Factory in a Digital Model

Encoding a timber framed façade panel manufacturing knowledge to improve its design process

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TU Delft

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by

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Cover Image: Sluishuis Building [1]

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Maria Cristina Roman Torres
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Summary

Façades within the building industry ore one the most important and expensive aspect of a project. They are the outer skin of a structure and are responsible for improving energy efficiency, while being both innovative and attractive [2]. At the same time, façades need to accommodate requirements to withstand the outdoor environmental conditions. To meet all of these requirements, there is need for designers to either have knowledge on the different subjects, such as human comfort, sustainability, stability, among others; or work together with different specialist to achieve an ideal design.

Following a traditional design process, once the conceptual design is defined it goes through an iteration process between designing and detailing before reaching the manufacturing stage. This process, even though is already considered within the planning of a building, is highly time consuming.

Considering this process, the idea of bringing the manufacturing knowledge into the early design stages to speed up the design process was taken into consideration. The idea of bringing the manufacturing knowledge upwards in the design process would help designers, focus only on designing, while the considerations for product availability and manufacturing possibilities are already taken into account.

On the other hand, the increasing use of parametric modeling to improve building solutions, has been a growing field. In regards to façade design, the inclusion of free form architecture in the building industry has pushed the need for innovative solutions. It has been proved in these projects that the use of parametric modeling highly increases the speed in which designs are developed. However, the need to adapt existing products and manufacturing techniques to these complex geometries, generates more iteration times and increases the costs of the final product.

Now, imagine that not only the available products are adapted to the conceptual designs proposed, but that these designs include from their conceptual stages knowledge acquired from previous experience. This would help avoid the iterations between designers and manufacturers, plus would improve the possibilities of generating a bigger amount of modularity in the design process.

With these considerations, the proposal for this project aimed to develop a proof of concept tool that would be capable of encoding a manufacturers knowledge in a digital model, and use it to design a façade that is almost ready to manufacture. For this purpose, the knowledge and information from the façades manufacturer Vianen Kozijnen was used as base for the development of this tool.

Once this was established, the modelling phase for the façade design tool begun. Initially the input parameters were set, the knowledge is gathered from the company's input, allowing

the designer to set up a model within the possibilities of the manufacturer. In the back end of the tool, the build-up of the main modular panel is generated. Four main variables were defined to generate the geometry of the panel and these are determined by the input parameters.

Next, with a finalized panel design, the testing phase is set in place. This phase was divided into two processes. First, the replication of the panel throughout an entire faÇade. This process begins with a conceptual shape that will be filled with the already designed panel. The results from this process determine the total amount of modular panels and the percentage and amount of customized panels needed.

Secondly, the panel is tested for Building Physics aspects relevant in early design stages, which for this case were daylight and sound proofing. The tool then with the geometrical parameters given, includes simulations for both daylight and sound proofing. The results obtained, give information on the performance of the design. For daylight simulations, the results given are for daylight autonomy and daylight factor; and for sound proofing the results obtained give information on the insulation value of the façade (R_A), sound proofing of the structure (G_A) and typical sound proofing ($G_{A;k}$). Both results, are information that is useful during early design stages, and can help shape the final project.

To test the functionality of the tool, the Sluishuis building was taken as a case study and the tool was applied to design and test one of the façade surfaces of the building. The process followed can be seen in Figure 1.

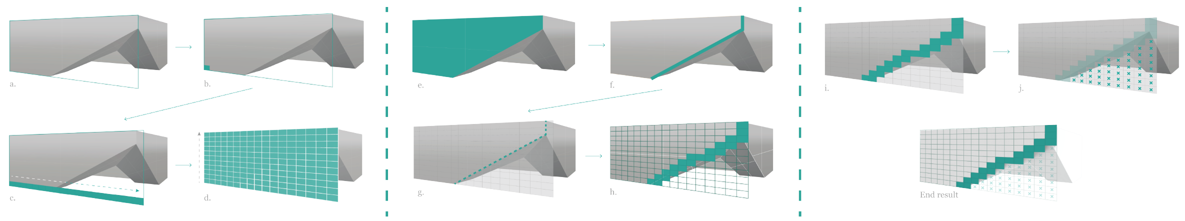

Figure 1: Façade design tool applied to case study - Sluishuis

The results obtained through this case study led to conclude the feasibility of encoding manufacturing knowledge. It was determined that as a proof of concept approach the tool generates almost immediate results that include the knowledge needed for manufacturing. However, to be applied into a real project further improvements need to be made; with more focus on, first, being able to apply the tool to a completed building and secondly, include more manufacturers knowledge to generate a library of possibilities; making it useful in real life projects.

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1 Introduction

Façades are the outer skin of a structure and are responsible for improving energy efficiency, while being both innovative and attractive [2]. Many different elements need to be considered when designing a façade. A mix of aesthetics and technical components make up the final result. As mentioned by Boswell [3] enclosures have to be designed to accommodate elements such as air, water, sun and withstand loads generated by natural forces such as wind, seismic, and thermal. What's more, façades are accountable for the biggest/highest effect on energy savings of a building and for that its design considerations are of high importance.

This sums up to a big number of characteristics that are sometimes miss-regarded, and when these arrive to the manufacturers hands, changes are necessary to make it possible to build the proposed element. When this happens a cycle of back-and-forth exchange of comments and changes occur until the final product is ready to be fabricated [4]. Even if considered from the planning stages, this back-and-forth process requires extra time, that might signify an increase in costs of the final product.

In past years actions have been taken to automate and support the design process, not only in façade design but also in other areas of the building industry. This is why the use of parametric engineering and design has been in the market for some years now, but only in recent years it has taken a real role within the building industry.

One of the earliest steps taken in this direction was the development of GenerativeComponents for the early stages of structural design. This software tool "uses parametric modelling to let the user define the logic of a structural design. It simultaneously analyses the performance of the resulting structure to give immediate feedback." [5] This approach has accelerated the adaptation of structures to changes in the architectural design without several modifications made by hand. Also, in this way it is possible to have the structural design running hand in hand with the architectural project and spot right away possible problems and therefore offer immediate solutions.

Despite the fact that in previous years façade developments have not been addressed, nowadays research within the façade industry is growing. As mentioned by Montali et al.[4] "Automation of repetitive design tasks and digitisation of knowledge is a possible route towards the improvement of how façades are designed". Following this line of thought the approach of Knowledge Based Engineering (KBE), has been studied for its possible use within the process of façade design. Knowledge Based Engineering (KBE) is considered a product-based approach that consists of a network of interrelated concepts that include specific characteristics of a product as well as its manufacturing knowledge [6]. With this approach it is possible to move the façade manufacturing from Engineered to Order to Make-to-Order type. However, the use of this approach in real life projects is yet to be fully developed.

In previous academic studies, the Make-to-Order approach as well as a Supply-driven approach have been taken into consideration, and tested as a possible initial solution for the Building and Construction industry. In the light of the state-of-the-art solutions for façade paneling, the question for this project arose. The development of it comes from trying to arrange the possibility of turning around the design process, creating a more efficient and cost reduced working process.

In common practice the design process starts with a finished conceptual design to which the products have to be adapted to fulfill its needs. In this proposal the objective is to involve the manufacturer characteristics early in the design stage to be able to provide feasible solutions. In fully functional scenario this would represent at most an 80% of modular panels and only 20% of customized panels. This can only be achieved if the manufacturers knowledge and limitations are taken into account from an early design stage. That is why, the objective of this project is to manage a proof of concept model, in which the characteristics of a specific manufacturer are modeled and then positioned into a conceptual envelope design. Then the following steps would consist on evaluating the fit of the panel, and pass from general dimensions into an specific detailed design of the panel. The final analysis would provide enough explanation to proof (or not) that the use of digitized factories, does in fact improve envelope design.

On that account, this report is presented in 6 chapters. Firstly, a study of several sources related to the development of façade design and the influence of parametric design, not only in the façade industry but in general in the Building and Construction industry. In this chapter the background information that supports the 'why' of this work is explained.

In Chapter 3, the problem is summarized. A problem definition is then established and the approach towards the research statement and research questions are presented. Finally the project approach is stated, specifically the methodology used to finally answer the established research statement and questions.

In Chapter 4, an introduction to the façade company Vianen Kozijnen is given. There, their timber framed panel system characteristics is explained, followed by an explanation of their manufacturing knowledge needed to develop these panels. In addition, the procedure the company undertakes when starting a project and how the design process, the manufacturing process and delivery stage are approached. Finally, the constrains of these processes will be addressed.

Chapter 5 presents the step by step development of this thesis project. This section begins with the explanation of the initial approach and logic used to develop the model. The model started by defining the geometrical aspects of the façade panel based on the specifications presented in chapter 4.

Then, the functionality of this panel against building physics aspects is tested. Finally, the functionality of the tool was tested for a complete façade.

With the results obtained in Chapter 5, Chapter 6 sets a discussion towards the limitations for the development of the tool, suggestions for improvement and future research. Whilst Chapter 7 presents the final conclusions and recommendations for future work. In the figure 1.1 the workflow of this report is schematically presented.

Figure 1.1: Report scheme

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Project proposal

2.1. Problem definition

Building enclosures could be defined as a series of unique elements in a construction [3] and to fulfill their function, several steps from design to construction need to be addressed. As mentioned before the required criteria for façade design sets the boundaries for designers and guides them into which direction the building envelope should be designed. For instance, the designing process starts with choosing the right façade type according to the location, building type, height, lifespan, etc. After this, each building enclosure has to fulfill requirements such as structural integrity, accommodate building movements, weathertightness, energy efficiency, acoustics, blast resistance, and additional functions for different force resistance or performance features [3].

This complete process is time consuming and assumes that the designer should have knowledge on all these areas or, as is currently done, consult experts opinions regarding each of the requirements. That is why in the present process a large amount of iterations between designer and manufacturers take place. This, even if planned, sums up to a great amount of time consumed on changes and since an optimal combination of these requirements is almost impossible to achieve [7], delays may be added to the process. Therefore, by using manufacturing and performance information from early stages in the design, this process can be substantially sped up.

In the past years the possibility of standardizing building processes has been explored. The opportunity of automation of the design process for different parts of a building has been under study for some years, and it has come to the fact that design is addressed as a unique solution for each new building [3]. However, when looking at it in more detail the fact is that even though every building starts as a unique solution, the steps taken to design it are similar or improved versions of things that have been done before. Nevertheless, not much has been done to encode these processes.

As an example, for the structural design, an approach known as StructuralComponents was worked out which improved greatly the initial conceptual design of a building structure

[5]. This tool allows structural designers to establish a model that can be modified rapidly and give initial results that help improve and approve the architectural design, reducing the time spent on calculations and increasing the accuracy of results rather than only having rule-of-thumb results that may drastically change when working in detail.

On other building aspects, specifically for façades, this type of approach has been mainly taken into account when talking about free form architecture. In these cases solutions have been presented that because of the complexity of the shapes, end up being too expensive or too demanding [8]. Nonetheless, no tool has been fully develop to approach this tasks in regards of façade design.

Considering the latter, the need for a design support system for façade design appears to be a needful solution. If developed, this tool will improve the façade design process. It will easily take into consideration the required criteria for a façade while the architect or designer will only need to worry about designing. Furthermore, reducing the number of iterations in the design decisions will most certainly reduce the time it takes for a design to reach the manufacturer and at the same time the risks of having a malfunctioning design are reduced.

In the thesis presented by Moreno [9] titled 'Applying the supply-driven integrated design upon a modular façade company', he considers a supply-driven approach by creating a tool that would allow the client to have more involvement in the design process and specifically focus the design based on predetermined standardize material specifications from a real company. This project can be taken as an example of an initial approach to the process of automating and encoding the design of façades. Having seen that approach, it is important to evolve and take the design process a step further. Developing a tool that not only aligns the design grid to known specifications but also has an almost full design ready to manufacture. Being able to set up a complete factory in a digital model that can be manipulated by architects or designers, and uses the knowledge acquired by years of experience and improvements of the Building and Construction industry. To take these steps it is necessary to work with realistic information, as shown in Moreno's work [9], which is why in this specific case the project with be developed with the collaboration of façades manufacturer Vianen Kozijnen.

2.2. Project description

The final aim of this proposal, that is in fact a product development, would be to create a digital environment in which various manufacturers potential can be explored by designers. Giving access to test the possibilities of their products in an early design stage and finalizing the design in detail with the chosen product would signify a step further in the current way of approaching the design process. In Scheurer's words 'ideally, this knowledge is available in the early design stages in order to optimise the design towards the fabrication method' [8]. At the same time architects or designers would have design flexibility while the tool sets the boundary conditions necessary to turn their designs into buildable elements. However, to develop such a product steps need to be taken, and the collaboration of various manufacturers would be required.

That is why the specific approach of this project would then focus on creating this digital environment, firstly using the knowledge of a single company. Meaning, it is a proof of concept approach. In this specific case Vianen's knowledge would be stored and used to create a model that complies with their manufacturing capabilities. More in depth the main attempt of this research is to encode Vianen's factory in a digital model; encode their knowledge and bring the manufacturing process upwards into early design stages.

The automation process could be as detailed as possible increasing the possibilities to adapt the design and stretch it to satisfy all or most of the designers desires. However, to fulfill the purpose of this project, and comply with the time constrains within it, some limitations to the design were established. This reduces the freedom of design but still allows to demonstrate the extent of work of the developed tool.

2.3. Project approach

For the development of this project the information mentioned previously was taken as the base step. From there and since this thesis will focus on the development of a tool a development statement was proposed, followed by design steps that would mark milestones throughout the project. Then the methodology was established in a manner that would create a sequence leading up to the completion of the set statement. In the following sections a more detailed explanation is presented.

2.3.1. Development statement

This thesis project attempts to encode the manufacturer's knowledge by automating the design process of a timber framed façade panel through a component-based tool; making it useful during the early design stage of a building design process.

2.3.2. Design steps

To be able to fulfill the statement presented above, design steps need to be taken. This steps will mark milestone points in the development of the proposed tool. Each step will then provide an outcome that will show if it is possible to continue with the development of the project or if changes need to made.

The steps were determined in order to generate as an outcome a façade design tool. These steps are listed below.

1. Review the state-of-the-art research in regards to parametric design of façades.
2. Encode the company's knowledge into a parametric model.
3. Investigate the possibility to replicate the panel to form a full façade system.
4. Retrieve the total amount of panels needed. Modular and customized panels.
5. Analyze the performance of the design for building physics aspects relevant to early design stages.

2.3.3. Methodology

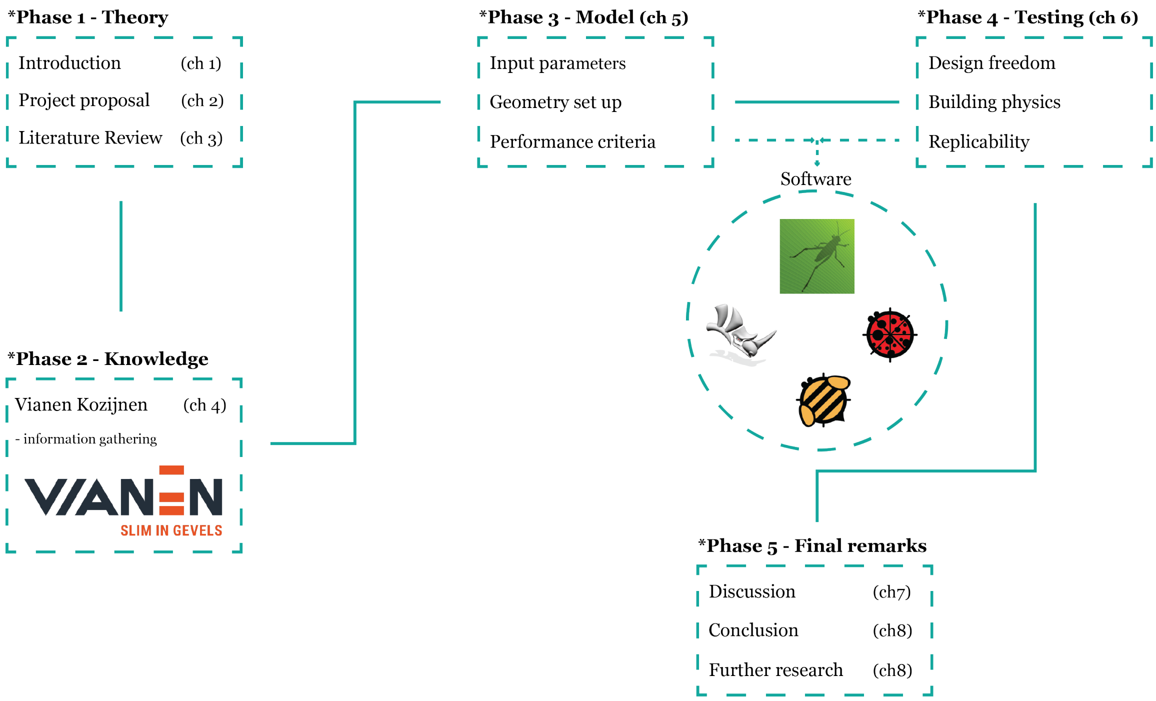

Figure 2.1: Workflow

The approach taken to realize this report, started with dividing the proposal into working phases. These phases would represent different aspects of the development process. In this sense and as seen in Figure 2.1, 5 phases were established. In the end, the connection between these phases would lead the project to be congruent with the development statement.

In phase 1, Chapters 1,2 and 3, present the theoretical framework of the thesis project. This is what led to the development of the project proposal and gives the background information necessary to determine the gap between the current and future design possibilities.

In phase 2, the project begins with capturing the knowledge from the manufacturer, Vianen Kozijnen. For this, it was needed to arrange meetings with the company experts and gather as much information as possible to digitize their product and process with as much accuracy as it is necessary. In this phase all the process and gathered information is presented.

During phase 3, the firsts steps to set up a digital model are taken. Input parameters are arranged into the different parts that shape the completed façade panel. Then the geometry combinations are set up. At the end, the performance in terms of geometry is shown, allowing for the model to vary its form while complying with the manufacturers boundary conditions.

Phase 4 evolves from this last step and starts by showing the flexibility of design, this however is always restricted by the manufacturer's standards, which means that there are certain characteristics that the façade panel must always fulfill to be able to be manufactured and distributed. To finalize this phase of the project, the possibility of replicating this façade panel and locating it into a conceptual façade surface is tested. During this step, the façade panels are arranged into standardize dimensions to cover the entire surface; however in the case of shape changes or need of customized panels, the tool will be able to spot where changes need to be made. Within this testing phase, the tool is set to simulate daylight and sound proofing performance of the proposed panel. These characteristics are tested during early design stages to give more information on the possibilities of performance of the building.

In the end, in phase 5 a section for discussion, conclusion and further developments is established. In the discussion part the logistics and main decisions of the project will be addressed as well as the boundary conditions and limits taken for the development of this thesis project. Then conclusions are drawn from the realized work, and the compliance with the main statement and design steps is determined in this section. Finally, a section for recommendations for future developments on this topic is presented; as well as different possibilities for improvement.

2.3.4. Scope

The general aim of this project is to develop a proof of concept tool and not a fully developed tool, this mainly due to time constrains and limitation on the accessibility to knowledge from different manufacturers. Within this scope, certain restrictions are made to be able to accomplish this goal. The steps taken into account serve as examples of the possibilities to be achieved by this tool. Taking this into consideration, the tool developed could be applied to a single façade surface at a time, using a simplified version of the final panel design. In addition, the simulations to be run for building physics will be specifically for one apartment and one type of panel, this keeping in mind that the goal is a proof of concept tool.

Having established the framework of this thesis project, the next chapter will focus on developing the first step of this process. Aiming in this way to provide as much background information on related topics as possible. Likewise, the aim of the chapter is to clarify the state-of-the-art research and developments in the fields of parametric design and façade design. Additionally, an overview on the possibilities of building physics analyses for buildings and specifically the developments that can be achieved through parametric tools is addressed.

3 Literature Review

In the following chapter the reviewed literature will be presented. These sources have been used as reference and background information to support and back up the development of this thesis project.

This chapter will present a combination of studies made in relation to Façade design and Parametric modelling. Additionally, there are also reviews on reports and papers that refer to the supply-driven approach of the Building and Construction Industry, this sets up a framework that presents the basis for the proposed project.

3.1. Façade design process

When considering the different parts that are involved during a building design, the development and design of the envelope is and has been one of the most important features [10]. This process begins in the early design stages and its importance relies not only on the aesthetic characteristics but on the unique combination between materials, materials properties and performance design principles [3]. However, envelope design has also proven to be one of the most problematic aspects [10] and is one feature that will probably undergo changes throughout all the stages of the building design process [11].

In an attempt to improve this process, throughout the years the technology and materials used for the realization of façades have been in constant development. They have evolved through history from clay, stone, wood, and brick to steel and glass to meet various functional and climatic needs [4]. Initially façades are divided into two categories; load-bearing facades, that are either the primary or secondary structural systems, or non load-bearing facades, that are suspended, contained or supported by the primary or secondary structural system [3]. These determine the link of the façade with the completed building, but in either case the façade elements must be designed to perform in terms of safety, sustainability, human comfort, durability and maintainability, and cost efficiency [7]. In Figure 3.1 a detailed explanation of these aspects is presented.

All these considerations need of course to be concluded into a design that after some detail-

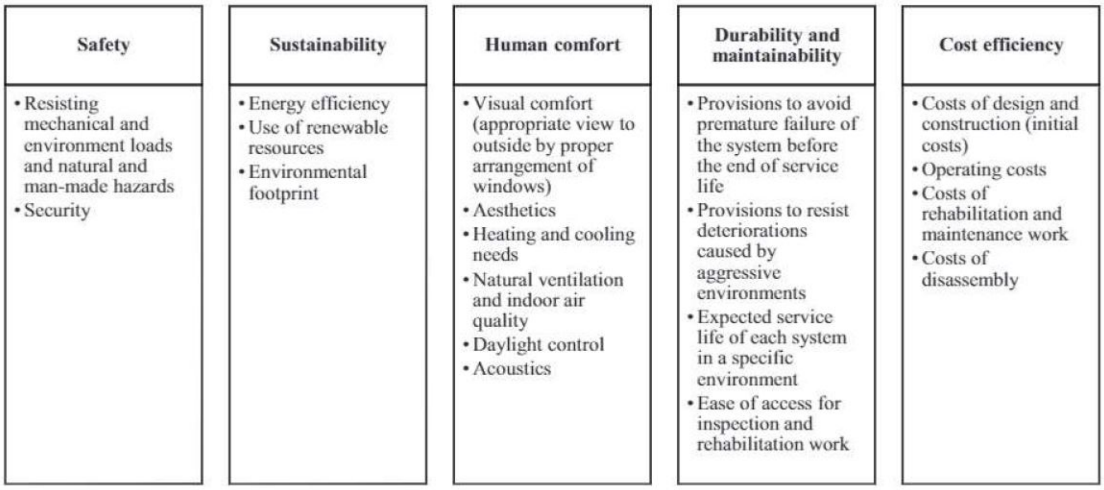

Figure 3.1: Major performance attributes of building envelopes [7]

ing will eventually be manufactured and installed as a finalized product. For years the process followed by designers has been more or less the same; a conceptual design is prepared then it goes through the engineering phase, where some iterations happen until a final design is decided and it is ready to manufacture. Later it would be put in place during construction and begin its operation stage. Years later a rehabilitation process may occur and finally the end of its functional life or demolition [7]. Figure 3.2 portrays this process.

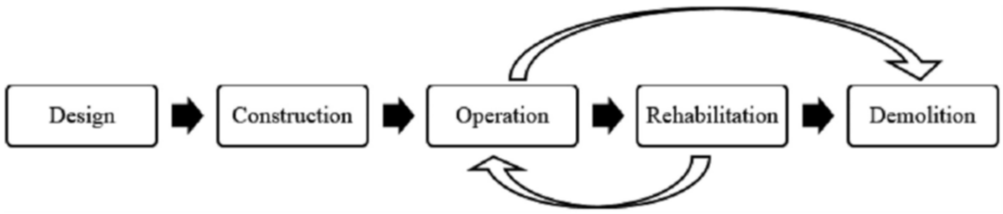

Figure 3.2: Façade design cycle [7]

This design cycle has defined façade products as Engineer-To-Order, having an almost infinite amount of solutions that result in a customisation for every design [6]. In the same manner due to the increased mount of requirements involved in façade design, the need for prefabricated elements has raised and it has proven to be a more and more used approach for the development and manufacturing of façade products. Such approach has since been in constant improvement.

Additionally in the past years increasing demands for high performance buildings with assured cost efficiency, quality and reduced delivery times [4], enhance the need to use digital tools that can deliver and meet these requirements more quickly while still giving the best possible solution. Consequently, different approaches and tool developments have been researched in order to efficiently deliver the required products.

These approaches have been taken in order to, as mentioned before, improve the time and costs linked to façade design and manufacture. Furthermore, in order to improve the façade design industry and in general the Architecture, Engineering and Construction industry (AEC), the use of parametric design and engineering has been a growing research field. Parametric design as an approach to improve design and engineering processes has been used for several years now. The path to digitalization of design and engineering processes can be said that begun with the use of CAD interfaces, later collaborative environments like BIM came into the picture and lately parametric design software are being used as a more abstract approach for designing [8]. Consequently, multiple research and studies have been carried out around these tools.

Since the incorporation of BIM in the AEC industry, it has become an almost indispensable tool within the industry [12]. In the research paper presented by Piroozfar et al. [12], an overview of BIM possibilities and current studies is presented, as well as the development of the knowledge gap that is currently existing in BIM developments. Their aim is to enable modularity of façade components with an approach to (mass) personalisation and customisation. The proposed platform design works through product configurators enabling decision choices between product features and costs, as well as providing an 'universal model' approach that allows this tool to be used on any other model. However, BIM environments have a limitation on their information knowledge, meaning that the system itself can explain what needs to be built and with what properties but it cannot give information about why these decisions are made [13].

In the same line, other research projects have approached the idea of digitazing the façade design process. For instance, the intention to turn façades into Make-To-Order products has taken an important role. As proposed by Montali et al. [6] on their research of Knowledge Based Engineering (KBE) as a design automation process; it is stated the use of this process has been successful on other industries. Hence, in this research the focus is oriented towards façade systems that need to combine different criteria. In the end, it is stated the need to consider façades as highly engineered products, and to keep in mind that even if façades become a MTO product, there has to be an understanding between the mass and customised part of these products[6].

In a later work, carried out by some of the same authors, continuing with the knowledge base approach the importance of involving optimisation of certain knowledge processes in early design stages is emphasized [4]. As a result, giving a straightforward work-plan where a façade is designed for manufacture. Making it viable to have downstream knowledge available in upstream design stages. Their final work concludes that further research is necessary to test the tool within real cases and sector experts [4].

Thereafter, the use of parametric modeling has been increasing in the past years. The ease with which parametric design involves multiple aspects of the AEC industry and also includes different actors within this industry, has made of the use of parametric design and engineering almost a requisite among the architecture and engineering firms [14]. It's use has extensively been researched in the different fields within the AEC industry; an initial more broad development was done for structural aspects. The introduction to StructuralComponents a toolbox designed to aid conceptual structural design, and link the work between architect and engineer

Figure 3.3: Louis Vuitton Foundation - double side bent glass panels for canopies

[5]. From its initial proposal the tool aims to provide immediate and almost precise design solutions that can be detailed in later stages [15]. It's research has been and continues to be a topic of interest because of the advances that can be acquired through this tool.

In spite of parametric associative design being broadly researched for structural elements, there is fewer progress made on other aspects of the building industry. However, the influence of free form in architecture with the inclusion of curve non- orthogonal lines, gave the base to enhance the use of parametric design in envelope design [8], this because complex geometry projects need a great amount of computational power to achieve their design goals.

Nowadays, there are examples of these shapes around the world [8] and there are still more being researched to improve the designing time and costs of such complex geometries. Some of the most known examples on how the use of parametric design has helped on the design process are visible in the work of Zaha Hadid, Frank Gehry or Norman Foster among others. In a research presented by Vaudeville et. al. [16], the design for the Louis Vuitton Foundation is discussed. The approach taken to solve the curved façade panels involved different technologies, after numerous adaptations and innovations, both from the technology applied and from the optimization of the panels, a final result could be obtained. In the end, the proposal presented the use of an innovative machine for the manufacturing of the double curved panels, that had to be refitted and optimised several times to adapt to the design while at the same time their manufacturing was possible [16].

