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Expert decision support for early design stage of facades for office buildings in Belgium: A parametric approach

Master's thesis in order to obtain a master degree in Architectural Civil Engineering,
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Abstract

Design decision-making during the early stages of facade development has an influence on the final performance of buildings. Moreover, as sustainable buildings are becoming increasingly important, the role of the architects and designers is to integrate their design with the energetic analysis. Thus, this increases the design decision fatigue and requires considerable time to work through a building simulation tool, especially when there are many choices and possibilities.

This study presents an approach based on building performance criteria. In particular, this thesis investigates a parametric design for façades of office buildings in cities with a climate similar to that of Belgium. The adapted methodology is to develop a parallel coordinator graph for facades in a user-friendly tool (Design Explorer) passing by a parametric design tool (Grasshopper) with environmental plugins (Honeybee and Ladybug) and based on European standards and norms. In addition, a focus on the most influential parameters that we should be aware of during the decision-making is discussed.

Finally, we obtain many options to help façade designers choose between and arrive at the optimal choice combining the desired design target and their energetic needs.

In conclusion, this thesis helps to reduce design decision fatigue and guide architects and designers towards a better decision.

Keywords

Design tools, energy approach, Daylighting, Window-to-wall ratio, Grasshopper, simulation

Summary

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The facade is one of the most important elements of a building that requires careful planning. In addition to being central in defining a building's identity and image, the facades also contribute to energy consumption and user comfort positively or negatively, especially in an office building, where facades are the main factors that influence energy efficiency.

However, the most important design parameter that integrates into the design process, particularly for window design, is the window-to-wall ratio (WWR). This indicator, with window characteristics, has an impact on the amount of daylight passing inside a room, on the energy use intensity and occupants comfort.

Thus, the main aim of the research presented in this paper is to support the design decision for facades. The methodology was to create a parametric design process for designing façades in Belgium, particularly for office buildings, based on the building's thermal environment performance. First, a simulation through EnergyPlus, Open studio, and Radiance was used with the help of Grasshopper in Rhino. Speed is essential. For that reason, a user-friendly interface tool was developed for this purpose. Thus, it will help designers to choose the desired design based upon a need quickly. Furthermore, designers can use this to do comparative studies to support decision-making for different proposed solutions, especially at the early design stage.

In addition, the study aims to take into account the correlation between facades parameters, such as the Window-to-Wall Ratio (WWR), U_{window} value, Solar Heat Gain Coefficient (SHGC), window division, window sill height and building orientation; and thus, study their degree of sensitivity and their impact on visual comfort, thermal comfort and energy efficiency. In addition, a focus on the most influential parameters that we should be aware of during the decision-making is discussed.

Results from different scenarios have been compared, and a sensitivity analysis followed to find the most influential facade parameters. It is demonstrated that WWR has a remarkable influence on daylight metrics and the Solar Heat Gain Coefficient on energy demand and thermal comfort, with a most negligible impact caused by window sill height and window division. Finally, a focus on the best design cases is mentioned.

In conclusion, this study helps to determine the degree of impact of facade parameters which will lead architects to better understand the influence of each parameter on the results and modify the variables according to their needs using a user-friendly interface.

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Abbreviations/Acronyms

ASE	Annual Sunlight Exposure
BREEAM	Building Research Establishment Environmental Assessment Method
DA	Daylight Autonomy
EPW	EnergyPlus Weather files
EPBD	Energy Performance of Buildings Directive | energy
EUI	Energy Use Intensity
IES	The Illuminating Engineering Society
GH	Grasshopper
HB	Honeybee
LB	Ladybug
LEED	Leadership in Energy and Environmental Design
NFRC	The National Fenestration Rating Council
RIBA	Royal Institute of British Architects
SHGC	Solar Heat Gain Coefficient
sDA	Spatial Daylight Autonomy
Uw-value	Heat transmission coefficient for the window (glass + frame)
VT/ Tvis	Visible Transmittance
WWR	Window-to-Wall Ratio

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1 Introduction

The most crucial part of a building is its façade. A façade is not just the exterior cover of a building. It is the first impact of a building type, the aesthetic aspect, and the first impact on energy performance. As a designer or an architect, to design a façade, there are many things to take into account. Furthermore, that needs time and experience to involve the energy aspect and the comfort.

Thus, nowadays, with the importance of the energetic aspect in buildings and occupants comfort, the architect has to integrate his design with it. From this goal, the traditional design methods are gradually replaced by new strategies based on building performance in which simulation tools are used to support design decision-making. In its turn, design decision-making is a process where we must choose an option among several others and compare, considering different aspects, parameters, and goals.

1.1 Background information and problem statement

Overall, in the context of office buildings, we have many requirements posed by the exterior environment and interior occupancy, following energy-conscious principles and maintaining user comfort. Furthermore, as represented in Figure 1-1, there are a very large number of elements and configurations to choose between and to be considered when we talk about facades: the aesthetics, structure, sociability aspects during the design phase, materials, security, and physics during the construction phase, management, and integrity during the operation phase. There are so many parameters that facade designers have to consider, such as budget, views, orientation, window size, type of glazing, and many more. In addition, it is especially important to focus on design goals: energy-saving, cost-efficiency, increase in solar radiation and heat gains within facades, or even protection of the interior areas from solar radiation.

Consequently, depending on the goals, it can take a long time to accomplish a well-defined facade. Moreover, there is a need to have a user-friendly interface that simultaneously considers the environmental aspect inside buildings and facilitates façade decision-making when there are many choices regarding the norms and climate in Belgium. Especially in tertiary buildings where we can find high energy consumption. Bearing in mind that offices generate quite a lot of heat internally from the IT equipment and the occupants. Therefore, office cooling accounts for a significant proportion of energy consumption.

Therefore, it is essential to develop a user-friendly design tool to help architects and designers save time and consider the environmental aspects around the building. It is important because of the large number of factors to be taken into account simultaneously for the façade design

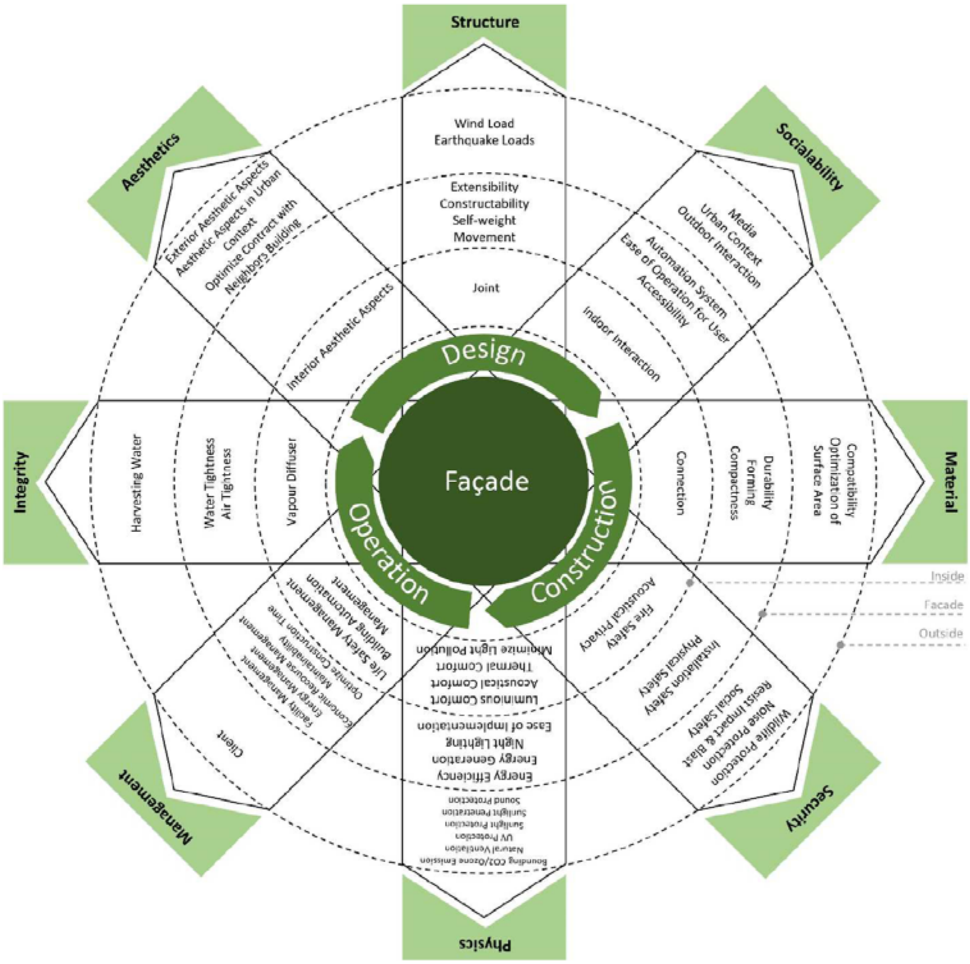


Figure 1-1 Façade engineering components conceptual Framework (Namazi et al., 2016)

Secondalt, glassed facades are most used in territory buildings and especially in office buildings. Glassed surfaces allow natural daylight to penetrate into rooms and have contact with the external world and the environment, especially with a view of the surrounding urban landscape around the building. In addition, large glass areas can also reduce the sense of enclosure for occupants and increase employees' comfort of employees who spent most of their time in that office room, where the external visual contact has an important impact on the wellness of the occupant. Thus, that will help to increase work productivity.

In-office buildings, we could face many scenarios related to glazing surface: basically, where the direct solar heat is undesirable, and a high temperature because of electrical equipment, the density of employees, and lightning. On the other hand, large glazing could bring on more heat loss. That will lead to discomfort, especially during warm seasons or very cold seasons.

Moreover, many parameters can change the undesired effects. For example, we could control the amount of entering daylight by choosing the right choice of glass, whether it is coated, coloured, or the energy properties.

More aspects should also be taken into account when designing a glazed façade, such as maintenance, structural aspects, fire safety and the aesthetic aspect. Also, for skyscrapers, we found the factor of wind, cleaning, and construction so that the percentage of glazing has many impacts.

The building design team is continuously being challenged by the ever-rising patterns of demand for energy that are usually combined within the ambitious objectives for the indoor environment. There has been an essential rise in the use of environmental assessment approaches in the recent past besides the stricter energy demands. Sustainability performance besides environmental efficiency of various structures and buildings has gained increasing attention, specifically since it was introduced as among the compliances of requirements of the erection of a new building in large economies globally.

The enhancement in buildings environmental efficiency is due to a sophisticated process of design involving passive alongside active design techniques and calls for taking into consideration different features of the building. Such features include the building geometry, for instance, spatial arrangement, aspect ratio and building orientation (Chen et al., 2018).

Furthermore, some studies showed that late design choices have an impact on daylight levels, such as furniture density with a high level of impact, or window sill height, furniture reflectance and partition height with a medium degree of impact, which is considered an inconclusive impact, whereas the colour of interior surfaces and their reflectance with a minor impact on daylight levels. These details with a different degree of impact could not be included in the early design stage. (Bálint Palmgren & Tran, 2021). Thus, we should be aware of many other parameters and variables to ensure high quality of living either on the interior surfaces or about the characteristics of the building envelope (facade).

However, even the furniture, interior partitions and internal elements have an impact, but they have a more limited lifetime, whereas the most important is the fact that the building envelope is the most crucial element as it is defined for a long term (the life of the building – 60 years). This justifies the importance of this study.

1.2 Research Objectives

The main objective of the research is to get simple, easily used approaches that reduce design decision fatigue, help the architect and designer to compare the percentage of glazing easily, and other variables to choose between scenarios according to their need.

In addition, this tool will help the designer to integrate the energy-matter at the very beginning of the project. The actual tendency in project design is to integrate all the study fields at the very beginning of a project, knowing that energy now has a significant impact on decision making in architectural projects. The actual tendency is to break the skills silos, remove the fences between the different disciplines, allow them to work closely with each other, and so more efficiently. The tool will give the architects more mastery of the energy subject applied to the façade and allow them to go deeper into the debate with the MEP Engineer.

Therefore, the specific objectives are;

- Examine facades indicators and factors

- Examine how to simplify the process of designing façade and reduce the decision fatigue
- Identifying the most changes in a high percentage would spot the light for designers to be aware of.
- Save energy and money
- Save time
- Try to make better decisions at the early design stage of a project to avoid backtracking the design process, which is very time consuming and sometimes the loss of motivation of the study teams.

However, these objectives could benefit designers, architects, facades engineers, and students. Therefore, the corresponding main research questions to these objectives are:

- How to simplify the decision-making of facade's design during early design stages without using building performance simulation?

- To which extent do the facade criteria influence the energy performance, visual and thermal comfort?

- What are the most influential design parameters?

- How do designers perceive the developed design support?

The thesis is structured as follow: Chapter 2 reviews the theories, the main concepts and variables related to the thesis. Also, the existing design tools and plans used during the design stage. Then, the adapted methodology to answer the research questions and simulation parameters are explained in Chapter 3. After that, Chapter 4 presents the parametric study results, the correlation between the parameters, and the sensitivity analysis. Also, Chapter 5 shows the results related to the usability testing. The discussion section is in Chapter 6, which contains the main findings, the recommendations, the strengths and the limitations of the research. Finally, Section 7 concludes the study.

2 Literature review

This chapter gathers the theories related to the thesis. A section is dedicated to describing the essential concepts that could be concerning facades in office buildings. Followed by the concepts and theoretical framework used.
It ends with a section that gathers the most relevant research related to the subject.

This study is mainly aimed at conducting reviewing in the identification of the state-of-the-art simulation tools that are used by construction project design teams in the early design stages of the project to aid the process of decision making. In addition, the review aims to evaluate the existing simulation tools used in evaluating the various components of building performance.

To complete an architectural project, many stakeholders and actors with different roles cooperate and work together. Where the design team could consist of: architects, engineers, cost consultants, specialists: acoustic consultants, security consultants, facades engineers, fire engineers, facility managers, and many others. All of them contribute to the design process.

Furthermore, since an architectural design process consists of many stages and phases, that will increase decision fatigue. For these reasons, a strategic approach suggested by the “RIBA” plan of work is used by many architects and engineers. In the same way, existing tools could be used to support decision-making and make it faster, more structural, and accurate. However, we can achieve our design goals and reduce decision fatigue by applying the right strategy regarding the needs and the available resources.

2.1.1 RIBA plan of work

Generally, architectural work follows an informal process. This could be easy to follow when we have a repeated building design or regular process, for example, when a single or two procurement stages are consistently used. But, on the other hand, this becomes inadequate when the design process becomes more complex with many aspects to include, such as sustainability in buildings, energy performance, or a big scale project. As a result, a structural design process map or plan of work is needed. (*RIBA Plan of Work*, n.d.-a).

One of the international work plans is the Royal Institute of British Architects (RIBA) plan of work. The RIBA Plan of Work is a comprehensive set of documentation and decision points. Its first major overhaul was in 2013, and now, it has become a widely used tool. It is not for a specific type of project or a particular scale, but it helps the architect to focus on architecture and follow structural steps. Thus, by following the RIBA plan of work, we can find eight stages considered as decision points for complete architectural work. These decision points serve to punctuate stages of work, from the inception stage (stage 0) to the final phase of completion, where this stage lasts for the life of the building (stage 7). The eight stages of the RIBA are:

- Stage 0: Strategic Definition
- Stage 1: Preparation and Briefing
- Stage 2: Concept Design

- Stage 3: Spatial Coordination
- Stage 4: Technical Design
- Stage 5: Manufacturing and Construction
- Stage 6: Handover
- Stage 7: Use

*Table 2-1 RIBA plan of work stages- source: (*RIBA Plan of Work*, n.d.-b):*

	Pre-Design		Design				Construction	Handover	In Use	End of Life
RIBA (UK)	0	1	2		3	4	5	6	7	
	Strategic Definition	Preparation and Brief	Concept Design	NOT USED	Developed Design	Technical Design	Construction	Handover & Close Out	In Use	NOT USED

As represented in Table 2-1, the first two stages are considered pre-design stages, and from the second stage to the fourth one, they are design stages. The most important stage in a building's life is stage 7, where we can find the impact on life-cycle costs and on the environment. These stages, from zero to seven, have clear tasks, where short descriptions of them are presented in Annex 3, leading to clearly defining the decision-making processes for each strategy. Generally, they are followed by another without a standard timescale. But also, we could face constraints and certain stages that might be overlapped. Besides this, the first four stages will generally be undertaken one after the other.

The RIBA Plan of Work is a precious tool, and it is flexible to the change, where it has passed by several improvements depending on real observations and feedback. The latest version was published in 2020.

The RIBA Plan of Work supports the design decision-making and helps to ensure that architectural work is highly professionally carried out. It will help to have good communication between the clients and the architects or even between the architects and the construction team. Furthermore, following this international plan of work during different projects will increase architects and engineers' confidence in their projects based on robust steps. (*RIBA Plan of Work*, n.d.-b).

It is important to mention that this working method is theoretical and based on a "waterfall" principle. The "waterfall" principle is traditional management, where each step is followed by another and must be completed. This method is used when there is a direct relationship between each step. But when there are many changes and an indirect relationship between variables, this does not work very efficiently (Sakikhales & Stravoravdis, 2017).

As well, in practical projects, the complexity and the number of actors or stakeholders involved rarely allow following a theoretical scheme. In practice, it is necessary to be flexible and also to be able to work transversally in an "Agile" way. Where the "Agile" principle is to follow a circle way between steps; planning, design, testing, getting feedback from people, and remodifying at the same time to arrive at the optimum solution. It follows guidelines for tasks but without timeline steps and boundaries.

To sum up, RIBA is a model and should be seen as a principle to strive for, but from which it is also necessary to be able to deviate at times to keep the creative dimension of the designers.

2.2 Parametric design

When we talk about parametric, we refer to a range of possible solutions. We get them by controlling some input parameters and modifying them based on algorithms. Thus, an algorithmic design process consists of a set of input parameters passing by mathematical simulations to get a set of outputs.

The parametric design is a way to create wide alternatives and arrive to visualise the final results within record-breaking time. It depends on the relations between the different parameters and the purpose of the design.

2.2.1 Parametric design tools and Decision-making

Building simulation discipline has maintained a constant rate of evolution to be one of the most vibrant disciplines since its inception resulting in the production of a range of Building Performance Simulation tools. These tools have been globally validated. The beginning of building simulation traced back to the 60s and 70s when it mainly concentrated on the building thermal performance with reference to load calculation and energy analysis. Such foundation research was mainly developed in the research team of the mechanical engineering domain. Then the development of simulation tools by the various technical researchers alongside building scientists. The aims were to address the needs of the engineers.

The Building Performance Simulation tools user base during then was majorly limited to the experts as well as researchers who specialised in detailed energy analysis adopted during the phases of development of a design. For instance, simulations were carried out to estimate peak hourly loads for cooling and heating seasons. Still, they were used to produce the consumed energy per year for the purposes of sizing besides the selection of mechanical equipment, especially for the case of large buildings.

A team in charge of the design of any construction project, regardless of the scale, is anticipated to attempt optimisation on most of the criteria, among them the indoor environment, the demand of energy, life cycle and materials, among others. These criteria have been noted to be conflicting in most of the cases and hence the need for a delicate balance (Gan et al., 2019).

Supporting decision making alongside guiding the process of design aimed at attaining high performance thus turns out to be of greatest significance during the early design phase in which decisions often bear the largest impacts on the ultimate costs and performance. While it might be a challenge to predict the effects of earlier decisions, they are important as adverse choices can reduce the remaining space for design and lead to greater strain and cost in meeting high-performance objectives.

For instance, the construction project design team might make an early decision on a decision concept having a heavily transparent façade. This would, in turn, promote the penetration of daylight in which possible issues regarding thermal comfort, cooling energy, and glare are prevented through a mixture of hybrid ventilation alongside automatic and exterior shading. In the event the initial conditions turn out to be later to be quite unrealistic, for instance, with the adopted solar shading, air change would be a need for the venting to ensure the temperatures are maintained within limits. Such will result in huge effects on both the design and cost in remedying such an early decision and attaining an ambitious objective.

The data gathered from building performance simulation software tends to be, in most cases, evaluative as opposed to being proactive despite the ability to conduct building simulations. The software is normally recommended for code compliance, control of quality and benchmarking. Even in cases, it tends to be complex, precise and able to evaluate a broad range of various performance indicators (Nik-Bakht et al., 2020). Limited work has been done on the development of tools used to provide real-time feedback on the performance effects and aid in comparison besides ranking numerous design variations. The ability of the software to offer such type of active support is at times known as intelligence. Usability and intelligence are among the most highly regarded features in selecting Building Performance Simulation tools (Batish et al., 2019).

Nowadays, and because the development of new technologies is needed, a variety of new computer modelling is getting more interest, including automated early daylight analyses, indoor comfort, energy performance and sustainability, with parametric studies. Some of these tools are presented in the following section.

Various techniques have been discussed which help in the process of decision making, taking into consideration conflicting as well as multiple objectives. Such approaches are pegged on the weighting averages, outranking, priority setting as well as fuzzy principles. Some studies adopted the Analytical Hierarchy Process to support multi-criteria decision-making under uncertainty depending on the stakeholders' preferences. More information is produced by propagating uncertainty from the design parameters into probability distributions of the various performance indicators (Yan, 2018). The effect of this is a complication of the entire process of decision making. Furthermore, Attia et al., (2019) investigate a study about new tools for bioclimatic design strategies in hot humid climates

OpenStudio is a simulation tool for building energy that is often used in design to support the energy simulation of the entire building based on EnergyPlus and advanced lighting analysis. The simulation is done based on lifecycle cost, thermal comfort, radiance and air condition. The design of OpenStudio was done to work in conjunction with SketchUp, allowing architects to carry out simulations prior to construction. A simplification approach was introduced by M. Picco et al. for the models of commercial buildings about energy efficiency optimization, especially at the early design stages. Such an analysis involves coming up with a large multi-story office structure having comprehensive information via the OpenStudio software, and after that, an analysis is done (Kamari et al., 2018).

OpenStudio, through the aid of the SketchUp plugin, allows access to the existing online libraries and hence incorporates numerous features of the needed knowledge-based data. A combination of these sets of tools might be made up of most of the features that are required for the proposed system. Honeybee has used OpenStudio to connect Rhino and Grasshopper framework, bringing together the various packages' strengths. Such a combination allows for parametric evaluation of the geometry of the building even as the link to OpenStudio permits an analysis of the building performance.

Lack of data is one of the major challenges affecting the performance of simulations, especially in the early design phase. This is mostly noted in a case for comprehensive simulation software whose effectiveness depends on the available information (Yu & Leng, 2020). Detailed simulation software often has expansive high levels of information to return meaningful results. A macro-component strategy can be used to overcome the challenge in which pre-defined construction permits assessment of the life cycle analysis and energy in the initial design stages through the use of detailed software.

2.2.1.1 Climate Studio

Climate studio is an advanced simulation plugin for Rhinoceros for analysing daylighting, electric lighting, and conceptual thermal. This software, developed by Solemma LLC, helps to achieve accurate environmental performance results for the Architecture, Engineering, and Construction (AEC) sector. Also, it helps to arrive at the optimum design with a user-friendly and simple interface. In comparison to traditional annual climate-based simulations, ClimateStudio is for the moment "the fastest and most accurate simulation software on the market" (*ClimateStudio*, n.d.)

This plugin offers a calculation for daylight performance based on LM-83 for LEED, for simple façade, and dynamic shading. Also, it offers a results comparison regarding climate files. (*How to Select a Climate File?*, n.d.). Moreover, climate studio offers parametric workflows for early design building energy modelling.

Using this software will be helpful during the design process at the same time, helps to design better buildings faster, and visualise results by each design individually (Figure 2-1).

Figure 2-1 Climate studio software- source: https://www.solemma.com/climatestudio

2.2.1.2 ES-SO ESBO

ESBO is an Early Stage Building Optimization software. ESBO offers an accurate simulation and results based on EN ISO 52022-3, EN 410, and ISO 15099 for glazing and shading properties. ESBO is based on the calculation engine in IDA ICE – *"The market-leading tool for simulation of energy and indoor climate in Northern Europe."* (*WINDOW Software Downloads | Windows and Daylighting*, n.d.). The climate conditions are according to the ASHRAE. It has an easy-to-use interface with a large number of real databases of real products.

By adding the input parameters, such as room dimension, glazing type, and layers, shading system, and many more details, we obtain results about energy performance and temperatures, as well as thermal properties details about windows with shading and glazing combinations where the energetic study could be for one room or multiple rooms.

There are two versions: the free of charge version, ES-SO ESBO, and the full version, which is paid, ES-SO ESBO. Case comparing reports are only available for ES-SO ESBO paid license, where we can compare the different possibilities of design directly and at the same time (Figure 2-2).

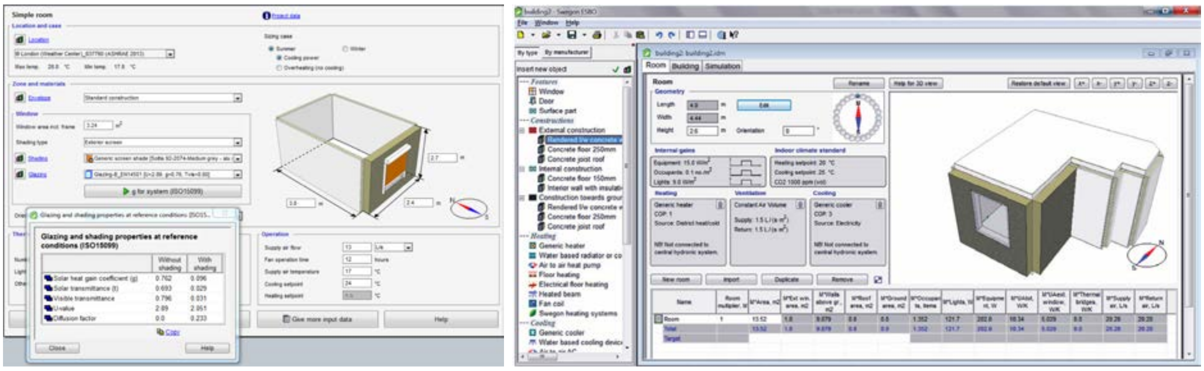


Figure 2-2 ES-SO ESBO- source: https://www.somfy.be/projets/aide-a-la-specification-/early-stage-building-optimization-software

2.2.1.3 Green Building Studio

Green Building Studio (GBS) is yet another integral simulation tool used to simulate the building energy constructed on Autodesk. Designers and architects commonly use this tool to realise the energy analysis, carbon-neutral design, and energy consumption of a building in the initial design phases (*Green Building Studio*, n.d.). The simulation in Green Building Studio is based on the DOE-2.2 -building energy simulation and cost calculation engine- and creates accurate input files for EnergyPlus (Han et al., 2018). GBS is based on one step consisting of a few inputs because it has default information. Based on this software, Gerber and Lin proposed a framework for Evolutionary Energy Performance Feedback for a Design (EEPFD). This supports early decision making by fast parametric analysis, optimisation of multi-objectives and automation (Lin & Gerber, 2014).
GBS consists of a one-step process, whereas the EEPFD process consists of six steps to integrate the design phase with the energy simulation: the design stage in Revit, then the energetic analysis in Green building studio and HDS. Beagle (a prototype tool) to evaluate results in which we can generate a decision-supported workflow.

An overview of the developments in the simulation tools in the construction industry that aid in faster decision making and improved quality of the decisions, especially at the construction project initial stages, has been presented in this part.
These Building simulation programs are basically deployed in the making to ensure there is compliance with the applicable building code. It is also used in the evaluation of the performance of certain alternative systems or even designs.

2.3 Concepts and variables of the research

Theories of the study are composed of concepts and variables linked by relationships. Figure 2-3 shows, in general, the relationship between the main conceptual parameters of this study.

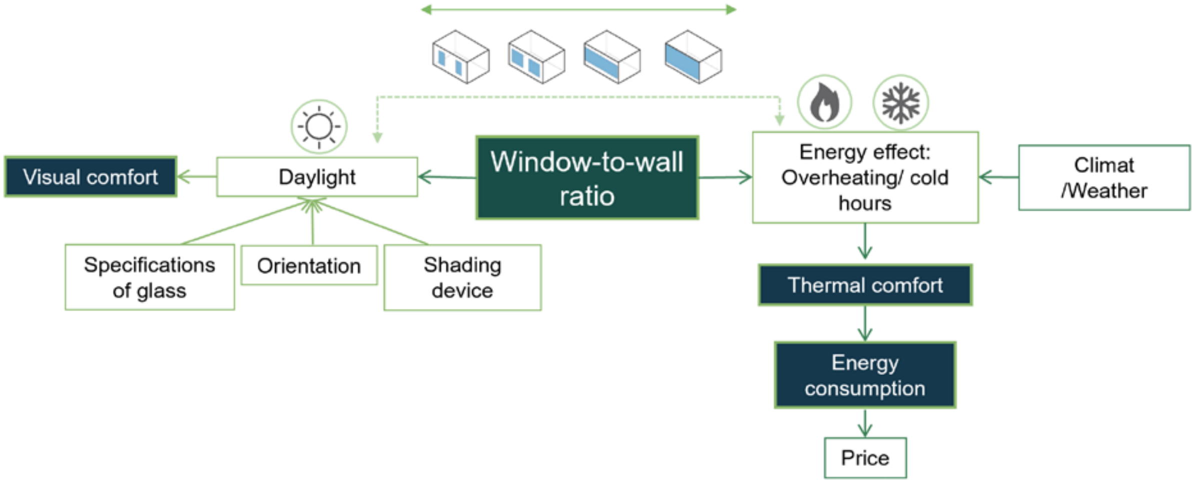


Figure 2-3 Relationship between the main conceptual parameters

This section explains some concepts related to the thesis. The certification adopted for this study and concepts related to the daylight metrics, which are supposed to be quality measures for office buildings' lighting performance and visual comfort.

2.3.1 LEED vs BREEAM certifications

We can consider the standards as a kind of a strategic guide for decision-making. Today, there are over 600 certifications for sustainable building around the world. (*3XN*, n.d.). It is a very important criterion in the purchase and rental process to allow future owners and tenants to evaluate the sustainability level of a building.
In Belgium, BREEAM certification is more often used. BREEAM is a British certification standard. It focuses mainly on three aspects: the environmental (66%), economic (5%) and social (29%) aspects and also on the use of resources, where the biodiversity for BREEAM is more important than in other certifications.

On the other hand, LEED is an American certification standard for sustainable building certifications. This standard takes into account energy consumption, occupant comfort and others. It focuses on the environmental (52%), economic (5%) and social (43%) aspects.

BREEAM and LEED both give credits for quality views, quality interior lighting, and sufficient daylighting (BREEAM: 1.1%, LEED: 2.7%). However, by comparing both certifications in Table 2-2, LEED is more advanced regarding information about daylight metrics: Spatial Daylight Autonomy (sDA) and Annual Sunlight Exposure (ASE). This is important to be considered, especially that the solar radiation in Belgium increases yearly regarding climate change.

Table 2-2 A Comparison between LEED and BREEAM about daylight and visual comfort specification

	LEED v4.1	BREEAM 2018 (Hea 01 Visual comfort)
Glare measure and control	✓	✓
Lightning contractibility	✓	✓
View out	✓	✓
Internal and external lighting	✓	✓
Daylight factor (DF)	✓	✓
Illuminance level	✓	✓
Daylight Autonomy	✓	✓
Spatial Daylight Autonomy (sDA)	The minimum value for visual comfort	No specification
Annual Sunlight Exposure (ASE)	The maximum value for visual comfort	No specification

2.3.2 Annual daylight metrics

Annual daylight metrics are a way of evaluating daylight in a space across a whole year. Based on local climate data, the simulation results will be hourly recorded to arrive at an average for an entire year. We can find the Annual Sunlight Exposure (ASE) and the Spatial Daylight Autonomy (sDA) as examples of these daylight metrics.

2.3.2.1 Spatial Daylight Autonomy (sDA)

To provide a guide for designers to achieve the sufficiency of daylight illuminance, a new daylight metric called Spatial Daylight Autonomy was developed for a more accurate measurement.
We can use the question "Is There Enough Daylight?" to talk about Spatial Daylight Autonomy (sDA). As seen in the Approved Method IES- LM-83-12[1], sDA is a dynamic metric for a more accurate measure of daylight. It describes the annual sufficiency of ambient daylight levels in an interior environment space.

It defines the percentage of the studied area for each analysis grid that meets a minimum daylight illuminance level during a specific portion of the operating hours per year (50% regarding IES- LM-83-12). The minimum illuminance is usually defined depending on the room type: an office room, classroom, healthcare room, or another type. Also, it depends on which norm we want to refer to. For example, if the studied room is an office room, the minimum illuminance regarding the NBN standard EN 12464-1: lighting and illumination of workplaces are set to 500 lux on the work zone (Figure 2-4). However, regarding IES- LM-83-12, the threshold is 300 lux.

[1] IES standard is The Illuminating Engineering Society of North America (IES) standards for the lighting industry. It is to ensure enough indoor illumination and lightning performance.

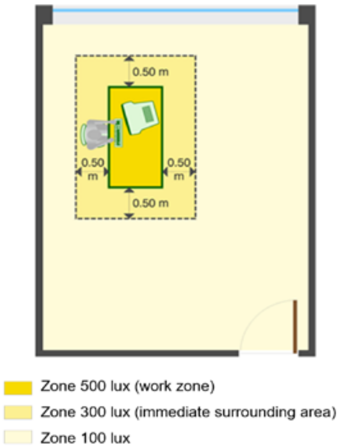


Figure 2-4 the minimum illuminance in an office room- (« Norme NBN EN 12464-1 », 2007)

This dynamic daylight metric (sDA) is based on hourly measurement with either manual window blinds or electronically controlled, operated depending on the amount of direct sunlight that passes through windows into space to maintain visual comfort. The blinds open and close based on the 2% rule according to IES LM-83-12; When more than 2% of the analysis grid points receive 1000 lux or greater (direct sun), blinds will close together for each window group until less than 2% receive direct sunlight.

Windows must be categorised into groups, and then the position of the blinds is determined hourly. Window group is determined based on: first, exterior shading device type and operation, second, building face and third for the same analysis grid. Figure 2-5 is an example to explain how window groups are considered: room A has one facade, and all windows are considered without external shadings. In that case, they are considered as one group. For room B, the front facade is divided into three planes. Thus, there are three window groups. In the same way, room C has one facade, but the upper windows are without shadings, whereas the bottom windows have an external shading over them. Therefore they are divided into two window groups.

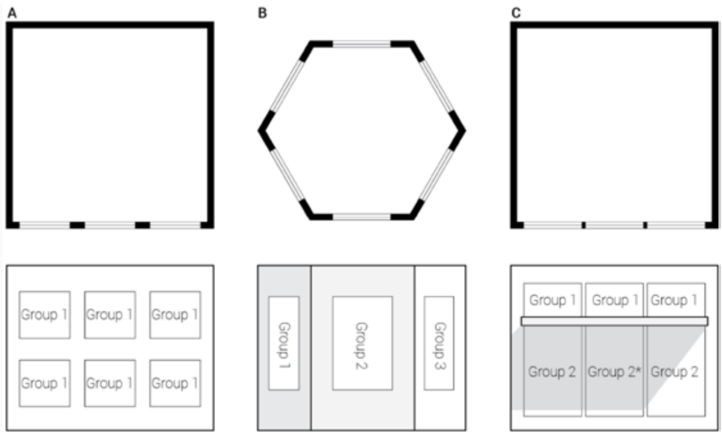


Figure 2-5 Window groups for sDA calculation- source: (lightstanza, 2016)

After determining windows into groups, there are two steps for the calculation of sDA: the first step is to determine blinds operation, whether it is controlled manually or electronically, to open or closed based on the 2% rule. We should note that dynamic glass does not need blinds. The second step is determining the level of illuminance at each grid point with an hourly simulation after the blinds are in position; thus, if there are more than 2% of the grid receive direct sun, it will assume that blinds will be closed and the sDA score will be the illuminance values with closed blinds. This metric takes thousands of blind positions, calculates hourly records and compact them into one value. For LEED V4, each grid point must meet a minimum illuminance of 300 lux for at least 50% of the year: $sDA_{300lux/50\%}$. Figure 2-6 presents that when there is direct sun, blinds for each window group are used to maintain visual comfort.

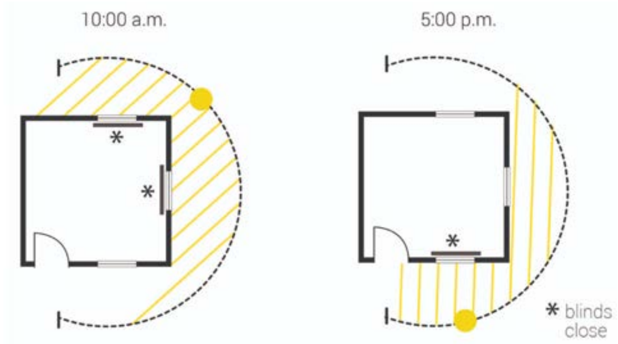


Figure 2-6 Blinds operation for sDA calculation- source: (lightstanza, 2016)

The blinds are included in this daylight simulation because they are "ubiquitous in the real world", and they contribute significantly to the quantity of light.

It is essential to use dynamic simulation software that takes into account the occupants behaviour and their interaction with blinds to calculate the sDA.

View of LEED v4.1- Daylight and Quality Views Calculator- option 1:

LEED defines a threshold of 300 lux for 50% of annual sunlight hours over a fraction of the occupied area. Where $sDA_{300/50\%}$ value achieves 75%, to be awarded 3 points, 55% for 2 points, and 40% for 1 point (*Daylight | U.S. Green Building Council*, n.d.) (Table 2-3).

Table 2-3 Points for daylight floor area: The average Spatial daylight autonomy sDA300/50% - source (LEED V4.1)

	New construction, Data centre, Schools, Warehouses and Hospitality	Healthcare
sDA (for regularly occupied floor area) at least:	Points	
40%	1	1
55%	2	2
75%	3	Exemplary performance
Each regularly occupied space achieves $sDA_{300/50\%}$ value of at least 55%	Exemplary performance or one additional point if only 1 or 2 points are achieved above.	Exemplary performance or one additional point if only 1 point is achieved above.

As an example of the spatial daylight autonomy, Figure 2-7 represents that 65% of the surface of a working plan on a level of 0.76m, receives a minimum illuminance value, which is in this case 300 lux, during at least 50% of the total annual operational hours from 8:00 to 18:00 (IES- LM-83-12). It can be represented as the following:

sDA 50% > 300 lux (8:00-18:00)

The $sDA_{300lux/50\%}$ = 65%; thus, regarding LEED v4.1, this value is above the acceptable threshold for sufficient daylight.

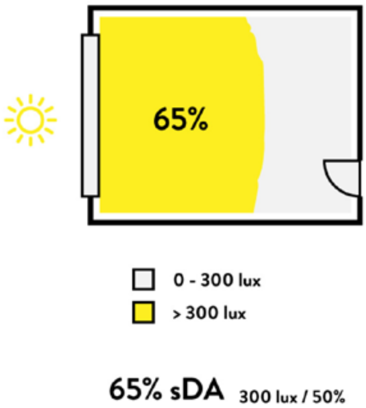


Figure 2-7 An example that represents the Spatial Daylight Autonomy (sDA)- source: (Daylight Metrics, 2018)

2.3.2.2 Annual Sunlight Exposure (ASE)

Annual Sunlight Exposure (ASE), according to IES- LM-83-12, is a dynamic daylight metric that represents visual discomfort, particularly the glare and direct sunlight, and overheating in an interior environment space. It is to assign the possible risk of excessive sunlight.

It defines the percentage of the studied area for each analysis grid that exceeds a specified direct sunlight illuminance level more than a specific number of the operating hours per year without any contribution from the sky (*IES LM-83-12*, n.d.)

As an example of the Annual Sunlight Exposure, Figure 2-8 shows that 8% of the surface of a working plan on a level of 0.76m, receives daylight above the maximum recommended illuminance value, which is 1000 lux, during more than 250 hours of the total annual operational hours from 8:00 to 18:00. It can be represented as the following:

ASE 8% > 1000 lux (8:00-18:00)

The $ASE_{1000ux/250h}$ = 8% this value is below the acceptable threshold value for visual comfort regarding LEED v4.1, which is less than 10%.

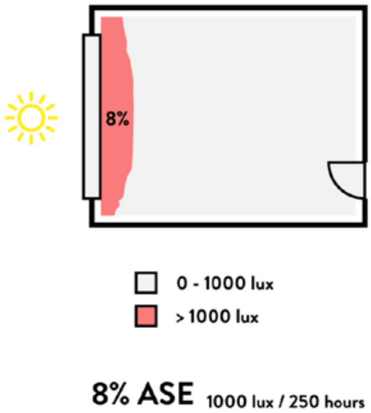


Figure 2-8 an example that represents the Annual Sunlight Exposure (ASE)- source: (Daylight Metrics, 2018)

2.3.2.3 Grid and working plan for sDA and ASE

To calculate the sDA and ASE, the analysis grid size should be no more than $0.6m^2$ (LEED v4) and be defined at a level of a working plan. The calculation is done at the centre point of each grid. It depends on the studied area and whether we want to calculate values for an interior surface (room plan) or exterior (urban context, masterplan). The standard height of a working plan required for LEED is equal to 0.76m above the floor level. However, another value could be used depending on the type of activities (i.e. science labs) and furniture (i.e. tables, desks) where the level of a working table in a science lab is about 0.8m. Interior partitions, equipment, and furniture may be taken into account.

The simulation should be based on a climate data file. It could be a typical meteorological year data file (TMY) or another equivalent taken from the nearest weather station (*Daylight | U.S. Green Building Council*, n.d.).

2.3.3 Low e-coating glass

Low emissivity helps reject the sun's heat back out where it comes from and from the rooms back in. The idea is to have a warmer winter and cooler summer. Two positions of glass coating exist, whether we want to keep the cold out or heat out, and on the orientation of the façade (Figure 2-9).
Generally, on the southern façade, the coatings are added on the second surface. That means inside of the outside glass panel. This position of coating will help to reject the heat and keep the cooling inside. On the other hand, for the north façade, the coating will be added on the third surface. Again, that means inside of the inside glass panel.
The position of the coating has a large impact on the glazed panel. For that reason, it is very important to choose the right glass for the right place and the needs.

We can also enhance any Low-E coating on a double pane window by adding argon gas. As a result, if the window panel consists of double glazing and Argon gas and Low-E coating, that is considered a benefit to the heating and cooling bill, comfort, and sound reduction.

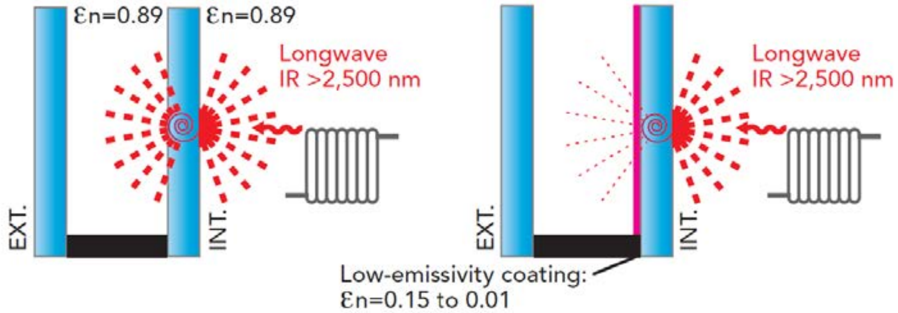
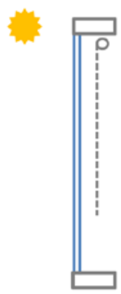


*Figure 2-9 Double glazings (left) and high-performance double glazing with a coating (right)- source: (*Your-Glass-Pocket-Uk-Versie Important for Glazing and Daylight Comfort.Pdf*, n.d.)*

2.3.4 Fixed solar shading devices

Solar radiation has a strong impact on indoor visual and thermal comfort and also on energy performance. For these reasons, the solar shading system is an important element. It could be an effective element for reducing glare and solar heat gain by blocking direct sunlight or for improving lighting and saving energy. (Settino et al., 2020). Furthermore, we can find an impact on the out-view, maintenance, cleaning, costs, and the aesthetics aspect of the facade.
Reducing glare and reflection on computer screens or furniture is one of the most important aspects of solar shading. Glare control is the ability of the solar shading device to control the illuminance level and to reduce the contrasts between different zones within the field of vision. Regarding the standards EN 14501, if Daylight Glare Probability (DGP) is below 35 %, glare is mostly imperceptible. If it is more than 45%, it is perceptible and mostly intolerable. (*Standard NBN EN 14501:2021*, n.d.)
There are various types of shading systems: window tinting, screens, awnings, horizontal overhangs, vertical fins, blinds, etc. However, the type of shading system and their positions depends on the purpose and facade orientation. Moreover, the position of roller blinds, whether it is inside or outside, has an impact on daylight performance and reduces energetic gain. But the degree of the impact varies from one to another. However, it is known that exterior blinds have more influence. Table 2-4 represents some of the differences between exterior metal roller blinds and interior sun protection blinds.

