÅLLANDEN	0.021	0.021	0.021	0.021
SET HEATING	21	21	18	5
SET COOLING	25	25	25	80
LIGHT [W/M2]	0	0	4.2	2.1
EQUIPMENT [W/M2]	3.00	5.0	0	0
OCCUPANCY [W/M2]	2.290	5.400	0	0
LIGHT SCHEDULE	Aldrig-pa	Aldrig-pa	1 hour/day (7/7)	1 hour/day (7/7)
EQUIPMENT SCHEDULE	Bostader occ	Lokaler occ	Aldrig-pa	Aldrig-pa
OCCUPANCY SCHEDULE	Bostader occ	Lokaler occ	Aldrig-pa	Aldrig-pa
HEAT_RECOVERY_WIN	1	1	1	1
HEAT_RECOVERY_SUM	1	1	1	1
AIR HEATING	1	1	1	0
AIR COOLING	0	1	0	0
EFFICIENCY %	0.8	0.5	0.5	0.5
COIL TEMPERATURE	10	10	10	10
SFP	1.8	1.5	1.5	1.5
T1	20	20	20	20
T2	18	18	18	18
T3	12	12	12	12
T4	18	18	18	18
COOLING SCHEDULE	Alltid-pa	Alltid-pa	Alltid-pa	Alltid-pa
RUMSKYLA	Vattenburen	Luftburen	Ingen kyla	Ingen kyla
RUMSTYP	Bostad	Lokal	Bostad	Garage

Appendix F **Massing studies input data**

Table F.1 Input data for massing and façade studies. All columns are used for calculation due to the ability to add more than one zone per building. Same input data as in Table E.1.

PARAMETERS	BOSTÄDER	LOKALER	BIYTOR	GARAGE
U_WALL	0.2	0.147	0.2	0.2
U_ROOF	0.12	0.1	0.12	0.12
U_BRIDGE	0.08	0.08	0.08	0.08
U_WINDOW	0.9	1.1	0.9	0.9
U_SKYLIGHT	0	0	0	0
HEAT CAPACITY	Lätt	Medel	Lätt	Medel
INTERNAL WALL AREAS	0.5	0.6	0.5	0.6
G_VALUE WINDOW	0.4	0.4	0.4	0.5
G_VALUE SKYLIGHT	0	0	0	0
SOLAR SHADING	0.7	0.7	0.7	1
SHADING CONTROL [W/M2]	100	100	100	0
HYGIENIC (L/SM2)	0.35	0.6	0.35	0.9
VENTILATIONSTIDER	Alltid-pa	Lokaler vent	Alltid-pa	Garage vent
LEAKAGE (L/SM2) VID NOMALA FÖRHÅLLANDEN	0.021	0.021	0.021	0.021
SET HEATING	21	21	18	5
SET COOLING	25	25	25	80
LIGHT [W/M2]	0	0	4.2	2.1
EQUIPMENT [W/M2]	3.00	5.0	0	0
OCCUPANCY [W/M2]	2.290	5.400	0	0
LIGHT SCHEDULE	Aldrig-pa	Aldrig-pa	1 hour/day (7/7)	1 hour/day (7/7)
EQUIPMENT SCHEDULE	Bostader occ	Lokaler occ	Aldrig-pa	Aldrig-pa
OCCUPANCY SCHEDULE	Bostader occ	Lokaler occ	Aldrig-pa	Aldrig-pa
HEAT_RECOVERY_WIN	1	1	1	1
HEAT_RECOVERY_SUM	1	1	1	1
AIR HEATING	1	1	1	0
AIR COOLING	0	1	0	0
EFFICIENCY %	0.8	0.5	0.5	0.5
COIL TEMPERATURE	10	10	10	10
SFP	1.8	1.5	1.5	1.5
T1	20	20	20	20
T2	18	18	18	18
T3	12	12	12	12
T4	18	18	18	18
COOLING SCHEDULE	Alltid-pa	Alltid-pa	Alltid-pa	Alltid-pa
RUMSKYLA	Vattenburen	Luftburen	Ingen kyla	Ingen kyla
RUMSTYP	Bostad	Lokal	Bostad	Garage