On the same line, the research presented by Eigensatz et. al. [17] portrays the possibilities of façade paneling, the research introduces a digital solution for the paneling of curved shapes. In this research, specifically the possibility of arranging a vast amount of panels within a large-scale free form surface was the point of focus. The results show a tool that allows to determine the different types of curvature that a certain panel might need depending on the position within the façade system. This algorithm was tested within some case studies, concluding that the algorithm indeed allows for "advanced exploration of cost effective rationalizations of architectural free form surfaces" [17].

As previously presented there are several aspects towards façade design that have been addressed, despite that there is still much more work to be done to improve the façade design processes. Scheurer [8] mentions the need of having manufacturing knowledge earlier in the design stages, and as also as mentioned by Moghtagdernejad et al. [7] the inclusions of these parameters would vastly improve the industry. This could turn the Made-to-Order process to a mainstream technology that can reduce time and costs, while at the same time optimising the knowledge gathered through years of experience while maintaining the design freedom to make buildings unique and improving the façade design and in general the AEC industry.

3.2. Building Physics analyses

”Building Physics is an applied science that studies hygrothermal, acoustical and light-related properties and the performance of materials, building assemblies (roofs, façades, windows, partition walls, etc.) spaces, whole buildings, and the built environment” [18]. It has been a focus of study due to the need to build a comfortable indoor environment. Its focus is to protect people from the weather conditions of the outdoor areas. To generate this safe environment the importance of the features of the building envelope increases. It then is not only meant to close up a building structure, but also, it has to withstand the various climate differences and loads that it is exposed to [18]. The combination of these two parts is what generates a comfortable indoor environment. To be able to provide this comfortable indoor space the building envelope, its materials and the structure, need to fulfil certain requirements for heat, moisture, airtightness, sound and light [19].

This aspects are taken into account in the current Building Decree and the requirements to be met have the intention, that on average 80% of the occupants are satisfied with the indoor environment [19]. The requirements related more closely to how a building envelope influences the indoor environment are the following [19]:

- Daylight
- View out
- Glare
- Acoustics
- Thermal energy
- Fire safety

These items are taken into consideration because they have a big effect in the façade’s design. These requirements can have an impact on the design of the façade, like daylight, while others will be affected by the façade’s design, for example thermal insulation.

Moreover, with the increasing use of parametric design, several new tools and plug-ins have been developed to increase its use in different building aspects. For example, when using Rhino, these tools are available to work within the Grasshopper environment and can run tests and simulations for several aspects within the building physics studies [14]. The simulations possible are listed below:

- Daylight
- Thermal

- Ventilation
- Acoustics
- Sight nuisance
- Fire safety
- Energy performance
- Sustainability

Furthermore, when in practice in a certain way the relevance of Building Physics aspects is boosted because the majority of the relevant possible issues are related to the performance of the finalized façade [4]. These capabilities have increased significantly in the past years, and are being developed not only as additional elements to the design companies but now-a-days there are specific companies specialized on solving building physics problems and requirements through a parametric approach.

4

Vianen - Timber framed façade panel

The following chapter introduces the façade manufacturer Vianen Kozijnen, this company designs and manufactures window frames and façade panels made out, almost entirely of wood. The aim of this chapter is to present an overview of the data gathered that is needed to model the digital tool that would ease the design process of the façade manufacturer. In this specific case Vianen agreed to share their design and manufacturing knowledge on timber framed façade panels, which will be the object of study of this thesis.

4.1. Introduction

Vianen Kozijnen is a façade and window frame manufacturer. It was founded in 1961 as Houtindustrie Vianen and has grown to become one of the leading wooden façade elements and wooden frame producer in the Netherlands. Vianen Kozijnen is located in Montfoort where they have an in-house factory and where all work is arranged from design to delivery.

The company's aim in the façade industry for some years was to find a solution to be able to use wooden façade elements in high-rise buildings. Due to the great influence of weather and wind, this was often considered impossible. Nowadays their research has focused on the design and production of wooden façade panels for high-rise buildings in the Netherlands. Their design solutions has led them to achieve a KOMO certification.

Being part of the construction industry for a long time now, Vianen Kozijnen has participated in the design and manufacture of a number of buildings in the Netherlands. Some of their design solutions are shown in the Figure below 4.1. These designs show that it is in fact feasible to have high-rise buildings with wooden façade panels; some of this projects are still under construction.

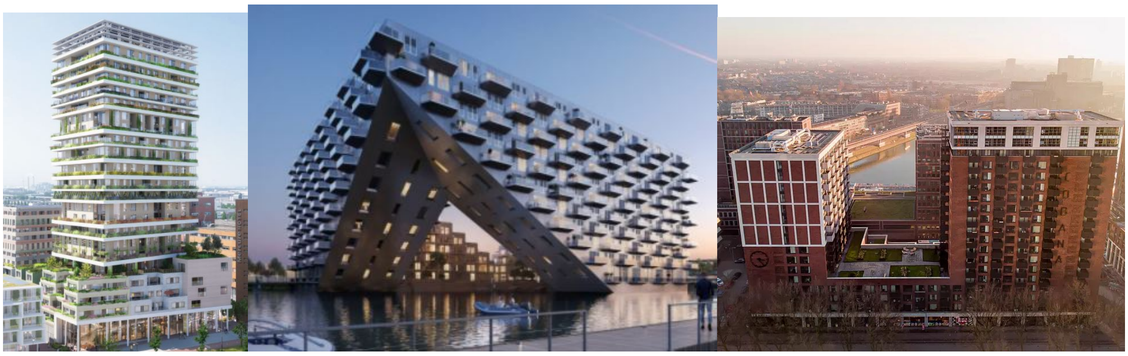

Figure 4.1: Project examples from Vianen - from left to right a) Vertical Building in Amsterdam; b) Sluishuis Building in Amsterdam; c) Cobanna Building in Rotterdam

4.2. Manufacturing process

Vianen's working process relies on the use of BIM models to share relevant information with all the working parts involved in each project. The use of BIM models also allows the company to automate certain characteristics of the façade panels design. Information about room functions, use of materials and planning of activities is stored centrally. From contractor to suppliers, all parties involved work directly in or with the available documents and the adjustments are processed in real-time, in the construction drawings and the 3D model. Therefore is possible to summarize their working process into seven steps, shown below. Installation is out of the scope of their work.

a. Sales - initial contact with sales manager
b. Calculation - first proposal offer
c. Engineering - clear knowledge of the work done
d. Work preparation - prepare project for production
e. Production - assembly of products
f. Transportation - transport taken care by Vianen's personnel
g. Delivery Service - delivery to construction site

Furthermore, in their recent work Vianen has been getting more involved from the beginning of the design process. Being present since the start of the project eases the complexity of modulating the panels, it also allows for suggestions or changes in the initial stages that are easily adaptable. Whilst having the finalized design delivered to solve, creates complications and generally a higher amount of specially made panels are needed to fit the design needs.

4.3. Manufacturing knowledge

Throughout their years of work the company has been able to gain knowledge in their field and summarize it as rules and standards to be considered and used in future projects without disrupting the flexibility of the panels design.

This gathered knowledge has been divided in two main topics; the geometrical characteristics and the building code regulations that need to be achieved. These topics are closely linked as they are dependant on each other to achieve the functionality of the finished façade panel.

In the next sections the pre-conditions and design rules established by Vianen will be presented. This information will be the base ground for the development of this thesis project. The information shown in these sections was obtained through an Excel document shared by Vianen, and also some additional information was gathered through meetings with the company experts.

4.3.1. Panel characteristics

When talking about panel characteristics, it is the geometrical features that are considered and that build up the façade panel. In this section the pre-established design rules are presented.

In table 4.1 the maximum and minimum values for the general design of a façade panel are shown. The values presented represent the main element characteristics. This values are a reference to the desirable design conditions to fulfill the necessary values according to the Building Codes standards.

Table 4.1: Maximum and minimum values of a standard panel

Description	Maximum Value	Minimum Value
Height	3200 mm	76 mm
Width at < 3200 mm	8000 mm	76 mm
Thickness excl. plating	235 mm	235 mm*
Outside plating	12.5 or 25 mm	12.5 mm
Inside plating	9 mm	9 mm

*The RC value 4.7 is easily attainable with wood of 235mm thickness

However, there are certain exceptions that can be made in relation to the dimensions. This exceptions will have an effect on the conditions mentioned above, and are not the most appropriate, but in situations where they are necessary the following values can be used. It is important to mention that not all the values have the possibility to extend their reach.

Table 4.2: Exception values standard panel

Description	Maximum Value	Minimum Value
Height	3600 mm	76 mm
Width at > 3200 mm	6300 mm	76 mm
Thickness excl. plating	235 mm	89, 120, 140, 184 mm
Outside plating	12.5 or 25 mm	12.5 mm
Inside plating	9 or 12.5 mm	0 (folie)

At the moment of considering the openings in the façade panel, there are as well certain geometrical conditions that need to be met. In the following table the maximum and minimum recess values are shown.

Table 4.3: Openings

Description	Maximum Value	Minimum Value
Height	300 mm	70 mm
Width	600 mm	76 mm
Recess top and side	-	36, 76, 114 mm or bigger
Recess bottom	-	60 mm
Continuous bottom and top rail	required*	required*

*Below and above every opening there must be a supporting rail, this will be a wood element with the same dimensions as the internal structure elements

In this case as well there are certain exceptions that can be taken into account in the design process.

Table 4.4: Openings exceptions

Description	Maximum Value	Minimum Value
Height	114 mm	50 mm
Width	76 mm	50 mm
Recess top and side	-	38 mm
Recess bottom	-	38 mm
Continuous bottom and top rail	required*	required*

Lastly, there are some values that are set for any panel design, this only have one established value that cannot be changed. These pre-established values are presented in the following table.

Table 4.5: Independent values

Description	Value
Thickness of internal structure	38 mm
Distance between internal structure	max. 600 mm
Insulation	max. 562 mm
Ventilation openings	115 or 70 mm

The set of values provided by Vianen, are a guide of information that helps to easily recognize the limitations of manufacturing of the final products. It is noteworthy to mention that generally the designs are kept within the standardize values as this represent the most common way of producing the façade panels. Therefore, when designing with the exception values there will be need for a recalculation of the façade element and this will translate into a specially manufactured product, meaning it will take more time to design and manufacture, making it a more expensive product.

4.3.2. Specifications

In the Netherlands there are specific building code specifications that need to be met by the manufacturer. This are already established values that need to be taken into account when designing, in this specific case, a timber framed façade panel. For this conditions, Vianen has made a list of the requirements needed and limitations on their design so this conditions are always met. In that sense, the values presented in Section 4.3.1 were predefined taking into consideration the building code specifications. In the table below the values considered for the design are presented.

Table 4.6: Building specifications

Description	Conditions
Openings limit to meet RC=4.7	= < 80%
Adjust space side & top	20 mm
Screed thickness	90 or 60 mm*
Fire resistance 30 min	No action required
Fire resistance 60 min	Double inner plate 25 mm + inner plate 9 mm
Soundproofing RW <45 dB	single inner plate 12.5 mm
Soundproofing RW 45-50 dB	double inner plate 25 mm

*60 mm will be an exceptional value in this case the standard will always be 90 mm

All the information that has been presented in this chapter is the base input used to begin the development of the design tool, which is the objective of this project. In the following chapter the process and methodology taken to develop the tool that will allow to encode Vianen's factory knowledge, is explained in detail.

5

Factory to digital model

In the following chapter the development of the proposal will be presented. This process demonstrates the development of phase 3 as shown in Figure 2.1, which corresponds to the modeling phase. Initially the geometrical features of the timber framed panel were set based on the information gathered from Vianen. The knowledge provided by Vianen was captured in the form of numerical sliders that are restricted to the company's possibilities for manufacturing; the detail information used for this is shown in Chapter 4.

Once the geometrical features were modeled, the steps taken to achieve the replication of the panel to form a façade system are explained. Then, the process to obtain preliminary results for daylight and acoustic simulations are presented. Overall, in this chapter the methodology applied to each of these processes is explained in detail.

5.1. Input parameters

The geometry of the timber framed façade panel was setup taking into consideration the parameters obtained from the knowledge shared by Vianen. These parameters were divided into initial input parameters that would control the base of the complete model, and secondary parameters that are applicable only to certain elements of the façade panel.

The steps taken were planned in a manner similar to what the process for designing these panels in the company is. In this way it can be said that for example, initially the general dimensions of the panel are chosen, hence the external frame is the first element to be designed; then the stability of the panel needs to be assured and so the internal structure is determined. Later, the panel needs to be 'closed' with a plating system from both outside and inside. Finally, in case there are openings to a certain panel design, then these have to be created.

As a reference design, the model portrayed in Vianen's website was taken as the base model in which all the elements that build up the panel are portrayed. This panel was used as a guideline prototype, but it won't be the only design portrayed within this project. The referenced panel can be seen in Figure 5.1.

Figure 5.1: Referenced timber framed panel front and back

From this example it was possible to generate the geometry, and four main variables within the frame were determined:

1. External frame structure
2. Internal structure
3. Openings
4. Plating - inside and outside

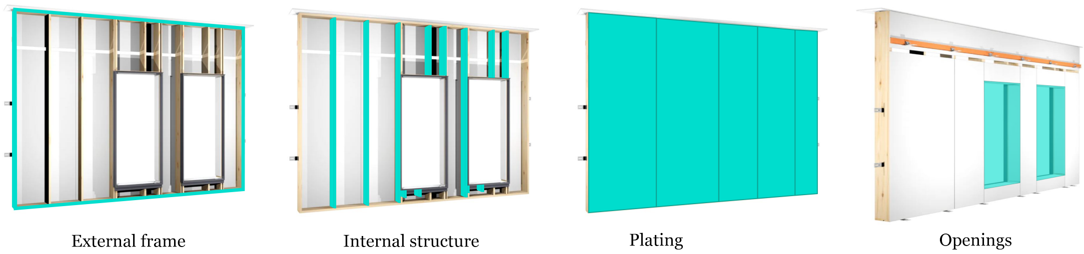

Figure 5.2: Façade variables

These variables would be the basic elements needed in the model, however, as learned from Vianen there are certain elements that need to be added that are dependant on different design conditions. These elements will be explained in detail when they become applicable in the following sections.

5.2. Geometry set up

Taking into consideration the variables broken down from the example panel, it was possible to begin modeling the panel's geometrical features. The outcome would then be the finalized design of a single panel. In the following sections a deeper explanation of the logic used to model each of these elements is presented.

5.2.1. External frame structure

The external frame structure of the panel is determined by the general dimensions of the proposed design. Therefore, four types of dimensions were determined for this aspect; these dimensions correspond to the general geometrical characteristics of the panel and the material; length, height, width and thickness of wood. From these dimensions and according to the information obtained from Vianen, three were set as variable inputs and one fixed input for the thickness of the wooden elements as specified by the manufacturer. In Table 5.1 the used dimensions are shown.

Table 5.1: Parameters consider for external frame structure

Parameter	Dimensions	Gh Component
Length	76 < 8000	slider
Height	76 < 3200	slider
Thickness	38 mm	panel
Width	235 mm	value list*

*value list with four extra variables 89, 120, 140, 184 mm. These variables present a warning as only for the standard dimension is possible to assure a façade resistance (RC) of 4.7 as required.

With these input parameters, the build up of the external frame was developed as follow:

a. line determined by the length parameter.
b. extrusion in Z plane of said line, the height is determined by the height parameter.
c. offset the obtained geometry, determines by the thickness.
d. extrusion in Y plane of the geometry on step (b).
e. extrusion in Y plane of geometry on step (c).
= output obtained by the subtraction of both solid elements.

And schematic representation of the procedure is shown in Figure 5.3.

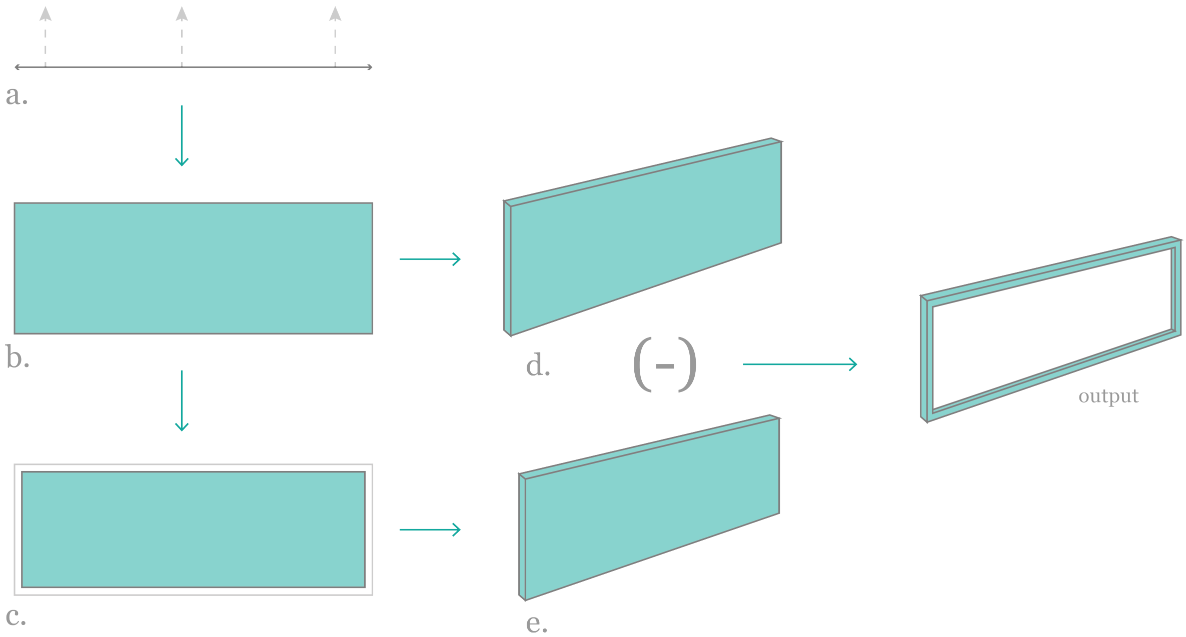

Figure 5.3: External frame logic

5.2.2. Internal structure

Once determined the logic for the external frame, the next step was to setup the internal structure of the panel. For this, first the dimension along which the elements will be positioned is determined by using the internal length found between the vertical elements of the external frame. Following the information retrieved from Vianen the distance between internal structural elements should be 600 mm, to ensure the panel's stability; the aforementioned length was divided by 600 mm obtaining (X) number of points along that line.

In a separate sequence the dimensions for the base of the internal structure are set. These have a thickness of 38 mm, as all the wooden elements used in the design of these panels; and the width is dependant on the width of the external frame. Once this rectangular area is determined, it is located in each of the points created before. Finally, these areas are extruded and its height is dependant on the internal height of the external panel, in this way the output is the internal structure of the panel.

The breakdown of the procedure into steps is shown in an schematic representation in Figure 5.4.

a. inputs taken from step c 5.3 of the external frame logic.
b. length to be covered by the internal structure.
c. length divided by 600mm, a dimension established by Vianen.
d. setup area of one structural element; with thickness 38mm and length dependant on the external frame width.
e. array along the points obtained in step c.
= output obtained by extruding the elements.

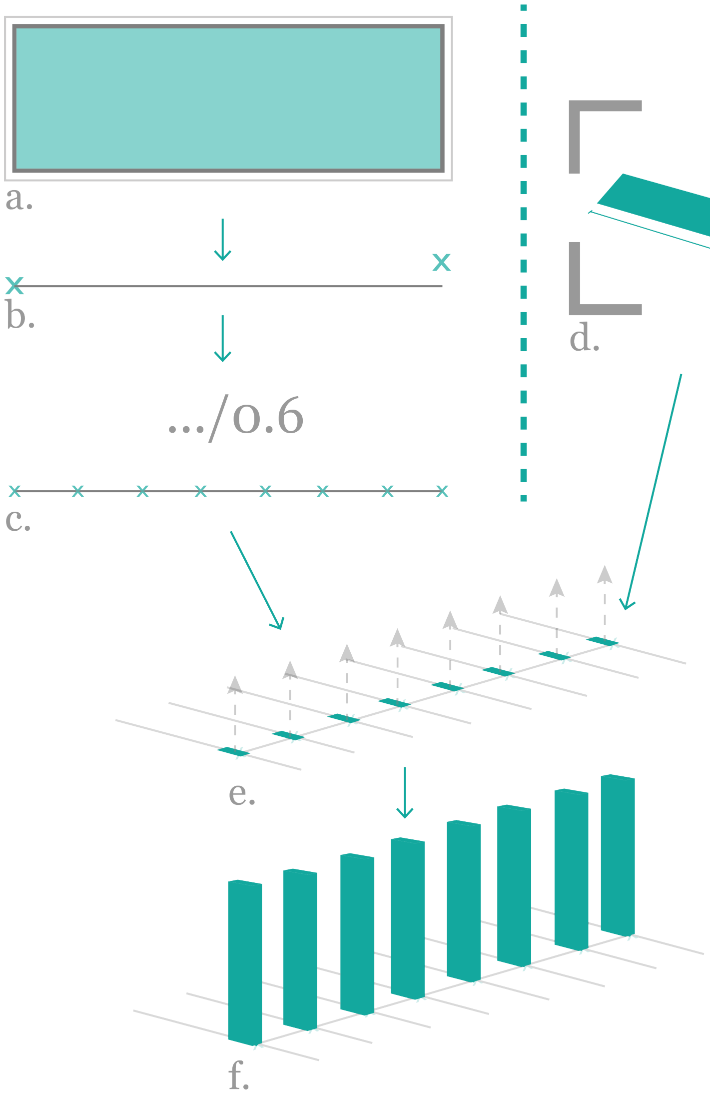

Figure 5.4: Internal frame logic

5.2.3. Plating

Following the design steps and conditions stated by Vianen, the third step in regards of the geometry setup is the close up of the panel. This is achieved by attaching Fermacell gypsum panels to the inside face and prefabricated concrete panels to close it from the outside. Even though the plating materials used for the inside and outside parts of the panel are different from each other, because of their end purpose, the logic to reproduce them in a model is similar for both cases.

The process followed to developed this logic starts with the length of the complete panel determined by the first variable used in Section 5.2.1. Then this distance is divided by 1200 mm, which corresponds to the length in which the panels provided by the manufacturer. The segments obtained, are then extruded until reaching the height defined by a variable slider in the input parameters. Finally for both inside and outside another extrusion is made in the Y direction to define the thickness for these panels; for instance a value list with two set values is defined for each of the paneling groups. In Figure A.5 the schematic representation of this logic is presented.

a. length taken from step a. of 5.3 for both inside & outside.
b. division of this length by 1200 mm.
c. segments obtained to be extruded.
d. output 1 obtained by extruding the elements.
= final output, extrusion on the Y axis to generate the thickness of the panels.

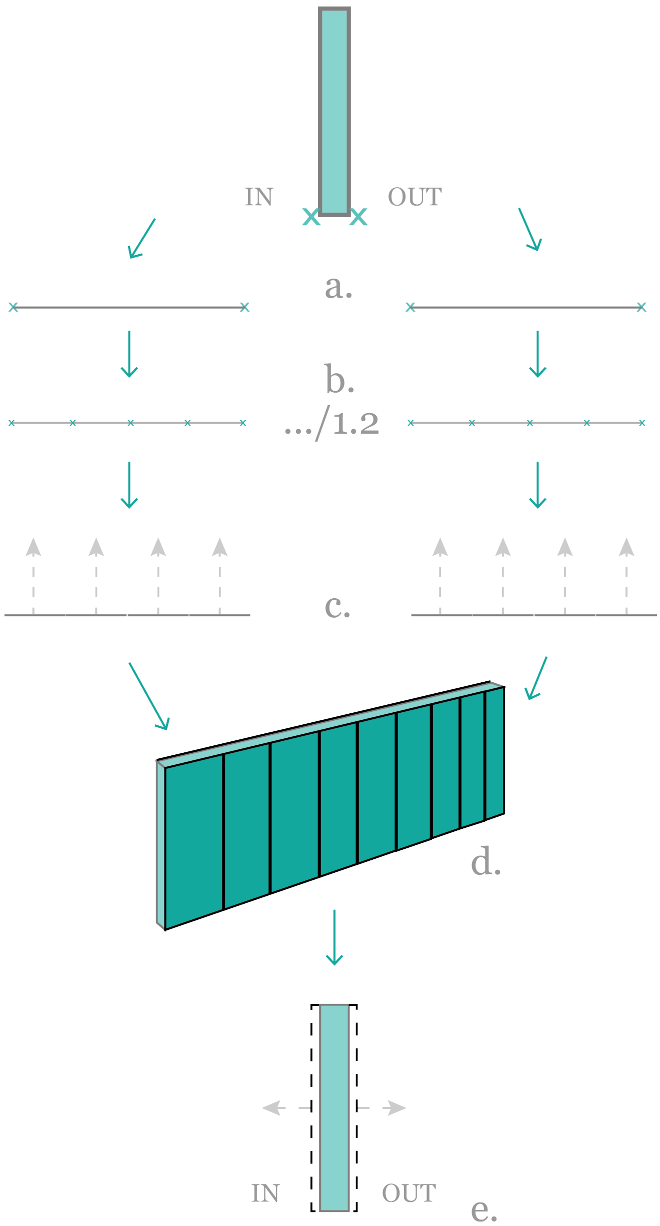

Figure 5.5: Inside & outside plating logic

5.2.4. Openings

The final step in the development of the geometrical model was the inclusion of openings. Since the inclusion of openings within the panel is dependant on the façade design, for this some boundary conditions were established. That is why three opening options were determined in this case for this panel. The options are:

a. No opening
b. Single opening
c. Four possible openings

No opening

In this case the no opening tab would correspond to a design in which the chosen design is a closed panel. For instance no changes will appear and the resulting design would correspond to basic geometry.

Single opening

The development of this option was planned taking into account the possibility of the panel of achieving a almost fully glass (open) design. However with the modeled logic it is possible to generate a single opening in any position within the panel. Initially a multidimensional slider is used to be able to determine the initial point, then the dimensions for the opening can be set with sliders. Once this is set, the cut out from the already modeled elements is required; a box is created with the dimensions previously determined and this shape is subtracted from the completed panel. Finally, an area with thickness 38 mm and length linked to the width of the panel, is used to create a frame surrounding the created opening, providing the additional support required for cutting out the internal structure elements. In Figure 5.6 the schematic representation of this logic is presented.

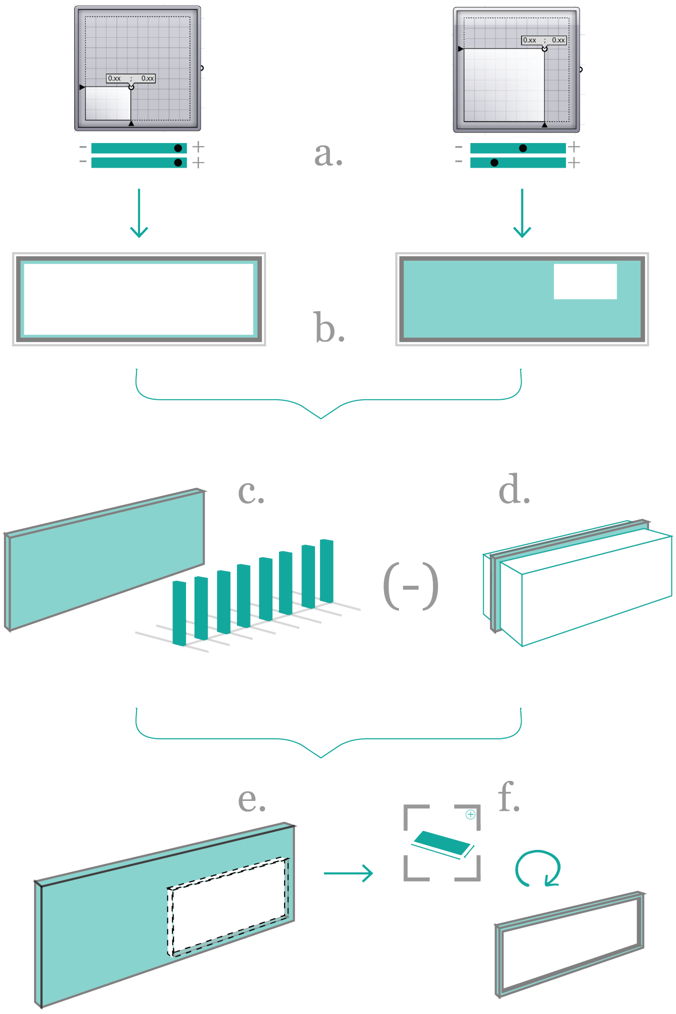

Figure 5.6: Single opening logic

Alternate openings

For this last option, it was considered suitable for a reasonable development of the geometry the possibility to create maximum four openings within the length of a panel. In that manner, the panel was divided equally into four areas and each of the four segments follows the same logic to develop an opening, or maintain a closed segment. In the same way as the procedure generated for the single opening, in this case each of the four segments is evaluated and has a multidimensional slider the allows to position an opening in any point within the selected segment area. Then, the opening dimensions are set through sliders. The generated area is extruded creating a box that would later be subtracted from the completed panel designed previously. Finally a frame around the opening is generated to provide the required support to the trimmed structure.