Table 2-4 Comparison between interior and exterior roller- source: WTC IV Brussels.

		Exterior metal roller blind		Interior sun protection blind
				
		an exterior motorised metal roller shutter		An interior motorised textile roller blinds, reflective
Thermal and visual comfort				
Inside surface temperature		The Interior surface remains comfortable	-	Interior textile can heat up and create discomfort
Out-view	+	Transparent sun protection system	-	no views of the outside
Energy Efficiency				
Sun protection capacity and U-value (W/m²K)		G total=0,07 (Ucw = approx. 1,3) U-value can be lower with triple IGU		G total=0,15 (Ucw = approx. 1,3) U-value can be lower with triple IGU
Economically				
Lower energy demand for cooling from external loads	+	Energy reduction approx. 50%	-	Energy reduction 0%
Higher electricity demand for artificial lighting (from sun protection glazing)	+	The transparent and translucent solar shading system		electric lighting necessary during daytime from daylighting blocked by interior sun shading system

The norms that define the standard about solar and visual properties for the shading system are EN 14501 for the requirements and EN 14500 for the test methods.

They are supporting standards for specific characteristics about visual comfort: Glare control, out-view, daylight privacy, and thermal comfort: total solar energy transmittance, secondary heat gains, and protection from direct transmittance.

These standards are mainly for assuring visual and thermal comfort. On the other hand, the calculation standards are the simple method: EN ISO 52022-1 and the more detailed method: EN ISO 52022-3. These standards calculate visual and solar properties for shading combined with glazing. (*Standard NBN EN 14501:2021*, n.d.)

Shutters and external Venetian blinds	External blinds and awnings	Internal blinds
EN 13659	EN 13561	EN 13120

2.4 Similar studies

This section summarises the most relevant studies, existing methods or software, for different types of buildings in different climates. Table 2-5 below gathers the review of the most relevant studies related to the investigated cases in the context of this thesis. Besides these papers and research, many other studies were used throughout the different chapters.

Table 2-5 Review of the most relevant key thematic and methodologically studies

	Relevant publications	Specific content
	Kültür, S., Türkeri, N., & Knaack, U. (2019). A Holistic Decision Support Tool for Facade Design. Buildings, 9(8), 186.	Design assistance tool (input and output) - Evaluation of the overall performance of the case study
	Ernesto Ochoa, Guedi Capeluto, (2019), Advice tool for early design stages of intelligent facades based on energy and visual comfort approach, Israel	Methodology but different climate: Mediterranean climate with long, hot, rainless summers and relatively short, cool, rainy winters (Köppen climate classification)
	Han, T., Huang, Q., Zhang, A., & Zhang, Q. (2018). Simulation-Based Decision Support Tools in the Early Design Stages of a Green Building—A Review. Sustainability, 10(10), 3696.	Simulation and design decision tools at early stages
	Selkowitz, S., Hitchcock, R., Mitchell, R., McClintock, M., & Settlemyer, K. (2014). COMFEN – Early Design Tool for Commercial Facades and Fenestration Systems. 120.	COMFEN- building energy software tool for commercial building applications
	Khadraoui, M. A., & Sriti, L. (2018). Etude et optimisation de l'impact des ouvertures sur le confort thermique et l'efficacité énergétique (Cas des bureaux dans un climat chaud et aride). J. Appl. Eng. Sci. Technol, 4(1), 89-99.	Study case methodology (empirical study) - impact of the glass surface -but different climate
	Herzog, T., Krippner, R., & Lang, W. (2007). Construire des façades. PPUR presses polytechniques.	conditions imposées aux façades
	Yun, G. Y., Steemers, K., & Baker, N. (2008). Natural ventilation in practice: linking facade design, thermal performance, occupant perception and control. Building Research & Information, 36(6), 608-624.	The thermal performance of office facades
	Arroyo, P. (2014). Exploring decision-making methods for sustainable design in commercial buildings (Doctoral dissertation, UC Berkeley).	Decision-making methods for commercial buildings
	Vullo, P., Passera, A., Lollini, R., Prada, A., & Gasparella, A. (2018). Implementation of a multi-criteria and performance-based procurement procedure for energy retrofitting of facades during early design. Sustainable cities and society, 36, 363-377.	performance criteria in design procedures
	Kolokotroni, M., Robinson-Gayle, S., Tanno, S., & Cripps, A. (2004). Environmental impact analysis for typical office facades. Building Research & Information, 32(1), 2-16.	Tool parameter
	Soudian, S., & Berardi, U. (2020). Development of a performance-based design framework for	performance criteria required for the design

	multifunctional climate-responsive façades. Energy and Buildings, 110589.	
	Attia, S. (2011). State of the art of existing early design simulation tools for net-zero energy buildings: a comparison of ten tools (No. 01/2011)—architecture et climate.	Simulation tools
	Østergård, T., Jensen, R. L., & Maagaard, S. E. (2016). Building simulations supporting decision making in early design–A review. Renewable and Sustainable Energy Reviews, 61, 187-201.	
	Attia, S., Hensen, J. L. M., Beltrán, L., & Herde, A. D. (2012). Selection criteria for building performance simulation tools: Contrasting architects' and engineers' needs. Journal of Building Performance Simulation, 5(3), 155–169.	Building performance simulation tools and usability testing for the interface
	Shen, H., Tzempelikos, A., Atzeri, A. M., Gasparella, A., & Cappelletti, F. (2015). Dynamic commercial facades versus traditional construction: Energy performance and comparative analysis. Journal of Energy Engineering, 141(4), 04014041.	Energy performance of commercial facades
	Galatioto, A., & Beccali, M. (2016). Aspects and issues of daylighting assessment: A review study. Renewable and Sustainable Energy Reviews, 66, 852-860.	Natural light and factors, visual comfort

Many other studies similar to the main concepts of the study or the methodology exist. However, the studies presented in the table above are considered relevant for the thesis's main ideas.
Several studies are made in another country with a climate different from Belgium. For example, Mohamed Amine & Leila, (2018) studied the windows' impact on offices' thermal comfort and energy efficiency in a hot and arid climate, using a numerical simulation with TRNSYS software. Another study by Pathirana et al. (2019) investigated the Effect of house building shape, orientation, window to wall ratios on energy efficiency and thermal comfort in a tropical climate. They use simulations in Design-Builder to evaluate the impact of the design parameters.

However, there is a lack of studies and approaches that suit the climate and buildings in Belgium.

Furthermore, since the primary phase of a project, most of the architectural work related to designing facades does not include thermal comfort and energy efficiency concepts. It is only later in the design process that it shifts to a level of detail. Moreover, using these kinds of simulation tools, listed in the literature review during the architectural design process, is very important and recommended to be developed. As our priorities are to achieve an accurate design quickly, this skill set will be one of the top priorities for new designers in the next decade, which seems a research need.

3 Methodology

3.1 Description of the research design and methods

This chapter assembles all the steps of the methodology. Where the research questions, as mentioned in the first chapter, are:

- *How to simplify the decision-making of facade's design during early design stages without using building performance simulation?*
- *To which extent do the facade criteria influence the energy performance, visual and thermal comfort?*
- *What are the most influential design parameters*
- *How do designers perceive the developed design support?*

The thesis is based on empirical research and a quantitative method, which depends on modelling a case and investigating the simulations with parametric variables since the window-to-wall ratio is the main variable between buildings. In this thesis, we are interested in Office buildings in Flanders, Belgium. Furthermore, the meteorological station of BEEK in the Netherlands is used with a 19.14 km radius for the case study in Genk. Observation, simulation, and documentation studies were used for data collection. A deductive-qualitative method was used for data analysis through the parametric software (Grasshopper). The result of these studies is a user-friendly interface to choose between different scenarios. In addition, a comparative analysis between chosen scenarios was done.

The adapted workflow in this study, including the RIBA plan of the work stages, is represented in Figure 3-1.

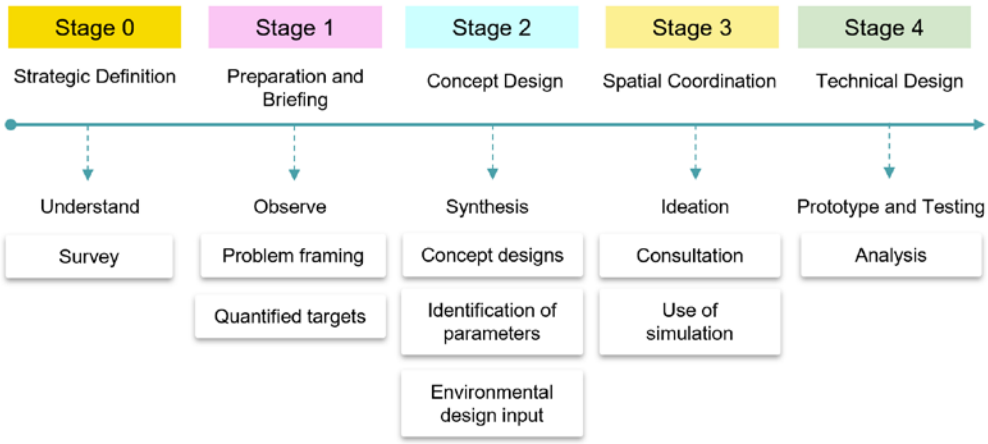


Figure 3-1 Study workflow- follow RIBA stages

3.2 Conceptual study framework

To better understand the main steps of the study and the research methodology, Figure 3-2 illustrates the schema of the Conceptual study framework of this thesis.

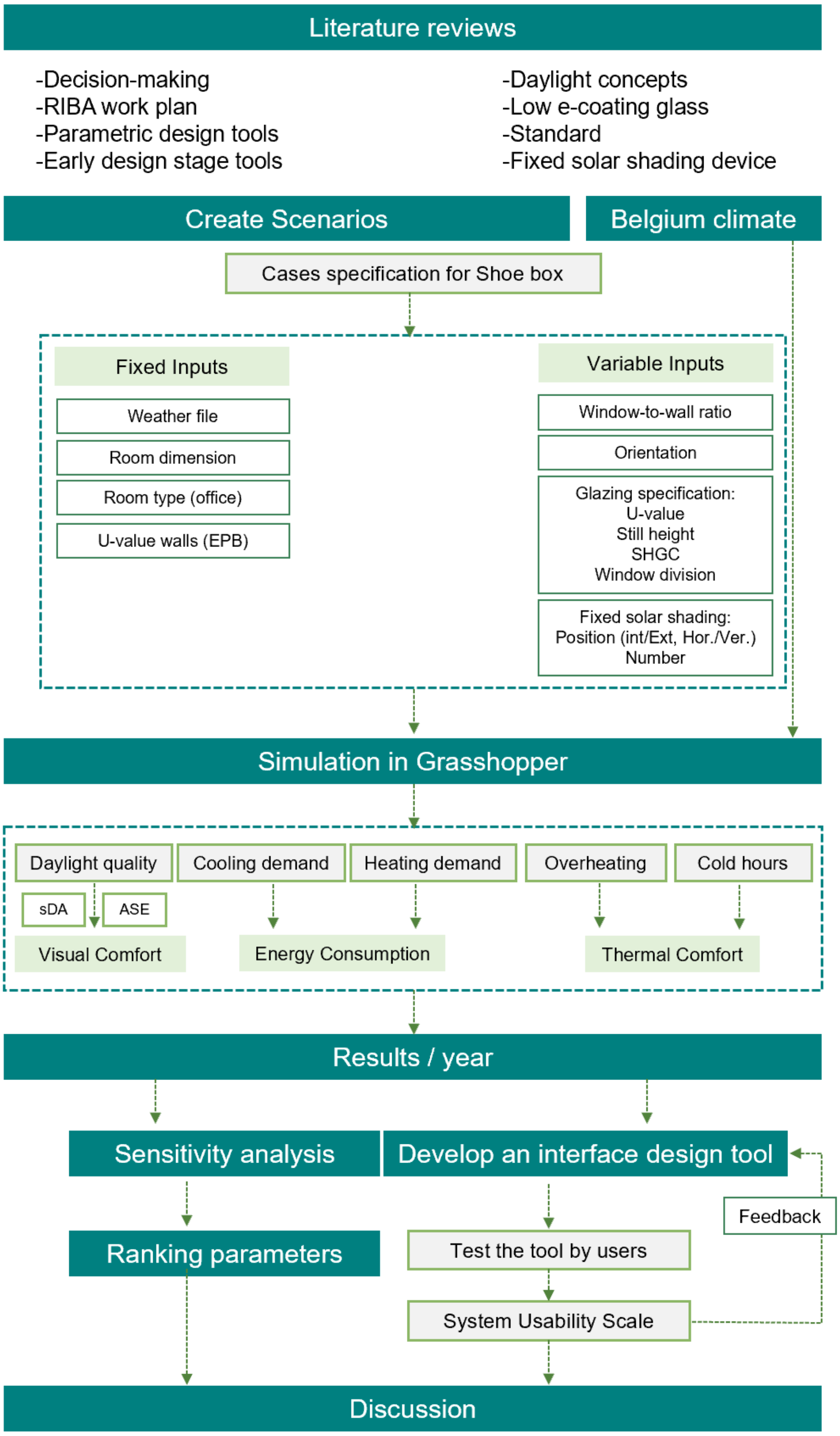


Figure 3-2 Conceptual study framework

3.3 Selected software

For this study, to have an idea about the thermal behaviour of buildings, it is necessary to use energy simulation software tools. This software helps to evaluate the thermal behaviour of existing buildings during operation time. Or even to predict their behaviour during the decision-making stage before construction.
There are several energy simulation software tools (Attia et al., 2009) that could be used for this parametric analysis, such as DesignBuilder or Grasshopper, which are interfaces designed to be easy to use. However, the simulation engine is EnergyPlus.

In this thesis, Grasshopper is used with Rhinoceros (version 7). They were chosen because the Rhinoceros offers the ability to build creative building forms. Also, it is widely used for repetitive components or for parametric facades. Rhino is one of the best dynamic design tools to explore and develop a wide range of solutions. Rhinoceros with Grasshopper is a robust 3D program (Associates, n.d.).

Figure 3-3 summarizes the links between software and plugins used in this thesis to generate a parametric design.

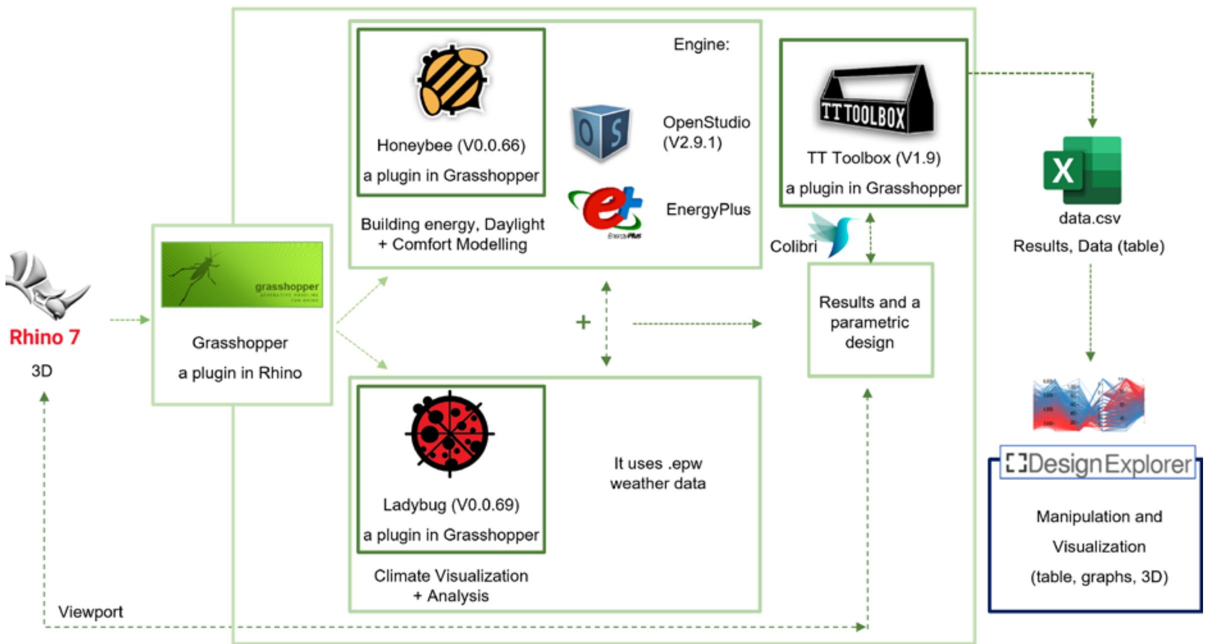


Figure 3-3 Framework that represents links between software and plugins used in this thesis to generate a parametric design

3.3.1 Grasshopper (GH)

Grasshopper is a plugin for the 3D modelling software Rhinoceros. GH is an interface for building information algorithms. It is the basic platform that includes other plugins; Ladybug, Honeybee, kangaroo, Butterfly, among many others. Each plugin from them is used for a specific purpose. It uses mathematics and geometry in programming as steps to develop a 3D model, simple or with complex details, in a parametric way. It is one of the most widely used platforms by designers today.

The main plugins inside Grasshopper used for this analysis are Ladybug and Honeybee. They are environmental design analysis plugins connected to validated simulation engines; EnergyPlus, OpenStudio, and Radiance.

3.3.2 Ladybug (LB)

Ladybug is mainly based on weather data files. By importing an EnergyPlus Weather file (.epw), LB allows analyzing and visualizing many diagrams in 2D or 3D, for example, radiation-rose, sun-path, or run radiation analysis (Figure 3-4). That has a benefit for helping designers in the design decision-making process, especially during the initial phases. (Sadeghipour Roudsari & Pak, 2013)

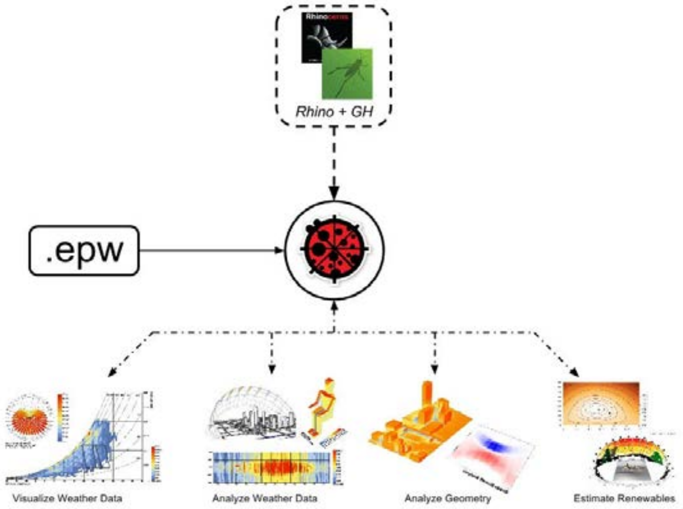


Figure 3-4 Ladybug plugin for Grasshopper-
source: (https://docs.ladybug.tools/honeybee-wiki/)

3.3.3 Honeybee (HB)

The Honeybee is a plugin for GH, passing by the climate weather file by Ladybug. The Honeybee plugin is used to get more advanced studies. There is a relationship between HB and energy or daylight engines; Daysim, Radiance, OpenStudio, and EnergyPlus, as described in the diagram below (Figure 3-5). It can be used to build indoor or outdoor comfort, lighting, daylighting, or energy simulations. The plugin Honeybee makes it possible to move from early analysis to more detailed and advanced analysis (Sadeghipour Roudsari & Pak, 2013).

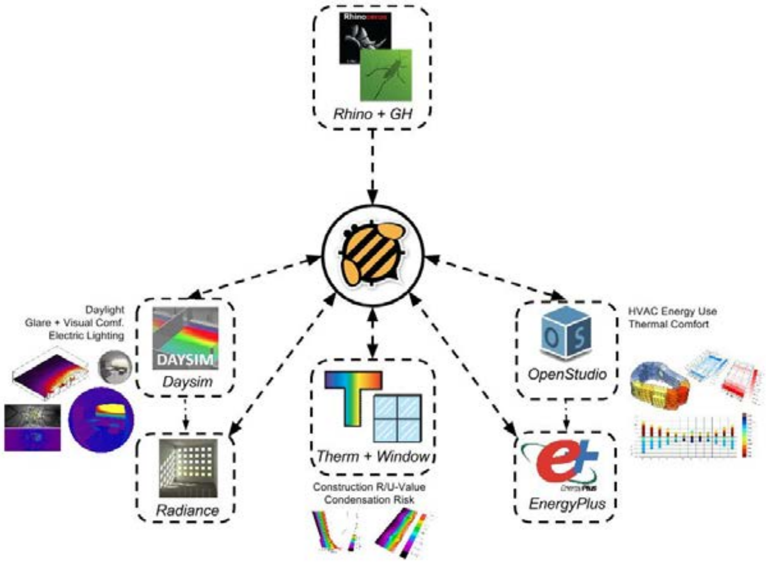


Figure 3-5 Honeybee plugin for Grasshopper-source: (https://docs.ladybug.tools/honeybee-wiki/)

Grasshopper, with its plugins, is not very easy to work with. However, the reason to choose this program is that it can adapt to the highly complex architectural buildings design. Moreover, we can add many details and variables to develop the tools for the future.

Figure 3-6 represents the preparation of the script of the study. More details are provided in Appendix 4.

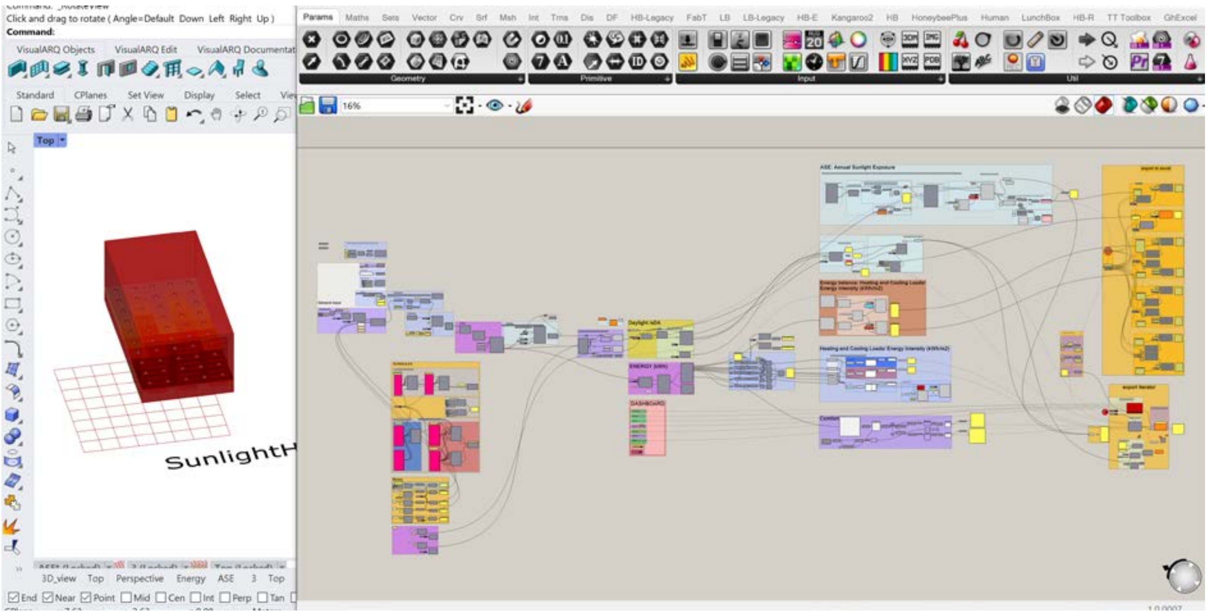


Figure 3-6 Graphical user interface using Rhinoceros, and Grasshopper script for this study

3.4 Variables, indicators

Regarding the above literature review and research questions, we are interested in input parameters that affect visual comfort, thermal comfort and energy consumption. However, there is an interaction between both of them with linking parameters.

The concepts of this thesis are operationalized into realistic measurements. This section lists the main variables in energy study for a building, their cause and effect.

More details, with the norms related to the variables, the causes, the effects and the relationship with sub-variables and indicators are listed in Table 3-1.
However, we will discuss later the links between each parameter depending on the simulation results and the percentage of the impact of each one.

Table 3-1 Relationship between variables: Causes and effects

	Cause variables	Effect variables	
Variable	Glass facade	Cooling in summer, Heating in winter → Energy use	CO2 emission
Sub-variable	Window / wall ratio	Annual energy consumption	Annual CO2 emissions
Indicator	Square meter of glazing ➔ U-value glazing	kWh / m² / year	Kg / Co2 / year
Standard	-	EN 13979	
Tool	AutoCAD	Grasshopper	
Sub-variable	Construction and quality of walls and insulation (Thermal characteristics of insulators)	Energy effect: overheating (Performance of thermal insulators)	
Indicator	fixed EPBD → U-value wall	Thermal performance of buildings and materials	
Standard	- Thermal conductivity: NBN B62-002 A1 -Specific heat: EN ISO 10456	NBN EN ISO 7345	
Tool	-	Grasshopper- Honeybee	
Sub-variable	Climate / weather	Energy effect	
Indicator	Heating/Cooling Degree days		
Standard	-year (TMY) ISO 15927 -weather station: NLD_Beek.063800_IWEC		
Variable	Glazed facade	Natural light	Visual comfort
Sub-variable	Orientation		
	Context		
	Shading (interior-exterior)		
Indicator	-		SDA- ASE
Standard	-		NBN standard EN 12464-1
Tool	-		Grasshopper
Variable	Glazed facade	Thermal comfort	
Sub-variable		Energy consumption	Relative humidity
Indicator		Hour of discomfort, annual hours of temperatures above 26 ° C / below 20 ° C	Discomfort hour

Standard		NBN standard EN 15251: 2007 (Interior ambience criteria)	Norme NBN EN 15251
Tool		Grasshopper- Honeybee	
Sub-variable	Occupation (hours of use) and their behaviour	Energy consumption	Cost (regional rate)
Indicator	person / m² / hour-days-week	kWh / m² / year	€ / kwh / year
Standard	ASHRAE Std 90.1	EN 13979	-
Tool	data logger (presence sensors) / schedule and type of work	Grasshopper	-
Variable	HVAC system	Thermal comfort	Energy consumption
Sub-variable		Indoor air quality	
Indicator	Consumption		
Standard	ASHRAE Standard 55		
Tool	Grasshopper	Grasshopper	

3.4.1 Fixed inputs

3.4.1.1 Location and weather file

Figure 3-7 Study case location-Google maps [05/2021]

The case studied in the thesis will be simulated for Genk (Figure 3-7), a town and municipality located in the Belgian province of Limburg. Located in northeast Belgium on the Holland border, Genk is one of the most important industrial towns in Flanders.

The city's climate is classified as warm and temperate. The average annual temperature is 10.8 °C, the average maximum temperature is 21°C of the year in the warmest months (July- August), and the lowest average temperature is 3.2°C in the coldest month (January). The city has heavy rainfall throughout the year, about 839 mm/year. *(Climate and Average Monthly Weather in Genk (Limburg), Belgium, n.d.)*

3.4.1.2 Case study

The case study is an energy research laboratory building and office spaces for the Catholic University of Leuven at the Genk-Waterschei campus "EnergyVille" (Figure 3-8). It is one of Flanders' most sustainable buildings in terms of energy use, based

on the cradle-to-cradle principles and CO2 reduction. The building has received the BREEAM certificate Outstanding.
Its location coordinates are: latitude 50.99, longitude 5.53, and the elevation above sea level is 84m.

A simplified geometry from the EnergyVille building model is used to generate a set of scenarios. In which, assumptions on three sensitivity parameters, namely: the yearly consumption of heating and cooling, visual comfort, and thermal comfort, are being altered.

Figure 3-8 EnergyVille 1, Thor Park 8310, 3600 Genk

The location and the weather file are introduced as fixed parameters. Concerning the weather data file, Figure 3-9 shows the available weather data in the region. The EnergyPlus weather file (EPW, markers in blue) was chosen. It is based on the typical meteorological year (records for a minimum of 10 years). The nearest available file has been found in the station of Beek, in the Netherlands, station ID: 063800. This weather station is located at latitude 50.918, longitude 5.766, elevation 116m, about 19km from the case study location (Figure 3-10). Therefore, an ASHRAE climate zone 4A is considered.

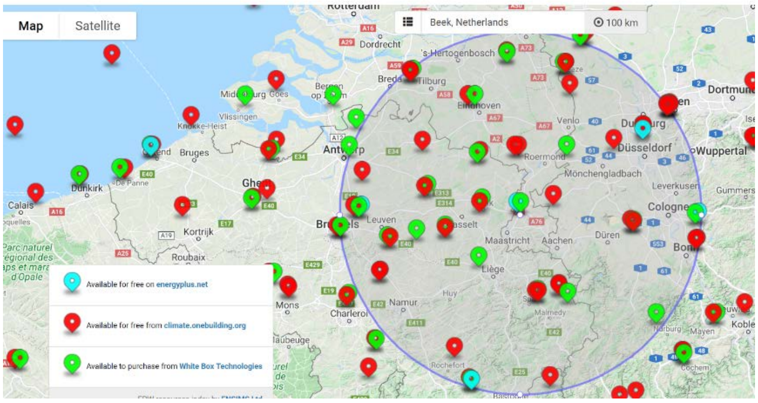


Figure 3-9 Available weather data in the region - Source: *(*ENSIMS EPW Map Tool*, n.d.)*

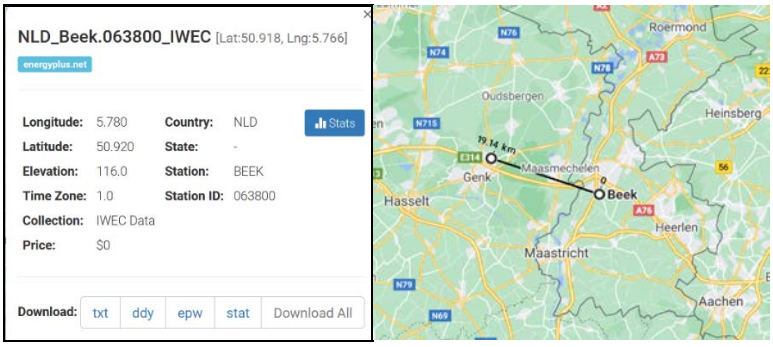


Figure 3-10 Beek Weather file information and location compared to the case study location- Google maps [05/2021]

3.4.1.3 Representing geometry parameters (mass, adiabatic)

A geometric room model of the case building was created using Grasshopper with the interface of Rhino 7. The units are also set in meters to obtain the results in meters. Dimensions are taken from the architectural drawing plans for the building: a shared office unit with a size of 7.2 m (width) × 11 m (length) × 3.2 m (height). The area where calculations are performed is considered as one thermal zone. Furthermore, it is considered an adiabatic room with no thermal exchange except one exterior wall, representing a façade that includes glazed openings. The furniture depends on the room type (an office) and as recommended in the standard IES. Descriptive layers names were chosen to allow the implementation of material identifications in the following simulations.

3.4.1.4 Occupancy Schedule

For this study, we are interested in annual results, so an annual occupancy schedule is needed. Occupancy schedule represents the work time in Belgium; five days per week from Monday to Friday, excluding the annual Belgian holidays from the 24th of December to the 6th of January. Regarding IES-LM-83, a standard by Illuminating Engineering Society about Spatial Daylight Autonomy and Annual Sunlight Exposure (*IES LM-83-12*, n.d.), the schedule should be 10 hours during the day, from 8 am to 6 pm with a one-hour break for lunch at noon.

3.4.1.5 Opaque specification

Without specifying in detail, the construction layers of the walls and the opaque part of the face respect the EPBD norms, where the U-value for the exterior wall is 2.4 W/m^2K, and for the interior walls is 1 W/m^2K.

3.4.1.6 HVAC specification

The studied case depends on natural ventilation with a 30% opening from the glazed surface. In addition, mechanical ventilation is provided in the actual scenario.

On the contrary, the room is considered without any mechanical or natural ventilation or HVAC system contribution for this study. That will give us a clear idea of what is needed in energy demand, whether heating or cooling system and discomfort hours. Also, the infiltration rate is 2.27×10^{-4} per area.

3.4.2 Variables inputs

A set of variable geometric design parameters were considered: orientations, window areas, shading device, and non-geometric design parameters: HVAC, walls. Figure 3-11 shows an example of the simulation model with specifications, such as grid level, the distance between windows, adiabatic surfaces and base case dimension.

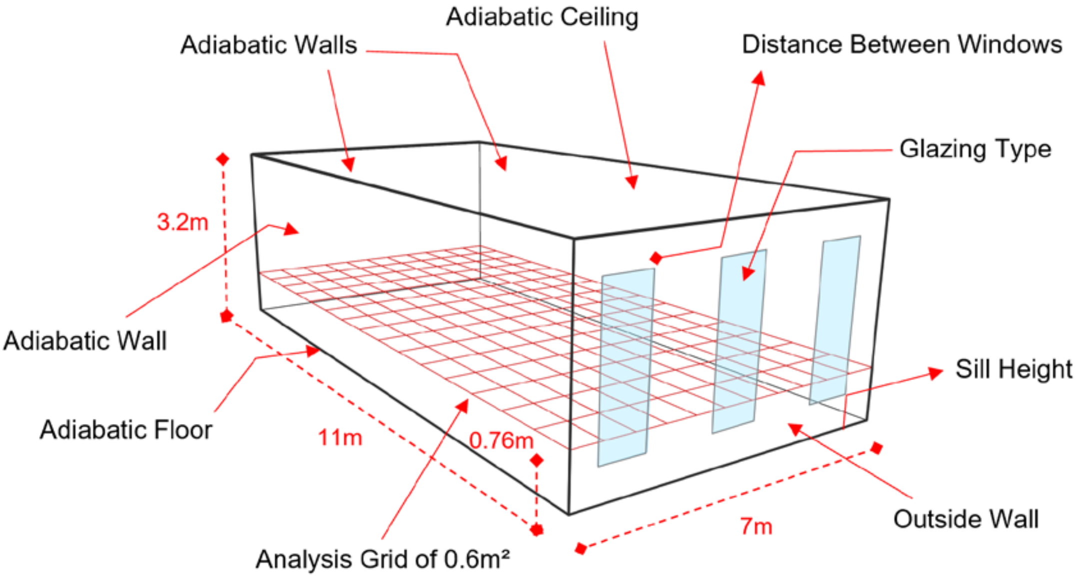


Figure 3-11 An example of the simulation model

3.4.2.1 Facade orientation

Different scenarios were examined among eight orientations starting with the north-south axis and with a 45 degrees step between each direction. The zero degrees (0°) represents a south-glazing façade, and the 180° represents the North (Figure 3-12)

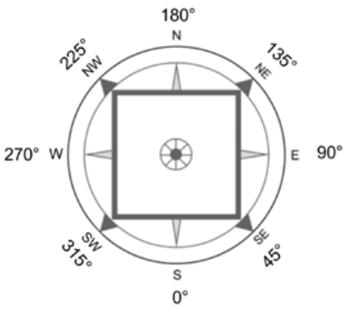


Figure 3-12 Shoebox orientation as modelled in Grasshopper

3.4.2.2 Window-to-wall ratio

Different percentages of glazing were tested from 10% to 90%, with a 10% difference. On the other hand, by adding the shading devices, the percentage of glazing was chosen from 30% to 90%.

3.4.2.3 Windows specification

Three different window sill heights were proposed: 0.5m, 1m, and 1.5m. The distance from the window lintel level is fixed to 0.3m. That will help to benefit from the sunlight passing into the room compared to a window in the middle of the wall. Nevertheless, that depends on the WWR: When the WWR is high, the sill height and lintel level will be changed automatically according to the glazed surface.

Also, different distances between the window panels were proposed: 1m, 2m, 3m, and 4m and 5m. These lead to different windows division: for example, for the same WWR of 30% glazing, we could design one large window panel in the middle of the wall or having multiple windows with a distance between them.

However, it depends on the window-to-wall ratio: if the WWR is high, there are no spaces between windows, and it will be considered one glazed surface. These details could influence daylighting, thermal comfort, or energy efficiency, which will be discussed in detail in the results chapter. However, we could find more complicated and more detailed information about windows in a real design that could be taken into account.

3.4.2.4 Glazing specification (type and properties: U-value, SHGC, VT)

Many glazing types exist in the market, and it varies regarding the thermal properties, other window parameters or price. These have a significant influence on the comfort and energy efficiency.

The type of glazing chosen for this study is “Stopsol Super Silver Dark Blue”. This glazing is used in Brussels, Belgium's office building “Covent Garden”, designed by Montois Partners Architects and Art & Build. This Brussels skyscraper built-in 2007 consists of 26 floors and is shown in Figure 3-13.

Figure 3-13 “Covent Garden” Tower- Brussels, Belgium- Source: AGC Glass Europe: (https://www.agc-glass.eu/en)

It is a solar control glass, double panels with 90% argon and 10% Air (AGC Glass Europe) with solar protection coatings on the external side. This coated glass ensures that the interior surfaces receive natural daylight while blocking out the excess heat.
Another type of glazing was chosen, “Stopsol Supersilver Clear”. This window consists of 6 mm Stopsol, 16 mm Air, 6 mm Planibel G (AGC Glass Europe).

These two types of glazing with the same main product were chosen to compare the results from dark blue glazing with a clear one.

Uw-value

The U-value has effects on the energy demand and thermal comfort. The lower value means more insulation. Nowadays, the double-glazing and the triple-glazing for facades of office buildings in Belgium are used. As two types of glazing were chosen, two U-values too. For this study, a Uw-value is used; the heat transmission coefficient for the whole window, which means the glazing part with the frame and the interlayer. For double-glazing, a conductivity value is 1.5W/m^{2}K, and for triple glazing is 0.6W/m^{2}K regarding the EPDB.

Visible Light Transmission

Visible Light Transmission is also known as, T_{vis}, T_v, VT, and LT. It is the percentage of natural light that passes through a window and varies between 0 and 1. The higher the value, the more daylight. VT is affected by the composition of glass and coatings. For this study, values of 0.3 for the Dark Blue glazing, 0.5 for the clear one was chosen regarding the glass-type properties.

Solar Heat Gain Coefficient (SHGC)

The U-value, solar heating gain coefficient, and air infiltration are three main energy efficiency contributions. The window's solar heat gain coefficient (SHGC) or (G-Value) shows how much solar heat is absorbed and transmitted through the glazing system. It is a value between 0 and 1. The lower the number means, the lower radiant heat allowed to pass through the window. Therefore, if SHGC is equal to 0, it means no heat gain pass-through window. On the other hand, if SHGC is equal to 1, it means the highest level of heat gain pass-through window. However, a range between 0.2 and 0.9 is typically used.

However, sometimes a higher value is better, and sometimes a lower is better. To know which value is better, we need to refer to some points and other factors: the recommended value by a standard based on geography and number of days heating or cooling, the type of activities (i.e. laboratory where the demand for cooling is high, or elderly house where the demand of heating is high), or the orientation (i.e. if we have a Nord-facing façade we need as much heat during winter, whereas a west-facing façade allowing more heat will lead to discomfort during summer). In addition, the context around the building, shaded area, diffuse radiation reflections from shading devices should also be considered. These have an impact on the heating and cooling demand, comfort level, and energy bills (Kohler et al., 2017).

For this study, SHGC values were calculated based on the window types: 0.3 and 0.58 for “Stopsol Super Silver Dark Blue”, “Stopsol Supersilver Clear”, respectively.

Values for glazing properties and specifications were calculated based on the type of glazing and the number of panels in different ways (Appendix 3).
The values have been obtained by comparing three resources. A deep discussion about the method is in section 3.8.

As an assumption: the same g-value and T_v are considered for all facade orientations.

3.4.2.5 Analysis Grid

The percentage of daylight is needed to be examined on the level of a working plan. It is represented in red in Figure 3-8, and it is set to 0.76m from the floor level, regarding LEED and the level of a working plan. A grid of 0.6m², recommended by LEED, is chosen regarding the room surface. However, a smaller grid means a higher resolution of results but needs more time to finish the simulation calculation.

3.4.2.6 Shading device system

The preferable fixed shading devices in an office building are those that can be adjusted manually by the occupants and control the solar radiation when needed, such as the Venetian blinds, vertical blinds, and roller shades. Some examples are presented in Figure 3-14:

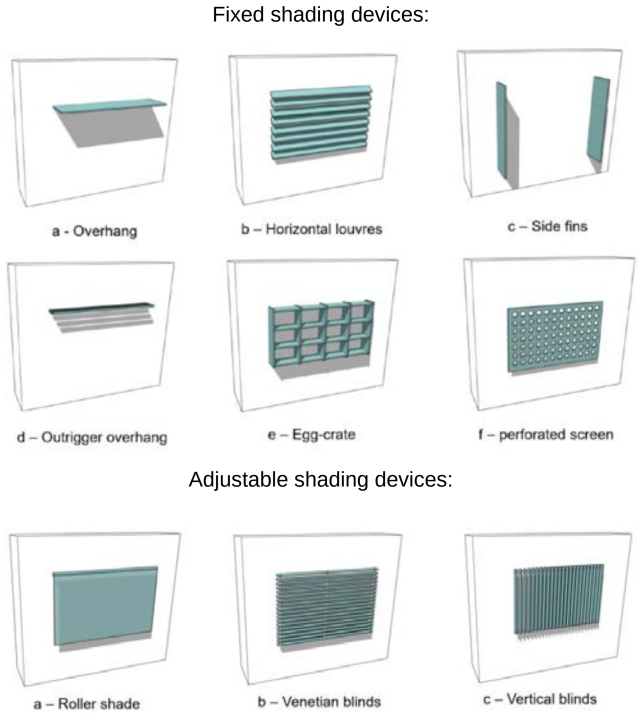


Figure 3-14 Example of fix and adjustable shading devices- (Bertrand., 2020)

The position of the blinds, whether it is inside or outside, impacts the daylight performance and reduces the energetic gain. But the degree of the impact varies from one to another. A comparison between the exterior and interior blinds positions was listed in the first Chapter. However, a comparison study for the percentage of influence will be discussed later depending on the simulation results.

Slat orientation

As mentioned earlier, the representing shoebox has been considered as an adiabatic room with one façade. A specific blinds position: horizontal, vertical, angled, inside or outside, had been chosen for each façade orientation based on the common positions to maximize the benefit of daylight or to use it as protection. For the Southern facade, data are recorded for horizontal overhangs and blinds position. For the west and east orientation, vertical fins are more effective than horizontal because we have a lower sun angle. For the west-facing glazed façade, vertical and horizontal blind positions were tested. In contrast, no blinds are considered on the north facades.

Figure 3-15 represents an example of a modelled room in Grasshopper with outdoor vertical blinds.

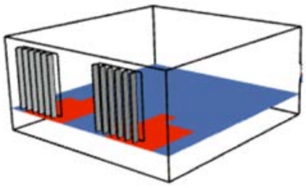


Figure 3-15 Example case of a room office with outdoor vertical blinds

Different parameters of blinds influence results. Figure 3-16 and Table 3-2 resume considered properties of the inputs of the blinds.

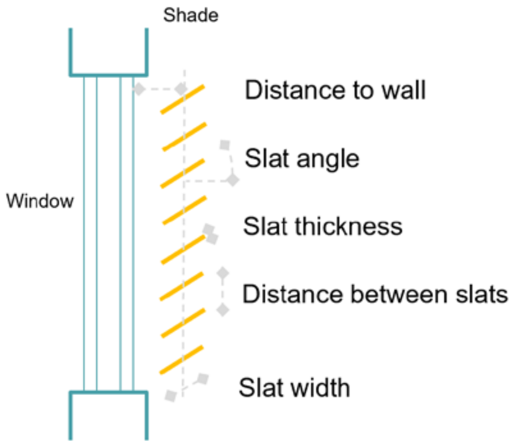


Figure 3-16 Shades parameters as represented in HB Energyplus window shade Generator

Table 3-2 Blinds properties in HoneyBee

Visible properties		Note
Distance to glass	0.05m	
Depth	0.6m	One southers slat
	0.03m	Exterior blinds
Distance between shades	0.005m	
Number of shadings	Without/regarding the distance between the slats and the percentage of glazing	
Shade angles (degree)	0	East and West
Slat orientation	Variable	Regarding the orientation
Slat thickness	0.25mm	The default value in the Energy-Plus window
Solar properties		
Shade set point	150 W/m²	Regarding the control type
Solar reflectance	0.65	Default values of Energy-Plus window
Transmittance	0	
Emittance	0.9	

To sum up, Table 3-3 summarises all the fixed inputs and variables that have been considered for this study. We should mention that in reality, many options exist, but justifications are mentioned for each choice and represented in the last column.

