Office-user oriented façade design

an interactive/adaptive design approach

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Colophon

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Abstract

Users in traditional office buildings often experience discomfort with the indoor environment and have issues with how this is being regulated. Research has shown that users' satisfaction in an office building, which consists of their comfort and health, reflects on their work productivity. Therefore, necessary measures need to be taken in order to be able to suffice the office users' needs. Also, due to the fact that the building sector in Europe is responsible for an energy consumption of 40% of the final energy use and this leads to high carbon emissions and dependence on fossil fuels, the European Commission has stipulated regulations, where it is stated that all new buildings have to be nearly zero-energy by the beginning of 2021. Due to the fact that the façade is one of the buildings' components which has high impact on the indoor comfort and energy use of the building, taking the user's comfort needs and designing this from the conceptual design phase, can help achieve user satisfaction and enhance work productivity, while also helping achieve nearly energy neutrality.

This research aims to investigate the relevant factors of user satisfaction that could be implemented into façade design, while also investigating state of the art interactive/adaptive façade technologies (passive and active) and energy efficient façade design methods, in order to provide design solutions which optimally satisfies office users' needs of comfort, and therefore increases work productivity, and also supports nearly energy neutrality of office buildings. This leads to the research question of, *"How can an interactive/adaptive office building façade element be designed to optimally satisfy its users in order to increase work productivity and to support nearly energy neutrality of office buildings?"*. Optimal indoor satisfaction is defined as office users being thermally comfortable, experiencing comfort in the air quality indoors, the acoustics, and the lighting, and also when other human preferences are met such as, having control of their environment, having a view, and having an appealing place to work.

Based on literature review regarding user satisfaction, façade design, state of the art interactive/adaptive technologies, and energy efficient design methods, the design considerations were stipulated. These are user comfort, user control, energy efficiency, and user preferences. The user preferences is the most subjective criteria, because it expresses the preferences and desires of specific type of people. Therefore, this research presents office façade designs for specific type of users, namely the Energy Efficient archetype, the Self-Adaptive environment archetype, and the Full-Control of their environment archetype. The evaluation of these design configurations show that it is almost impossible to have one interactive/adaptive façade design that complies with all of the user preferences of all types of users, because every type of user has different preferences and some might contradict each other. Nevertheless, this research concludes on design characteristics derived from the presented design configurations, which show how the most optimal officer-user oriented façade design should function, that can ensure user satisfaction for different types of users and can help its building become nearly energy neutral.

Keywords: user satisfaction, façade design, interactive/adaptive technologies, energy efficient design methods, office user preferences.

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I would also like to thank TU Delft's Campus & Real Estate for helping me find the right information regarding the case study and providing me with this. Furthermore, I would like to thank Jochem Frehe for providing me with more information regarding the cases study building and for clarifying uncertainties regarding the previous and future plans for the building. Also, my gratitude goes to the anonymous user of the case study building which provided me with sufficient insight on the user experience regarding the current situation of the indoor environment of the office spaces and desires and preferences for future developments.

To my colleagues and friends at TU Delft, I thank you for your support, motivation, and feedback which helped me take a more critical look at my research. To my family, I want to thank them for their tremendous support, love, and positive encouragement. Last but not least, I would like to thank my fiancée for her patience and constant support during my long learning experience, for taking care of me during my long hours of work, for being my rock and motivation, for listening to my concerns late at night, and for always believing in me even when I did not have the strength to do so. Thank you!

Sasha V. Rodriguez Arambatzis

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Abbreviations

BENG	“Bijna Energie Neutral Gebouwen”
BIPV	Building Integrated Photovoltaics panels
BIS	Building Integrated Services
Clo	clothing insulation value
CO_2	carbon dioxide
EF	Energy efficient archetype
FC	Full Control archetype
HVAC	Heating, ventilation, and air conditioning
l/s	liter per second
m^2	square meter
nZEB	Nearly Zero Energy Buildings
PCM	Phase Change Material
PV	Photovoltaic panels
PV/T	Thermal photovoltaic panels
SA	Self-Adaptive archetype
SBS	Sick Building Syndrome
VIP	Vacuum Insulated Panels
VOC’s	volatile organic compounds
WWR	window-to-wall ratio
TES	thermal energy storage
THEX	total heat exchanger

Chapter 1 - Research Framework

This chapter introduces the background information and the motivation for this research due to an existing problem. The research objectives, questions, and boundary conditions are stated, along with the approach and methodology and the planning and relevance of this research.

1.1 Background

Office user oriented facade design means designing a façade which adapts according to user satisfaction factors and to outdoor conditions in order to satisfy users' needs of comfort. Although considering user's needs are complex because it is a subjective issue, it is necessary to understand and reflect their needs in façade design.

The users' satisfaction in an office building is very important due to the fact that their satisfaction, which consists of their comfort and health, reflects on their work productivity (Sant'Anna, Dos Santos, Vianna, & Romero, 2018). An unsatisfied user will miss work more often than usual, will take longer than usual to finish the tasks assigned, and will constantly complain about their environment affecting the satisfaction of other users.

According to studies, there are multiple factors within the built environment that can affect office users' satisfaction and therefore the productivity of employees at work. These are thermal comfort, indoor air quality, intelligible speech (or noise distraction), and visual comfort (Kwon, Remøy, & van den Dobbelsteen, 2018). These are factors related to indoor conditions of office buildings. The personal control that office users have on their environment, has also proven to increase users' satisfaction. According to Shahzad et al. (2017) users' personal thermal control can improve up to 35% of users' satisfaction. Other factors such as, building- and office aesthetics have also proven to affect work productivity (Göçer, Candido, Thomas, & Göçer, 2019). Kaczmarczyk's (2001) research on which environmental variables were seen by office employees as having the most impact on their productivity, shows, among other things, that personal control of the users climate, quiet offices, the possibility of personalizing their worksite, visually attractive work environment, options to adjust lighting levels, privacy, sufficient daylight and an attractive view, scores high. These results backs up the previous mentions studies.

The most successful buildings are the ones which are designed and equipped to meet user's needs. To improve their physical and psychological comfort and to avoid health issues such as, stress and anxiety. Even so, this is not regularly taken into account, because it is not a standard principle within the built environment and due to absence of actual information about requirements and needs (Heydarian, Pantazis, Wang, Gerber, & Becerik-Gerber, 2017).

The façade quality, besides energy performance, strongly relates to indoor climate conditions which has high impact on thermal comfort and user satisfaction, due to the fact that the façade controls the amount of light, ventilation and temperature indoors. Therefore, considering users' need from the conceptual design phase of buildings, where normally only the energy performance of the buildings are taken into account, and reflecting this into the façade design can help achieve user satisfaction and enhance work productivity.

According to the European Commission, the building sector in Europe is responsible for an energy consumption of 40% of the final energy use. Office buildings consume 26% energy of this amount (Eurostat, 2014), where the envelope (façades, roofs, windows and skylights) is responsible for 57% (heating, cooling, and lighting) of the energy use in commercial buildings (Selkowitz, Dillon, Lara-Curzio, & Pelton, n.d.). For the electricity use in office buildings, the highest consumer is the lighting with a value of 44% (Todd, 2011). High energy use means high carbon emissions and dependence on fossil fuels. Therefore, the European Commission (2019) has stipulated regulations, where it is stated that all new buildings have to be nearly zero-energy by the beginning of 2021, making energy production due to renewable energy the essence for achieving this goal. Therefore, the façade design has to have a good energy performance in order to help future buildings achieve nearly zero-energy.

1.2 Problem statement

For the design of the façade, an interactive/adaptive façade is proposed that is able to adapt the factors which are important for office users' needs of comfort. According to Cambridge Dictionary (n.d.), interactive means involving communication between people or reactions between things that work together. Adaptive means to change to suit different conditions. For this research, the idea is to allow interaction between the office users and the office façade in order for them to work together, adapting indoor conditions according to exterior conditons and also to users' preferences, and therefore allowing for optimal indoor satisfaction. Optimal indoor satisfaction is achieved when office users are thermally comfortable, experience comfort in the air quality indoors, the acoustics, and the lighting, and also when other human preferences are met such as, having control of their environment, having a view and having an appealing place to work. Comfort is experienced when certain limit values are met, such as a comfortable temperature degree or when a preferred user condition is achieved.

For the design strategy, van den Dobbelsteen's (2008) New Stepped Strategy, which are reduce, re-use, and produce, will be used in order for the design of the façade to be done in a sustainble way using its proposed passive and active methods. Designs will be proposed that use different interactive/adaptive technologies in order to optimally satisfy office users' needs of comfort. Passive solutions, such as materials which can react or interact with the users will be looked at and also materials that react to outdoor conditions, such as Phase Change Materials (PCM). Active solutions in technologies, such as electrical installations, will also be researched. The challenge at this point is the selection of the most appropriate interactive/adaptive technologies in order to achieve optimal user comfort and also how the user satisfaction factors could be implemented in these technologies.

During the design of the façade it is important to understand which factors related to user satisfaction that affect work productivity could be implemented into a façade and how this could be done. Furthermore, choosing between which different passive and active building design technologies to use and how to do this is also another challenge. Therefore, state of the art passive and active technologies will be investigated in order to identify their challenges and potentials and to learn from this. Taking into account that the façade design has to meet up with the 21st century requirements, a design criteria should be determined in order to establish if the proposed design configurations meet up with these requirements and in this way to be able to choose the most appropriate façade design. It is important to understand the relationship between façade and energy and to analyze multiple implementation methods to be able to achieve the most energy efficient interactive/adaptive façade.

The proposed design configurations for the façade should also be evaluated by the use of computer simulations and calculations, where comfort limit values can be established to see if the proposed designs achieves those limits and stays within the parameters of comfort and if it also achieves nearly energy neutrality. It should also be established if the proposed designs are acceptable according to users' preferences.

To sum up, due to the gap between façade design, office users satisfaction factors, and interactive/adaptive technologies, this research focuses on the design of an interactive/adaptive office façade which adapts according to users' satisfaction factors and to outdoor conditions, while also being as energy efficient as possible in order for the façade to help the building become nearly energy neutral.

1.3 Objectives

This paragraph presents the objectives which consist of a main objective followed by sub-objectives. Also, the presumed idea for the final products are presented along with the boundary conditions of the research.

1.3.1 Main objectives

Following the problems previously mentioned, the aim of this research is to investigate the relevant factors of user satisfaction that could be implemented into façade design, while also investigating state of the art interactive/adaptive façade technologies (passive and active) and energy efficient façade design methods, in order to provide design solutions which optimally satisfies office users' needs of comfort, and therefore increases work productivity, and also supports nearly energy neutrality of office buildings.

1.3.2 Sub-objectives

To be able to achieve the main objectives, the following sub-objectives need to be pursued:

- To understand how employees' surroundings and which factors related to user satisfaction can affect work productivity and what are the comfortable limit values of these factors;
- To analyze façade design based on the new stepped strategy and also to analyze how and which of the user satisfaction factors could be implemented into façade design;
- To investigate and analyze state of the art passive and active technologies that are of relevance for this research, to identify their challenges and potentials and to see how the user satisfaction factors can be implemented into these technologies;
- To understand how to design an energy efficient office façade in order to help a building achieve nearly energy neutrality;
- To define multiple design configurations that comply with the set up criteria, to evaluate if the designs meets up with the user satisfaction limit values, preferences, and if it helps support nearly energy neutrality.

1.3.3 Final products

The final product will be an office façade element design, which is designed in order to suffice office users' needs of comfort and to support nearly energy neutrality of office buildings, derived from the results of the design configurations. The design configurations of the office façade will be validated with simulations and calculations in order to identify how they theoretically perform and they will also be implemented in a case study where office users can indicate their preference for the designs. The designed façade element should be applicable in any office building.

1.3.4 Boundary conditions

The assumptions made for the design of the façade element are that the office is a traditional cellular office, with two employees sitting right in front of each other with a minimal distance to the façade. The application of the designed façade element on a case study will be on an existing office façade renovation within the TU Delft's campus in The Netherlands, which is the renovation of the Applied Physics building. Therefore, the façade will be designed taking into account the office grid of this building.

The research limits itself to the changing climate conditions in The Netherlands which is becoming + 2°C - 3°C warmer in the summer and taking Dutch building regulations into account for the design of the office façade element.

1.4 Research questions

This paragraph presents the research questions which consist of a main research question followed by sub-questions.

1.4.1 Main research question

Based on the research objectives, the following research question is formulated:

"How can an interactive/adaptive office building façade element be designed to optimally satisfy its users in order to increase work productivity and to support nearly energy neutrality of office buildings?"

1.4.2 Sub-questions

In order to assess the problem as thorough as possible, the main question is divided into categories followed by sub-questions.

User satisfaction – *"How does employees' surroundings affect office users' work productivity, which are the user satisfaction factors that can affect work productivity, and what are the comfortable limit values of these factors?"*

1. What is the impact of the employees' surroundings on their work productivity?
2. Which factors affect users' satisfaction and therefore work productivity?
3. What are the comfortable limit values for user satisfaction?

Façade design – *"How to design a façade, what are passive and active design measures, and how and which of the users satisfaction factors can be implemented into façade design?"*

4. How to design a façade according to The New Stepped Strategy?
5. What are passive and active design measures?
6. Which of the factors that affect user satisfaction can be implemented into façade design and how can this be done?

Interactive/adaptive technologies – *"Which state of the art interactive/adaptive projects and technologies (passive and active) are of relevance for this research and how can these technologies be integrated into a façade along with the user satisfaction factors?"*

7. What are the state of the art passive and active façade technologies and what are their challenges and potentials?
8. How to integrate users satisfaction factors into a façade along with passive and active technologies?

Energy – *"How can an energy efficient façade be designed in order to help a building achieve nearly energy neutrality?"*

9. How can a façade support the energy neutrality of office buildings?
10. How to design an energy efficient office façade?

Design, validation, and evaluation – *"Which criteria fits for the purpose of this research, how to have multiple façade designs which influence the facades' performance and user satisfaction, and which of the design configurations is the most suitable to be further developed in this research?"*

11. What is the most relevant criteria for the design in order for the façade to fit the purpose of this research?
12. How do different design configurations influence the performance of the facade and the satisfaction of the office users?
13. Which design configuration meets up with the user satisfaction limit values, preferences, and does it help support nearly energy neutrality?

1.5. Approach and methodology

The research methodology consists of four research phases.

Phase I – literature study

In phase I, the necessary literature will be assessed in order to gain sufficient knowledge on the relevant subjects and to analyze them sufficiently in order to have a good understanding of these. These subjects are related to factors that affect user satisfaction and work productivity and indoor comfort limit values according to regulations. Moreover, on how to design a façade according to The New Stepped Strategy by using passive and active design measures for the relevant user satisfaction factors. Also, state of the art passive and active projects and technologies will be investigated in order to identify their challenges and potentials to see the possibilities of implementing these technologies into a façade design along with the relevant user satisfaction factors. Furthermore, research will be done on how to design an energy efficient façade and how a façade can help a building achieve nearly energy neutrality. These questions are addressed by scientific literature research, simulations, case study, interviews/surveys, and necessary drawings and visualizations.

Databases

The databases that are going to be used for searching scientific literature are for example, Google Scholar, ResearchGate, Scopus, and ScienceDirect. These last two have peer-reviewed literature to ensure the quality of the obtained information. Google Scholar and ResearchGate on the other hand refer more to scientific papers, articles, and books from different Universities, countries, and continents. Therefore, their quality can be also guaranteed. Sources from Government agencies, such as regulations, will also be used. The literature is organized by the structure of the research and therefore to the sequence of the sub-questions. Researches from 2000 and onwards were only selected. Literature before this time will only be used if it is considered to be the founding literature of a subject.

Phase II – research through design

In phase II, based on the outcomes of the literature study, a design criteria will be determined. The office façade element will be designed based on this criteria and also based on the current office façade grid of the case study which is the Applied Physics building located on the Campus of the Technical University of Delft (TU Delft), building 22. Multiple concepts will be designed and also evaluated by computational simulations in order to identify how the configurations theoretically perform to see if they meet up with the user satisfaction limit values and to check if they help support nearly energy neutrality. Furthermore, the necessary climate and energy calculations will be performed in order to assess how the designed façades will perform during winter and summer and if they sufficiently support the nearly energy neutrality of the building. The façade configurations will be continuously optimized if necessary. At the end, they will be assessed on their comfort level and energy demand. The design strategy is to start with a linear process in the beginning and then an iterative process, which will be continuously going back to the main question and criteria to check if the problem is being solved by the proposed designs.

Phase III – validation (partially cancelled due to COVID-19 pandemic)

In phase III, after the designs are fully optimized, the chosen façade designs will be validated through the implementation of the design into the case study. Interactive models will be made together with the necessary visualizations of the designed façades. Also, the necessary drawings, such as sections, details along with 3D designs, will be drawn. In this way, the design of the office-user oriented façades will be performed.

Phase IV – finalization (partially cancelled due to COVID-19 pandemic)

In phase IV, after having finalized the office-user oriented façades, interviews will be held with the current office users of the building where they will indicate their preferences on a specific façade design. The results of these interviews will be taken into account for the possible optimization of these designs. The designs will also be assessed again on the advantages and disadvantages of implementing these. Figure 1 shows the research approach in a scheme.

Research Methodology

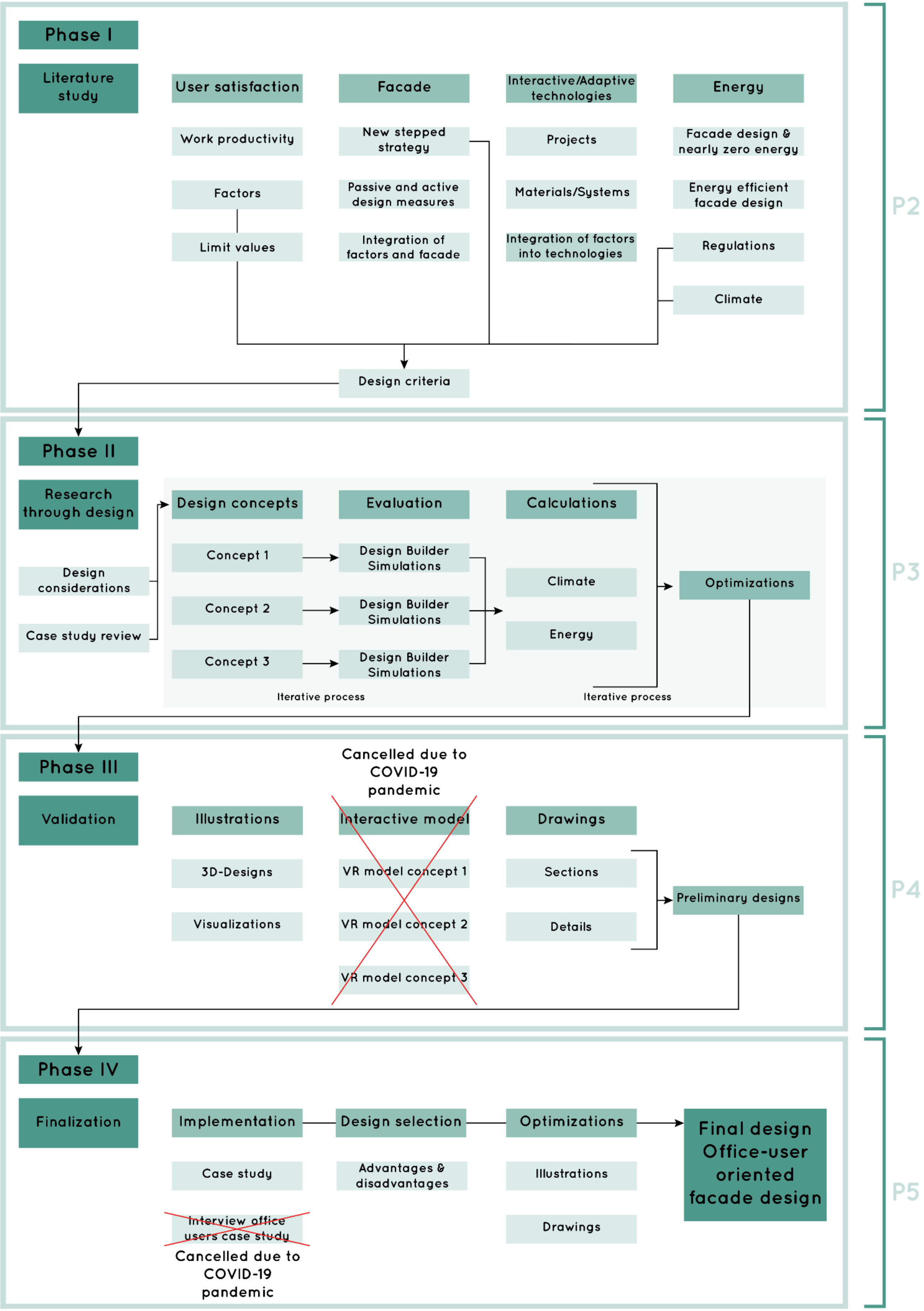
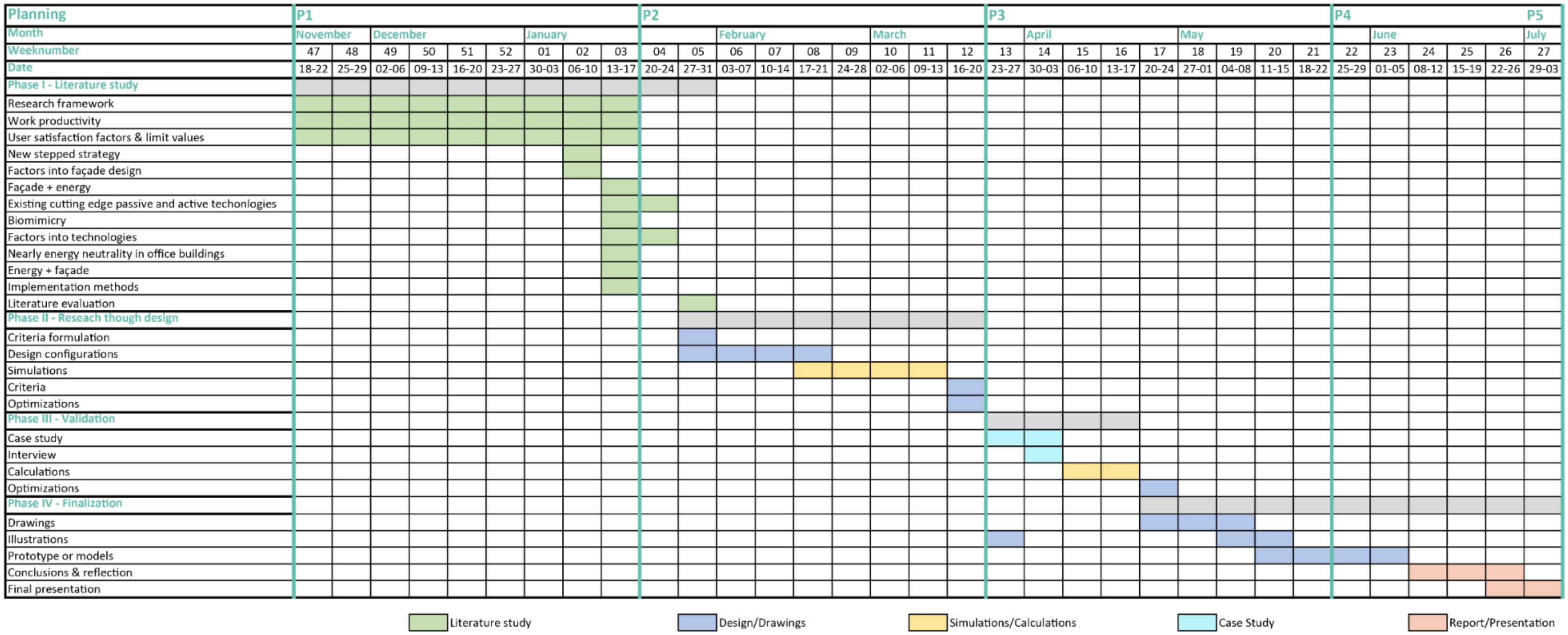


Figure 1: research methodology scheme. Image by author

1.6. Planning and organization

The planning for this research can be found in figure 2. On this planning can be seen that most of the literature study will be finished before the P2 presentation. After the P2, the literature study will be finished and a design criteria will be determined based on the outcomes of the literature study. Then, different design configurations will be made, where they will be evaluated and optimized in order to continue with the best designs to be finished before the P3. After the P3, the designs will be evaluated by simulations on their comfort level and energy demand. At the same time the simulations are taking place, the necessary climate and energy calculations will be done and the designs will be continuously optimized if necessary. When the designs are fully optimized, drawings, illustrations, and interactive models will be made. For the P4, conclusions will be drawn, the reflection will be written and the final presentation will be made. After the P4, the design will be implemented in the case study and interviews will be held with the office users of the case study in order to determine their preferences on the designed façades.