In Figure 5.7 an schematic representation of this procedure is presented.

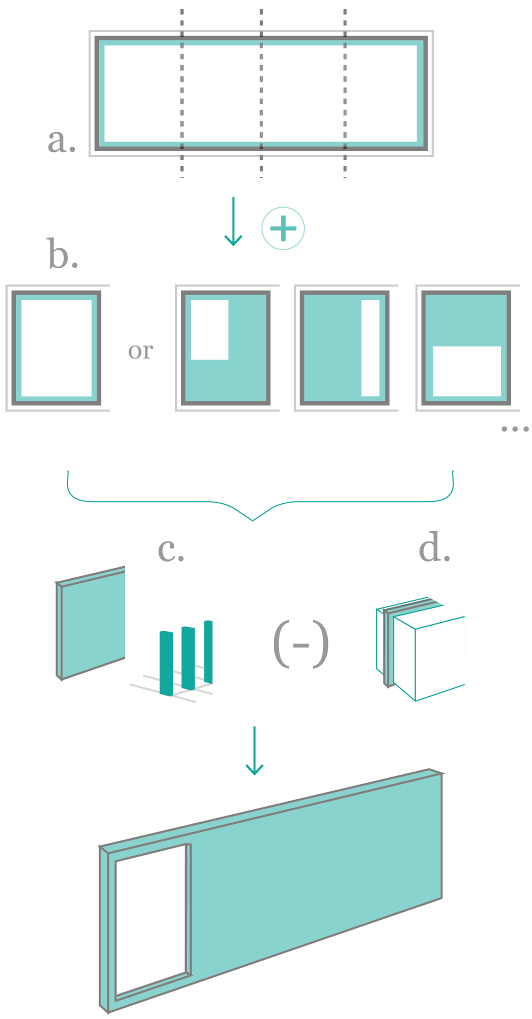

Figure 5.7: Alternate opening logic

In short, in Figure 5.8 the complete sequence of elements that build up the facade are presented. This geometry will now give a base design to work on tests that give the panel the necessary requirements to put it a step closer to be fully manufactured.

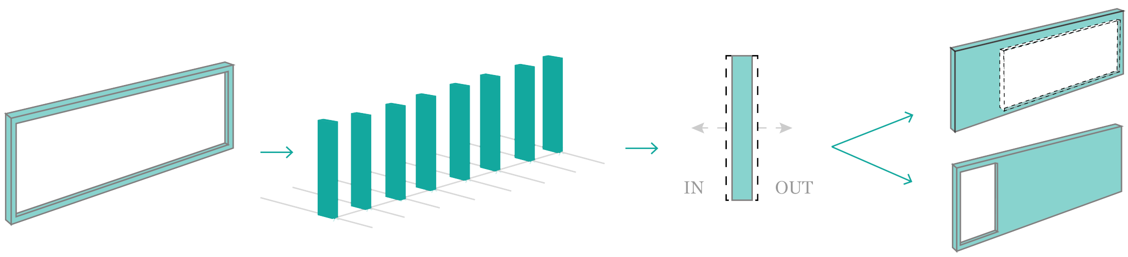

Figure 5.8: Design sequence

5.3. Model testing

To enhance the validation of this proof-of-concept model, two factors were determined. The first one was to manage to replicate the previously designed panel throughout an entire façade. In this case the tool would analyze the conceptual façade shape and determine where the modular panels can be arranged and were these will need to be customized. Later the selected panel is tested for two building physics aspects that can give the information required to determine possible changes in the orientation of the building, opening sizes, material choice, and other related factors. For this, simulations on daylight and acoustics performance were analyzed.

For both cases, replicability and building physics simulations, a practical case study was taken into consideration. The selected building was the Sluishuis Building in Amsterdam. This project was selected among some projects in which Vianen has previously worked. This particular building was chosen due to its particular shape, that is complex enough to test the possibilities of the tool while being geometrically feasible to be solved with planar panels, as the used in this proposal. The application of the tool to this case study and its results is further developed in Chapter 6.

In the following sections a detailed explanation of the methodology followed to determine the feasibility of these aspects within the proposed tool are presented.

5.3.1. Replicability

According to the Oxford dictionary of languages [20] *Replicability* refers to the quality of being able to be copied or reproduced. With this in mind, the replicability aspect was raised in this proposal because one of the aims for the development of this tool is the ability to generate within a certain façade the greatest amount of modular panels. For this purpose it was important to determine the fitting of the previously designed panel across a conceptual façade proposal.

Initially, as in any project, a conceptual design of the building and the façade are given by the architect or designer. For this project, the decided case study was modeled as a building block in Rhino 7, from which it was possible to retrieve the information needed to begin the process. Once the conceptual façade is input into the Grasshopper canvas, the process begins. This process was divided into four steps, that are explained below.

Step 1

The first step begins with the analysis of the conceptual surface. This process determines the surface points from which a grid is generated. With this information the length of the surface is determined and it is set to be divided according to the previously defined length of the designed panel. Then, the designed panel is located in the starting point of the conceptual facade; this point, currently, is manually determined by the designer, giving the freedom to choose where the panels location should begin. Having set the starting point the panel is arrayed along the length division determined before. Then these group of panels is arrayed again in the vertical path and the amount of levels is determined by the input value for number of floors of the building.

At this point the result is a square surface full of panels. This needs to be trimmed to fit the actual shape of the conceptual façade.

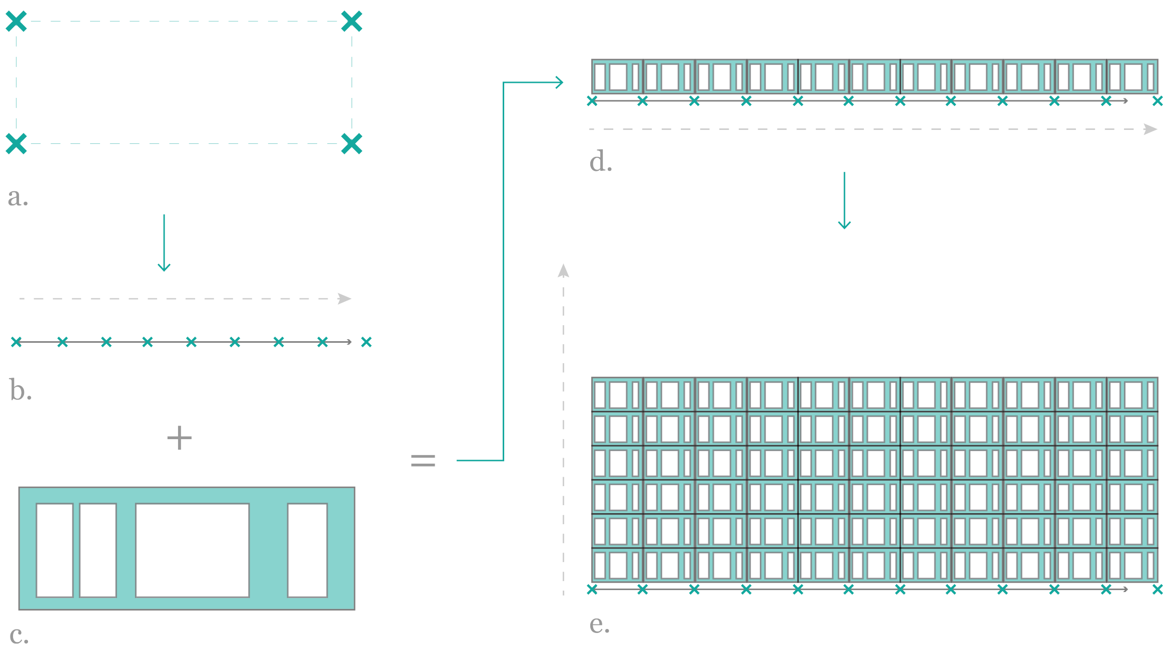

Figure 5.9: Replicability - Step 1

Step 2

The second step is focused on retrieving the cutting lines to finally determine the panels that would be part of the façade. For this, the perimeters of both shapes, the conceptual façade and the full panel array, are extracted and intersected. Through this process it is possible to determine which lines are shared among both shapes and it is possible to extract the 'odd' lines, which will determine where the panel array needs to end. When these lines are sorted through a deconstruction of the shapes, it is possible to extract the cutting lines.

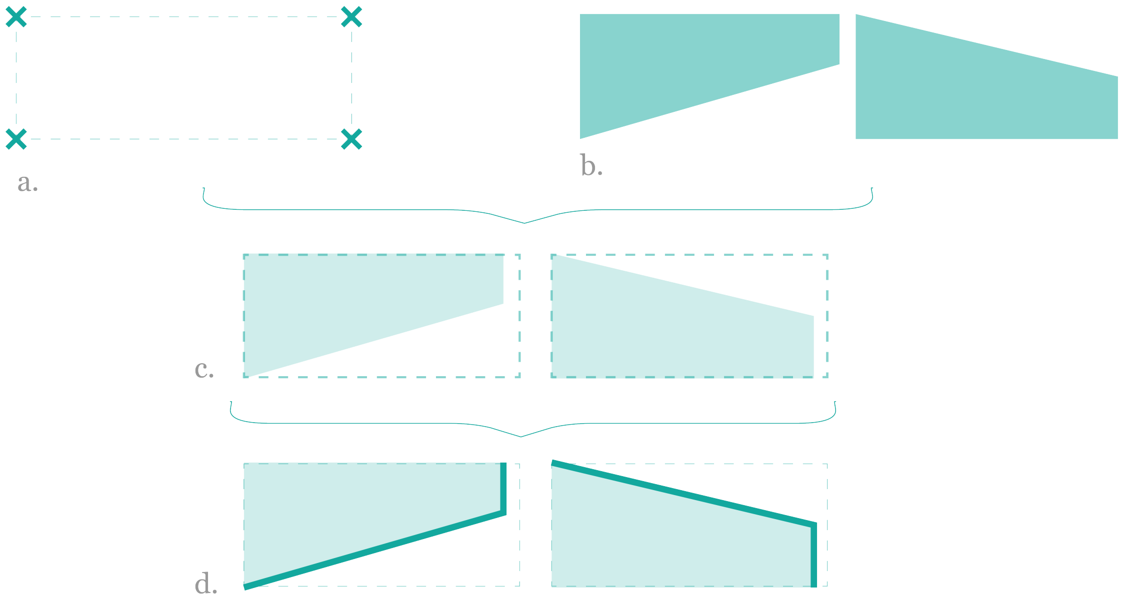

Figure 5.10: Replicability - Step 2

Step 3

Once the cutting lines were defined, the individual panels within the array are analyzed. This determines its midpoints, and at the same time the points through the cutting lines are determined. Then the midpoints in the panel array are compared against points in the cutting lines, determining the closest ones to it. These points are then related to the panel they belong to, and these panels are marked in a different color, representing the customized panels. From this process it is possible as well to determine the exact amount of customized panels.

Step 4

At this point, there are still panels that need to be accounted for to determine the total amount of modular panels. Following a similar logic to Step 3, the midpoints representing the panels, closest to the customized panels that are outside the boundaries of the conceptual façade are marked to be deleted. Then the ones left, that are located fully within the boundaries of the conceptual façade account for the final amount of modular panels.

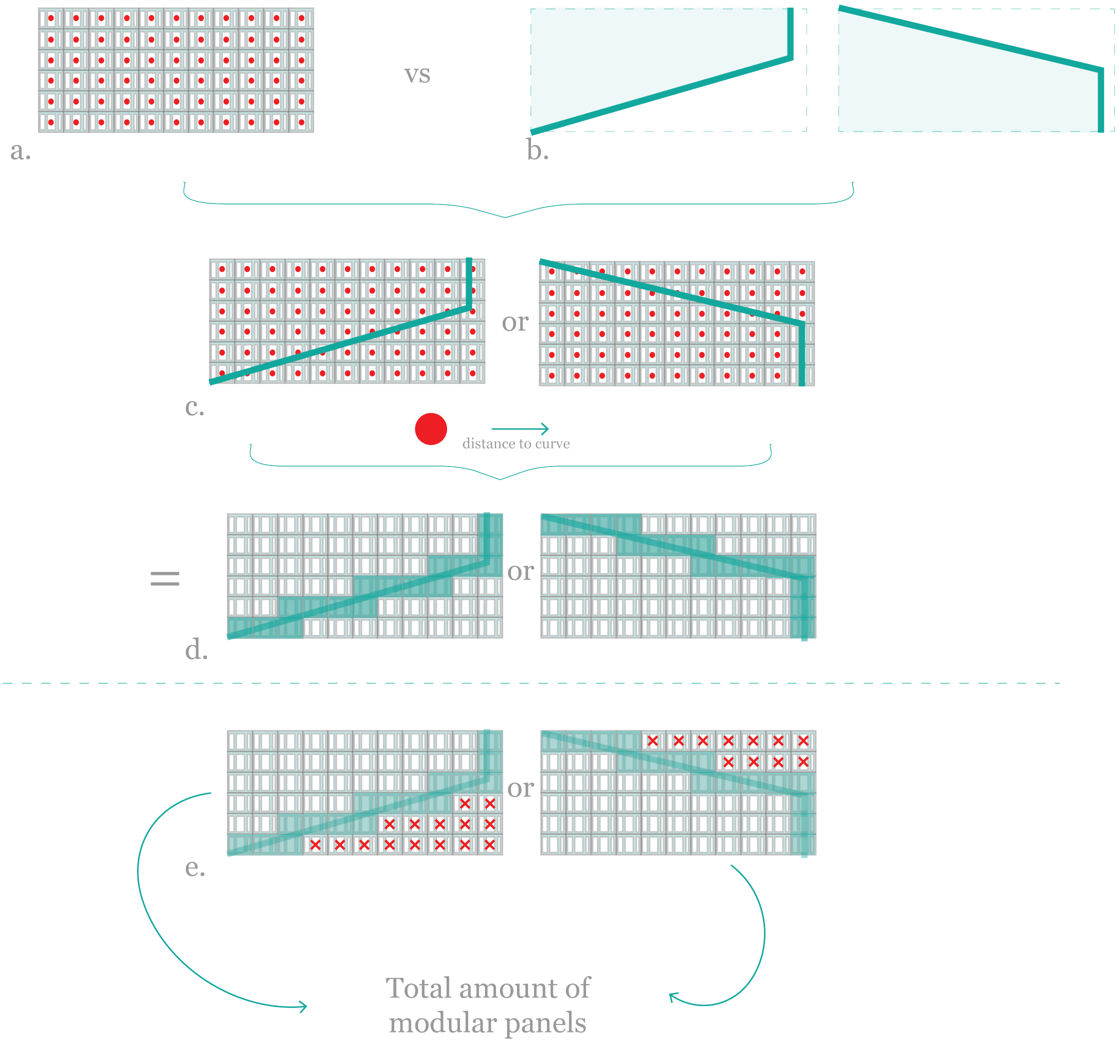

Figure 5.11: Replicability - Step 3 & 4

The results obtained from this process are three numbers; one determines the total amount of modular panels needed to generate the desired façade; the second one determines the amount of panels that need to be customized and the final value gives the percentage of customized panels in relation to the full façade.

At this point the replicability is shown to be feasible. The set-up of the input parameters obtained from the manufacturer for both design and replicability of the panel are shown to be, succesfully, an automated process. With these results the geometrical aspect of this proof-of-concept proposal is established.

5.3.2. Building physics

Once the replicability aspect of the façade system is established the next step relies on testing the system for its building physics characteristics. As mention in Chapter 3, there are different aspects related to Building Physics analysis that apply to different stages of a façade and building design.

With that in mind, it is important to mention that there are some Building Physics aspects already taken into consideration by the manufacturer, in this case Vianen has some standardize considerations, that are presented in Chapter 4.

Table 5.2: Specifications

Description	Conditions
Openings limit to meet RC=4.7	= < 80%
Adjust space side & top	20 mm
Screed thickness	90 or 60 mm*
Fire resistance 30 min	No action required
Fire resistance 60 min	Double inner plate 25 mm + inner plate 9 mm
Soundproofing RW <45 dB	single inner plate 12.5 mm
Soundproofing RW 45-50 dB	double inner plate 25 mm

The conditions presented on Table 5.2 have already been tested by Vianen and are proven to work within the limitations presented in the previous section.

In this project's case the façade is already a market product, and as mentioned before some of the required regulations towards Building Physics are already taken into account. This in contrast with the common practice design solutions of a top-down approach, that first designs and later-on adapts the available products in the market to fit the unique requirements, is what causes a series of design iterations that delay and can even generate more costs [4].

This is why in the framework of this proposal, through a bottom-up approach is trying to ensure that these requirements are digitally double checked, saving iterations time between designer and specialist. Taking into account the previously mentioned characteristics, for the development of this project, the tests and validations to be carried out will be focused mainly in the influence of daylight and sound insulation performance, these parameters have a big influence in the early design stages of the façade system. In the end the results obtained from these iterations would give the opportunity to define if there are big changes or what are the possibilities for improvement. For example, if better insulation is needed, changes of glazing may be required or additional elements to improve the occupants comfort.

This approach will also help to define if the results obtained in the different cases, vary significantly and so the use of the proposed tool is validated. The possibility of making this iterations in an automated way would highly improve the time/cost relation within a building envelope design.

In the following sections the development of the automated process for daylight and acoustics simulations is presented.

Daylight

Daylight in an interior space depends mainly on the availability of natural light and the characteristics of its surroundings [21]. During the design process the simulation of the lighting environment helps the designer choose a possible orientation, size of the openings, building type, energy saving strategies, and more. [22]. To determine this, the workflow related to daylight simulations has around six steps, this however may vary a little through different software or methods. The first steps involve the generation and set up of the model, the last three refer to the simulation, collection and analysis of the data. These results obtained are used to define details on the design process [22].

In the same manner, these results have to fulfill minimum requirements stated in the European Standart NEN-EN 17037 [21]. Mentioned in this standard are three target illuminance categories; minimum, medium and high, with values of 300, 500 and 750 lux respectively. In the standard the minimum value recommended is the value that is achieved through 95% of the space for an specific target illuminance, for 50% of daylight hours. These parameters are given for office or working spaces, in the case of dwellings these parameters are set as a recommendation.

Additionally, in the norm NEN-EN 12464-1 detailed information for work spaces requirements is give. An example of one of the requirements for offices is given in Figure 5.12.

Table 34 — Offices

Ref. no.	Type of task/activity area	$\bar{E}_m$ lx		U_o	R_a	R_{UGL}	$\bar{E}_{m,z}$ lx	$\bar{E}_{m,wall}$ lx	$\bar{E}_{m,ceiling}$ lx
		required[a]	modified[b]				$U_o \geq 0{,}10$		
34.1	Filing, copying, etc.	300	500	0,40	80	19	100	100	75
34.2	Writing, typing, reading, data processing	500	1 000	0,60	80	19	150	150	100
34.3	Technical drawing	750	1 500	0,70	80	16	150	150	100
34.4	CAD work stations	500	1 000	0,60	80	19	150	150	100
34.5.1	Conference and meeting rooms	500	1 000	0,60	80	19	150	150	100
34.5.2	Conference table	500	1 000	0,60	80	19	150	150	100
34.6	Reception desk	300	750	0,60	80	22	100	100	75
34.7	Archiving	200	300	0,40	80	25	75	75	50

[a] required: minimum value
[b] modified: considers common context modifiers in 5.3.3

Figure 5.12: Light requirements for offices

There is also the possibility to present daylight simulations on daylight factor terms. Daylight factor is used when considering an overcast sky, an there are minimum requirements depending on the location, the requirements are presented in NEN-EN 17037 [21]. This factor is used to determine the level of illuminance through daylight and it is the relationship between the illuminance indoors and the illuminance outdoors (sky) [23].

In the norm there are two possible calculation methods explained; one based on daylight factor and the second using hourly climate data. In the simulation made in Grasshopper, with the plug-in Honeybee the method applied considers the hourly climate data [14]. This calculation method, as described in the standard [21], determines daylight from the simulated illuminance in the reference plane and it should achieve the target illuminance for 2190 hours, that represent the half of the daylight hours per year.

Hence, the set up to determine this values through a parametric model, was managed within the Grasshopper environment with the use of the plug-in Honeybee. As mentioned before the simulations run through Honeybee take into account the hourly climate data. This process was set-up in the following three steps.

Step 1

To be able to begin using the Honeybee (HB) components, it is first needed to transform the Grasshopper geometry into HB objects. In this case the geometry is retrieved from the final designed panel. Then using the replicated geometry the length of the space to be analyzed is established. With this length and using the height of the panel plus a manually input value for the depth of the building or apartment, a box like volume is generated, this element will represent the geometry to be analyzed.

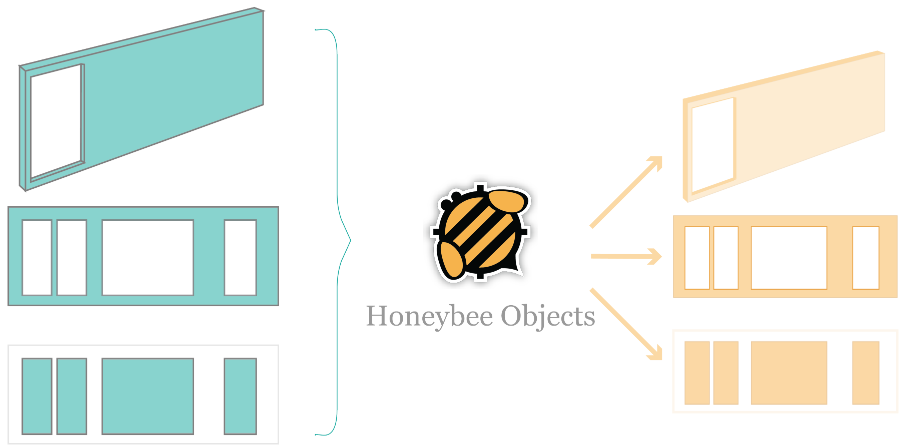

Figure 5.13: Daylight simulation set up

Step 2

To be able to generate a daylight simulation, it is important to indicate which are the opening areas. For this from the openings created for the final designed panel, the area of the openings is determined.

Step 3

Once the geometry needed is determined, it is possible to connect these two elements to a component to generate an 'HB object'. The next point is then to generate an HB model, to this component the HB object and HB shades (if there are any) are connected. Parallel to this procedure, a grid plane has to be created. The grid is generated from the base plane of the volume previous created. This grid works as the area where the daylight simulation results will be displayed.

With the HB model created, it is linked to the grid and the resulting component is then connected to both the annual daylight generator and the daylight factor generator. Finally these components are connected to heatmap components that will display in a colored grid the results obtained.

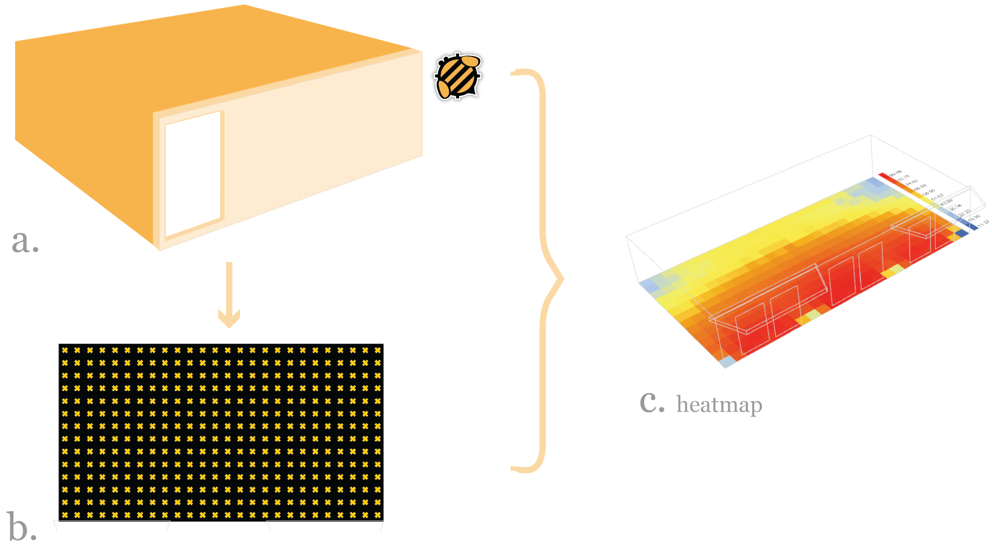

Figure 5.14: Daylight simulation example

The parameters taken into consideration for the daylight simulation were established to give an overview of the functionality of these simulations during early stages of the design process. These factors can help determine aspects related to orientation, size of the openings and even the type of materials needed, among other characteristics. Hence, it represents an important role to have the possibility of running several simulations with varying characteristics in early design stages, this would later in the design process alleviate the need for excessive artificial lighting, which leads to a higher energy consumption in buildings.

Acoustics

Building acoustics accounts for all kinds of acoustic and vibration phenomena related to buildings. Within these are considered sound insulation, room acoustics, and noise and vibration problems from internal or external factors [24]. In regards to sound insulation, there are two possible cases to be considered; airborne sound insulation and structure-borne insulation; airborne insulation refers to the insulation needed against sound waves present in air whereas structure-borne insulation refers to vibrational waves encountered inside materials [25]. These sound waves in turn travel in various ways that can be differentiated between direct, flanking or indirect sound transmission [26]. Therefore to be able to define the way that sounds travels in a specific construction, it is important to define the type of construction; the built up of the structure can be differentiated between single-leaf and cavity (double-leaf) walls [27].

Concerning the analysis of the acoustic properties of the panel designed within this thesis the following characteristics are taken into account:

- Sound insulation
- Airborne sound insulation
- Direct sound transmission

- Cavity wall construction

Theoretically the sound insulation required for a cavity construction is predicted by mass law and considers a mass spring resonance principle. This means that cavity constructions have a frequency dependant behaviour; below that specific frequency (mass spring frequency) the insulation will be the same as a solid construction, at mass spring frequency there is nearly 0 insulation, and above it the sound insulation becomes better than a solid construction [28], this is graphically represented in Figure 5.15.

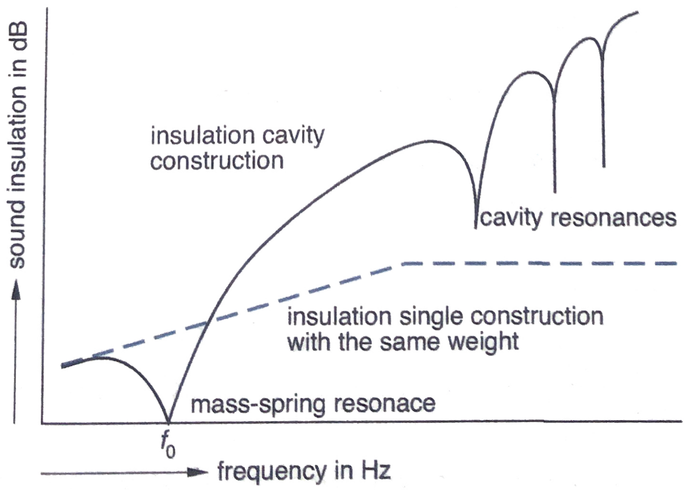

Figure 5.15: General insulation curve for a cavity structure
[23]

In order to find the sound insulation values of a cavity construction, the first step is to determine the mass-spring resonance frequency, this is done through equations 5.1 or 5.2 if the normal values for ρ_{air} (1.21 kg/m^3 at $20°$) and c_{air} (343 m/s at $20°$) are taken as well as an incidence angle of $\theta = 0°$ [26].

$$f_0 = \frac{c}{2\pi\cos\theta}\sqrt{\frac{\rho}{d_{cav}}\left(\frac{1}{m_1}+\frac{1}{m_2}\right)} \tag{5.1}$$

$$f = 60\sqrt{\frac{1}{d}\mid\frac{1}{m_1}+\frac{1}{m_2}} \tag{5.2}$$

Once the mass-spring resonance is determined, calculations can be carried out for the sound insulation below and above the mass frequency. As mentioned before, below mass frequency a cavity construction acts equal to a solid construction, meaning that every doubling of the frequency the sound insulation increases by 6 dB, this can be calculated through equation 5.3.

$$R_\theta = 20\log\left(\frac{\omega\,(m_1+m_2)\cos\theta}{2\rho c}\right) \tag{5.3}$$

On the other hand, above mass-spring resonance equation 5.4 is used. In this case, the sound insulation for both masses (or more) is calculated as well as the insulation of the cavity [28].

$$R_\theta = 20\log\left(\frac{2\pi f m_1 \cos\theta}{2\rho_{air}c_{air}}\right) + 20\log\left(\frac{2\pi f m_2 \cos\theta}{2\rho_{air}c_{air}}\right) + 20\log\left(\frac{2\times 2\pi f d_{cav}\cos\theta}{c_{air}}\right) \quad (5.4)$$

However, the last portion of the equation 5.5 has a limit insulation of 6 dB, because if the sound is too high the wavelength inside the cavity would be very short and then the cavity starts to act as a space and the sound becomes diffused [28].

$$... + 20\log\left(\frac{2\times 2\pi f d_{cav}\cos\theta}{c_{air}}\right) \quad (5.5)$$

To determine this break point, the frequency transition has to be calculated according to equation 5.6. So below transition frequency R rises 18 dB/oct and above transition frequency R rise 12 dB/oct [28].

$$R_\theta = 20\log\left(\frac{2\pi f m_1 \cos\theta}{2\rho_{air}c_{air}}\right) + 20\log\left(\frac{2\pi f m_2 \cos\theta}{2\rho c}\right) + 6 \quad (5.6)$$

The final part considered above the transition frequency, are cavity resonances which happen when standing waves fit inside the thickness of the cavity. This can become an issue in very wide cavities, because the frequencies that fit within these cavities are in the hearing or noise range [28].