Table 3-3 Characteristics of the variable parameters

Components	Characteristics	Fixed	Parametric range	Justification
Office room	Width * Length * Height		7 m*11m*3.2m	Case Study
			7m*7m*3.2m	Optimization
	Window-to-Wall-Ratio		10%, 20%, 30%, 40%, 50%, 60%, 70%, 80%, 90%	
	Glazed façade orientation		0° (South),45°, 90°(East), 135°, 180° (Nord), 225°, 270 (West), 315°	
Exterior Wall	U-value (max) R-value (min) Solar reflectance	0.24 W/m²K 4.16 m²K/W 0.7		EPBD[2]
Adiabatic Walls	U-value	1 m²-K/W		EPBD
Floor	U-value	0.24 W/m²K		
Ceiling	U-value	0.24 W/m²K		
Window	Sill height		0.5m, 1m, 1.5m*	
	Distance between individual windows		2m, 4m*	
	Lintel level		0.3m*	
Glazing	Visible transmittance		0.3, 0.5	
	SHGC		0.3	Dark blue, low-E coating
			0.58	Clear, low-E coating
	Uw, max	1.5 W/m²K		EPBD- double glazing (frame & glass)
		0.6 W/m²K		EPBD - triple
Shading	Orientation	South East West South-East South-West	Hor. Ver. Hor./Ver. Ver.	
	Width		0.025m, 0.6m, 0.8m	
	Separation		0.3m, 0.6m, 0.8m	

*This input can be changed automatically when the glazing ratio is high.

[2] (*Guide PEB 2018*, n.d.)

3.4.3 <u>Output features</u>

3.4.3.1 Visual comfort

Visual performance is considered in this study. Honeybee runs daylight simulations using the analysis engine “Radiance”. Two dynamic daylight metrics are analyzed to evaluate this aspect: Spatial Daylight Autonomy (sDA) and Annual Sunlight Exposure. The daylight studies are done at the level of 0.76m, which is the level of the activities in an office.

As mentioned earlier, the sDA value is expressed as the percentage of the studied area, during 50% of occupied hours, which are the working hours per year that receive minimum illuminance, which is 500 lux for an office room (Norm NBN EN 12464-1 », 2007). However, the standard threshold is for 300 lux (*IES LM-83-12*, n.d.).
On the other hand, ASE represents the glare and direct sunlight; visual discomfort. It is the percentage of the studied area that meets 1000 lux more than 250 hours from total annual operating hours.
In the calculation of sDA according to LEED, all exterior windows should be modelled with interior blinds to block direct sunlight. In this case, the ASE will always be zero without any risk of glare. However, it can be acceptable to be modelled without blinds if both criteria have been considered.

One of this study's goals is visual comfort, and since the sDA does not provide information about possible visual discomfort, the ASE should always be additionally calculated. In that case, to meet the percentage of annual hours in which the level of daylight falls in the visual comfort range, we should subtract the ASE percentage from the sDA percentage (sDA - ASE), as seen in the example in Figure 3-17.

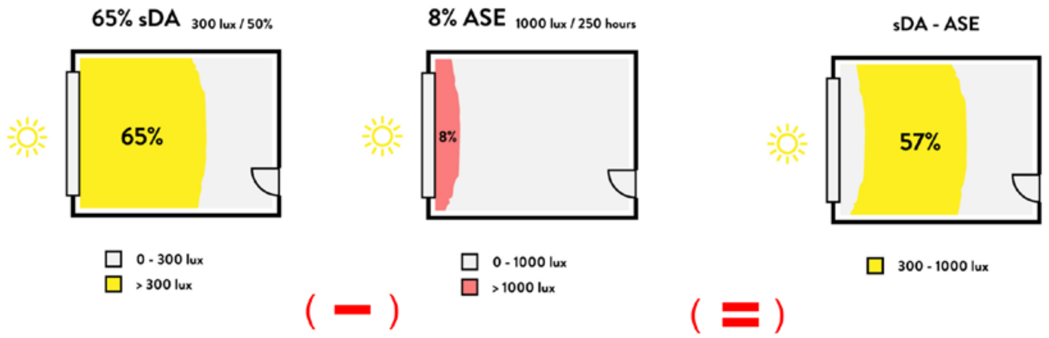


Figure 3-17 The level of comfort daylight illuminance- source (Daylight Metrics, 2018)

However, this study calculates both daylight metrics and considers both criteria simultaneously, aiming to choose the optimal glazing ratio and glazing configuration, which meet minimum sDA and maximum ASE requirements according to LEED v4.

3.4.3.2 Indoor thermal comfort

The second aspect that has been studied is indoor thermal comfort. The HVAC system was not modelled for the simulation case. However, the overheating and cold levels were based on the standard NBN EN 16798, where the optimal indoor temperature is defined between 21°C minimum for heating and 25,5°C maximum for cooling (*EN 16798-1*, n.d.). Results are measured in hours/year as average hourly values based on the weather file. Visualization maps have not been used because the simulation time will be higher.

3.4.3.3 Energy Use Intensity

Another aspect that has been considered and the third approach of investigation is the energy demand. The output Energy Use Intensity (EUI) for heating, cooling and electric lighting have been calculated by creating an energy workflow and energy model with Honeybee.

For this study, as we are interested in daylight metrics, energy demand, and thermal comfort, the energy workflow was relayed to daylight results. Thus, the same variable inputs for all workflows.

The energy consumption results are obtained based on data from (.epw) weather file, based on an energy schedule and hourly time step simulation for a one year analysis period. Results are measured in Kwh/m²/year without the visualizations charts since it will increase the calculation time.

3.5 Data collection

The next step is to pass from Grasshopper to Design Explorer. To perform parametric automation and to export the different iterations, the plugin Colibri is used. It is included in TT-Toolbox, developed by Mingbo Peng, an application developer and project consultant at Thonton Tomasetti (TT). The Colibri allows us to turn results into Design Explorer, where everything is automated.
From the parametric authoring tool, Grasshopper, we export the data as a .csv- format file, 2D visualizations as .png- format, and 3D object as .json- format.

The recorded results are loaded and displayed in Design Explorer, which is an open-source interface for exploring the design space data and multi-dimensional parametric studies on the web. It can visualize and filter sets of design solutions or iterations as shown below (Figure 3-18), which are generated by traversing the parametric model.

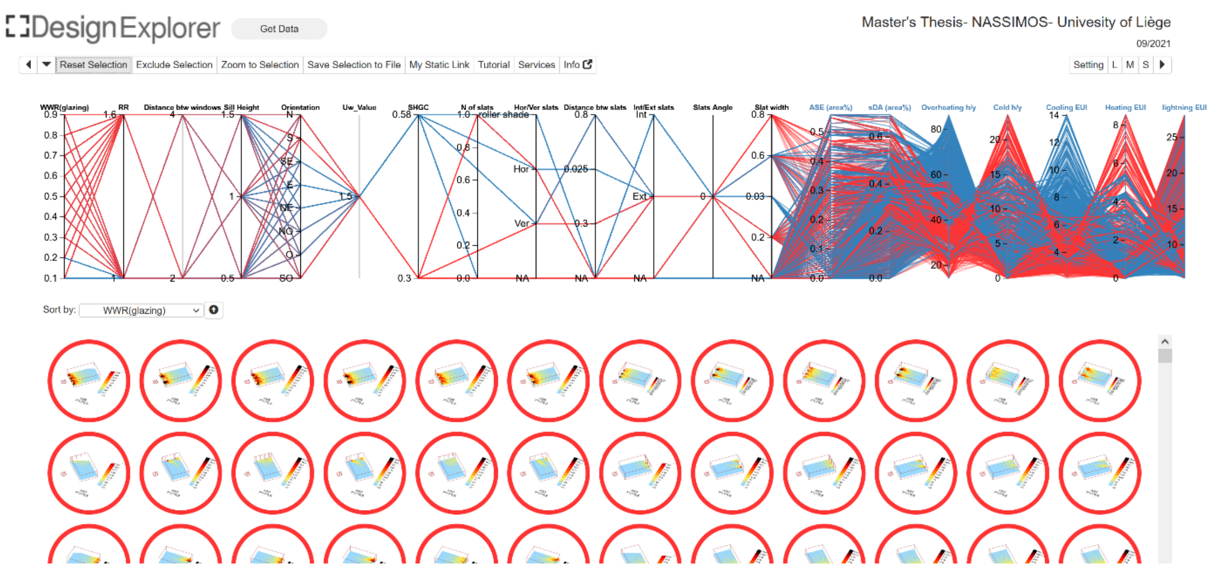


Figure 3-18 Parametric design model interface- Design Explorer

3.6 Data analysis

The next step for this study is a correlation analysis between variable input parameters on the outputs. Firstly, data from all iterations were collected and analysed. Following this, some attempts are tested in section 4.2 as results improvement trials. Then by using all the simulation data from the excel file, some input variables are studied according to three groups: visual comfort, energy efficiency, and thermal comfort.
Thus, the most affected results regarding the specific variable input are detailed according to visual inspection of graphs created in google data studio based on the excel file. Followed by correlation comparison and sensitivity analysis. The ranking of the influential variables is explained and presented in section 4.5

Finally, by interacting with the tool and determining the study's objectives, excel data files are collected for the selected scenarios. As a result, some of the best scenarios regarding visual comfort or for all the outputs together (ASE, sDA, thermal comfort and energy consumption) will be presented.

3.7 Boundary conditions

In this section, we will identify the boundary conditions of the study with the challenges and limitations:

- Generally, the parametric range of variables or fixed inputs investigated in this study have been chosen based on the European norms and international standards, such as NBN EN 16798-7:2017 to define the acceptable range, and some based on international building rating systems such as LEED. The LEED standard was selected for this study because it gives more detailed and more relevant information about the daylight metrics, as represented in the comparison between LEED and BREEAM certification in the first chapter.
- To do the parametric study, a simple shoebox was chosen. The reason for choosing a shoebox and not a whole building is, first, for the question of time. Moreover, we notice that most office buildings consist of repetitive units. So, we can consider that this shoebox represents a single module in reality.
- The study aims to analyse the visual comfort, thermal comfort, and energy consumption regarding the percentage of glazing in a simple design facade. However, due to some limitations in Grasshopper, and since the input data are more complex for dynamic facades, they are not studied for this thesis.
- Since this study aims to obtain numbers and visualization maps to help better choose between the scenarios, however, regarding the time needed to get visualizations maps for overheating and underheating comfort leads to results that are represented only in numbers for this part.
- Parametric design for building facades doesn’t offer much flexibility in design because it is based on specific choices, limiting the creativity and innovation of the designer.
- We could face other parameters that have not been included in the study, and we cannot predict it on a range frame, such as the context around the building, which may have negative or positive effects on the daylighting or the temperature.

- The parametric study is based on a tool so that we could face any problem regarding the tool, such as the experience with the program, bugs, a good machine, free licenses. For example, Rhinoceros has a free trial version for 90 days, whereas Grasshopper, Ladybug, and Honeybee are free.
- Due to the limitations and complexity of the software used (Grasshopper), which leads to not simulating cases with dynamic shading devices, our studies are based only on the simple fixed ones. However, alternatively, we can use EnergyPlus and Energy Management System (EMS) for programming. Nevertheless, more experience and more time are needed for this purpose.
- Because the visual maps of comfort need more time to be calculated and visualized, the results will be without visualization.
- To visualize the maps of sDA and ASE calculation, we define a calculation grid at a specific level from the floor. The calculation will be at the centre point of each grid. However, a higher number of grid points with a smaller surface is more accurate and representative, as shown in Figure 3-19, but needs more time to be calculated.

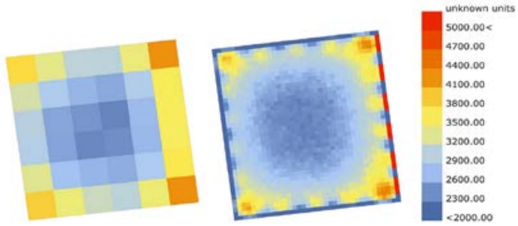


Figure 3-19 Illuminance map, examples of grid size (left: six meters, right one meter)

As presented in Figure 3-20, the spacing between grid points affects the daylight calculation values. Despite this, and because of reasons of time and numerous iterations, a 0.6m for a grid size is chosen. However, regarding LEED v4, the standard grid size should be no more than 0.6m². However, generally, we should choose a value that adapts for the study's main purpose and the size of the project, whether it is one room, a building, or an urban neighbourhood scale.

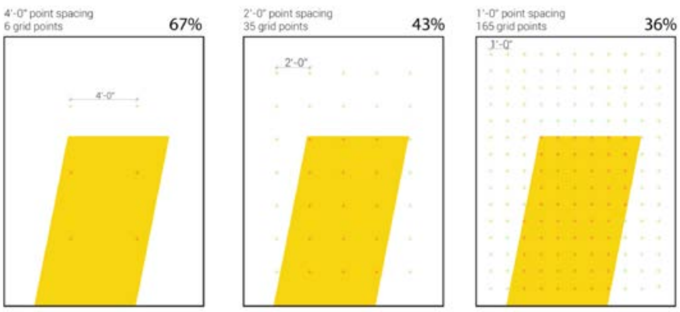


Figure 3-20 Different illuminance levels regarding the spaces between grid points

- Using the Colibri plugin with the Design Explorer helps us to visualize the results better and to manipulate the tool. However, we should be very careful because any minor fault in the .csv file will not present desired results, such as changing nomenclature, duplicate value or information, false value, or empty rows.

3.8 Quality criteria

Since the design tool is for the early design stage and the focus is on the simplicity of the tool, we are not waiting for the results that represent the real scenarios. Undoubtedly, deeper studies will come up before passing to the construction phase and before the conception design becomes a reality. If we need more accurate resources to collect data from, for example, about daylight, we must measure the illuminance value by the illuminance meter in place. However, this study collects data from the nearest weather data station, gets information from experts, and is based on norms, standards, and literature reviews.

This part will discuss how the quality criteria are assured:

3.8.1 Information and norms

In this study, the two used Daylight Dynamic Performance Metrics, spatial daylight autonomy (sDA) and annual sun exposure (ASE) were analyzed. Both were based on values and recommendations from LEED v4.

To know the type of glazing used for office buildings in Belgium, it was needed to contact many glass manufacturer companies, asked experts about the most used tool for glazing information. As a result, we were able to get the glazing configurations and thermal properties by comparing values from three different sources:

- The tool “LBNL WINDOW” :

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- The tool “LBNL WINDOW” :

It is a software that offers calculations and information about thermal performance for windows. A version of 7.8 was used. This tool is consistent with the ISO 15099 standard (thermal performance of windows). It has a comprehensive library with thermal properties by glass manufacturers: AGC, Saint-Gobain glass, and many others. Shading layers, window frames, materials, and many products could be found in this software. A calculation will be done depending on the choice.

- Glass Configurator by AGC company:

Where we can create and specify the type of glazing; single, double, or triple panels, the type of glass and whether it is coated or not, the materials of gaps, and the thickness. As a result, we get details about light and energy performance (solar heat gain coefficient, thermal transmittance, colour, and others). This information and calculations are based on standards: EN 410 and ISO 9050 for light and energy values and EN 673 for thermal transmittance.

- Brochures from glass manufacturers:

These were provided by glass companies' site web or by direct contact, containing examples of real estate buildings in Belgium, with the type of glass used in these buildings and tables with glazing properties.

3.8.2 Usability testing (ISO 9241-210)

Qualitative usability testing, user-based research, was done to ensure the simplicity of the developed tool, to check the interaction between potential users and this design tool, and how effective the tool is. The System Usability Scale (SUS) is a reliable and flexible method, usually used for the early interactive prototype. It consists of 10 standard questions.

The tests were taken by making a video call. First, a presentation of the study's main purpose was explained, then the tool was presented and how it works. Furthermore, a brief description of the variables (sDA, ASE). Once the presentation was completed, each participant was asked to try the tool by accomplishing tasks; choosing window to wall ratio (WWR), Uw-value, a specific orientation, and other suggested inputs. At this point, the evaluator is asked to select the highest values of the positive output sDA and the lowest values of the negative outputs ASE, heating and cooling demand, overheating, and cold hours. Then, they were asked to visualize the images and the 3D for the filtered proposed solutions and sort them based on the desired variable. The duration that each participant took to achieve the mission has been recorded. Finally, each one was asked to fill in the usability questions and a few general questions for feedback by Google Forms.

The recommended number of participants for the SUS test is usually between 4 and 12. So, seven different participants were asked to test the tool; a project manager of a real estate company in Belgium, an architectural engineering student and assistant professor, an architectural student and architect specializing in metal building envelopes, and an expert in facades design in a real company. Their different specializations gave us multiple points of view.

Their feedback and remarks have been carried out as much as possible to improve the tool to make it easier for the audience's needs and potential users.

3.8.3 Detect errors

Firstly, plugins inside Grasshopper can detect some errors and give warning messages during the simulations. Moreover, most inputs are provided by default values representing the acceptable range based on international standards.

Secondly, by exporting the results to Design Explorer, we can detect some errors. For example, as represented in Figure 3-21, the blue line represents an error value as the range scale of results is not correctly and well presented.

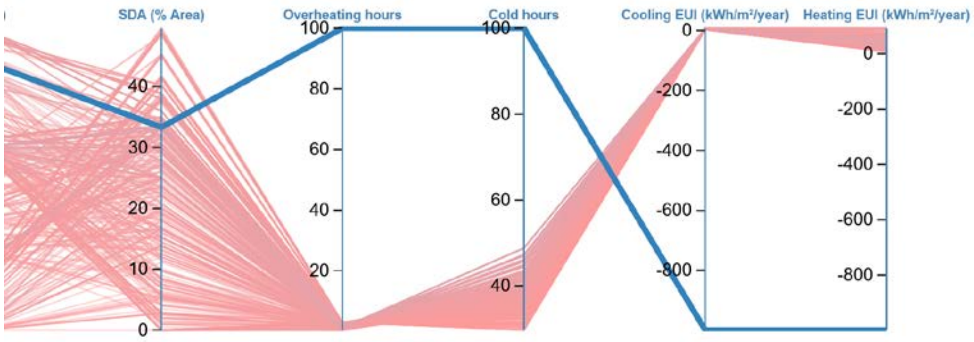


Figure 3-21 Detect errors in calculation by Design Explorer interface

Moreover, Design Explorer offers the possibility for developers to detect some errors in the simulation results by correlation graphs visualization. As shown in Figure 3-22, the left chart shows errors on ASE results because one point is on (0) and another on (-900). In contrast, simulation results on the right are represented on a correct scale.

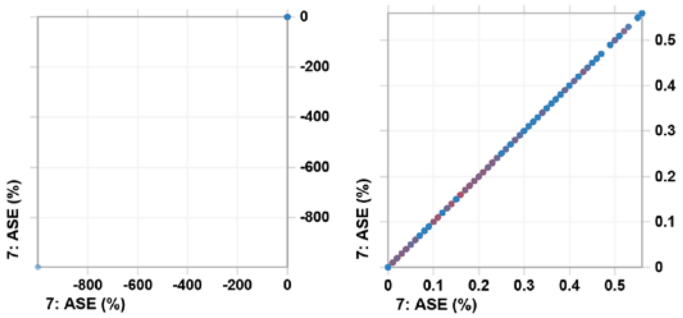


Figure 3-22 An example of a sign of error (left) chart vs the correct one on (right)

Finally, the main objective of this tool is to reduce the design stress and not the accuracy of the results or detailed specificity. Even though many tries, work repetition, exchanges, and consultations with experts and architects have helped detect and spot the light on some issues, such as evaluating the parametric tool's efficiency based on their experience, detecting errors in the script, so, trying to solve them. Moreover, the model is accessible online. Also, all input files and data are provided in the Annexes section.

4 Result of the tool

4.1 Introduction

This chapter will present the results obtained by following the methodology explained in the previous chapter regarding the tool and results obtained from the simulation. This chapter gathers all annual results from the simulation in Grasshopper. First, the final design tool with all iterations is presented. Second, the results obtained based on the system usability score are explained. Then, general interaction with parameters and the effect of each variable inputs are defined according to comparison and correlation studies. Finally, a sensitivity analysis is adapted to rank the impact of the studied parameters on specific outputs.

The first question of this study is:

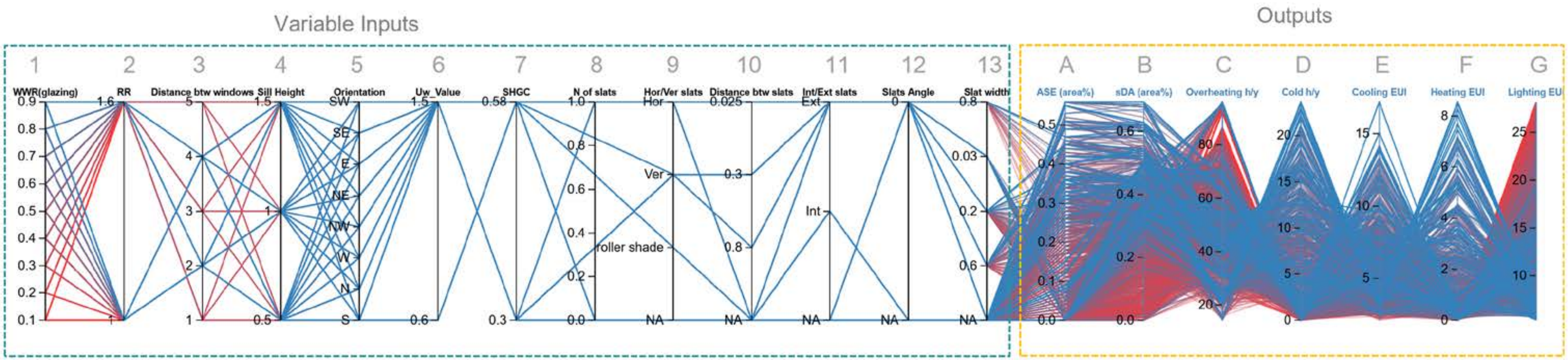
- *How to simplify the decision-making of facade's design during early design stages without using building performance simulation?*

The final tool is a user-friendly parallel coordinate graph, table, and visualizations used in Design Explorer (Design Explorer, n.d.). Data exported by the dynamic simulation using grasshopper is added to this tool. This tool will help architects visualize results and compare different choices in a few minutes without passing by a building performance simulation tool that is already done.

Data for this study can be accessed online at the link below:

http://tt-acm.github.io/DesignExplorer/?ID=BL_3iQzicX

Adding the variable inputs gives 2600 different solutions with different scenarios (Figure 4-1). It follows that we obtain different results about daylight performances, indoor thermal comfort, heating, cooling and electric lighting consumption.



Legend:

Variable Inputs:

1.Window-to-wall ratio 2. Room ratio 3. Distance between windows 4.Sill height 5. Orientation 6.Uw-value (window) 7. SHGC
8. Number of slats 9. Hor./Ver. Slats 10. Distance between slats 11. Int./Est. shading 12.Slats angle 13.Slat Width

Outputs:

A. ASE B. sDA C. Overheating hours D. Cold hours E. Cooling consumption F.Heating consumption G. Lighting consumption

Figure 4-1 Diagram for the different implemented design options

This user-friendly interface helps architects interact easily with the model, which could be considered as one module. Furthermore, it can be used during the interaction with a client during the early design stage. The designer can change a specific parameter to suit a client's requirement without passing by a simulation tool which will need more time and more detailed study. Moreover, the images, 3D models, and charts are considered helpful at the preliminary design stages (Figure 4-2).

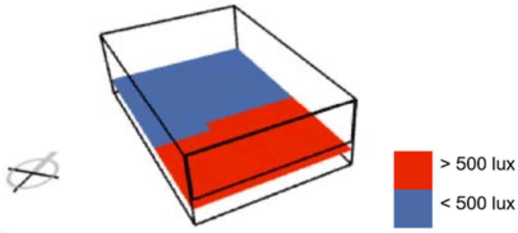


Figure 4-2 Room with Spatial Daylight Autonomy map

4.2 Results improvement trials

On the first round of simulations, 549 results were obtained based on five variables inputs: the Window-to-Wall Ratio (WWR), the distance between windows, window sill height, Solar Heating Gain Coefficient (SHGC), and orientation. As outputs, six features were used: ASE, sDA, heating consumption, cooling consumption, overheating, and cold hours. We notice that we obtained just a few choices between the iterations that respect the minimum threshold of sDA, which is 40%, as shown in Figure 4-3 in Design Explorer.

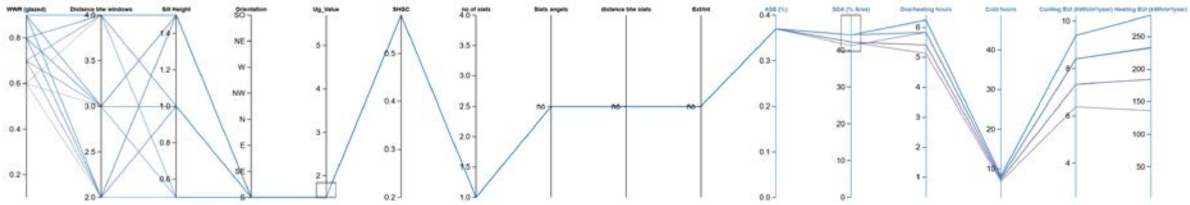


Figure 4-3 Selective results for 40% of sDA

Table 4-1 shows the lower limit, upper limit, and levels of the five inputs. Table 4-2 shows the minimum, maximum, median, and mean values of output features of the first 549 iterations.

Table 4-1 Input design parameters- first attempt

	WWR (%)	Distance btw windows (m)	Sill Height (m)	Orientation	SHGC
Lower limit	0.1	2	0.5	-	0.3
Upper limit	0.9	4	1	-	0.58
Levels	9	2	2	8	2

Table 4-2 output design parameters- first attempt

	ASE (%)	SDA (% Area)	Cooling EUI (kWh/m²/year)	Heating EUI (kWh/m²/year)	Cold hours/ year	Overheating hours/ year
Max	40%	44.23%	10.7	283.45	25.12	6.4
Min	0%	0.51%	2.5	4.7	2.9	0.352
Mean	17.55%	22.88%	5.1	108.91	13.82	2.265
Median	14%	25.65%	4.78	101.28	13.81	1.92

As we notice the maximum values obtained using the listed inputs, heating consumption is very high compared to cooling consumption. This is because, in the first round of the simulation, natural ventilation was used. Also, the heat production generated by occupants and computer equipment was not taken into account. Because in reality, in a well-insulated building, the cooling consumption in offices is generally more important than the need for heating. For these reasons, a modification and other variable inputs were added based on the workflow below Figure 4-4.

Figure 4-4 Workflow parametric design based on building performance

This part of the thesis will present the attempts to improve results and raise the number of efficiency scenarios regarding the main objectives. These suggested attempts are changing room dimensions, adding interior or exterior shading devices, and adding more variable inputs such as U-w value.

4.2.1 Changing room ratio benefit

In this study, the room dimension was from a case study office room, with 7m length, 11m depth and 3.2 height. More simulations were done on a square room space of 7m length and depth and 3.2m height to try to arrive at better results.

Figure 4-5 compares and correlates between room dimensions on heating and cooling demand and daylight metrics. We obtained better results for a room ratio of 1 (7m*7m*3.2) for sDA (left y-axis) and cooling consumption (right y-axis), where cooling consumption is less in the rectangular base case room. In contrast, the ASE is very high regarding the threshold, also a higher heating consumption for a square room.

Generally, regarding the length, the smaller room depth is the more favourable solution concerning daylight. That is because the sunlight does not have to go deep into space. Nonetheless, most office rooms are rectangular modules.

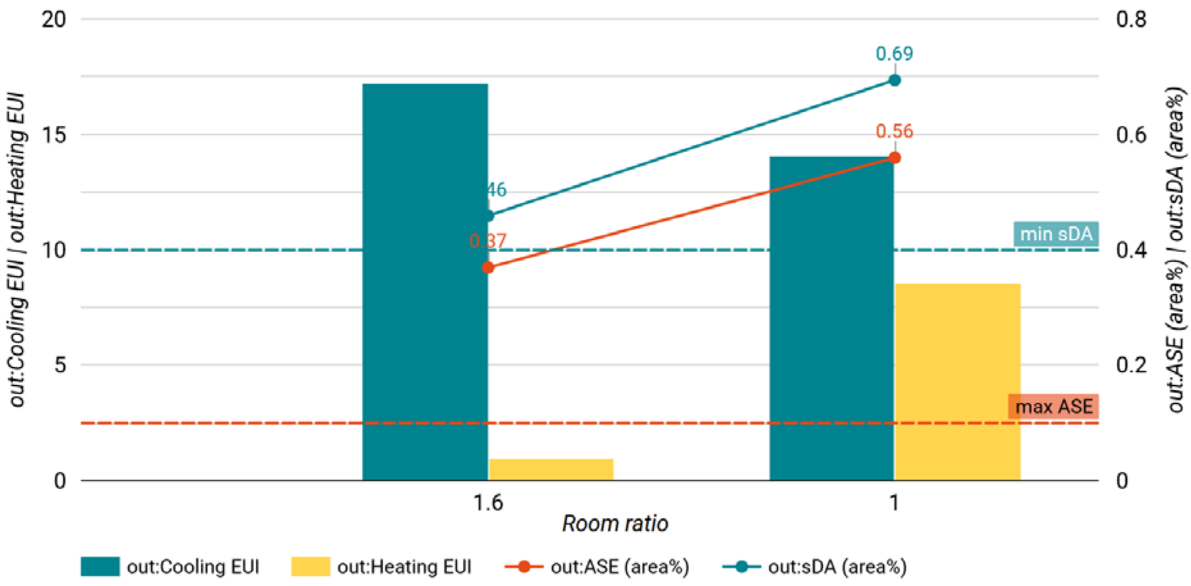


*Figure 4-5 Room ratio benefit- left (7m*11m*3.2m), right (7m*7m*3.2m)*

4.2.2 Shade benefit

The base case is modelled without shading devices. However, to study different cases, more features were added. Figure 4-6 represents the results on a South facade with a WWR of 0.9 for three different scenarios. The left y-axis is for heating and cooling consumption, and the right y-axis is for daylight metrics. The first scenario is a facade without shading. It is illustrated in the figure with the letters (NA). In this case, the sDA is high and favourable. In contrast, the ASE, which represents visual discomfort, is also very high compared to the maximum threshold. As well as, this case has a high cooling and low heating consumption.

The second scenario uses an interior roller shade (Int). This will be closed to ensure visual comfort when the direct sun becomes undesirable. In this case, the ASE is null, and the sDA is lower compared to the case without shading, but it is still above the threshold. We also notice that there is no change in energy consumption, or it is not very important. Finally, the third scenario is about an external shading system (Ext) represented as one horizontal slat with a width of 0.6m. in this case, we notice a change in energy consumption, less cooling energy, and higher demand for heating than the base case. In contrast, daylight metrics are less than the case without shading, but the ASE is still unacceptable.

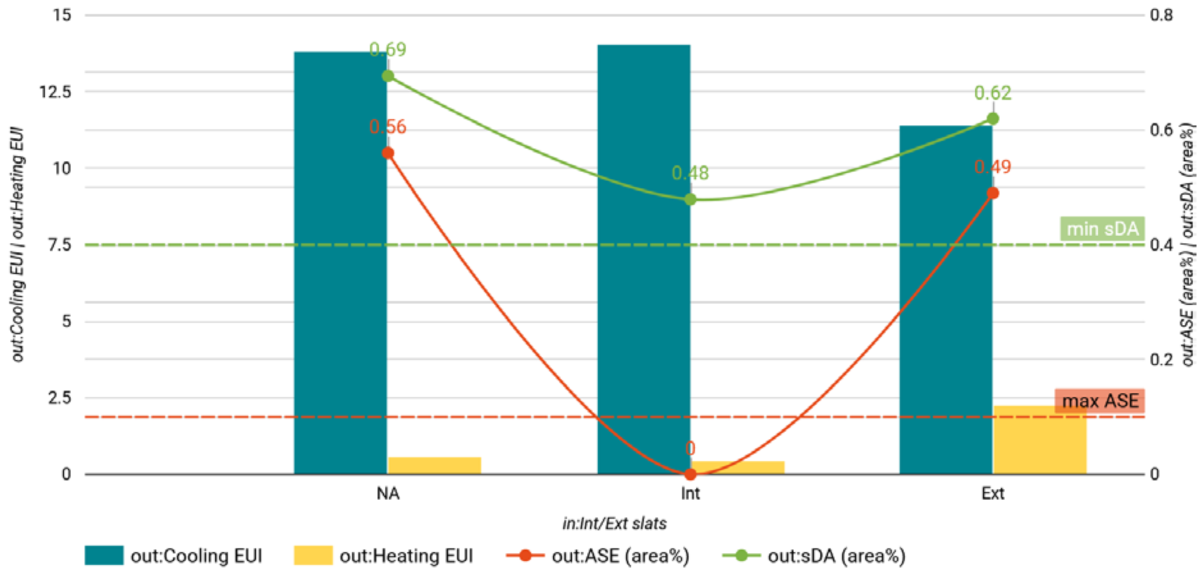


Figure 4-6 Shading system benefit

Table 4-3 shows four examples of scenarios on a south facade, where the first highlighted scenario is the case without a shading system. This case is considered the base case. The second scenario uses horizontal blinds on the exterior face with a 0.03m width and 0.025m space between the slats. The third choice uses one outer horizontal slat with a 0.6m width. Finally, the last scenario uses an interior roller shade.

Table 4-3 Example scenarios of Shading system benefit- Inputs features

id	WWR (%)	RR	Distance btw windows (m)	Sill Height (m)	Orientation	Uw_Value (W/m²K)	SHGC	in:N. of slats	in:Hor/Ver slats	in:Distance btw slats (m)	in:Int/Ext slats	in:Slats Angle	in:Slat width (m)
	Shading system benefit: Inputs												
1	0.9	1	2	0.5	S	1.5	0.58	0	NA	NA	NA	0	NA
2	0.9	1	2	0.5	S	1.5	0.58	NA	Hor	0.025	Ext	0	0.03
3	0.9	1	2	0.5	S	1.5	0.58	1	Hor	NA	Ext	0	0.6
4	0.9	1	2	0.5	S	1.5	0.58	NA	roller shade	NA	Int	NA	NA

Following this, Table 4-4 and Table 4-5 show the output results. In addition, the percentage of the change for each case compared to the base case is calculated.

The second case, which consists of horizontal slats covering all the 90% glazing, translates into about 87% less ASE percentage. On the other hand, the sDA percentage is getting lower. It is about 39% less. However, sDA value for this case is about 42%, which is still above the minimum acceptable threshold (40%).

It also translates into about 67% fewer overheating hours, 74% less cooling energy, and 14% more lighting energy. The most significant change was more cold hours, for about 278%, thus 288% more heating demand compared to the base case.

Table 4-4 Example scenarios of Shading system benefit- Output features for daylight metrics and discomfort hours

id	ASE (area%)	Correlation to a base case	ASE change (%)	sDA (area%)	Correlation to a base case	sDA change (%)	Overheating h/y	Correlation to a base case	change (%)	Cold h/y	Correlation to a base case	change (%)
	Shading system benefit- Outputs											
1	0.560	1.000	0.00%	0.694	1.000	0.00%	68.013	1.000	0.00%	2.724	1.000	0.00%
2	0.070	0.125	87.50%	0.422	0.607	39.28%	22.276	0.328	67.25%	10.321	3.788	-278.82%
3	0.490	0.875	12.50%	0.620	0.893	10.72%	64.359	0.946	5.37%	3.429	1.259	-25.88%
4	0.000	0.000	100.00%	0.479	0.690	30.96%	69.583	1.023	-2.31%	2.147	1.718	-71.79%
		min	12.50%		min	10.72%		min	-2.31%		min	-278.82%
		max	100.00%		max	39.28%		max	67.25%		max	-25.88%

Table 4-5 Example scenarios of Shading system benefit- Output features for energy demand

id	Cooling EUI (KWh/m²/y)	Correlation to a base case	change (%)	Heating EUI (KWh/m²/y)	Correlation to a base case	change (%)	Lighting EUI (KWh/m²/y)	Correlation to a base case	change (%)
1	13.818	1.000	0.00%	0.587	1.000	0.00%	5.790	1.000	0.00%
2	3.495	0.253	74.71%	2.281	3.887	-288.74%	6.603	1.141	-14.05%
3	11.442	0.828	17.20%	0.748	1.274	-27.42%	5.852	1.011	-1.08%
4	14.054	1.017	-1.71%	0.438	0.747	25.27%	9.928	1.715	-71.48%
		min	-1.71%		min	-288.74%		min	-71.48%
		max	74.71%		max	25.27%		max	-1.08%

Moreover, by comparing two different types of external shading device, in Figure 4-7, for the same WWR and orientation (South), we found that there is a significant difference between using exterior horizontal fins blinds that cover all the window surface, with a 0.03m depth, in comparison to using one horizontal slat with a 0.6m depth. The first case is more efficient regarding cooling consumption, the maximum ASE, and an acceptable value for sDA. However, in this case, the sDA value is close to the threshold, and more energy is needed for heating compared to the second scenario. Finally, this scenario is an optimizing choice for the main objectives.

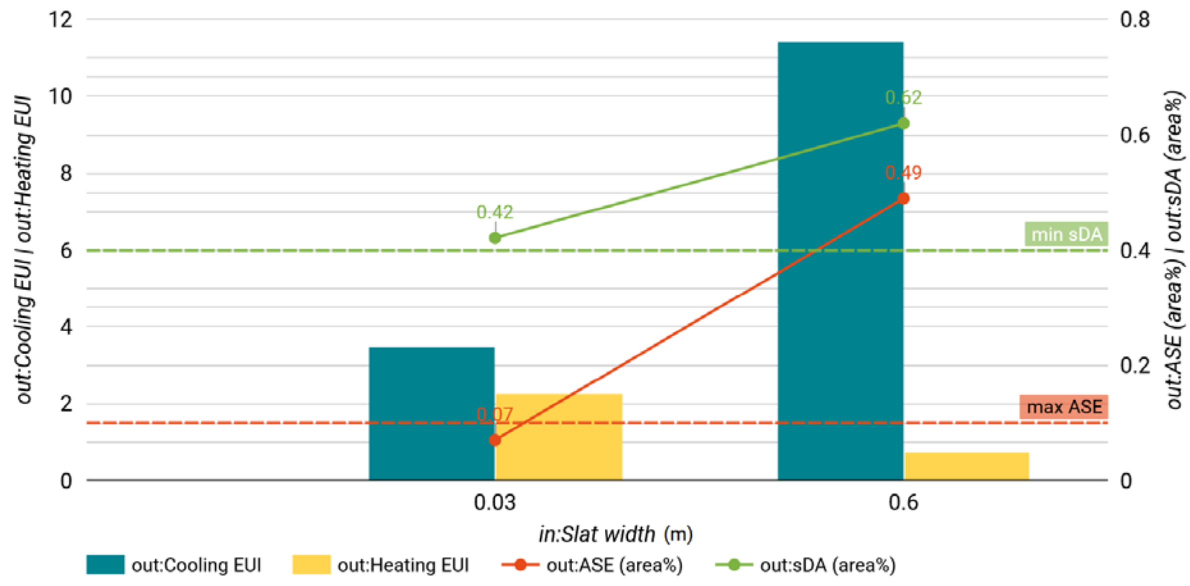


Figure 4-7 Exterior shading system benefit

For this section, two types of results improvement trials were proposed. However, some other fixed inputs could be changed, such as the slats material. Moreover, many other variables can be added and tested their efficiency.

4.3 Correlation parameters analysis

We can notice the correlation between parameters in the Design Explorer and optimize results by using the scatter chart that helps detect the linearity or non-linearity of parameters (Figure 4-8).

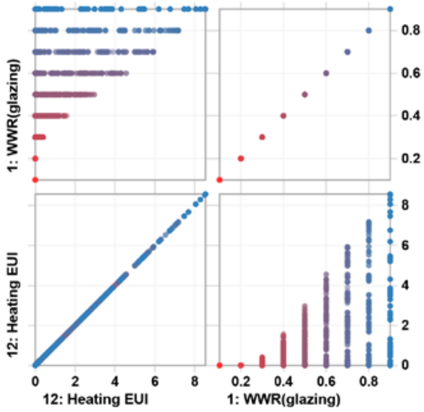


Figure 4-8 Using Scatter Plots- Design Explorer

However, for this section, results of the selective alternatives have been exported to an excel file and treated in google data studio. Tables and different graphs are used for some variables to notice their impact.

4.3.1 <u>Correlation between heating, cooling, and electric lighting demand according to WWR</u>

Figures 4-9 and 4-10 represent the energy consumption regarding the window-to-wall ratio. We found no heating consumption for a glazing percentage of 10% and 20% and few heating consumptions for a WWR of 30% and 40%. If we compare annual heating and cooling demand per m², we find that the need for cooling is more than the demand for heating. So that, even if the heating consumption is negligible or does not appear for WWR of 0.1, 0.2, and 0.3, the cooling consumption appears. And in reality, that is the case; the need for cooling is generally more important than heating for offices in a well-insulated building. It is due to the heat production generated by occupants and computer equipment.

In that case, as mentioned earlier, the simulation study did not consider any contribution from the mechanical or natural HVAC system to obtain a clear idea about what is needed, whether a heating or cooling system and the degree of discomfort.

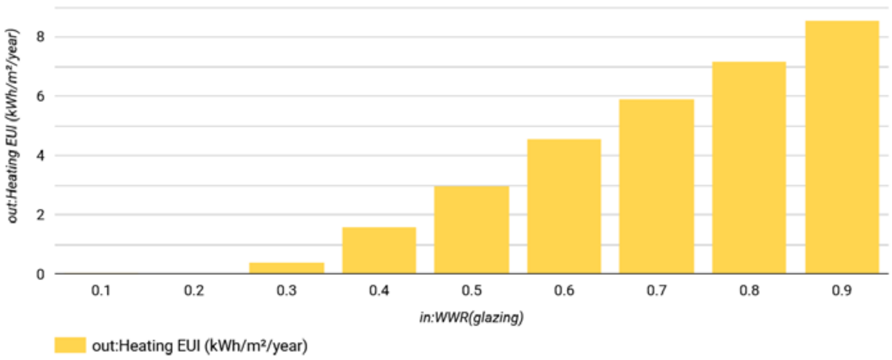


Figure 4-9 Heating demand regarding the window-to-wall ratio

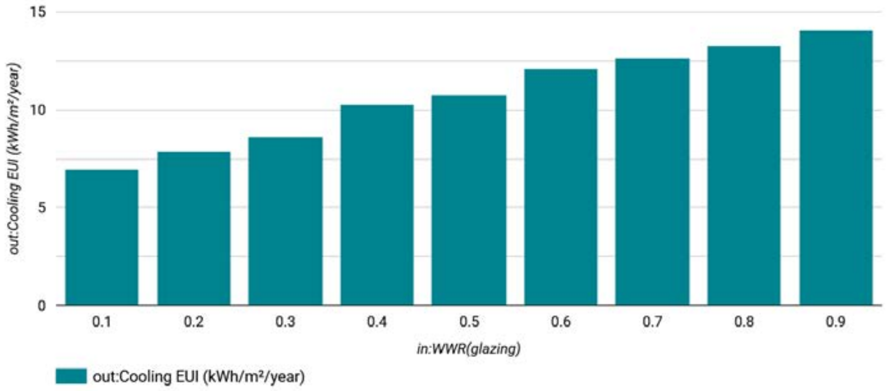


Figure 4-10 Cooling demand regarding the window-to-wall ratio

In addition, in Figure 4-11, we can find that electric lighting has a highly significant impact and is an important factor of energy consumption in office buildings. Moreover, enough daylight that meets the minimum requirement for occupants' comfort during work will reduce electrical lighting consumption.

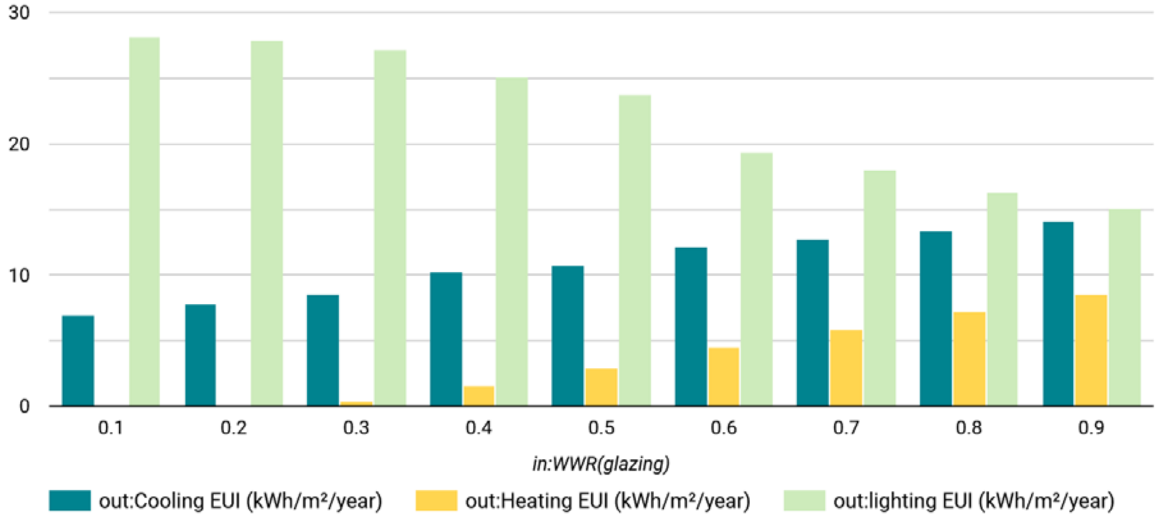


Figure 4-11 Heating and cooling comparison regarding the window-to-wall ratio

Even though it is known that the energy demand will be higher for a higher glazed surface, we are interested in this study to determine the degree of influence if we raise the window-to-wall ratio by 10%. Therefore, the next chapter will discuss the sensitivity analysis for energy demand regarding WWR.