Planning	P1									P2									P3									P4					P5
Month	November		December				January					February				March				April				May					June				July
Weeknumber	47	48	49	50	51	52	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27
Date	18-22	25-29	02-06	09-13	16-20	23-27	30-03	06-10	13-17	20-24	27-31	03-07	10-14	17-21	24-28	02-06	09-13	16-20	23-27	30-03	06-10	13-17	20-24	27-01	04-08	11-15	18-22	25-29	01-05	08-12	15-19	22-26	29-03
Phase I - Literature study	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨																						
Research framework	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩																								
Work productivity	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩																								
User satisfaction factors & limit values	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩																								
New stepped strategy								🟩																									
Factors into façade design								🟩																									
Façade + energy									🟩																								
Existing cutting edge passive and active techonlogies									🟩	🟩																							
Biomimicry									🟩																								
Factors into technologies									🟩	🟩																							
Nearly energy neutrality in office buildings									🟩																								
Energy + façade									🟩																								
Implementation methods									🟩																								
Literature evaluation											🟩																						
Phase II - Reseach though design											▨	▨	▨	▨	▨	▨	▨	▨															
Criteria formulation											🟦																						
Design configurations											🟦	🟦	🟦	🟦																			
Simulations														🟨	🟨	🟨	🟨																
Criteria																		🟦															
Optimizations																		🟦															
Phase III - Validation																			▨	▨	▨	▨											
Case study																			▤	▤													
Interview																				▤													
Calculations																					🟨	🟨											
Optimizations																							🟦										
Phase IV - Finalization																							▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
Drawings																							🟦	🟦	🟦								
Illustrations																			🟦						🟦	🟦							
Prototype or models																										🟦	🟦	🟦	🟦				
Conclusions & reflection																														🟧	🟧	🟧	
Final presentation																																🟧	🟧

🟩 Literature study
🟦 Design/Drawings
🟨 Simulations/Calculations
▤ Case Study
🟧 Report/Presentation

Figure 2: research planning. Image by author

Research team

The research team consist of Professor Dr. Ir. Andy (A.J.F.) van den Dobbelsteen, from the chair Climate Design & Sustainability, and Assistant Professor Dr. Ing. Thaleia Konstantinou MSc from the chair Building Product Innovation. Dr. Ir. Stefan van der Spek will be part of the team as a delegate of the Board of Examiners.

1.7 Relevance

Societal relevance

The development of an office façade element which adapts according to users' needs, will provide users with a comfortable and healthy indoor environment ultimately increasing their overall satisfaction. Poor indoor conditions can lead to an unhealthy work environment which ultimately can lead to health problems, such as stress and anxiety. Therefore, it is essential to provide users with a comfortable and healthy place of work. By designing a façade which can help improve indoor conditions and increase user satisfaction, these issues can be avoided. In addition, there is also an economical benefit in the development of such façade, not only because it lowers health costs, but also because satisfied employees will miss work less than usual and also could take less than usual to finish the tasks assigned.

Environmental relevance

As already mentioned, the building sector is responsible for an energy consumption of 40% of Europe's final energy use, where office buildings consume 26% of this amount. High energy use means high carbon emissions and dependence on fossil fuels. Therefore, it is crucial to find solutions within the buildings' envelope in order to help decrease or completely remove this amount. The façade is one of the buildings' components which is responsible for this high energy use. By designing façades which are not only energy efficient, but that also helps its building become nearly energy neutral, can definitely decrease the high energy use in buildings and also help decrease carbon emissions and dependence on fossil fuels.

Scientific relevance

The scientific relevance of this research is that it highlights topics that are not very well known yet and that it shows how an interactive/adaptive energy efficient façade could be designed which also takes office users' satisfaction factors into account. This research takes into account results from previous researches and studies in the field of climate design, indoor comfort, façade design, building product innovation, sustainability, and renovation. One of the most relevant studies for this research were the results of the PhD Research *"Energy-Efficient Office Renovation, developing design principles based on user-focused evaluation"* by Doctor M. Kwon (2019). The results of this PhD research form the basis of this Master thesis.

Innovative relevance

The innovative relevance of this research is the effort of bridging the gap between façade design, office users satisfaction factors, and interactive/adaptive technologies. Furthermore, it will provide multiple innovative façade designs, specially designed in order fulfill specific users' design principles while also being energy efficient and therefore helping its building become nearly energy neutral. The strategies that will be used in order to achieve the previous statement are strategies learned during the Master Track courses, such as zero energy design, climate design, and façade design.

Chapter 2 - Literature study

This chapter describes the results of the literature study, which consists of user satisfaction, façade design, interactive/adaptive technologies, and energy efficiency. Each paragraph describes its content before going into the sub-paragraphs.

2.1 User satisfaction

In this paragraph, the impact of employees' surroundings on their productivity will be investigated, along with the factors which affect office users satisfaction, and comfortable limit values.

2.1.1 Impact of the employees' surroundings on their work productivity

Employees' work environment consists of the surrounding conditions in which employees operate. This is composed of physical conditions, such as temperature and office appliances, and also of psychological conditions, such as privacy, territoriality, and communication (De Croon, Sluiter, Kuijer, & Frings-Diesen, 2005) (Brennan, Chugh, & Kline, 2002). Poor quality of these conditions can lead to an unhealthy work environment which ultimately can lead to health problems, such as stress and anxiety. Research has suggested that stress at work is a major public health risk due to the fact that it is associated with cardiovascular morbidity (Thayer, et al., 2010) and with substantial economic consequences, including absenteeism, increased worker turnover, decreased employees satisfaction and has associated decreases in worker productivity (Duijts, Kant, Swaen, van den Brandt, & Zeegers, 2007) (Harter, Schmidt, & Hayes, 2002). Due to the fact that physical factors of the work environment, such as temperature, air quality, lighting, and noise, have been linked to office users' satisfaction, this means that these factors are directly implicated in the effects of work induced stress on health.

Office aesthetics, which consists of office design and layout, have also proven to affect work productivity (Göçer, Candido, Thomas, & Göçer, 2019). These do not only refer to desk location and furniture, but also to color use in offices, contact with nature, and so on.

Colors play a vital role on the human body, mind, and spirit, due to the fact that it can impact both work productivity and wellness (Dr. Sarode & Shirsath, 2014). Each color has a different effect on the human body, therefore appropriate colors should be chosen in order to ensure the right effect. A job which requires a lot of concentration requires a neutral color scheme, while a journalist's office would require exciting and energetic colors with great contrast values (Kamarulzaman, Saleh, Hashim, & Abdul-Ghani, 2011). According to O'Brien (2003) the color blue is a productive color and is therefore ideal for employees who must focus and concentrate on numbers, because it helps slow down the heart rate. Green refers to nature, fresh air and plant life and is therefore associated with growth and renewal, broader thinking and creativity, it can reduce anxiety and promote balance, which makes it the perfect color for management for when weighing in the advantages and disadvantages of a situation. It is also good for employees who work long hours, because it does not cause eye fatigue and gives a calm feeling which helps to remain efficient at the same time. The color yellow is a very exciting color and promotes cheer which can fuel optimism and innovation and is therefore the perfect color for creative work. According to studies the color red is a warm color which increases the blood flow, boosts the heart's rates and activates more brain wave. Although it is seen as a warm color, it could also induce hostility. Too much red could lead a team toward competition rather than collaboration (Pochepan, 2018). White has a clean and modern appeal, but it can also be experienced as a clinical and cold color. In offices, white can lead employees to reflect on non work related matters and can make employees more prone to error. White has another meaning when used as an accent color, because it can help diffuse brigther colors and adds a softness to it.

Multiple studies show that office employees that have access to indoor plants or window view to nearby nature report to be less tired and prefer a working environment with living plants (Kamarulzaman, Saleh, Hashim, & Abdul-Ghani, 2011). According to Mangone, Capaldi, van Allen, & Luscuere (2017) contact with nature in the workplace has been associated with increased productivity and creativity, as well as positive emotional and physical health outcomes. Their study shows that participants found images of natural outdoor spaces to be more fascinating, relaxing, open, bright, and quiet. Plants are also important in removing indoor air pollutants and in increasing employees' perception of wellbeing (Smith & Pitt, 2009). In both their research, Smith, Tucker, & Pitt (2011) and Bjørnstad, Patil, & Raanaas (2016), found a substantial reduction in sickness absence in office areas which have a great amount of indoor nature contact or plants and also lower levels of job-related stress were found along with fewer subjective health complaints. Besides indoor plants, there is also the possibilty of having an indoor green wall or a living wall system. This is a wall which is intentionally covered by vegetation (Gunawardena, Wells, & Kershaw, 2017) which consists of a vertically applied growth medium, such as soil or substrate as well as an integrated watering- and fertigation system. It has the same benefits for work productivity, health, and wellbeing as indoor plants, but they also have a great deal of benefits on indoor air quality, thermal comfort and reducing the energy demand of buildings (Medl, Stangl, & Florineth, 2017). A living wall system can be used as a passive design solution (Perez, Rincón, Vila, González, & Cabeza, 2011) which contributes to buildings' sustainability performance (Eumorfopoulou & Kontoleon, 2009) due to the fact that vegetation has the potential to improve the microclimate in all seasons. It functions as a complementary insulation layer helping the indoor climate to stay warm in the winter and cool in the summer by avoiding heat gains and losses and therefore also reducing the energy demands for heating and cooling (Manso & Castro-Gomes, 2015).

Designing with nature is known as biophilic design. Biophilia is defined as the urge to affiliate with other forms of life (Kellert & Wilson, The Biophilia Hypothesis, 1995). In his book, Wilson (1984) suggests that humans possess an innate tendency of seeking connections with nature and other forms of life, because of so much of our evolutionary history was spent intimately living in and interacting with nature that a need to connect with nature persists to this day (Mangone, Capaldi, van Allen, & Luscuere, 2017). Biophilic desing is therefore the deliberate attempt to translate an understanding of this inherent human affinity into the design of the built environment (Kellert, Heerwagen, & Mador, Biophilic Design, 2008). Nature refers to living plants and animals, but also to rocks, water, soil, forest, wood/bamboo, and so on.

Nature can also be used as a form of inspiration. This study is known as biomimetic. It refers to human-made systems that imitate nature. Its concerned with functional solutions, translating adaptations in biology into solutions in architecture (Pawlyn, 2016). This type of design is known as biomimicry. Biomimicry has grown substantially since the introduction of this term, but it has evolutionated more in the fields of robotics and materials science and less in architecture. Even so, it has inspired the world's most known buildings and systems, such as solar panels which mimics the way leaves harvest energy, synthetic materials which are self-healing mechanicsm that mimics human skin's way of healing, responsive façade that mimics the concept of spiky or fibrous husk plant that protect the fruit or the seeds inside againts the sun, the Eastgate Center in Zimbabwe which mimics termite mounds' ventilation structure in order for the building to remain with a constant temperature throughout the seasons, and the Eden Project which imitates soap bubbles with their huge trasparent semi-spherical domes.

2.1.2 Factors which affect user satisfaction and therefore work productivity

User satisfaction depends on multiple factors, such as thermal comfort, indoor air quality, intelligible speech (or noise distraction), and visual comfort (Kwon, Remøy, & van den Dobbelsteen, 2018). According to Kwon, Remøy and van den Bogaard (2019), there are some influential office design factors which can ensure employees satisfaction. In their study, they concluded which design parameters can bring better satisfaction to office users. According to their article, the design factors spatial office design, such as layout and position of workplaces, and façade design, such as window-to-wall-ratio (WWR) and orientation, have the most influence on user satisfaction and therefore work productivity. These are factors which are related to thermal comfort, visual comfort, psychology, and energy. For the design of the office façade element of this research, only the aspects window-to-wall-ratio and orientation are relevant and can be taken into account for the design.

Figure 3 shows the level of importance of orientation and window-to-wall-ratio on thermal and visual comfort of the user satisfaction per season. This figure shows that for thermal and visual comfort, orientation is important in all the season, but it is most important during summer. This is because, depending on the orientation, for thermal comfort the heat gain can be very high and therefore it can affect the temperature. For visual comfort, it is because users enjoy looking outside during summer. For WWR, it shows that for thermal comfort it is most important during winter due to the fact that during this season the sun helps heating up the offices. For visual comfort, WWR is most important during mid-season and is completely neglected and not important during summer and winter. This is because in these seasons there is less daylight and also because they are rainy seasons. Therefore, office users do not really enjoy looking outside.

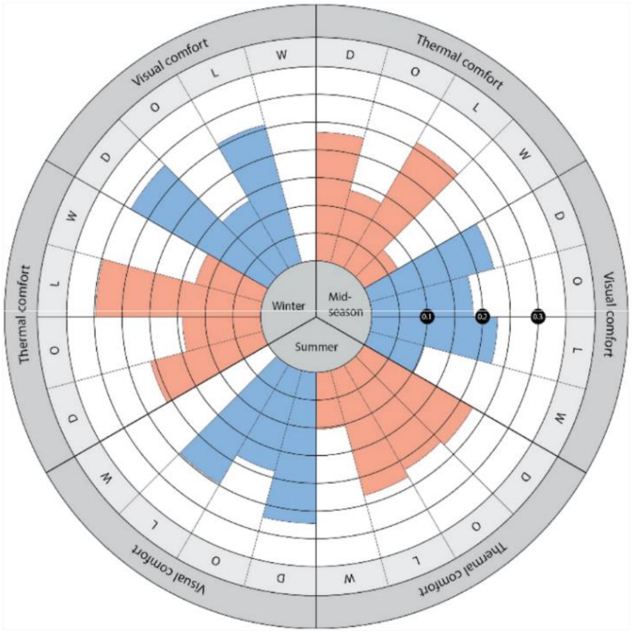


Figure 3: level of importance of design factors on user satisfaction with thermal and visual comfort.
Image by Kwon, Remøy and van den Bogaard (2019)

Literature shows that seating orientation contributes to the visual comfort of office users and that particularly extreme illuminance can be experienced in both southwest and northeast orientations (Hua, Göçer, & Göçer, 2014). For thermal comfort, the study shows that certain orientations can cause high levels of thermal dissatisfaction, but it is difficult to establish if orientation indeed is the main reason causing users' discomfort since other factors, such as glazing area, artificial lighting, and blinds can also affect users satisfaction (Kwon, Remøy, & van den Bogaard, 2019).

Literature shows that window-to-wall ratio's (WWR) influence on daylight, heat gain and -loss, and optical properties have an impact on building performance, where windows and outside views showed a psychological importance to office users (Smith, James, & Pitt, 2011). Literature proposes that the range of 35-45% of WWR is the optimal rate in terms of energy minimisation (Goia, Haase, & Perino, 2013), although optimal WWR's vary depending on orientations and climate conditions in different parts of the world (Goia, 2016). For The Netherlands, the Köppen Classification is Cfb, which means that The Netherlands is located in the Marine West Coast Climate (Kwon, Remøy, & van den Bogaard, 2019), and therefore the optimal WWR would be of 37-45% for south, 40-45% for north, 37-43% for west, and 37-43% for east orientation (Goia, 2016).

According to Kwon, Remøy and van den Dobbelsteen's (2018) research on user-focused office renovation, the parameters which are believed to affect user satisfaction were analyzed and classified into levels of importance. They developed a theoretical framework which determined the order of priority and the degree of importance among factors which affect user satisfaction. Findings present physical, functional, and psychological influential factors or parameters that can increase user satisfaction in a workplace. These are:

A. Physical comfort:
    1. Thermal comfort;
    2. Air quality;
    3. Lighting;

   4. Intelligible speech (noise);
- B. Functional comfort:
   5. User control;
   6. Privacy;
   7. Concentration;
   8. Communication;
- C. Psychological comfort:
   9. Social contact;
   10. Spatial comfort.

The research concludes on a design framework based on these physical, functional, and psychological Influential factors. They are integrated into a three step requirement structure that can be followed in order to achieve user satisfaction, see figure 4. Using this framework, the design of the façade element of this research can be developed, by deciding up to which level the façade should be designed in order to enhance work productivity while also having a sufficient a balance between energy saving and user satisfaction.

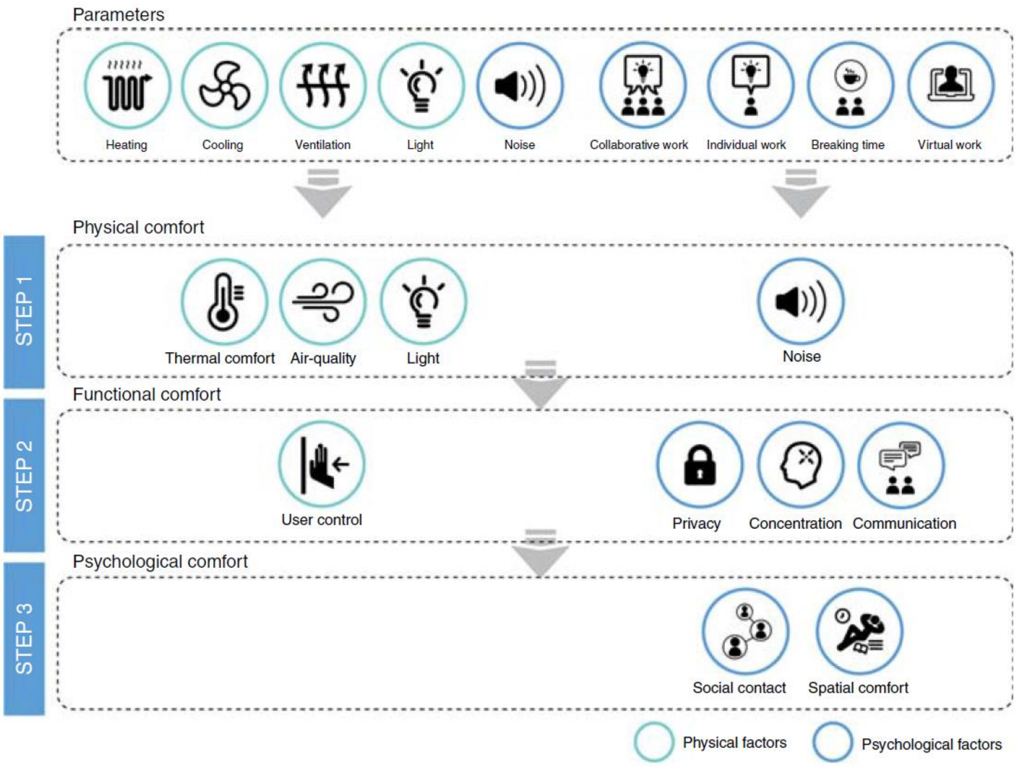


Figure 4: classification of physical and psychological factors based on the dimensions of comfort.
Image by Kwon, Remøy and van den Dobbelsteen (2018)

For the design of the office façade element of this research, the most interesting factors are the physical factors of the physical- and functional comfort steps, steps one and two. For the psychological factors, only noise of step one can be relevant and can be taken into account to some extent for the design.