In practice, the 'pamphlet revised calculation method for sound proofing of facades' provides a calculation method for soundproofing external partitioning structures. These steps, as mentioned by A.C. van der Linden et al. in the book Building Physics [23], are the following:

1. Determine sound insulation of the composite facade [R_A]
2. Determine sound proofing of the external partitioning structure [G_A]
3. Determine typical sound proofing of the external partitioning structure [$G_{A;k}$]

Considering this procedure, that is as well taken into account in the specification NEN 5077; for this project the model's sound insulation was developed following the above mentioned steps.

Firstly, the calculation for sound insulation R_A needs to be done, but it requires a correction for the sensitivity of human ear and the spectrum sound of the source. In table 5.3 the correction values C_i for different sources is presented [23].

Table 5.3: Derivation values C_i for outdoor sounds

C_i [dB] for octave band	125	250	500	1000	2000
traffic noise & other	-14	-10	-6	-5	-7
railway traffic noise	-27	-17	-9	-4	-4
air traffic noise	-21	-11	-7	-4.5	-6

Since in practice, many of the materials have been already defined and tested, the sound insulation values R and R_A can be retrieved from different books of tables, depending on the material to be used. Once this values are acquired, if the façade has more than one element equation 5.7 has to be used [23].

$$R_A = -10\log\left(\sum \frac{1}{S_{tot}}(S_j 10^{\frac{-R_{j;A}}{10}} + 10 \times 10^{\frac{-D_{n;j;A}}{10}}) + K\right) \tag{5.7}$$

In case there are no ventilation provisions for the façade the term 5.8 can be omitted.

$$...10 \times 10^{\frac{-D_{n;j;A}}{10}} \tag{5.8}$$

Once the sound insulation value of the façade (R_A) is obtained the next step is to define the sound proofing of the structure (G_A). Having obtained the R_A does not give any proper results on how the sound proofing of the façade performs, which is why the factor G_A needs to be calculated [23], this is done through equation 5.9.

$$G_A = R_A + 10\log\left(\frac{V}{6 * T_0 * S}\right) - 3 + C_g \tag{5.9}$$

Considering that the façade proofing is related to the room (behind) conditions, the room-factor term is used here. In regards to the term -3, it is used to correct a reduction from real measurements compared to laboratory results. Finally the term C_g represents a structure correction that depends on the façade type. All these are pre-determined values that can be found on the standard NEN 5272 [29].

Finally, the typical facade sound proofing factor has to be calculated. This is done because in the Building decree a layout of independent variables are being introduced as much as possible, which is why the room factor is substracted in this step; leaving equation 5.10 to be used for this step.

$$G_{A;k} = G_A + 10\log\left(\frac{V}{6 * T_0 * S}\right) \tag{5.10}$$

The results obtained from equation 5.10 can then be used to perform a check on the sound proofing performance of a façade. According to the Building decree there are minimum values that need to be achieved, these are dependant on the type of outdoor noise and the building use. The values for different types of buildings and outdoor noise can be found in the Building

Decree [23] and are also shown in Figure B.8. The threshold values for dwellings is 35 dB(A) and for offices is 40 dB(A).

Up until this point the development procedure for the proposed tool has been explain. The process explained throughout this chapter intends to communicate the methodology behind the tool, and the procedure followed to develop the intended tool. Overall it can be determined that the tool in fact can be developed and after this process it is theoretically functional. However, it is important to validate the functionality of the tool and the test that it can be used in various cases. Consequently in chapter 6, the validation of the tool's functionally through a case study is presented.

6

Results

In the following chapter the validation for the tool developed is presented. In Chapter 5, the methodology followed to solve the proposed tool is presented. Throughout the chapter a generic approach is addressed, so in order to prove the usefulness of the tool, a case study was proposed. The objective of using a case study is to make tangible the functionality of the tool. By putting the tool into practice, in a certain way in a real project, it is possible to show the reach that this tool has. Through the development of this chapter the applicability of the tool to the case study and the obtained results are presented.

Sluishuis - Amsterdam

The building chosen as a case study is the Sluishuis, this building represents a good a combination of characteristics with regards to its geometry and location. As mentioned briefly in Chapter 5, the intention when choosing this specific case study relies on the complexity of the shape that at the same time allows to use planar panels to complete its façade.

Figure 6.1: Sluihuis location

The Sluishuis is located in Ijburg, a residential neighbourhood that is being built on artificial islands in the eastern part of Amsterdam [30]. The building is an ongoing project that begun in 2016 and its meant to be finished by 2022. It was designed by Bjarke Ingels Group and Barcode Architects. The design is intended to link the rural and urban areas that surround it; in addition the building not only provides benefits for its residents but also for the neighbouring residents the scenic walk and water entertainment are accessible. The building complex houses 442 apartments plus a ground floor program that includes a lobby, sailing school, watersports center and a restaurant [31]. One of the main characteristics of the building is its focus on sustainability. It has achieved a energy performance coefficient of 0; the energy consumption throughout the building has been reduced to its minimum by use of efficient materials for insulation, heat recovery systems and heat pumps for water cooling and heating. The remaining energy needed is compensated with solar panels [31].

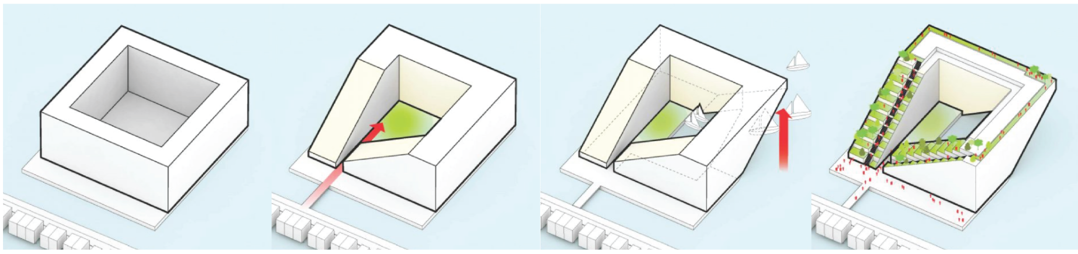

Figure 6.2: Sluishuis design process

[32]

In regards to the façade design for this building it was done by Vianen, in collaboration with Sorba & Facedo, façade cladding and aluminium frame suppliers. All the façade panels were fully designed, manufactured and assembled in Vianen's factory [1].

Due to the points discussed, it was decided to choose this project as a case study to validate the proposed tool. In practice for the development of a façade design a base geometry will be given. Which is why to begin the testing a 3D model was generated that would be used as the base geometry. For this, basic plans, elevations and renderings of the building were retrieved; using this material to prepare a conceptual 3D model, as a base geometry. In Annex C the complete information obtained for the building is available.

6.1. Design Tool

The tool consists of two parts; the Façade Analysis and the Building Physics simulations. In Figure 6.3 the final interface is shown, through this section the main input parameters and the results needed can be accessed.

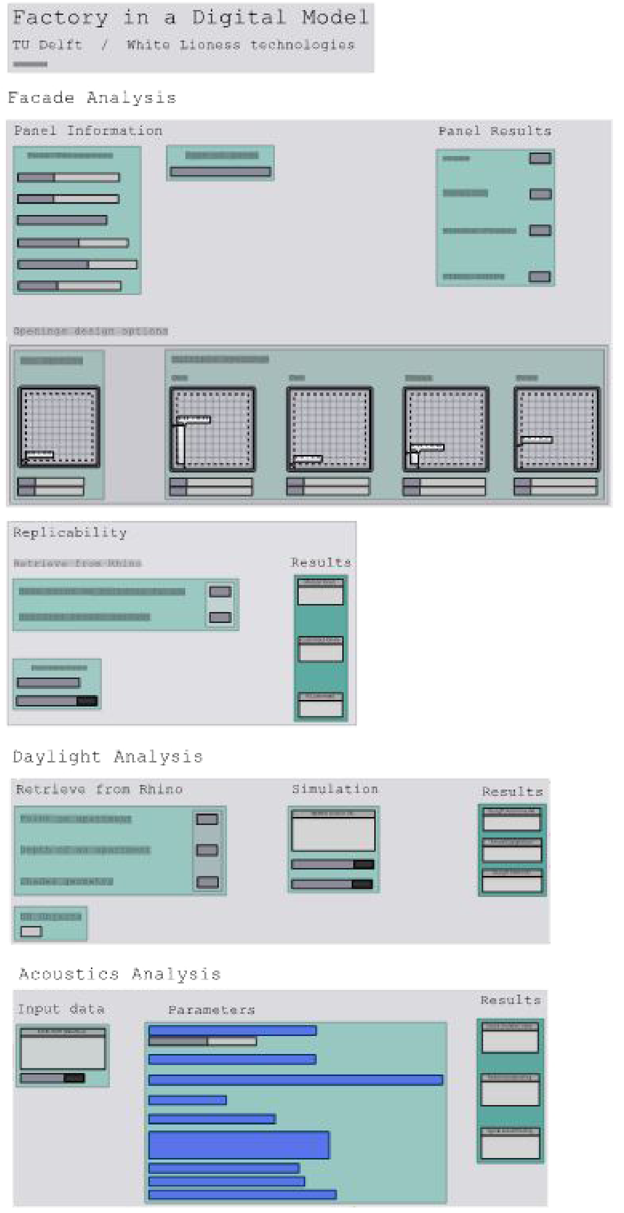

Figure 6.3: Tool Interface

6.1.1. Façade Analysis

Within the façade analysis section, there are two processes that occur. First the individual panel design needs to be made and its characteristics are determined. Later, as a second step, the finished designed panel is used to be replicated along the conceptual faç giving as a final result the amount of modular panel and the amount of customized panels.

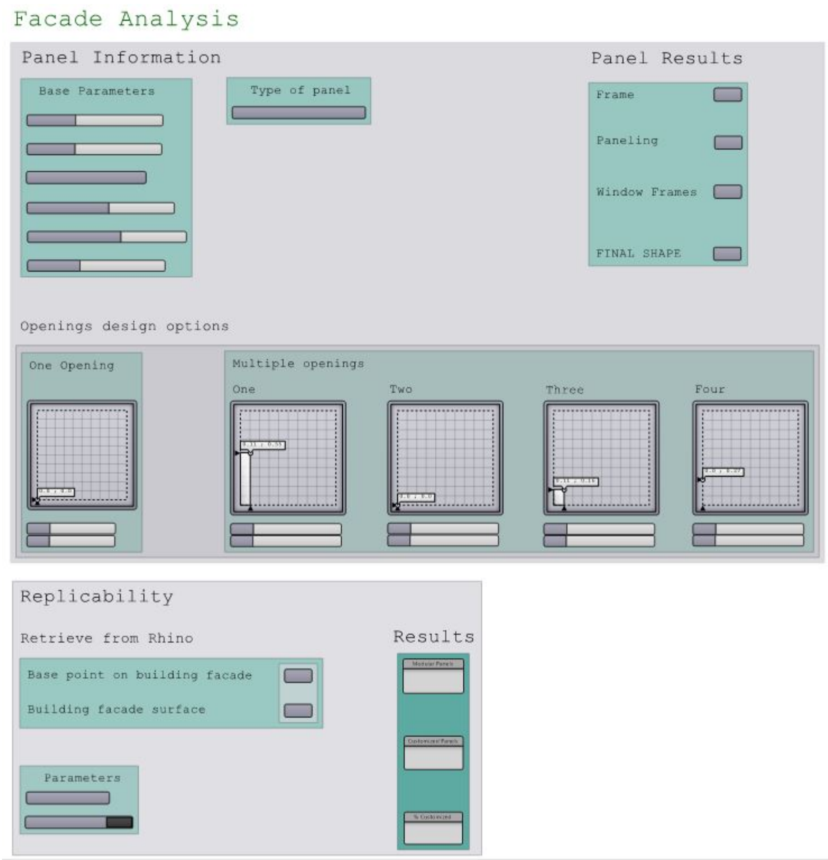

Figure 6.4: Façade analysis

Panel Design

Following the methodology mentioned in Chapter 5, the modular panel needs to be designed. With the information retrieved from the base model of the case study, the characteristics of the individual panels were determined and entered as input parameters. In Figure 6.5 the parameters used for this specific case are shown.

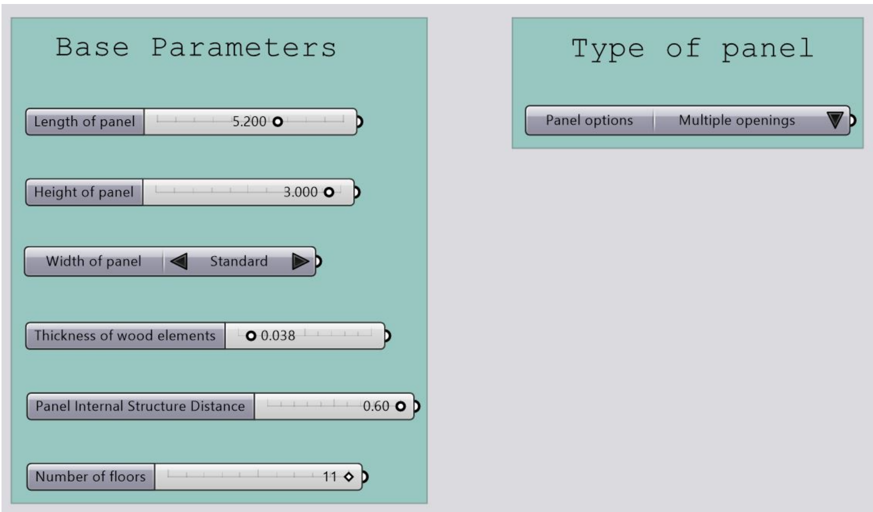

Figure 6.5: Panel parameters

Then the process is followed using the same approach as mentioned in Chapter 5. First the length and height of the panel are chosen, in this case the dimensions were chosen considering the distance between the structural elements of the building; since Vianen's panels are non-structural, it is most probable that they will be connected to the main structure of the building.

With these parameters set, the next step for the panel is to define the openings, their size and location. Again following the design from the case study, the most common panel seen consists of two openings that are almost of the panels height. This information was translated to the model. Choosing the multiple openings option, it was then possible to define the exact location and dimensions of the openings.

Once the openings dimensions and locations are defined the rest of the elements within the panel are automatically arranged to fit the input parameters. What is visible for the user is then the finalized design. Figure 6.6 shows the obtained result as seen in the Rhino canvas. In the next step to begin the replicability process the finalized panel design is needed.

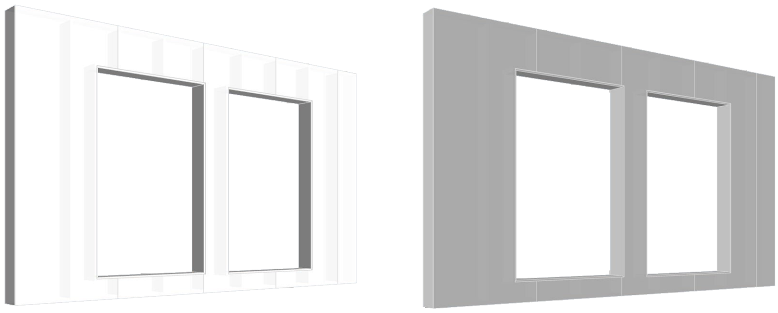

Figure 6.6: Panel result

Replicability

After defining the design of the panel, to begin the replication of it some input information from the base geometry is needed. Firstly, the building surface to be filled needs to be internalized in Grasshopper, as well as a base point in said façade. Figure 6.7 shows the elements needed. Then, the axis in which the façade is located needs to be determined (x or y).

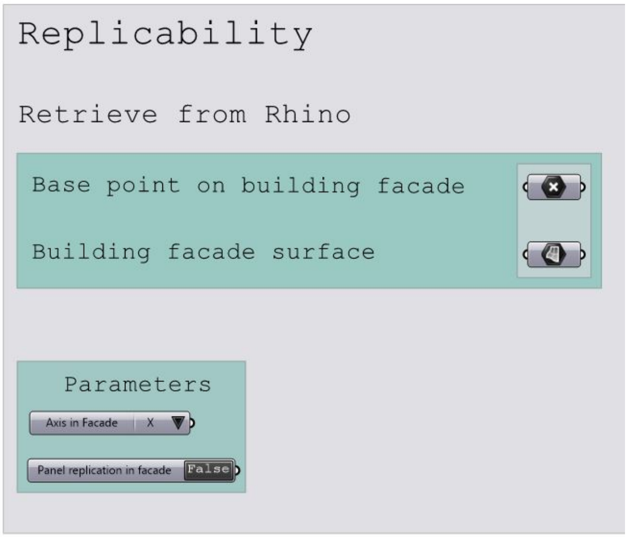

Figure 6.7: Replicability parameters

Once this input parameters are set the replication of the panel is made automatically according to the methodology presented in Chapter 5. As explained in the chapter, the process needs to give the amount of modular panels and customized panels needed for the desired façade. How this process occured for this case study is explained below.

It is important to highlight that for this specific case due to the need of a large computational time the final panel was simplified into a box shape with the same dimensions. Despite that, this does not mean that the tool cannot perform the replication on the actual panel. Having said that, the inpuntted base geometry is analyzed generating a surface length in which the panels are arranged, then using the number of floors input the full area is filled with panels.

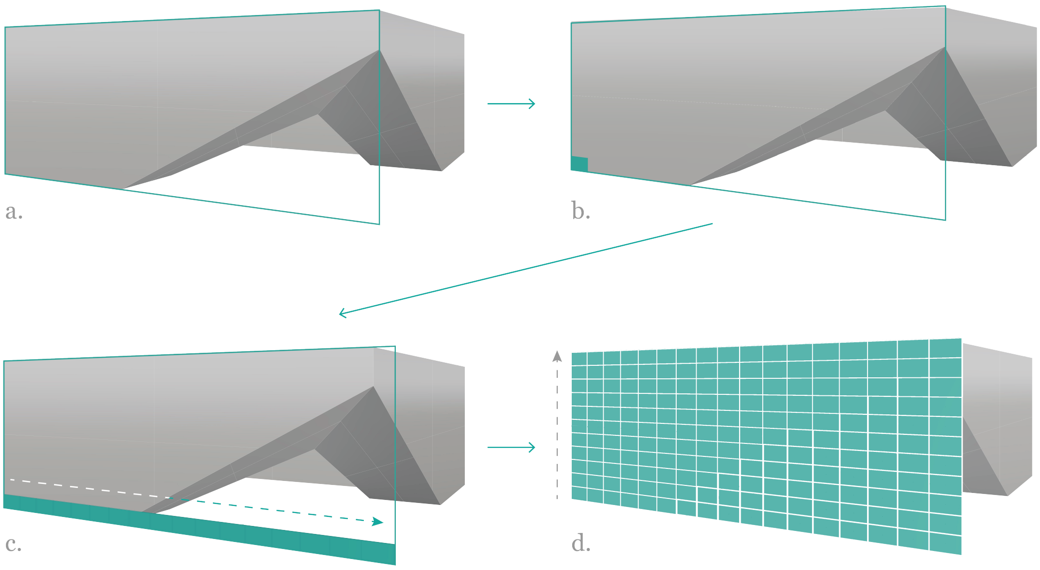

Figure 6.8: Replicability Sluishuis - Step 1

Then, the cutting curves are retrieved from the entered geometry. With this it is then possible to point-out the panels that are crossed by this lines, giving the first result, it being the amount of customized panels, it is possible to visualize these panels marked in a different color in the Rhino interface.

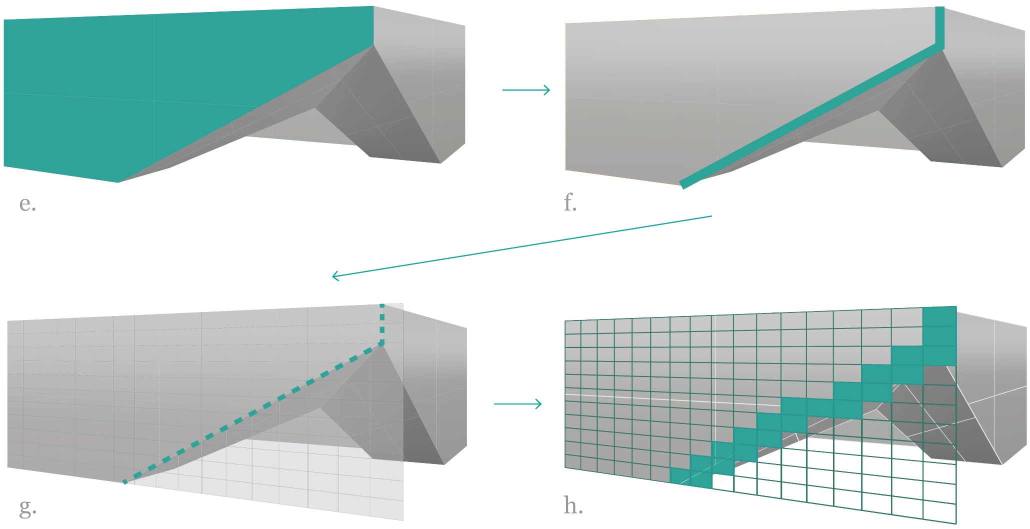

Figure 6.9: Replicability Sluishuis - Step 2

Having marked the customized panels, the tool analyzes the panels that are located outside the boundaries of the cutting lines, and as a visualization result it marks the panels that do not belong to the final façade. Finally the panels that are left and are within the boundaries of the cutting lines, are calculated and this is number is the result for amount of modular panels. There is a last result calculated, which is the percentage of customized panels, this can be taken as a reference number, in this case study it is stated that 28% of the panels need to be customized.

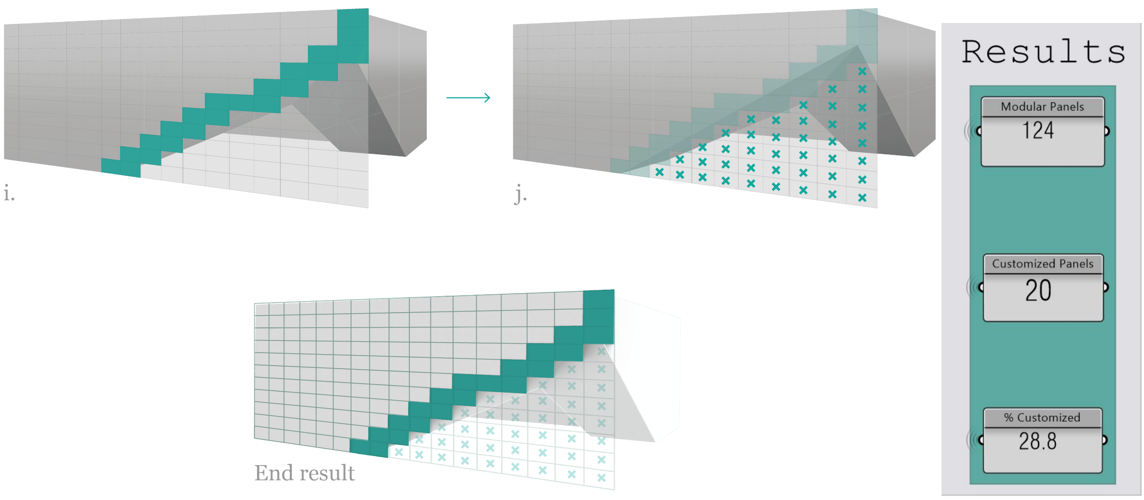

Figure 6.10: Replicability Sluishuis - Step 3

6.1.2. Building physics

To perform the simulations for Building physics, the Sluishuis Building was also taken as a case study. To be able to perform these simulations, information on the entire volume and internal characteristics of the building are needed, and these are not within the scope of this proposal. Which is why, for the purpose of this project, the simulations were done for one of the apartments located right behind the analyzed façade. This allowed to test the performance of the tool.

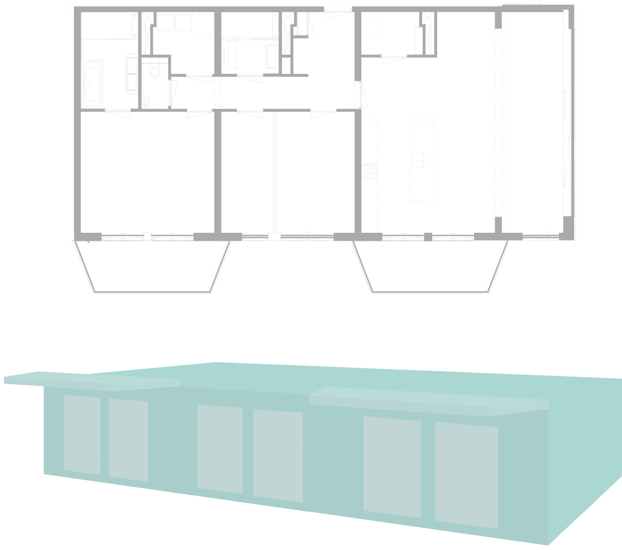

Figure 6.11: Apartment plan & 3D scheme

Daylight

Daylight simulations, is useful in the early stages of the design to help determine the orientation and openings size, in later stages it is also useful to determine possible strategies for energy savings. The simulation will be applied to one apartment from the chosen case study. This choice was made because the main objective of this proposal is to present a proof-of-concept tool and for a full analysis the computation time is too long. This way eases the computation time and shows the possibilities within the tool.

Firstly, to be able to initiate a daylight simulation the geometry to be studied needs to be transformed into Honeybee (HB) objects. For this specific case, initially the plans for this apartment were entered into the Rhino interface. Then a base point and base surface from the apartment are internalized into Grasshopper, also in this case there are shades(balconies), these geometries also need to be included in the simulation.

Once the base parameters are there, the tool generates a box like element that takes into account the dimensions of the panel plus the depth of given plan. Then, the openings surfaces are retrieved from the data created in the Panel design section. These parameters can then be connected to the HB objects component; with this it is possible to begin the simulation. To run the simulation an *.epw* file is needed, in this tool a default file for Amsterdam is entered but if needed this information can be changed.

With the geometry set up and the location chosen, it is possible to run the simulations. The user/ designer has two possible simulations to run; the annual daylight simulation that gives results for Daylight autonomy in luxes or percentages, and the Daylight factor simulation that gives the results in percentages.

The results obtained can be seen as a table of values within the Grasshopper canvas, or a visualization result available within the Rhino interface. In the following figures the results obtained for the apartment analyzed are shown.