4.3.2 Overheating hours per year regarding WWR and orientation

Figure 4-12 shows annual discomfort hours for overheating in correlation to the orientation and the window-to-wall ratio. It is shown that for all WWR and all directions, the risk of overheating exists. Also, the lowest percentage, the more overheating hours. The southern facade is the most critical orientation where the risk of overheating is very high for all the WWR. Moreover, the points are very close to each other; thus, we can find that changing the window-to-wall ratio for this orientation will not significantly affect yearly overheating hours.

The less affected façades orientation for this objective is the North, North-East and North-West. Furthermore, changing room orientation between these three positions for the same window-to-wall ratio will not highly impact the results, especially for the lowest WWR: the 0.1, represented by the yellow line, 0.2, 0.3 and the 0.4 ratios.

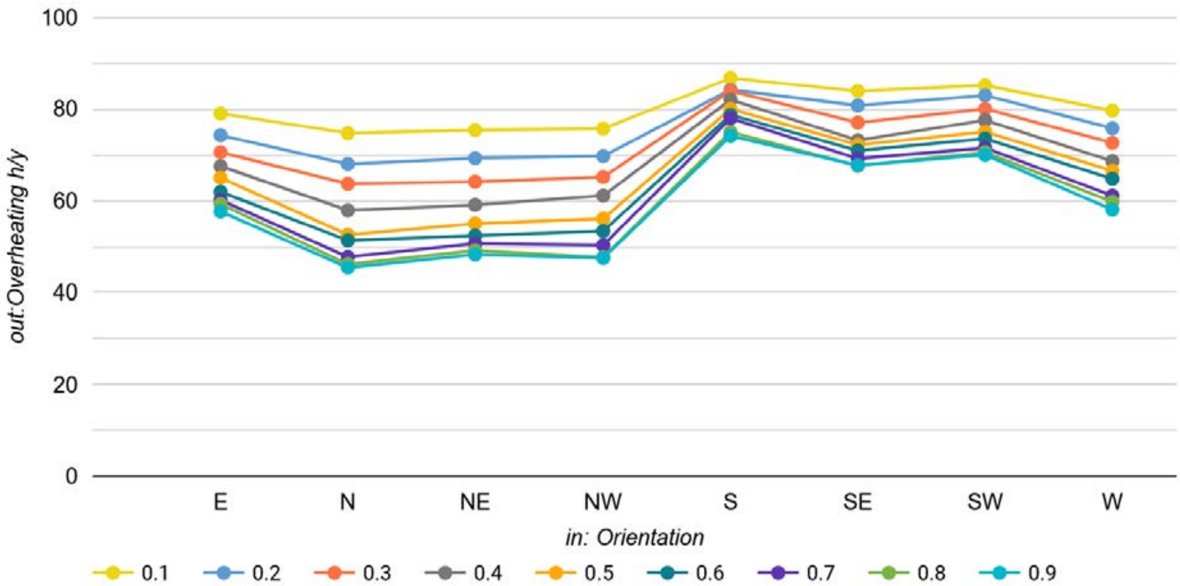


Figure 4-12 Comparing yearly overheating hours regarding WWR and orientation

4.3.3 Cooling consumption per year regarding WWR

Comparing cooling consumption regarding WWR, Figure 4-13 shows that the South façade orientation needs the highest cooling energy. On the other hand, the North-East direction needs the lowest cooling energy.

All the window-to-wall ratio needs a cooling system to arrive at the comfort temperature. When the WWR is low, we also notice less impact generated by the orientation on the cooling demand. If we compare the glazing percentage impact on North-East, North-West, we see that increasing WWR within these façade has a minor effect on cooling demand, as the points are very close to each other. In the same way about the north and east façade, where it varies between 5 to 7.5 kWh/m²/year.

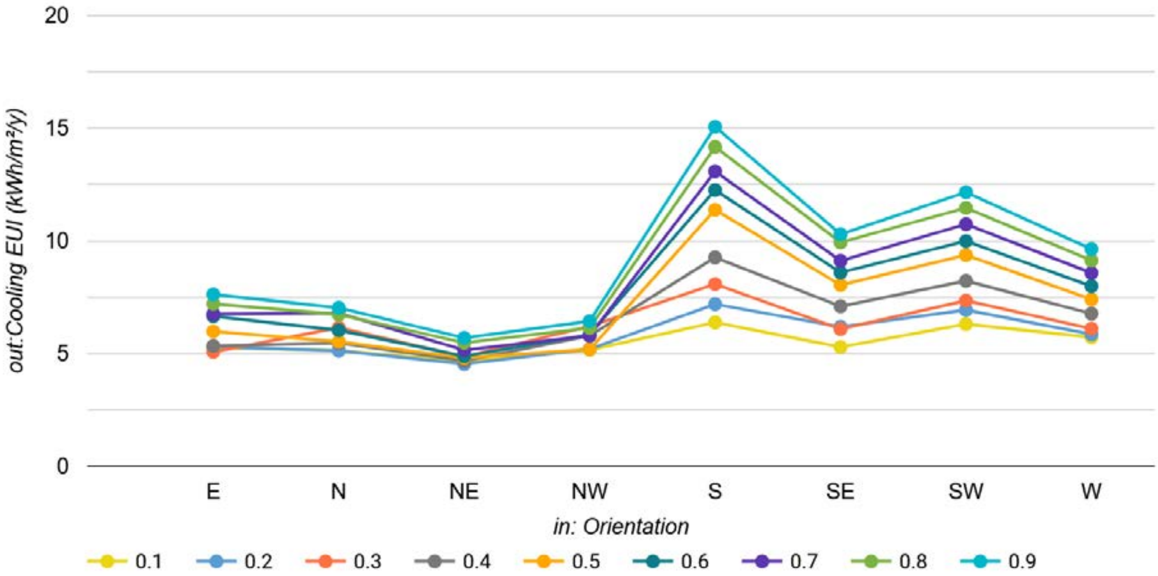


Figure 4-13 Comparing cooling consumption regarding WWR and orientation

4.3.4 Heating consumption per year regarding orientation and WWR

The heating demand is related to the cold hours of discomfort. So, a comparison of heating consumption according to the direction and WWR is shown in Figure 4-14. The North orientation needs the highest heat energy. In contrast, the south orientation and South-West need the lowest heat energy. Also, we can find that there is no heating demand for WWR of 10%, till 0.4 and minor heating demand for WWR of 0.4 to 0.6.

In addition, if we look at the same WWR, we notice that the most critical glazed faced percentage is 0.9, where the orientation highly impacts the heating demand results. Whereas, for the lowest WWR, there is not as much difference. Furthermore, the correlation between WWR and orientation is translated in the fact that the lower the percentage, the less difference we can face for heating demand according to facade orientation.

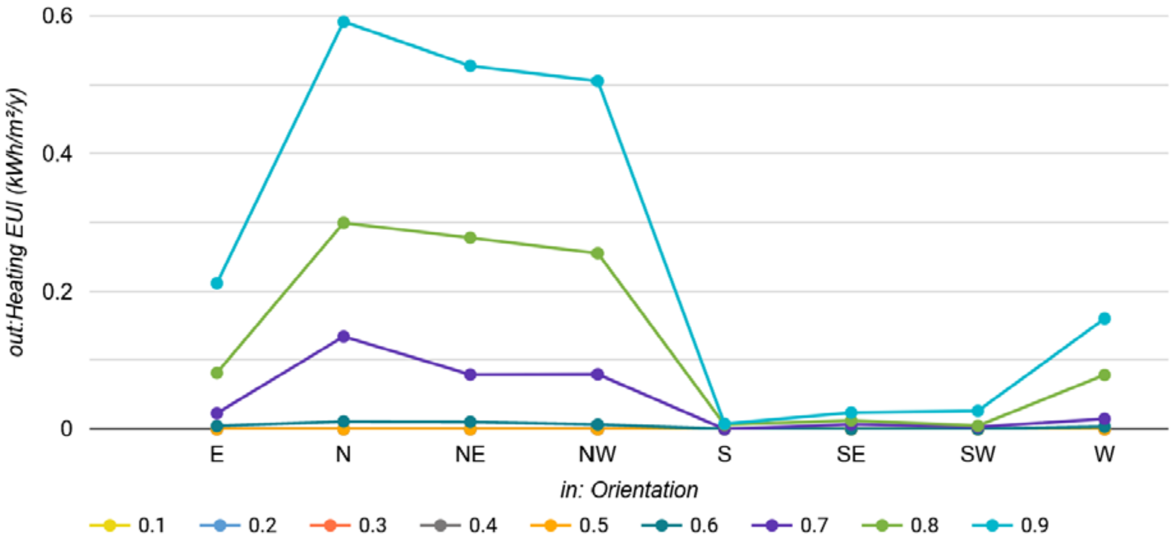


Figure 4-14 Comparing heating consumption regarding WWR and orientation

4.3.5 Daylight metric performance and energy consumption

When the visible daylight passes through windows into the room, it will be translated into thermal energy gain. If the benefit from the natural sunlight is sufficient, this energy gain will reduce the demand for heating. In contrast, if it is too high, that will affect thermal comfort and increase the need for a cooling system. However, this correlates with the glazing percentage, as the glazed parts mean less insulation and more thermal change with the outdoor temperature.

Figure 4-15 shows the correlation between daylight factors and energy demand concerning the WWR. These values are for a room ratio equal to 1. It represents the maximum values for energy consumption: heating, cooling and electrical lighting represented on the left y-axis on kWh/m²/year, concerning sDA and ASE, represented on the right y-axis, regarding WWR.

When the WWR is higher, all the parameters will be higher, except electrical lighting demand due to the glazing surface. Thus, finding the most influential parameters would be needed to find an equilibrium between daylight and energy.

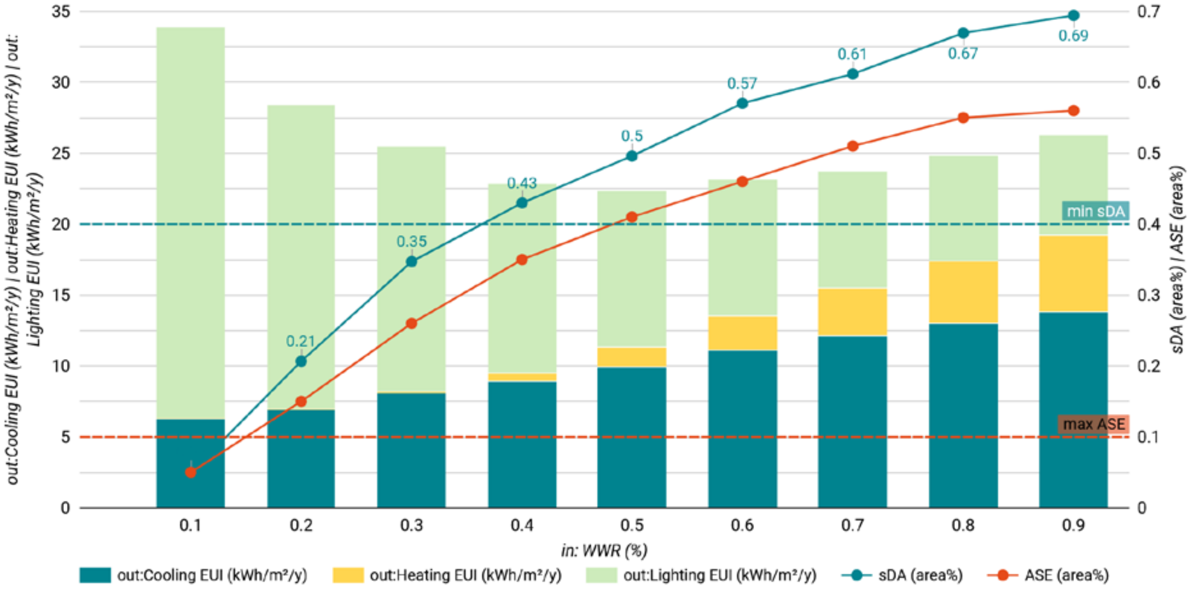


Figure 4-15 Daylight metrics and energy regarding the WWR

4.3.6 Daylight metric performance and orientation

Figure 4-16 below shows a comparison between the influence of building exposure on daylight metrics. It represents the maximum values on each orientation. We can find that the North direction has the most significant difference between ASE and sDA. It respects the most the criteria about ASE, where there is no risk of discomfort exposed by direct sunlight and the minimum of sDA. Since the maximum value of sDA is represented in this figure, it is critical because it is close to the acceptable threshold for the north direction. In addition, it depends on the window-to-wall ratio. In contrast, both daylight metric values are close in the South-West and West façade direction with very high values of ASE.

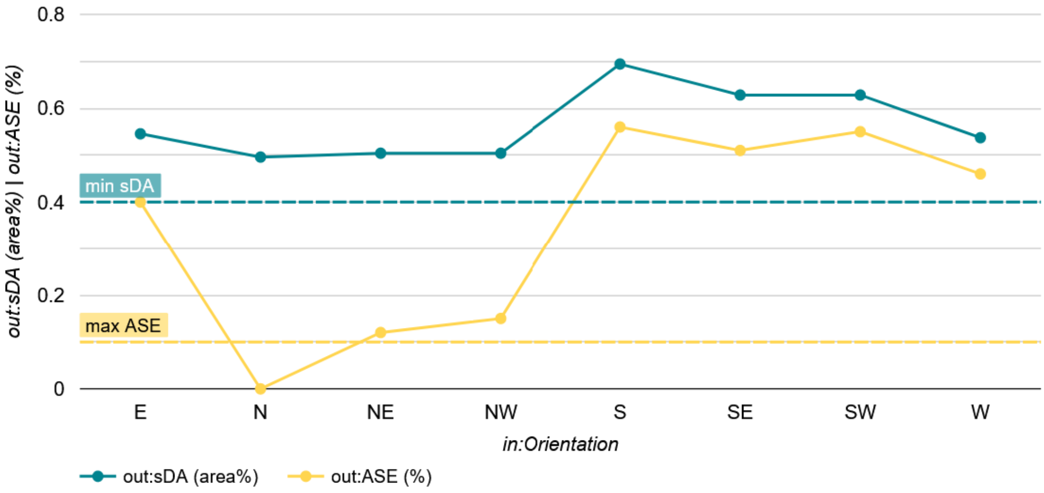


Figure 4-16 Daylight metrics regarding orientation

4.4 Sensitivity analysis

Depending on the results presented in the section above, a sensitivity analysis will be carried out to answer the second question of the research:

- *To which extent do the facade criteria influence the energy performance, visual and thermal comfort?*

So, this part will study the degree of influence of each parameter on the main objectives of this study: Daylighting, thermal comfort, and energy consumption. Moreover, it will discuss the most sensitive parameters that influence the overall results.

The variable inputs that have been chosen to study their influence are: the Window-to-wall ratio, the orientation, SHGC, U-window value, the sill height and different window breaking up as they are the main inputs for this study.

To evaluate the influence of the chosen input parameters, each studied input will be considered variable, and all other information will be considered fixed.

Thus, understanding the degree of change for each one of the outputs: ASE, sDA, overheating hours, cold hours, heating and cooling demand. Finally, based on visualisation results, sensitivity analysis on some outputs could be skipped if there is no change.

4.4.1 Window-to-wall ratio

To understand the degree of influence by changing the WWR, we add the WWR as a variable input and fix all the other information: the room dimension is 7m (exterior wall), 11m (depth) and 3.2m height on a south façade, U-window of 1.5 W/m^2k, and SHGC of 0.58 as these values are the most used in reality. The degree of change will be studied on the following outputs: daylight metrics, energy demand. Finally, the cases are compared to the mean results between the nine scenarios (highlighted in green).

- Window-to-wall ratio on daylight metrics

Table 4-6 shows the percentage of change by increasing 10% of the glazed surface. The ASE and sDA percentage is almost the same for WWR from 0.6 to 0.9. It is about 38.5% more for ASE and 20.6 % more benefit for sDA.

In general, the change range for ASE is higher than the change range for sDA, with a difference of about 14%.

Table 4-6 Sensitivity analysis- Window-to-wall ratio on daylight metrics

WWR (%)	RR	Distance btw windows	Sill Height (m)	Orientation	Uw_Value (W/m²K)	SHGC	ASE (area%)	Correlation to a base case	ASE change (%)	sDA (area%)	Correlation to a base case	sDA change (%)
Sensitivity analysis- Window-to-wall ratio on Daylight metrics												
0.1	1.6	2	1.5	S	1.5	0.58	0.000	0.000	100.00%	0.000	0.000	100.00%
0.2	1.6	2	1.5	S	1.5	0.58	0.090	0.346	65.38%	0.182	0.493	50.69%
0.3	1.6	2	1.5	S	1.5	0.58	0.200	0.769	23.08%	0.298	0.808	19.18%
0.4	1.6	2	1.5	S	1.5	0.58	0.260	1.000	0.00%	0.369	1.000	0.00%
0.5	1.6	2	1.5	S	1.5	0.58	0.300	1.154	-15.38%	0.424	1.151	-15.05%
0.6	1.6	2	1.5	S	1.5	0.58	0.360	1.385	-38.46%	0.444	1.205	-20.53%
0.7	1.6	2	1.5	S	1.5	0.58	0.360	1.385	-38.46%	0.444	1.205	-20.53%
0.8	1.6	2	1.5	S	1.5	0.58	0.360	1.385	-38.46%	0.444	1.205	-20.53%
0.9	1.6	2	1.5	S	1.5	0.58	0.360	1.385	-38.46%	0.460	1.247	-24.65%
								min	-38.46%		min	-24.65%
								max	100.00%		max	100.00%
								change range	138.46%		change range	124.65%

- Window-to-wall ratio on energy demand

The percentage of change and the augmentation for cooling demand is about 58.37%, from 0.1 to 0.9 (Table 4-7). Furthermore, as the studied facade is on the south, there is no heating demand for the WWR from 10% to 70%. In contrast, we notice a significant change when the WWR is 0.8 and 0.9 compared to an average scenario.

The change of lighting consumption, for example, by changing WWR from 0.4 to 0.5 it will be about 17% less lighting energy.

In general, the total change range of electrical lighting consumption is about 83%.

Table 4-7 Sensitivity analysis- Window-to-wall ratio on energy demand

WWR (%)	Cooling EUI (kWh/m²/y)	Correlation to a base case	Cooling change (%)	Heating EUI (kWh/m²/y)	Correlation to a base case	Heating change (%)	Lighting EUI (kWh/m²/y	Correlation to a base case	Lighting change (%)
Sensitivity analysis- Window-to-wall ratio on energy demand									
0.1	5.892	0.643	35.65%	0.000	0.000	100.00%	27.9	1.5	-54%
0.2	6.226	0.680	32.00%	0.000	0.000	100.00%	26.6	1.5	-47%
0.3	6.396	0.699	30.14%	0.000	0.000	100.00%	22.1	1.2	-22%
0.4	6.555	0.716	28.41%	0.000	0.000	100.00%	18.2	1.0	0%
0.5	9.287	1.014	-1.42%	0.000	0.000	100.00%	15.1	0.8	17%
0.6	9.913	1.083	-8.26%	0.000	0.000	100.00%	14.2	0.8	22%
0.7	9.156	1.000	0.00%	0.000	0.000	100.00%	13.5	0.7	26%
0.8	11.236	1.227	-22.71%	0.002	1.000	0.00%	12.8	0.7	30%
0.9	11.997	1.310	-31.03%	0.008	3.452	-245.23%	12.9	0.7	29%
		min	-22.71%		min	-245.23%		min	-54%
		max	35.65%		max	100.00%		max	30%
		change range	58.37%		change range	345.23%		change range	83%

- Window-to-wall ratio on thermal comfort

Concerning the impact of changing WWR on annual overheating hours, Table 4-8 shows a range change of about 14,6%. Also, a few discomfort cold hours start from WWR of 0.7. For example, increasing the WWR from 0.7 to 0.8, there are about 200% fewer cold hours.

Table 4-8 Sensitivity analysis- Window-to-wall ratio on thermal comfort

WWR (%)	RR	Distance btw windows	Sill Height (m)	Orientation	Uw_Value (W/m²K)	SHGC	Overheating h/y	Correlation to a base case	change (%)	Cold h/y	Correlation to a base case	change (%)
Sensitivity analysis- WWR on thermal comfort												
0.1	1.6	2	1.5	S	1.5	0.58	85.673	1.090	-9.01%	0	0.000	100.00%
0.2	1.6	2	1.5	S	1.5	0.58	84.038	1.069	-6.93%	0	0.000	100.00%
0.3	1.6	2	1.5	S	1.5	0.58	82.179	1.046	-4.57%	0	0.000	100.00%
0.4	1.6	2	1.5	S	1.5	0.58	79.744	1.015	-1.47%	0	0.000	100.00%
0.5	1.6	2	1.5	S	1.5	0.58	78.590	1.000	0.00%	0	0.000	100.00%
0.6	1.6	2	1.5	S	1.5	0.58	76.186	0.969	3.06%	0	0.000	100.00%
0.7	1.6	2	1.5	S	1.5	0.58	75.673	0.963	3.71%	0.032051	1.000	0.00%
0.8	1.6	2	1.5	S	1.5	0.58	74.423	0.947	5.30%	0.096154	3.000	-200.00%
0.9	1.6	2	1.5	S	1.5	0.58	74.167	0.944	5.63%	0.224359	7.000	-600.01%
								min	-9.01%		min	-600.01%
								max	5.63%		max	100.00%
								change range	14.64%		change range	700.01%

4.4.2 Orientation

To study the impact of being in a specific orientation, we fixed all the input parameters and changed room rotation. As shown in Table 4-9, the chosen WWR is 0.8, as it is the most critical, the U-window value is 1.5 W/m²K, and SHGC is 0.58 for a room dimension of 7m*7m*3.2m, as these values are the most used in real buildings.

- Orientation on daylight metrics

Thus, if we study the effect of changing the orientation on daylight metrics, we found, in Table 4-9, about a 22,2% difference in ASE if we shift a façade orientation 45°: from the east to the south-east. Also, about 66,67% less ASE for a north-east façade compared to the east direction.

In general, the orientation has a change range of about 29.27% on the sDA, whereas about 137% on the ASE.

Table 4-9 Sensitivity analysis- Orientation on daylight metrics

WWR (%)	RR	Distance btw windows (m)	Sill Height (m)	Orientation	Uw_Value (W/m²K)	SHGC	ASE (area%)	Correlation to a base case	ASE change (%)	sDA (area%)	Correlation to a base case	sDA change (%)
Sensitivity analysis- Orientation on Daylight metrics												
0.8	1.6	2	1.5	SW	1.5	0.58	0.370	1.370	-37.04%	0.434	1.144	-14.41%
0.8	1.6	2	1.5	W	1.5	0.58	0.320	1.185	-18.52%	0.380	1.000	0.00%
0.8	1.6	2	1.5	NW	1.5	0.58	0.090	0.333	66.67%	0.349	0.918	8.19%
0.8	1.6	2	1.5	E	1.5	0.58	0.270	1.000	0.00%	0.384	1.012	-1.24%
0.8	1.6	2	1.5	SE	1.5	0.58	0.330	1.222	-22.22%	0.434	1.144	-14.41%
0.8	1.6	2	1.5	N	1.5	0.58	0.000	0.000	100.00%	0.333	0.878	12.20%
0.8	1.6	2	1.5	NE	1.5	0.58	0.090	0.333	66.67%	0.354	0.931	6.88%
0.8	1.6	2	1.5	S	1.5	0.58	0.360	1.333	-33.33%	0.444	1.171	-17.07%
								min	-37.04%		min	-17.07%
								max	100.00%		max	12.20%
								change range	137.04%		change range	29.27%

- Orientation on energy demand

The impact of the facade direction on energy demand is shown in Table 4-10. The total change range on the annual cooling consumption is about 49%, and the yearly heating consumption is nearly 236% difference. Furthermore, the difference in cooling consumption for a room facing the northwest will be about 26% less cooling demand than a room on the west orientation.

Table 4-10 Sensitivity analysis- Orientation on energy demand

WWR (%)	RR	Distance btw windows (m)	Sill Height (m)	Orientation	Uw_Value (W/m²K)	SHGC	Cooling EUI (KWh/m²/y)	Correlation to a base case	change (%)	Heating EUI (KWh/m²/y)	Correlation to a base case	change (%)
Sensitivity analysis- Orientation on energy demand												
0.8	1.6	2	1.5	SW	1.5	0.58	9.022	1.170	-16.96%	0.005	0.060	93.96%
0.8	1.6	2	1.5	W	1.5	0.58	7.714	1.000	0.00%	0.079	0.964	3.57%
0.8	1.6	2	1.5	NW	1.5	0.58	5.694	0.738	26.18%	0.255	3.132	-213.16%
0.8	1.6	2	1.5	E	1.5	0.58	6.309	0.818	18.22%	0.082	1.000	0.00%
0.8	1.6	2	1.5	SE	1.5	0.58	8.143	1.056	-5.55%	0.013	0.154	84.56%
0.8	1.6	2	1.5	N	1.5	0.58	5.690	0.738	26.24%	0.300	3.673	-267.29%
0.8	1.6	2	1.5	NE	1.5	0.58	5.016	0.650	34.98%	0.278	3.407	-240.73%
0.8	1.6	2	1.5	S	1.5	0.58	11.236	1.456	-45.65%	0.002	0.028	97.22%
								min	-45.65%		min	-267.29%
								max	34.98%		max	97.22%
								change range	80.63%		change range	364.51%

- Orientation on thermal comfort

In the same way, comparing the influence of the orientation on the annual hours of discomfort is about 49% total range change on overheating hours and about 235% total range change on the yearly cold hours (Table 4-11).

Also, the difference between the east and west façade is minor regarding annual overheating hours. It is almost 1.42%, and the maximum change is between the west and the south with 27%.

The cold hours for a facade on the northwest has more annual cold hours than the east facade of about a 118% difference.

Table 4-11 Sensitivity analysis- Orientation on thermal comfort

WWR (%)	RR	Distance btw windows (m)	Sill Height (m)	Orientation	Uw_Value (W/m²K)	SHGC	Overheating h/y	Correlation to a base case	change (%)	Cold h/y	Correlation to a base case	change (%)
Sensitivity analysis- Orientation on thermal comfort												
0.8	1.6	2	1.5	SW	1.5	0.58	70.577	1.204	-20.39%	0.064	0.051	94.87%
0.8	1.6	2	1.5	W	1.5	0.58	58.622	1.000	0.00%	0.865	0.692	30.77%
0.8	1.6	2	1.5	NW	1.5	0.58	47.660	0.813	18.70%	2.724	2.179	-117.95%
0.8	1.6	2	1.5	E	1.5	0.58	57.788	0.986	1.42%	1.250	1.000	0.00%
0.8	1.6	2	1.5	SE	1.5	0.58	67.436	1.150	-15.04%	0.256	0.205	79.49%
0.8	1.6	2	1.5	N	1.5	0.58	45.641	0.779	22.14%	2.821	2.256	-125.64%
0.8	1.6	2	1.5	NE	1.5	0.58	48.077	0.820	17.99%	3.013	2.410	-141.03%
0.8	1.6	2	1.5	S	1.5	0.58	74.423	1.270	-26.95%	0.096	0.077	92.31%
								min	-26.95%		min	-141.03%
								max	22.14%		max	94.87%
								change range	49.10%		change range	235.90%

4.4.3 SHGC

As mentioned in the methodology section, we chose two types of glazing: Stopsol SuperSilver Dark Blue and Stopsol SuperSilver Clear. These glazings have different thermal properties: SHGC values of 0.58 and 0.3, VT values of 0.5 and 0.3, respectively. However, all input parameters should be fixed for specific choices, and the Solar Heating Gain Coefficient value (SHGC) should be changed to compare and study its impact.

Figure 4-17 below represents the correlation between SHGC and the orientation on each aspect. The first two figures show no difference in sDA and ASE when the value of solar heating gains change between 0.3 and 0.58. It remains the same. The second line of graphs that illustrate the heating and cooling demand show that we need more cooling with an SHGC value of 0.58 and more heating when using a lower value of SHGC. Moreover, the orientation has a high impact on heating demand where the coloured bars are varying. Finally, the annual overheating hours are high, but the direction and changing SHGC value have less impact as they are almost at the same level.

This visual inspection will help detect the impact on a specific parameter and do the sensitivity analysis study on the affected variables.

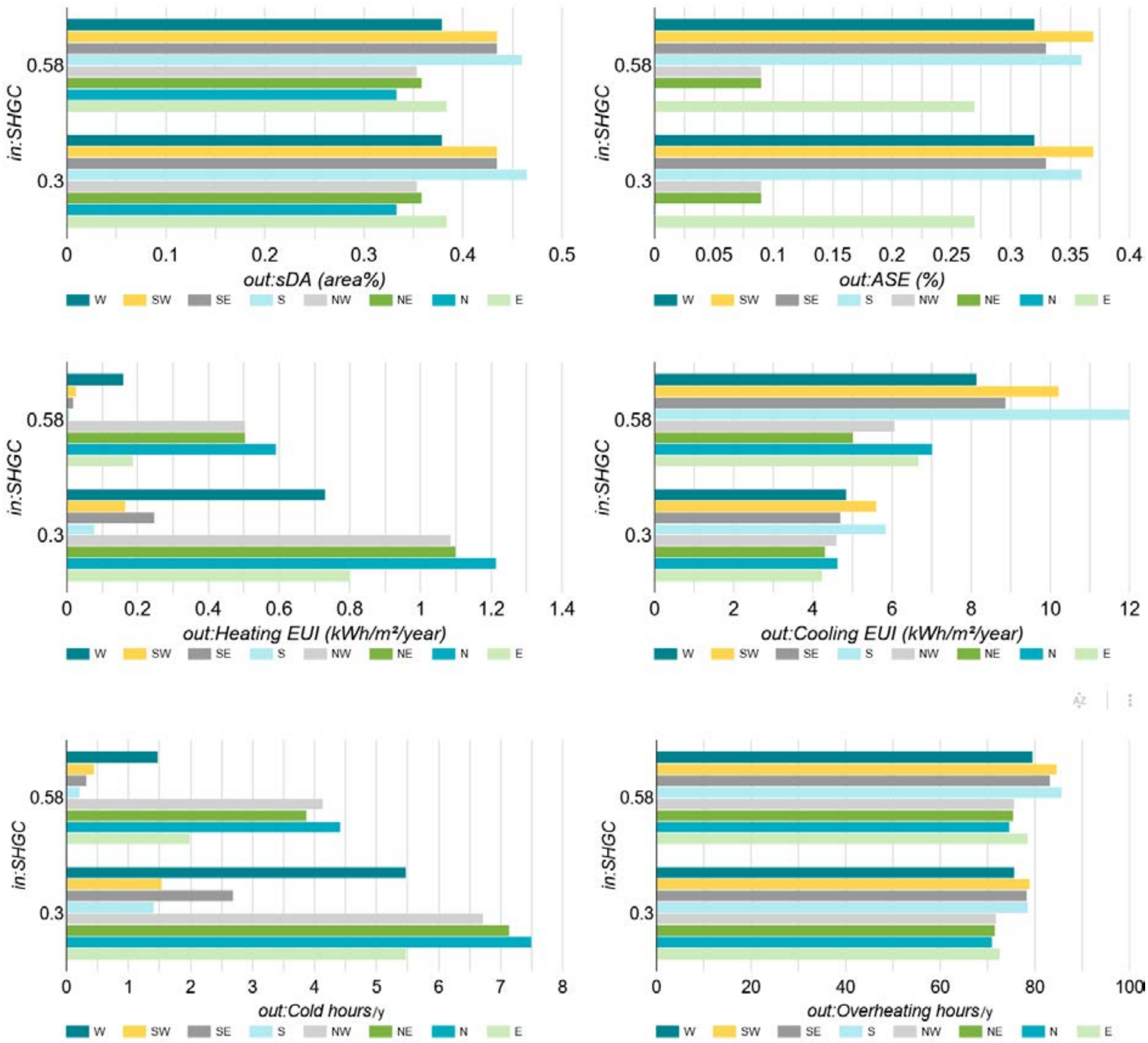


Figure 4-17 SHGC impact regarding the orientation

In the same way, Figure 4-18 detects the influence of SHGC on WWR. It presents the correlation between sDA and ASE regarding WWR. Two values of SHGC for a rectangular room on the south orientation, with a Uw-value of 1.5W/m²K, windows sill height of 1.5m (it changes regarding WWR) is drawn for each WWR represented in a different coloured line. There is no difference, and it is unnecessary to study it because it is assumed that SHGC is not sensitive to daylight metrics: ASE and sDA.

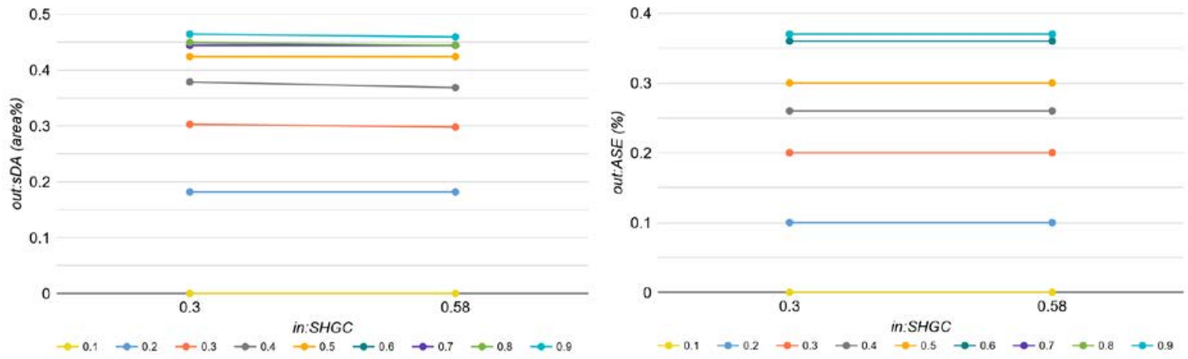


Figure 4-18 The sensitivity analysis results of SHGC on sDA and ASE regarding WWR

Similarly, Figures 4-19 and 4-20 show that we can notice the impact of SHGC regarding heating demand and discomfort cold hours starting from WWR of 0.6 with a minimal difference, where the more significant change will be for 0.8 and 0.9.

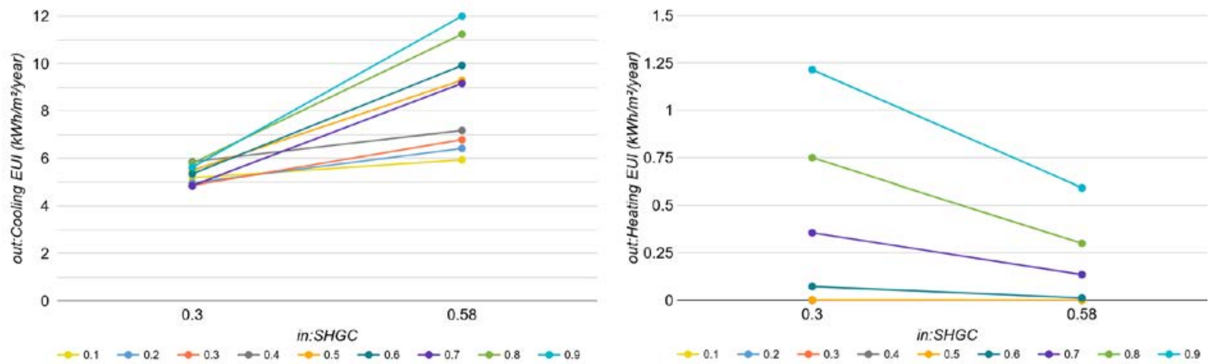


Figure 4-19 The sensitivity analysis results of the SHGC on the heating and cooling consumption regarding the window-to-wall ratio

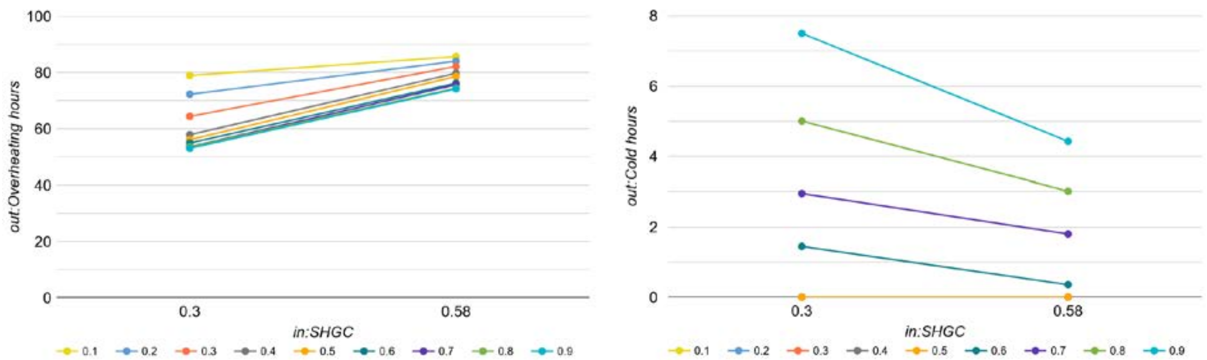


Figure 4-20 The sensitivity analysis results of the SHGC on the cold hours and overheating hours regarding the window-to-wall ratio

Thus, by adding more variables about SHGC to test the degree of its influence, seven variables were tested (Table 4-12) based on obtained results. The other inputs are fixed: a south facade with a WWR of 50%, a U-window value of 1.5 W/m²K, for a room dimension of 7m*7m*3.2m.

- SHGC on thermal comfort and energy

As the SHGC does not affect daylight metrics, the sensitivity analysis will be studied on thermal comfort and energy.

The SHGC varies between 0.18 and 0.58 for seven levels. The change difference is about 41.65% more overheating hours if we use a window whose SHGC value equals 0.58. Also, more cooling consumption of approximately 63.22% compared to an SHGC of 0.3.

Table 4-12 shows the sensitivity analysis results comparing the effect of seven variable values for SHGC.

Table 4-12 Sensitivity analysis- SHGC on Overheating hours and cooling consumption

WWR (%)	RR	Distance btw windows (m)	Sill Height (m)	Orientation	Uw_Value (W/m²K)	SHGC	Overheating h/y	Correlation to a base case	change (%)	Cooling EUI (KWh/m²/y)	Correlation to a base case	change (%)
Sensitivity analysis- SHGC												
0.5	1.6	2	1.5	S	1.5	0.51	73.686	1.328	-32.81%	8.284	1.456	-45.60%
0.5	1.6	2	1.5	S	1.5	0.46	68.942	1.243	-24.26%	7.601	1.336	-33.59%
0.5	1.6	2	1.5	S	1.5	0.41	65.128	1.174	-17.39%	6.982	1.227	-22.73%
0.5	1.6	2	1.5	S	1.5	0.3	55.481	1.000	0.00%	5.689	1.000	0.00%
0.5	1.6	2	1.5	S	1.5	0.21	45.064	0.812	18.78%	4.687	0.824	17.62%
0.5	1.6	2	1.5	S	1.5	0.18	39.391	0.710	29.00%	4.333	0.762	23.84%
0.5	1.6	2	1.5	S	1.5	0.58	78.590	1.417	-41.65%	9.287	1.632	-63.22%
								min	-41.65%		min	-63.22%
								max	29.00%		max	23.84%

4.4.4 U-window value

Two U-window values regarding EPBD were tested: 1.5W/m²K for double glazing window and 0.6 for triple glazing. Changing Uw-value has no impact on daylight metrics, thus on electric lighting, as represented in Figure 4-21.

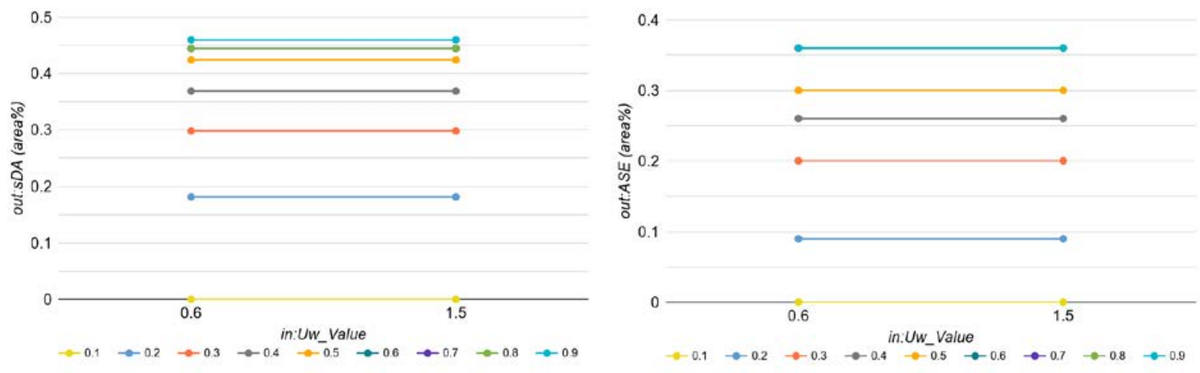


Figure 4-21 The sensitivity analysis results of Uw-value on sDA and ASE regarding the window-to-wall ratio

Figure 4-22 represents the correlation between discomfort hours and Uw-value concerning WWR. We can find that there are no cold hours when using triple glazing on the south facade for any portion of a glazed surface. In the same way, when using double glazing with WWR of 0.1 until 0.6, there is no risk of having cold hours. On the other hand, we can notice the difference from WWR of 0.7.

Alternatively, discomfort caused by overheating hours exists when using windows with a Uw-value of 0.6W/m²K but also for a Uw-value of 1.5W/m²K. However, the overheating hours are less for 1.5W/m²K. We can also notice, for example, that WWR of 0.1 represents the lowest overheating hours compared to the higher surface of glazing when the Uw-value is 0.6W/m²K. In contrast, the same portion represents the highest overheating hours compared to higher glazing surfaces when the Uw-value is 1.5W/m²K.

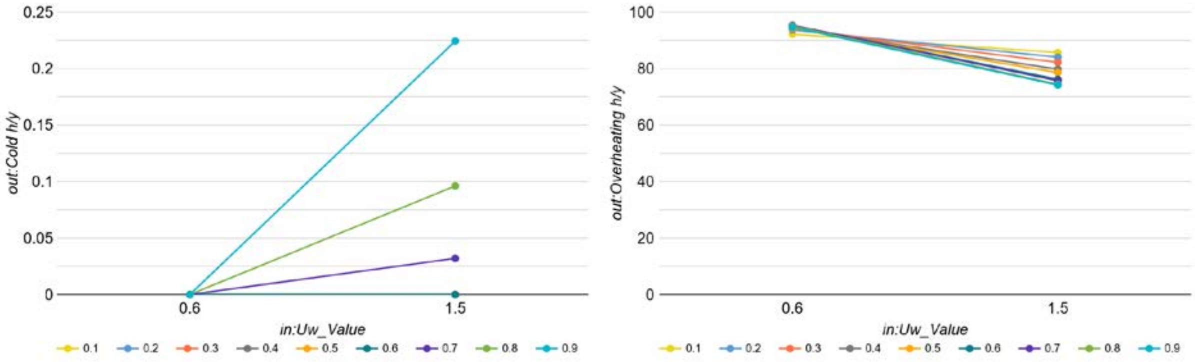


Figure 4-22 The sensitivity analysis results of Uw-value on cold hours and overheating hours regarding the window-to-wall ratio

Figure 4-23 shows the correlation between energy consumption and Uw-value regarding WWR. As shown, the U-window value has an important impact on the heating demand when the WWR is between 0.8 and 0.9. Moreover, there is no change in heating demand when the WWR is less than 0.7. A small impact is noticed on the cooling demand for a window-to-wall ratio less than 0.4.