Users personal control of their environment have also proven to affect work productivity. According to Kwon, Remøy, van den Dobbelsteen and Knaack's (2019) research on personal control and environmental user satisfaction in office buildings, office users showed that a higher controllability of their environment reflected in more user satisfaction in terms of thermal and visual comfort. The results for thermal comfort show that for mid-season, the most important factor of user control was temperature, in terms of heating, cooling, and operable windows, where cooling control was the least significant of user control regarding indoor temperature. The most significant user control factors were the temperature, air quality, and humidity caused by control of ventilation due to operable windows. For summer, the results were similar to mid-season, where the most significant user control factor was operable windows in terms of temperature satisfaction, air quality, humidity, and comfort followed by the cooling control of temperature. For winter, heating control shows a higher importance than cooling control, which is logical due to the season, and the most significant user control factor was again operable windows in terms of temperature satisfaction, air quality, humidity, and overall comfort. In conclusion, user control on heating was strongly related to overall satisfaction in mid-season and winter and cooling control to overall satisfaction in the summer. According to the results, there was no important relation between users' control of the heating and cooling related to air quality and humidity.

For visual comfort, the results show that the most important factor which users like to control are sunshades, artificial light and daylight, over all the seasons. After this, the lighting control of daylight shows an importance to user satisfaction over all the seasons.

Corroborating these results, Raja, Humphreys, McCartney and Nicol's (2001) study also concluded that the opening of windows and user control of sunshades are the most significant factors for the user satisfaction of thermal conditions and that user dissatisfaction was mainly caused by ventilation control. For visual comfort, the personal control of sunshading was the most relevant factor for user satisfaction.

Multiple studies have shown that direct user control of the users' environment contributes to user satisfaction, with an 80% contribution in the research of Brager and Baker (2009), and according to Shahzad et al. (2017) research, users' personal thermal control can improve up to 35% of users' satisfaction.

2.1.3 Comfortable limit values for user satisfaction

In order to ensure that user satisfaction is achieved for the relevant factors of thermal comfort and visual comfort, it is important to know what are the comfortable limit values of these according to literature.

Thermal comfort

Thermal comfort consists of temperature and indoor air quality, where indoor air quality refers to humidity, draught or air velocity, volatile organic compounds (VOC's), and carbon dioxide (CO_2). The comfortable limit values will be stated according to the values of The Netherland's building norm (NEN norms) NEN-EN 15251 on indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics (Nederlands Normalisatie-instituut, 2007).

According to the NEN-norm NEN-EN 15251, the comfortable limit values of indoor temperature for the design of cellular offices without mechanical cooling systems, lies between 20–24°C for the winter season when the outside temperature has a minimum value of 15°C. This increases when the outside temperature also increases. For the summer season, the temperature lies between 23-26°C when the outside temperature has a minimum value of 10°C and also variates depending on the outside temperature. As can be seen, there is a high difference in the values per season due to the fact that people cloth differently in each season. For winter, it is expected for people to use a clothing insulation value of clo 1,0, which means that people have more clothing layers on. For summer, the clothing insulation value is of clo 0,5, which means that people tend to have less clothing layers on in this season. These values can only be considered when the offices are equipped with operable windows which open to the outdoors or methods which can readily be adjusted by the office users. It is also important to take into account that there is always a 10% of people which fall out of this comfort zone, which will feel the comfortable limit values being either too cold or too hot. (Nederlands Normalisatie-instituut, 2007)

For indoor air quality there does not exist a common standard index. Therefore, this is expressed as the required level of ventilation or CO_2 concentrations. Indoor air quality is influenced by users' emissions and their activities, from building and furnishing, and from the HVAC systems. The last two are known as the building components. The appropriate ventilation of a space is determined by health and comfort criteria, which is also met by the appropriate ventilation for comfort, where comfort is related to the perceived air quality by office users.

The recommended design ventilation rates for offices can be calculated by using the equation below.

$$qtot = n \cdot qp + A \cdot qB \qquad \text{(E1)}$$

Where:

q_{tot} = total ventilation rate of the room, l/s

n = design value for the number of occupants, -

q_p = ventilation rate for occupancy per person, l/s per person

A = room floor area, m^2

q_B = ventilation rate for emissions from building, l/s per m^2

Using the tables below for the basic required ventilation rates for diluting emissions from people (table 1) and the ventilation rates (q_B) for the building emissions (table 2), the recommended design ventilation rates for offices can be calculated.

Table 1: basic required ventilation rates for diluting emissions from people. Table by author, derived from Nederlands Normalisatie-instituut (2007)

Category	Expected percentage dissatisfied	Airflow per person (l/s/pers)
I	15	10
II	20	7
III	30	-
IV	> 30	< 4

Table 2: ventilation rates (q_B) for the building emissions. Table by author, derived from Nederlands Normalisatie-instituut (2007)

Category	Very low polluting building	Low polluting building	Non low polluting building
I	0,50 l/s, m^2	1,0 l/s, m^2	2,0 l/s, m^2
II	0,35 l/s, m^2	0,7 l/s, m^2	1,4 l/s, m^2
III	0,30 l/s, m^2	0,4 l/s, m^2	0,8 l/s, m^2

Very low polluting or low polluting buildings are those whose majority of building materials used for finishing the interior surfaces meet the national or international criteria of very low polluting or low polluting materials. Very low polluting and low-polluting materials are natural traditional materials, such as stone, glass, and metals, which are known to be safe with respect to emissions, and materials which fulfil the following requirements: (Nederlands Normalisatie-instituut, 2007)

- **very low polluting:**
    - emission of total VOC's is below 0,1 mg/m^2h;
    - emissions of formaldehyde is below 0,02 mg/m^2h;
    - emissions of ammonia is below 0,01 mg/m^2h;
    - emissions of carcinogenic compounds (IARC) is below 0,002 mg/m^2h;
    - material is not odorous (dissatisfaction with the odor is below 10%).

- **low polluting:**
    - emission of total VOC's is below 0,2 mg/m^{2}h;
    - emissions of formaldehyde is below 0,05 mg/m^{2}h;
    - emissions of ammonia is below 0,03 mg/m^{2}h;
    - emissions of carcinogenic compounds (IARC) is below 0,005 mg/m^{2}h;
    - material is not odorous (dissatisfaction with the odor is below 15%).

According to Nederlands Normalisatie-instituut (2007) the recommended ventilation rates for a single office can be seen in table 3.

Table 3: examples of recommended ventilation rates for single offices. Table by author, derived from Nederlands Normalisatie-instituut (2007)

Type of building	Category	Floor area m^2/pers	q_p	q_B	q_{tot}	q_B	q_{tot}	q_B	q_{tot}
			l/s per m^2 for occupancy	l/s per m^2 for very low polluted building		l/s per m^2 for low polluted building		l/s per m^2 for non-low polluted building	
Single office	I	10	1,0	0,5	1,5	1,0	2,0	2,0	3,0
	II	10	0,7	0,3	1,0	0,7	1,4	1,4	2,1
	III	10	0,4	0,2	0,6	0,4	0,8	0,8	1,2

Relative humidity is of particular concern in residential ventilation and not so much in office spaces as most of adverse health effects and building disorder (condensation, molds) is related to humidity. Humidity has only a small effect on thermal sensation and perceived air quality in the rooms of sedentary occupancy, however, long term high indoor humidity levels can cause microbial growth, and very low humidity can cause respiratory problems, dry eyes and irritated eyes and air ways (Nederlands Normalisatie-instituut, 2007). In The Netherlands, there are no regulations for humidity levels in office spaces, but there are a couple of institutions in the world which give advice on humidity levels in office spaces. According to Canada's guideline of office ergonomics (Standards Council of Canada, 2016), the optimal level for humidity in office spaces ranges between 40-60%, where it is advised to keep this between 30-70%. Humidity levels below 40% will cause problems for employees and will affect their health and productivity. These values are similar to the values recommended by the American Society of Heating, Refrigerating, and Air Conditioning Engineers (American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., 2010).

Unacceptable values of indoor air quality can cause a medical condition known as the Sick Building Syndrome (SBS), where building occupants suffer from symptoms of illness or feel unwell for no apparent reason. Occupants experience complaint reactions, such as thermal discomfort, stuffy air, dry air or malodors. They can also experience illnesses, such as hypersensitivity pneumonitis, building-related asthma, and legionellosis. Occupants also report medical symptoms, such as dry/watering eyes, blocked/runny nose, dry/irritated throat, chest tightness, shortness of breath, headaches, and lethargy/fatigue. The sick building syndrome can be reason for disabling whole workspaces, rendering offices as non-functional (Norbäck, 2009). On-site assessment of buildings, can be extremely helpful with avoiding SBS. Causes of SBS can be inadequate ventilation, chemical contaminants from indoor sources, chemical contaminants from outdoor sources, biological contaminants, electromagnetic radiation, psychological factors, and poor and inappropriate lighting with absence of sunlight, bad acoustics, poor ergonomics, and low humidity (Joshi, 2008). If an office space is affected by SBS, the employees and the office spaces need to be treated by alleviating the symptoms of the employees and bringing changes, such as ventilation improvements and reduction of sources of environmental contamination, which can help decontaminating the spaces.

Visual comfort

Visual comfort consists of daylight and artificial light. For daylight, there are no legal obligations regarding daylight in the workplace in The Netherlands, but provisions and target regulations have been drawn up. According to Dutch regulations, section 3.1.1 of "Het Bouwbesluit" (2012), the requirements for daylight in office buildings are that the office room has to have at least relative an equivalent daylight area of 2,5% of the whole office area with a minumum absolute equivilant daylight area of 0,5 m^2. According to Dutch standards (Nederlands Normalisatie-instituut, 2001), the equivalent daylight area can be determined using the following equation:

$$Ae,i = Ad,i \cdot Cb,i \cdot Cu,i \cdot CLTA \qquad \text{(E2)}$$

Where:

$A_{e,I}$ = the equivalent daylight area of a daylight opening, m^2

$A_{d,I}$ = area of daylight opening, m^2

$C_{b,i}$ = the obstruction factor of a daylight opening, -

$C_{u,i}$ = the external reduction factor of a daylight opening, -

$C_{LT\,A}$ = the reduction factor for translucent materials with an LTA value less than 0,60, -
Materials which has with an LTA value higher than 0,60, the $C_{LT\,A}$ = 1

In order to determine the equivalent daylight area of a space, all equivalent areas, *n*, in that particular space have to be added together, as can be seen in equation 3.

$$\sum_{i=1}^{n} Ae,i \qquad \text{(E3)}$$

Where:

$A_{e,I}$ = the equivalent daylight area of a space, m^2

There are specific methods to determine the daylight area (A_d), the obstruction factor ($C_{b,i}$), and the external reduction factor ($C_{u,i}$), which can be found in the NEN 2057. (Nederlands Normalisatie-instituut, 2001)

For artificial lighting, according to the European standard EN 12464-1, the recommended examples of design illumination levels for office buildings can be seen in table 4. The UGR values refers to the Unified Glare Rating limit and the Ra value to the Color Rendering Index. (European Committee for Standardization, 2002)

Table 4: example of design illumination levels for office buildings. Table by author, derived from European Committee for Standardization (2002)

Type of building	Space	Maintained illuminance, $\hat{E}_m$ at working areas, *lx*	UGR	Ra	Remarks
Office buildings	Single offices - Writing, typing reading, data processing – CAD work stations	500	19	80	at 0,8 m

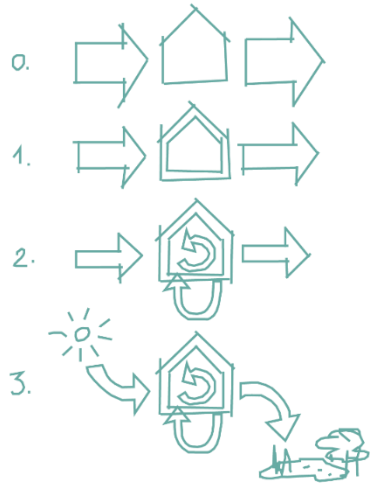
There are specific methods to determine the UGR and the Ra value, which can be found in the EN 12464-1. (European Committee for Standardization, 2002)

2.2 Façade design

As already mentioned in the previous chapter, office users dissatisfaction can be caused by the interior conditions of the office spaces. These interior conditions can be affected by indoor activities, but also by exterior conditions. The facades' main purpose is to separate inside from outside and therefore not allowing for the exterior conditions to affect the indoor conditions. Most of the offices in buildings are placed around the buildings' facades, in order for the office space to have sufficient illuminance and for the users to have view to outside. Therefore, office employees have a direct connection with façades. Besides separating the inside and outside, the façade also protects the interior from wind, water, moisture, cold, heat, noise, vermin, and unwanted visitors. It is one of the most important exterior elements in buildings. Nowadays the façade is also responsible for energy efficiency and energy production. This means that the interior part of the façade should not allow energy loss to take place and the exterior part of the façade should produce sufficient energy to help run the building. It is important to understand what are the relevant factors to take into account when designing a façade in order for it to function properly. Therefore, in this paragraph, designing according to the new stepped strategy will be investigated and its translation into façade design, along with the implementation of the user satisfaction factors into façade design.

2.2.1 Façade design according to the New Stepped Strategy

The need for building passive and sustainable buildings is a main principle in this era of zero energy and zero carbon emissions design. There are multiple design methods for designing sustainable buildings which use appropriate building design, but not all of them take consideration of the local environment with the use of less non-renewable sources and the re-use of waste streams. Taking the "Trias Energetica" design approach, van den Dobbelsteen (2008) proposed incorporating a new step inspired by 'Cradle to Cradle' (C2C) in order to achieve more effective means towards sustainability. The new stepped strategy can be seen in figure 5.



1. Reduce the demand
2. Reuse waste streams
3. Use renewable energy sources (a) and ensure that waste can be used as food (b)

Figure 5: the new stepped strategy. Image by author, derived from van den Dobbelsteen A. (2008)

The first step involves investigating the location, orientation, and local climate of the building. Then, making sure to reduce the energy demand as much as possible by smart design, followed by the recycling of waste streams, such as heat recovery, waste water, and so on. Finally, supplying renewable energy sources and allowing only clean and nutritious waste to nature. (van den Dobbelsteen A. , 2008)

For the façade design of this research according to this strategy, the same methods apply. First, multiple designs for the façade can be developed according to different orientations, taking the local climate of The Netherlands into account. Then, by selecting materials and systems for the thermal and visual comfort of the façade, which helps it reduce the heat losses and increase heat gains respectively in order to reduce the energy demand (Konstantinou & Prieto, 2018), incorporating user control into these systems, and selecting materials which help with maintaining comfortable noise levels. Finally, incorporating systems and technologies which helps re-use waste streams, such as heat recovery of the indoor air, and producing sufficient energy on the façade's surface in order for the façade to help the building become nearly energy neutral. These type of technologies (materials and systems) are known as passive and active design principles or measures. Figure 6 shows an overview of passive and active measure and their objective, within the scope of environmental design.

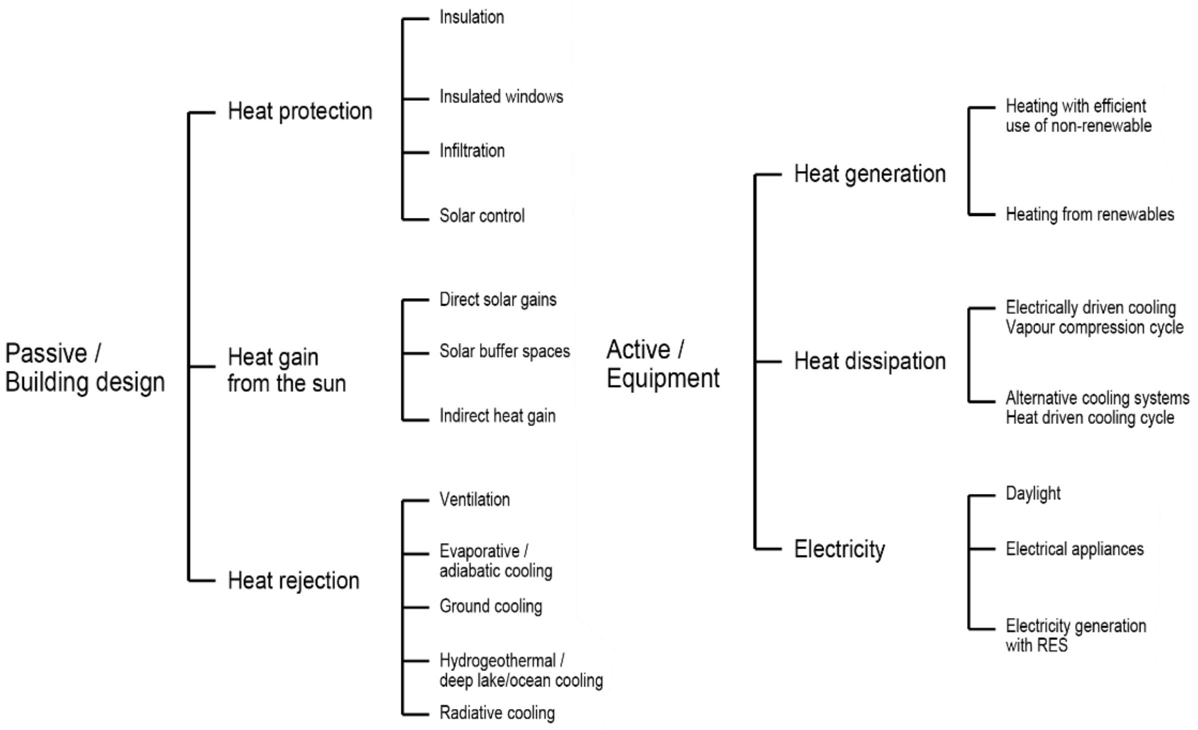


Figure 6: overview of passive and active measure and their objective, within the scope of environmental design.
Image derived from Konstantinou & Prieto (2018)

Sub-paragraph 2.2.3 will go into more depth on which passive and active design measures can be implemented in this research's office-user oriented façade design in order for it to achieve optimal satisfaction of office users.

2.2.2 Passive and active design measures

Passive façade design consists of reducing the energy demand of a façade. This can be done by taking consideration of the local climate and environmental elements, building layout, and material properties (Konstantinou & Prieto, 2018). Some passive measures can also help re-use heating. As can be seen in figure 6, three mayor functions play a key role on the passive design of a façade. These are heat protection, heat gain from the sun, and heat rejection.

Due to the fact that passive design measures alone cannot completely eliminate the total energy demand of a façade, active façade design measures are necessary. These active measures consists of design measures for heat generation, heat dissipation, and electricity (see figure 6) and are related to the use (systems) and generation of heat and electricity and the re-use of heating and cooling. Also, the use of smart technologies (automated computer-based controls) fall in this category.

2.2.3 User satisfaction factors and façade design

In order to be able to implement the user satisfaction factors into façade design, the user satisfaction factors need to be directly linked to the categories of the passive and active design measures within the new stepped strategy, see figure 7.

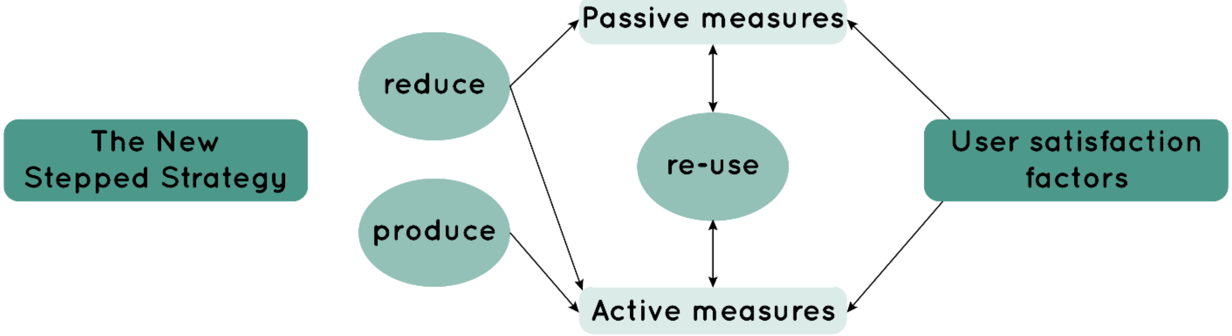


Figure 7: user satisfaction factors linked to the new stepped strategy design measures passive and active. Image by author

Table 5 shows the user satisfaction factors implemented into the passive and active measures of the new stepped strategy.

Table 5: user satisfaction factors implemented into passive and active measures. Table by author

Passive measures	User satisfaction factors and Energy	Components		Active measures
Heat protection and heat gains	WWR	Opaque (wall)		
		Glazing		
	Orientation	North/South/East/West		
	Office aesthetics	Colors		
Heat protection and heat rejection		Biomimicry		Heat generation and heat dissipation
Heat protection and heat rejection		Plants		Heat dissipation
Heat protection and heat rejection		Living wall system		Heat dissipation
Heat protection, heat gains, and heat rejection	Thermal comfort	Temperature	Heating	Heat generation and heat dissipation
			Cooling	
Heat rejection		Indoor air quality	Humidity	Heat generation and heat dissipation
			Air velocity	
			VOC's	
			CO_2	
Heat protection and heat gains	Visual comfort	Daylight		Electricity
		Artificial light		
	Intelligible speech	Noise		
Heat protection, heat gains, and heat rejection	User control	WWR		
		Office aesthetics		
		Thermal comfort		Heat generation and heat dissipation
		Visual comfort		Electricity
	Energy	Power		Electricity

Reviewing table 5, it can be concluded that there are no passive or active measures that could be implemented in a façade which benefits the user satisfaction factor of colors. This is the same for intelligible speech. These two factors can still be implemented in the façade design, but will not have any effect on the reduce, re-use, and produce measures of the new stepped strategy. It is still beneficial to take them into account, because they are relevant factors for user satisfaction and therefore work productivity, but only to some extent. The rest of the user satisfaction factors along with energy fall in the categories of the passive and active design measures within the new stepped strategy.

For the façade design of this research, passive and active measures for these user satisfaction factors need to be found in interactive/adaptive technologies in order for the façade to optimally satisfy users' needs of comfort. Paragraph 2.3 goes more in depth into this.