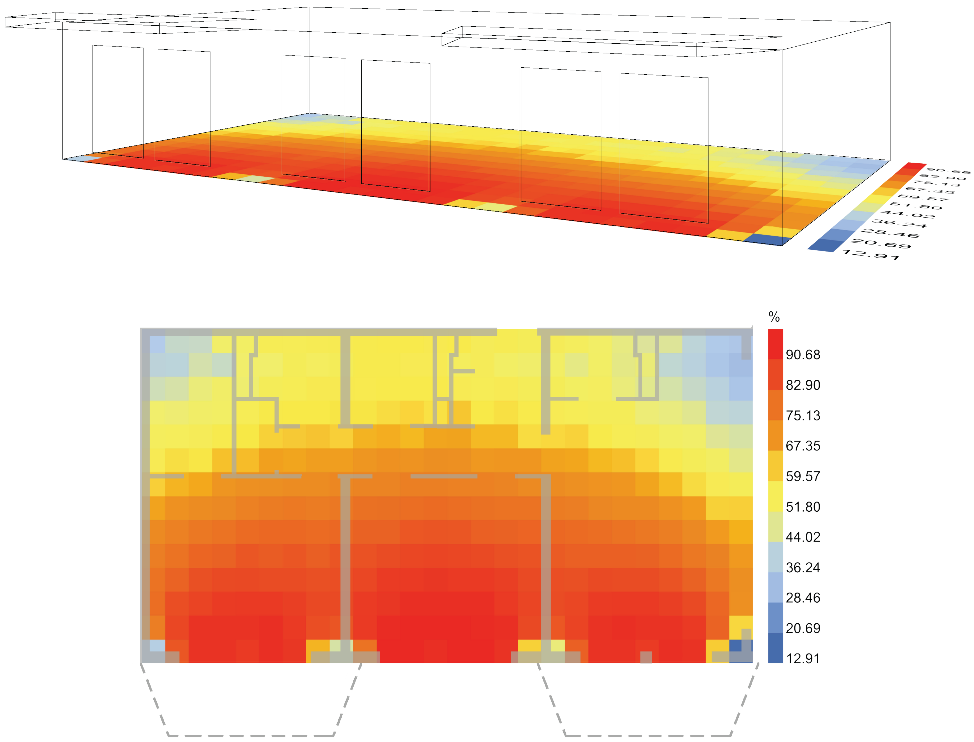

Figure 6.12: Annual daylight - Daylight autonomy in percentage

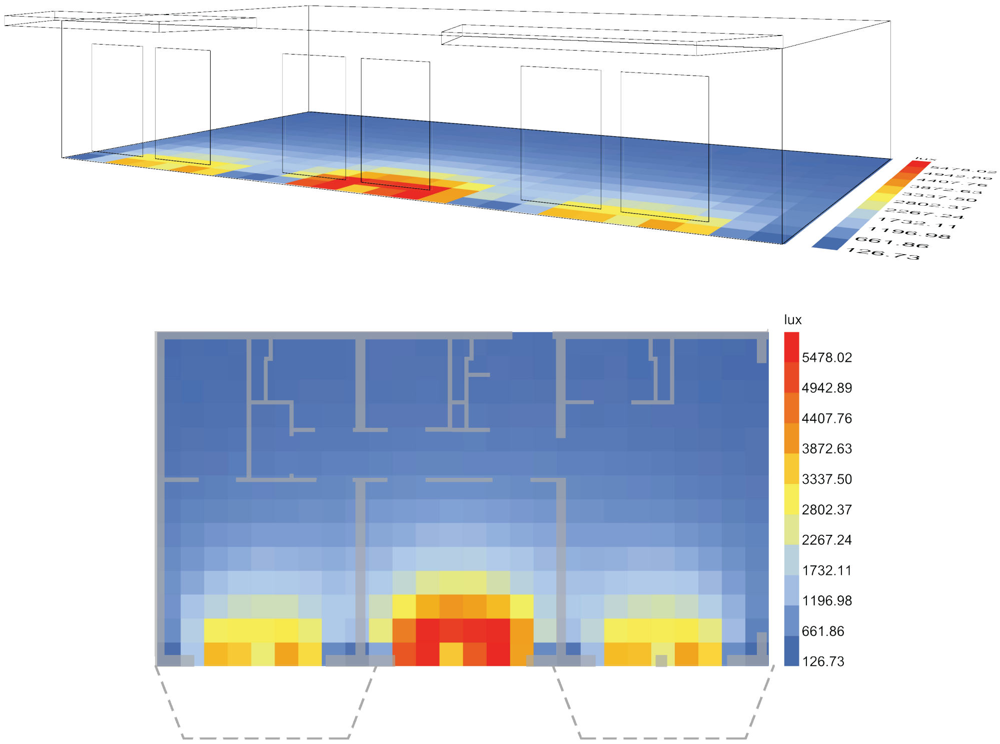

Figure 6.13: Annual daylight in lux

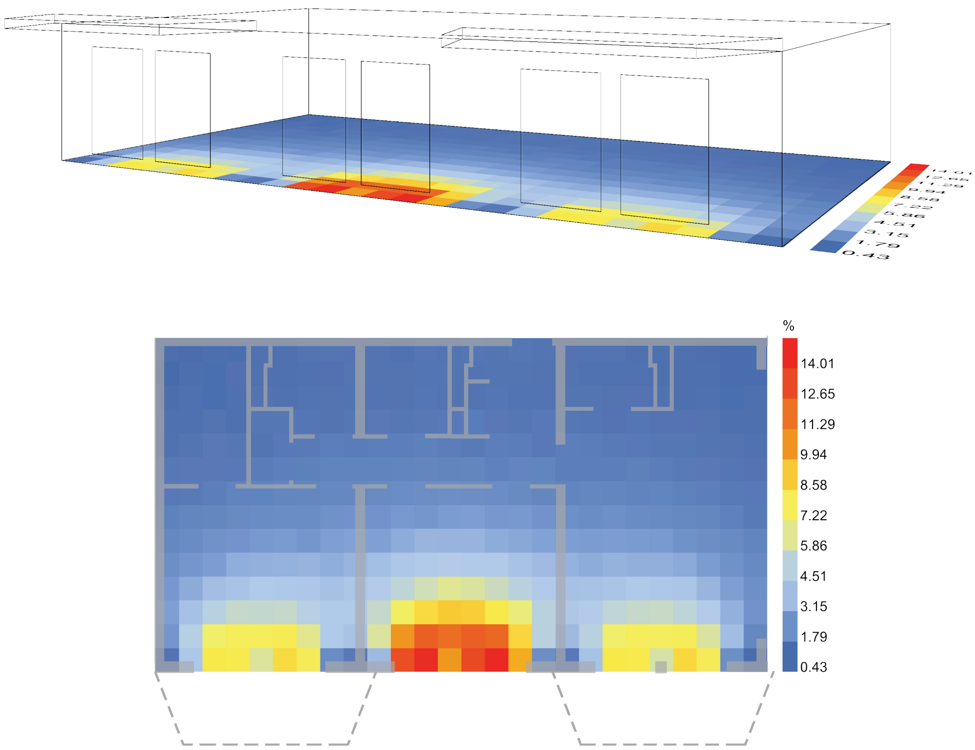

Figure 6.14: Daylight factor in percentage

The results presented show that the amount of daylight for the building is according the Building decree requirements mentioned in Chapter 5.

Besides these results, to provide a validation, daylight simulations were realized in Dialux. Dialux is a lighting design software, commonly used for indoor and outdoor areas. The software provides results for daylight autonomy in lux and daylight factor in percentage. The results obtained from both softwares, return similar results, the differences between them rely on the background programming of each software. These results are presented fully in Annex F.

Having obtained these results, it is important to clarify that they are only valid for the same orientation given to the apartment, more calculations need to be performed for the different façade orientations and eventually for the complete building.

Acoustics

In regards of the acoustic performance of a façade, in early design stages it is helpful to determine the sound insulation needed depending on the outdoor noise. This knowledge from early stages of the design can help determine possible material changes or improvements. For this specific case the acoustic performance and sound insulation of one of the façade panels is performed. The apartment dimensions used for the daylight simulation are also used as parameters for the sound insulation calculation.

As mention in Chapter 5 most of the materials and products available nowadays have already been tested for their acoustic performance, and it is possible to retrieve this information from different manufacturers.

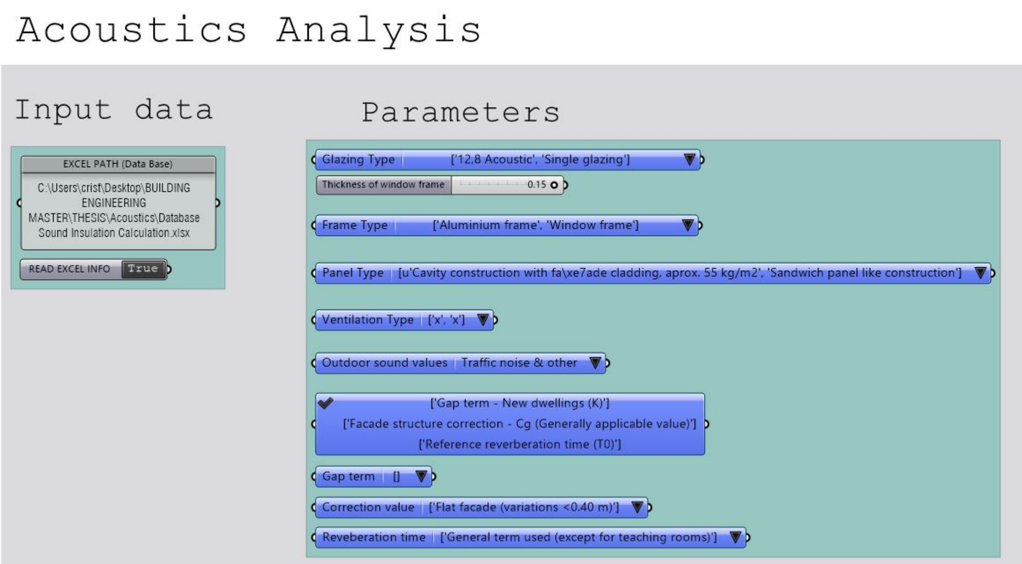

Figure 6.15: Sound insulation - parameters

Taking this into account, a data file was created that would work as a base to input the parameters needed to run the simulation. This database is a file created in Microsoft Excel that consists of three worksheets. The first one contains the information related to the materials that can be used to build up the panel, it contains the sound insulation value R for each frequency $(125 - 2000 Hz)$. The second worksheet contains the information of derivation values C for outdoor sounds. The final worksheet contains values for gap term, façade structure correction and reverberation time; the factors within this tab cannot be omitted from the calculation but may be variable. There is also possible to add information from different type of materials to this database and this will immediately be updated for calculation. The file so far contains a small amount of materials taken as reference for the validation of the tool, this information was retrieved from the standard NEN 5272 [29]. Exact information from the materials used by Vianen in the manufacturing of these panels could not be obtained; the detailed information used is shown in Annex D.

Once the database is set, this file is imported inside the Grasshopper canvas. With the information imported, the next step is to differentiate this information to be able to retrieve the data for each of the materials and characteristics stated. In Figure 6.16 the interface for acoustic is shown, here three steps are visible: the first part is the input data and a toggle that allows the tool to read the information in the database. The second one allows the user/designer to choose the build-up of the panel from the list of different material, it is possible to choose different types of glazing, window frames, panel combination and ventilation grills; plus the options for outdoor sound, gap term, façade correction and reverberation are available at this point. The last step shown is the results portion, in which the weighted sound insulation R_A, the partial sound proofing G_A and the typical sound proofing $G_{A;k}$ are available.

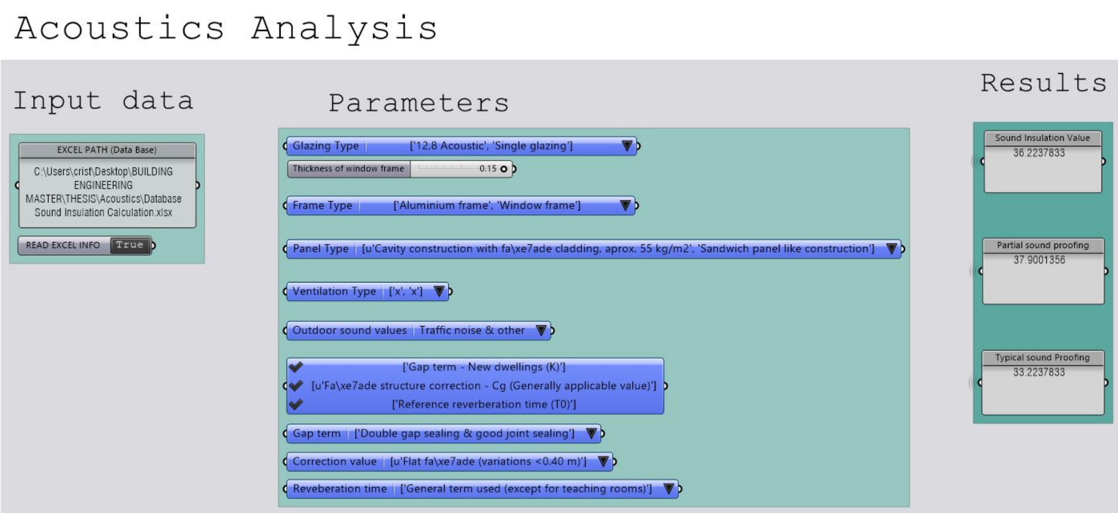

Figure 6.16: Sound insulation - results of one combination of parameters

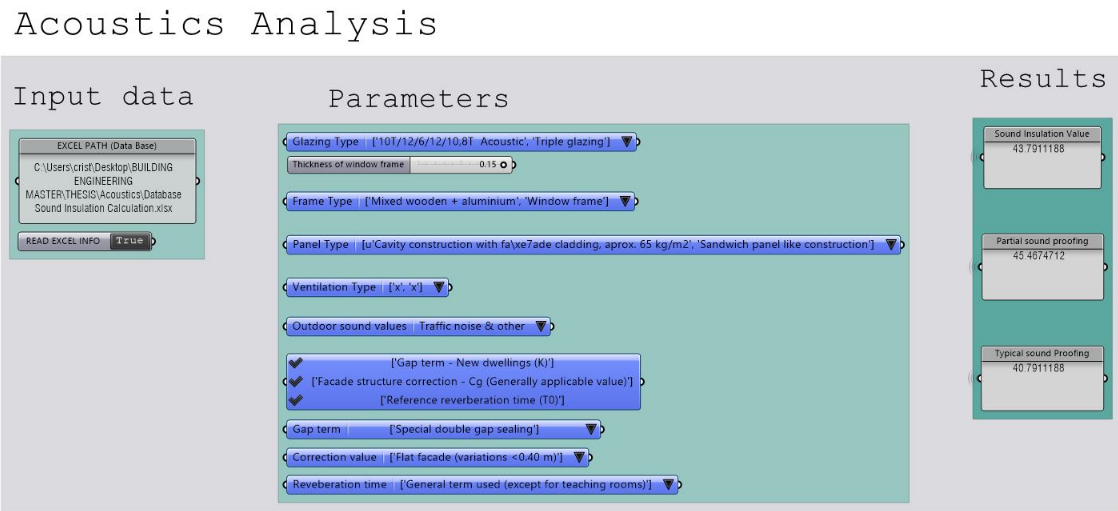

Figure 6.17: Sound insulation - results of improved combination of parameters

To determine the reaction and accuracy of the tool, different changes were tested. These changes show that, as expected, the smaller the size of the windows the better the insulation of the façade; also changes were made in the composition of the materials used and these also affect the sound proofing. The complete extended of these tests are shown in Annex E.

7 Discussion

In the following chapter the final remarks of this thesis project are presented. A discussion on the process, steps and the results obtained are addressed. The discussion is focused on outstanding points and decisions taken throughout the process to obtain the results shown in Chapter 6.

This thesis proposal began with the aim of developing a tool that could encode the knowledge of a manufacturer and will digitally allow designers to generate an almost ready to produce façade system. Throughout the process this broad approach was constrained, in this way determining that to achieve the overall goal firstly a proof-of-concept proposal had to be addressed. Therefore, this proposal focused on developing the first steps to determine the feasibility and functionality of such a tool.

As seen in literature, some attempts to automate the design process of building envelopes have been researched. However, most of the studies approach this issue from a top-down view, aiming always on having a design to which the manufacturing possibilities need to adapt to. This in the end results in the same current situation, where the manufacturing knowledge and expertise is not taken into consideration as parameters in early design stages. With this consideration in mind, the project proposal was developed.

Initially, the information and knowledge gathered from Vianen was sorted and introduced as input parameters. The obtained information was sufficient to set-up the basic model, in which the main parameters (height, length, width and thickness) could be modified. In the same manner, information regarding the internal structure was retrieved. This aspect was developed only for the standard solution in regards to the stiffness and stability of the panel, this standard solution is a condition pre-calculated by the company and has already been proved and tested. However, when discussing with Vianen, it was briefly mentioned that in certain cases when the width of the panel varies or the size of the openings are larger than the recommended, additional steel plates need to be used to assure the panels functionality. This aspect in the geometrical development of the project was not introduced as it is not a typical modular solution, and would required an extensive study on the structural behaviour of the panel to then be able to determine the need (or lack of it) for additional reinforcement. In any case, such consideration would then improve the accuracy of the model, generating in the end more detailed information required to achieve a ready to manufacture product.

Following the process proposed, once the design of the panel is established, the next step considered is the replication of this panel throughout a conceptual façade. During this process, and as mentioned before in Chapter 6, a simplification of the proposed panel was used. The decision of using a simplified version was taken, mainly, due to the computational power needed to run the full process with the designed panel. In the case of the finalized panel, the replication process analyzes every part that composes it and hence takes longer to determine which part of each panel is, inside the area where customized panels should be shown. This is why, to be able to use the tool efficiently the simplification of the panels was the best solution; allowing the tool to show results faster.

Considering also the replication process, in the development of this thesis it was decided to work only on one of the façade surfaces of the conceptual building. This decision was based on the fact that the tool is in a proof-of-concept stage, hence the initial idea was to test its functionality first only in a section, in this case one façade. Once this step is considered functional, the following course of action would be to improve the tool for it to generate a complete building envelope. This would arise different questions and tests.

On the other hand, in regards to the building physics analysis made for this project, the aspects chosen were based on two conditions. First, the functionality of the analysis for early design stages, which is why, the chosen aspects (daylight and acoustics) give preliminary results that can be used to determine features of early design stages, like orientation, opening sizes, material choice, etc. Secondly, these aspects were chosen because they can be analyzed for only one façade at a time, with (almost) no information from the inside characteristics of the building. As an example, a thorough thermal analysis could not be performed under these conditions and would not be realistic without considering the rest of the façade surfaces plus the internal characteristics of the completed volume.

In the same manner, the decision of running these simulations only for one of the apartments was taken considering the fact stated before, that the purpose of this proposal is a proof-of-concept tool. On that note, the possibility of expanding the simulation for the completed building is a next step for the tool to be fully useful for designers in regards of the said building physics simulations.

This last statement is also applicable to the overall process of this thesis. Therefore it is important to mention that the reach that this proposal has achieved is a preliminary stage. Further development would then greatly improve the accuracy and the usefulness of it. As a consequence the idea 'ready to manufacture' could in fact become a reality.

8

Conclusion & Recommendations

In the following chapter the conclusions drawn from the development of this project are addressed. Additionally, recommendations on future research for this project are provided.

8.1. Conclusion

The process of this proposal was developed following the methodology plan shown in Chapter 2. It consisted of a development statement, supported by design steps. The process undertaken was meant to follow a step by step development process that marked milestone points throughout the project. The conclusions then formulate an achievement of these steps. The initial sequence to develop the project was formulated following the design steps below:

1. Review the state-of-the-art research in regards to parametric design of façades.
2. Encode the company's knowledge into a parametric model.
3. Investigate the possibility to replicate the panel to form a full façade system.
4. Retrieve the total amount of panels needed. Modular and customized panels.
5. Analyze the performance of the design for building physics aspects relevant to early design stages.

The conclusion to these steps were divided into three phases, related to the phases presented for the methodology of this project. Hence, these steps answer to a theory phase, a model phase and a testing phase.

Theory

The development began with an initial analysis of the background information related to this project

1. Review the state-of-the-art research in regards to parametric design of façades.

First the research approach was aimed at finding studies where parametric tools are mostly used throughout the Architecture, Engineering and Construction industry. This led to narrow the search specifically on developments for the façade industry. From there, it was determined that façade design is managed, in general terms, as an almost unique process for each new project, not considering much of the experience of previous work or manufacturing expertise. In the same manner, research and developments done for the structural behaviour of buildings were reviewed, although not in depth, these determined that for this part of the industry more detailed research and developments were being used.

The information gathered for the façade industry compared to research done for other building fields determined that, despite the increasing use and research of parametric tools, a gap between the design and manufacturing process of the façade industry is still present, which led to the development of this project.

Model

2. Encode the company's knowledge into a parametric model.

Encoding the knowledge was carried out following the information gathered through meetings with the company; the information gathered is presented in Chapter 4. The company shared and explained their design and manufacturing process in detail, plus some digital information that summarizes their parameters. With this information, the knowledge as such was translated into limitations within the parametric model; providing the user with the possibility to design and make changes within the manufacturing boundaries of the company.

The encoding of the company's knowledge was then concluded as a feasible procedure, as shown in the results in Chapter 6. However, as mentioned in Chapter 7 there are additional parameters that can be implemented to improve the final tool.

Testing

3. Investigate the possibility to replicate the panel to form a full façade system

Based on the panel design established in the modeling stage, the following step involved the possibility to replicate the panel into a full façade system. The replicability process was then realized for only one of the conceptual façade surfaces. With the results obtained it was concluded that for an early design stage it is a feasible approach. The parametric model developed within the Rhino-Grasshopper environment provides a near real-time visualisation of the changes on design.

The bottom-up approach taken for the development for one façade surface can indeed be used fro designing. However, further development on the complete façade system is still required for the tool to be useful in a real life project.

4. Retrieve the total amount of panels needed. Modular and customized panels.

The final aim of managing a full façade design, was to be able of retrieving information on the amount of modular panels that will be required to manufacture. Within the development of the tool this results feature was included.

In general terms, it was achieved the possibility to get numerical and visual results for the amount of modular and customized panels, as shown in Chapter 6. However, there are improvements required to have a fully functional tool, which is why it can be concluded that this step set the base for a full development, the ability to not only identify customized panels but be able to modified them has to be be further studied.

5. Analyze the performance of the design for building physics aspects relevant to early design stages.

Considering the research presented in Chapter 3, within the requirements of façade design, are the consideration of building physics aspects that would affect the design and build-up of a façade. These considerations were then taken into account in the development of this project, including within the tool early design stage analysis for daylight and sound proofing. The results of these simulations can be compared against the requirements stated in the Building Decree.

The effects of the resolution can then be described in two different manners. Firstly, as a proof-of-concept approach it was determined that simulations for both daylight and sound insulation can be included and do deliver reliable results, as shown in Chapter 6. On the other hand, since these simulations were run only for one apartment, it is therefore necessary to apply the tool to the complete structure and obtain results that can be used during real-life design decisions.

Development statement

This thesis project attempts to encode the manufacturer's knowledge by automating the design process of a timber framed façade panel through a component-based tool; making it useful during the early design stage of a building design process.

Taking into consideration the development statement proposed for this thesis, in general terms it can be concluded that, as a proof-of-concept solution, the tool presented for automating the design process of a timber framed façade panel is possible to be developed. It can also represent an improvement in the time spent by designers and manufacturers on design iterations. These reductions need to be statistically proven, however, on a general note with the manufacturing possibilities and restrictions already accounted for, the time spent on iterations between designers and manufacturers can be said that is decreased. Still, a fully developed tool is required to determine if besides time reductions it can be a useful implementation for cost reductions. Additionally, a fully developed tool will require more automated knowledge in geometrical aspects and a higher range of simulations. This way making the tool useful for the early stage design.

8.2. Recommendations

The global aim of this proposal is to achieve the development of a tool that can successfully introduce the knowledge and expertise from manufacturers into early design stages. In this way designers can propose projects that are within a manufacturers possibilities, consequently reducing the time consumed in iterations between design proposal and manufacturing detailing.

This proposal was then focused on the proof-of-concept development of said tool. The goal was then to prove in what ways can this help the design of façade systems. Until the conclusion of this project the outcome is a preliminary tool, that successfully automates the design of the timber framed panel, and generates preliminary results for daylight and sound insulation simulations. However, there is still work to be done to achieve the global aim. Some of the most relevant aspects that would lead to the completion of this tool are presented below. These recommendation for further research are related to geometry aspects, simulations for validation or cost related proposals.

Geometry

- Within the same manufacturer environment involve advanced geometrical features and changes of the panel design that in the end can generate a complete building envelope.
- Test the accuracy of the tool when applied to a complete building envelope, and to what extend is the tool able to replicate the panel for different building shapes.

Testing

- Preliminary analysis on the stability of the panel and of it when applied to a façade system.
- With a fully developed building envelope, generate simulations not only for daylight and sound insulation, but include thermal properties of the façade system; this being one of the most problematic aspects within façade design.

Costs

- Study of the cost reductions, related not only to time reductions but also considering the benefits of using the automated design panel to reduce the percentage of customized panels.

Finally, in future development two external aspects could be adapted to the tool. The first is the inclusion of other manufacturers knowledge to be able to compare the different products available and how the tool would help decide which product is the more accurate for a certain design. In this case considerations of the parameters to choose one or the other between manufacturers should be established. On the other hand, a thorough energy balance analysis and LCA for the chosen product can be a added value to a digital designing tool.

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A

Parametric Modeling

In the following pages the complete Grasshopper script is presented. The model as mentioned in chapter 5, was developed using the knowledge gathered from Vianen, with the parameters explained in chapter 4.

In this appendix the step by step process is shown in detail; all the components used and the logic followed is shown. The first image is an overall view of the canvas, it is composed of two main sections. The tool, with input parameters and results; and the process part where all the process is developed. The last image shows this overview of the full Grasshopper canvas, but this image allows to zoom-in to understand the connections between different components.

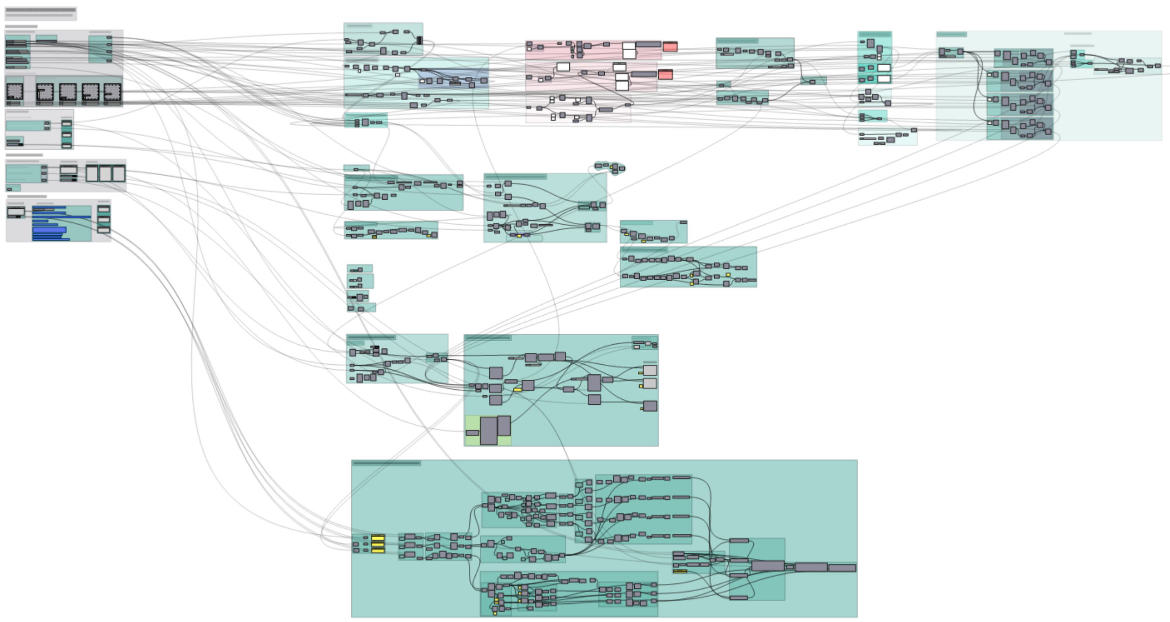


Figure A.1: Overview of Grasshopper canvas

A.1. Tool

In Figure A.2, the tool to be used by designers is presented. This represents the interface that would be available for the user.