Appendix G Case study plot: Parallel coordinates

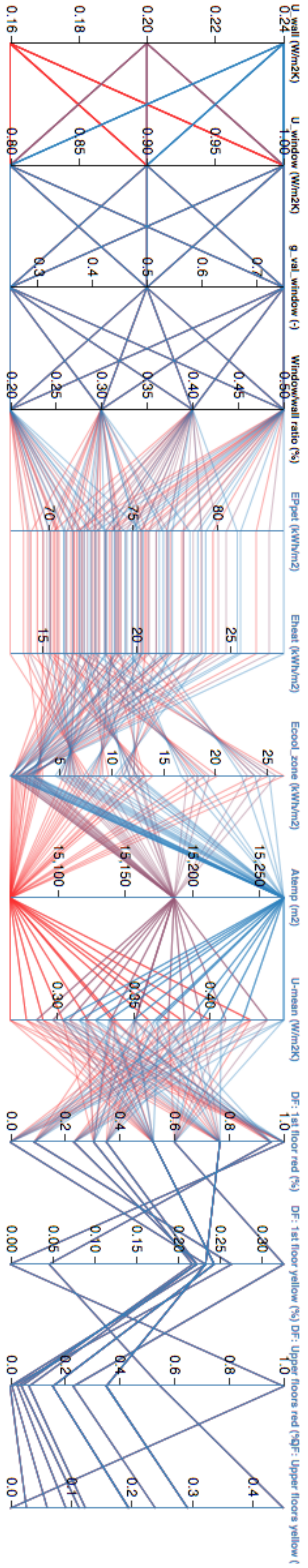


Figure 8.5 *Parallel coordinates plot.*

Appendix H Calculation of d_{wall} as function of U_{wall}

For the case study, a standard construction for a CLT wall was chosen as envelope wall. This was a choice based on the project brief and the opinions of the architect. The chosen wall detail was illustrated in Figure 8.6. The layers that were assumed to affect the thermal resistance of the envelope wall were the inner layers up to the wind board. Calculation of the wall thickness d_{wall} was made in Grasshopper in order to provide input for floor area calculations to the energy simulation, see Figure 8.7. The procedure follows an initial calculation of layer resistances for all layers except insulation, and then follows the known equation for serially coupled resistances, finding the depth of the insulation layer, which is the only unknown value, see equation 1 below. Table H.1. describe the input values, with thermal conductance and resistance values referenced from Hagentoft (2001).

Table H.1 Input data for the calculation of d_{wall}. Thermal conductance referenced from Hagentoft (2001).

R_{se} [m^2K/W]	Windboard (wb)	Mineral wool (mw)	CLT	R_{si} [m^2K/W]
0.04	$d_{wb} = 0.022$	d_{mw}	$d_{CLT} = 0.139$	0.13
	$\lambda_{wb} = 0.13$	$\lambda_{mw} = 0.035$	$\lambda_{CLT} = 0.11$	

$$d_{mw} = \left(\frac{1}{U_{wall}} - \sum_{i=1}^{n} R_i\right) \times \lambda_{mw} \quad [\mathrm{m}^2] \tag{1}$$

Where U_{wall} is input data from the Excel sheet, i represent all wall layers but mineral wool.