2.3 Interactive/adaptive technologies

In order to design a smart and sustainable façade element to comply with the needs of office users, research must be done on state of the art smart passive and active technologies which adapt according to office users needs of comfort, the local climate, and outdoor conditions, to understand them and identify their challenges and potentials for the development of this research's façade element. In this paragraph, first, passive and active technologies of state of the art projects will be discussed where the most relevant technologies will be evaluated on their potential for interacting/adapting with the users' preferences of temperature and indoor air quality (thermal comfort), daylight and artificial lighting (visual comfort), user control, and office aesthetics. Second, research will be done on relevant state of the art passive and active materials and systems that can interact/adapt with users' preferences also on thermal comfort, visual comfort, user control, and office aesthetics. These technologies will be examined, along with methods on how to integrate the passive and active measures for the users satisfaction factors into a façade.

2.3.1 Interactive/adaptive technologies – state of the art projects

AdaptiWall

AdaptiWall is a building façade which adapts to outdoor conditions in order to regulate the indoor conditions. It is an adaptive insulation façade system which harvest solar energy on the façade surface and then transmits this energy into the indoor environment when it is necessary. AdaptiWall consists of three key components: adaptive insulation, a lightweight concrete buffer, and a total heat exchanger (THEX). As can be seen in figure 8, the lightweight concrete structure is situated in the center of the element and its used as a buffer to store heat and cold. The adaptive insulation, which is a PCM material, is situated on both sides of the buffer in order to control the heat flows to and from the buffer. The THEX makes sure to recover sensible heat, latent heat and is incorporated in the buffer. The edges of the concrete buffer and the THEX are insulated in order to avoid leaking of energy and insulation is also applied around the doors and windows. The cladding and windows are not key components, by they can influence the performance of the AdaptiWall. According to the results of simulations it was determined that for the outside layer a glazing system should be used and plasterboard for the inside layer. These systems and materials have a good reaction with the AdaptiWall system and make the system more efficient. Theoretical simulations of the system show that by being able to adapt the thermal properties of the façade, the system has the potential of reducing the total heating and cooling demand by more than 20% to over 90% with respect to current retrofitting solutions. Therefore, significant energy savings can be achieved. (Lacave Azpeitia, Rodriguez Pando, Donkervoort, & Dijkmans, 2015)

The system adapts according to a control strategy that can be adapted according to the users' needs of comfort. This refers to a specific temperature degree where the stored heat or cold in the buffer can be released. The storing of energy and the release of this energy to the indoors takes place depending on the season. In case that the indoor temperature is too low and the buffer is not be able to heat the room quickly, additional space heating can be used and can be adopted into the control strategy. For cooling this would mean applying cool air, which means that the windows will open automatically for cooling by ventilation or by applying another type of additional cooling when the buffer is not able to cool the room quickly. The control strategy can also be set according to the office use hours. (Dijkmans, Donkervoort, Phaff, & Valcke, 2014)

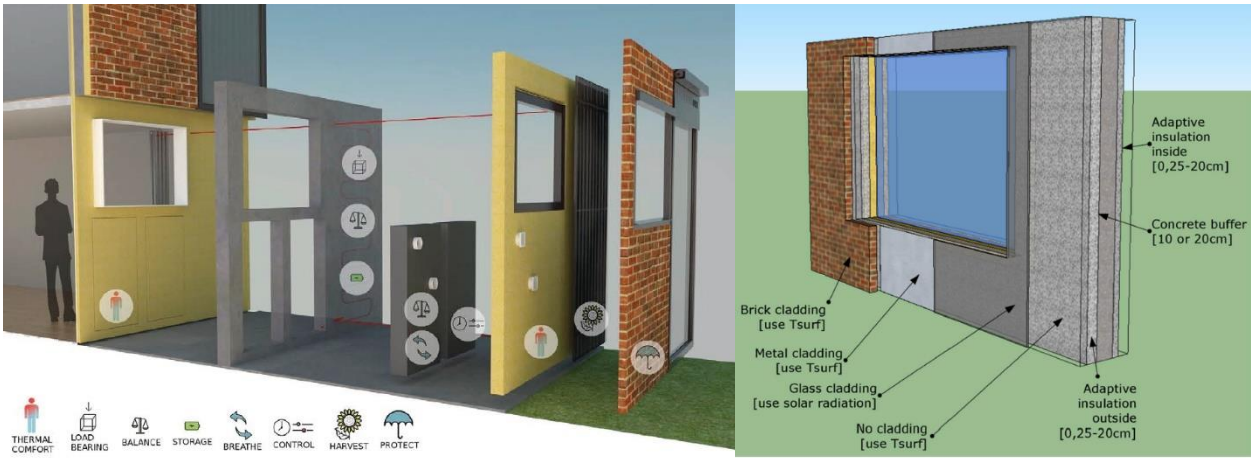


Figure 8: AdaptiWall elements. Images derived from ADAPTIWALL.EU (n.d.) and from Dijkmans, Donkervoort, Phaff and Valcke (2014)

Evaluation

The AdaptiWall has very interesting and relevant passive and active solutions that could be implemented in the design of the office-user oriented façade design of this research. This project shows potentials in the passive measures heat protection, heat gain, heat rejection, and the active measure, heat generation. Having a façade which automatically adapts the indoor conditions according to the outdoor conditions and to limit values of user preferences, can definitely increase user satisfaction and therefore work productivity. This system tackles the user satisfaction factors of temperature and some of the indoor air quality factors, such as ventilation (in some extent), noise, and user control due to a control strategy, but not the consequences of office aesthetics. This system can be enhanced by adding the office aesthetics factors, such as efficient color use depending on the tasks performed in the space. Other office aesthetics factors, such as having a living wall system as the inside layer, which also helps improving the indoor air quality, seem to be more challenging, because the heat or cold that the buffer releases can jeopardize the plants on the wall. Also, adding the proper WWR according to the façade's orientation, and smart lighting systems along with active measure to generate energy on the façade, could be an improvement or enhancement of the AdaptiWall.

BRESAER

BRESAER or BREaktrough Solutions for Adaptable Envelopes in building Refurbishment, is an innovative and standardized system for façades which integrates different technological solutions in order to enhance the energy efficiency, thermal comfort, air quality, visual comfort, and acoustics in buildings, mainly focusing on refurbishment. The team has come up with an envelope system that is able to combine different technologies from market technologies, novel technologies, passive and active technologies, architectural technologies, and facility electronics ultimately creating a single and versatile envelope system which is adaptable. Due to its adaptability, different coverings can be installed, such as a modular ventilated system which uses nanotechnology, thermal insulation multilayer panels, fiber reinforced concrete which uses nanotechnology properties, and metallic active envelopes which can be connected to the ventilation system and windows that have automated dynamic slats which have high thermic properties for solar radiation control and light. The complete system can be monitored by an innovative Building Energy Management System which has a specific control system that governs most of the envelope's functions and energy facilities, including the generated energy by the system (figure 9a). (Aguirre, Azpiazu, Lacave, Álvarez, & Garay, 2018)

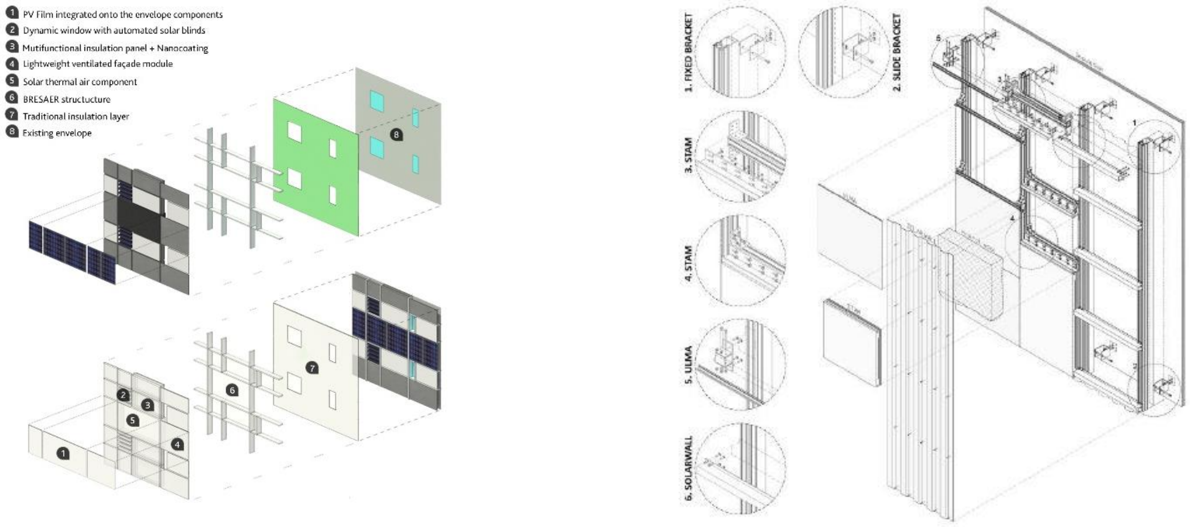


Figure 9(a): BRESAER systems' scheme *(b) integration of systems*
Images derived from BRESAER.EU (n.d.) and from Aguirre, Azpiazu, Lacave, Álvarez, and Garay (2018)

The system consists of modular solutions integrated in a lightweight structural mesh (figure 9b). According to Aguirre, Azpiazu, Lacave, Álvarez and Garay (2018), the system has "aluminum frames which supports different modules or panels, such as the lightweight mechanical ventilation system module, a multifunctional and multilayer insulation panel made out of Ultra High Performance Concrete (UHPFRC), a solar active thermal envelope system or better known as the SolarWall system, dynamic windows with automated solar controlled blinds, and nanocoatings such as PV-glass coating, thermo-reflective coating and self-cleaning coating for external surfaces". The systems within the façade are all interchangeable and demountable, which helps the adaptation and maintenance of the system. Due to its features, the system is capable of adapting the indoor conditions according to the external climatic conditions. (Aguirre, Azpiazu, Lacave, Álvarez, & Garay, 2018)

According to energy calculations, it is expected for the system to have a payback time of seven years. It is also expected that the BRESAER will record a reduction of at least 60% of the total primary energy consumption having a consumption below the 60 kWh/m^2 per year, with 30% energy demand reduction for heating, 15% of solar thermal energy reduction for conditioning, and around 75% reduction of the electricity consumption. Multiple prototypes have been installed in order to verify the correct energy performance and mechanical performance of the system.

Evaluation

The BRESAER system is intended for residential use, but it shows potential for traditional office buildings, that do not consist of only curtain walls. It has interesting technologies that could be implemented in the façade design of this research. Some components, such as he multifunctional multilayer UHPFRC panels, the integrated HVAC system in the Solarwall, the PV-glass coating, the thermo-reflective coating, and the self-cleaning coating. These technologies can help increase the thermal comfort, help reduce the energy demand of the building, and help produce sufficient energy in order for the building to be nearly energy neutral. Besides all of its features, one key factor is still missing, which is the user control factor. It does not really allow for user control in terms of desired temperatures and levels of lighting. The blinds do adapt according to the sun's path, but it is not quite clear if this can be overwritten by users. Due to the fact that the system is designed for refurbishment, it only has implementations for the outside of the building and not the indoor layer. This does leave a potential for the inner wall to be adapted according to users' needs for office aesthetics, without affecting the systems' properties. Therefore, this system can be enhanced by adding a control strategy where users can adapt their indoor environment by letting more air inside in order to manipulate the temperature, adjusting the blinds for more daylight, and adapting the indoor layer for office aesthetics to enhance office users satisfaction.

Double Face 2.0

Double face 2.0 is a new type of Trombe wall which allows the wall to adjust itself to changing environmental conditions and seasonal differences. In difference from the traditional Trombe wall, this wall is much lighter in weight due to the fact that it consists of a Phase Change Material (PCM) for latent heat storage which has a higher storage capacity than a regular concrete wall, and aerogel for thermal insulation which has a very good thermal conductivity, making it possible to create a very slim Trombe wall (figure 10a). The implementation of PCM within the wall makes it possible to not only store heat from the sun during winter during its phase change from solid to liquid state, but also to capture heat from internal heat sources during summer and thereby acting as a cooling device (figure 10b) (RUMOER , 2018).

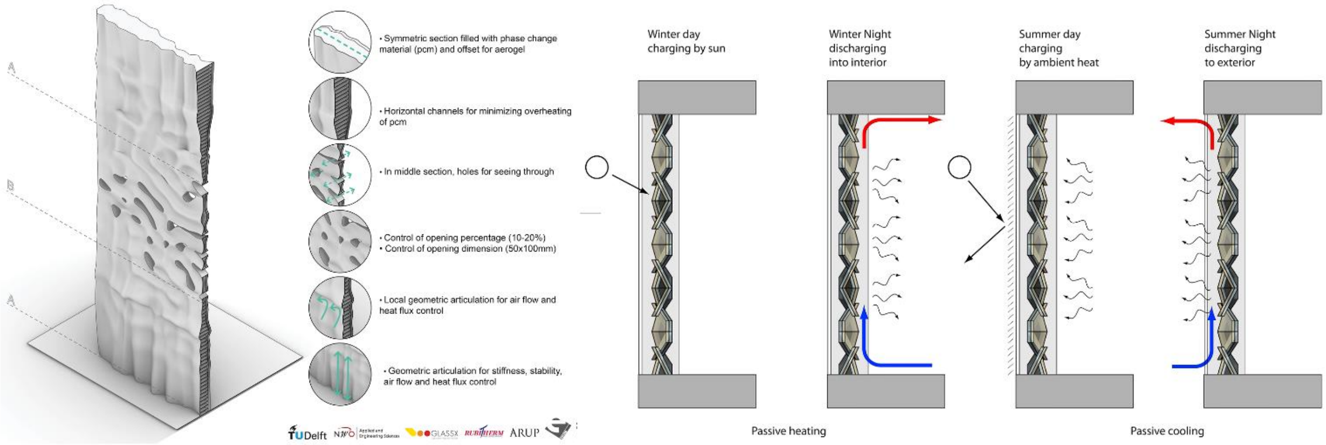


Figure 10 (a): Double Face 2.0 section and impression *(b) winter and summer modes*
Images derived from Tenpierik, Turrin, Wattez, Cosmatu, & Tsafou (2018)

One of the key features of this innovative Trombe wall is its adjustability to change of position of the face (figure 11). During a winter day, the PCM can face to the window where it will slowly melt due to the direct heat of the sun and thereby change its state from solid to liquid, going from opaque to translucent. During the night, the system can rotate in order for the PCM to face the interior of the space and where it can slowly disperse the stored heat, changing again from state (translucent to opaque) and making sure that the indoor conditions remain comfortable for the next day. During summer, the PCM is faced to the indoors during the day in order to store the heat from internal sources and releasing this during the night via cold outdoor air by facing to the window. According to simulations, due to its adjustability, this innovative Trombe wall can lead to an energy reduction of about 30%.

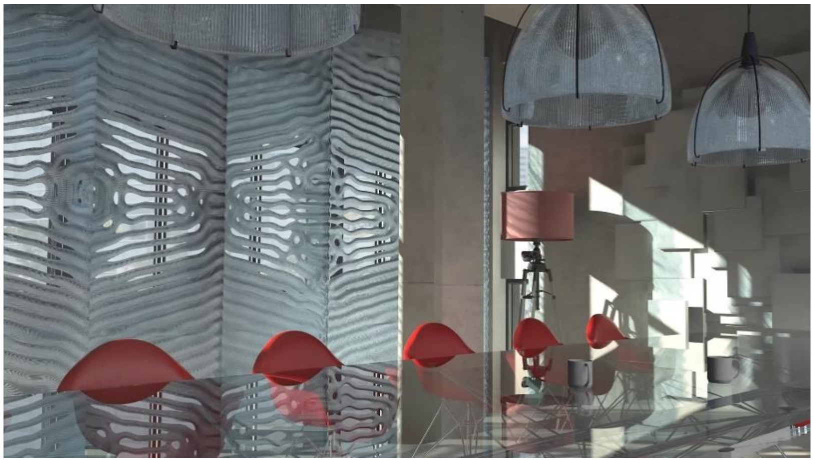


Figure 11: rotation of Double Face 2.0. Image derived from Double Face 2.0 VIMEO video (2018)

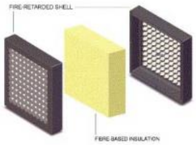
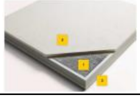
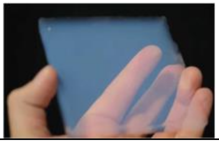
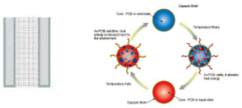
Evaluation

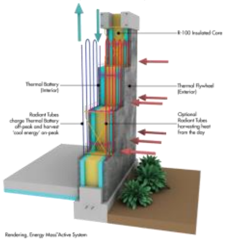
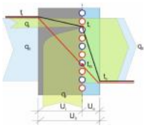
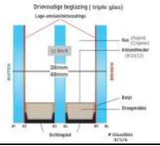
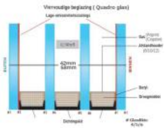
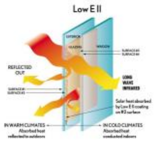
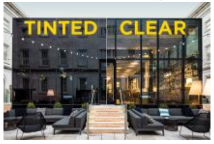
The Double Face 2.0 is a perfect example of how to take an existing, well known, concept to its innovative and future proof state. By using a PCM to store the heat, it allows the indoor environment to be more in balance, to store more heat, and to have more free space in the room, instead of having a very thick concrete heat storage wall. By making it adjustable by rotating to either release or store its heat, makes the Double Face 2.0 a more energy efficient Trombe wall. However, due to its thinness and constant direct solar radiation exposure, the PCM can easily overheat making the indoor environment uncomfortable. Therefore, choosing the right thickness for a specific space is a very important parameter of the system. Also, as the Double Face 2.0 is being introduced now, it is a system which is intended for enhancement of existing curtain walls in spaces and does therefore not really completely block the solar radiation exposure to the indoor environment. Introducing this as or within the building envelope, can be an enhancement of the system. Another issue is the visual comfort that the system provides. Even though it changes from an opaque- to a translucent state when exposed to direct sun, it still only provides a glimpse to the outside, blocking most of the outside view. Besides this, it offers no control strategy for the users to be able to control their environment, but it surely has a very appealing look.

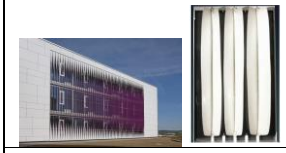
2.3.2 Interactive/adaptive technologies – state of the art materials and systems

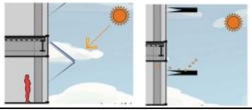
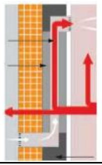
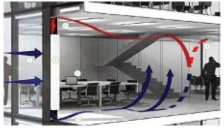
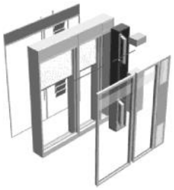
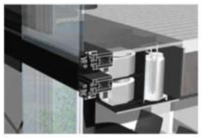
There are multiple interactive/adaptive passive and active smart methods, materials, and systems that could enhance the thermal comfort, visual comfort, user control, and office aesthetics of the indoor environment. The most relevant for this research are introduced in Appendix A and will now be evaluated in table 6 on their advantages and disadvantages for their thermal comfort, visual comfort, user control, office aesthetics, and overall behavior.