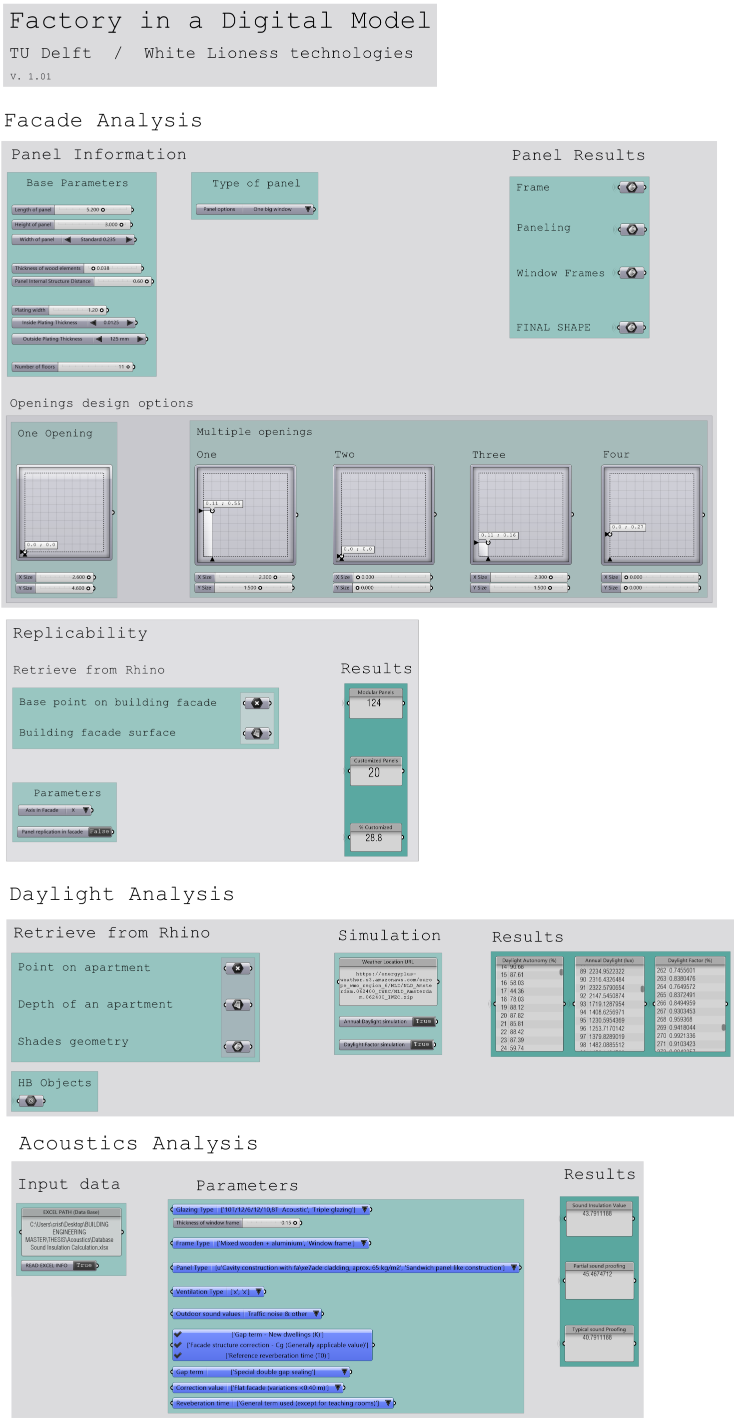


Figure A.2: Tool interface

A.2. Process

Within the process section, the full description of the development of the tool presented previously is shown. The explanation follows the same sequence presented in Chapter 5.

Geometry setup

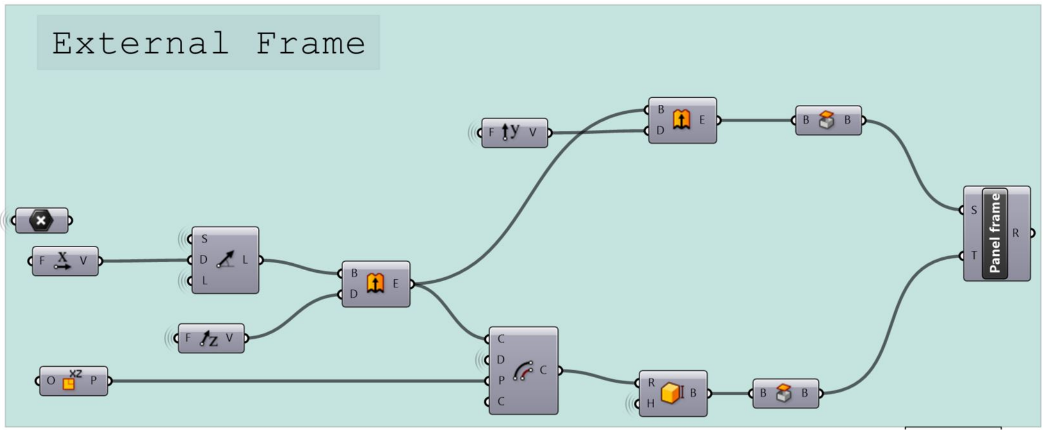


Figure A.3: External frame logic

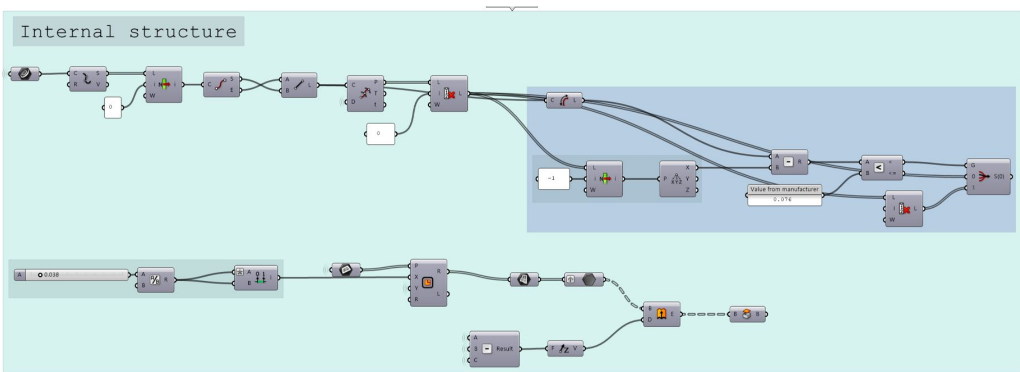


Figure A.4: Internal structure logic

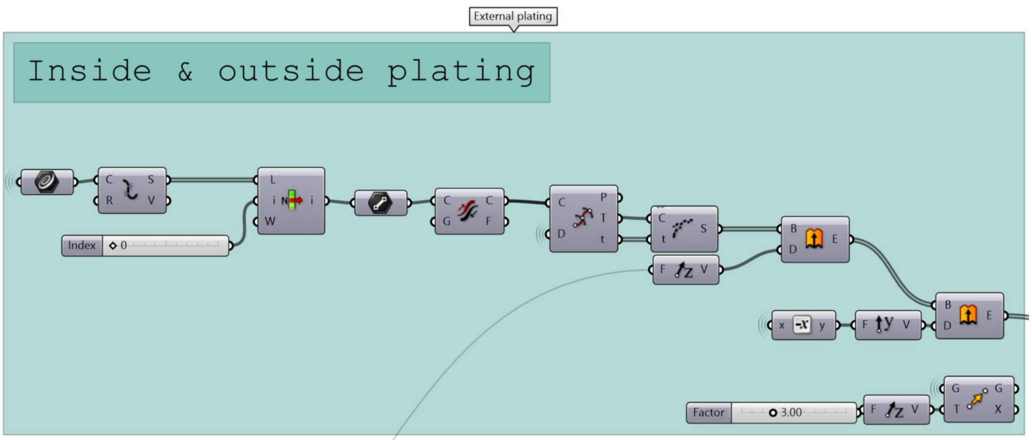


Figure A.5: Plating logic - 1

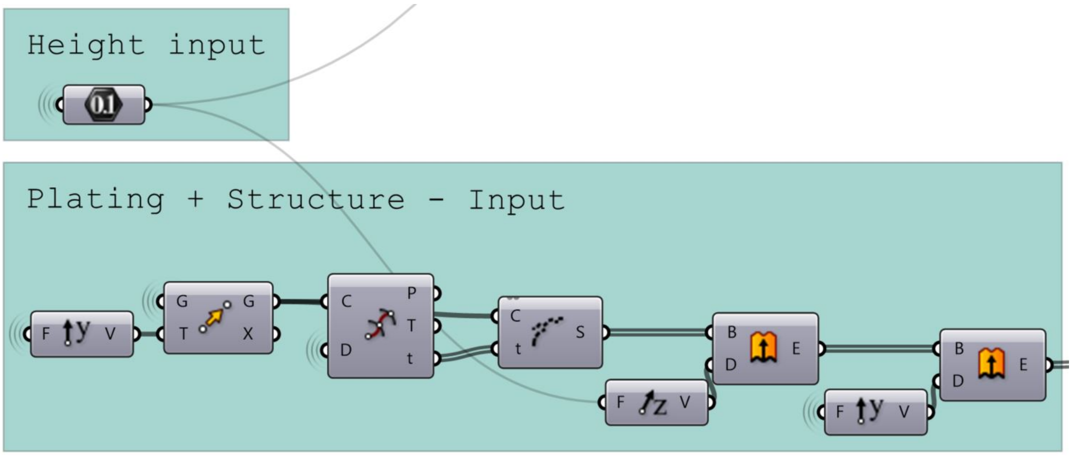


Figure A.6: Plating logic - 2

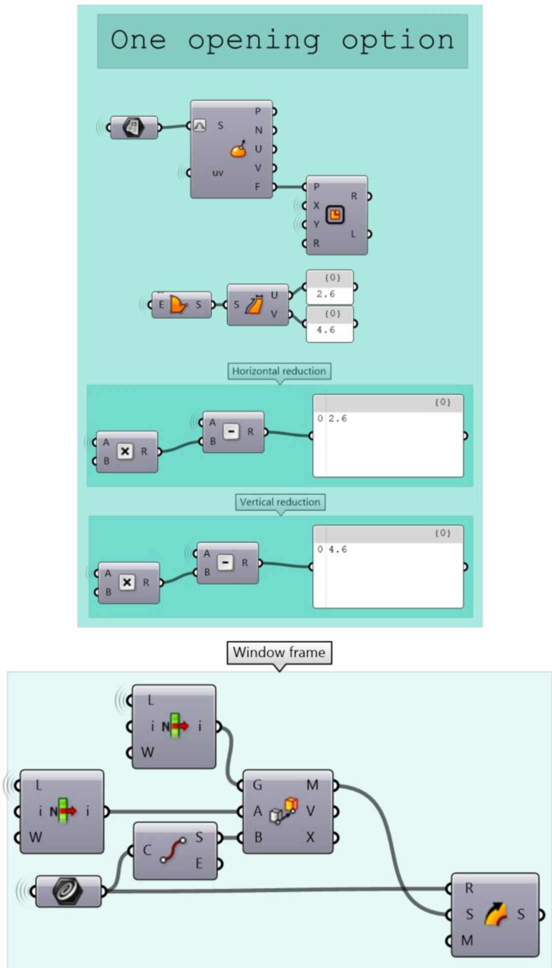


Figure A.7: One opening logic - 1

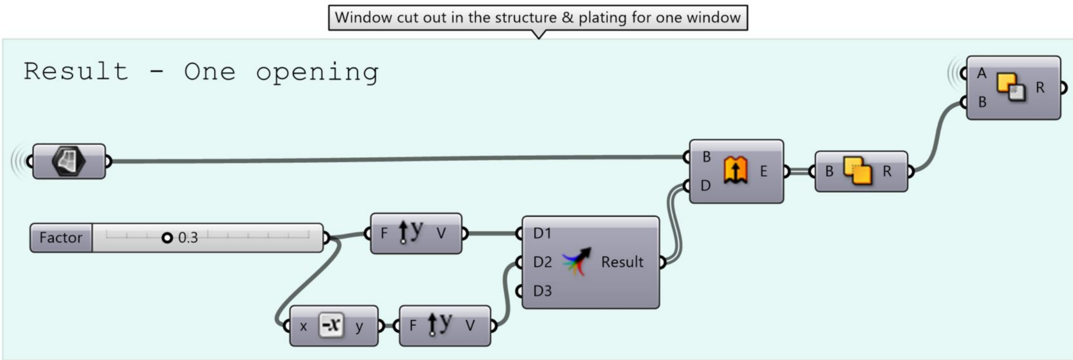


Figure A.8: One opening logic - 2

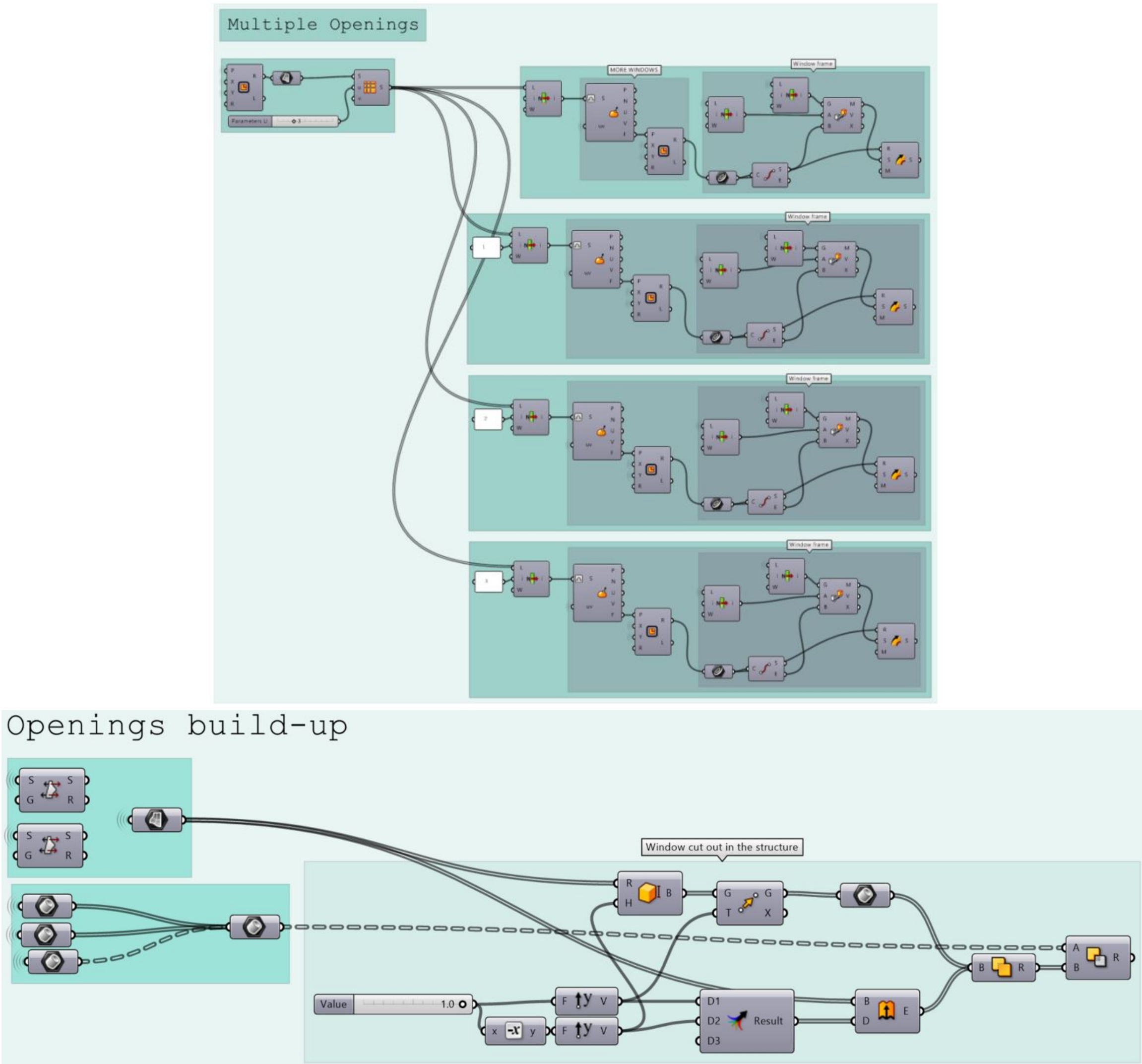


Figure A.9: Multiple openings

Replicability

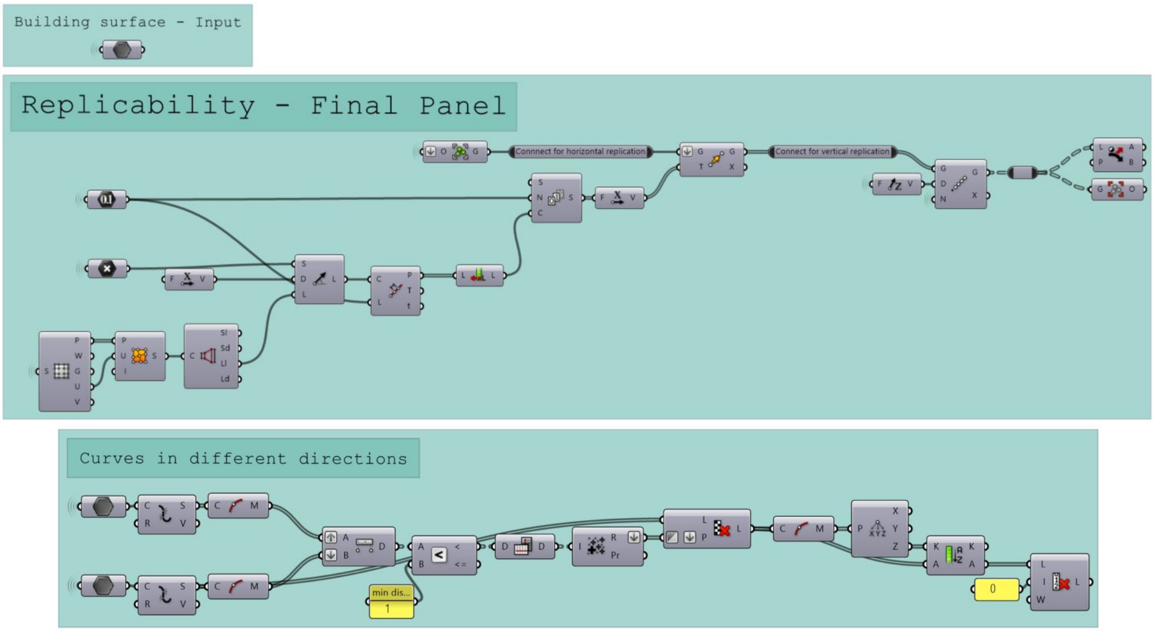


Figure A.10: Replicability logic

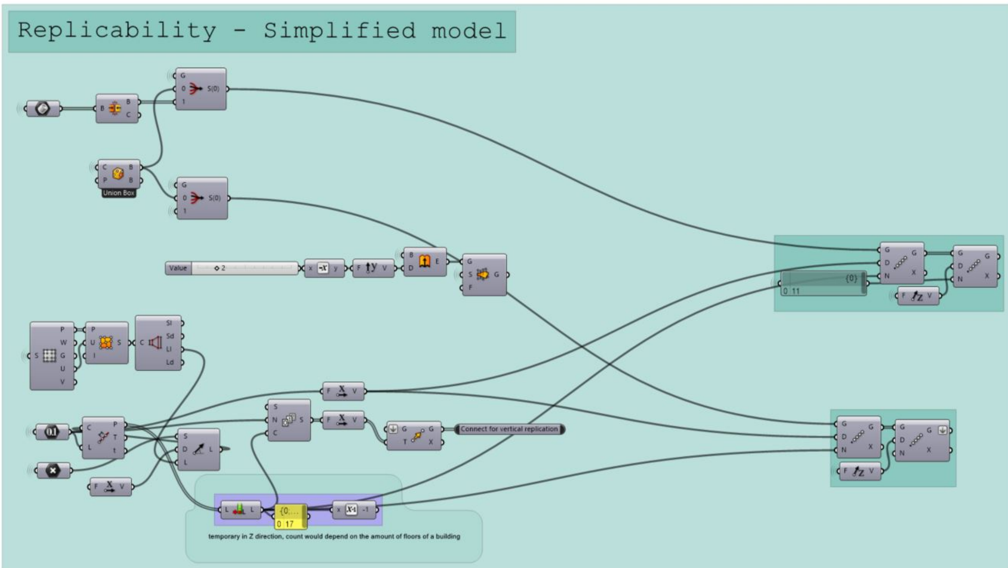


Figure A.11: Replicability logic - simplified model

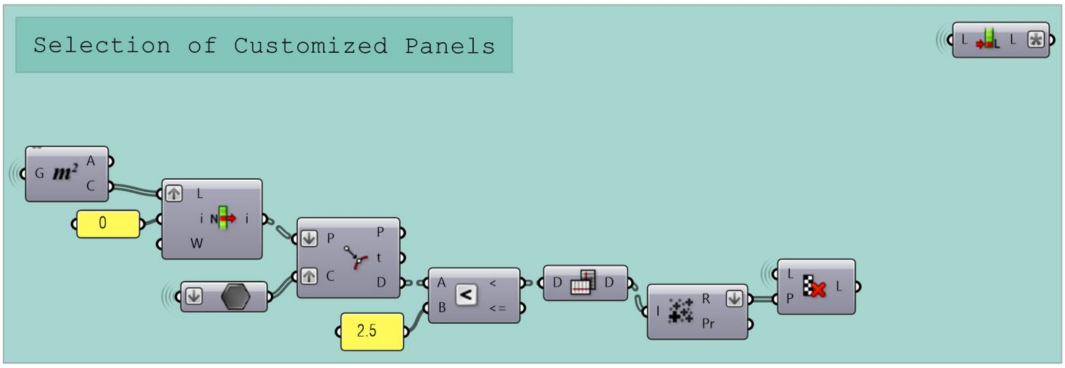


Figure A.12: Replicability logic - customized panels

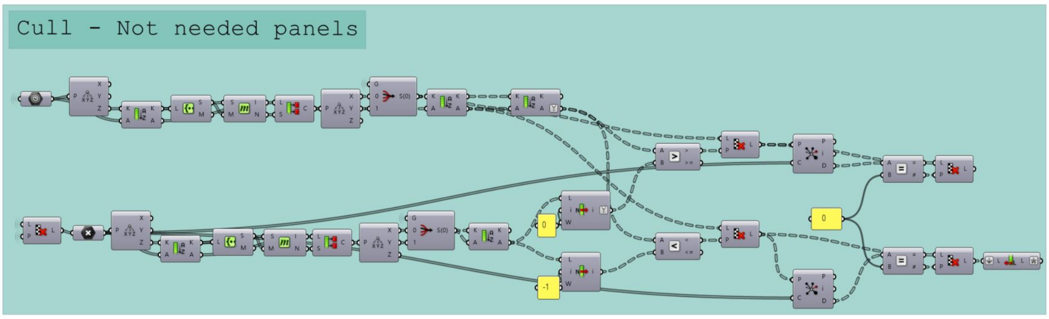


Figure A.13: Replicability logic - culled panels not needed

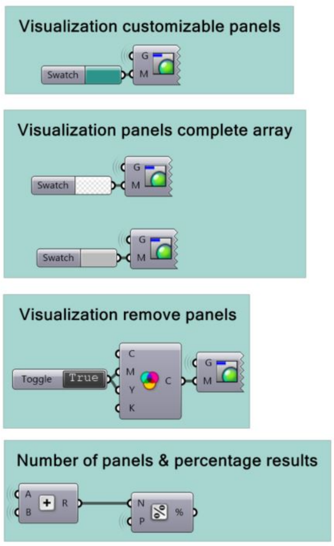


Figure A.14: Replicability logic - visualization input

Daylight simulation

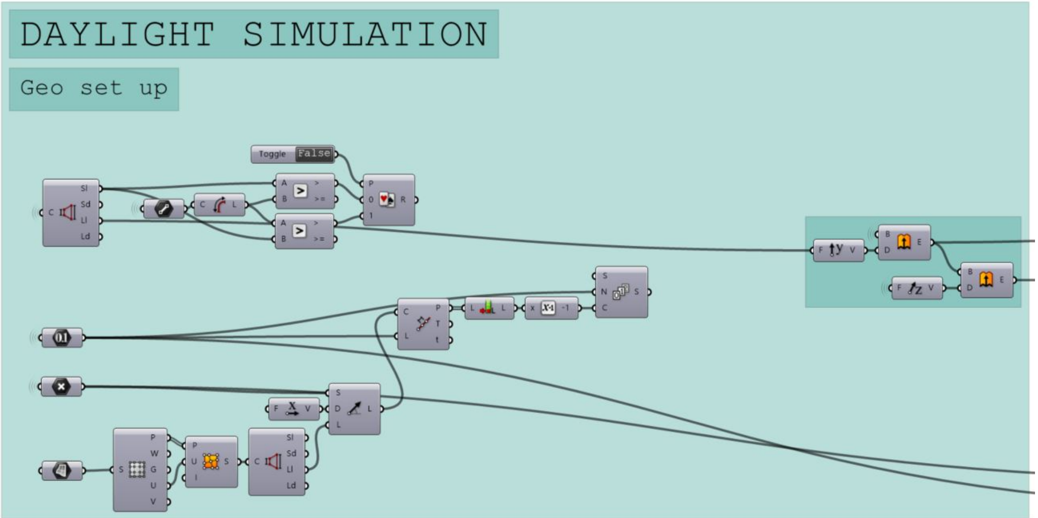


Figure A.15: Daylight - geometry set up

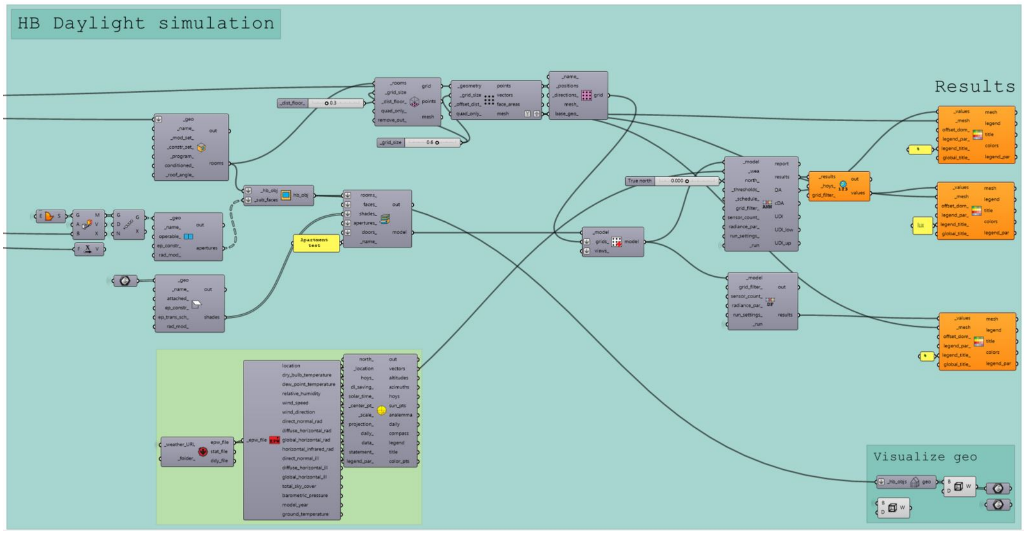


Figure A.16: Daylight - Honeybee simulation

Sound insulation

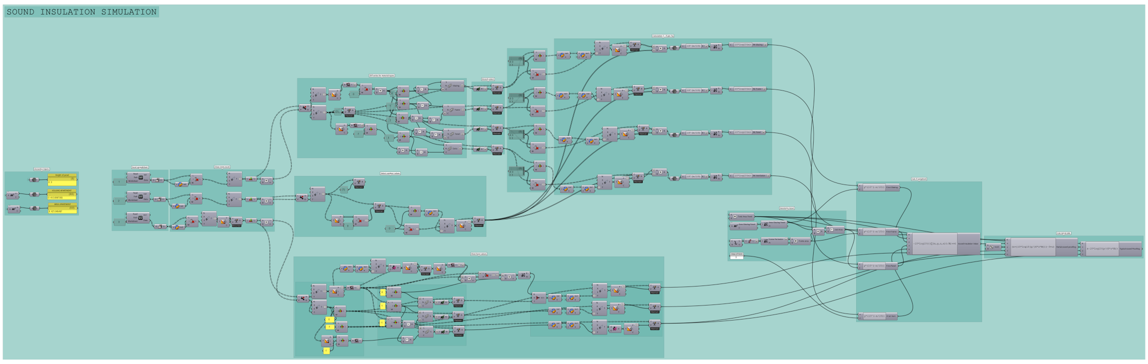


Figure A.17: Overview sound insulation logic

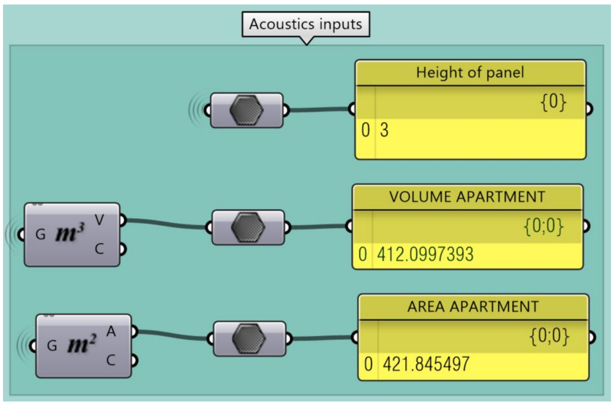


Figure A.18: Sound proofing - input parameters

The complete overview of the database set up is presented in Appendix D.