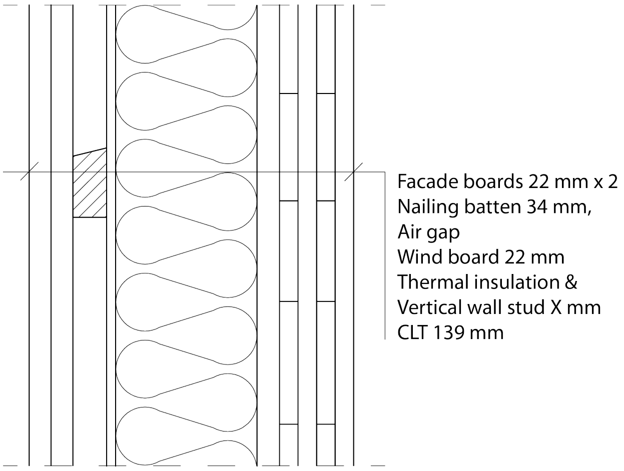
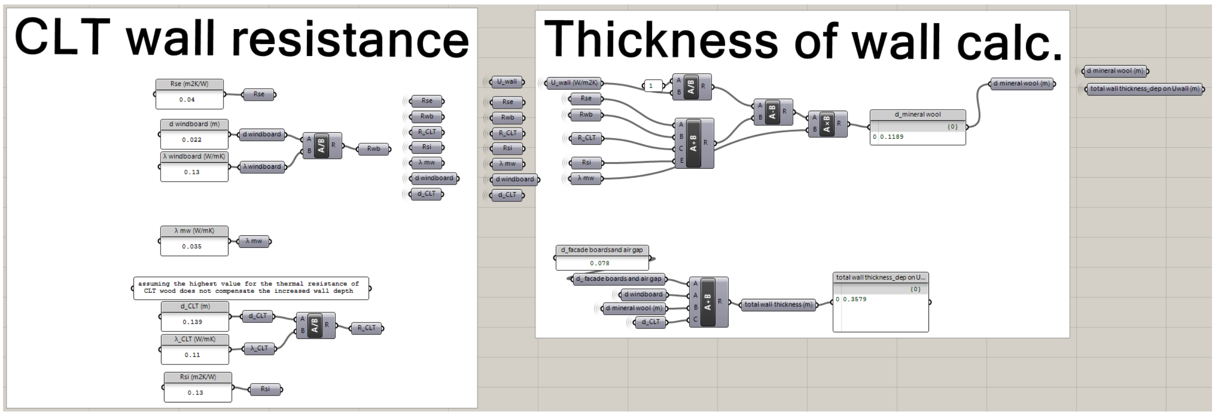


Figure 8.6 Detail of envelope wall with fixed wall depth on all parts except from insulation, which is dependent on Uwall.



Rse (m2K/W) 0.04

d windboard (m) 0.022

λ windboard (W/mK) 0.13

λ mw (W/mK) 0.035

assuming the highest value for the thermal resistance of CLT wood does not compensate the increased wall depth

d_CLT (m) 0.139

λ_CLT (W/mK) 0.11

Rsi (m2K/W) 0.13

d_mineral wool {0} 0 0.1189

d_facade boardsand air gap 0.078

total wall thickness_dep on U... {0} 0 0.3579

Figure 8.7 Grasshopper definition for calculating CLT wall resistance and the thickness of the wall.

Appendix I Floor area approximation

Assumptions were made for approximations of the actual floor areas because of the influence it has got in BeDOT for e.g. hygienic flow rate, effective mass area, heat capacity, conductance and solar gains. This section describes how the floor area was estimated for the both zoning methods.

Single-zoning

Calculations were made on the floor area using the building envelope geometry (which in this case were the zones) by estimating number of floors. As the zones were defined from the outside of the facades, the in-plane area of the envelope wall was subtracted from the initial theoretical floor area, where the walls have no thickness. The result was the remaining floor area.

Multi-zoning

The script was built to identify which zone walls were exterior walls, using HoneyBee's "decomposeByType" component, extracting the outlines of those and offsetting those at the thickness of the exterior walls. The offset curves were joined to form a floor outline describing the floor area. The total of all zone floor areas subtracted with the external wall areas was divided over the total of all zone floor areas, resulting in the percentage of area left after reduction of external walls, see equation I.1. All zones with external walls had the floor area reduced by the estimated proportion.

$$Floor_{remaining} = \frac{Area_{floor,total} - Area_{extwalls,in\ plane}}{Area_{floor,total}} \quad [-] \qquad (I.1)$$

Comments on assumptions

It was difficult finding a general visual scripting algorithm for estimating floor area for the zones and reducing the area due to the exterior wall thickness. The scripts for single-zoning were adapted to the orientation of the zones and the estimated floor areas. For perimeter-zoning, the offsetting of the thickness of exterior walls proved to be inconsistent in the case where an exterior wall of one zone intersect with an interior wall of another zone.