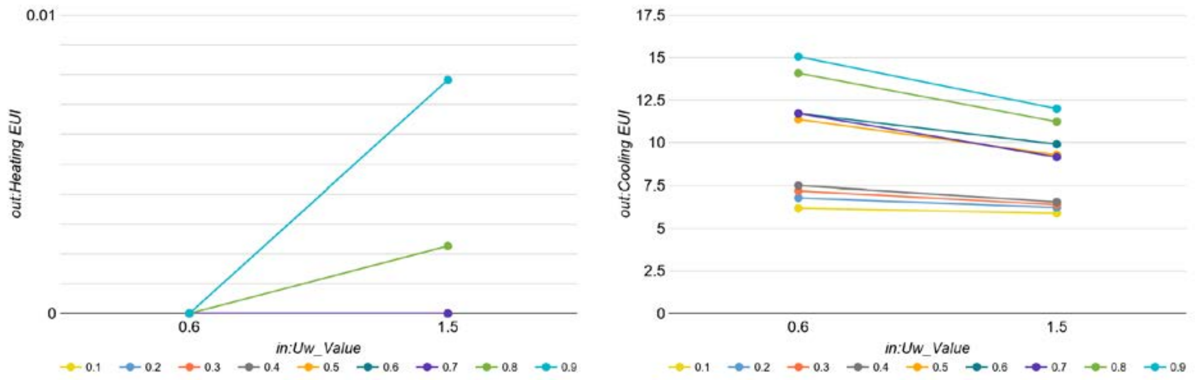


Figure 4-23 The sensitivity analysis results of Uw-value on Heating and Cooling consumption regarding the window-to-wall ratio

As there is no influence on sDA and ASE, the sensitivity analysis will be calculated for energy consumption and thermal comfort.

As represented in Table 4-13, the degree of influence when changing Uw-value on cold hours and overheating hours. Seven different values are used for Uw-value as a variable input, and the other parameters are fixed. The analysis is for a rectangular room on the south facade with a 0.58 value for the SHGC.

We found that U-value has an impact on overheating hours for about 20% more annual heating hours when using a U-value of 0.6, which could be considered for triple glazing, compared to a U-value of 1.5, which could be regarded as for double glazing. In the same way, it has about 22,48% more impact on annual cooling demand.

Table 4-13 Sensitivity analysis results – Uw-value on annual overheating hours and cooling demand

WWR (%)	RR	Distance btw windows (m)	Sill Height (m)	Orientation	Uw_Value (W/m²K)	SHGC	Overheating h/y	Correlation to a base case	change (%)	Cooling EUI (KWh/m²/y)	Correlation to a base case	change (%)
Sensitivity analysis- Uwindow value on thermal comfort												
0.5	1.6	2	1.5	S	0.6	0.58	94.327	1.200	-20.02%	11.373	1.225	-22.47%
0.5	1.6	2	1.5	S	0.9	0.58	89.071	1.133	-13.34%	10.614	1.143	-14.30%
0.5	1.6	2	1.5	S	1.2	0.58	83.846	1.067	-6.69%	9.911	1.067	-6.73%
0.5	1.6	2	1.5	S	1.5	0.58	78.590	1.000	0.00%	9.287	1.000	0.00%
0.5	1.6	2	1.5	S	1.7	0.58	73.878	0.940	6.00%	8.917	0.960	3.98%
0.5	1.6	2	1.5	S	2.8	0.58	57.532	0.732	26.79%	7.302	0.786	21.37%
0.5	1.6	2	1.5	S	5.7	0.58	42.756	0.544	45.60%	6.536	0.704	29.61%
								min	-20.02%		min	-22.47%
								max	45.60%		max	29.61%

4.4.5 Window sill height

Figure 4-24 represents the minimum values of sDA for each orientation concerning window sill height. We can find that the minimum results for sDA changed the most within the three sill heights proposed: 0.5m, 1m and 1.5m is on the south-façade.

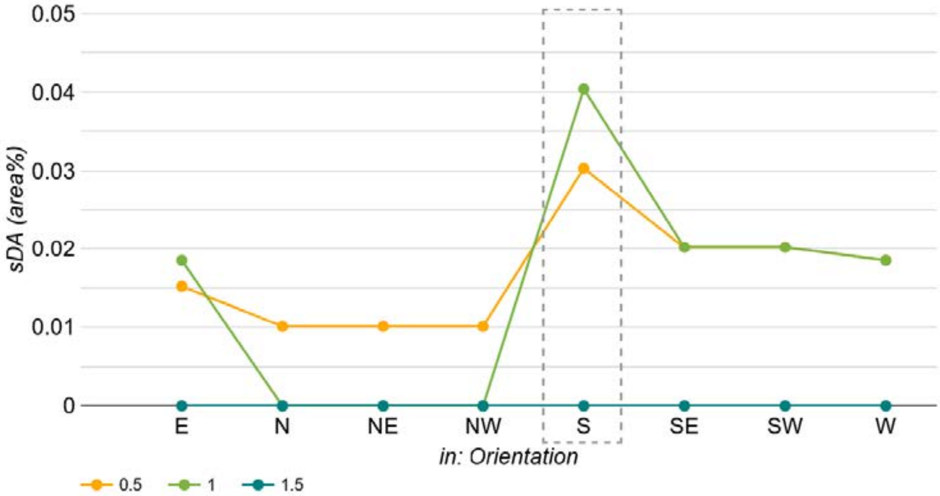


Figure 4-24 Correlation between the sill height and orientation on sDA minimum values

In addition, since the windows lintel level is fixed at 0.3m thus, changing the sill height within the same window-to-wall ratio will lead to a change in window dimension.

Figure 4-25 below shows three scenarios of different window dimensions to compare spatial daylight autonomy:

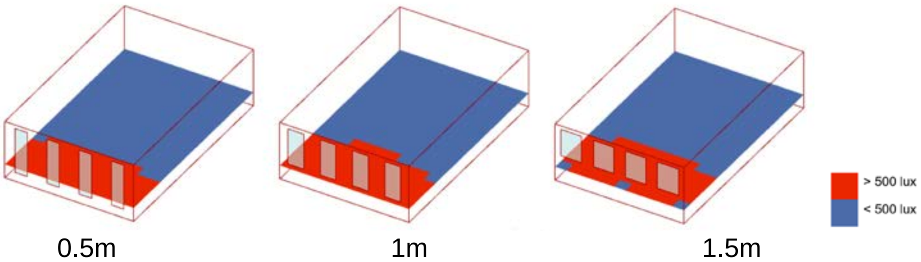


Figure 4-25 Changing of the window sill height and window dimension

The sensitivity analysis results of the SHGC on the daylight metrics, heating and cooling consumption, and thermal comfort regarding the window-to-wall ratio are presented in Figure 4-26

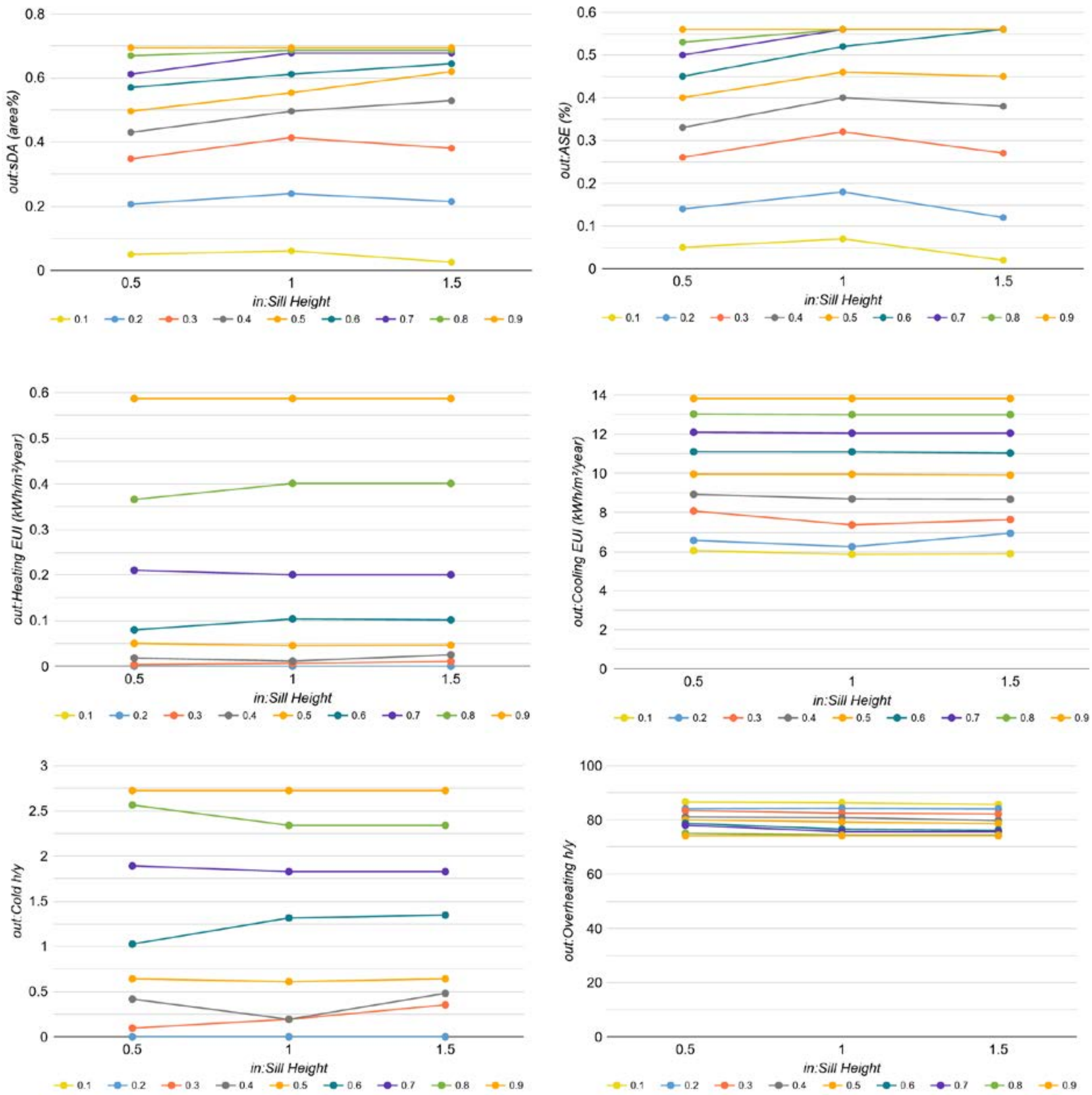


Figure 4-26 The sensitivity analysis results of sill height regarding the window-to-wall ratio

Tables 4-14 and 4-15 show sensitivity analysis results for window shape within the same percentage. This could impact about 18% on ASE, 10% on sDA, and no important impact on the cooling demand or the thermal comfort compared to the reference case, which is considered the mean input sill height of 1m.

Table 4-14 Sensitivity analysis results – window sill height on daylight metrics

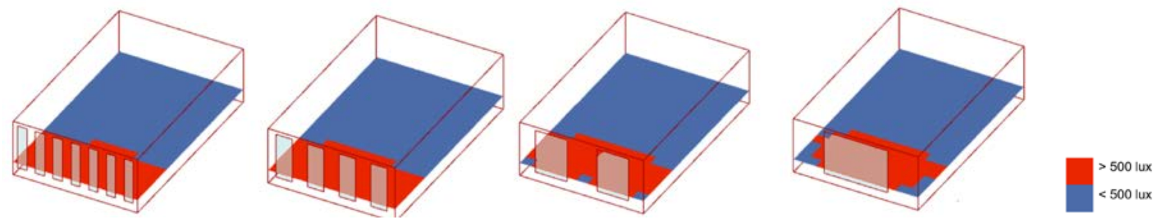
WWR (%)	Sill Height (m)	ASE (area%)	Correlation to a base case	ASE change (%)	sDA (area%)	Correlation to a base case	sDA change (%)
0.3	0.5	0.180	0.818	18.18%	0.263	0.897	10.34%
0.3	1	0.220	1.000	0.00%	0.293	1.000	0.00%
0.3	1.5	0.200	0.909	9.09%	0.298	1.017	-1.74%
			min	0.00%		min	-1.74%
			max	18.18%		max	10.34%

Table 4-15 Sensitivity analysis results – window sill height on overheating and cooling demand

WWR (%)	Sill Height (m)	Overheating h/y	Correlation to a base case	change (%)	Cooling EUI (KWh/m²/y)	Correlation to a base case	change (%)
0.3	0.5	83.429	1.011	-1.13%	7.099	1.028	-2.84%
0.3	1	82.500	1.000	0.00%	6.903	1.000	0.00%
0.3	1.5	82.179	0.996	0.39%	6.396	0.927	7.34%
			min	-1.13%		min	-2.84%
			max	0.39%		max	7.34%

4.4.6 <u>The same percentage, different window division</u>

Here, the break-up window refers to adding multiple windows on the wall or having a single-window per wall surface by assigning the distance between windows; the larger space means one window (Figure 4-27).



1m 2m 3m 4m

Figure 4-27 Changing the windows division

We find different results if we compare results from the same glazed percentage but with varying window designs.

For example, as represented in Figure 4-28, the blue line represents a WWR of 0.2. The x-axis represents the distance between the windows, 1m, 2m, 3m, 4m, and 5m. The 1m distance means the window panels are in the middle of the wall and close to each other, or they could form one window surface. That depends on WWR. If the WWR is high, there is no distance between the window, and it will be as one glazed surface.

It shows no impact on cold hours and heating consumption; thus, a sensitivity analysis will not be studied on these outputs. However, there is a minor impact on daylight metrics. Also, it is almost the same value on overheating.

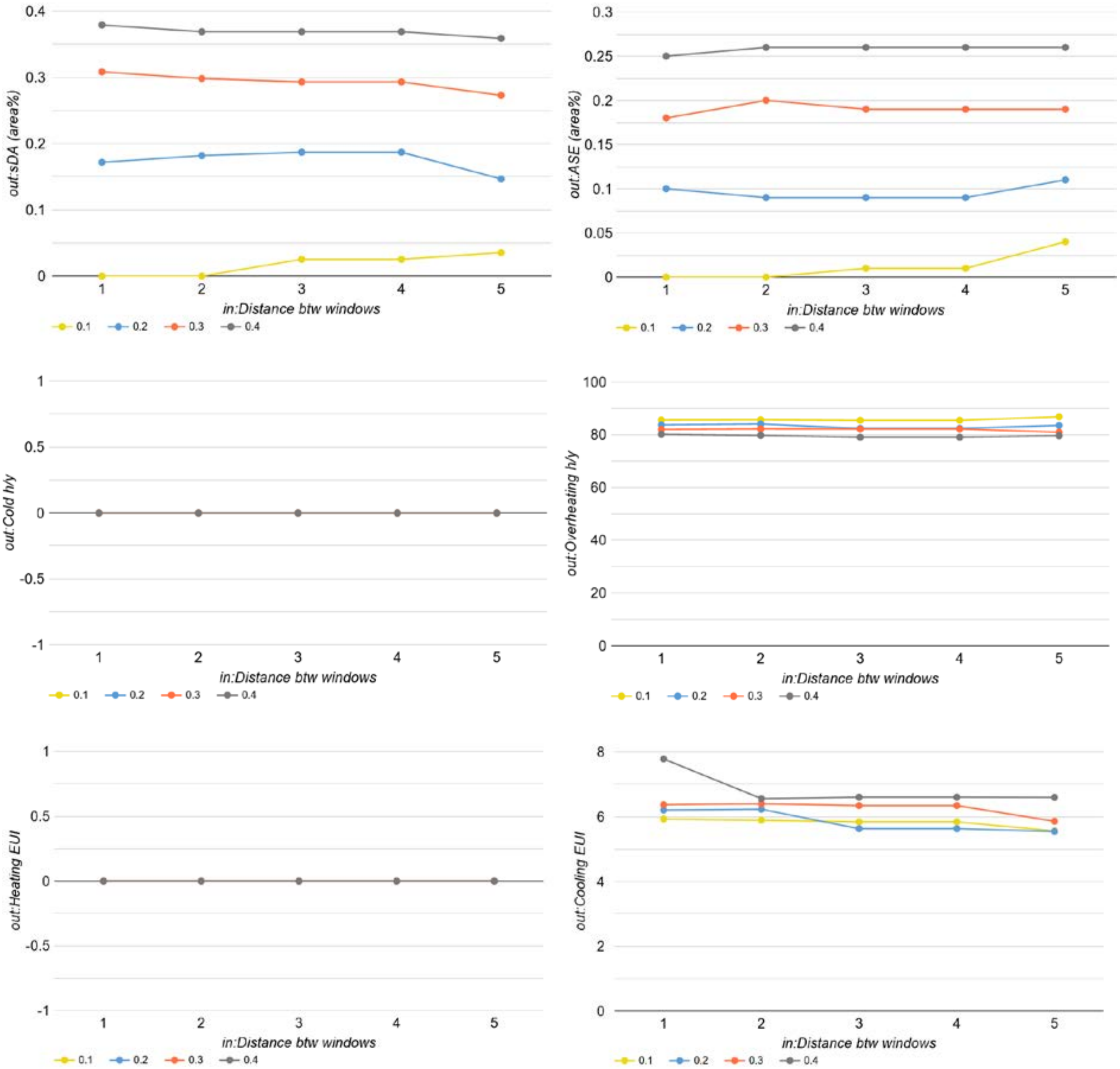


Figure 4-28 Sensitivity analysis results of different windows distance for the same WWR

The comparison in Table 4-16 shows that the window division influences Spatial Daylight Autonomy of about 13.4% of a range change for the studied office room, with a WWR of 0.4 on the south façade, and a difference of 18% on ASE

Table 4-16 Sensitivity analysis results – window division on daylight metrics

WWR (%)	RR	Distance btw windows (m)	Sill Height (m)	Orientation	Uw_Value (W/m²K)	SHGC	ASE (area%)	Correlation to a base case	ASE change (%)	sDA (area%)	Correlation to a base case	sDA change (%)
Sensitivity analysis- break-up window												
0.4	1.6	2	0.5	S	0.6	0.58	0.230	1.045	-4.55%	0.308	1.034	-3.39%
0.4	1.6	1	0.5	S	0.6	0.58	0.230	1.045	-4.55%	0.298	1.000	0.00%
0.4	1.6	3	0.5	S	0.6	0.58	0.220	1.000	0.00%	0.298	1.000	0.00%
0.4	1.6	4	0.5	S	0.6	0.58	0.220	1.000	0.00%	0.298	1.000	0.00%
0.4	1.6	5	0.5	S	0.6	0.58	0.190	0.864	13.64%	0.268	0.898	10.17%
								min	-4.55%		min	-3.39%
								max	13.64%		max	10.17%

Moreover, the change percentage on cooling demand is small (4%). Also, the impact on the overheating hours can be negligible (Table 4-17).

Table 4-17 Sensitivity analysis results – window division on overheating and cooling demand

WWR (%)	RR	Distance btw windows (m)	Sill Height (m)	Orientation	Uw_Value (W/m²K)	SHGC	Overheating h/y	Correlation to a base case	change (%)	Cooling EUI (KWh/m²/y)	Correlation to a base case	change (%)
0.4	1.6	2	0.5	S	0.6	0.58	94.839744	1.000	0.00%	8.112583	0.977	2.35%
0.4	1.6	1	0.5	S	0.6	0.58	94.967949	1.001	-0.14%	8.534267	1.027	-2.73%
0.4	1.6	3	0.5	S	0.6	0.58	94.839744	1.000	0.00%	8.307443	1.000	0.00%
0.4	1.6	4	0.5	S	0.6	0.58	94.839744	1.000	0.00%	8.307443	1.000	0.00%
0.4	1.6	5	0.5	S	0.6	0.58	95.160256	1.003	-0.34%	8.336236	1.003	-0.35%
								min	-0.34%		min	-2.73%
								max	0.00%		max	2.35%

4.5 Ranking of the influential variables

After the correlation study and the sensitivity analysis presented in the previous section, this section will answer the third research question, which is:

- *What are the most influential design parameters?*

This section ranks the most influential parameters of the studied variables regarding the base case on ASE, sDA, overheating consumption and cold hours. This ranking is based on the simulation results and the sensitivity analysis in Section 4.4.

Figure 4-29 shows that the most influential parameter on the Annual Sunlight Exposure (ASE) is the WWR. It follows building orientation, window division, and sill height. However, as seen in Section 4.4, the Solar heating Gain Coefficient (SHGC) and the U-window value have no impact on the ASE value.

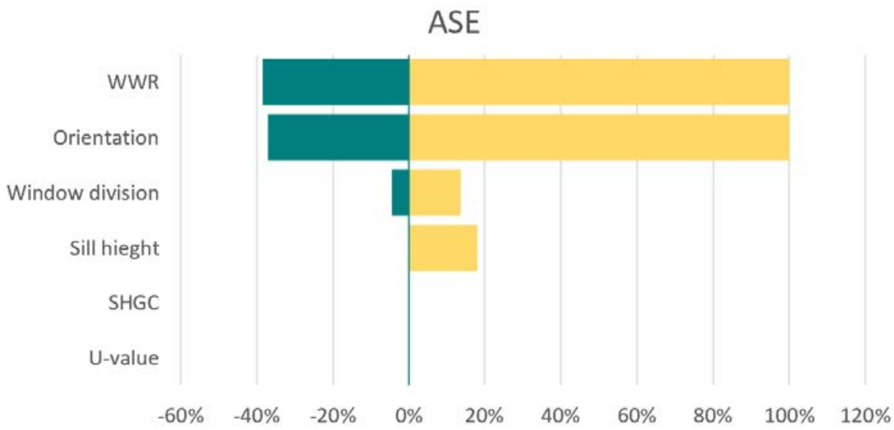


Figure 4-29- Ranking of the influential parameters on the ASE

Similarly, Figure 4-30 shows that the most influential parameter on Spatial Daylight Autonomy (sDA) is the WWR; it has a remarkable effect on sDA. Then the building orientation. However, the influence range of the orientation for the sDA is less than the ASE. In addition, we notice a minor impact was caused by changing window division and the sill height.

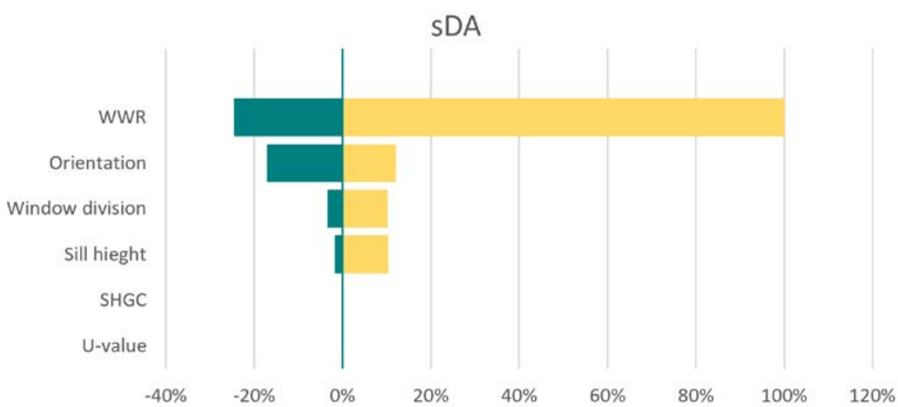


Figure 4-30 Ranking of the influential parameters on the sDA

Regarding cooling consumption, the most influential parameters are the SHGC, building orientation, and WWR, respectively (Figure 4-31). Furthermore, we notice that all the studied variables impact the cooling demand.

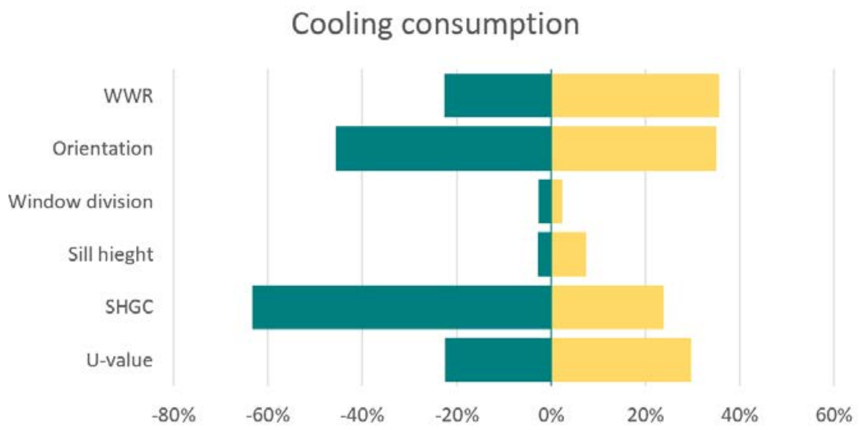


Figure 4-31 Ranking of the influential parameters on cooling consumption

As shown in Figure 4-32, the most influential parameters on the overheating hours are the SHGC and U-value. The third parameter is the building orientation, and a small impact will be caused by changing the WWR. Moreover, changing the window division or the window sill height will not change the final result.

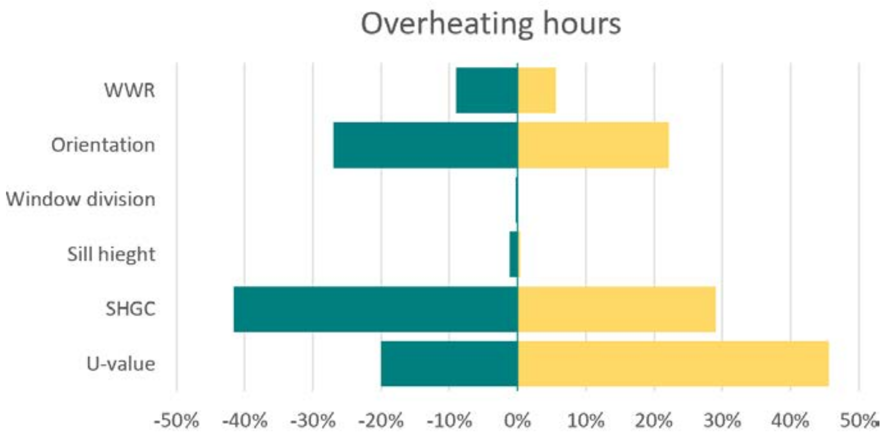


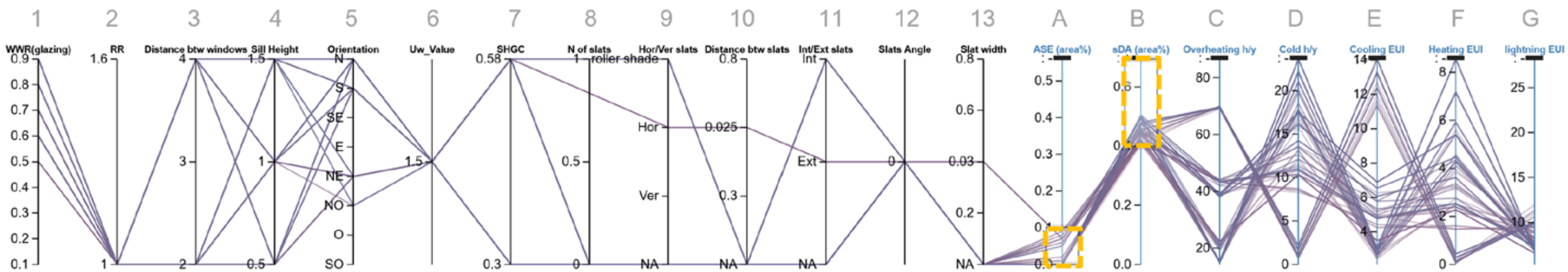
Figure 4-32 Ranking of the influential parameters on overheating hours

4.6 Best scenarios

This part will show the best options for a specific design objective, whether visual comfort, thermal comfort, energy consumption, or all of them together. It is based on the 2600 choices and scenarios.

4.6.1 Visual comfort

Figure 4-33 represents the design iterations that meet the minimum sDA requirement (40%) and the maximum value acceptable for the ASE (10%), arrived by selecting the desired range.



Legend:

Variable Inputs:

1.Window-to-wall ratio 2. Room ratio 3. Distance between windows 4.Sill height 5. Orientation 6.Uw-value (window) 7. SHGC

8. Number of slats 9. Hor./Ver. Slats 10. Distance between slats 11. Int./Est. shading 12.Slats angle 13.Slat Width

Outputs:

A. ASE B. sDA C. Overheating hours D. Cold hours E. Cooling consumption F.Heating consumption G. Lighting consumption

Figure 4-33 Design Options in Design Explorer that meets Daylight Requirement

We can see from the desired criteria that the best values are obtained when the window-to-wall ratio is from 0.5 and for the North-East, North, North-West, and South orientation. Figures 4-34 and 4-35 show the top scenarios about sDA and ASE together regarding WWR and orientation. The best scenarios are when WWR is 0.5 or 0.6 for the North-West facade, from 0.5 to 0.7 for the northeast façade, and from 0.6 to 0.9 for Southern and Northern facade orientation. The scenario of 0.8 represents a case with interior roller shade, as the ASE value is zero%.

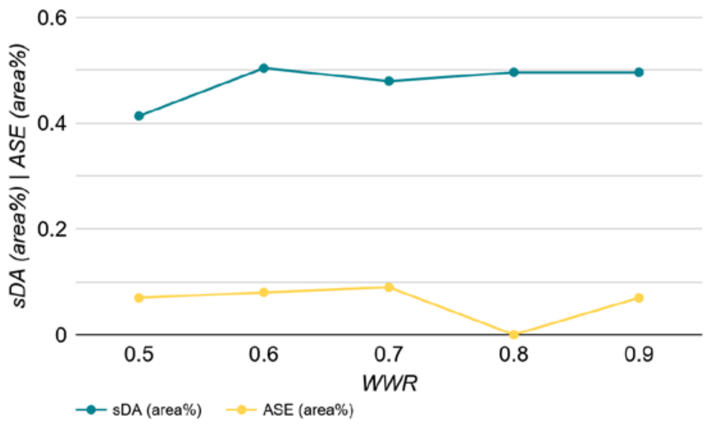


Figure 4-34 the minimum sDA requirement and max ASE values for best scenarios

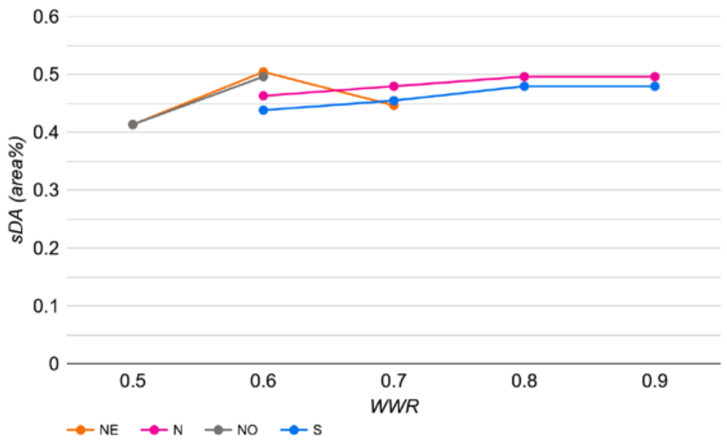


Figure 4-35 Best orientation and WWR scenarios regarding sDA and ASE

More specifically, according to the room ratio, the room dimension satisfying the chosen criteria is for 7m (length) *7m (depth) *3.2m (height) for both 0.3 or 0.58 values for the SHGC. Furthermore, some scenarios are between the best scenarios when using interior roller shade, especially for the South direction and WWR from 0.6. All results are available in Annex 5. However, some of the input variables and output features are represented in Table 4-18 and Table 4-19, where the first three scenarios are the top three regarding sDA and ASE simultaneously.

Table 4-18 Input features of 5 different scenarios from the best scenarios concerning daylight metrics

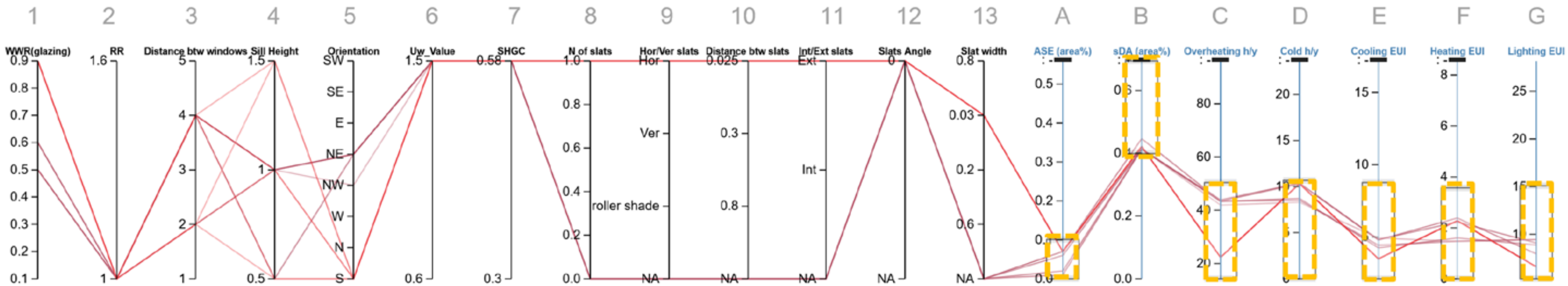
id	WWR	RR	Distance btw windows	Sill Height	Orientation	Uw_Value	SHGC	N of slats	Hor/Ver slats	Distance btw slats	Int/Ext slats	Slats Angle	Slat width
1	0.6	1	2	1.5	NE	1.5	0.3	0	NA	NA	NA	0	NA
2	0.6	1	4	1.5	NE	1.5	0.3	0	NA	NA	NA	0	NA
3	0.6	1	2	1.5	NE	1.5	0.58	0	NA	NA	NA	0	NA
4	0.6	1	4	1.5	NO	1.5	0.58	0	NA	NA	NA	0	NA
5	0.7	1	2	1	N	1.5	0.3	0	NA	NA	NA	0	NA
6	0.9	1	4	0.5	S	1.5	0.58	NA	roller shade	NA	Int	NA	NA

Table 4-19 Output features of 5 different scenarios from the best scenarios concerning daylight metrics

id	ASE (area%)	sDA (area%)	Overheating h/y	Cold h/y	Cooling EUI (kWh/m²/y)	Heating EUI (kWh/m²/y)	Lightning EUI (kWh/m²/y)
1	0	0.5041	20.576923	17.564103	2.650001	4.287105	7.290344
2	0	0.5041	20.576923	17.564103	2.650001	4.287105	7.290344
3	0	0.5041	43.205128	11.025641	4.772066	2.541179	7.314972
4	0.05	0.4959	42.051282	11.314103	5.347309	2.518586	7.397381
5	0	0.4793	14.903846	21.057692	2.900496	5.925347	6.909085
6	0	0.4793	69.583333	2.147436	14.053937	0.438442	9.928139

4.6.2 Scenarios that gathers all objectives

We can define our objective in Design Explorer by selecting the desired range, thereby choosing the maximum value acceptable of ASE, the minimum value of sDA, the lowest results for overheating hours, cold hours, heating, cooling, and lighting consumption. Thus, we arrived at solutions that meet these objectives together (Figure 4-36) :



Legend:

Variable Inputs:

1.Window-to-wall ratio 2. Room ratio 3. Distance between windows 4.Sill height 5. Orientation 6.Uw-value (window) 7. SHGC

8. Number of slats 9. Hor./Ver. Slats 10. Distance between slats 11. Int./Est. shading 12.Slats angle 13.Slat Width

Outputs:

A. ASE B. sDA C. Overheating hours D. Cold hours E. Cooling consumption F.Heating consumption G. Lighting consumption

Figure 4-36 Design Optimum in Design Explorer that meets all objectives

We can find that the optimum WWR value related to visual comfort, thermal comfort and energy consumption is from 0.5. for a room of 7m*7m*3.2m.

A scenario that gathers all objectives together is for the south orientation with a WWR of 0.9. a fixed shading device protects the glazed surface with a distance between slats of 0.025m. It is shown in Figure 4-37.

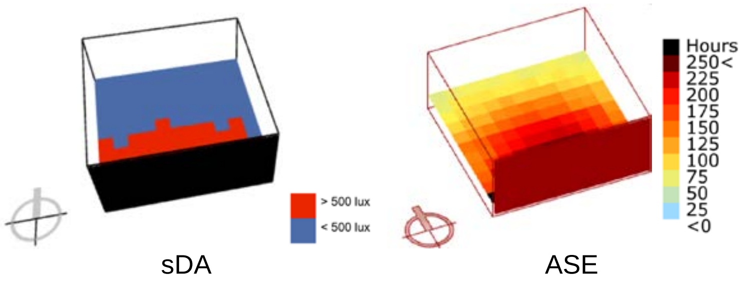


Figure 4-37 Design Optimum- visualization maps for sDA (left) and ASE (right)- scenario 1- WWR of 0.9 covered by an exterior shading device

Another scenario is represented in Figure 4-38 for a North-west room with 1m of window sill height, consisting of two window surfaces.

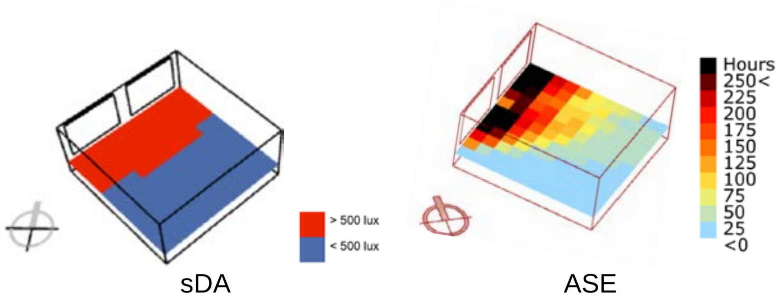


Figure 4-38 Design Optimum- visualization maps for sDA (left) and ASE (right)- scenario 2

Tables 4-20, and 4-21 list some of the optimal solutions regarding all parameters together. They show the most efficient thresholds. These choices seem to be the best compromise between daylight metrics, energy consumption, and thermal comfort between the suggested alternatives and different variables.

Table 4-20 Some of the optimal solutions regarding all parameters together- Input features

id	WWR	RR	Distance btw windows (m)	Sill Height (m)	Orientatior	Uw_Value (W/m²K)	SHGC	N of slats	Hor/Ver slats	Distance btw slats (m)	Int/Ext slats	Slats Angle	Slat width (m)
1	0.9	1	_	_	S	1.5	0.58	NA	Hor	0.025	Ext	0	0.03
2	0.5	1	2	1	NW	1.5	0.58	0	NA	NA	NA	0	NA
3	0.5	1	2	1	NE	1.5	0.58	0	NA	NA	NA	0	NA
4	0.5	1	2	1	NE	1.5	0.58	0	NA	NA	NA	0	NA
5	0.6	1	_	1	NE	1.5	0.58	0	NA	NA	NA	0	NA
6	0.6	1	_	0.5	NE	1.5	0.58	0	NA	NA	NA	0	NA

Table 4-21 Some of the optimal solutions regarding all parameters together- Output features

id	ASE (area%)	sDA (area%)	Overheating h/y	Cold h/y	Cooling EUI (kWh/m²/y)	Heating EUI (kWh/m²/y)	Lightning EUI (kWh/m²/y)
1	0.07	0.4215	22.275641	10.320513	3.4948	2.280814	6.603367
2	0.07	0.4132	41.923077	8.301282	4.93008	1.471628	9.456892
3	0.01	0.4132	43.269231	8.717949	4.252191	1.601387	8.891397
4	0.02	0.4132	43.397436	8.525641	4.431042	1.475936	9.449196
5	0.07	0.4463	43.397436	10.320513	4.795994	2.385645	7.954351
6	0.06	0.4132	43.878205	10.384615	4.825803	2.228449	9.098958

In conclusion, this chapter has tried to answer three main research questions regarding the design tool, the performance evaluation, and a ranking of the criteria. Even though the study was done on a shoebox model, it succeeded in the results' simulation. Decoupling these simulations and representing them through a parallel coordinator graph, which is simple, make it very fast and effective to be used and allow variate parameters to be explored.

In the next chapter, an investigation of the tool's friendliness and usability will be studied.

5 Results usability testing

The fourth question of this research is related to the interaction with the design tool proposed in Design Explorer:

- *How do designers perceive the developed design support?*

Therefore, usability testing has been followed, as described earlier in the methodology chapter, section 3.8.2, according to ISO 9241-210. The System Usability Scale (SUS) was adapted to quantify the user experience and evaluate their interaction with the design interface. Seven potential users have tested the tool.

5.1.1 General analysis of the interaction with the tool

Table 5-1 shows the answers of the seven participants on the ten SUS questions. The degree of agreement is represented from one to five, and the satisfaction degree is expressed in a coloured scale.

Table 5-1 System Usability Scale (SUS) of the design tool.

	P1	P2	P3	P4	P5	P6	P7
I would use the design tool regularly	4	4	5	4	4	4	3
I found it unnecessarily complex	2	1	1	2	2	1	1
It was easy to use the tool by Design Explorer	4	5	5	4	4	4	5
I would need help to use it	3	1	4	2	2	2	3
The various parts of the interface worked well together	4	4	5	4	4	4	5
Too much inconsistency	3	1	1	1	1	1	1
I think others would find it easy to use	4	5	5	4	4	3	4
I found it very cumbersome to use	2	1	1	2	2	2	2
I felt very confident using the Design tool	4	5	5	4	4	3	4
needed to understand how it worked in order to get going	3	4	4	3	3	5	4

Legend: Dissatisfaction → Satisfaction

Strongly Disagree 1 → 5 Strongly Agree

The SUS score for each participant is represented in Figure 5-1, which means the degree of satisfaction. It is out of 100 (a total score out of 100 and not a percentage). Thus, by calculating and comparing the satisfaction for each participant, the percentage of satisfaction should be more than 70.

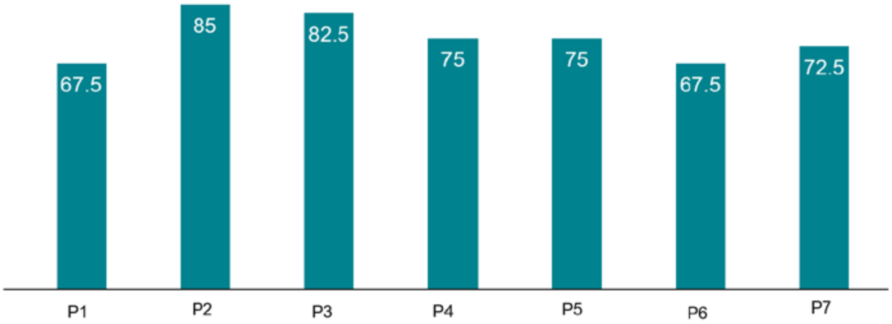


Figure 5-1 SUS score by participants

The average SUS score for the suggested design tool is 75 out of 100. This result indicates that the design tool needs a minor improvement, and it is in the acceptable range (Figure 5-2).

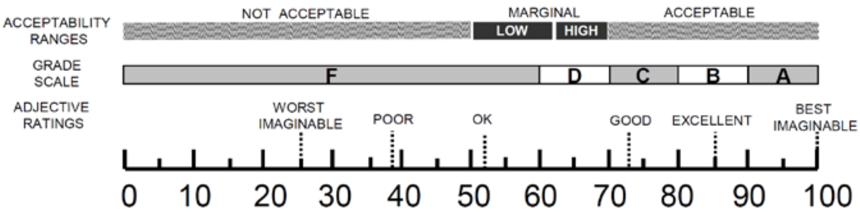


*Figure 5-2 SUS score of the adjective ratings, acceptability ranges, and grade scale (*Determining what individual SUS scores mean*, n.d.)*

5.1.2 Report Feedback from Usability Testing

The scores were recorded by each participant and by each question in a percentage. For example, questions 4 and 10 address learnability, and the others address usability.

Using the system usability system (SUS) testing, we found that the participants, the potential users, had a positive reaction to the tool. However, this usability testing could be repeated after the improvement and the participants' feedback to compare the tool's progress. Also, to know where we should focus on improving the tool for the future. Some feedbacks have been taken into account, for example:

- Adding a precise nomenclature for each parameter was a demand from most participants to understand the tool better without "the support of a technical person".
- *"Giving the dimensions of the basic module"* by adding a parametric input for room ratio and room dimensions on the 2D images.
- "*Identify the acceptable and unacceptable results"* by adding a rating scale.

Moreover, some feedback could be improved for future work:

- "*Giving prior explanations for the use of the tool and the standards."*
- *"Adding critical rooms such as corner areas."*

To report the tool's efficiency, it is important to measure each participant's average task completion time to try the tool and complete the task successfully, represented in Figure 5-3. The average time taken is four minutes and 47 seconds. However, this time is relative. It is the time needed to follow the exact instructions. So, we can evaluate the ease of use of the tool.

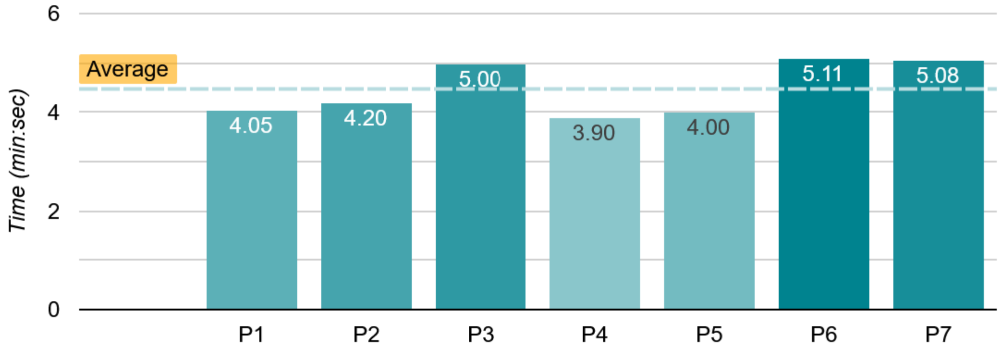


Figure 5-3 Average task completion time per participant

It is important to mention that the time-saving is a sign of productivity for the design decision-making. Furthermore, it is not just about the efficiency of the tool. It is also to report user experience and their satisfaction.