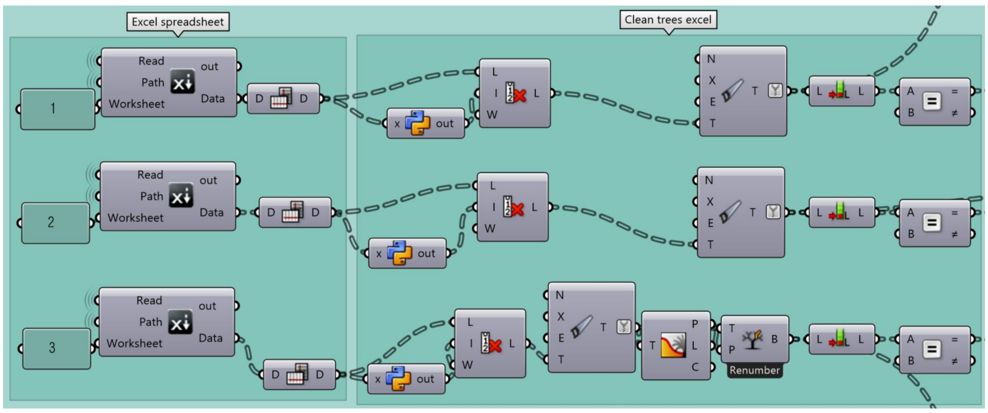


Figure A.19: Sound proofing - database

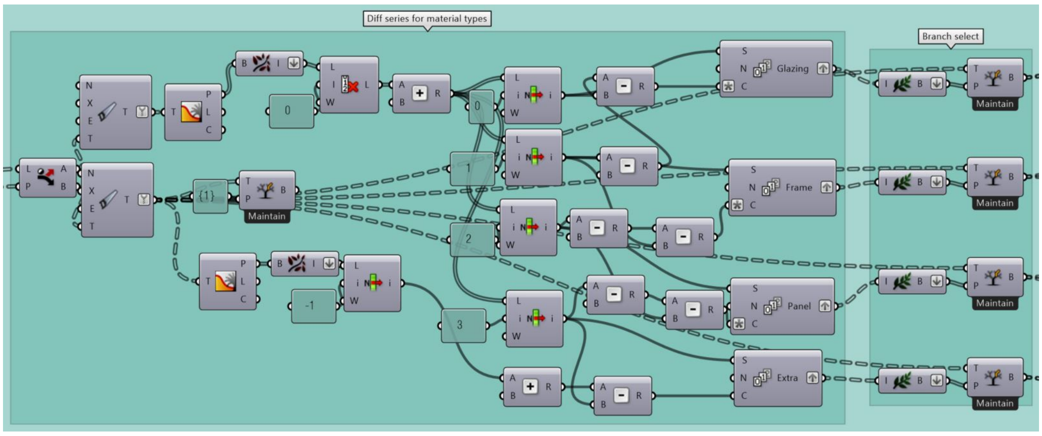


Figure A.20: Sound proofing - spreadsheet 1 - materials

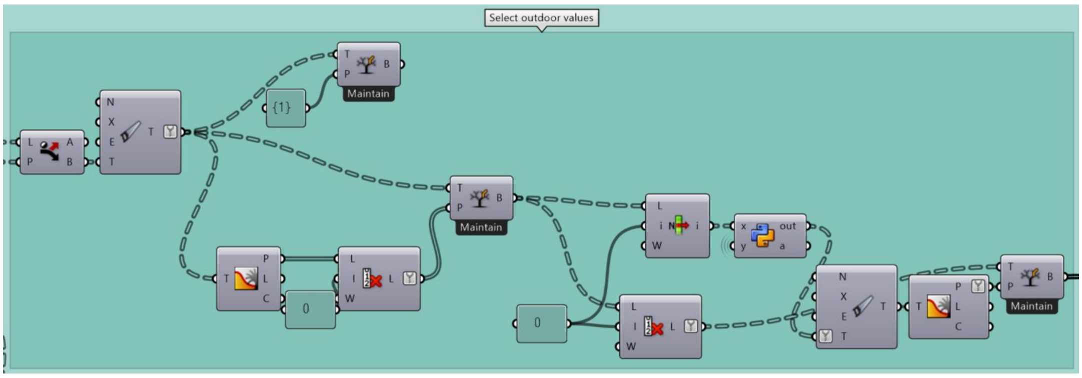


Figure A.21: Sound proofing - spreadsheet 2 - outdoor values

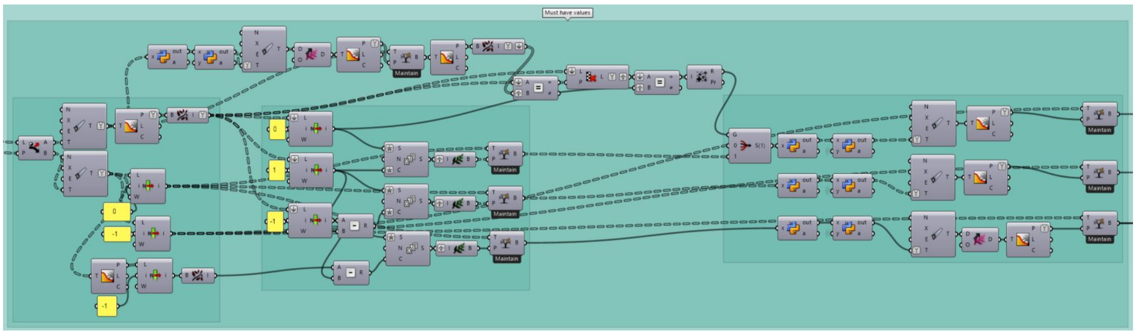


Figure A.22: Sound proofing - spreadsheet 3 - required values

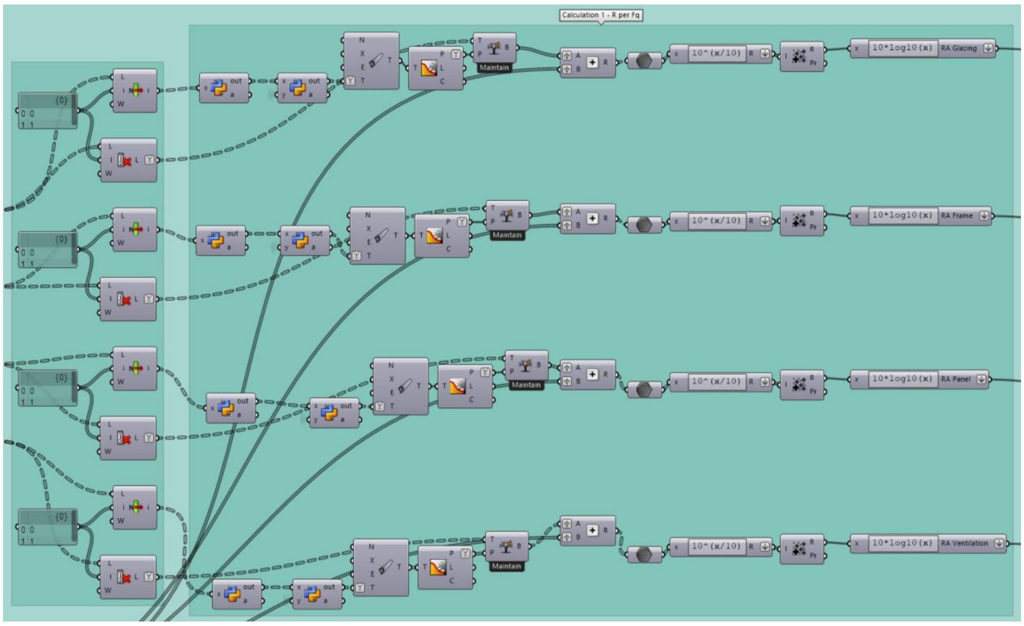


Figure A.23: Sound insulation per frequency for each material

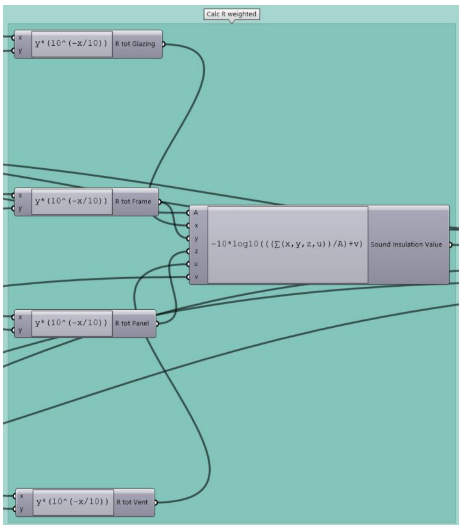


Figure A.24: Calculation 1 - R_A, sound insulation

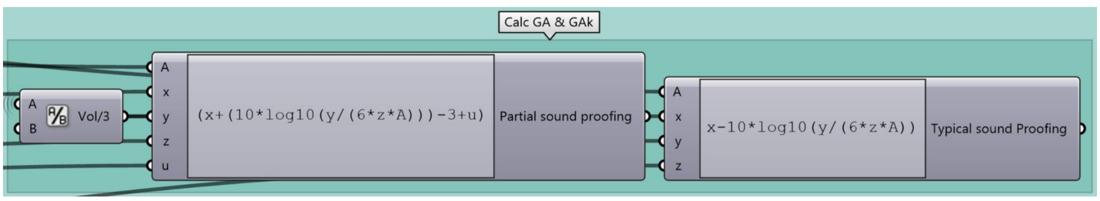


Figure A.25: Calculation 2 & 3 - G_A, sound proofing & $G_{A;k}$, typical sound proofing

The final image presented, allow the reader to zoom in the Grasshopper canvas and explore how this project was build-up.

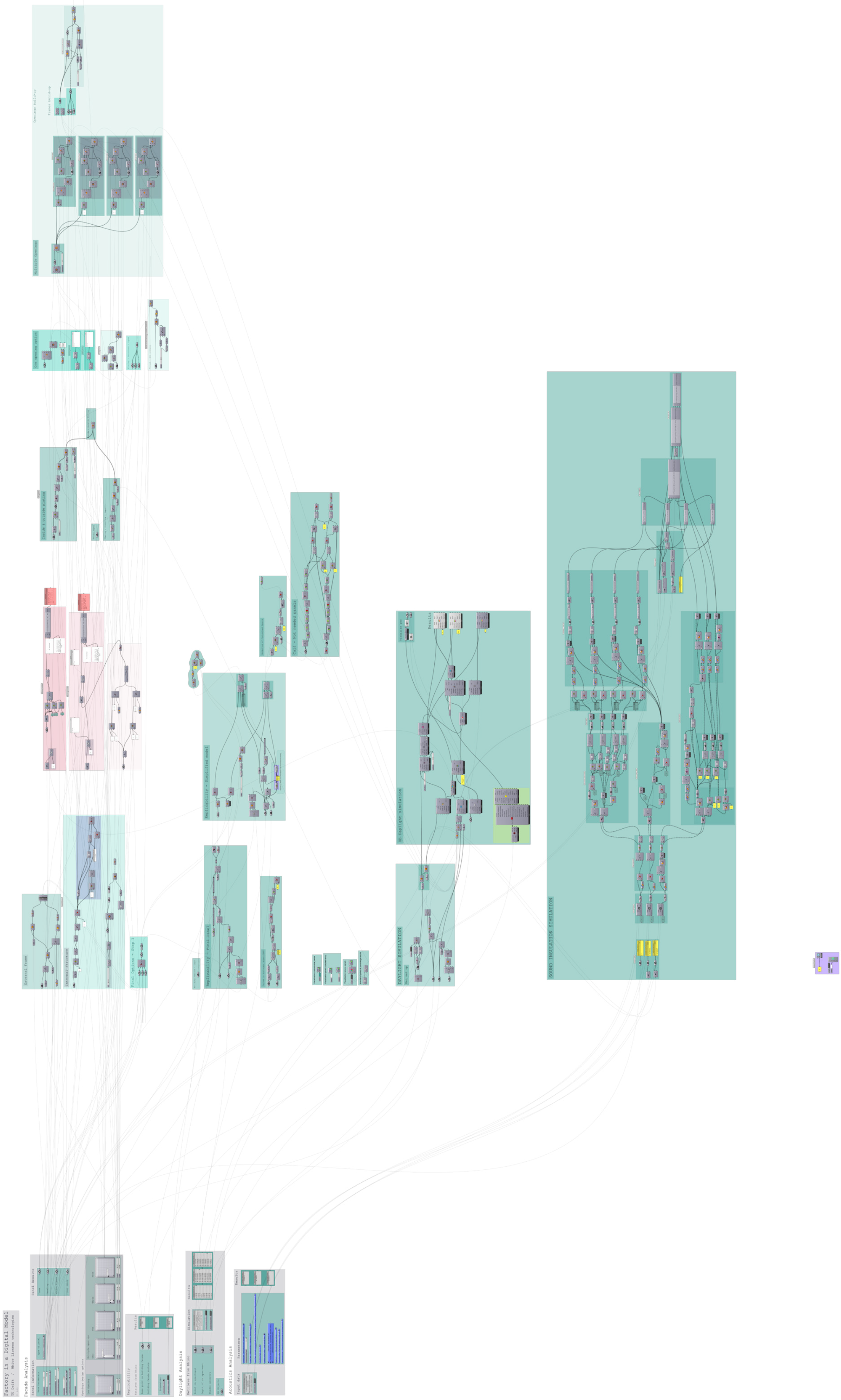


Figure A.26: Detailed Grasshopper canvas (Zoomable)

B

Value Tables

In this appendix the tables from which different values, needed for the daylight and sound proofing simulations, were retrieved are presented. These values were obtained from the book Building Physics [23], however these tables are also available in the building decree [29].

The following images contain the full information for the different options and values that can be used in the simulations, specifically for the changes that can be made to the sound proofing simulation.

Daylight

In regards to daylight, Table B.1 portrays some of the recommended average levels of illuminance for different activities.

Nature of the activities	Recommended average levels of illuminance
Orientation lighting	
• observing large objects and movement of persons (storage areas, car parks)	50 lx
• observing basic details and recognising persons (corridors, staircases)	100 lx
Lighting in the work place	
• observing basic details (building site, smithy, warehouse)	200 lx
• reading and writing, comparable details and contrasts (offices, classrooms)	400 lx
• observing finer details and subtler contrasts (drawing office, detailed editing work)	800 lx
Special work lighting	
• observing very fine details on a dark background (precision work, cadastral drawing work, close inspection work)	1600 lx
• observing at the limits of visual scrutiny (microminiaturisation, operating theatres)	> 3200 lx

Figure B.1: Minimal daylight requirement

Sound proofing

In regards to sound proofing the different values used are presented in the tables below. These present the full information that can be used for different types of buildings or outside noise characteristics.

frequency [Hz]	A-weighting [dB]
63	–26.1
125	–16.1
250	–8.6
500	–3.2
1000	0.0
2000	1.2
4000	1.0
8000	–1.0

Figure B.2: Attenuation or amplification in accordance to A-weighting

room	*T* [s]
well-furnished room	approx. 0.5
office room	0.5–0.7
open-plan office	0.7–0.9
school classroom	0.6–0.8
music room	0.8–1.2
theatre	0.9–1.3
chamber music room	1.2–1.5
opera	1.2–1.6
concert hall	1.7–2.3
church (organ music)	1.5–2.5

Figure B.3: Guide values for reverberation time

C_i [dB] for octave band *in middle frequency (Hz)*	125 *i = 1*	250 *i = 2*	500 *i = 3*	1000 *i = 4*	2000 *i = 5*
traffic noise and other	−14	−10	−6	−5	−7
railway traffic noise	−27	−17	−9	−4	−4
air traffic noise	−21	−11	−7	−4.5	−6

Figure B.4: Derivation values for outdoor sound

Situation	gap term	R_A
existing dwellings		
façades		
• without provisions	$3 \cdot 10^{-3}$	25
• single gap sealing	$1 \cdot 10^{-3}$	30
• double gap sealing and improved joint sealing	$3 \cdot 10^{-4}$	35
• special double gap sealing*	$3 \cdot 10^{-5}$	45
roofs		
• with gaps in roof boarding	$1 \cdot 10^{-3}$	30
• with gap-tight roof boarding	$1 \cdot 10^{-4}$	40
new build dwellings		
façades		
• single gap sealing and good joint sealing	$3 \cdot 10^{-4}$	35
• double gap sealing and good joint sealing	$1 \cdot 10^{-4}$	40
• special double gap sealing*	$1 \cdot 10^{-5}$	50
roofs		
• with single scale roof elements < 30 kg/m²	$3 \cdot 10^{-5}$	45
• other roof structures	$3 \cdot 10^{-6}$	55

* – remaining good joint sealing
– two or three-point clamp fixing
– draught mouldings welded to corners
– sound attenuator connection, carefully sealed

Figure B.5: Gap term values

façade type	flat façade	façade with eaves			façade with gallery								
façade cross-section													
details about the façade structure	fully flat façade (variations in depth less than 0.40 m)	eaves or protruding part wider than 1 m above the façade			gallery			gallery			high parapet (10% open on the top side)		
parapet	n/a	n/a			none			closed			closed		
absorption coefficient of the ceiling in %	n/a	0	50	100	0	50	100	0	50	100	0	50	100
value of C_g in dB(A): generally applicable value (sightline meeting point lower than 1.5m)	0	-1	-1	0	-1	-1	0	0	0	1	n/a	n/a	n/a
value of C_g in dB(A): if sightline meeting point is between 1.5 and 2.5 m	0	n/a	n/a	n/a	-1	0	2	0	1	3	n/a	n/a	n/a
value of C_g in dB(A): if sightline meeting point higher than 2.5 m	0	n/a	n/a	n/a	1	1	2	2	2	3	3	4	6

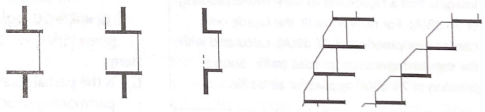
façade type	façade with balcony									terrace façade					
façade cross-section															
details about the façade structure	semi-recessed balcony or corner balcony			semi-recessed balcony or corner balcony			fully recessed balcony (loggia)			terrace façade with or without ceiling			terrace façade with or without ceiling		
parapet	open			closed			open/closed			open			closed		
absorption coefficient of the ceiling in %	0	50	100	0	50	100	0	50	100	0	50	100	0	50	100
value of C_g in dB(A): generally applicable value (sightline meeting point lower than 1.5m)	-1	-1	0	0	0	1	1	1	2	1	1	1	3	3	3
value of C_g in dB(A): if sightline meeting point is between 1.5 and 2.5 m	-1	-1	3	0	2	4	1	1	2	3	4	5	5	6	7
value of C_g in dB(A): if sightline meeting point higher than 2.5 m	1	2	3	2	3	4	1	1	2	4	4	5	6	6	7

Figure B.6: Façade structure correction

structure	$G_{A;k}$ [dB(A)]
partition between accommodation area and outdoors	sound load od – threshold values minimum 20;
if a higher sound load is permitted in the accommodation area	sound load od – sound load id minimum 20;
partition between accommodation room and outdoors	sound load od – threshold value – 2 minimum 20;

Figure B.7: Requirements for typical sound proofing

air traffic noise	$G_{A;k}$ [dB(A)]	
partition between accommodation area and outdoors	*dwelling function**	*office function*
load 36–40 Cu	30–33	27–30
load 41-45 Cu	33–36	30–33
load 46-50 Cu	36–40	33–36
load > 50 Cu	40	36

* Except for a dwelling function for a caravan.

Figure B.8: Requirements for fac cade sound proofing of air traffic noise

C

Sluishuis Building

In the following annex the information obtained to develop the study case is presented. Plans and sections found from the architects involved, Barcode & BIG, are shown. Also the information found on the Sluishuis website and that was relevant for this project is presented.

Some assumptions on the exact dimensions of the project were made, due to lack of availability of this information. This is why, despite only using one of the apartments as case study, several other plans were revised to gather more accurate information on the dimensions of the building.

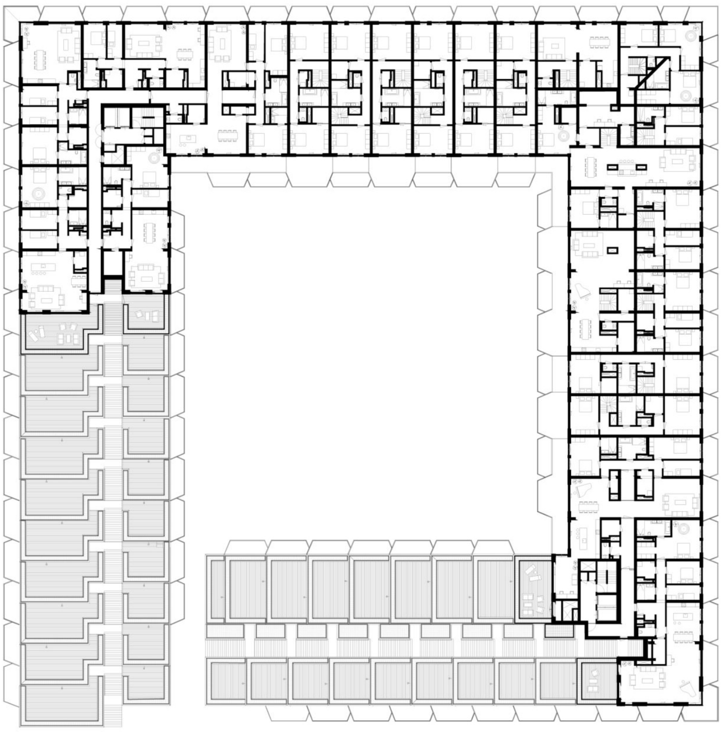


Figure C.1: General building plan [31]

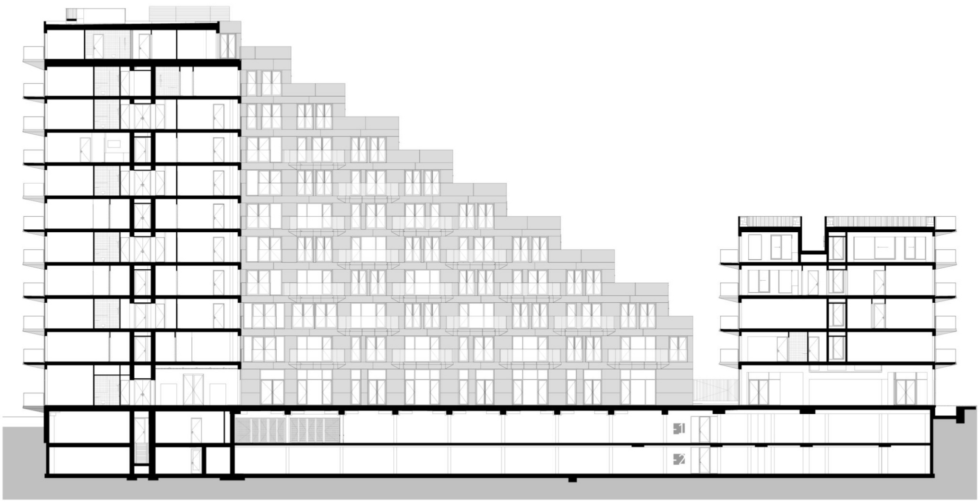


Figure C.2: General section A-A' [31]

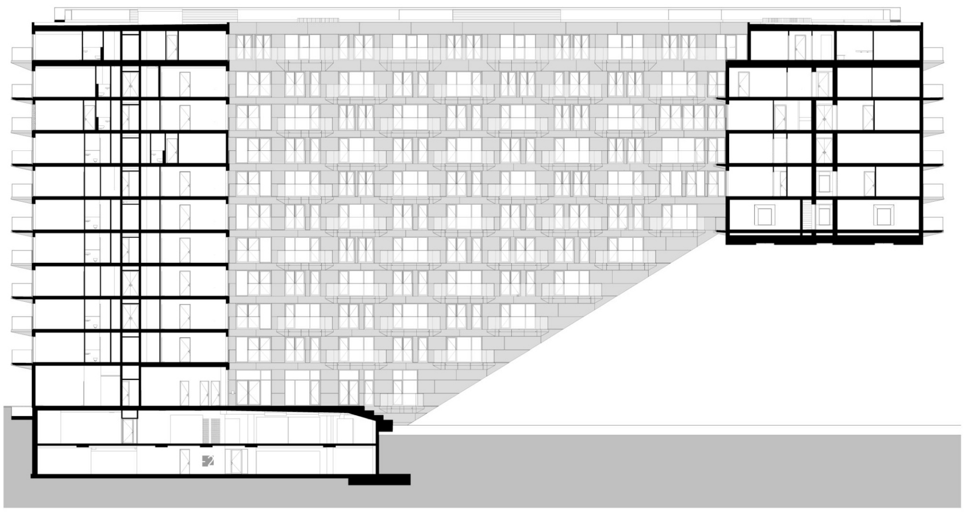


Figure C.3: General section C-C' [31]

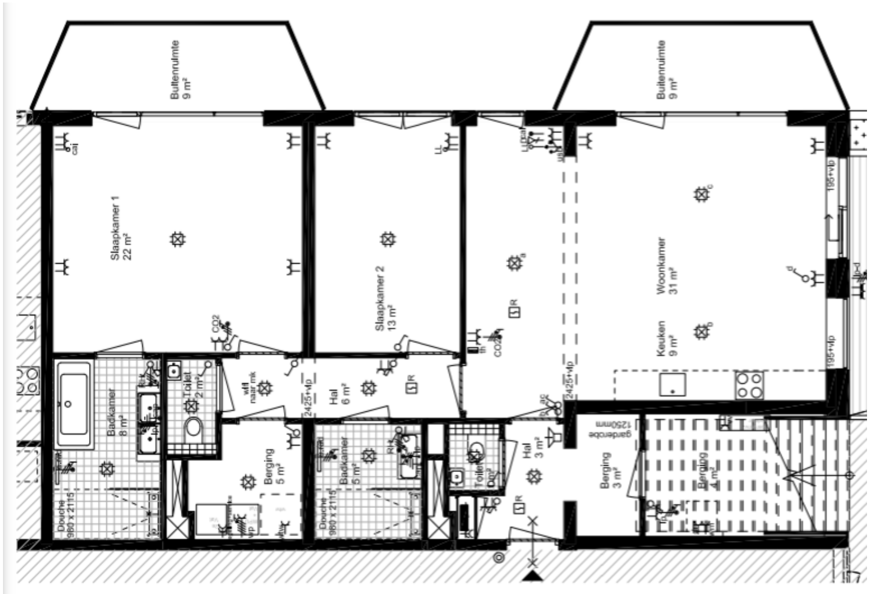


Figure C.4: Apartment example - 1

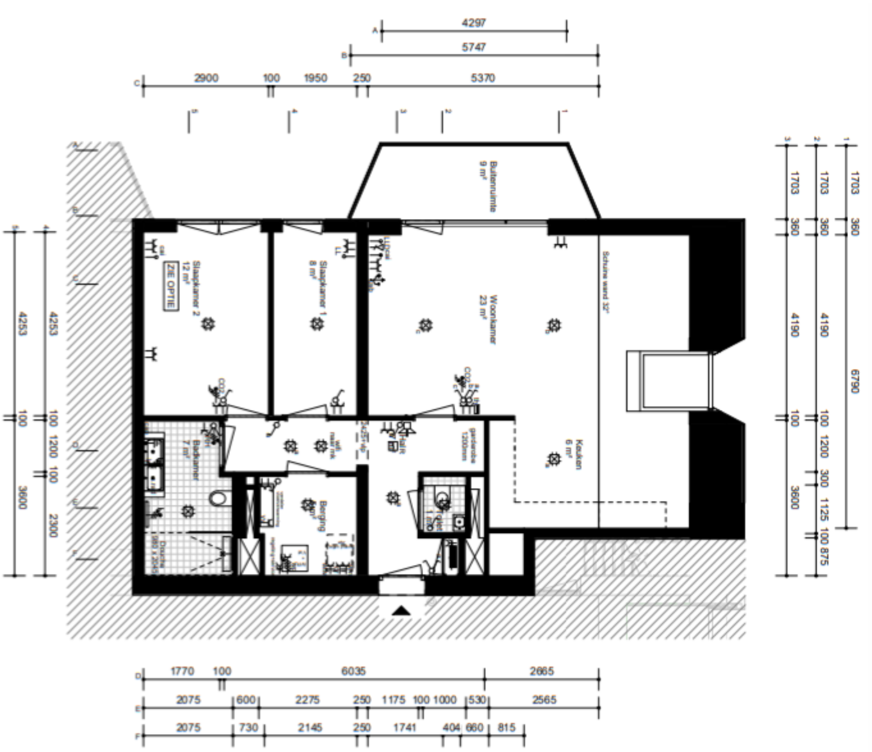


Figure C.5: Apartment example - 2

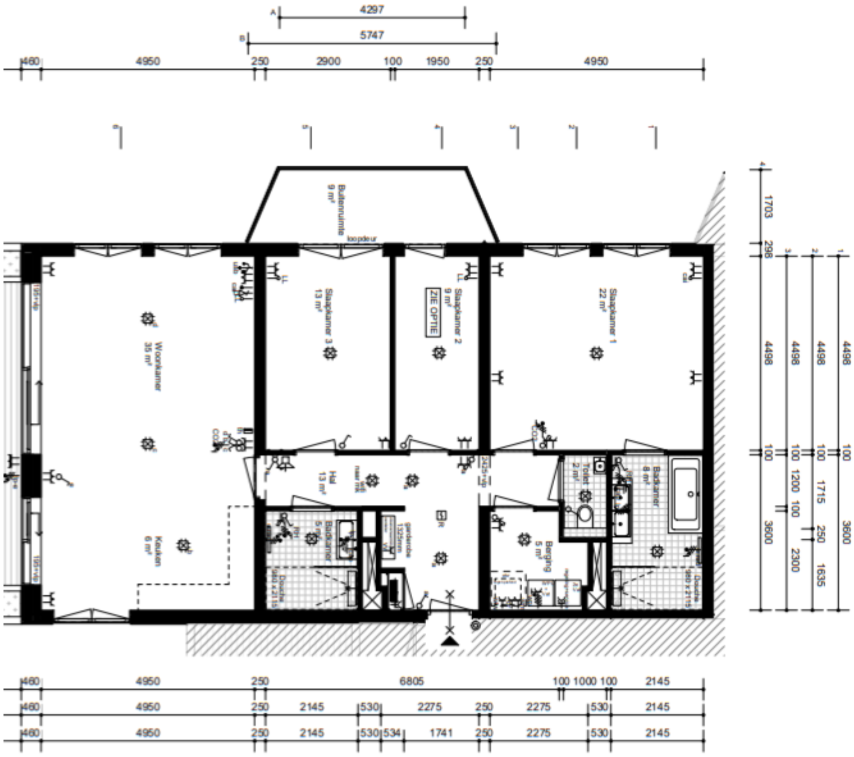


Figure C.6: Apartment example - 3

Figure C.7: Apartment example - 4

D

Acoustics Database

In the following appendix the Excel database created for the sound proofing simulation is presented. To fulfill the data needed for the sound proofing calculations, mentioned in Chapter 5; certain pre-calculated values need to be included. These values were organized in a database that can be updated to include more materials or parameters.