Also, the offsetting direction was dependent on the outline direction that was a result of the drawing technique, which may differ among users. This resulted in choosing the described method of reducing the floor areas with external walls with an overall reduction factor. This assumption made the floor area estimation not entirely correct on the zone level but more reasonable on a building level.

Appendix J Best practice using the proposed BPS tool

A common practice in building performance simulation is that the architect is modelling geometries as a design model, which is sent to the engineer for analysis. The calculation model must meet the following requirements to ensure a solid calculation:

Checklist for early stage modelling

- Model north is parallel to modelling environment y-axis.
- The plane where building meets ground is at z = 0.
- The model should be close to Rhino origin [0, 0, 0].
- No overlapping or intersection of surfaces.
    - The reason is that HoneyBee's geometry interpreter does not have any geometrical tolerance. In practice, this means that a more sound calculation model is drawn without 'snap to CAD' functionality.
- Ensure adjacencies by modelling zones adjacent to one another and validating it by Rhino command 'Intersect'.
- Communicate the modelling principle. Suggestion; draw the outer border of the façade and the upper border of each floor level. *Figure 8.8* illustrates this by showing how the surface is modelled for each zone, and the actual thickness of the building elements.
- Ensure that surfaces are directed towards the exterior.
- Ensure optimal use of computer memory by settings in Grasshopper:
    - Do not auto-save on wire event.
    - Set the display recent files to 0.
- At occasions when the HoneyBee geometry identification does not work, the user may need a re-start of the computer. Reasons for malfunctioning was not investigated.
- Avoid keeping internalised data in Grasshopper, export it instead.

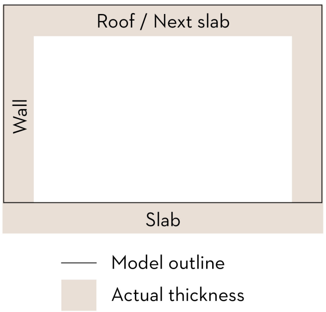


Figure 8.8 Section of architectural model geometry definition. Courtesy of Ona Forss.

A better solution would be that the architect got feedback while modelling whether the model meets the named requirements. This is seen as further development of BeDOT, to integrate the model domain into BeDOT. While it is out of the thesis scope, the current solution is to implement a common understanding in the very first meeting of how to model for building performance design in early stages. For the architect to model "correctly" for the calculation environment should be considered as best practice from a holistic view of the project, where the engineer consults the architect on how to provide a sound model for building performance simulation. Thus, the engineer does not have to re-draw all models sent from architect to engineer. The benefit of this workflow is a total reduction of required time to perform early stage analysis.

Appendix K Time requirement data

The raw data for the time requirement charts is presented in the tables below.

Table K.1 Time requirement raw data for Massing 3.3.

CALCULATION	COMPONENT	REQUIRED TIME	COMMENTS
ITERATION	Massing 3.3		
AMOUNT OF ZONES	60	[minutes]	Possible cause of slow computation
	runDaylightAnalysis	14.2	Mesh high resolution
	Solar radiation per zone	18.4	Solar gains-code slow because it search illuminance files to pair right zone values.
	AHU	0.4	
	Heat balance	0.8	
	SHL meshing	15	
	View meshing	8.2	
	DF meshing	0.1	
	Sunlight hours meshing	0.1	
TOTAL TIME		**57.2**	

Table K.2 Time requirement raw data for Façade study 2.0.

CALCULATION	COMPONENT	REQUIRED TIME	COMMENTS
ITERATION	Facade study 2.0		
AMOUNT OF ZONES	60	[minutes]	
	runDaylightAnalysis	39.7	
	Solar radiation per zone	16.2	
	AHU	0.4	
	Heat balance	0.8	
	SHL meshing	58	Many gridpoints: 629
	View meshing	3.2	
	DF meshing	0.1	
	Sunlight hours meshing	0.1	
TOTAL TIME		**118.5**	