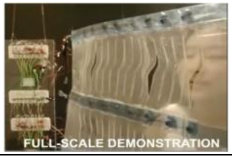
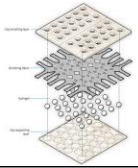
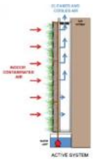
Table 6: evaluation of interactive/adaptive state of the art materials and systems. Table by author
Images references can be found in reference list Appendix A

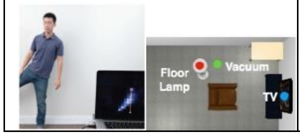
Materials/Systems	Components function	Advantages	Disadvantages
Dynamic insulation  	Heat protection (insulation)	Adaptive thermal comfort Good thermal conductivity	Self-adaptive, therefore indoor environment could be considered uncomfortable for a few
Vacuum Insulated Panels (VIP) 		Exceptional thermal conductivity with slim thickness which allows for more user space	Increase of thermal conductivity due to its short lifespan
Aerogel insulation 		Very good thermal conductivity Sufficient visual comfort due to its translucency	Uncertain long-term physical properties
Aerogel based plaster 		Very good thermal conductivity	Uncertain long-term physical properties
PCM 		Adaptive thermal comfort Heat storage Possibility of user control	Slow thermal change Complex system

Energy Mass Wall (EMW) 		Adaptive thermal comfort Heat storage	Slow thermal comfort Difficult to reach in case of repair Less flexible office aesthetics
Active thermal insulation 		Improves thermal comfort Reduces heat losses considerably	Difficult to reach in case of repair
Triple glazing 	Heat protection (glazing)	Good thermal conductivity Good visual comfort depending on coating or filling	Increase in window thickness
Quadruple glazing 		Very good thermal conductivity Good visual comfort depending on coating or filling	Increase in window thickness
Low-e glazing 		Blocks direct sunlight while providing sufficient daylight	Prevents passive heating through glass during winter Traps heat radiating from the inside possibly causing overheating
Polaroid glazing 		Blocks direct sunlight while providing clear view Diminishes glare and reflections	Less daylight due to tint Prevents passive heating through glass during winter
Prismatic glazing 		Blocks direct light avoiding glare Distributes daylight to the indoors	Lights only the area near the window
Thermochromic glazing Photochromic glazing 		Internal heat gain control Reduction of glare while providing clear view	Less daylight due to tint Can overheat and change color Prevents passive heating through glass during winter
Electrochromic glazing 		User control possibility Reduction of glare while providing clear view	Less daylight due to tint Electricity usage

PolyArch window 		Passive heating in winter possible by IR light, while blocking IR light during summer Provides clear view User control possibility	Color change possible at some incident light angles
Physee Power window 		Solar cells integrated in window-spacer converting sunlight into green electricity	Blinds can only be place within the window blocking the view
Physee Smart window 		Measures light intensity, temperature, pressure and air quality and communicates this actuators such as sun blinds	Electricity usage
Physee Eesy window 		Besides integrated sensors, it has power storage, user control systems and self-adaptation according to user behavior	Electricity usage
Deformation of louvres by temperature or solar control 	Heat protection (solar control)	Self-adaptive and/or user controlled Avoids glare and heat gains Appealing look	Blocks the view Electricity usage
Green wall 	Heat protection	Improves thermal comfort acting as an extra insulation layer No soil needed Appealing look	Maintenance
Breathing skins 		Self-regulates the amount of light, view, temperature and air through skin	Complex system
Thermal collector blinds or cladding 	Heat protection Heat generation	Reduction in direct sunlight and therefore heat gains	Obstructs the view Maintenance

Integrated PV in shading features 	Heat protection (solar control) Electricity	Electricity production Avoids direct sunlight and glare	Obstructs the view
Solar controlled shading with integrated PV's + daylight expansion 		Better PV-efficiency Daylight increase View not completely obstructed	Complex installation
Air alternation through facade 	Heat rejection (ventilation)	Pre-heating of fresh air Reduced ventilation load Reduction of heat losses Heat recovery	Could overheat during summer
Decentralized ventilation 		Self-adaptive ventilation Pre-heating of air Heat recovery	Not user controllable
Next Active Façade 		Self-adaptive and user controllable ventilation, heating and cooling (BIS) Heat recovery System is hidden in frame	-
Schüco E2 system 		Self-adaptive ventilation, heating and cooling (BIS) Heat recovery System is hidden in floor	Not user controllable
TE motion 		Self-adaptive ventilation, heating and cooling (BIS) Redirects daylight PV-cells integrated in system for electricity production	Not user controllable Not appealing Takes up a lot of the façade surface
Smartbox 		Self-adaptive ventilation, heating and cooling (BIS) Heat recovery System is hidden in floor	Not user controllable

Living glass – responds to human presence 		Self-adaptive and user controllable ventilation Interacts with users	Complex system
Hydroceramic hydrogel 	Heat rejection (cooling)	Adaptive thermal comfort Helps indoors to remain in balance	Slow thermal change
Active Living Wall System (ALWS) 		Air purification by plants Improves thermal comfort acting as an extra insulation layer No soil needed Appealing look	High maintenance
SolarWall PV/T 	Heat generation Heat rejection (ventilation)	Electricity and thermal heat production in one system Pre-heating of incoming air possible Improves PV-efficiency	-
Algae bio-reactive façade (biomass) 	Heat generation Electricity	Electricity and thermal heat production Can be stored with no energy loss	Not appealing Carbon required to feed the algae
Color changing Building integrated PV-panels (BIPV) 	Heat protection Electricity	Electricity production Appealing look	Less efficient than regular PV's
Transparent PV-panels 		Electricity production No view obstruction	Less efficient than regular PV's
Semi-transparent PV-panels 		Electricity production	Obstructs the view Less efficient than regular PV's

Wind energy 		Electricity production Appealing look	Complex system Noise production
Kinetic energy 		Electricity production Appealing look	Obstructs the view
Wall++  	Electricity	Detects human behavior adapting the indoor conditions User controllable	-

2.3.3 Integration of user satisfaction factors along with interactive/adaptive technologies

The integration of the user satisfaction factors within a façade along with interactive/adaptive technologies can happen in different manners, such as in static layers, in dynamic features (moving parts), or an integration of both static layers and dynamic features. The idea for the design of the office user façade element of this research is that the façade should have components which allows it to adapt itself according to its interaction with users and therefore increasing the users' comfort of temperature, indoor air quality, visual comfort, and office aesthetics (figure 12) . Also, that users have the freedom to adapt their environment according to their wishes at any moment in time. The façade should at all time suffice their needs in relation to their environment. This can be done by using passive and active measures, such as materials and systems, but also by intelligent technologies, such as sensors and data analysis, in order for the actuators to respond to the needs of users (figure 13). For the façade design of this research, these possibilities will be taken into account.

Figure 12: user control factors. *Image by author*

Figure 13: process of adaptive feature and data flow of an intelligent façade. *Image by author, derived from Upadhyay & Ansari (2017)*

2.4 Energy

In this chapter, research will be done on how to design an office façade as energy efficient as possible, taking European agreements and National regulations into account. Also, on how much energy office spaces use and how much of this energy has to be produced by a façade in order to help the building achieve nearly energy neutrality. Furthermore, research will be done on what does it mean to be nearly energy neutral in terms of values.

2.4.1 Façade design and nearly energy neutrality of office buildings

In The Netherlands and in Europe, agreements have been made to combat climate change. A major challenge is making the existing building stock in The Netherlands more sustainable. Therefore, the government has stipulated laws, rules, and instruments for achieving the climate goals. For office buildings this means that as of January 1, 2023, every existing office buildings which are larger than 100 m^2, have to achieve an Energy label C as a minimum. This means an Energy Index of 1.3 or better. If the building does not meet the requirements, the building may no longer be used as an office from the 1st of January 2023. This obligation is stated in the 2012 Building Decree. Achieving this value helps office buildings become nearly energy neutral. However, the national government is striving for a complete energy-neutral built environment in 2050, also for the existing building stock. An energy label can be determined based on the Energy Index. The Energy Index is a voluntary instrument that can be used to calculate the energy performance of a building. (Rijksdienst voor Ondernemend Nederland, n.d.)

This regulation encouraged research on to understanding the energy usage of office buildings and why this meets a certain value, in order to know where changes need to be made. One of those researches is The Netherlands Central Statistical Office's (2017) research on energy labels and the actual energy consumption of offices, where they investigated the energy consumption of 1000 offices. The research concluded that there was a 46% reduction in gas intensity between an A-Energy label office and a G-Energy label office and a 23% increase in electricity intensity, also between these two energy labels. At a first glance the results seemed not to be logical, but according to their research, they accomplished understanding the reason behind this observation. This increase in electricity is due to two factors: the buildings and the users. The buildings themselves have an electricity increase due to the fact of the implementation of cooling and mechanical ventilation, but this simultaniously decreases due to the implementation of energy efficient lighting. The other factor is that with the increase of energy labels, the office spaces are identified as being able to have a higher occupancy rate. For the electricity this means an increase due to an increase in employees. The research concluded that sustainability goes hand in hand with a high occupancy rate and more office units, so an office with a good energy label "may" have a higher electricity consumption. (Central Statistical Office, 2017)

In the research they also stated the theoretical electricity use for building-related energy of different energy labels. According to the research, office buildings with an Energy label A would have a minimum electricity use of 40 kWh/m^2 usable area. (Central Statistical Office, 2017)

There are also other national agreements for achieving the climate goals, such as the BENG-requirements or in English, the nZEB (Nearly Zero Energy Buildings) requirements, which is applies to new buildings. The nZEB have indicators that state that from the 1st of January 2021, the energy performance for nZEB's are determined based on requirements related to the maximum energy requirement per year, the maximum primary fossil energy consumption per year, and the minumum share of renewable energy. This varies per type of building. For office buildings the requirements can be seen in table 8.

Table 7: nZEB/BENG requirements. Table by author, derived from Nieman Raadgevende Ingenieurs (n.d.)

Building function	Energy requirement (BENG 1) kWh/m^2.yr*	Primary fossil energy requirement (BENG 2) kWh/m^2.yr	Share renewable energy (BENG 3) %
Office building	If, $A_{ls}/A_g \leq 1{,}8$: BENG 1 ≤ 90	≤ 40	≥ 30
	If, $A_{ls}/A_g > 1{,}8$: BENG 1 ≤ 90 + 30 x (A_{ls}/A_g - 1,8)		

* A_{ls} = loss area (facade, floor, and roof) A_g = usable area

The nZEB/BENG values can be calculated by using the new NTA 8800 calculation method for the energy performance of buildings.

Although these requirements are for new buildings, the values can be used for the development of this research's office façade element.

In contrast to the requirements of the energy label, where it is stated that buildings with an A-label would have a minimum electricity use of 40 kWh/m^2 usable area, the nZEB state energy requirements which consists of heating and electricity. Therefore, both values can not be directly compared, but both are usefull as a design criteria on which this research's office façade element should comply in order to help the office building achieve nearly energy neutrality.

There are also other regulations related to the energy performance of a building's façade. The Dutch 2012 Building Decree states regulations for the heat resistance (Rc-value) of a façade, the heat transmittance of transparent objects within a façade (U-value), and the infiltration of air around openings in a façade ($q_{v;10;spec}$). The requirements can be seen in table 9.

Table 8: façade energy performance requirements and values. Table by author, derived from Online Bouwbesluit (2012) and

Requirements		Values
Rc-value façade		4,5 m^2·K/W
U-value	Windows	2,2 W/ m^2·K
	Doors	1,65 W/ m^2·K
Infiltration		0,420 dm^3/s·m^2

These values are standard values and do not help with achieving energy neutrality. The most common Rc-values, U-values, and infiltration values that are used for nZEB's buildings can be seen in table 10.

Table 9: nZEB buildings most common Rc-value, U-values, and infiltration values. Table by author, derived from Rijksdienst voor Ondernemend Nederland (2019), Nieman Raadgevende Ingenieurs (2019), DECEUNINCK (n.d.), and Kegro (2010)

Requirements		Values
Rc-value façade		4,5 – 7,0 m^2·K/W
U-value Glazing (U_g)	HR ++ glazing	1,1 W/ m^2·K (28mm argon gas filling)
	Triple glazing	0,5 - 0,6 – 0,7 W/ m^2·K (36mm argon gas – 44mm argon gas – 36mm krypton gas)
	Quadruple glazing	0,3 – 0,4 W/ m^2·K (36mm krypton gas)
U-value Frame (Uf)	Plastic	1,0 W/ m^2·K
	Insulating profile	0,8 W/ m^2·K
	Passive wood	0,7 W/ m^2·K

U-value Doors	Passive wooden doors	0,77 W/ m²·K
Infiltration		0,125 dm³/s·m²

The Rc-value of a façade is calculated per layer of material within a façade, where the thickness (d) and the heat conduction coefficient of the material (λ), which shows the amount of heat that flows through a layer of a material, are important for the calculation of the Rc-value. Equation 5 shows how the Rc-value of a façade can be calculated.

$$Rc = \frac{d}{\lambda} \qquad \text{(E5)}$$

The total Rc-value of a façade can be calculated by adding together all the Rc-values of the layers within a façade, see equation 6. The higher this value is, the better the energy performance of the façade.

$$Rc, total = \ Rc1 + Rc2 + Rc3 \qquad \text{(E6)}$$

The total U-value of a transparent object, such as a window (U_w), can be calculated using equation 7. The lower this value is, the better the energy performance of the façade.

$$Uw = \frac{Ug+Uf}{2} \qquad \text{(E7)}$$

The infiltration value of air around openings in a façade depend on the amount of sealing and seams around these openings. These vary from 0,420 dm³/s·m² for a regular amount of sealing and seams around these openings and 0,125 dm³/s·m² for double amount of sealing and seams. The lower this value is, the better the energy performance of the façade is.

The local climate conditions are also a relevant factor on the energy performance of a façade. Designing a façade according to its orientation to the sun, the placing of the transparent objects according to the sun's angles and taking into account the amount of daylight hours, and the choosing of façade layers according to the changing outdoor temperatures, can optimize the energy performance of a façade. Therefore, it is necessary to understand the climate conditions of The Netherlands and also to take into account its changing pattern due to climate change.

Temperatures

The climate in The Netherlands is changing, with temperatures rising with + 2°C - 3°C in the summer, making cooling in buildings not a luxury anymore, but a necessity. According to the Royal Dutch Meteorological Institute (2020), the year 2014 was the hottest year for the past 20 years with an average temperature of 11,7°C, with the year 2018 in the second place with an average temperature of 11,3°C, and 2019 in third place with an average temperature of 11,2°C (Royal Dutch Meteorological Institute, 2020). The hottest summer within these years was the one of 2019, reaching temperatures as high as 40,7°C on the 25th of July, making it the highest reached temperature in The Netherlands since the beginning of measurements. On this day, the temperature in Delft (measured from the nearest weather station of Rotterdam) was of 37,2°C. In this year, also the temperatures in August where higher than normal, with a heat wave at the end of the month, making it the second one in that year and the latest heat-wave ever measured. 2019 overall was a very warm year with a lot of sunny days and fairly dry on average. This year had a total of 99 warm days (max. temp. ≥20°C), 26 summer days (max. temp. ≥25°C), and 11 tropical days (max. temp. ≥30°C).

The winter in 2019 had its coldest day on the 20th of January with a temperature of -10,2°C and in Delft on the 21st with a temperature of -7,4°C. After this, the temperatures started to rise, making February a very soft and also very sunny month, where on the 27th of February the temperature even reached 20,5°C, making it the highest temperature ever measured during winter since 1901. In Delft, the temperature reached 18,7°C on the 26th of February.

The mid-seasons of spring and autumn were as usual, with in spring the highest temperature measured was on the 20th of April, reaching a temperature above 20°C in most places, and above 25°C on the Southern part of the country.

During the whole winter there were 2 ice days (max. temp. ≤0°C) and 99 frost days (min. temp. ≤0°C) recorded. (Royal Dutch Meteorological Institute, 2020)

Although these extreme temperature were not precisely measured in the city of Delft, for the façade design of this research, these temperatures can be taken into account as extreme temperatures which the façade should be able to handle.

According to figure 14, the average minimum and maximum temperatures in Delft, measured from the nearest weather station in Rotterdam, were of 21°C in July and August and 0°C in January, making these the warmest and coldest months of the year.

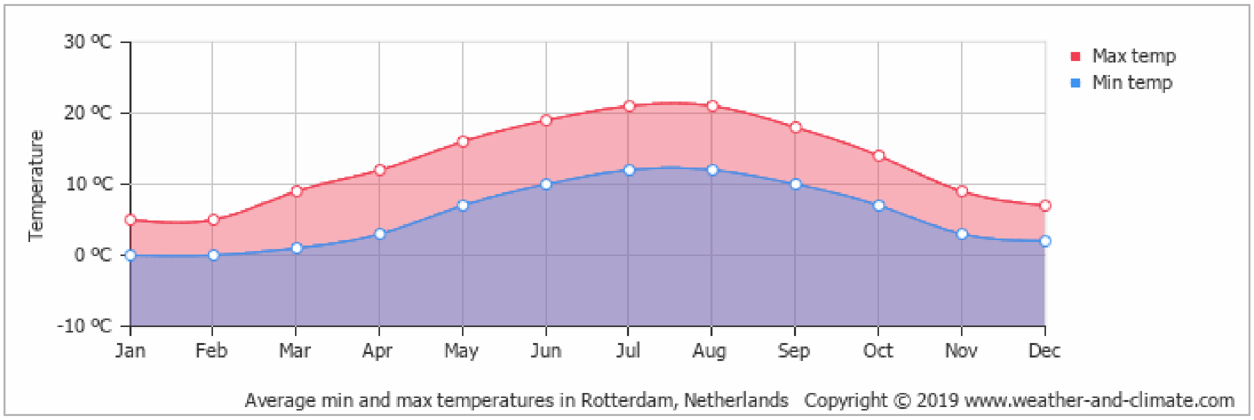


Figure 14: minimum and maximum temperatures in Rotterdam weather station. Figure derived from Weather and Climate (n.d.)

Sun

In 2019, there were 1964 sun hours, making this year a very sunny one and ranking it on third place of the sunniest years. Normally, the average is of 1639 sun hours. Almost every month in 2019 were sunnier than normal, only January and October were on the gloomy side. The least sunniest part of the country was the East part of Limburg (1823 sun hours) and the sunniest part of the country was the coast side near Vlissingen (2067 sun hours).

According to figure 15, for the city of Delft this means May having over 200 hours of sun, and June having the longest day on the 21st, with a daylength of 16:44:04 hours. On this day, the sunrise was from the Northeast and the sunset on the Northwest with the sun reaching an angle of 61 degrees at midday (Timeanddate.com, n.d.) making this the highest sun angle of the year. Figure 15 also shows that the period with the least amount of sun was in December with less than 50 hours of sun, with the 22nd being the shortest day of the year with a daylength of 7:44:31. On this day, the sunrise was from the Southeast and the sunset on the Southwest with the sun reaching an angle of 15 degrees at midday making this the lowest sun angle of the year (Timeanddate.com, n.d.). The solar irradiance on the location varies from 30 W/m^2 to 50 W/m^2.

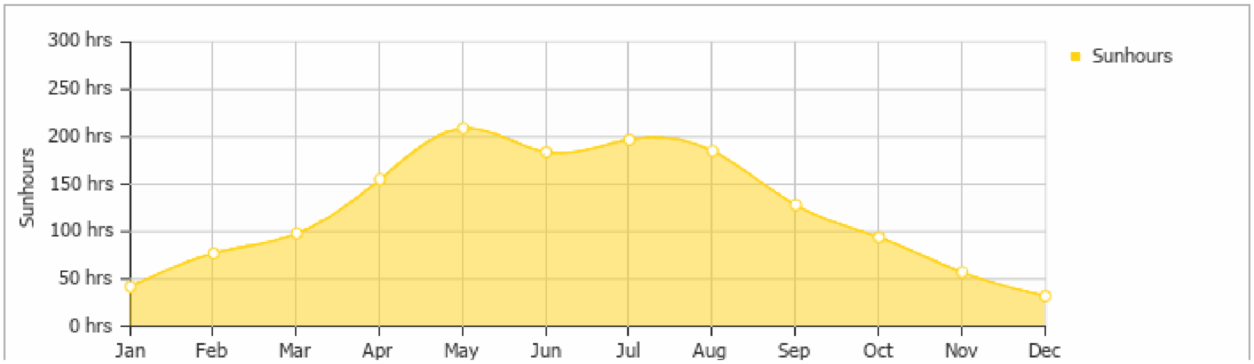


Figure 15: monthly sun hours in Rotterdam weather station. Figure derived from Weather and Climate (n.d.)

Wind

The wind direction in Delft varies during the year, but its direction is mostly from the Southwest towards Northeast (figure 16).

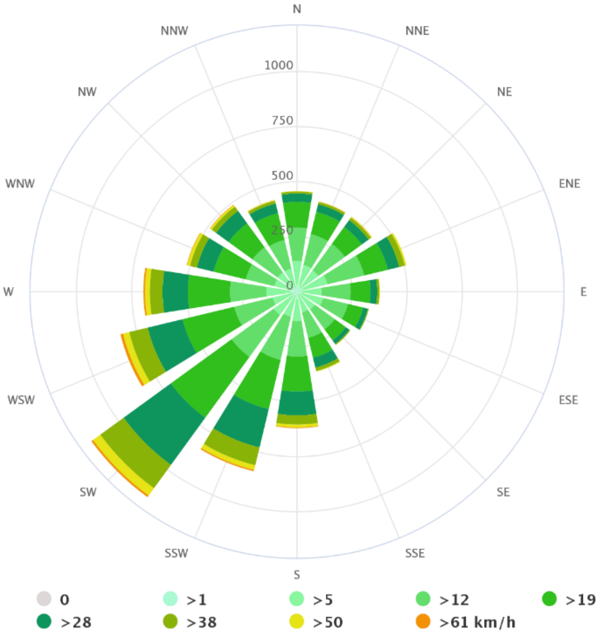


Figure 16: wind direction in Delft. Figure derived from Meteoblue AG (n.d.)

The average wind speed in Delft (measured from the nearest weather station of Rotterdam) is of 16,9 KPH (kilometers per hour) with 46 days of strong winds. Strong winds being defined as windspeeds greather than 41 KPH.

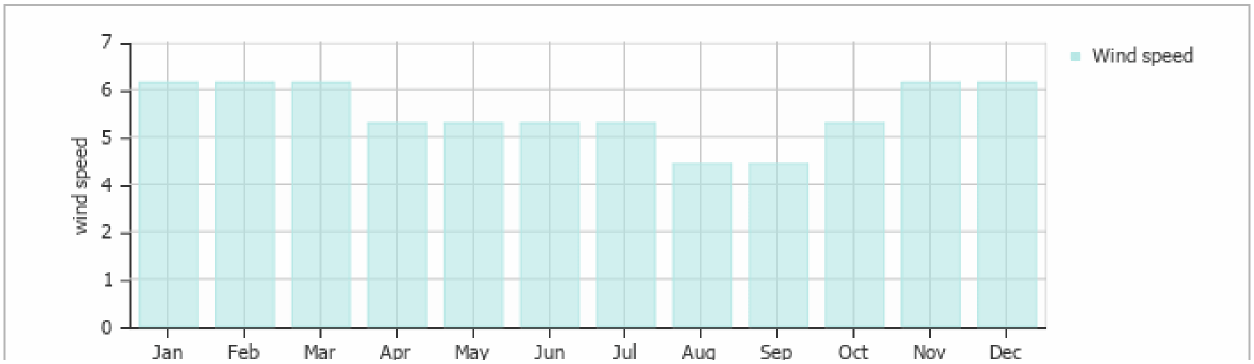


Figure 17: average wind speed in Rotterdam weather station. Figure derived from Weather and Climate (n.d.)

According to figure 17, January, February, March, November, and December had the most amount wind on average in 2019 and August had the least amount of wind. On the 10th of March the Royal Dutch Meteorological Institute issued a code orange for heavy gusts on the southern provinces, where Delft is situated. On this day, the maximum gusts of wind reached 90 KPH in Delft. Other parts of the country reached higher gusts of wind, such as in Zeeland reaching 122 KPH and Ell reaching 119 KPH.

For the façade design of this research it is important to understand the outdoor conditions it will be exposed to. Designing the façade taking these outdoor values will increase the performance of the façade and help achieve indoor user satisfaction.