6 Discussion

This chapter is a summary of the main findings and recommendations. Then, it presents the strengths, limitations and difficulties of the study. Finally, the implication on practice and future research are presented

6.1 Summary of the main findings

The main findings of the tool and the simulation results:

- The top three design scenarios for an office room designed according to the Belgium climate and the European norms are:
  - A south face room with a WWR of 0.9. with fixed exterior blinds covered the glazed surface with a distance between slats of 0.025m.
  - A northwest room consists of two windows with a sill height of 1m and 50% glazing.
  - Another scenario is with a WWR of 0.6 on the northeast, a window sill height of 0.5m without a shading system.

  All of them were for a room of 7m (length),7m (depth), 3.2m (height), an SHGC of 0.58, and a U_{window} value of 1.5W/m²K. These choices seem to be the best compromise between the energy consumption, thermal comfort, and daylight metrics: a percentage of spatial Daylight Autonomy more than 40% ($sDA_{500lux/50\%}$). And a percentage of Annual Sunlight Exposure less than 10% of the room surface Annual ($ASE_{1000ux/250h}$)
  Those top three solutions are between the suggested alternatives and different variables regarding all the studied objectives together.

- In general, to control solar gains and maximize daylighting, it is suggested to be aware of window configuration, design, orientation, and WWR to achieve the optimum solution.
- From the sensitivity analysis, we can arrive that changing window dimensions without changing window lintel level have a small impact on the output data.
- Changing windows division for the same glazed ratio also has a minor impact on the results.
- The WWR mostly influences the daylight metrics sDA and ASE more than the energy demand and thermal comfort.
- Designing a room with a ratio equal to 1 (a square plan of 7m.*7m.*3.2m H.) gives us better results about spatial Daylight Autonomy and less cooling demand compared to a rectangular module.
- Using an interior roller shade that will be closed when the direct sun becomes undesirable deletes the impact of the ASE. In this case, the sDA is above the threshold when the WWR is 0.8 or 0.9. Also, the change in energy consumption is negligible.
- The WWR and the building orientation are the two design parameters that have an impact on all the results.
- The SHGC and U_{window} have no impact on daylight metrics, whereas they impact the overheating hours with a range of change of about 65%
- When the minimum value required for sDA is 40%, and the maximum ASE is no more than 10% 250h/year, it is challenging to ensure both criteria simultaneously. However, the newest version of LEED v4. deemphasizes the

glare requirements (ASE) and encourages increasing daylight (sDA). (*Effective Daylighting Workflows for LEED V4*, 2019)

6.2 Recommendations

Generally, it would be suggested to improve the interface by adding more variable parameters related to the glazing surface. However, in this study, the SHGC and U-value show an impact on the overheating hours and energy consumption on the Daylight performance, so other thermal properties could be studied to evaluate its impact, such as the Visible window Transmittance (VT). However, many other variables can be added and tested for efficiency.

Moreover, the interior roller shade tested in this study shows improvement in ASE and cooling demand. However, the sDA value was above the threshold for a high glazing surface for about 43%. Thus, it could be studied in detail with other parameters in order to find an equilibrium solution for a WWR of less than 80%.

The best scenarios are regarding the suggested inputs used for this study. However, we can arrive at other solutions by changing the threshold for some outputs, such as using minimum illuminance of 300 lux to calculate sDA instead of 500 lux. That will increase values of sDA compared to the minimum threshold, where the minimum illuminance of 300 lux is the threshold recommended by the IES- LM-83-12.

This study was done on a simple type of facade and fixed shading. Therefore, future studies can be for a different kind of façade with more complex parameters such as dynamic facades or double skin facades. It can be developed to include adaptive facade solutions (Attia et al., 2020).

Furthermore, a dynamic shading device could be integrated. However, based on an interview with an expert in daylight simulation, the results are more accurate when using the Energy Management System (EMS) feature in the EnergyPlus launch, then adding the information into Grasshopper. But that would need more time to understand each value, do the script code, and integrate it into Grasshopper, especially with the lack of guides or resources that easily explain the procedure. Furthermore, we need an expert to judge and evaluate the results because even if there are no error messages, results could not be correctly represented. This is because the energy Management System (EMS) is an *"advanced feature of EnergyPlus and not for beginners"* (*Application Guide for EMS*, n.d.).

Moreover, because the sDA and ASE are daylight factors based on metric values thus, results can change every minute or every second. Making a schedule for dynamic shading based on that will take much time and need a deep study. However, it could be studied in another thesis for future students by adding more complex details.

6.3 Strength and Limitations of the process and the tool

This study was done on simple geometry, where it is only a shoebox. On the other hand, the tool's strength is that it is based on international and European standards related to office buildings where occupants comfort is really important. Moreover, the

studied concepts are universally used, and some of them are new such as the spatial Daylight Autonomy (sDA) and the Annual Sunlight Exposure (ASE).
It is also evaluated based on a complex and powerful parametric program as Grasshopper. Moreover, the use of the parallel, coordinated graph is similar to many studies that used this way of visualization (Mahmoud et al., 2020). In addition, the design interface, based on the usability testing results, is easy to use. Many choices and a comparison can be shown in a minute where it does not need any education in running simulation, which will take more time and effort.

On the contrary, as a limitation, integrating the energetic study during the early design stage represents significant uncertainties. Besides this, architects prefer having many choices to choose between at the early design stage instead of high-quality information. Therefore, the main goal of this tool is to reduce design decision stress. Undoubtedly, a more precise and detailed study will follow the design stage with high-quality energetic software.

Secondly, the parametric studies could be a limitation for the creativity in design façades because it is just for façade with a simple predicted design. On the contrary, we could find unlimited propositions for designing a facade.

Finally, one of the limitations of the parametric design tool is that the time needed to do the simulation in Grasshopper for a high number of iterations is an obstacle:

6.3.1 Limitations: Calculation time

Each iteration in Grasshopper took about 2.5 minutes to be calculated. However, it depends on the needed number of parameters, details, degree of accuracy, and the power of the machine. This duration seems reasonable per simulation, but when we talk about a high number of iterations, it takes weeks to be calculated.

As we are interested in a parametric study with high-speed calculation to save time, so we should follow the following tips:

- Try to assemble as many parameters and avoid repetitions.
- Clean unused components.
- Using the latest versions

Future studies suggest using the web-based simulation interface “Pollination” (*Pollination*, n.d.), which speeds up the simulation faster depending on the online server. This method is new and in the progress of development. Because this method, for the moment, does not support exporting images and 3D objects into Design Explorer, and it is not widely tested to know the accuracy of results, it has not been used for this study. However, developers are working on improving this method, and it is highly suggested to be tested and used for future work.

6.4 Restatement of Study Purpose

This study was designed to provide a user-friendly interface tool and determine the effect of facades design parameters and window configurations based on norms and Belgian or international standards to adjust the parametric range and the simulation model. In addition, a sensitivity analysis has been used to select influential parameters that affect office buildings' thermal comfort, visual comfort, and energy performance. Moreover, the suggested interface's efficiency and usability have been validated through System Usability Scale, depending on a test with potential users.

Moreover, based on the sensitivity analysis results and ranking the parameters in this research, this will help designers to choose between the design parameters according to their needs. For example, if the building is on the south face, they do not need to change the orientation, where it will be fixed. However, if they change just one and see the results, they will only know how the WWR will affect the cooling demand, overheating hours, or daylight metrics. So, it depends on what they prefer. For example, if the designers want to increase the heating demand or other results, they will select the related design parameters and change them to obtain different results. In this way, the purpose of this thesis has been reached.

For this study, we are not looking for the optimum solution. Instead, it offers an idea about how the design parameters will affect the buildings if the designer wants to change the WWR according to their needs, for cooling or heating demand, or ASE or other. So this paper presents the relationship between inputs and outputs, and it is their choice. Thus, the main objective of this thesis is to enable facade designers to be able to understand before the construction phase, during the design phase, how each parameter will affect their buildings

6.5 Implications on practice and future work

This suggested tool could be suitable for architects depending on the size of the project. Also, it could be in the case of multidisciplinary solutions or glazing specialization. The architects can use it as a primary study for the early design stage and then ask the engineer to validate the choice with detailed studies regarding the objective.

This tool and study have been done to help design decision-making at the early design stage of a project. However, it could be developed to be used from the early design stage to the operation and occupancy stage.

The Rhino/ Grasshopper and the diverse plugins into it offer a wide choice for studies; for example, the plugin Dragonfly helps to do environmental analysis on a large-scale, urban weather generator and for the future climate.

Nowadays, BIM (Building information modelling) is one of the most important and robust processes for design and construction. Therefore, many studies aim to integrate plugins into BIM, such as the study of Natephra, which aims to integrate thermal information with BIM for building envelopes in naturally ventilated environments (Natephra et al., 2017). Therefore, the results of this thesis can be integrated into BIM (*Rhino.Inside®.Revit*, n.d.). That will lead to a 4D design during the design stage, where we can integrate design facades, especially glazing parameters, with the comforts of occupants; visual comfort evaluation, thermal performance analysis, and thermal comfort evaluation.
Furthermore, it can be used for an office building with environmental weather similar to the weather conditions in Belgium, or even other types of building in Belgium. However, since the geometry is a shoebox, it will mainly be used for buildings with a repetitive module. It could also help to understand the importance of each design parameter and its impact more than take a final decision when the geometry is different.

Also, some studies have shown that we could obtain different results by using different locations for the weather station in the same region (*How to Select a Climate File?*, n.d.). Microclimate could have a remarkable influence on energy and comfort. Therefore choosing other nearby weather stations and comparing results could be very interesting for future studies.

It can also be repeated using another climate and other standards (BREEAM, DGNB, NFRC, Green Star, HQE, WELL, or another.) to achieve this work worldwide.

Other studies can be developed by adding other variables and more parameters such as wall constructions, different types of glazing. Or for other design objectives, for example, zero energy buildings, low carbon, or passive buildings.

7 Conclusions

The development of simulation tools in the construction industry is interesting since they aid in faster decision-making and improve the quality of the decisions, especially at the initial stages of a project. Building simulation software is deployed to ensure there is compliance with the applicable building code. It is also used in the evaluation of the performance of specific alternative systems or even designs. The simulation tools also reflect the organizational structure, and they are a support for professional practice. Thus, the tool's ease of use and the interaction with a user-friendly interface is necessary to permit the designers and architects to integrate energy study with the design at the early design stage.

This paper has tried to answer four main questions related to the tool and user experience based on simulation results from a parametric tool such as Grasshopper.

Accordingly, this study is about office buildings linked explicitly to Belgium climate.

We presented the effectiveness of each studied input on the outputs: Daylight metrics as Annual Sunlight Exposure and spatial Daylight Autonomy, annual thermal comfort and energy intensity where the main goals are improving the benefit from daylight and ensuring visual and thermal comfort, minimizing undesirable direct sun, reducing energy use. In that case, the balancing act is to involve all of them.

The results show that the choice of glazing specifications can have a significant consequence on energy performance. Thus, it should have a focus and interest in studying.

The study showed that some façade design parameters could significantly impact the daylight levels in interior spaces and energy use. They could be ranked as having the most impact on visual comfort, thermal comfort and energy consumption as follows:

- The high impact on daylight metrics is caused by the Window-to-Wall ratio (WWR), building orientation, and window division, respectively.
- The most influential parameters on annual cooling demand are the Solar Heat Gain Coefficient (SHGC), building orientation, and WWR, respectively.
- The most influential parameters on annual overheating hours are the Solar Heat Gain Coefficient (SHGC), U_{window}- value, and building orientation, respectively.
- The least impact is produced by the window sill height and window division.

Finally, many opportunities exist to support design decision-making during the early stages by using energetic and environmental plugins in a design program. It could be improved and developed in the future. This method can be the solution to reduce the design-decision fatigue for designers and architects.

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Appendix 1: RIBA plan of work

RIBA Plan of Work 2020

The RIBA Plan of Work organises the process of briefing, designing, delivering, maintaining, operating and using a building into eight stages. It is a framework for all disciplines on construction projects and should be used solely as guidance for the preparation of detailed professional services and building contracts.

	0 Strategic Definition	1 Preparation and Briefing	2 Concept Design	3 Spatial Coordination	4 Technical Design	5 Manufacturing and Construction	6 Handover	7 Use
		← Projects span from Stage 1 to Stage 6; the outcome of Stage 0 may be the decision to initiate a project and Stage 7 covers the ongoing use of the building. →						
Stage Outcome at the end of the stage	The best means of achieving the **Client Requirements** confirmed If the outcome determines that a building is the best means of achieving the **Client Requirements**, the client proceeds to Stage 1	**Project Brief** approved by the client and confirmed that it can be accommodated on the site	**Architectural Concept** approved by the client and aligned to the **Project Brief** The brief remains "live" during Stage 2 and is derogated in response to the **Architectural Concept**	Architectural and engineering information **Spatially Coordinated**	All design information required to manufacture and construct the project completed Stage 4 will overlap with Stage 5 on most projects	Manufacturing, construction and **Commissioning** completed There is no design work in Stage 5 other than responding to **Site Queries**	Building handed over, **Aftercare** initiated and **Building Contract** concluded	Building used, operated and maintained efficiently Stage 7 starts concurrently with Stage 6 and lasts for the life of the building
Core Tasks during the stage **Project Strategies** might include: - **Conservation** (if applicable) - **Cost** - **Fire Safety** - **Health and Safety** - **Inclusive Design** - **Planning** - **Plan for Use** - **Procurement** - **Sustainability** See *RIBA Plan of Work 2020 Overview* for detailed guidance on **Project Strategies**	Prepare **Client Requirements** Develop **Business Case** for feasible options including review of **Project Risks** and **Project Budget** Ratify option that best delivers **Client Requirements** Review **Feedback** from previous projects Undertake **Site Appraisals** No design team required for Stages 0 and 1. Client advisers may be appointed to the client team to provide strategic advice and design thinking before Stage 2 commences.	Prepare **Project Brief** including **Project Outcomes** and **Sustainability Outcomes**, **Quality Aspirations** and **Spatial Requirements** Undertake **Feasibility Studies** Agree **Project Budget** Source **Site Information** including **Site Surveys** Prepare **Project Programme** Prepare **Project Execution Plan**	Prepare **Architectural Concept** incorporating **Strategic Engineering** requirements and aligned to **Cost Plan**, **Project Strategies** and **Outline Specification** Agree **Project Brief Derogations** Undertake **Design Reviews** with client and **Project Stakeholders** Prepare stage **Design Programme**	Undertake **Design Studies**, **Engineering Analysis** and **Cost Exercises** to test **Architectural Concept** resulting in **Spatially Coordinated** design aligned to updated **Cost Plan**, **Project Strategies** and **Outline Specification** Initiate **Change Control Procedures** Prepare stage **Design Programme**	Develop architectural and engineering technical design Prepare and coordinate design team **Building Systems** information Prepare and integrate specialist subcontractor **Building Systems** information Prepare stage **Design Programme** Specialist subcontractor designs are prepared and reviewed during Stage 4	Finalise **Site Logistics** Manufacture **Building Systems** and construct building Monitor progress against **Construction Programme** Inspect **Construction Quality** Resolve **Site Queries** as required Undertake **Commissioning** of building Prepare **Building Manual** Building handover tasks bridge Stages 5 and 6 as set out in the **Plan for Use Strategy**	Hand over building in line with **Plan for Use Strategy** Undertake review of **Project Performance** Undertake seasonal **Commissioning** Rectify defects Complete initial **Aftercare** tasks including light touch **Post Occupancy Evaluation**	Implement **Facilities Management** and **Asset Management** Undertake **Post Occupancy Evaluation** of building performance in use Verify **Project Outcomes** including **Sustainability Outcomes** Adaptation of a building (at the end of its useful life) triggers a new Stage 0
Core Statutory Processes during the stage: Planning Building Regulations Health and Safety (CDM)	Strategic appraisal of **Planning** considerations	Source pre-application **Planning Advice** Initiate collation of health and safety **Pre-construction Information**	Obtain pre-application **Planning Advice** Agree route to **Building Regulations** compliance Option: submit outline **Planning Application**	Review design against **Building Regulations** Prepare and submit **Planning Application** See ***Planning Note*** for guidance on submitting a **Planning Application** earlier than at end of Stage 3	Submit **Building Regulations Application** Discharge pre-commencement **Planning Conditions** Prepare **Construction Phase Plan** Submit form F10 to HSE if applicable	Carry out **Construction Phase Plan** Comply with **Planning Conditions** related to construction	Comply with **Planning Conditions** as required	Comply with **Planning Conditions** as required
Procurement Route Traditional Design & Build 1 Stage Design & Build 2 Stage Management Contract Construction Management Contractor-led	Appoint client team	Appoint design team	ER Appoint contractor ER	Pre-contract services agreement Preferred bidder	Tender — Appoint contractor ER CP — Appoint contractor CP — Appoint contractor CP — Appoint contractor			Appoint **Facilities Management** and **Asset Management** teams, and strategic advisers as needed
Information Exchanges at the end of the stage	**Client Requirements** **Business Case**	**Project Brief** **Feasibility Studies** **Site Information** **Project Budget** **Project Programme** **Procurement Strategy** **Responsibility Matrix** **Information Requirements**	**Project Brief Derogations** Signed off **Stage Report** **Project Strategies** **Outline Specification** **Cost Plan**	Signed off **Stage Report** **Project Strategies** Updated **Outline Specification** Updated **Cost Plan** **Planning Application**	**Manufacturing Information** **Construction Information** **Final Specifications** Residual **Project Strategies** **Building Regulations Application**	**Building Manual** including **Health and Safety File** and **Fire Safety Information** **Practical Completion** certificate including **Defects List** **Asset Information** If **Verified Construction Information** is required, verification tasks must be defined	**Feedback** on **Project Performance** **Final Certificate** **Feedback** from light touch **Post Occupancy Evaluation**	**Feedback** from **Post Occupancy Evaluation** Updated **Building Manual** including **Health and Safety File** and **Fire Safety Information** as necessary

Stage Boundaries:
Stages 0-4 will generally be undertaken one after the other.
Stages 4 and 5 will overlap in the **Project Programme** for most projects.
Stage 5 commences when the contractor takes possession of the site and finishes at **Practical Completion**.
Stage 6 starts with the handover of the building to the client immediately after **Practical Completion** and finishes at the end of the **Defects Liability Period**.
Stage 7 starts concurrently with Stage 6 and lasts for the life of the building.

Planning Note:
Planning Applications are generally submitted at the end of Stage 3 and should only be submitted earlier when the threshold of information required has been met. If a **Planning Application** is made during Stage 3, a mid-stage gateway should be determined and it should be clear to the project team which tasks and deliverables will be required.
See *Overview* guidance.

Procurement:
The RIBA Plan of Work is procurement neutral – See *Overview* guidance for a detailed description of how each stage might be adjusted to accommodate the requirements of the **Procurement Strategy**.
ER Employer's Requirements
CP Contractor's Proposals

RIBA
Architecture.com

Core RIBA Plan of Work terms are defined in the *RIBA Plan of Work 2020 Overview* glossary and set in **Bold Type**.

Further guidance and detailed stage descriptions are included in the *RIBA Plan of Work 2020 Overview*.

Appendix 2: A comparison study for façade's type

Source: Project World Trade Center 4- Befimmo

	date: 2021-04-09		OPTION 1	OPTION 1b	OPTION 2	OPTION 3 (BENCHMARK)
	Evaluation matrix facade options evaluation levels: good / fair, can be recommend / poor, not recommend **PRELIMINARY DRAFT** **PROJECT NAME: WTC IV Brussels**	Criteria weighing	**Closed Cavity Facade**	**Double Skin Facade outwards ventilated**	**Single Skin Facade exterior metal roller blind**	**Single Skin Facade interior sun protection blind**
	Technical parameters / assumptions		Exterior single glass pane, laminated safety glass Interior triple layer IGU, U-value glass = 0,6 W/m2K g-value glass = approx. 0,35 - 0,45 motorized venetian binds in the facade cavity Fc-value approx. 0,2 (conservative value) **TOTAL G-VALUE = approx. 0,05 - 0,10**	Exterior single glass pane, laminated safety glass Interior double layer IGU, U-value glass = 1,0 W/m2K g-value glass = approx. 0,35 - 0,45 motorized venetian blinds in the facade cavity Fc-value approx. 0,2 (conservative value) **TOTAL G-VALUE = approx. 0,05 - 0,10**	Thermal layer IGU, U-value glass = 1,0 W/m2K g-value glass = approx. 0,35 - 0,45 exterior motorized metal roller shutter, wind resistant Fc-value approx. 0,2 (conservative value) **TOTAL G-VALUE = approx. 0,05 - 0,10**	Thermal layer IGU, U-value glass = 1,0 W/m2K g-value glass = approx. 0,35 interior motorized textile roller blinds, reflective Fc-value approx. 0,5 (optimized value) **TOTAL G-VALUE = approx. 0,15 - 0,2**
1	**Integration into architecture (needs to be studied further)**					
1.1	Diagrid inside or outside of the facade		No conflict with necessary operable parts of the facade	Interior opening sash for cleaning can conflict with diagrid	No conflict with necessary operable parts of the facade	No conflict with necessary operable parts of the facade
1.2	Transparent glass building (Current assumption: same glass for all options)		Low reflection glass, no change of exterior appearance with solar protection lowered	Low reflection glass, no change of exterior appearance with solar protection lowered	Low reflection glass, change of exterior appearance with solar protection lowered	High reflective solar protection glass, highly reflective interior solar protection system can affect the exterior appearance
2	**Good work environment, comfort, IEQ**					
2.1	Noise protection of facade (with opening sash closed)		**up to Rw=50 dB**	**up to Rw=48 dB**	**up to Rw=45dB**	**up to Rw=45dB**
2.2	Natural ventilation through facade system		Only with additional operable sash	Possible through facade	With additional sash window elements	With additional sash window elements
2.3	Inside surface temperature - secondary heat transfer		Heat remains in cavity - triple glazing necessary	Over-temperature in facade cavity, interior surface remains comfortable	Interior glass surface remains comfortable	Interior surface of solar protection layer can heat up and create discomfort / secondary heat gain
2.4	Daylighting of office and living spaces with open sunshading system		Assumption: same g-value and TVL for all facade options	Assumption: same g-value and TVL for all facade options	Assumption: same g-value and TVL for all facade options	Assumption: same g-value and TVL for all facade options
2.5	View to outside / transparency with sun shading		Venetian blinds can be partially transparent in cut-off position	Venetian blinds can be partially transparent in cut-off position	Transparent sun protection system	Effective textile roller blinds are not transparent when in use - no views of the outside
3	**Energy Efficiency / U-value / physical performance of facade**					
3.1	Sun protection capacity and U-value (W/m²K)		**gtotal=0,08 (Ucw = approx. 1,0)**	**gtotal=0,07 (Ucw = approx.1,1) U-value can be lower with triple IGU**	**gtotal=0,07 (Ucw = approx. 1,3) U-value can be lower with triple IGU**	**gtotal=0,15 (Ucw = approx. 1,3) U-value can be lower with triple IGU**
4	**Cleaning & maintainance**					
4.1	Cleaning effort of glass (cleaning concept pending)		2 glass surfaces (1 in outdoor air)	4 glass surfaces (3 in outdoor air)	2 glass surfaces (1 in outdoor air)	2 glass surfaces (1 in outdoor air)
4.2	Cleaning effort of sun shading system (cleaning concept pending)		System in protective cavity	System in outdoor air - many surfaces	System in outdoor air - simple surface	System in indoor air
4.3	Maintainance of facade and system parts		Low maintainance	Maintainance of engine and hardware, operable sash windows	Maintaince of roller blinds	Low maintainance
5	**Economic Feasibility**					
5.1	Construction costs (base facade element, ROUGH ESTIMATE)		**approx. 1.000 EUR/m²**	**approx. 1.000 EUR/m²**	**approx. 850 EUR/m²**	**approx. 700 EUR/m²**
5.2	Lower energy demand for cooling from external loads		**Energy reduction approx. 45%**	**Energy reduction approx. 50%**	**Energy reduction approx. 50%**	**Energy reduction 0% (Benchmark)**
5.3	Operation costs (hardware, engines, pressurized air system, air extraction)		Pressurized air maintainance	Engines in outdoor air, venetian blinds in outdoor air	Roller shutter system in outdoor air	No parts in outdoor air, controlled climate
5.4	Electricity demand pressurized air or air extraction		Low demand	No demand	No demand	No demand
5.5	Higher electricity demand for artificial lighting (from sun protection glazing)		can be better than option 3	can be better than option 3	Transparent and translucent solar shading system	electric lighting necessary during daytime from daylighting blocked by interior sun shading system
5.6	GFA area efficiency by small facade build up depth		Build up 220-280mm	Build up 250-360mm	Build up 180 mm + 150 mm horizontal roller shutter casement	Build up 180-220mm

Appendix 3: Glass specification provided by AGC glass Europe

Technical specifications

STOPSOL POSITION 1

	EUROPEAN STANDARDS							AMERICAN STANDARDS							
	EN 410 (2011)						EN 673	NFRC 100				NFRC 200 & NFRC 300			
								WINTER		SUMMER					
	External appearance	LT (%)	SF (%)	LR ext (%)	LR int (%)	SC	Ug value W/(m².K) (1)	U-Factor Night time BTU/(hr.ft2.F)	U-Factor Night time W/(m².K)	U-Factor Day time BTU/(hr.ft2.F)	U-Factor Day time W/(m².K)	SC	SHGC	RHG BTU/(hr.ft2)	RHG W/m²
6 mm Stopsol pos. 1 - 16 mm Air - 6 mm Planibel G pos. 3															
Stopsol Classic Clear	amber silver	33	43	34	29	0.49	1.7	0.34	1.94	0.30	1.72	0.53	0.46	109.5	345
Stopsol Classic Grey	silver grey	15	25	32	16	0.28	1.7	0.34	1.94	0.30	1.72	0.31	0.27	67.3	212
Stopsol Classic Green	silver green	26	23	33	23	0.26	1.7	0.34	1.94	0.30	1.72	0.28	0.24	60.2	190
Stopsol Classic Bronze	amber gold	18	27	32	18	0.32	1.7	0.34	1.94	0.30	1.72	0.36	0.31	74.5	235
Stopsol Supersilver Clear	briliant silver	53	57	39	33	0.66	1.7	0.34	1.94	0.30	1.72	0.67	0.58	138.3	436
Stopsol Supersilver Grey	briliant grey	25	31	35	17	0.36	1.7	0.34	1.94	0.30	1.72	0.39	0.34	82.0	259
Stopsol Supersilver Green	steel green	43	31	37	27	0.36	1.7	0.34	1.94	0.30	1.72	0.37	0.32	77.1	243
Stopsol SilverLight PrivaBlue	silvery blue	23	18	25	15	0.21	1.7	0.34	1.94	0.30	1.72	0.23	0.20	49.0	155
Stopsol Classic Dark Blue*	amber blue	21	24	33	20	0.28	1.7	0.34	1.94	0.30	1.72	0.30	0.26	63.6	201
Stopsol Supersilver Dark Blue*	steel blue	33	31	37	22	0.36	1.7	0.34	1.94	0.30	1.72	0.37	0.32	78.2	247
Stopsol Supersilver Blue Green*	amber blue/green	36	29	37	23	0.33	1.7	0.34	1.94	0.30	1.72	0.33	0.29	71.9	227
6 mm Stopsol pos. 1 - 16 mm Air - 6 mm iplus Solid pos.3															
Stopsol Classic Clear	amber silver	29	37	33	22	0.43	1.6	0.33	1.86	0.28	1.59	0.45	0.39	92.7	292
Stopsol Classic Grey	silver grey	14	21	32	12	0.24	1.6	0.33	1.86	0.28	1.59	0.26	0.23	57.5	181
Stopsol Classic Green	silver green	24	21	32	18	0.24	1.6	0.33	1.86	0.28	1.59	0.25	0.22	54.6	172
Stopsol Classic Bronze	amber gold	17	24	32	13	0.28	1.6	0.33	1.86	0.28	1.59	0.30	0.26	63.2	199
Stopsol Supersilver Clear	briliant silver	48	51	36	26	0.59	1.6	0.33	1.86	0.28	1.59	0.59	0.51	120.3	379
Stopsol Supersilver Grey	briliant grey	22	28	34	13	0.32	1.6	0.33	1.86	0.28	1.59	0.34	0.30	71.7	226
Stopsol Supersilver Green	steel green	39	30	35	21	0.34	1.6	0.33	1.86	0.28	1.59	0.33	0.29	71.7	226
Stopsol SilverLight PrivaBlue	silvery blue	21	18	25	11	0.21	1.6	0.33	1.86	0.28	1.59	0.22	0.19	46.7	147
Stopsol Classic Dark Blue*	amber blue	19	22	32	15	0.25	1.6	0.33	1.86	0.28	1.59	0.26	0.23	56.5	178
Stopsol Supersilver Dark Blue*	steel blue	30	29	36	17	0.33	1.6	0.33	1.86	0.28	1.59	0.33	0.29	71.0	224
Stopsol Supersilver Blue Green*	amber blue/green	33	27	35	18	0.31	1.6	0.33	1.86	0.28	1.59	0.31	0.27	66.5	210
6 mm Stopsol pos. 1 - 16 mm Air - 6 mm iplus AS pos.3															
Stopsol Classic Clear	amber silver	35	39	33	27	0.45	1.4	0.31	1.77	0.26	1.45	0.46	0.40	95.5	301
Stopsol Classic Grey	silver grey	17	22	32	13	0.25	1.4	0.31	1.77	0.26	1.45	0.28	0.24	58.2	184
Stopsol Classic Green	silver green	28	21	33	21	0.24	1.4	0.31	1.77	0.26	1.45	0.25	0.22	54.6	172
Stopsol Classic Bronze	amber gold	20	24	32	15	0.28	1.4	0.31	1.77	0.26	1.45	0.30	0.26	64.3	203
Stopsol Supersilver Clear	briliant silver	57	53	37	33	0.61	1.4	0.31	1.77	0.26	1.45	0.61	0.53	124.8	394
Stopsol Supersilver Grey	briliant grey	27	29	34	14	0.33	1.4	0.31	1.77	0.26	1.45	0.34	0.30	73.2	231
Stopsol Supersilver Green	steel green	46	30	36	25	0.34	1.4	0.31	1.77	0.26	1.45	0.34	0.30	72.4	228
Stopsol SilverLight PrivaBlue	silvery blue	24	18	25	12	0.21	1.4	0.31	1.77	0.26	1.45	0.21	0.18	45.8	144
Stopsol Classic Dark Blue*	amber blue	23	22	32	17	0.25	1.4	0.31	1.77	0.26	1.45	0.26	0.23	56.8	179
Stopsol Supersilver Dark Blue*	steel blue	35	30	36	20	0.34	1.4	0.31	1.77	0.26	1.45	0.34	0.30	71.9	227
Stopsol Supersilver Blue Green*	amber blue/green	39	28	36	21	0.32	1.4	0.31	1.77	0.26	1.45	0.32	0.28	67.1	212

Other glass configurations can be calculated on the AGC glass configurator available on www.agc-yourglass.com

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STOPSOL POSITION 2

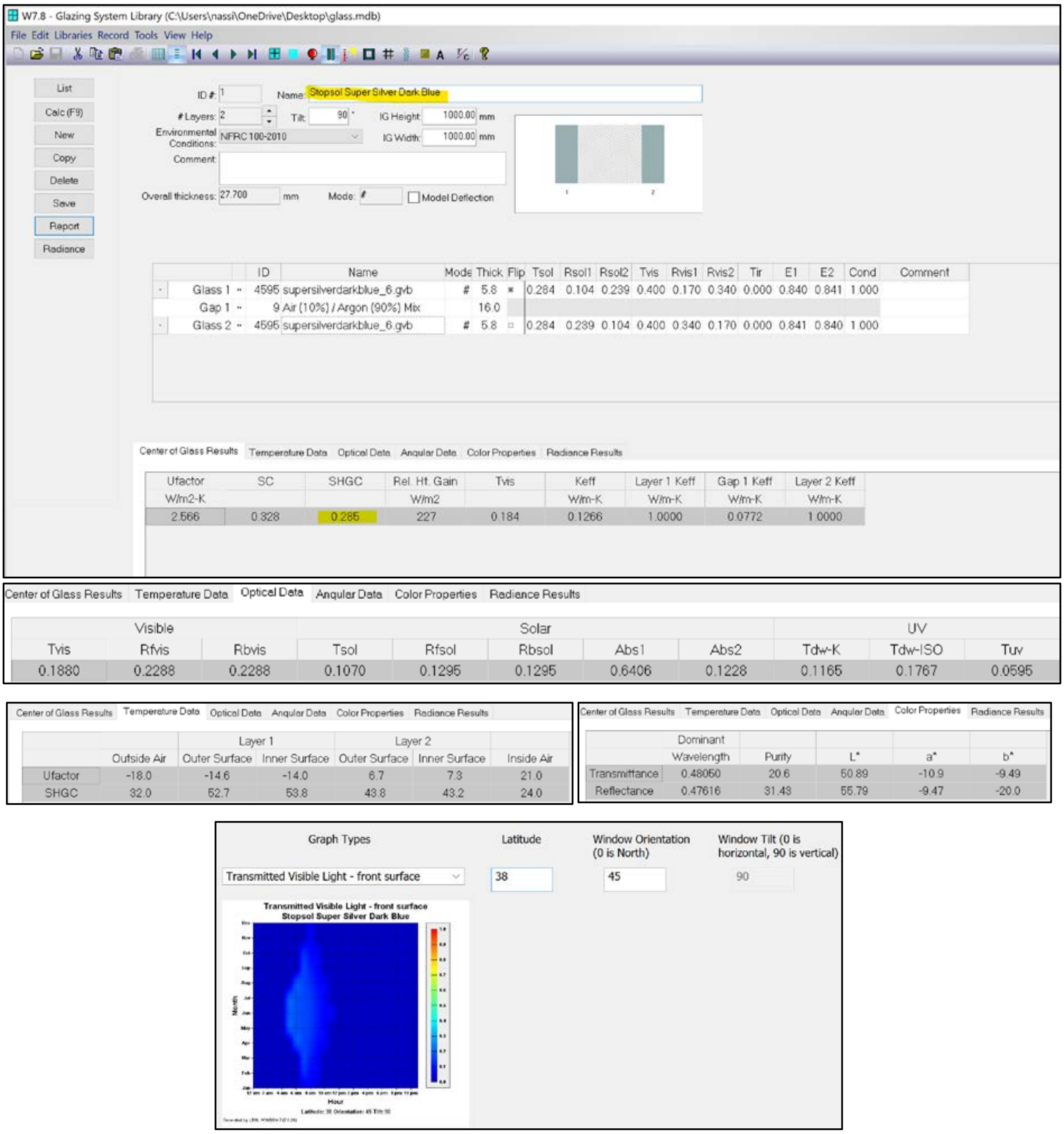
	EUROPEAN STANDARDS							AMERICAN STANDARDS							
	EN 410 (2011)						EN 673	NFRC 100				NFRC 200 & NFRC 300			
								WINTER		SUMMER					
	External appearance	LT (%)	SF (%)	LR ext (%)	LR int (%)	SC	Ug value W/(m².K) (1)	U-Factor Night time BTU/(hr.ft2.F)	U-Factor Night time W/(m².K)	U-Factor Day time BTU/(hr.ft2.F)	U-Factor Day time W/(m².K)	SC	SHGC	RHG BTU/(hr.ft2)	RHG W/m²
6 mm Stopsol pos. 2 - 16 mm Air - 6 mm Planibel G pos. 3															
Stopsol Classic Clear	clear, metallic	33	43	29	32	0.49	1.7	0.34	1.94	0.30	1.72	0.53	0.46	110.9	350
Stopsol Classic Grey	metallic grey	16	26	10	32	0.30	1.7	0.34	1.94	0.30	1.72	0.33	0.29	71.9	227
Stopsol Classic Green	metallic green	27	24	21	32	0.28	1.7	0.34	1.94	0.30	1.72	0.30	0.26	64.4	203
Stopsol Classic Bronze	metallic bronze	19	29	12	32	0.33	1.7	0.34	1.94	0.30	1.72	0.37	0.32	78.8	248
Stopsol Supersilver Clear	slightly bluish silver	53	57	38	34	0.66	1.7	0.34	1.94	0.30	1.72	0.68	0.59	139.1	439
Stopsol Supersilver Grey	metallic steel	25	33	12	33	0.38	1.7	0.34	1.94	0.30	1.72	0.41	0.36	86.4	273
Stopsol Supersilver Green	brilliant green	43	33	27	34	0.38	1.7	0.34	1.94	0.30	1.72	0.38	0.33	80.7	254
Stopsol SilverLight PrivaBlue	intense blue	23	19	9	27	0.22	1.7	0.34	1.94	0.30	1.72	0.24	0.21	52.3	165
Stopsol Classic Dark Blue*	metallic blue	22	25	15	32	0.29	1.7	0.34	1.94	0.30	1.72	0.32	0.28	68.3	215
Stopsol Supersilver Dark Blue*	silvery blue	34	33	19	35	0.38	1.7	0.34	1.94	0.30	1.72	0.39	0.34	82.4	260
Stopsol Supersilver Blue Green*	brilliant blue/green	37	30	21	34	0.34	1.7	0.34	1.94	0.30	1.72	0.36	0.31	76.0	240
6 mm Stopsol pos. 2 - 16 mm Air - 6 mm iplus Solid pos.3															
Stopsol Classic Clear	clear, metallic	30	38	28	25	0.44	1.6	0.33	1.86	0.28	1.59	0.45	0.39	94.0	296
Stopsol Classic Grey	metallic grey	14	23	10	25	0.26	1.6	0.33	1.86	0.28	1.59	0.29	0.25	61.9	195
Stopsol Classic Green	metallic green	24	22	20	25	0.25	1.6	0.33	1.86	0.28	1.59	0.28	0.24	58.5	185
Stopsol Classic Bronze	metallic bronze	17	25	12	25	0.29	1.6	0.33	1.86	0.28	1.59	0.32	0.28	67.3	212
Stopsol Supersilver Clear	slightly bluish silver	48	51	35	27	0.59	1.6	0.33	1.86	0.28	1.59	0.59	0.51	121.2	382
Stopsol Supersilver Grey	metallic steel	23	30	11	26	0.34	1.6	0.33	1.86	0.28	1.59	0.36	0.31	75.8	239
Stopsol Supersilver Green	brilliant green	39	31	25	27	0.36	1.6	0.33	1.86	0.28	1.59	0.36	0.31	74.8	236
Stopsol SilverLight PrivaBlue	intense blue	21	19	8	21	0.22	1.6	0.33	1.86	0.28	1.59	0.23	0.20	49.5	156
Stopsol Classic Dark Blue*	metallic blue	19	23	14	25	0.26	1.6	0.33	1.86	0.28	1.59	0.29	0.25	60.9	192
Stopsol Supersilver Dark Blue*	silvery blue	30	30	18	27	0.34	1.6	0.33	1.86	0.28	1.59	0.36	0.31	74.7	236
Stopsol Supersilver Blue Green*	brilliant blue/green	33	28	20	27	0.32	1.6	0.33	1.86	0.28	1.59	0.33	0.29	70.2	221
6 mm Stopsol pos. 2 - 16 mm Air - 6 mm iplus AS pos.3															
Stopsol Classic Clear	clear, metallic	35	39	28	32	0.45	1.4	0.31	1.77	0.26	1.45	0.47	0.41	96.7	305
Stopsol Classic Grey	metallic grey	17	23	10	31	0.26	1.4	0.31	1.77	0.26	1.45	0.30	0.26	62.3	197
Stopsol Classic Green	metallic green	29	22	20	31	0.25	1.4	0.31	1.77	0.26	1.45	0.28	0.24	58.3	184
Stopsol Classic Bronze	metallic bronze	20	26	12	31	0.30	1.4	0.31	1.77	0.26	1.45	0.32	0.28	68.1	215
Stopsol Supersilver Clear	slightly bluish silver	57	53	36	34	0.61	1.4	0.31	1.77	0.26	1.45	0.61	0.53	125.6	396
Stopsol Supersilver Grey	metallic steel	27	30	11	33	0.34	1.4	0.31	1.77	0.26	1.45	0.37	0.32	77.1	243
Stopsol Supersilver Green	brilliant green	46	31	26	33	0.36	1.4	0.31	1.77	0.26	1.45	0.36	0.31	75.4	238
Stopsol SilverLight PrivaBlue	intense blue	25	19	8	25	0.22	1.4	0.31	1.77	0.26	1.45	0.23	0.20	48.5	153
Stopsol Classic Dark Blue*	metallic blue	23	23	14	31	0.26	1.4	0.31	1.77	0.26	1.45	0.29	0.25	61.0	192
Stopsol Supersilver Dark Blue*	silvery blue	36	31	18	34	0.36	1.4	0.31	1.77	0.26	1.45	0.36	0.31	75.5	238
Stopsol Supersilver Blue Green*	brilliant blue/green	39	29	20	34	0.33	1.4	0.31	1.77	0.26	1.45	0.33	0.29	70.6	222

Other glass configurations can be calculated on the AGC glass configurator, available on www.agc-yourglass.com.