The values presented at this point were established to determine the functionality of the tool for sound proofing and for the proof-of-concept objective of this project.

		Octave band [Hz]				
		125	**250**	**500**	**1000**	**2000**
MATERIAL	**Type**					
Glazing						
12,8 Acoustic	Single glazing	27.9	32.2	37.2	40.6	40.8
6/12/6T	Double glazing	22.6	19	32.2	40.3	30.1
6/20/10,8T Acoustic	Double glazing	24.6	33.5	42.6	49.6	44.6
8/12/8,4T Acoustic	Double glazing	28.8	27.6	38.1	47.8	49.1
10T/12/6/12/10,8T Acoustic	Triple glazing	24.9	40.2	45.9	49	50.4
Frame						
Aluminium frame	Window frame	22	25	33	35	35
Double wooden frame	Window frame	26	28	34	36	40
Mixed wooden + aluminium	Window frame	31	34	34	39	44
Panel						
Cavity construction with façade cladding, aprox. 55 kg/m2	Sandwich panel like construction	25	35	40	45	50
Cavity construction with façade cladding, aprox. 40 kg/m2	Sandwich panel like construction	21	30	37	41	44
Cavity construction with façade cladding, aprox. 65 kg/m2	Sandwich panel like construction	27	38	45	50	50
Ventilation grill						
x	x	x	x	x	x	x
x	x	x	x	x	x	x

Figure D.1: Sound insulation values per octave band frequency for each material

	Octave band [Hz]				
Derivation values C for outdoor sounds	**125**	**250**	**500**	**1000**	**2000**
Traffic noise & other	-14	-10	-6	-5	-7
Railway traffic noise	-27	-17	-9	-4	-4
Air traffic noise	-21	-11	-7	-4.5	-6

Figure D.2: Required values for various types of outdoor sounds

Gap term - New dwellings (K)	
Double gap sealing & good joint sealing	1 * 10^-4
Special double gap sealing	1 * 10^-5
Facade structure correction - C_g (Generally applicable value)	
Flat facade (variations <0.40 m)	0
Facade with balcony	-1
Reference reverberation time (T_0)	
General term used (except for teaching rooms)	0.5

Figure D.3: Required values for Gap term, façade structure and average reverberation time

E

Sound proofing tests

In this appendix the different results obtained for various changes on the characteristics of the panel are presented. It is clearly shown that the lesser the amount of glass the better the insulation of the façade, as would be expected. Several changes and combinations were made to test different possibilities. Here some of the more relevant results are presented.

Figures E.1, E.2, E.3 show the changes in results when the materials that build up the façade are changed. This example maintains the same dimensions of the panel used in the results shown in Chapter 6.

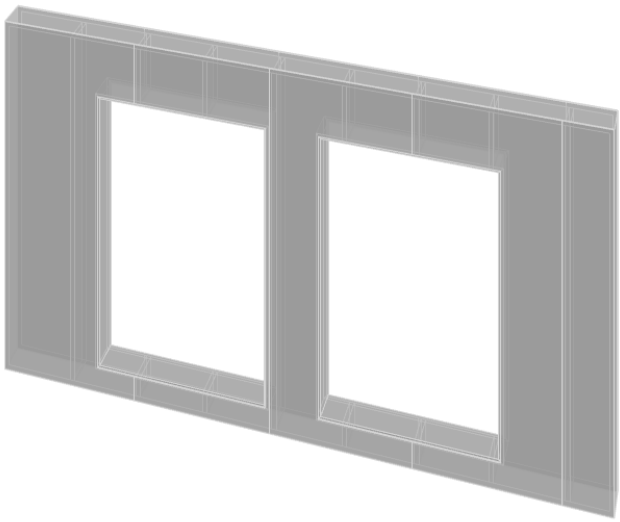


Figure E.1: Base panel

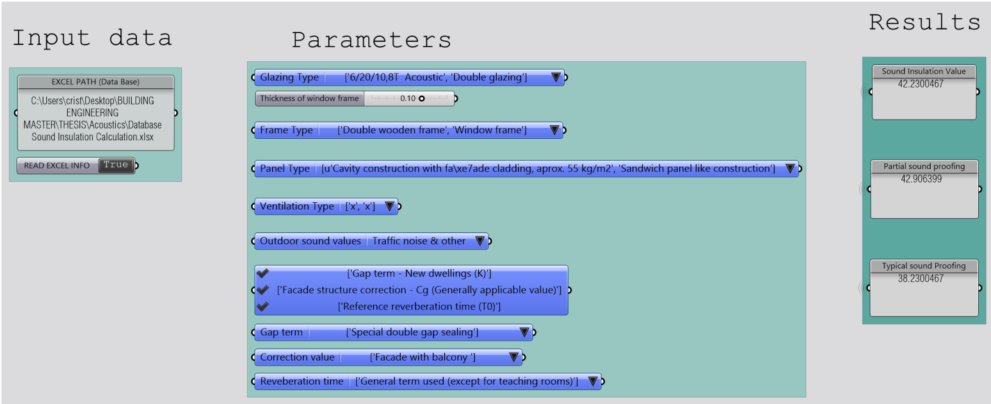


Figure E.2: Base panel - change of parameters

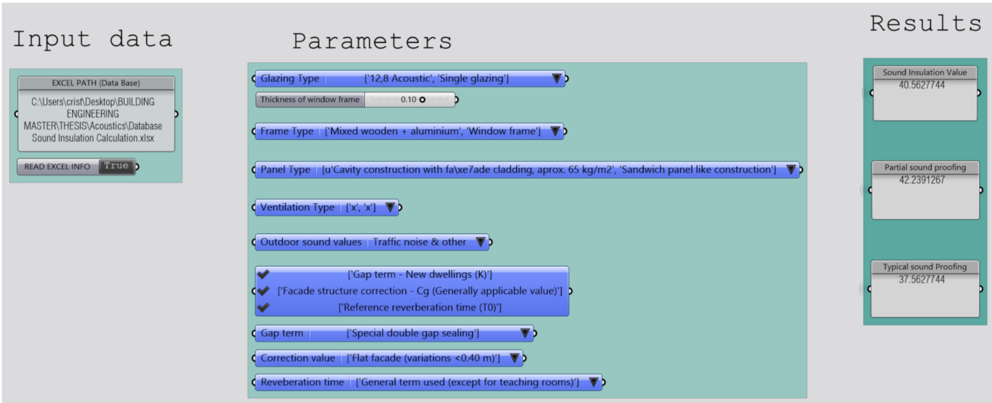


Figure E.3: Base panel - different combination of parameters

Then, some changes on dimensions were made for only one of the windows. In Figures E.4, and E.5 the changes made and the results obtained are shown. These show and increase in sound proofing compared to the previous results presented. Also here in Figure E.6 different parameters were used.

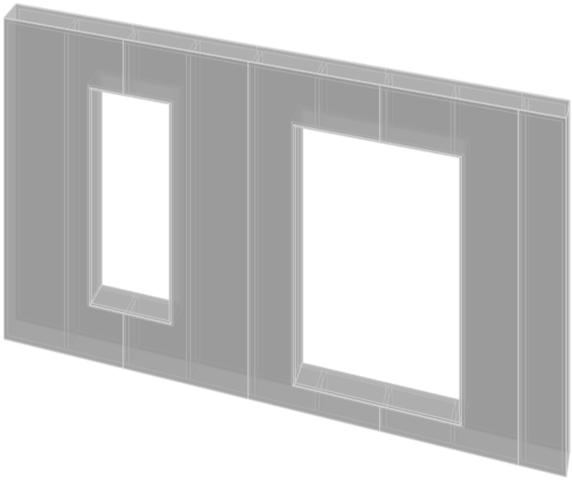


Figure E.4: Panel - changes in one window's dimension

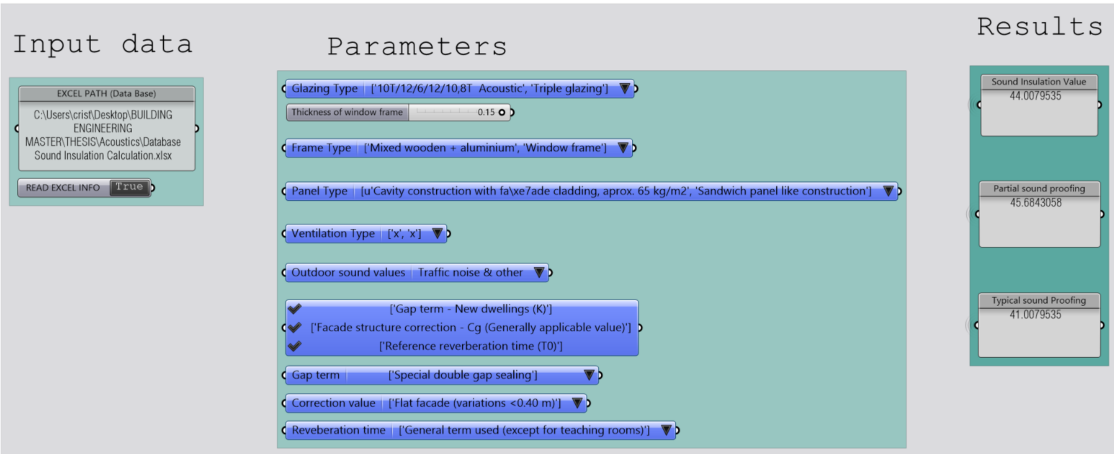


Figure E.5: Panel - changes in one window's dimension

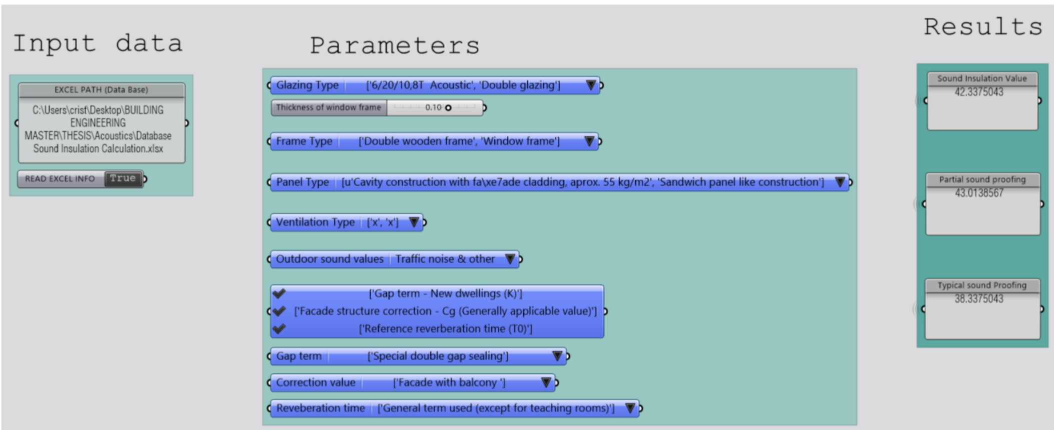


Figure E.6: Panel - changes in one window's dimension, different parameters

In the following figures, changes in dimensions as well as modifications of the materials were made, for every change made the results are given.

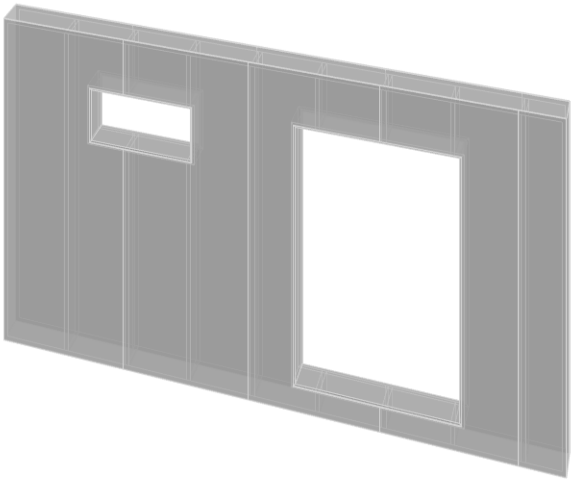


Figure E.7: Panel - changes in one window's dimension

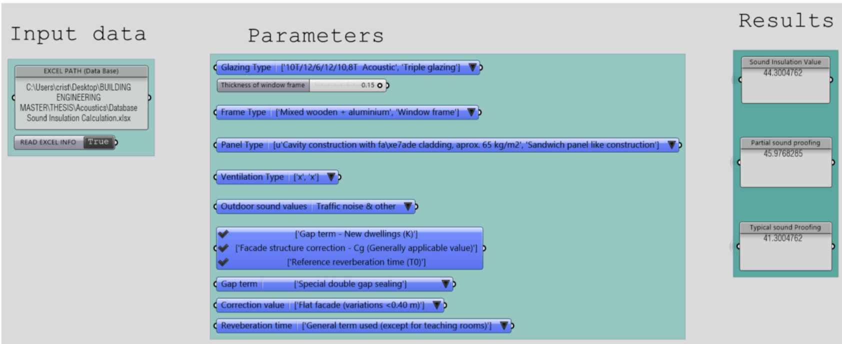


Figure E.8: Panel - changes in one window's dimension

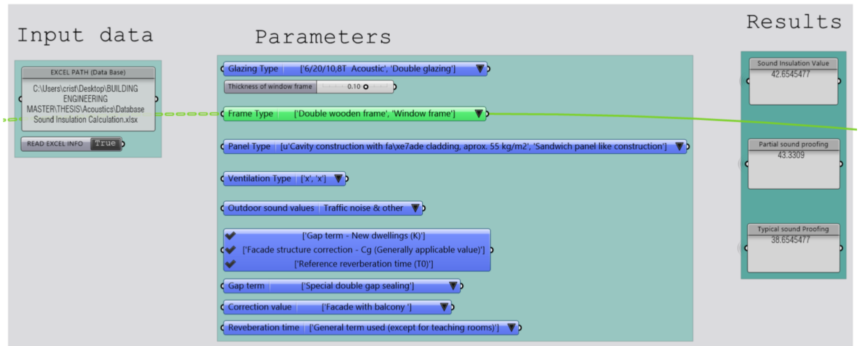


Figure E.9: Panel - changes in one window's dimension, different parameters

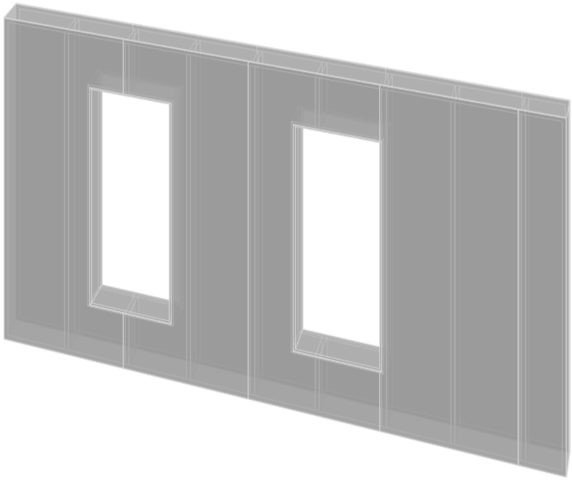


Figure E.10: Panel - changes in dimensions

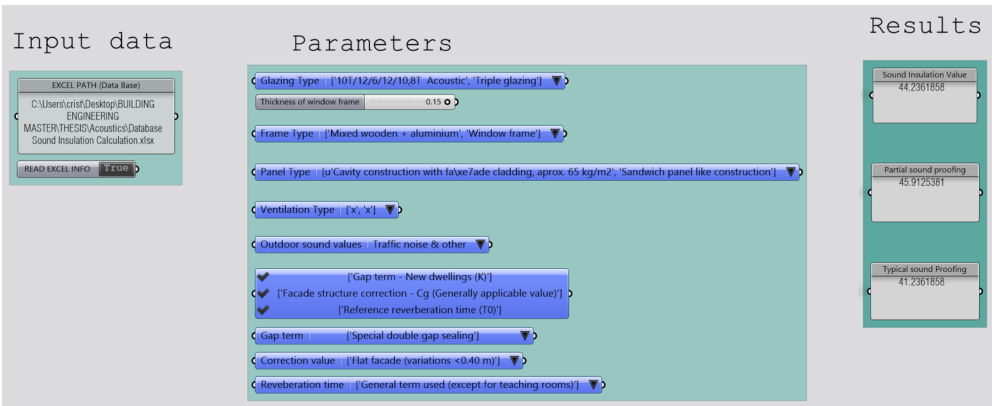


Figure E.11: Panel - changes in dimensions of both windows

Considering the results shown in this appendix, it is possible to conclude that the tool gives reliable results in regards to sound proofing. These results, however, to be used as base information for any project need to be compared against the Building Decree requirements, and only then could be determined is the materials combination of the panel is enough or changes need to be made.

F

Dialux results

In this section the results obtained for the simulations made in Dialux are presented. Two different set of results were obtained. Daylight autonomy values in lux and daylight factor values in percentages. The results obtained from Dialux given an average value, plus maximum and minimum achievable values.

It is important to keep in mind that the results given by Dialux, are set for one day of the year in contrast with the results obtained from Grasshopper that give a annual daylight estimate. This is one the parameters that affects the difference between values obtained from both software.

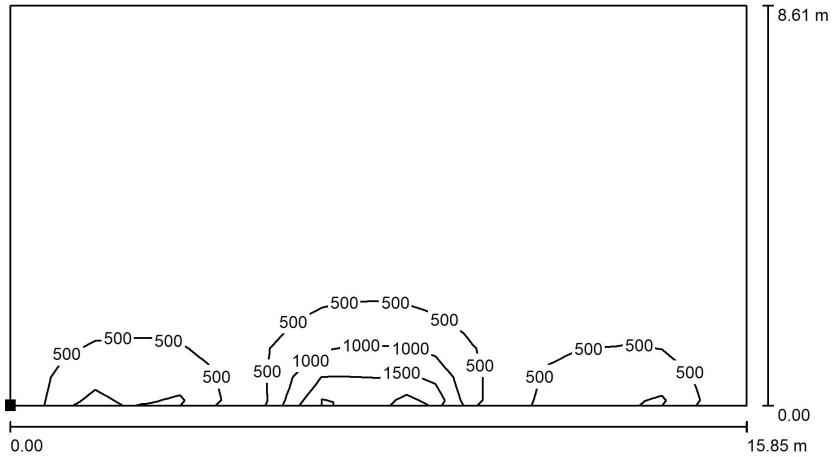
However, for daylight factor the values do not depend on a day or yearly basis, which makes it easier to compare the obtained results.

Project 1

DIALux
18.11.2021

Operator
Telephone
Fax
e-Mail

Room 1 / Light scene 4 / Calculation Surface 1 / Isolines (E, Perpendicular)



Values in Lux, Scale 1 : 114

Position of surface in room:
Marked point:
(-5.027 m, -1.546 m, 0.400 m)

Grid: 26 x 14 Points

E_{av} [lx]	E_{min} [lx]	E_{max} [lx]	u0	E_{min} / E_{max}
248	66	2318	0.268	0.029

Page 2

Figure F.1: Dialux daylight results

Project 1

DIALux
18.11.2021

Operator
Telephone
Fax
e-Mail

Room 1 / Light scene 4 / Calculation Surface 1 / Value Chart (E, Perpendicular)

108	96	102	105	106	109	110	110	106	103	97	94	94
91	77	80	81	81	84	83	84	84	81	76	74	79
86	71	73	78	75	78	76	75	74	74	68	67	73
99	79	84	86	88	88	88	91	86	83	84	73	79
108	92	89	96	101	102	99	102	98	94	90	77	89
113	106	104	107	115	115	118	119	112	105	98	91	98
126	114	122	125	125	138	141	137	125	127	102	101	108
141	134	149	141	153	165	178	165	150	136	128	116	121
157	157	167	172	186	197	226	224	163	163	154	144	132
187	194	215	215	233	270	284	283	224	196	190	182	156
202	246	275	240	262	338	423	382	267	218	242	237	178
240	482	512	396	366	650	931	866	401	334	451	474	242
225	741	691	499	338	1000	1315	1404	426	356	602	700	253
145	1295	794	714	179	1422	1452	<u>2318</u>	226	329	867	1183	169

8.61 m
0.00
0.00
15.85 m

Values in Lux, Scale 1 : 114

Not all calculated values could be displayed.

Position of surface in room:
Marked point:
(-5.027 m, -1.546 m, 0.400 m)

Grid: 26 x 14 Points

E_{av} [lx]	E_{min} [lx]	E_{max} [lx]	u0	E_{min} / E_{max}
248	66	2318	0.268	0.029

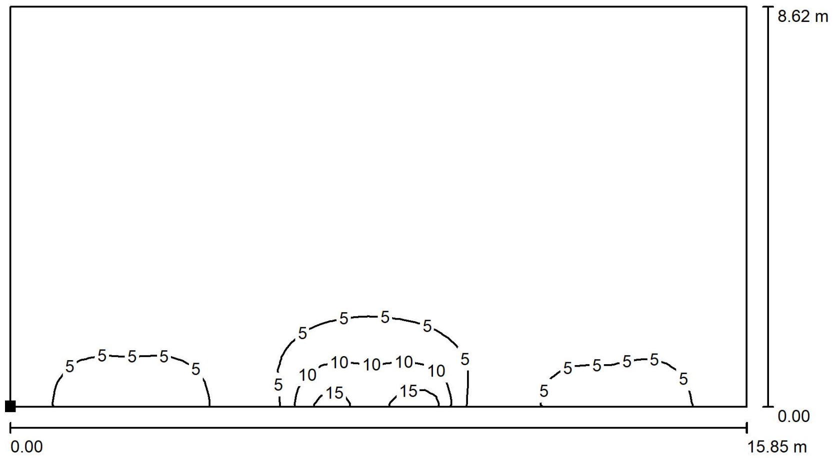
Figure F.2: Dialux daylight results

Project 1

DIALux
18.11.2021

Operator
Telephone
Fax
e-Mail

Room 1 / Light scene 4 / Daylight factor calculation surface 1 / Isolines (D)



Scale 1 : 114

Position of surface in room:
Marked point:
(-5.027 m, -1.546 m, 0.300 m)

Grid: 64 x 32 Points

D_{av} [%]	D_{min} [%]	D_{max} [%]	D_{min} / D_{av}	D_{min} / D_{max}
2.06	0.55	18	0.269	0.030

Horizontal illuminance outdoors E_o: 12840 lx

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Figure F.3: Dialux daylight results

Project 1

DIALux
18.11.2021

Operator
Telephone
Fax
e-Mail

Room 1 / Light scene 4 / Daylight factor calculation surface 1 / Value Chart (D)

0.68	0.65	0.65	0.68	0.68	0.68	0.71	0.72	0.72	0.72	0.69	0.66	0.64	0.61	0.62	0.63
0.62	0.59	0.60	0.62	0.65	0.63	0.66	0.63	0.64	0.66	0.64	0.63	0.59	0.57	0.56	0.58
0.70	0.61	0.64	0.65	0.71	0.69	0.73	0.70	0.74	0.69	0.69	0.69	0.63	0.62	0.59	0.60
0.72	0.63	0.65	0.68	0.70	0.71	0.74	0.74	0.76	0.71	0.70	0.67	0.65	0.63	0.60	0.64
0.76	0.71	0.74	0.77	0.78	0.82	0.83	0.83	0.83	0.83	0.79	0.77	0.76	0.68	0.67	0.72
0.82	0.81	0.81	0.87	0.87	0.93	0.94	0.99	0.96	0.96	0.91	0.85	0.86	0.75	0.77	0.79
0.92	0.87	0.93	0.97	1.06	1.06	1.17	1.20	1.23	1.17	1.07	1.05	0.98	0.95	0.90	0.89
1.06	1.03	1.10	1.15	1.20	1.29	1.39	1.45	1.46	1.29	1.22	1.12	1.08	1.11	1.06	1.01
1.19	1.22	1.31	1.41	1.39	1.55	1.66	1.84	1.76	1.66	1.36	1.36	1.31	1.26	1.21	1.08
1.39	1.41	1.71	1.76	1.78	1.91	2.24	2.35	2.36	2.29	1.85	1.65	1.62	1.64	1.38	1.25
1.52	1.92	2.08	2.26	1.98	2.18	2.75	3.27	3.32	2.82	2.18	1.85	1.97	2.06	1.91	1.46
1.81	2.34	2.97	2.91	2.71	2.69	4.04	4.92	4.93	4.18	2.79	2.36	2.56	2.70	2.37	1.78
1.94	3.20	4.12	4.22	3.28	3.02	5.28	7.35	7.45	5.96	3.32	2.76	3.54	3.84	3.49	2.00
1.68	4.82	5.72	5.93	4.13	2.68	7.86	11	11	9.73	3.49	2.93	5.06	5.24	5.41	2.03
0.98	8.87	8.55	9.46	5.81	1.36	11	17	15	16	1.70	2.67	8.40	6.11	9.56	1.29

8.62 m
0.00
0.00
15.85 m

Scale 1 : 114

Not all calculated values could be displayed.

Position of surface in room:
Marked point:
(-5.027 m, -1.546 m, 0.300 m)

Grid: 64 x 32 Points

D_{av} [%]	D_{min} [%]	D_{max} [%]	D_{min} / D_{av}	D_{min} / D_{max}
2.06	0.55	18	0.269	0.030

Horizontal illuminance outdoors E_o: 12840 lx

Figure F.4: Dialux daylight results