2.4.2 Designing an energy efficient office façade

There are multiple methods to design an energy efficient façade. Most of the design depends on the climatic conditions the façade is going to be exposed to. For The Netherlands, the climate is most of the time a heating-dominated climate, with nowadays intense cooling-dominated summers, which makes it a mixed climate. According to Aksamija (2015) for this type of climate, the following façade design strategy in table 11 can help reduce the energy consumption and help maintain internal comfort conditions.

Table 10: façade design strategy for mixed climate conditions. Table by author, derived from Aksamija (2015)

Climate type	Design strategies for sustainable façades
Basic methods	Orientation of façades to solar position
	Geometry and mass of façade to solar position
	Reduced WWR for all climate types (improves energy efficiency)
	Solar shading to improve thermal comfort and control cooling loads
	Optimizing exterior insulation and the use of daylight in order to minimize energy consumption for artificial lighting, heating, and cooling
Mixed climate (Heating- and cooling-dominated climate)	Solar control: Protecting facades from direct solar radiation (shading) during warm seasons
	Solar collection and passive heating: Collection of solar heat through building envelope during cold seasons
	Heat Storage: Storage of heat in the mass of the façade
	Cooling: Using natural ventilation through windows to reduce cooling loads
	Daylight: Natural light sources using increased glazed areas in the façade, high performance glazing, using shading devices to minimize heat gain during summer, and use of light shelves to redirect light into interior spaces

For the design of an energy efficient façade, it is also important to understand the façade's properties, the building it is being designed for, the occupancy patterns, and the façade type. There are essentially two façade types, opaque- and glazed façades. Opaque façades consists of layers of solid materials, such as stones, bricks, precast concrete panels, aluminum cladding, insulation, and framing. Glazed façades consist of transparent or translucent glazing materials and metal framing components and are known as curtain walls or storefront façades. Each type of façade has its own physical behavior, due to the fact that their properties are different. Opaque façades tend to have more mass, more insulation, and better heat retention than glazed façades, where glazed façades allow for more daylight to the interior, providing better work illuminance and better views for the users. Ultimately, façades have the obligation to allow sufficient daylight into the indoor space, to prevent unwanted solar heat inside the space, to store heat within the façades' mass, to prevent heat transfer though improved insulation, keeping air or moisture out of going through the façade, and allowing for sufficient natural ventilation for the improvement of the indoor air in the space cooling the indoor environment. (Aksamija, 2015)

Most of the architectural façade designs of the last decade for the energy efficiency of buildings, have focused more on the heat protection of the buildings via shading features and devices and less on other passive and active measures where materials and technologies work together. Also, although the shading features do help increase thermal comfort, and visual comfort, not all are designed to also produce energy, an important factor which can increase the energy efficiency of buildings and ultimately can help the buildings become nearly energy neutral. Nevertheless, there are some great examples in architecture for energy efficient buildings.

Post Tower Bonn

This office building consists of a twin-shell façade, where the outer shell is made completely out of glass, enabling natural ventilation due to its openings (figure 18). This outer shell protects the building from weather conditions and acts as shading. Office users have the possibility to control the shading system and the windows and in this way helping the building to remain cool, reducing solar heat gain, and helping reduce costs by 60%. (ArchDaily, 2012)

Figure 18: Post Tower Bonn. Images derived from ArchDaily (2012)

Edith Green-Wendell Wyatt Federal Building

This is a 1970's building transformed into a sustainable tower, where each side of the building responds to the solar exposure (figure 19). The west façade of the building has a façade of reeds which besides from providing 50% of shading and in this way reducing solar heat gain, it also supports plant growth and provides a native ecosystem. The south and east facades have both horizontal and vertical shading systems. The lower part of the horizontal shelves

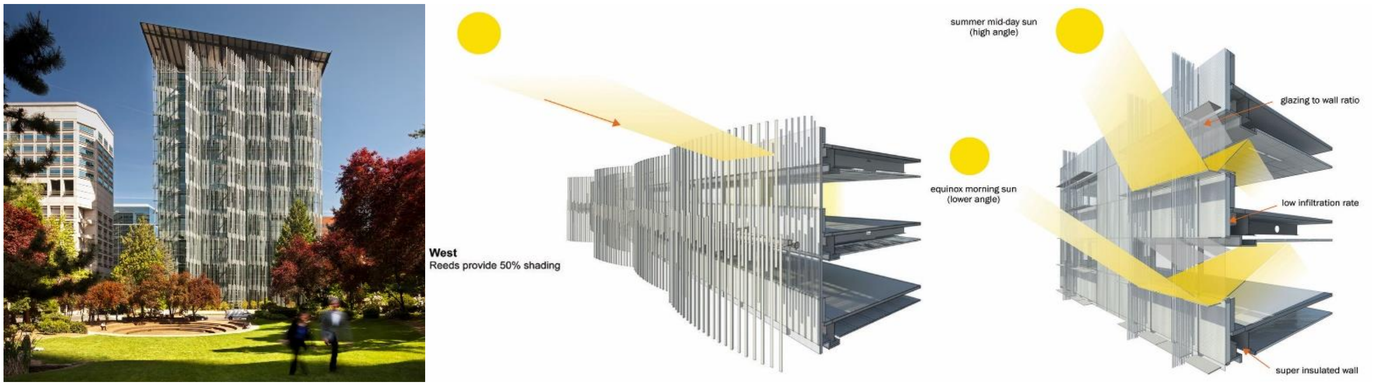


Figure 19: Edith Green-Wendell Wyatt Federal Building. Images derived from ArchDaily (2014)

cast a slight downward shadow on the façade, while the upper part bounces daylight into the inside spaces. By reducing the building's exposure to the sun due to the use of these shading systems, the cooling loads are also being reduced. The façade's window sill panels have two layers of insulation in order to prevent heat loss through the envelope. (ArchDaily, 2014)

ThyssenKrupp Quarter Essen (Q1)

This building has two types of façades, a glazing façade and a façade which is covered by 400.000 stainless steel lamellas. These lamellas are oriented in response of the sun's path, reducing solar heat gain, and enabling light redirection allowing view (figure 20). (ArchDaily, 2013)

Figure 20: ThyssenKrupp Quarter Essen. Images derived from ArchDaily (2013)

Al Bahr Towers

This high rise building located in Abu Dhabi was designed with a shading system around the façade in order to protect the indoor environment from the high temperatures of approximately 50°C. This system is located around the south, east, and west facades (figure 21) and consists of 2000 umbrella-like components which are coated with fiberglass and are programmed to respond to the sun's movements in order to help reduce solar heat gains and glare. The building's façade glazing was also slightly tinted with the aim of improving the office's indoor comfort level, providing a better view, and allowing more light to enter the indoor spaces. During the night, the "Masharabiya" shading system is closed in order to keep the indoor environment cool. (ArchDaily, 2012)

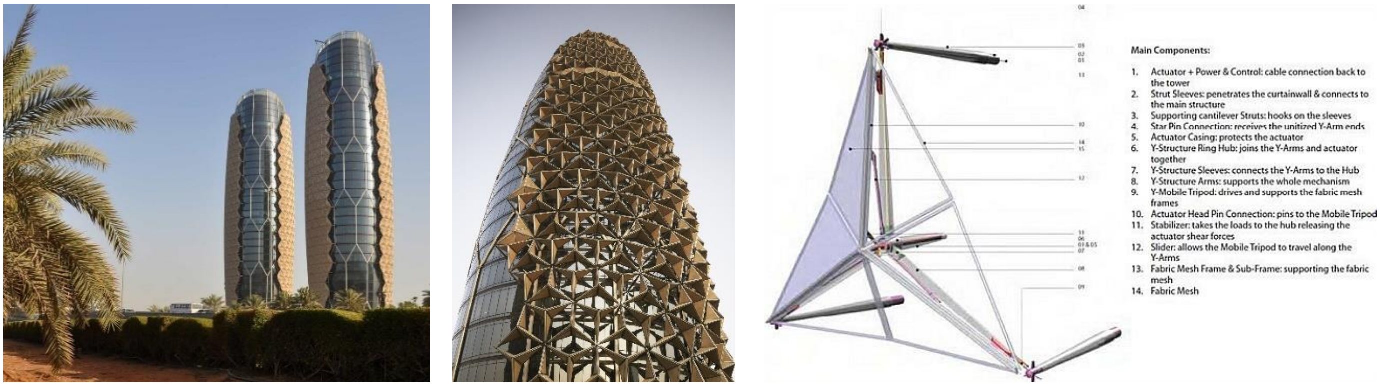


Figure 21: Al Bahr Towers. Images derived from ArchDaily (2012)

Material selection is another factor for designing energy efficient façades, depending on the function of the façade. For an energy efficient façade which also needs to interact/adapt to user satisfaction factors and outdoor conditions, the selected materials need to have properties which allows this.

Chapter 3 – Design considerations

This chapter describes the design considerations for the design of multiple façade configurations for the office-user oriented façade. It also describes the case study.

3.1 Design considerations

From the literature study, the following design considerations derive. These are the design criteria, types of office users, and a generic façade guideline developed according to the interactive/adaptive technologies presented in chapter 2.33 together with some more traditional technologies.

3.1.1 Design criteria

The design criteria on which the facade design configurations will be based on, are the following:

User comfort
User control
Energy efficient
User preferences

The requirements for each of these design criteria will now be further explained.

User comfort

User comfort consists of thermal comfort and visual comfort. According to the literature study, the following comfort values in table 11 are considered to be comfortable by office users and therefore the proposed designs should meet up to these.

Table 11: thermal comfort and visual comfort values. Table by author.

Thermal comfort: temperature and air quality	
Winter temperature range	20 - 24°C
Summer temperature range	23 - 26°C
Rc-value opaque objects	4,5 - 7,0 $m^2 \cdot K/W$
U-value transparent objects:	
Windows	1,0 $W/m^2 \cdot K$
Doors	0,77 $W/m^2 \cdot K$
Air infiltration	0,125 $dm^3/s \cdot m^2$
Airflow per person	7 l/s/person
Expected percentage of dissatisfied	20 %
Ventilation rate	0,7 l/s, m^2

Visual comfort: daylight and artificial light	
Daylight factor	2,5% of office area
Minimum daylight	0,5 m^2
Artificial light	500 lux.

User control

The components within the façade design should be able to adapt themselves according to users behavior in relation to the temperature, indoor air quality, daylight, artificial light, and office aesthetics. Also, the users should always have the freedom to adapt their environment according to their wishes at any moment in time and therefore being able to overwrite the current values. The adaptive system should be able to recognize this behavior and self-adapt in the future when the same environment conditions occur. This concerns user comfort values and also user perception conditions. The façade should at all time suffice their needs in relation to their environment.

Energy efficient

The façade configurations should be designed in an energy efficient manner using energy efficient technologies in order to help its building become nearly energy neutral. They should acquire passive and active measures, should be designed according to local climate conditions, and should use the energy efficient strategies described in chapter 2.4 as a design guideline. In order for the façades to help its building become nearly energy neutral, they should be designed to achieve the following energy values in table 12.

Table 12: nZEB/BENG requirements. Table by author, derived from Nieman Raadgevende Ingenieurs (n.d.)

Building function	Energy requirement (BENG 1) kWh/m².yr*	Primary fossil energy requirement (BENG 2) kWh/m².yr	Share renewable energy (BENG 3) %
Office building	If, $A_{ls}/A_{g} \leq 1,8$: BENG 1 ≤ 90	≤ 40	≥ 30
	If, $A_{ls}/A_{g} > 1,8$: BENG 1 ≤ 90 + 30 x (A_{ls}/A_{g} - 1,8)		

User preferences

The façade design configuration should help enhance the users' experience in the office space by giving them a space which matches with their character and lifestyle. Users should be able in some way to personalize their environment. This can make office users feel more comfortable with their environment, ultimately helping to increase work productivity. Even though every office user has a different character and lifestyle, most of them have the same behavior and preferences. Dr. M.A. Ortiz's (2019) study reflects on different Archetypes and their comfort and energy behavior indoors. From the five different Archetypes that he presents (figure 22), three of these will be used for the façade designs of this research. These are choosen based on their comfort and energy level, varying from neutral to having extreme comfort levels and extreme energy saving behavior. These are the Restrained Conventionals, the Vulnerable Pessimisists, and the Sensitive Wasters. These archetypes will be presented in the next sub-paragraph.

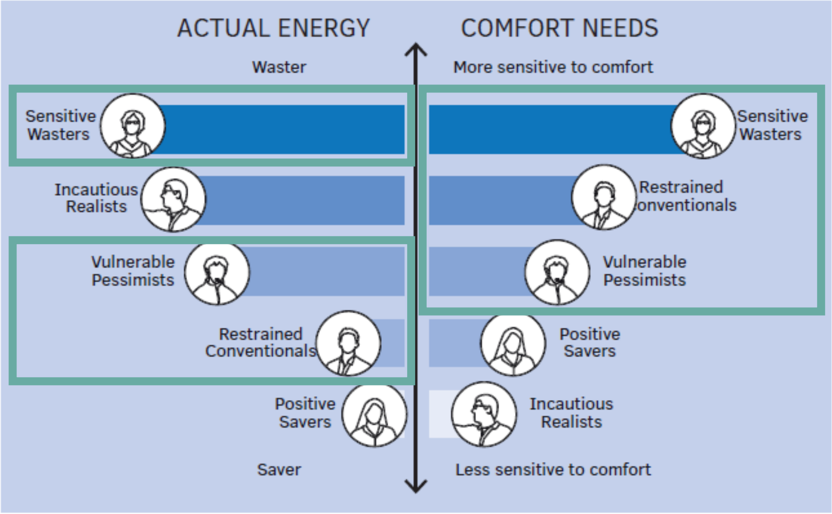


Figure 22: Ranking of Archetypes for energy use and comfort affordance needs.
Image by Dr. M.A. Ortiz (2019)

3.2.2 Archetypes

Each of the previoulsy mentioned Archetypes have different indoor preferences and expectations. Table 13 shows these preferences and expectations and their translation into design principles.

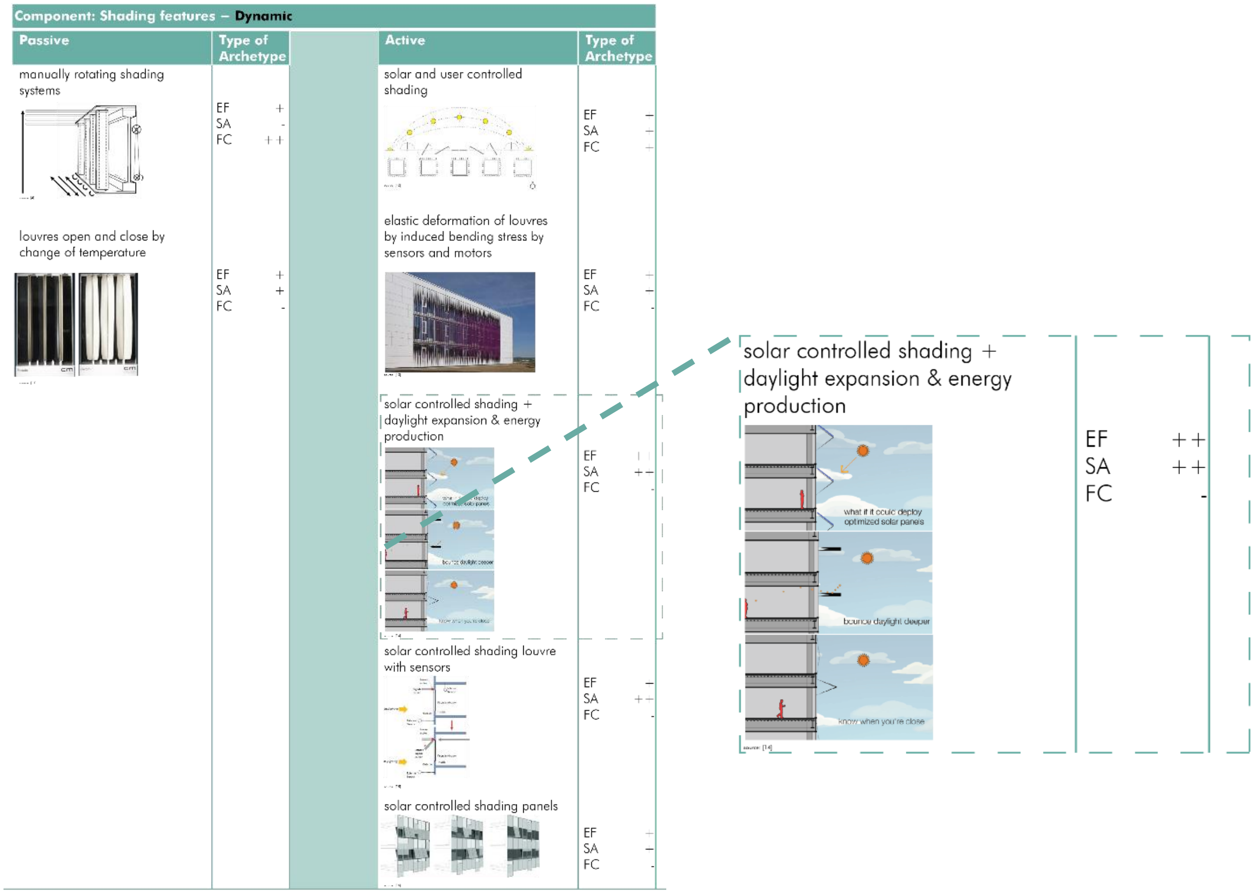
Table 13: Archetypes preferences translated into design principles. Table by author.

Restrained conventionals	**Design principles**
Outside view	Large window area for a view: maximum WWR according to Dr. M. Kwon's study or high performance functioning fully glazed façade (Kwon, Remøy, & van den Bogaard, 2019)
Contact with nature	Implementation of biomimicry/biophilic in design
Energy efficient	As much energy production as possible within the facades' components
High external control/low internal control	Façade components should go well together and complement each other so that the façade can function optimally according to the local climate conditions
Vulnerable Pessimists	**Design principles**
Technologies are main experience	Using or activating technologies for the enhancement of the user experience
Space matching lifestyle	Possibility to adapt the environment to the users' preferences
High external control/low internal control	Façade components should go well together and complement each other so that the façade can function optimally according to the local climate conditions
Sensitive Wasters	**Design principles**
Comfort above energy use	User needs to feel comfortable at all times, completely disregarding the energy this can cost. Smart features should be designed in order to help them save energy and make them aware of the ecological consequences
Own privacy and high freedom	The use of components which enhance the users' privacy and allows them to have freedom in their space
High internal control/low external control	Users have the possibility to control the components in order to adapt them according to their current comfort needs

Based on these preferences and expectations, for this research, these Archetypes are going to be known as the Energy Efficient Archetype (EF) for the Restrained Conventionals, the Self-Adaptive Archetype (SA) for the Vulnerable Pessimisists, and the Full Control Archetype (FC) for the Sensitive Wasters.

3.2.3 Generic façade design guideline

Creating a high performing facade is a balancing act that involves all of the components and succeeds due to their good relation to each other and to their environment. Therefore, it is important to understand what each component represents and how they behave to be able to establish how they will perform. Before starting with the design configurations, the passive and active state of the art technologies presented in paragraph 2.3 together with some more traditional technologies, were placed together and organized per façade component and divided between static and dynamic systems. Then, these were evaluated and weighted against the design principles of each Archetype in order to see which materials or systems were applicable and most suitable per Archetype. In this way, a generic overview of all the technologies is presented and a guideline is created on how to choose a material or system for a component of the façade design of each Archetype. The materials and systems are scored as double plus (++) for very applicable, one plus (+) for applicable, and minus (-) for not applicable. One plus (+) represents if the system itself is Energy Efficient (EF), Self-Adaptive (SA) or Full Controllable (FC), where the other plus (+) represents if the material or system matches at least one of the specific design principles of the Archetypes. One minus (-) represents that the material or system is neither Energy Efficient, Self-Adaptive or Full Controllable, nor does it matches any of the specific design principles of the Archetypes. For example, figure 23 shows a self-adaptive solar controlled shading feature with PV-panels on top and daylight expansion. It is scored double plus (++) for energy efficient, because it helps reduce the energy demand, produces energy, and fits the design principles of sufficient outside view and high external control of this Archetype. The system also scored double plus (++) for self-adaptive, because the system responds to human presence, self-adapts by adjusting the shading depending on the sun's position, and because it fits this archetype's design principles of technologies is main experience and high external control. Due to the fact that this system is not full controllable by the user and it does not meet the design principles of the full control archetype, this systems get a minus (-) for full control. By following this generic façade design guideline the design configurations will be made.



Component: Shading features – Dynamic

Passive	Type of Archetype		Active	Type of Archetype
manually rotating shading systems	EF + SA - FC ++		solar and user controlled shading	EF + SA + FC +
louvres open and close by change of temperature	EF + SA + FC -		elastic deformation of louvres by induced bending stress by sensors and motors	EF + SA + FC -
			solar controlled shading + daylight expansion & energy production	EF ++ SA ++ FC -
			solar controlled shading louvre with sensors	EF + SA ++ FC -
			solar controlled shading panels	EF + SA + FC -

solar controlled shading + daylight expansion & energy production

EF ++
SA ++
FC -

Archetype Energy Efficient (EF): outside view/ contact with nature/ high external control/ low internal control
Archetype Self–Adaptive (SA): use of technologies is main experience/ space matches lifestyle/ high external control/ low internal control
Archetype Full Control (FC): own privacy and high freedom/ comfort above energy use/ low external control/ high internal control

++ very applicable
\+ applicable
\- not applicable

Figure 23: example generic facade design guideline. *Image by author.*

The façades' components are divided as can be seen in figure 24. The generic overview can be found in Appendix B and the evaluation of these technologies per Archetype can be seen in table 14.