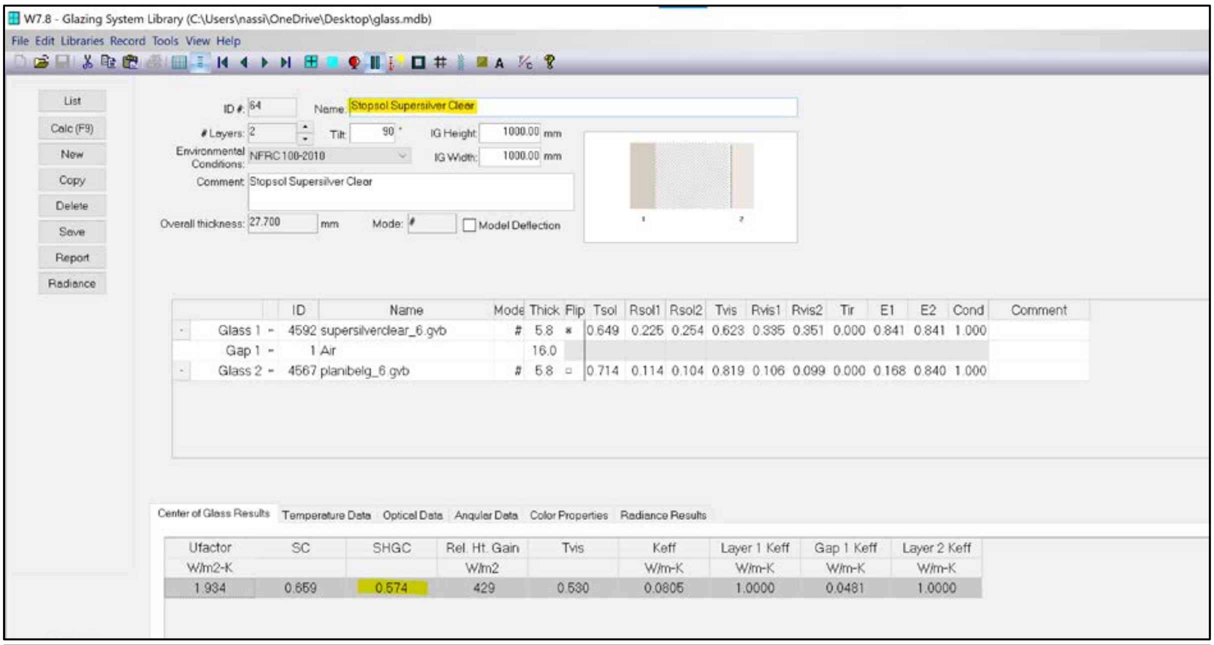
*Made in Indonesia with Belgian technology

For more details about a specific configuration in glazing where we can choose the layers and calculate the U-value, VT, SHGC, etc. instantly and easily:

- The tool “LBNL WINDOW”: https://windows.lbl.gov/software/window
    - Stopsol SuperSilver Dark Blue:



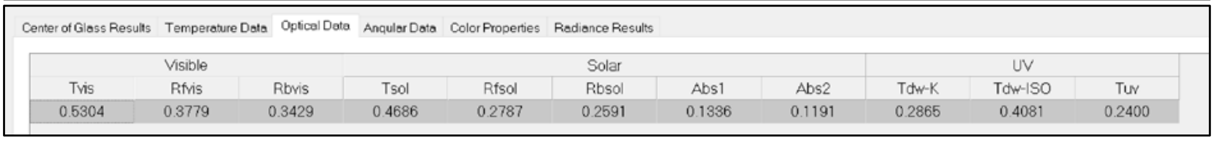
o Stopsol SuperSilver Clear:



	ID	Name	Mode	Thick	Flip	Tsol	Rsol1	Rsol2	Tvis	Rvis1	Rvis2	Tir	E1	E2	Cond	Comment
Glass 1	4592	supersilverclear_6.gvb	#	5.8	☒	0.649	0.225	0.254	0.623	0.335	0.351	0.000	0.841	0.841	1.000	
Gap 1	1	Air		16.0												
Glass 2	4567	planibelg_6.gvb	#	5.8	☐	0.714	0.114	0.104	0.819	0.106	0.099	0.000	0.168	0.840	1.000	

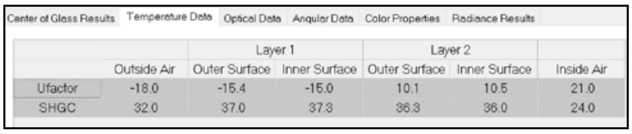
Center of Glass Results | Temperature Data | Optical Data | Angular Data | Color Properties | Radiance Results

Ufactor	SC	SHGC	Rel. Ht. Gain	Tvis	Keff	Layer 1 Keff	Gap 1 Keff	Layer 2 Keff
W/m2-K			W/m2		W/m-K	W/m-K	W/m-K	W/m-K
1.934	0.659	0.574	429	0.530	0.0805	1.0000	0.0481	1.0000



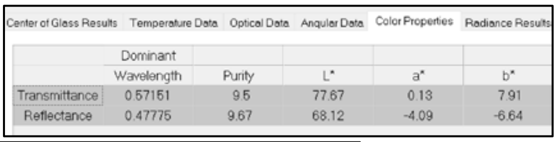
Center of Glass Results | Temperature Data | Optical Data | Angular Data | Color Properties | Radiance Results

Visible			Solar					UV		
Tvis	Rfvis	Rbvis	Tsol	Rfsol	Rbsol	Abs1	Abs2	Tdw-K	Tdw-ISO	Tuv
0.5304	0.3779	0.3429	0.4686	0.2787	0.2591	0.1336	0.1191	0.2865	0.4081	0.2400



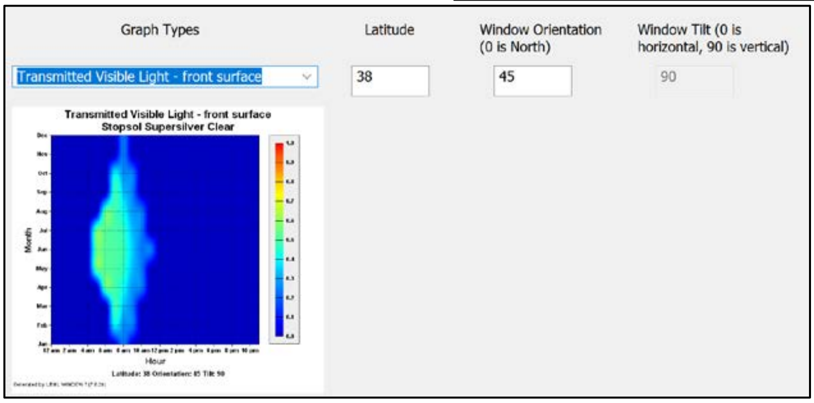
Center of Glass Results | Temperature Data | Optical Data | Angular Data | Color Properties | Radiance Results

		Layer 1		Layer 2		
	Outside Air	Outer Surface	Inner Surface	Outer Surface	Inner Surface	Inside Air
Ufactor	-18.0	-15.4	-15.0	10.1	10.5	21.0
SHGC	32.0	37.0	37.3	36.3	36.0	24.0

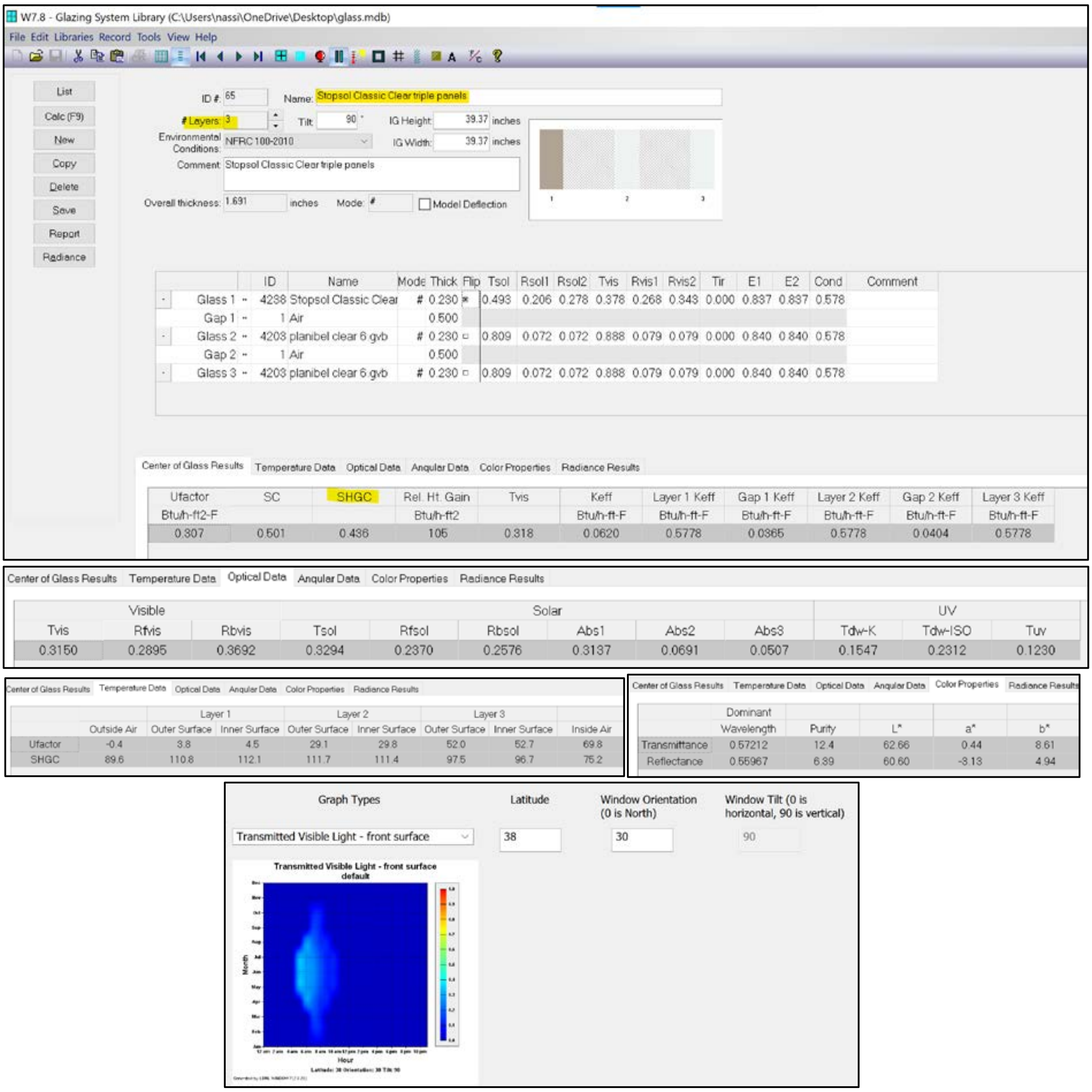


Center of Glass Results | Temperature Data | Optical Data | Angular Data | Color Properties | Radiance Results

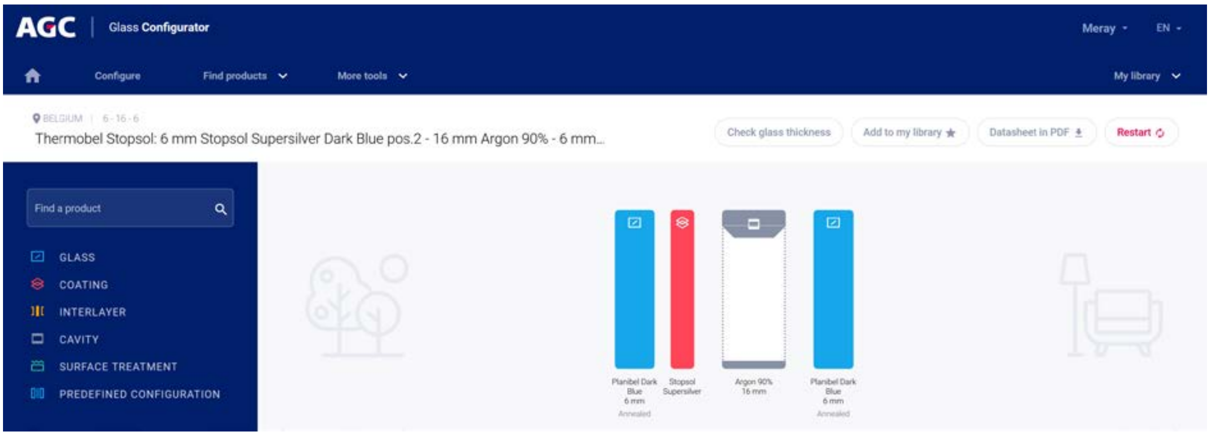
	Dominant Wavelength	Purity	L*	a*	b*
Transmittance	0.57151	9.5	77.67	0.13	7.91
Reflectance	0.47775	9.67	68.12	-4.09	-6.64



- Stopsol Clear triple panels



- AGC online configurator: https://www.agc-yourglass.com/configurator/en
    - o Stropsol Supersilver Dark Blue Double panels



Glass performance data simulation

Light properties - EN 410

Light transmittance : τv [%]	24
External light reflection : ρv [%]	18
Internal light reflection : ρvi [%]	18
Colour rendering index : Ra [%]	67

Energy properties - EN 410

Total solar energy transmittance : g [%]	30
External energy reflection : ρe [%]	12
Internal energy reflection : ρei [%]	12
Direct energy transmission : τe [%]	15
Energy absorption glass 1 : αe1 [%]	59
Energy absorption glass 2 : αe2 [%]	14
Total energy absorption : αe [%]	73
Shading coefficient : SC	0.34
UV transmission : τuv [%]	7
Selectivity	0.80

Thermal properties - EN 673

Thermal transmittance (vertical glazing) : U value [W/(m².K)]	2.6

Acoustic properties

Direct airborne sound reduction - Interpolated : Rw (C;Ctr) [dB] 1	32 (-1;-3)

Safety properties

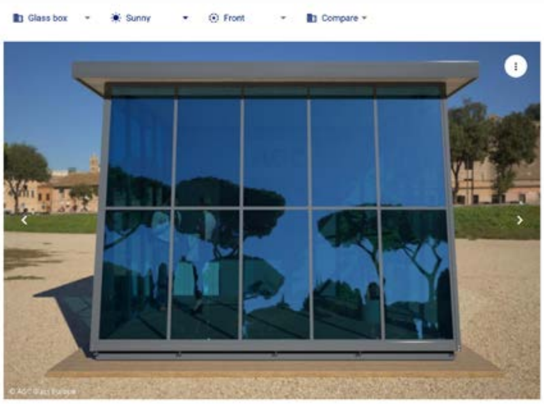
Resistance to fire - EN 13501-2	NPD
Reaction to fire - EN 13501-1	NPD
Bullet resistance - EN 1063	NPD
Burglar resistance - EN 356	NPD
Pendulum body impact resistance - EN 12600	NPD / NPD
Explosion resistance - EN 13541	NPD

Thickness and weight

Nominal thickness : [mm]	28.0
Weight : [kg/m²]	30

1. The sound reduction indexes are interpolated (no test available). They correspond to glazing with dimensions 1230 mm by 1480 mm according to EN ISO 10140-3. In-situ performances may vary according to the effective glazing dimensions, supporting system, installation, environment, noise sources etc. The accuracy of the given indexes is +\/- 2 dB.

Glass Visualizer



- o Stropsol Clear triple panels

Thermobel TG Stopsol:
① 6 mm Stopsol Classic Clear pos.2* Annealed ② 16 mm Air 100% ③ 6 mm Planibel Clearvision** Annealed ④ 16 mm Air 100% ⑤ 6 mm Planibel Clearvision** Annealed

Glass performance data simulation

Light properties - NFRC 200 and NFRC 300

Visible transmittance : Tvis	0.34
External visible reflectance : Rfvis	0.29
Internal visible reflectance : Rbvis	0.41

Energy properties - NFRC 200 and NFRC 300

Solar transmittance : Tsol	0.42
External solar reflectance : Rfsol	0.24
Internal solar reflectance : Rbsol	0.34
Solar abs. glass 1 : αe 1	0.32
Solar abs. glass 2 : αe 2	0.01
Solar abs. glass 3 : αe 3	0.01
Shading coefficient : SC	0.53
UV transmission : Tuv	0.16
Solar heat gain coefficient : SHGC	0.46
Relative heat gain : RHG [W/m²]	350
Relative heat gain : RHG [Btu/h.ft²]	111.0

Thermal transmittance - NFRC 100-2010

U–factor (winter/night) : [W/(m².K)]	1.71
U–factor (summer/day) : [W/(m².K)]	1.87
U–factor (winter/night) : [Btu/(h.ft².F)]	0.30
U–factor (summer/day) : [Btu/(h.ft².F)]	0.33

Acoustic properties - ASTM

Sound transmission class - Interpolated : STC [dB] 1	35
Outdoor-Indoor transmission class - Interpolated : OITC [dB] 1	25

Thickness and weight

Nominal thickness : [mm]	50.0
Weight : [kg/m²]	45

1. The two single number ratings, Sound Transmission Class (STC) and Outdoor-Indoor Transmission Class (OITC), are interpolated (no test available). They correspond to glazing with dimensions 1230 mm by 1480 mm. In-situ performances may vary according to the effective glazing dimensions, supporting system, installation, environment, noise sources etc. The accuracy of the given single number ratings is +/- 2 dB.

* Performance values presented are center of glass based on representative production samples and product modeling utilizing NFRC 100 Environmental Design Considerations. Actual values may differ due to variations in the manufacturing process.

** The data are calculated using spectral measurements that are conform to standards EN 410 and WIS/WINDAT. This product is not officially registered in the IGDB.

- Shading device: ES-SO ESBO Light 2.3, EN14501

win-ref: output object in building1.Room.Wall 3.window

EQUA SIMULATION TECHNOLOGY GROUP

Standard properties of glazing with solar shading

Project		**Window**	
Case	Building	Glazing	Glazing-D_EN14501
Created by	meray nassimos	Solar shading	Generic interior blind slat material
Customer		Simulated	28/07/2021 20:42:11

		Without shading	**With shading**
EN ISO 52022-3 (summer conditions):			
Total solar energy transmittance	g_{tot}	0.334	0.273
Convection factor	g_c	0.019	0.043
Thermal radiation factor	g_{th}	0.040	0.092
Ventilation factor	g_v	0.000	0.053
Secondary internal heat transfer factor	q_i	0.059	0.188
EN ISO 52022-3 (reference conditions):			
Total solar energy transmittance	g_{tot}	0.321	0.260
U-value of glazing	U_g	1.053	0.972
EN 410:			
Direct solar transmittance	τ_e	0.275	0.085
Solar reflectance outside	ρ_e	0.288	0.315
Solar reflectance inside	ρ'_e	0.379	0.399
Visual transmittance	τ_v	0.626	0.175
Visual reflectance outside	ρ_v	0.105	0.235
Visual reflectance inside	ρ'_v	0.126	0.379

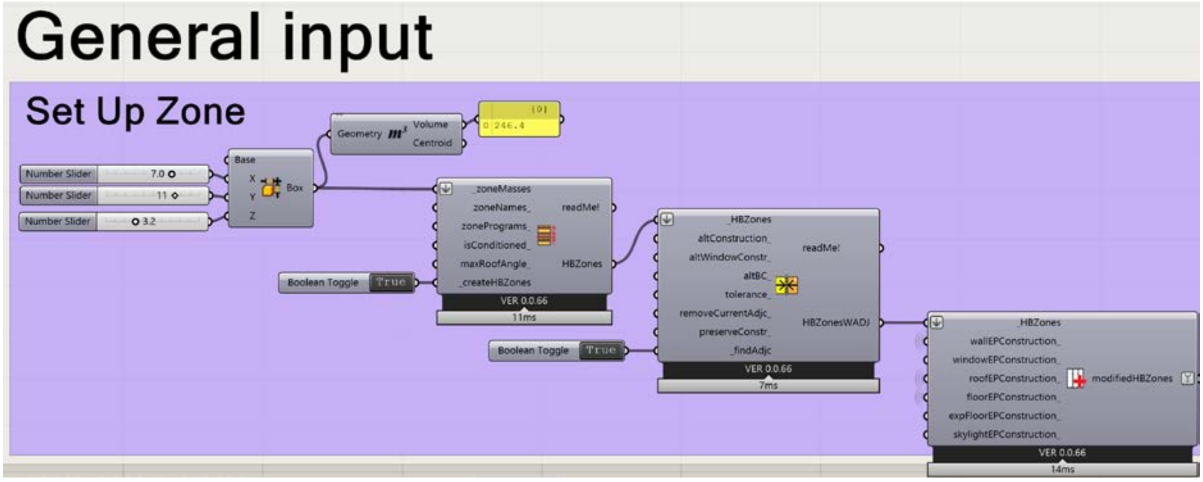
	Layer	**d [mm]**	**T [°C]**	**α_e [-]**
	Outside		25.0	
1.	Solar_glass-EN14501	4.0	40.8	0.432
2.	Argon - EN673 (WIN7)	16.0	37.4	
3.	Clear_glass-EN14501	4.0	34.0	0.046
4.	Air	59.4	26.6	
5.	Generic interior blind	21.2	33.6	0.123
	Inside		25.0	

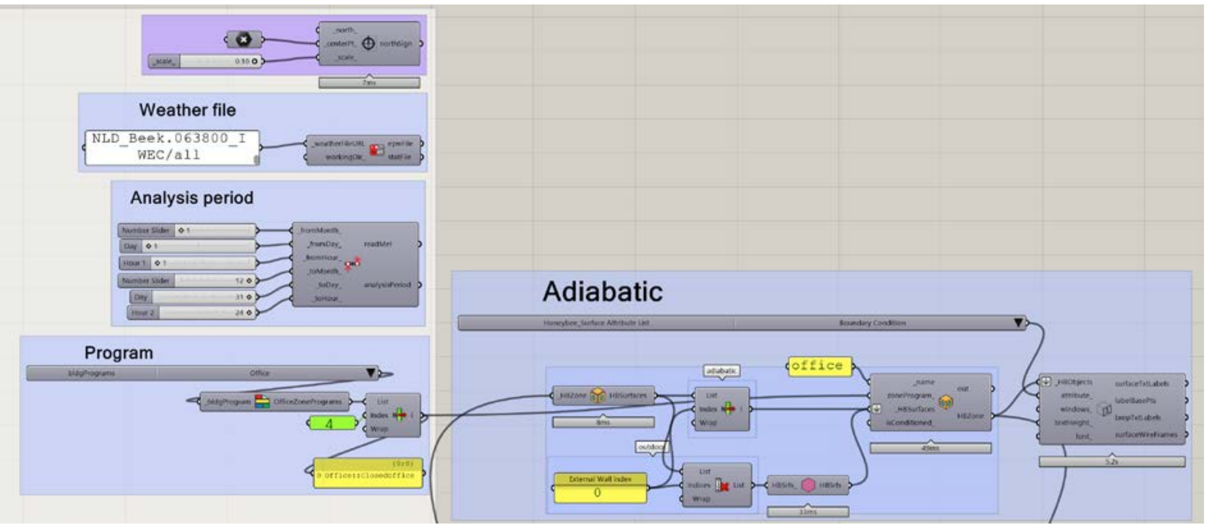
Hide ISO 15099 properties

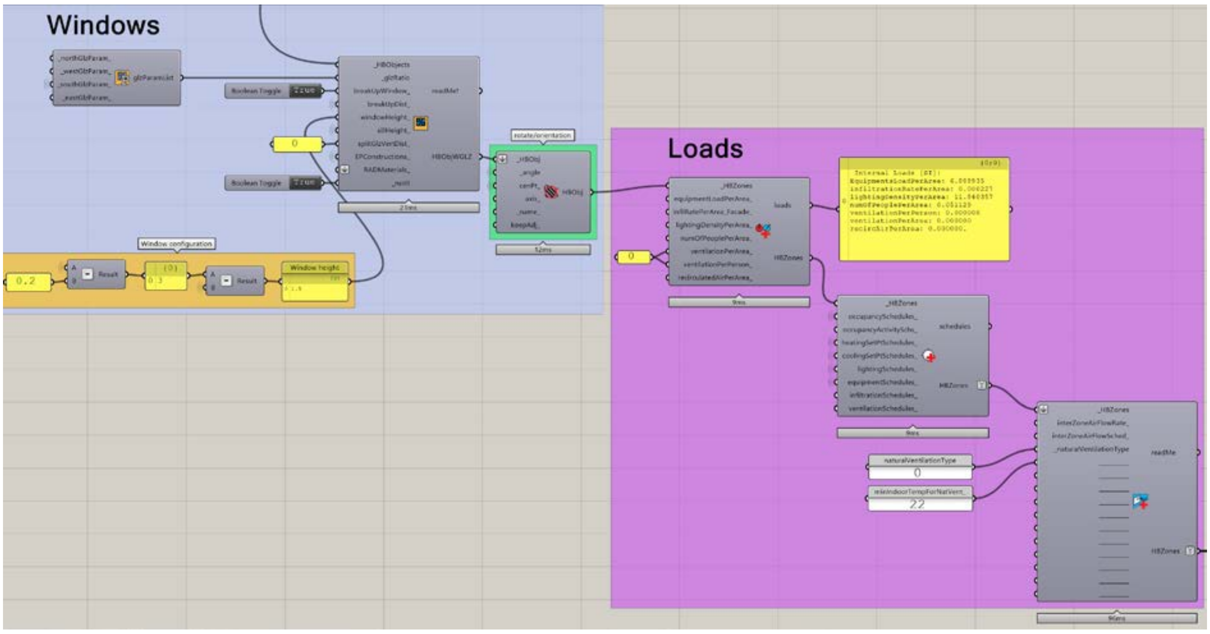
		Without shading	**With shading**
ISO 15099 (summer conditions):			
Total solar energy transmittance	g_{tot}	0.335	0.275
ISO 15099 (winter conditions):			
U-value of glazing	U_g	1.209	1.123

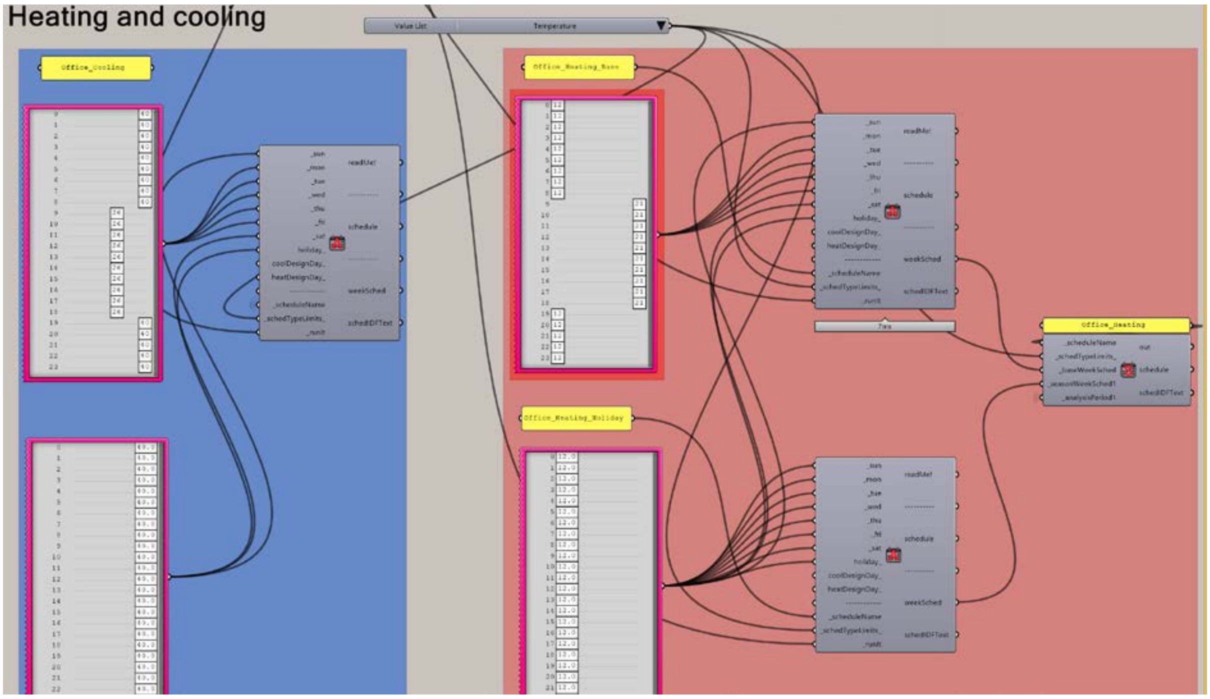
IDA Indoor Climate and Energy
Version: 4.98038

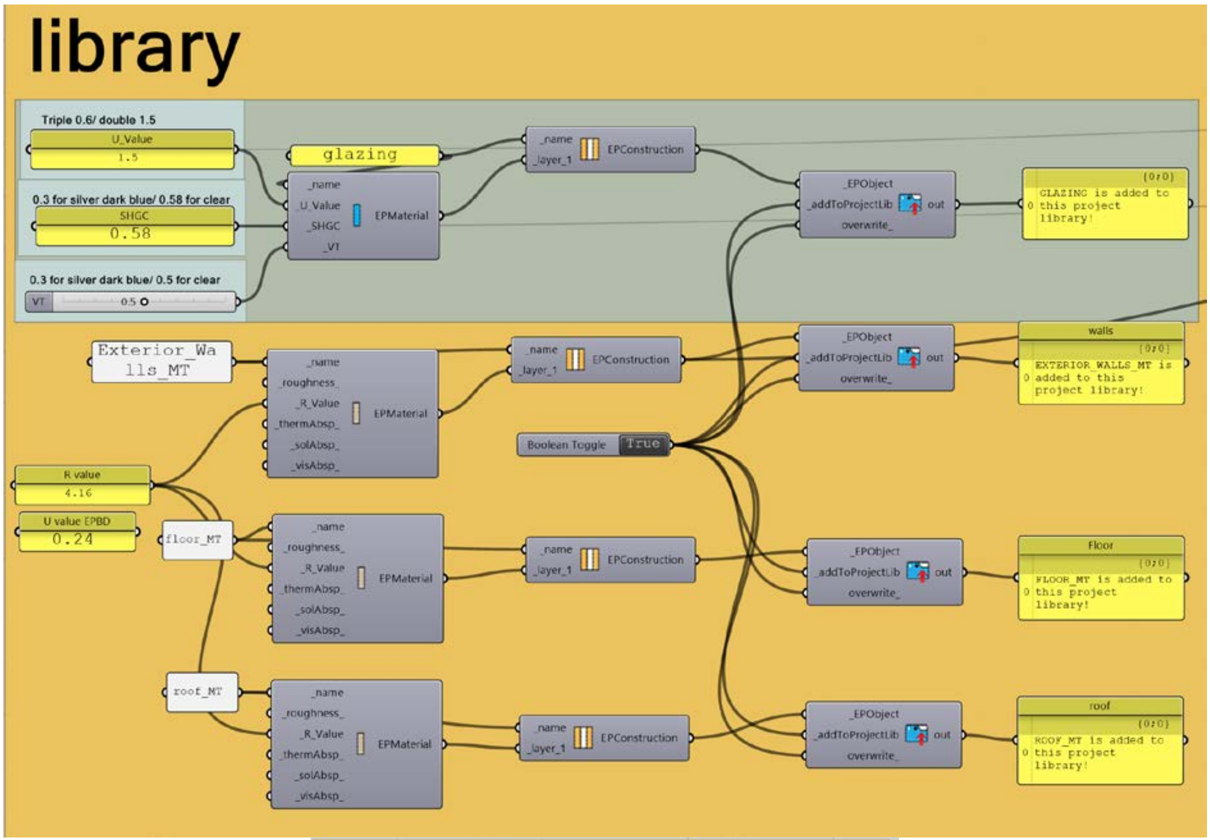
Appendix 4: Screenshots of parametric programming workflows made in Grasshopper

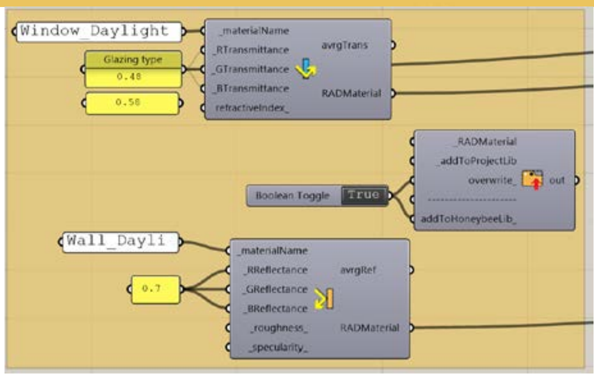


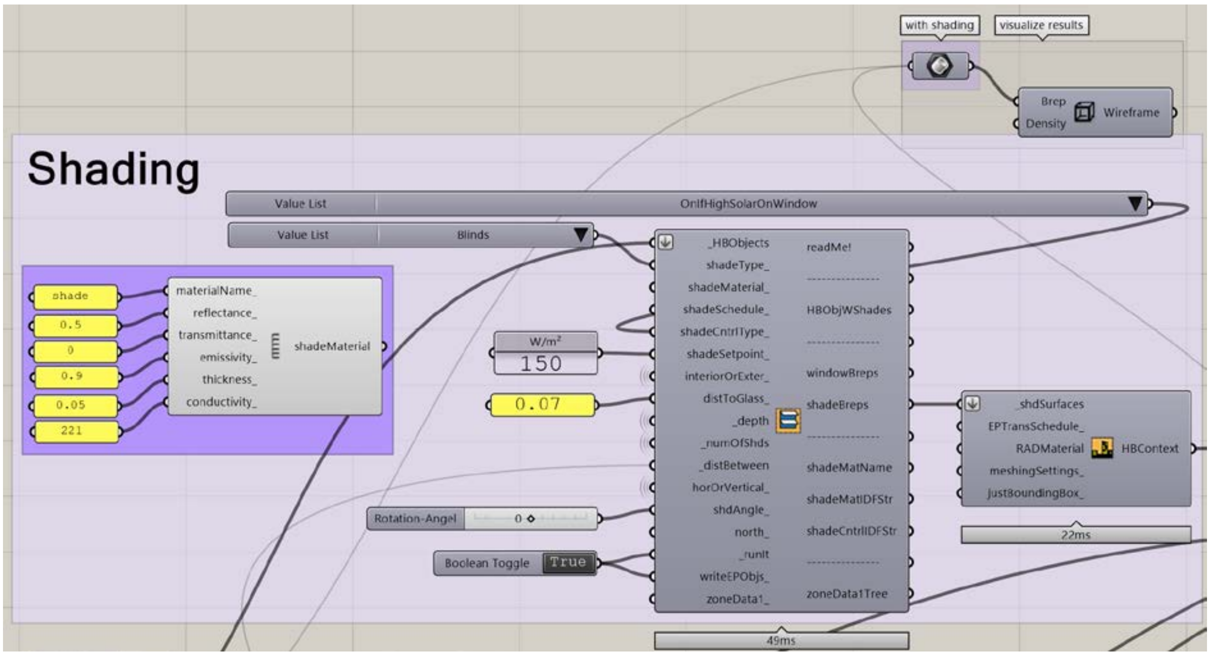



Windows
Loads

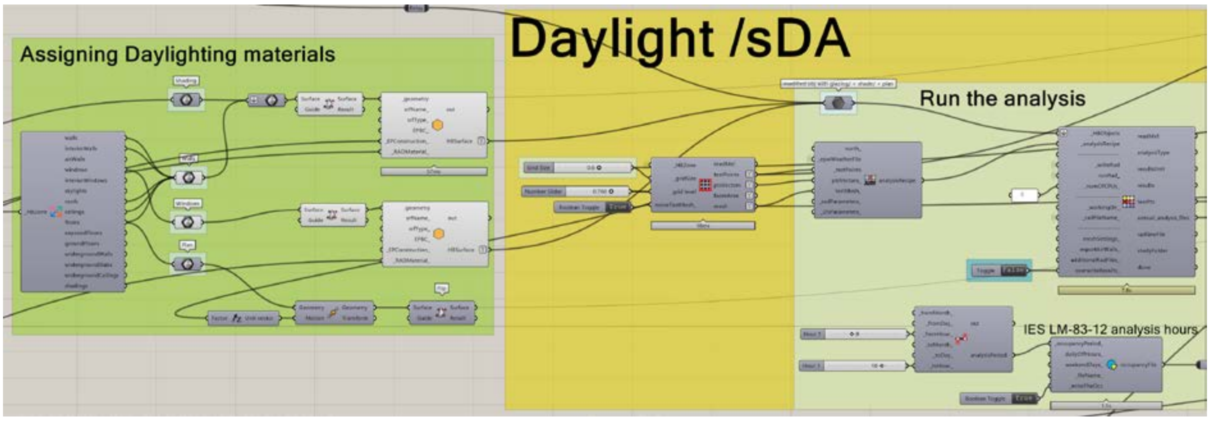

Heating and cooling


library
Triple 0.6/ double 1.5
U_Value
1.5
glazing
0.3 for silver dark blue/ 0.58 for clear
SHGC
0.58
0.3 for silver dark blue/ 0.5 for clear
VT
0.5
_name
U_Value
_SHGC
_VT
EPMaterial
_name
_layer_1
EPConstruction
_EPObject
_addToProjectLib
overwrite_
out
GLAZING is added to this project library!
Exterior_Walls_MT
_name
roughness
_R_Value
thermAbsp
solAbsp
visAbsp
EPMaterial
Boolean Toggle
True
walls
EXTERIOR_WALLS_MT is added to this project library!
R value
4.16
U value EPBD
0.24
floor_MT
Floor
FLOOR_MT is added to this project library!
roof_MT
roof
ROOF_MT is added to this project library!

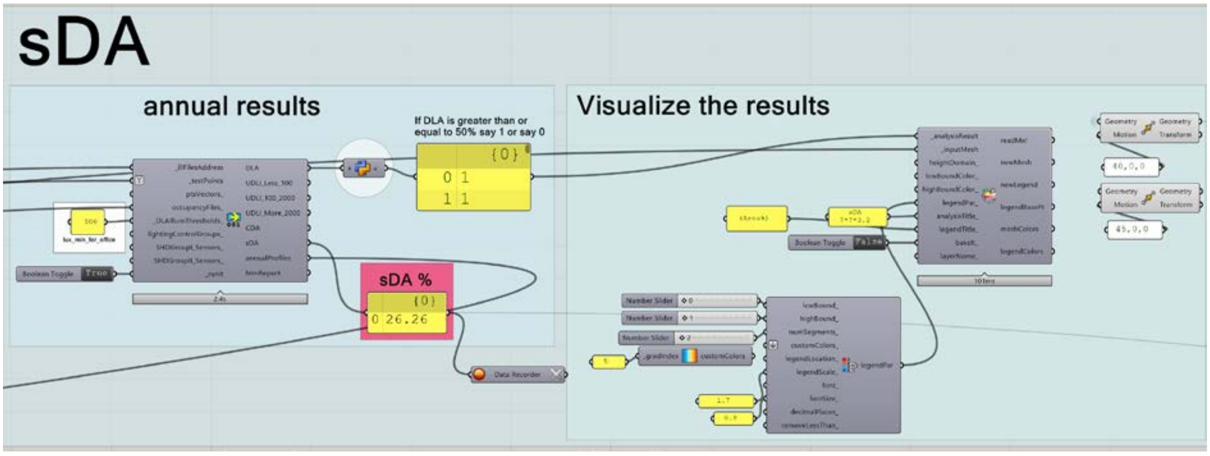

Window_Daylight
Glazing type
0.48
0.58
_materialName
_RTransmittance
_GTransmittance
_BTransmittance
refractiveIndex_
avrgTrans
RADMaterial
_RADMaterial
_addToProjectLib
overwrite_
out
addToHoneybeeLib_
Boolean Toggle
True
Wall_Dayli
0.7
_materialName
_RReflectance
_GReflectance
_BReflectance
roughness
specularity
avrgRef
RADMaterial



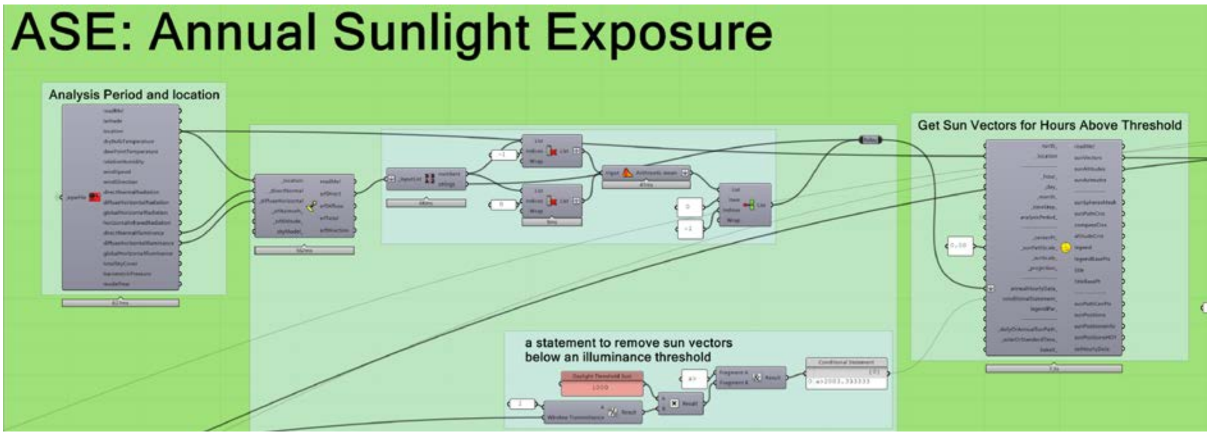
with shading
visualize results
Brep
Density
Wireframe
Shading
Value List
OnlfHighSolarOnWindow
Value List
Blinds
_HBObjects
shadeType_
shadeMaterial_
shadeSchedule_
shadeCntrlType_
shadeSetpoint_
interiorOrExter_
distToGlass_
_depth
_numOfShds
_distBetween
horOrVertical_
shdAngle_
north_
_runIt
writeEPObjs_
zoneData1_
readMe!
HBObjWShades
windowBreps
shadeBreps
shadeMatName
shadeMatIDFStr
shadeCntrlIDFStr
zoneData1Tree
49ms
shade
0.5
0
0.9
0.05
221
materialName_
reflectance_
transmittance_
emissivity_
thickness_
conductivity_
shadeMaterial
W/m²
150
0.07
Rotation-Angel
0
Boolean Toggle
True
_shdSurfaces
EPTransSchedule_
RADMaterial
HBContext
meshingSettings_
JustBoundingBox_
22ms

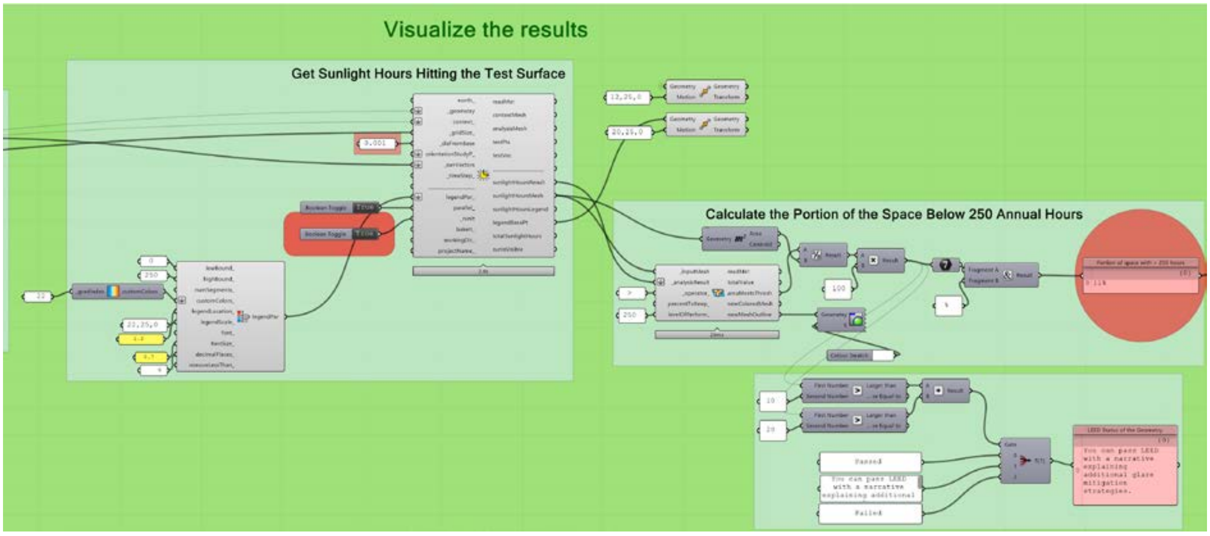


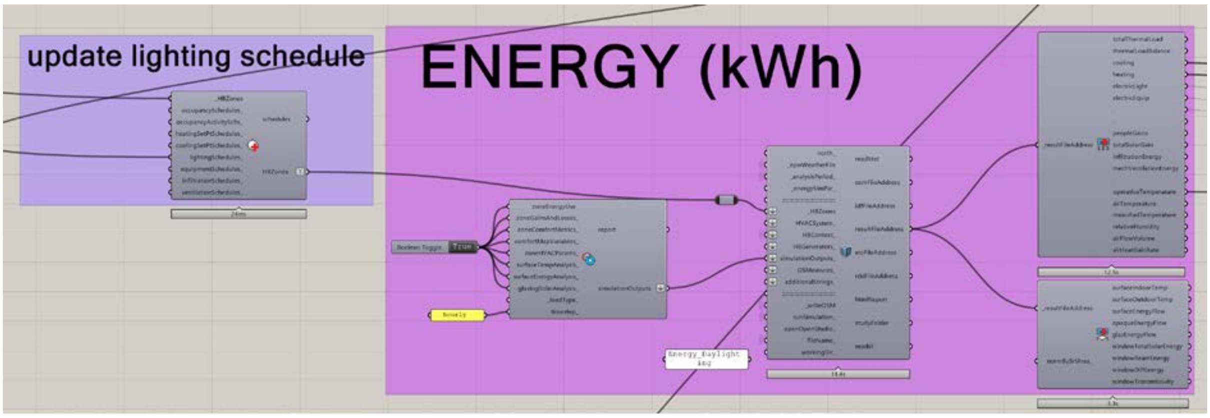
Daylight /sDA
Assigning Daylighting materials
Run the analysis
IES LM-83-12 analysis hours

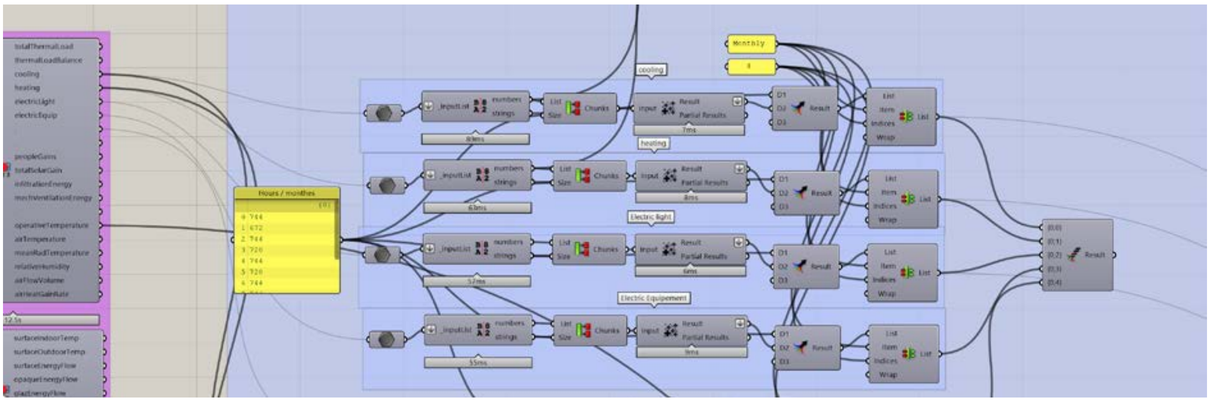


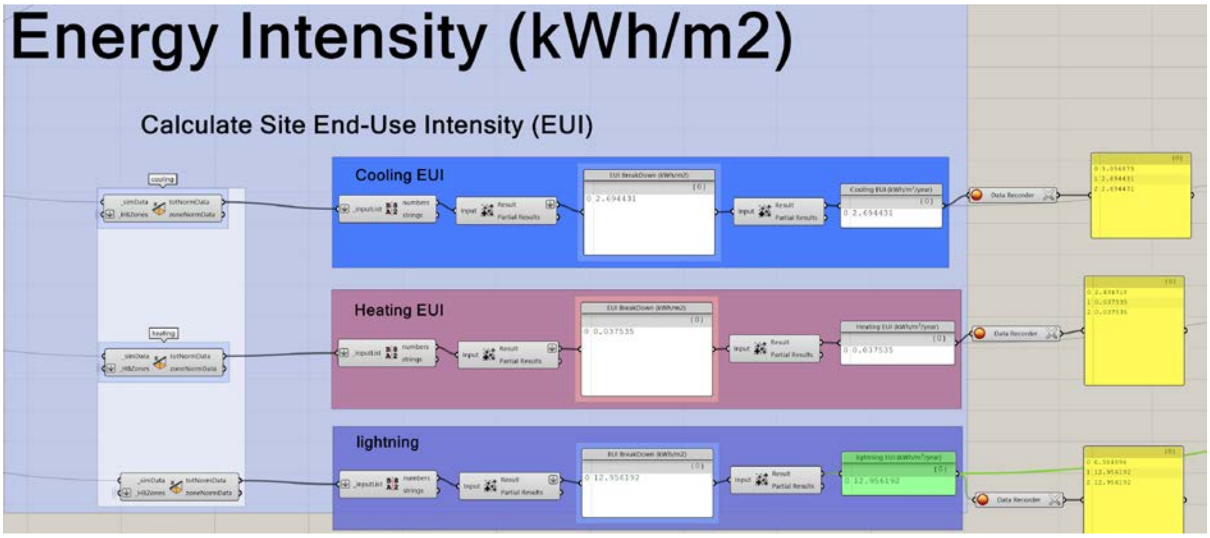
sDA
annual results
Visualize the results
If DLA is greater than or equal to 50% say 1 or say 0
{0}
0 1
1 1
sDA %
{0}
0 26.26
Data Recorder
Boolean Toggle
True
False