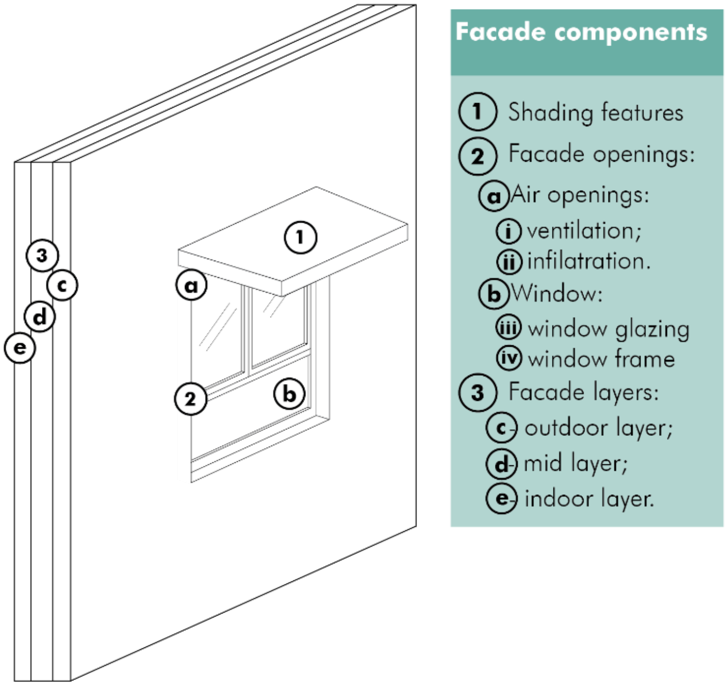


Figure 24: facade divided in components. Figure by author.

Table 14: evaluation of technologies in relation to Archetypes' design principles. Table by author.

<table>
<tr><th colspan="3">Energy efficient (EF) Self-Adaptive (SA) Full Controllable (FC)</th><th>++ very applicable
+ applicable
- not applicable</th></tr>
<tr><th>Materials/Systems</th><th colspan="2">Score</th><th>Evaluation</th></tr>
<tr><td colspan="4">1. Shading features Static – Passive</td></tr>
<tr><td>Overhang</td><td>EF
SA
FC</td><td>+
+
-</td><td>Blocks direct sunlight during summer allowing it during winter as passive heating.
Self-adapts according to the sun angle.
It is not full-controllable and does not meet with the Archetype's design principles.</td></tr>
<tr><td>Horizontal blades</td><td>EF
SA
FC</td><td>++
+
-</td><td>Blocks direct sunlight during summer and allows for sufficient outside view.
Self-adapts according to the sun angle.
It is not full-controllable and does not meet with the Archetype's design principles.</td></tr>
<tr><td>Vertical blades</td><td>EF
SA
FC</td><td>+
+
+</td><td>Blocks the sunlight, but also blocks the view.
Self-adapts according to the sun angle.
Allows own privacy</td></tr>
<tr><td>Horizontal and vertical blades</td><td>EF
SA
FC</td><td>+
+
+</td><td>Blocks the sunlight, but also blocks the view.
Self-adapts according to the sun angle.
Allows own privacy</td></tr>
<tr><td>One sided vertical blade with air openings</td><td>EF
SA
FC</td><td>+
+
-</td><td>Blocks the sunlight, but also blocks the view.
Spacing helps pre-heat the incoming air, self-adapting the indoor environment.
It is not full-controllable and does not meet with the Archetype's design principles.</td></tr>
</table>

1. Shading features Static – Active		
Shading bouncing daylight to inside	EF ++	Allows more daylight inside and allows for sufficient outside view.
	SA +	Self-adapts according to the sun angle.
	FC -	It is not full-controllable and does not meet with the Archetype's design principles.
Thermal collector as blinds	EF +	Produces heat using the direct sunlight.
	SA -	It is not self-adaptive and it does not meet with the Archetype's design principles.
	FC -	It is not full-controllable and does not meet with the Archetype's design principles.
Thermal collector on top of shading feature	EF ++	Produces heat using the direct sunlight and allows for sufficient outside view.
	SA -	It is not self-adaptive and it does not meet with the Archetype's design principles.
	FC -	It is not full-controllable and does not meet with the Archetype's design principles.
Integrated PV's on blinds	EF +	Produces electricity using the direct sunlight.
	SA -	It is not self-adaptive and it does not meet with the Archetype's design principles.
	FC -	It is not full-controllable and does not meet with the Archetype's design principles.
Integrated PV's on top of shading feature	EF + +	Produces electricity using the direct sunlight and allows for sufficient outside view.
	SA -	It is not self-adaptive and it does not meet with the Archetype's design principles.
	FC -	It is not full-controllable and does not meet with the Archetype's design principles.
1. Shading features Dynamic – Passive		
Manually rotating shading systems	EF +	Blocks the sunlight, but also blocks the view.
	SA -	It is not self-adaptive and it does not meet with the Archetype's design principles.
	FC ++	System is full-controllable and allows for own privacy.
Louvres open and close by change of temperature	EF +	Blocks the sunlight, but also blocks the view.
	SA +	Louvres self-adapt by opening and closing according to the surface temperature.
	FC -	It is not full-controllable and does not meet with the Archetype's design principles.
1. Shading features Dynamic – Active		
Solar and user controlled shading	EF +	Blocks the sunlight, but also blocks the view.
	SA +	Self-adapts according to the sun's path.
	FC +	System is full-controllable.
Elastic deformation of louvres	EF +	Blocks the sunlight, but also blocks the view.
	SA +	Self-adapts according to the sun's path based on a schedule.
	FC -	It is not full-controllable and does not meet with the Archetype's design principles.
Solar controlled shading, daylight expansion & energy production	EF + +	Allows more daylight inside, sufficient outside view and produces electricity.
	SA + +	Self-adapts according to the sun's path and to users presence.
	FC -	It is not full-controllable and does not meet with the Archetype's design principles.
Solar controlled shading louvre with sensors	EF +	Blocks the sunlight, but also blocks the view.
	SA + +	Self-adapts according to the sun's path and to users presence.
	FC -	It is not full-controllable and does not meet with the Archetype's design principles.
Solar controlled shading panels	EF +	Blocks the sunlight, but also blocks the view.
	SA +	Self-adapts according to the sun's path.
	FC -	It is not full-controllable and does not meet with the Archetype's design principles.
2a. Façade openings – Air openings Static – Passive		
Openings in façade for ventilation	EF -	It is not energy efficient and it does not meet with the Archetype's design principles.
	SA +	Self regulates the income and outcome of air to indoors.
	FC -	It is not full-controllable and does not meet with the Archetype's design principles.
Altering route of ventilation	EF +	Pre-heating of fresh air by cavity decreasing the heat demand.
	SA +	Self regulates income of air to indoors.
	FC -	It is not full-controllable and does not meet with the Archetype's design principles.
Ventilation grilles on window	EF +	No mechanical ventilation needed.
	SA +	Self regulates income of air to indoors.

	FC	-	It is not full-controllable and does not meet with the Archetype’s design principles.
Ventilation through glazing gap	EF	-	It is not energy efficient and it does not meet with the Archetype’s design principles.
	SA	+	Self regulates the income and outcome of air to indoors.
	FC	-	It is not full-controllable and does not meet with the Archetype’s design principles.
Decentralized ventilation through window frame	EF	+	No mechanical ventilation needed.
	SA	+	Self regulates the income of air to indoors.
	FC	-	It is not full-controllable and does not meet with the Archetype’s design principles.
2a. Façade openings – Air openings Static – Active			
Decentralized ventilation with heat exchanger	EF	+	Pre-heating of fresh air by system decreasing the heat demand.
	SA	+	Self regulates the income of air to indoors.
	FC	-	It is not full-controllable and does not meet with the Archetype’s design principles.
Next Active Façade Ventilation + heat exchanger	EF	+	Pre-heating of fresh air by system decreasing the heat demand.
	SA	+	Self regulates the income of air to indoors.
	FC	+	System is full-controllable.
Hybrid ventilation	EF	+	Passive and mechanical introduction of air.
	SA	+	Self regulates the income of air to indoors.
	FC	-	It is not full-controllable and does not meet with the Archetype’s design principles.
Air supply and extraction unit in facade	EF	+	One small unit that directly supplies and extracts air from and to the outside.
	SA	+	Self regulates the income of air to indoors.
	FC	-	It is not full-controllable and does not meet with the Archetype’s design principles.
2a. Façade openings – Air openings Dynamic – Passive			
Operable windows	EF	+	No mechanical ventilation needed.
	SA	-	It is not self-adaptive and it does not meet with the Archetype’s design principles.
	FC	+	System is full-controllable.
Operable windows grilles	EF	+	No mechanical ventilation needed.
	SA	-	It is not self-adaptive and it does not meet with the Archetype’s design principles.
	FC	+	System is full-controllable.
2a. Façade openings – Air openings Dynamic – Active			
Automatically opening and closing of windows for ventilation	EF	+	No mechanical ventilation needed.
	SA	+	Self regulates the income and outcome of air to indoors.
	FC	-	It is not full-controllable and does not meet with the Archetype’s design principles.
Pre-heating of incoming air through double skin façade	EF	+	Pre-heating of fresh air by system decreasing the heat demand.
	SA	+	Self regulates the income and outcome of air to indoors.
	FC	-	It is not full-controllable and does not meet with the Archetype’s design principles.
2b. Façade openings – Window glazing – Passive			
Triple glazing/ Quadruple glazing	EF	++	Decreases solar heat gains and allows for sufficient outside view.
	SA	-	It is not self-adaptive and it does not meet with the Archetype’s design principles.
	FC	-	It is not full-controllable and does not meet with the Archetype’s design principles.
Low-e glazing	EF	++	Decreases solar heat gains during summer, traps radiant heat during winter, and allows for sufficient outside view.
	SA	+	Self-adapts according to season.
	FC	-	It is not full-controllable and does not meet with the Archetype’s design principles.
Polaroid glazing	EF	+	Decreases solar heat gains.
	SA	+	Self-adapts according to sun angle.
	FC	-	It is not full-controllable and does not meet with the Archetype’s design principles.
Prismatic glazing	EF	++	Allows more daylight inside and sufficient outside view.
	SA	+	Self-adapts according to sun angle.

	FC -	It is not full-controllable and does not meet with the Archetype's design principles.
Thermochromic/ Photochromic glazing	EF +	Decreases solar heat gains.
	SA +	Self-adapts according to sun intensity.
	FC -	It is not full-controllable and does not meet with the Archetype's design principles.
2b. Façade openings – Window glazing – Active		
Electrochromic glazing	EF +	Decreases solar heat gains.
	SA -	It is not self-adaptive and it does not meet with the Archetype's design principles.
	FC +	System is full-controllable.
PolyArch	EF +	Blocks solar heat gains during summer, allowing it during winter as passive heating.
	SA +	Self-adapts according to sun intensity.
	FC +	System is full-controllable.
Physee Power Window	EF ++	Produces electricity and allows for sufficient outside view.
	SA -	It is not self-adaptive and it does not meet with the Archetype's design principles.
	FC -	It is not full-controllable and does not meet with the Archetype's design principles.
Sem-transparent PV's	EF +	Produces electricity, but blocks most of the view.
	SA -	It is not self-adaptive and it does not meet with the Archetype's design principles.
	FC -	It is not full-controllable and does not meet with the Archetype's design principles.
Transparent PV's	EF ++	Produces electricity and allows for sufficient outside view.
	SA -	It is not self-adaptive and it does not meet with the Archetype's design principles.
	FC -	It is not full-controllable and does not meet with the Archetype's design principles.
2b. Façade openings – Window frame – Passive		
Insulated frames	EF ++	Decreases heat losses and allows for sufficient outside view.
	SA -	It is not self-adaptive and it does not meet with the Archetype's design principles.
	FC -	It is not full-controllable and does not meet with the Archetype's design principles.
Passive window frames	EF ++	Decreases heat losses and allows for sufficient outside view.
	SA -	It is not self-adaptive and it does not meet with the Archetype's design principles.
	FC -	It is not full-controllable and does not meet with the Archetype's design principles.
2b. Façade openings – Window frame – Active		
Physee Smart Window	EF ++	Produces electricity and allows for sufficient outside view.
	SA + +	Self-adapts indoor climate according to internal conditions, tech. user experience.
	FC -	It is not full-controllable and does not meet with the Archetype's design principles.
Physee Eesy Window	EF ++	Produces electricity, has power storage, and allows for sufficient outside view.
	SA + +	Self-adapts indoor climate according to user behavior, tech. main user experience.
	FC +	System is full-controllable.
3c. Façade layers – Outdoor layer Static – Passive		
Green wall	EF +	Decreases solar heat gains through the façade.
	SA -	It is not self-adaptive and it does not meet with the Archetype's design principles.
	FC -	It is not full-controllable and does not meet with the Archetype's design principles.
Cactus shape cladding	EF +	Decreases solar heat gains through the façade.
	SA -	It is not self-adaptive and it does not meet with the Archetype's design principles.
	FC -	It is not full-controllable and does not meet with the Archetype's design principles.
Double skin facade	EF +	Pre-heating of air within cavity decreasing the heat demand.
	SA +	Self-regulates the income of air through the cavity and then to the indoors.
	FC -	It is not full-controllable and does not meet with the Archetype's design principles.
Trombe wall	EF +	Wall absorbs heat and releases it when necessary decreasing the heat demand.
	SA +	Self-regulates the absorption and release of heat.
	FC -	It is not full-controllable and does not meet with the Archetype's design principles.
3c. Façade layers – Outdoor layer Static – Active		
Color changing BIPV's	EF +	Produces electricity.
	SA +	Self-adapts the color depending on the sun-intensity.
	FC -	It is not full-controllable and does not meet with the Archetype's design principles.

Algae bio-reactive façade	EF +	Produces electricity and solar thermal heat.
	SA -	It is not self-adaptive and it does not meet with the Archetype's design principles.
	FC -	It is not full-controllable and does not meet with the Archetype's design principles.
Thermal collectors as cladding	EF +	Produces heat using the direct sunlight.
	SA -	It is not self-adaptive and it does not meet with the Archetype's design principles.
	FC -	It is not full-controllable and does not meet with the Archetype's design principles.
SolarWall PV/T & NightSolar	EF +	Pre-heating of incoming air by excess heat of PV-panel improving PV-efficiency.
	SA +	Self-regulates the pre-heating of the air.
	FC -	It is not full-controllable and does not meet with the Archetype's design principles.
3c. Façade layers – Outdoor layer Dynamic – Passive		
PCM	EF +	Acts as an adaptive heat storage and extra insulation.
	SA +	Self regulates the absorption and release of heat.
	FC -	It is not full-controllable and does not meet with the Archetype's design principles.
Aluminum moving panels	EF -	It is not energy efficient and it does not meet with the Archetype's design principles.
	SA +	Self-adaptation of the panels due to the wind.
	FC -	It is not full-controllable and does not meet with the Archetype's design principles.
Breathing skin	EF +	Allows for sufficient view.
	SA +	Self-regulates the amount of daylight, views, temperature, and air through the skin.
	FC -	It is not full-controllable and does not meet with the Archetype's design principles.
Operable disks facade	EF +	Produces electricity.
	SA +	Self-regulates the evaporative cooling and the air through the disks.
	FC -	It is not full-controllable and does not meet with the Archetype's design principles.
3c. Façade layers – Outdoor layer Dynamic – Active		
Wind-energy harvesting façade	EF +	Produces electricity.
	SA -	It is not self-adaptive and it does not meet with the Archetype's design principles.
	FC -	It is not full-controllable and does not meet with the Archetype's design principles.
The COR building with façade integrated wind turbines	EF +	Produces electricity by wind turbines.
	SA -	It is not self-adaptive and it does not meet with the Archetype's design principles.
	FC -	It is not full-controllable and does not meet with the Archetype's design principles.
3d. Façade layers – Mid layer Static – Passive		
PUR insulation	EF +	Reduces heat gains in the summer and heat losses in the winter.
	SA -	It is not self-adaptive and it does not meet with the Archetype's design principles.
	FC -	It is not full-controllable and does not meet with the Archetype's design principles.
Resol Rigidfoam insulation	EF +	Reduces heat gains in the summer and heat losses in the winter.
	SA -	It is not self-adaptive and it does not meet with the Archetype's design principles.
	FC -	It is not full-controllable and does not meet with the Archetype's design principles.
Aerogel (silica) nano insulation	EF +	Reduces heat gains in the summer and heat losses in the winter with slim thickness.
	SA -	It is not self-adaptive and it does not meet with the Archetype's design principles.
	FC -	It is not full-controllable and does not meet with the Archetype's design principles.
VIP insulation	EF +	Reduces heat gains in the summer and heat losses in the winter with slim thickness.
	SA -	It is not self-adaptive and it does not meet with the Archetype's design principles.
	FC -	It is not full-controllable and does not meet with the Archetype's design principles.
3d. Façade layers – Mid layer Static – Active		
Energy Mass Wall (EMW)	EF +	Dampens thermal flow and stores thermal energy to use when necessary.
	SA +	Self regulates the absorption and release of heat.
	FC -	It is not full-controllable and does not meet with the Archetype's design principles.
3d. Façade layers – Mid layer Dynamic – Passive		
PCM	EF +	Acts as an adaptive heat storage and extra insulation.
	SA +	Self regulates the absorption and release of heat.
	FC -	It is not full-controllable and does not meet with the Archetype's design principles.
Dynamic insulation	EF +	Reduces heat gains in the summer and heat losses in the winter.

	SA	+	Self regulates the air through the façade.
	FC	-	It is not full-controllable and does not meet with the Archetype's design principles.
3d. Façade layers – Mid layer Dynamic – Active			
Active thermal insulation	EF	+	Increases the ability of reducing heat gains and heat losses within the façade.
	SA	+	Self regulates the absorption and release of heat.
	FC	-	It is not full-controllable and does not meet with the Archetype's design principles.
3e. Façade layers – Indoor layer Static – Passive			
Green pods	EF	+ +	Acts as an extra insulation layer and allows contact with nature.
	SA	+	User have the possibility to adapt the pods to their lifestyle.
	FC	+	Pods give the user high freedom on how to arrange their own space.
Aerogel-based plaster	EF	+	Reduces heat gains in the summer and heat losses in the winter with slim thickness.
	SA	-	It is not self-adaptive and it does not meet with the Archetype's design principles.
	FC	-	It is not full-controllable and does not meet with the Archetype's design principles.
3e. Façade layers – Indoor layer Static – Active			
Active Living Wall system (ALWS)	EF	+ +	Acts as an extra insulation layer, purifies the air and allows contact with nature.
	SA	-	It is not self-adaptive and it does not meet with the Archetype's design principles.
	FC	-	It is not full-controllable and does not meet with the Archetype's design principles.
Interactive working surface	EF	-	It is not energy efficient and it does not meet with the Archetype's design principles.
	SA	-	It is not self-adaptive and it does not meet with the Archetype's design principles.
	FC	+	Full control over façade surface.
Wall++	EF	+	Decreases the energy use in a space due to the detection of behavior and presence.
	SA	++	Self-adapts indoor climate according to user behavior, tech. main user experience.
	FC	++	Full control over façade surface, reacts to human touch and to patterns.
3e. Façade layers – Indoor layer Dynamic – Passive			
Hydroceramic	EF	+	Provides passive cooling by absorbing large quantities of water in the air.
	SA	+	Self-adapts the indoor temperature and humidity.
	FC	-	It is not full-controllable and does not meet with the Archetype's design principles.
3e. Façade layers – Indoor layer Dynamic – Active			
Living glass	EF	+	No mechanical ventilation needed.
	SA	++	Self-regulates the income of air by users' presence, tech. main user experience.
	FC	-	It is not full-controllable and does not meet with the Archetype's design principles.
Building Services Integrated (BIS) in façade			
Smartbox	EF	+ +	Energy efficient heating, cooling and ventilation, does not obstruct view.
	SA	+	Self-adaptive ventilation, heating and cooling (BIS).
	FC	-	It is not full-controllable and does not meet with the Archetype's design principles.
Schüco E2	EF	+ +	Energy efficient heating, cooling and ventilation, does not obstruct view.
	SA	+	Self-adaptive ventilation, heating and cooling (BIS).
	FC	-	It is not full-controllable and does not meet with the Archetype's design principles.
Capricorn Haus	EF	+	Energy efficient heating, cooling and ventilation.
	SA	+	Self-adaptive ventilation, heating and cooling (BIS).
	FC	+	System is full-controllable.
TE Motion	EF	+ +	Energy efficient heating, cooling, ventilation and light redirection, does not obstruct view.
	SA	+	Self-adaptive ventilation, heating and cooling (BIS).
	FC	+	System is full-controllable.
Next Active Façade	EF	+ +	Energy efficient heating, cooling and ventilation, does not obstruct view.
	SA	+	Self-adaptive ventilation, heating and cooling (BIS).
	FC	+	System is full-controllable.
User control			
Voice control	EF	-	It is not energy efficient and it does not meet with the Archetype's design principles.
	SA	-	It is not self-adaptive and it does not meet with the Archetype's design principles.
	FC	+	System is full-controllable.

Monitor and response	EF	+	Decreases the energy use in a space due to the detection of behavior and presence.
	SA	+	Self-regulates the indoor conditions based and sensors, data analysis, and actuators.
	FC	+	System is full-controllable.

The façade design of each Archetype can now be done by following the scores and evaluation of each façade component and their suitability for being Energy Efficient, Self-Adaptive or Full Controllable.

3.2 Case study review

The façade design configurations will be designed according to a specific case study which is the Applied Physics building located on the Campus of the Technical University of Delft (TU Delft), building 22. This is done in order to be able to illustrate, validate, and evaluate the façade design configurations against the current situation of the existing building.

3.2.1 Applied Physics Building

The Applied Physics building (figure 25) within the Campus of the TU Delft is a building which was built in 1963 and has not gotten much renovation since then. The building is therefore outdated and no longer fits in with the current requirements. Office users often complain about the poor conditions of the indoor environment and of the building itself. From all the buildings within the Campus, this building is the one with the highest energy use. Therefore the building is in need of renovation. According to the CO_2-roadmap study done by Blom & van den Dobbelsteen (n.d.), in order to achieve the future climatic goals, the building should have 80% less heat demand and therefore the only possible way to achieve this is by applying a midlife-renovation where the whole façade should be replaced together with the building's installation systems. (Blom & van den Dobbelsteen, n.d.)