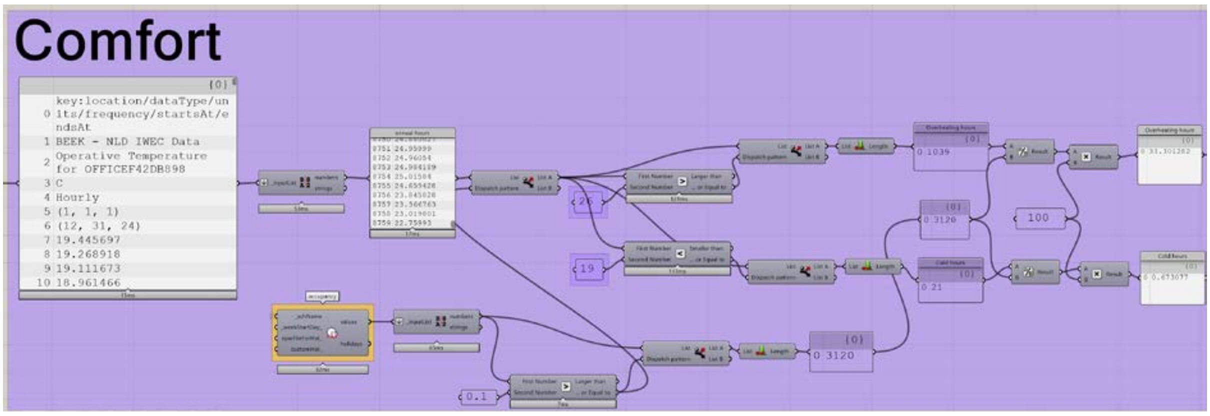

ASE: Annual Sunlight Exposure
Analysis Period and location
Get Sun Vectors for Hours Above Threshold
a statement to remove sun vectors below an illuminance threshold

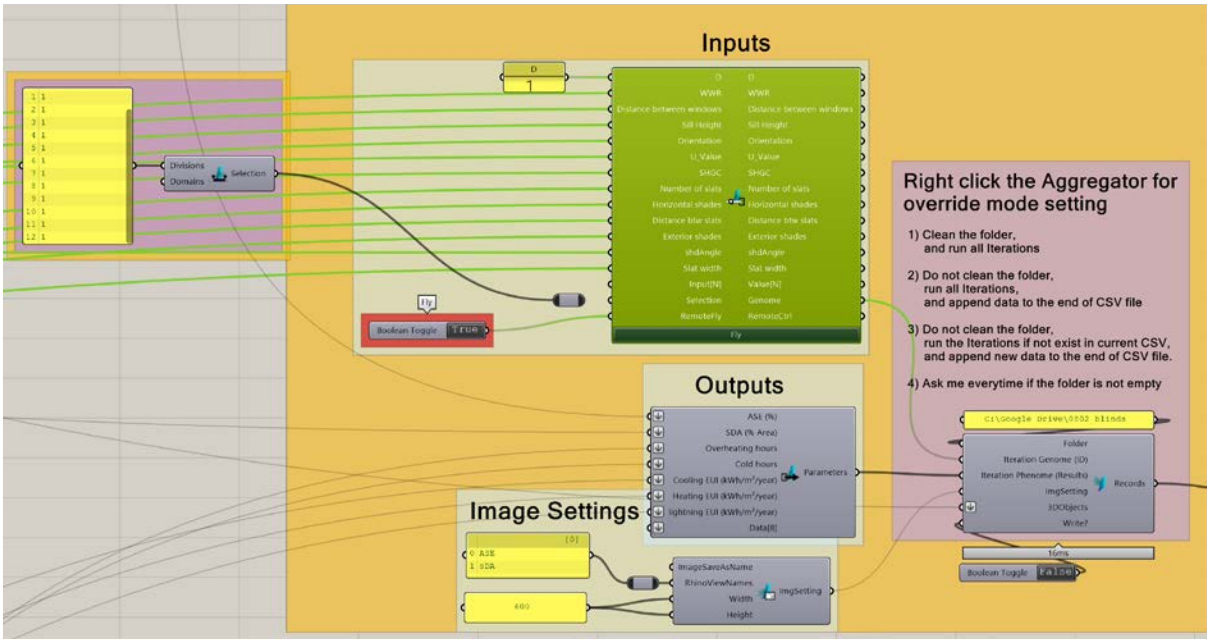

Visualize the results
Get Sunlight Hours Hitting the Test Surface
Calculate the Portion of the Space Below 250 Annual Hours

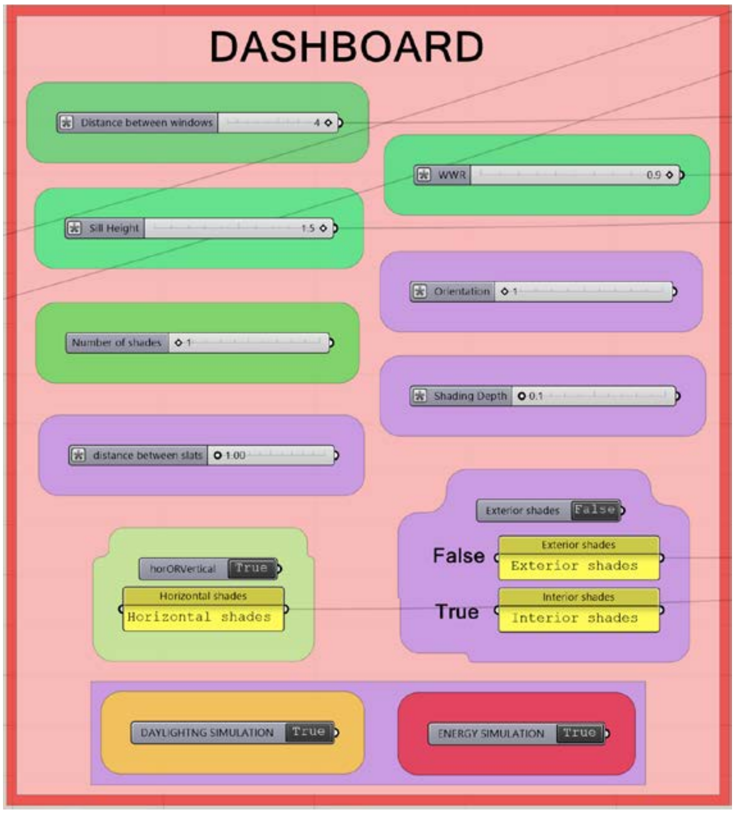

update lighting schedule
ENERGY (kWh)




Energy Intensity (kWh/m2)
Calculate Site End-Use Intensity (EUI)
Cooling EUI
Heating EUI
lightning


Comfort


Inputs
Right click the Aggregator for override mode setting
1) Clean the folder, and run all Iterations
2) Do not clean the folder, run all Iterations, and append data to the end of CSV file
3) Do not clean the folder, run the Iterations if not exist in current CSV, and append new data to the end of CSV file.
4) Ask me everytime if the folder is not empty
Outputs
Image Settings


DASHBOARD
Distance between windows
WWR
Sill Height
Orientation
Number of shades
Shading Depth
distance between slats
Exterior shades
False
True
horORVertical
Horizontal shades
Interior shades
DAYLIGHTING SIMULATION
ENERGY SIMULATION

Appendix 5: The usability testing for the tool

Early design tool for facades in Belgium

The purpose of this research is to create parametric design workflows for facades based on an energetic performance. This method, as shown in earlier studies, can help to save design time when we have too many choices. In particular, this study investigates a parametric design for façades of office buildings in cities that have climate like that of Belgium. This study aims to take into account the relationship between designing a façade and the energetic effect of this glazed façade on the comfort of occupancy and energy consumption.
Depending on variable inputs, based on European standards and norms, and by using the parametric program "Grasshopper", we obtain many options to help façade designers choose between and arrive at the optimal choice combining the desired design target and energetic needs. As a result, the designer has a simple and effective tool.

To access the tool please follow the link below:
http://tt-acm.github.io/DesignExplorer/?ID=BL_2Vq9uuJ

To evaluate the efficency of the tool, we need you to answer the following questions please.

Please note that data is collected anonymously and it is for an academic research purpose. You need about 4-6 minutes to answer the questions below.

Next

Page 1 of 5

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Google Forms

Early design tool for facades in Belgium

* Required

General questions

1) Evaluator profile: I am a *

- ◯ Student
- ◯ Teacher
- ◯ Architect
- ◯ Façade designer
- ◯ Energy Engineer
- ◯ Other: ____________

If other please specify your field

Your answer

2) Are you interested in the subject of building facade? *

	1	2	3	4	5	
Not at all	◯	◯	◯	◯	◯	Very interested

3) When you design a facade, do you usally think about the energy aspect (thermal comfort, visual comfort, energy consumption, price...)

- ◯ Yes, at the same time of facade conception.
- ◯ First I choose my facade's design, then the energetic studies come later at the end after I fix my design.
- ◯ I follow a a circle: design --> energetic studies --> design modifications.
- ◯ I do not think about the energetic aspect (I am not interessted).
- ◯ I do not think about the energetic aspect (it is the specialist's mission).
- ◯ Other: ____________

4) What tool do you already use to choose/create your facade design?

Your answer

Back Next Page 2 of 5

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Section 3 of 5

The interaction with the suggested tool:

Description (optional)

5) I would use the design tool regularly *

	1	2	3	4	5	
Strongly disagree	○	○	○	○	○	Strongly agree

6) I found it unnecessarily complex *

	1	2	3	4	5	
Strongly disagree	○	○	○	○	○	Strongly agree

7) It was easy to use the tool by Design Explorer *

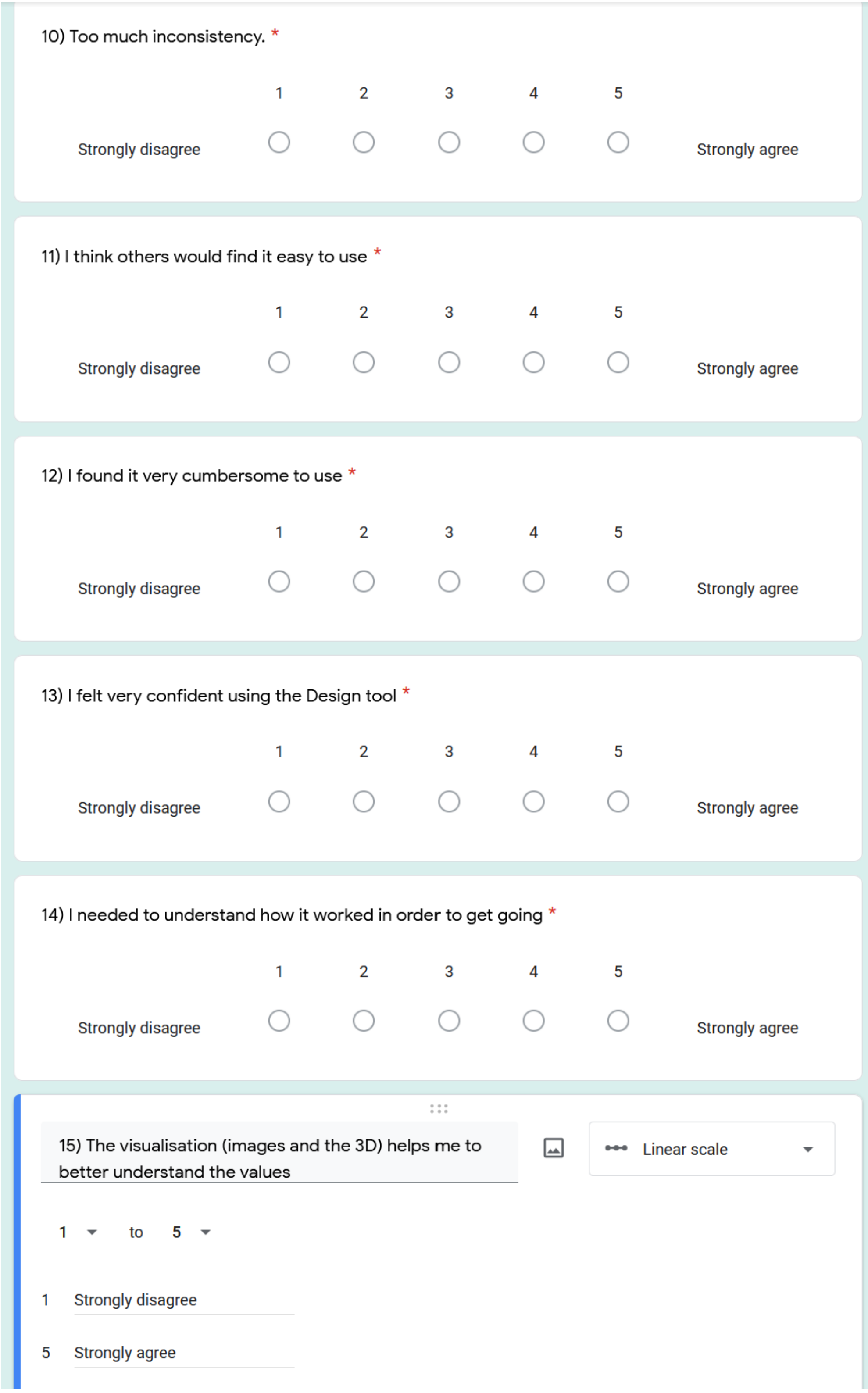
	1	2	3	4	5	
Strongly disagree	○	○	○	○	○	Strongly agree

8) I would need help to use it. *

	1	2	3	4	5	
Strongly disagree	○	○	○	○	○	Strongly agree

9) The various parts of the interface worked well together. *

	1	2	3	4	5	
Strongly disagree	○	○	○	○	○	Strongly agree



10) Too much inconsistency. *

Strongly disagree 1 2 3 4 5 Strongly agree

11) I think others would find it easy to use *

Strongly disagree 1 2 3 4 5 Strongly agree

12) I found it very cumbersome to use *

Strongly disagree 1 2 3 4 5 Strongly agree

13) I felt very confident using the Design tool *

Strongly disagree 1 2 3 4 5 Strongly agree

14) I needed to understand how it worked in order to get going *

Strongly disagree 1 2 3 4 5 Strongly agree

15) The visualisation (images and the 3D) helps me to better understand the values

Linear scale

1 to 5

1 Strongly disagree

5 Strongly agree

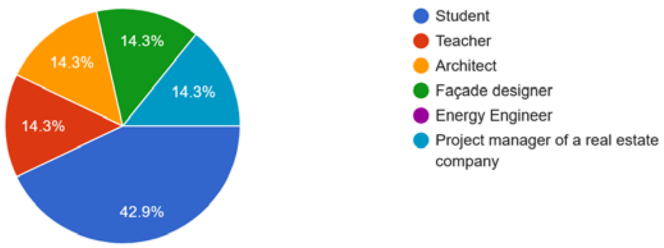
Questions Responses 7

Please note that data is collected anonymously and it is for an academic research purpose. You need about 5-7 minutes to answer the questions below.

General questions

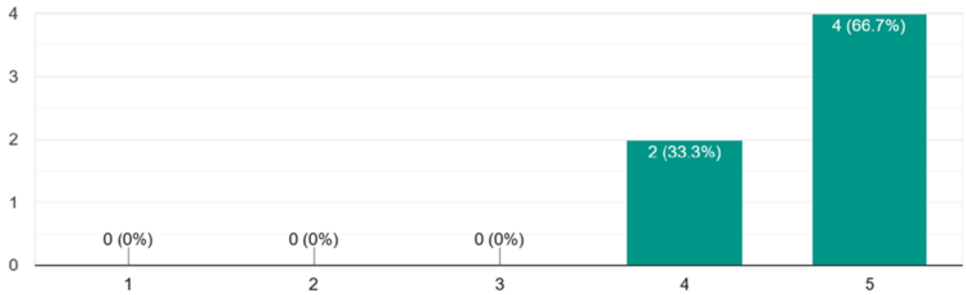
1) Evaluator profile: I am a

7 responses



2) Are you interested in the subject of building facade?

7 responses



3) When you design a facade, do you usally think about the energy aspect (thermal comfort, visual comfort, energy consumption, price...)

7 responses

4) What tool do you already use to choose/create your facade design?

4 responses

No Specific tools, but several input from our engineer and architects offices

Thermal simulations, sun study tools

Design builder

Vectorworks

Timestamp	1) Evaluator profile: I am a	5) I would use the design tool regularly	6) I found it unnecessarily complex	7) It was easy to use the tool by Design Explorer	8) I would need help to use it.	9) The various parts of the interface worked well together.	10) Too much inconsistency.	11) I think others would find it easy to use	12) I found it very cumbersome to use	13) I felt very confident using the Design tool	14) I needed to understand how it worked in order to get going	15) The visualisation (images and the 3D) helps me to better understand the values
7/16/2021 22:53:58	Student	4	2	4	Just at the beginning like a little tutorial	4	3	4	2	4	3	2
7/18/2021 10:27:06	Student	4	1	5	1	4	1	5	1	5	4	5
7/18/2021 19:43:25	Project manager of a real estate company	5	1	5	4	5	1	5	1	5	4	5
7/19/2021 13:17:26	Student	4	2	4	2	4	1	4	2	4	3	4
7/28/2021 9:50:38	Façade designer	4	2	4	2	4	1	4	2	4	3	2
7/30/2021 15:07:18	Teacher	4	1	4	2	4	1	3	2	3	5	5
8/1/2021 14:59:14	Architect	3	1	5	3	5	1	4	2	4	4	5

Appendix 6: Best alternatives

- Regarding thresholds of ASE and sDA- inputs features

	WWR	RR	Distance btw windows	Sill Height	Orientation	Uw_Value	SHGC	N of slats	Hor/Ver slats	Distance btw slats	Int/Ext slats	Slats Angle	Slat width
1	0.5	1	4	1	NO	1.5	0.3	0	NA	NA	NA	0	NA
2	0.5	1	4	1	NO	1.5	0.58	0	NA	NA	NA	0	NA
3	0.5	1	2	1	NE	1.5	0.3	0	NA	NA	NA	0	NA
4	0.5	1	4	1	NE	1.5	0.3	0	NA	NA	NA	0	NA
5	0.5	1	2	1	NE	1.5	0.58	0	NA	NA	NA	0	NA
6	0.5	1	4	1	NE	1.5	0.58	0	NA	NA	NA	0	NA
7	0.5	1	2	1	NE	1.5	0.58	0	NA	NA	NA	0	NA
8	0.5	1	4	1	NE	1.5	0.58	0	NA	NA	NA	0	NA
9	0.6	1	2	1	N	1.5	0.3	0	NA	NA	NA	0	NA
10	0.6	1	4	1	N	1.5	0.3	0	NA	NA	NA	0	NA
11	0.6	1	2	1.5	N	1.5	0.3	0	NA	NA	NA	0	NA
12	0.6	1	4	1.5	N	1.5	0.3	0	NA	NA	NA	0	NA
13	0.6	1	2	1.5	NO	1.5	0.3	0	NA	NA	NA	0	NA
14	0.6	1	4	1.5	NO	1.5	0.3	0	NA	NA	NA	0	NA
15	0.6	1	2	1	N	1.5	0.58	0	NA	NA	NA	0	NA
16	0.6	1	4	1	N	1.5	0.58	0	NA	NA	NA	0	NA
17	0.6	1	2	1.5	N	1.5	0.58	0	NA	NA	NA	0	NA
18	0.6	1	4	1.5	N	1.5	0.58	0	NA	NA	NA	0	NA
19	0.6	1	2	1.5	NO	1.5	0.58	0	NA	NA	NA	0	NA
20	0.6	1	4	1.5	NO	1.5	0.58	0	NA	NA	NA	0	NA
21	0.6	1	2	0.5	NE	1.5	0.3	0	NA	NA	NA	0	NA
22	0.6	1	4	0.5	NE	1.5	0.3	0	NA	NA	NA	0	NA
23	0.6	1	2	1	NE	1.5	0.3	0	NA	NA	NA	0	NA
24	0.6	1	4	1	NE	1.5	0.3	0	NA	NA	NA	0	NA
25	0.6	1	2	1.5	NE	1.5	0.3	0	NA	NA	NA	0	NA
26	0.6	1	4	1.5	NE	1.5	0.3	0	NA	NA	NA	0	NA
27	0.6	1	2	1	S	1.5	0.58	NA	roller shade	NA	Int	NA	NA
28	0.6	1	4	1	S	1.5	0.58	NA	roller shade	NA	Int	NA	NA
29	0.6	1	2	1.5	S	1.5	0.58	NA	roller shade	NA	Int	NA	NA
30	0.6	1	4	1.5	S	1.5	0.58	NA	roller shade	NA	Int	NA	NA
31	0.6	1	4	0.5	NE	1.5	0.58	0	NA	NA	NA	0	NA
32	0.6	1	2	1	NE	1.5	0.58	0	NA	NA	NA	0	NA
33	0.6	1	4	1	NE	1.5	0.58	0	NA	NA	NA	0	NA
34	0.6	1	2	1.5	NE	1.5	0.58	0	NA	NA	NA	0	NA
35	0.6	1	4	1.5	NE	1.5	0.58	0	NA	NA	NA	0	NA
36	0.6	1	4	0.5	NE	1.5	0.58	0	NA	NA	NA	0	NA
37	0.6	1	2	1	NE	1.5	0.58	0	NA	NA	NA	0	NA
38	0.6	1	4	1	NE	1.5	0.58	0	NA	NA	NA	0	NA
39	0.6	1	2	1.5	NE	1.5	0.58	0	NA	NA	NA	0	NA
40	0.6	1	4	1.5	NE	1.5	0.58	0	NA	NA	NA	0	NA
41	0.7	1	2	0.5	N	1.5	0.3	0	NA	NA	NA	0	NA
42	0.7	1	4	0.5	N	1.5	0.3	0	NA	NA	NA	0	NA
43	0.7	1	2	1	N	1.5	0.3	0	NA	NA	NA	0	NA
44	0.7	1	4	1	N	1.5	0.3	0	NA	NA	NA	0	NA
45	0.7	1	2	1.5	N	1.5	0.3	0	NA	NA	NA	0	NA
46	0.7	1	4	1.5	N	1.5	0.3	0	NA	NA	NA	0	NA
47	0.7	1	2	0.5	N	1.5	0.58	0	NA	NA	NA	0	NA
48	0.7	1	4	0.5	N	1.5	0.58	0	NA	NA	NA	0	NA

	WWR	RR	Distance btw windows	Sill Height	Orientation	Uw_Value	SHGC	N of slats	Hor/Ver slats	Distance btw slats	Int/Ext slats	Slats Angle	Slat width
49	0.7	1	2	1	N	1.5	0.58	0	NA	NA	NA	0	NA
50	0.7	1	4	1	N	1.5	0.58	0	NA	NA	NA	0	NA
51	0.7	1	2	1.5	N	1.5	0.58	0	NA	NA	NA	0	NA
52	0.7	1	4	1.5	N	1.5	0.58	0	NA	NA	NA	0	NA
53	0.7	1	2	0.5	NE	1.5	0.3	0	NA	NA	NA	0	NA
54	0.7	1	4	0.5	NE	1.5	0.3	0	NA	NA	NA	0	NA
55	0.7	1	2	0.5	S	1.5	0.58	NA	roller shade	NA	Int	NA	NA
56	0.7	1	4	0.5	S	1.5	0.58	NA	roller shade	NA	Int	NA	NA
57	0.7	1	2	1	S	1.5	0.58	NA	roller shade	NA	Int	NA	NA
58	0.7	1	4	1	S	1.5	0.58	NA	roller shade	NA	Int	NA	NA
59	0.7	1	2	1.5	S	1.5	0.58	NA	roller shade	NA	Int	NA	NA
60	0.7	1	4	1.5	S	1.5	0.58	NA	roller shade	NA	Int	NA	NA
61	0.7	1	2	0.5	NE	1.5	0.58	0	NA	NA	NA	0	NA
62	0.7	1	4	0.5	NE	1.5	0.58	0	NA	NA	NA	0	NA
63	0.7	1	2	0.5	NE	1.5	0.58	0	NA	NA	NA	0	NA
64	0.7	1	4	0.5	NE	1.5	0.58	0	NA	NA	NA	0	NA
65	0.8	1	2	0.5	N	1.5	0.3	0	NA	NA	NA	0	NA
66	0.8	1	4	0.5	N	1.5	0.3	0	NA	NA	NA	0	NA
67	0.8	1	2	1	N	1.5	0.3	0	NA	NA	NA	0	NA
68	0.8	1	4	1	N	1.5	0.3	0	NA	NA	NA	0	NA
69	0.8	1	2	1.5	N	1.5	0.3	0	NA	NA	NA	0	NA
70	0.8	1	4	1.5	N	1.5	0.3	0	NA	NA	NA	0	NA
71	0.8	1	2	0.5	N	1.5	0.58	0	NA	NA	NA	0	NA
72	0.8	1	4	0.5	N	1.5	0.58	0	NA	NA	NA	0	NA
73	0.8	1	2	1	N	1.5	0.58	0	NA	NA	NA	0	NA
74	0.8	1	4	1	N	1.5	0.58	0	NA	NA	NA	0	NA
75	0.8	1	2	1.5	N	1.5	0.58	0	NA	NA	NA	0	NA
76	0.8	1	4	1.5	N	1.5	0.58	0	NA	NA	NA	0	NA
77	0.8	1	2	0.5	S	1.5	0.58	NA	roller shade	NA	Int	NA	NA
78	0.8	1	4	0.5	S	1.5	0.58	NA	roller shade	NA	Int	NA	NA
79	0.8	1	2	1	S	1.5	0.58	NA	roller shade	NA	Int	NA	NA
80	0.8	1	4	1	S	1.5	0.58	NA	roller shade	NA	Int	NA	NA
81	0.8	1	2	1.5	S	1.5	0.58	NA	roller shade	NA	Int	NA	NA
82	0.8	1	4	1.5	S	1.5	0.58	NA	roller shade	NA	Int	NA	NA
83	0.9	1	2	0.5	N	1.5	0.3	0	NA	NA	NA	0	NA
84	0.9	1	4	0.5	N	1.5	0.3	0	NA	NA	NA	0	NA
85	0.9	1	2	1	N	1.5	0.3	0	NA	NA	NA	0	NA
86	0.9	1	4	1	N	1.5	0.3	0	NA	NA	NA	0	NA
87	0.9	1	2	1.5	N	1.5	0.3	0	NA	NA	NA	0	NA
88	0.9	1	4	1.5	N	1.5	0.3	0	NA	NA	NA	0	NA
89	0.9	1	2	0.5	N	1.5	0.58	0	NA	NA	NA	0	NA
90	0.9	1	4	0.5	N	1.5	0.58	0	NA	NA	NA	0	NA
91	0.9	1	2	1	N	1.5	0.58	0	NA	NA	NA	0	NA
92	0.9	1	4	1	N	1.5	0.58	0	NA	NA	NA	0	NA
93	0.9	1	2	1.5	N	1.5	0.58	0	NA	NA	NA	0	NA
94	0.9	1	4	1.5	N	1.5	0.58	0	NA	NA	NA	0	NA
95	0.9	1	2	0.5	S	1.5	0.58	NA	Hor	0.025	Ext	0	0.03
96	0.9	1	4	0.5	S	1.5	0.58	NA	Hor	0.025	Ext	0	0.03
97	0.9	1	2	1	S	1.5	0.58	NA	Hor	0.025	Ext	0	0.03
98	0.9	1	4	1	S	1.5	0.58	NA	Hor	0.025	Ext	0	0.03
99	0.9	1	2	1.5	S	1.5	0.58	NA	Hor	0.025	Ext	0	0.03

	WWR	RR	Distance btw windows	Sill Height	Orientation	Uw_Value	SHGC	N of slats	Hor/Ver slats	Distance btw slats	Int/Ext slats	Slats Angle	Slat width
49	0.7	1	2	1	N	1.5	0.58	0	NA	NA	NA	0	NA
50	0.7	1	4	1	N	1.5	0.58	0	NA	NA	NA	0	NA
51	0.7	1	2	1.5	N	1.5	0.58	0	NA	NA	NA	0	NA
52	0.7	1	4	1.5	N	1.5	0.58	0	NA	NA	NA	0	NA
53	0.7	1	2	0.5	NE	1.5	0.3	0	NA	NA	NA	0	NA
54	0.7	1	4	0.5	NE	1.5	0.3	0	NA	NA	NA	0	NA
55	0.7	1	2	0.5	S	1.5	0.58	NA	roller shade	NA	Int	NA	NA
56	0.7	1	4	0.5	S	1.5	0.58	NA	roller shade	NA	Int	NA	NA
57	0.7	1	2	1	S	1.5	0.58	NA	roller shade	NA	Int	NA	NA
58	0.7	1	4	1	S	1.5	0.58	NA	roller shade	NA	Int	NA	NA
59	0.7	1	2	1.5	S	1.5	0.58	NA	roller shade	NA	Int	NA	NA
60	0.7	1	4	1.5	S	1.5	0.58	NA	roller shade	NA	Int	NA	NA
61	0.7	1	2	0.5	NE	1.5	0.58	0	NA	NA	NA	0	NA
62	0.7	1	4	0.5	NE	1.5	0.58	0	NA	NA	NA	0	NA
63	0.7	1	2	0.5	NE	1.5	0.58	0	NA	NA	NA	0	NA
64	0.7	1	4	0.5	NE	1.5	0.58	0	NA	NA	NA	0	NA
65	0.8	1	2	0.5	N	1.5	0.3	0	NA	NA	NA	0	NA
66	0.8	1	4	0.5	N	1.5	0.3	0	NA	NA	NA	0	NA
67	0.8	1	2	1	N	1.5	0.3	0	NA	NA	NA	0	NA
68	0.8	1	4	1	N	1.5	0.3	0	NA	NA	NA	0	NA
69	0.8	1	2	1.5	N	1.5	0.3	0	NA	NA	NA	0	NA
70	0.8	1	4	1.5	N	1.5	0.3	0	NA	NA	NA	0	NA
71	0.8	1	2	0.5	N	1.5	0.58	0	NA	NA	NA	0	NA
72	0.8	1	4	0.5	N	1.5	0.58	0	NA	NA	NA	0	NA
73	0.8	1	2	1	N	1.5	0.58	0	NA	NA	NA	0	NA
74	0.8	1	4	1	N	1.5	0.58	0	NA	NA	NA	0	NA
75	0.8	1	2	1.5	N	1.5	0.58	0	NA	NA	NA	0	NA
76	0.8	1	4	1.5	N	1.5	0.58	0	NA	NA	NA	0	NA
77	0.8	1	2	0.5	S	1.5	0.58	NA	roller shade	NA	Int	NA	NA
78	0.8	1	4	0.5	S	1.5	0.58	NA	roller shade	NA	Int	NA	NA
79	0.8	1	2	1	S	1.5	0.58	NA	roller shade	NA	Int	NA	NA
80	0.8	1	4	1	S	1.5	0.58	NA	roller shade	NA	Int	NA	NA
81	0.8	1	2	1.5	S	1.5	0.58	NA	roller shade	NA	Int	NA	NA
82	0.8	1	4	1.5	S	1.5	0.58	NA	roller shade	NA	Int	NA	NA
83	0.9	1	2	0.5	N	1.5	0.3	0	NA	NA	NA	0	NA
84	0.9	1	4	0.5	N	1.5	0.3	0	NA	NA	NA	0	NA
85	0.9	1	2	1	N	1.5	0.3	0	NA	NA	NA	0	NA
86	0.9	1	4	1	N	1.5	0.3	0	NA	NA	NA	0	NA
87	0.9	1	2	1.5	N	1.5	0.3	0	NA	NA	NA	0	NA
88	0.9	1	4	1.5	N	1.5	0.3	0	NA	NA	NA	0	NA
89	0.9	1	2	0.5	N	1.5	0.58	0	NA	NA	NA	0	NA
90	0.9	1	4	0.5	N	1.5	0.58	0	NA	NA	NA	0	NA
91	0.9	1	2	1	N	1.5	0.58	0	NA	NA	NA	0	NA
92	0.9	1	4	1	N	1.5	0.58	0	NA	NA	NA	0	NA
93	0.9	1	2	1.5	N	1.5	0.58	0	NA	NA	NA	0	NA
94	0.9	1	4	1.5	N	1.5	0.58	0	NA	NA	NA	0	NA
95	0.9	1	2	0.5	S	1.5	0.58	NA	Hor	0.025	Ext	0	0.03
96	0.9	1	4	0.5	S	1.5	0.58	NA	Hor	0.025	Ext	0	0.03
97	0.9	1	2	1	S	1.5	0.58	NA	Hor	0.025	Ext	0	0.03
98	0.9	1	4	1	S	1.5	0.58	NA	Hor	0.025	Ext	0	0.03
99	0.9	1	2	1.5	S	1.5	0.58	NA	Hor	0.025	Ext	0	0.03

	WWR	RR	Distance btw windows	Sill Height	Orientation	Uw_Value	SHGC	N of slats	Hor/Ver slats	Distance btw slats	Int/Ext slats	Slats Angle	Slat width
100	0.9	1	4	1.5	S	1.5	0.58	NA	Hor	0.025	Ext	0	0.03
101	0.9	1	2	0.5	S	1.5	0.58	NA	roller shade	NA	Int	NA	NA
102	0.9	1	4	0.5	S	1.5	0.58	NA	roller shade	NA	Int	NA	NA
103	0.9	1	2	1	S	1.5	0.58	NA	roller shade	NA	Int	NA	NA
104	0.9	1	4	1	S	1.5	0.58	NA	roller shade	NA	Int	NA	NA
105	0.9	1	2	1.5	S	1.5	0.58	NA	roller shade	NA	Int	NA	NA
106	0.9	1	4	1.5	S	1.5	0.58	NA	roller shade	NA	Int	NA	NA

- Regarding thresholds of ASE and sDA- inputs features

	ASE (area%)	sDA (area%)	Overheating h/y	Cold h/y	Cooling EUI (kWh/m²/y)	Heating EUI (kWh/m²/y)	Lightning EUI (kWh/m²/y)
1	0.07	0.4132	19.230769	12.115385	2.781499	2.488483	9.456892
2	0.07	0.4132	41.923077	8.301282	4.93008	1.471628	9.456892
3	0.01	0.4132	20.512821	13.173077	2.420969	2.758425	8.884648
4	0.02	0.4132	20.160256	13.108974	2.637467	2.509852	9.492295
5	0.01	0.4132	43.269231	8.717949	4.252191	1.601387	8.891397
6	0.02	0.4132	43.397436	8.525641	4.431042	1.475936	9.449196
7	0.01	0.4132	43.269231	8.717949	4.252191	1.601387	8.891397
8	0.02	0.4132	43.397436	8.525641	4.431042	1.475936	9.449196
9	0	0.438	14.903846	17.275641	2.493171	4.122777	8.1792
10	0	0.4545	15.064103	17.628205	2.4702	4.108703	8.189265
11	0	0.4628	14.871795	18.557692	2.880037	4.55332	7.320774
12	0	0.4628	14.871795	18.557692	2.880037	4.55332	7.320774
13	0.05	0.4959	19.230769	17.820513	2.896727	4.267886	7.397381
14	0.05	0.4959	19.230769	17.820513	2.896727	4.267886	7.397381
15	0	0.438	38.589744	10.801282	4.940653	2.410667	8.1792
16	0	0.4545	38.653846	11.602564	4.889528	2.3983	8.189265
17	0	0.4628	38.301282	12.115385	5.784732	2.753759	7.320774
18	0	0.4628	38.301282	12.115385	5.784732	2.753759	7.320774
19	0.05	0.4959	42.051282	11.314103	5.347309	2.518586	7.397381
20	0.05	0.4959	42.051282	11.314103	5.347309	2.518586	7.397381
21	0.06	0.405	20.512821	16.826923	2.677122	3.95057	8.789452
22	0.06	0.4132	21.666667	15.801282	2.700788	3.846285	9.456419
23	0.08	0.4463	20.25641	17.916667	2.660738	4.325122	7.294015
24	0.07	0.4463	20.99359	17.692308	2.686945	4.271499	7.647804
25	0	0.5041	20.576923	17.564103	2.650001	4.287105	7.290344
26	0	0.5041	20.576923	17.564103	2.650001	4.287105	7.290344
27	0	0.4215	69.00641	0.705128	11.671483	0.054028	11.023017
28	0	0.438	69.647436	0.737179	11.479412	0.0625	10.595462
29	0	0.4298	69.871795	0.705128	11.318128	0.059114	11.324591
30	0	0.4298	69.871795	0.705128	11.318128	0.059114	11.324591
31	0.06	0.4132	43.878205	10.384615	4.825803	2.228449	9.098958
32	0.08	0.4463	43.237179	10.833333	4.767408	2.526869	7.666275
33	0.07	0.4463	43.397436	10.320513	4.795994	2.385645	7.954351
34	0	0.5041	43.205128	11.025641	4.772066	2.541179	7.314972
35	0	0.5041	43.205128	11.025641	4.772066	2.541179	7.314972
36	0.06	0.4132	43.878205	10.384615	4.825803	2.228449	9.098958
37	0.08	0.4463	43.237179	10.833333	4.767408	2.526869	7.666275
38	0.07	0.4463	43.397436	10.320513	4.795994	2.385645	7.954351
39	0	0.5041	43.205128	11.025641	4.772066	2.541179	7.314972
40	0	0.5041	43.205128	11.025641	4.772066	2.541179	7.314972
41	0	0.438	15.384615	19.839744	2.993207	5.41557	8.247519
42	0	0.438	15.064103	19.74359	2.596957	5.424723	8.27937
43	0	0.4793	14.903846	21.057692	2.900496	5.925347	6.909085
44	0	0.4793	14.903846	21.057692	2.900496	5.925347	6.909085
45	0	0.4793	14.903846	21.057692	2.900496	5.925347	6.909085
46	0	0.4793	14.903846	21.057692	2.900496	5.925347	6.909085
47	0	0.438	38.525641	13.621795	6.267271	3.263903	8.247519
48	0	0.438	38.653846	13.621795	5.268182	3.26422	8.27937

	ASE (area%)	sDA (area%)	Overheating h/y	Cold h/y	Cooling EUI (kWh/m²/y)	Heating EUI (kWh/m²/y)	Lightning EUI (kWh/m²/y)
49	0	0.4793	38.012821	14.262821	6.076237	3.61263	6.909085
50	0	0.4793	38.012821	14.262821	6.076237	3.61263	6.909085
51	0	0.4793	38.012821	14.262821	6.076237	3.61263	6.909085
52	0	0.4793	38.012821	14.262821	6.076237	3.61263	6.909085
53	0.07	0.4463	21.474359	20.160256	2.686055	5.424403	7.821384
54	0.09	0.4463	21.282051	20.128205	2.826025	5.587122	7.569658
55	0	0.4298	69.967949	0.929487	11.929867	0.131406	10.690422
56	0	0.405	70.128205	1.153846	12.695462	0.144611	11.965865
57	0	0.4545	69.326923	1.057692	12.402353	0.131434	10.044885
58	0	0.4545	69.326923	1.057692	12.402353	0.131434	10.044885
59	0	0.4545	69.326923	1.057692	12.402353	0.131434	10.044885
60	0	0.4545	69.326923	1.057692	12.402353	0.131434	10.044885
61	0.07	0.4463	43.910256	12.596154	4.990072	3.186605	7.894557
62	0.09	0.4463	44.070513	13.49359	5.148256	3.366397	7.582564
63	0.07	0.4463	43.910256	12.596154	4.990072	3.186605	7.894557
64	0.09	0.4463	44.070513	13.49359	5.148256	3.366397	7.582564
65	0	0.4545	15.480769	22.307692	2.755728	7.147516	7.458478
66	0	0.4545	15.480769	22.307692	2.755728	7.147516	7.458478
67	0	0.4959	15.096154	22.147436	2.997661	7.179376	7.102675
68	0	0.4959	15.096154	22.147436	2.997661	7.179376	7.102675
69	0	0.4959	15.096154	22.147436	2.997661	7.179376	7.102675
70	0	0.4959	15.096154	22.147436	2.997661	7.179376	7.102675
71	0	0.4545	39.166667	16.346154	5.77909	4.352296	7.458478
72	0	0.4545	39.166667	16.346154	5.77909	4.352296	7.458478
73	0	0.4959	38.717949	16.089744	6.549834	4.462925	7.102675
74	0	0.4959	38.717949	16.089744	6.549834	4.462925	7.102675
75	0	0.4959	38.717949	16.089744	6.549834	4.462925	7.102675
76	0	0.4959	38.717949	16.089744	6.549834	4.462925	7.102675
77	0	0.4793	69.647436	1.730769	13.313069	0.285222	10.132978
78	0	0.4793	69.647436	1.730769	13.313069	0.285222	10.132978
79	0	0.4711	69.487179	1.602564	13.246985	0.284782	9.830456
80	0	0.4711	69.487179	1.602564	13.246985	0.284782	9.830456
81	0	0.4711	69.487179	1.602564	13.246985	0.284782	9.830456
82	0	0.4711	69.487179	1.602564	13.246985	0.284782	9.830456
83	0	0.4959	15.064103	23.653846	3.084697	8.558068	7.067983
84	0	0.4959	15.064103	23.653846	3.084697	8.558068	7.067983
85	0	0.4959	15.064103	23.653846	3.084697	8.558068	7.067983
86	0	0.4959	15.064103	23.653846	3.084697	8.558068	7.067983
87	0	0.4959	15.064103	23.653846	3.084697	8.558068	7.067983
88	0	0.4959	15.064103	23.653846	3.084697	8.558068	7.067983
89	0	0.4959	38.974359	17.532051	6.896489	5.39748	7.067983
90	0	0.4959	38.974359	17.532051	6.896489	5.39748	7.067983
91	0	0.4959	38.974359	17.532051	6.896489	5.39748	7.067983
92	0	0.4959	38.974359	17.532051	6.896489	5.39748	7.067983
93	0	0.4959	38.974359	17.532051	6.896489	5.39748	7.067983
94	0	0.4959	38.974359	17.532051	6.896489	5.39748	7.067983
95	0.07	0.4215	22.275641	10.320513	3.4948	2.280814	6.603367
96	0.07	0.4215	22.275641	10.320513	3.4948	2.280814	6.603367
97	0.07	0.4215	22.275641	10.320513	3.4948	2.280814	6.603367
98	0.07	0.4215	22.275641	10.320513	3.4948	2.280814	6.603367
99	0.07	0.4215	22.275641	10.320513	3.4948	2.280814	6.603367

	ASE (area%)	sDA (area%)	Overheatin g h/y	Cold h/y	Cooling EUI (kWh/m²/y)	Heating EUI (kWh/m²/y)	Lightning EUI (kWh/m²/y)
100	0.07	0.4215	22.275641	10.320513	3.4948	2.280814	6.603367
101	0	0.4793	69.583333	2.147436	14.053937	0.438442	9.928139
102	0	0.4793	69.583333	2.147436	14.053937	0.438442	9.928139
103	0	0.4793	69.583333	2.147436	14.053937	0.438442	9.928139
104	0	0.4793	69.583333	2.147436	14.053937	0.438442	9.928139
105	0	0.4793	69.583333	2.147436	14.053937	0.438442	9.928139
106	0	0.4793	69.583333	2.147436	14.053937	0.438442	9.928139