Figure 25: Applied Physics Building. Image derived from Campusdevelopment (n.d.)

There are already plans made to renovate the building. As can be seen in figure 26 half of the building will be demolished whereas the other half will be fully renovated. For the façade design of this research, the front façade will be used to illustrate how the façade should look like and function taking the current location and the different Archetypes into account.

Figure 26: renovation of the Applied Physics Building. Images derived from Cepezed.

The building consists of offices, mainly on the front façade, laboratories, and lecture rooms. There are different type of offices, varying in width, but most of the offices on the front façade have the same width and height. The technical aspects of these offices can be seen in table 15.

Table 15: technical aspects Applied Physics building. Table by author.

Technical aspects Applied Physics building	Dimension/type
Length	5,94 meter
Width	3,60 meter
Height	3,67 meter
Window	1 external window
Door	1 internal door

These values will be used for the construction of the design configurations in order to be able to conduct performance evaluations and simulations of these design configurations and to compare them to the current situation.

3.2.2 Sun study

Before going into the design configurations, it is important to understand the building's position on its location and the sun's behavior on the façade. The sun study (figure 27) shows the path of the sun on the building's façades and the sun angles each season.

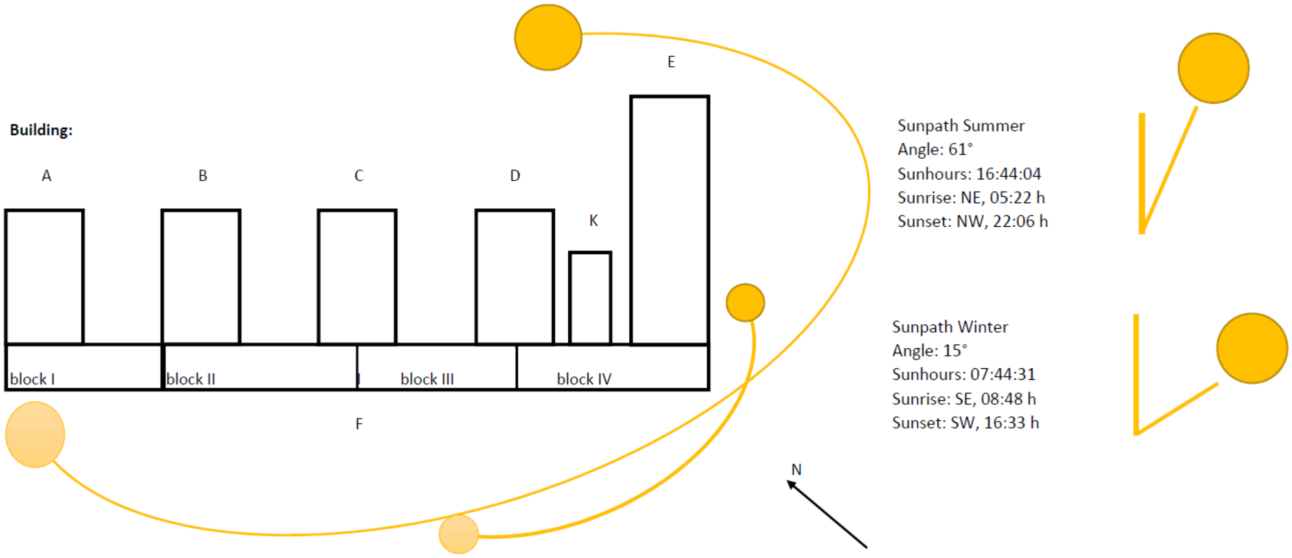


Figure 27: sun's path on facade and sun angles each season. Image by author.

As already mentioned, for the façade designs of this research, the front façade will be used to illustrate how the façade should look like and function. Due to the current renovation plans, this means façade designs for block IV. The more relevant results of the sun study of block IV, can be found in table 16.

Table 16: results sun study block IV. Table by author.

Sun study Applied Physics Building	
Orientation	West-southwest
Summer sun angle	61° – 7,5°
Sun hours exposure	8 hours (13:45-21:45)
Winter sun angle	14,6° – 0,50°
Sun hours exposure	4 hours (12:45-16:45)

During winter, the shadow of the buildings across the street falls multiple times directly on the front façade of the Applied Physics building (figure 28). The sun's path on the building together with the sun's angle per season and the shadow of the buildings across the street on the front façade, will be taken into account for the design configurations.

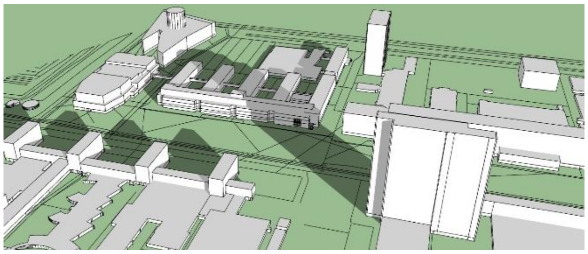


Figure 28: shadow on facade of buildings across the street. Image by author.

3.2.3 User experience

One of the most important factors of user comfort is the users' experience in a space. It is important to understand how the users feel in a space, what they find to be missing, and what can be made better. Therefore, an interview/questionnaire was held with one of the office users of the Applied Physics building. It was the intention to have more than one interview, but sadly this was not possible. Nevertheless, the office user has worked in this building for quite some time and therefore has great insight on the issues present in the office spaces within the building. The most interesting results will be discussed here. The complete interview can be found in Appendix C.

The office user works in one of the offices located on the front façade of block IV. Besides general information about type of employment, amount of hours at the office, specific location of office, and so on, the user was asked about how the comfort experience was regarding the indoor temperature, air quality, lighting, noise, outside view, humidity, and overall comfort in all seasons. The user indicated to be extremely dissatisfied regarding the temperature, air quality, lighting, noise, and overall comfort in the winter and summer season, to be extremely satisfied with the outside view, and neutral regarding the humidity. During spring and autumn, the user indicated to being extremely dissatisfied regarding the air quality, artificial light, and noise, somewhat dissatisfied with the temperature, daylight, and overall comfort, neutral about humidity, and extremely satisfied with the outside view. In addition, the user indicated to sense the indoor temperature in the office as cold during winter, cool during spring and autumn, and hot during summer. Therefore, the user stated a preference for the indoor temperature to be warmer during winter, colder during summer, and wishes no change during spring and autumn. The user was also asked to state if having experienced one of the symptoms related to the sick building syndrome. Regarding having experienced dry/watering eyes, blocked/runny nose, and dry/irritated throat, the user stated to experiencing these regularly. Regarding experiencing headaches or lethargy/fatigue, the user stated to experiencing these sometimes. According to the user, these symptoms presented the most during winter and summer and most of the times in the afternoon.

Regarding glare, the user stated to experience glare discomfort most of the time. Regarding having control over the indoor conditions, the user stated to have no control whatsoever on the indoor conditions and that it was also not possible to regulate this through the building management. The only control that the user has on the indoor conditions is the ability to open/close windows, having some control on the sun-shading, and having the possibility to switch the artificial lights on/off.

When the user was asked about what is important to have in the workspace, the user stated to having an outside view, privacy, personal space, and social interaction, as being important. The user stated to being neutral about having control of the environment, the environment being self-adaptive, and the energy use. The user found contact with nature, use of innovative technologies, and the space matching the lifestyle as not being important.

The user reflected on what is it like working in the office space of the Applied Physics building and stated that the indoor climate is largely determined by the outside conditions. Windy and cold outside conditions means cold and unpleasant inside conditions. Warm outside means warm inside.

Analyzing the results of the user experience interview/questionnaire, it can be concluded that the indoor conditions of the office space are not comfortable at all and that the users' health is being affected by it. The fact that the user has no control over the indoor environment and that this is also not possible to regulate through the building management, makes it a problem that the user has no way to solve and is obligated to deal with it. Taking into account that the user is not really interested in having self-control of the environment, self-adaptivity or efficient energy use, it can be concluded that the only thing that this user finds important is having good indoor conditions and being comfortable and that it doesn't really matter how. This reflects on how bad the indoor conditions are. If the user was already comfortable with this, the user would have been more interested in new technological advancements for being comfortable in the office space. But, due to the fact that the indoor conditions are so poor, the user is only interested in having a healthy and comfortable indoor space and nothing else. It can be therefore strongly concluded that the work productivity of this user is being affected and that this issue can be solved by adjusting the space in order for it to comply with the current comfort and energy requirements. This can easily be done by replacing the current façade of the office space to a façade which helps adapt the indoor conditions to the users preferences and comfort values, while also being energy efficient.

3.2.4 Analysis existing facade

In order to understand what the issues are with the existing façade of the front offices in block IV of the Applied Physics building, this was analyzed.

With the information provided by TU Delft's Campus & Real Estate, an analysis was done on the materials and systems within the façade. Figure 29 shows the view, plan, and section of the building's façade.

As can be seen in figure 29, the façade consists of an external window with a panel underneath, taking together more than 50% of the WWR. Because of this, the façade has a high amount of linear heat transfers and therefore heat losses. The façade has no insulation and because it was originally built in 1963, it can be assumed that it also has a high infiltration value. The façade also has no shading feature in order to avoid overheating or glare discomfort. It does provide the users with indoor blinds.

The façade consist, from the inside to the outside, of a 10 mm thin material which could be gypsum board, two layers of bricks with a total thickness of 200 mm with a cavity of 20 mm in between, a 40 mm air cavity, and 30 mm natural stone. This means that the façade could have a minimum Rc-value of 0,65 $m^2{\cdot}K/W$, which is extremely low in comparison with today's requirements.

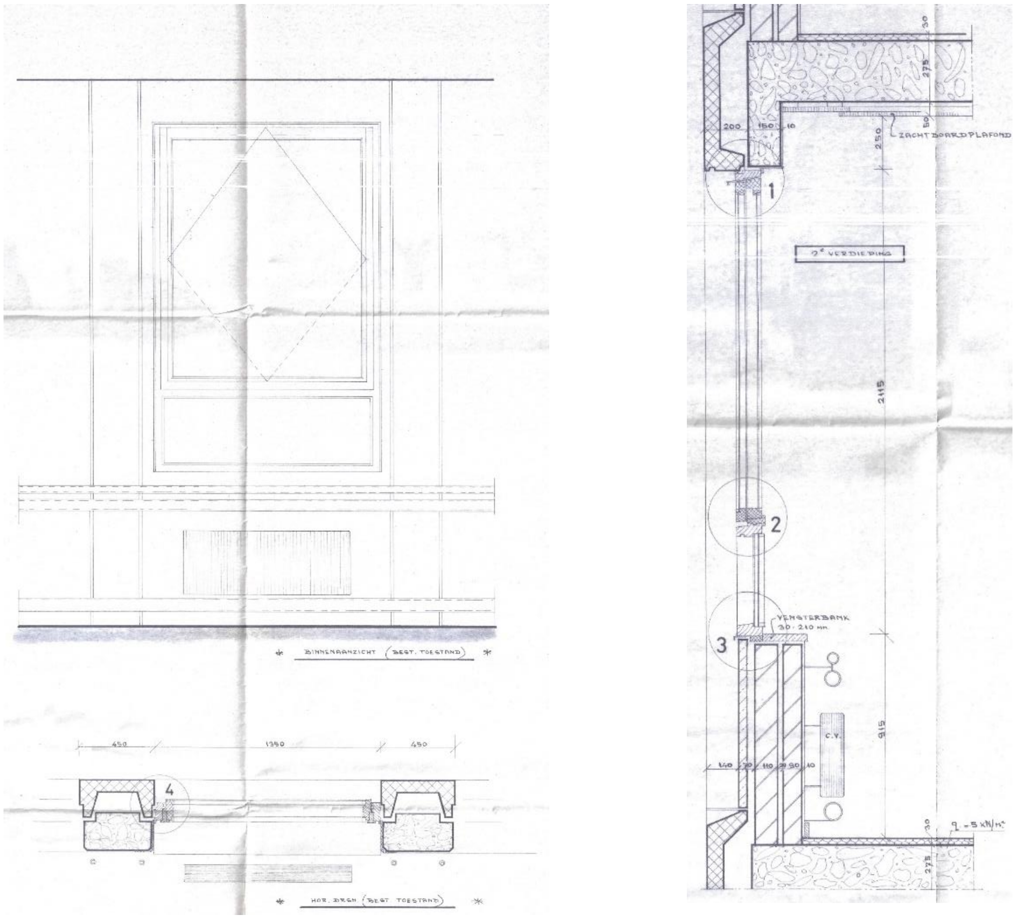


Figure 29: front façade view, plan, and section. Image derived from Campus and Real Estate.

The analysis shows how the façade is in serious need for a renovation in order to comply with the current and future climatic and sustainable requirements. As already mentioned, the façade is one of the building's envelope component which is responsible for a high percentage of the energy use. The analysis shows a lot of possibilities in passive and active measures that can be implemented in the façade, which could help increase the indoor comfort and decrease the energy demand of the building and in this way help increase user satisfaction and work productivity, and help the building become nearly energy neutral.

Chapter 4 – Design exploration

This chapter describes the design configurations for the office-user oriented façade. It also describes the evaluation of these configurations and concludes on the designs.

4.1 Design configurations

For the design configurations, two façade designs per Archetype will be made. Based on the technologies presented in subparagraph 2.3, the results of the generic façade design guideline, and the evaluation of the technologies per Archetype, one static and one dynamic façade design per Archetype will be made. For each design, first passive measures were taken into account, and if needed, then sustainable active measures were implemented.

4.1.1 Design configuration archetype Energy Efficient (EF)

Static design – PV-Trombe wall

For this design the most relevant features are the energy reducing and producing features. This design consists of a PV-Trombe wall (figure 30) for the production of electricity and for heat storage. Fresh air from outside comes inside the cavity of the PV-Trombe Wall, absorbing the excess heat from the PV-panels making the air hot and then travelling to the indoors. By absorbing this excess heat the PV-panels' efficiency increases, because they perform better when they are cool. Due to the fact that the PV-panels hinder the penetration of direct sunlight into the air space, the efficiency of the Trombe wall is reduced in terms of heat gain. According to Sun, Ji, Luo, & He's (2011) study, the efficiency decreases with 17%. Nevertheless, the PV-panels produce sufficient electricity making it a benefit.

The massive wall acts as a thermal storage and releases the stored heat when it is necessary. Furthermore, the wall consists of a top air vent on the upper part that opens when the temperature inside the space is too high, for example during summer. The window to wall ratio is of 50%, which is a bit higher than the recommended percentage for this orientation. Nevertheless, it allows a valuable amount of outside view which is a very important factor for this Archetype. Due to the fact that a shading feature would obstruct the performance of the PV-panels and of the heat produced within the Trombe wall, it was decided not to place one on this design, but rather to have windows with triple thermochromic glazing in order to avoid overheating or glare discomfort. The rest of the wall is composed as can be seen in figure 31 and table 17.

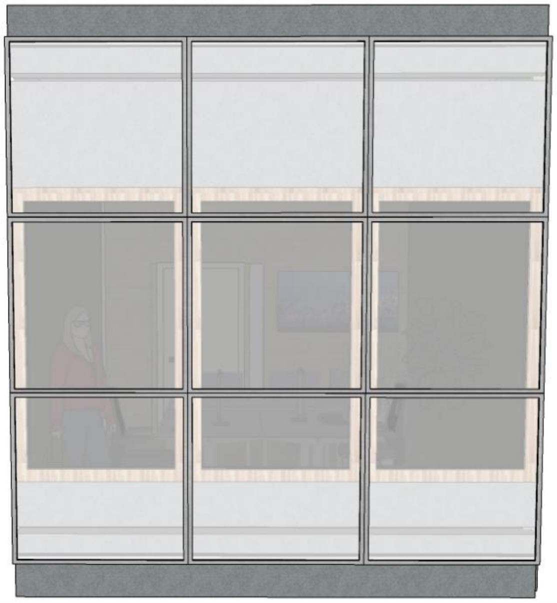


Figure 30: PV-Trombe wall. Image by author.

Table 17: PV-Trombe wall properties. Table by author.

Façade design Passive measures	Thickness m	Thermal Conductivity W/m·K	Rc-value m²·K/W
Air outside			0,043
Transparent PV-panels	0,030	0,171	0,18
Ventilated cavity	0,100	0,400	0,25
Massive wall	0,120	0,700	0,17
VIP insulation	0,040	0,006	6,67
Aerogel-based plaster	0,010	0,014	0,71
Air inside			0,13
Total	0,300		8,15
U-value (W/m²·K) opaque			0,12
U-value (W/m²·K) transparent (window)			0,75

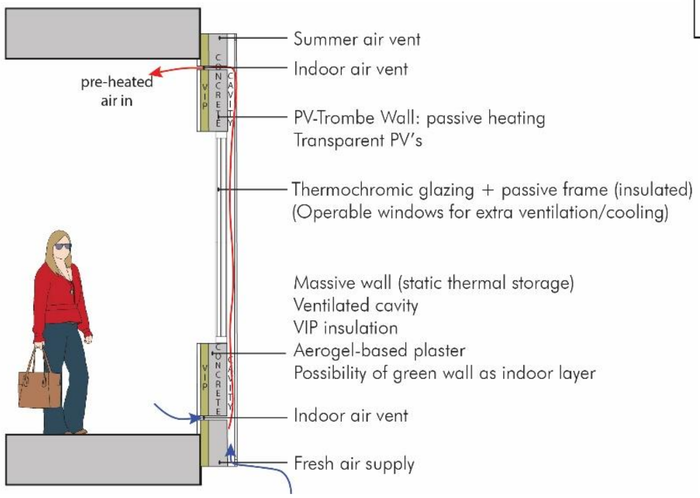


Figure 31: PV-Trombe wall section. Image by author.

Dynamic design – SolarWall PV/T

For this design the most relevant features are also the energy reducing and producing features. This design consists of a SolarWall PV/T (figure 32) on the lower part of the façade, which is a thermal collector for heating and cooling. Solar radiation heats the metal SolarWall panels, generating a boundary layer of fresh solar-heated air on the surface of the collector. This air is drawn into the SolarWall panel through thousands of micro-perforations and gathers within the cavity of the collector. Then, this warm air flows out of the SolarWall and into the façades' cavity pre-heating the fresh air that is supplied there. Afterwards, the pre-heated air goes through the rest of the façade and into the indoor space. The panel has also the possibility of cooling the indoor space. During the night, the panel can remove energy from the outside cool air using the principle of nocturnal radiation cooling. The upper part of the façade also consists of a SolarWall PV/T panel with color changing PV-panels on top. In this case the SolarWall PV/T draws the excess heat from the PV-panels increasing their efficiency. The façade is composed as airtight as possible in order to not let the heat or cool air to escape.

Figure 32: SolarWall PV/T. Image by author.

The permanent shading features have sun angled lamellas designed taking the sun's position and angle on the location, into account. They provide sufficient shading in order to avoid overheating and glare in the summer and allow for sufficient heat gains for passive heating during winter without having glare discomfort. Also, the shading feature in the middle has a lamella at the end which has a reflective coating in order to bounce daylight to the inside and therefore reducing lighting costs and discomfort. Furthermore, the window to wall ratio is of 50%, which is again a bit higher than the recommended percentage for this orientation. Nevertheless, it allows a valuable amount of outside view which is a very important factor for this Archetype. The windows are operable and consists of triple glazing. The rest of the wall is composed as can be seen in figure 33 and table 18.

Table 18: SolarWall PV/T properties. Table by author.

Façade design Passive measures	Thickness m	Thermal Conductivity W/m·K	Rc-value $m^2 \cdot K/W$
Air outside			0,043
Color BIPV's	0,010	1,800	0,01
SolarWall PV/T	0,03	16,000	0
SolarWall PV/T air space	0,100	0,7	0,14
Air supplied cavity	0,100	0,400	0,25
VIP insulation	0,040	0,006	6,67
Aerogel-based plaster	0,010	0,014	0,71
Air inside			0,13
Total	0,263		7,95
U-value ($W/m^2 \cdot K$) opaque			0,13
U-value ($W/m^2 \cdot K$) transparent (window)			0,75

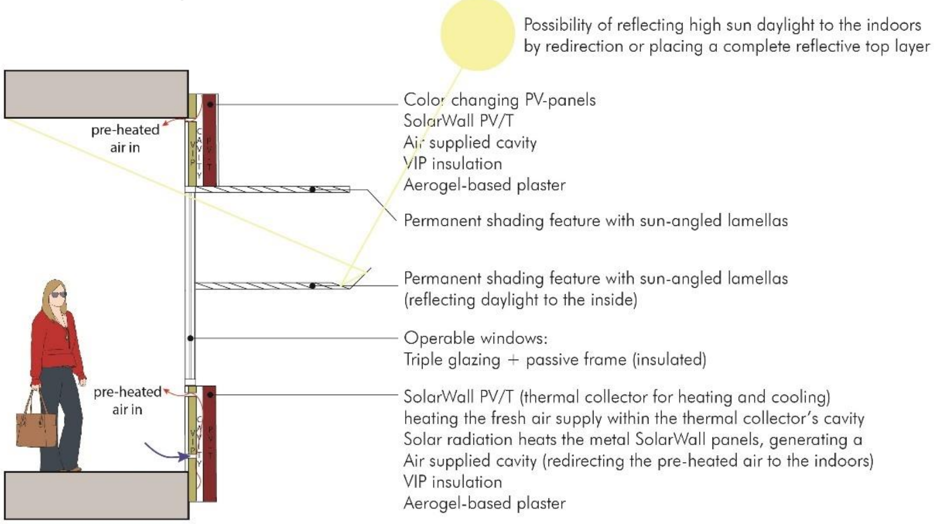


Figure 33: SolarWall PV/T section. Image by author.

4.1.2 Design configuration archetype Self-Adaptive (SA)

Static design – PCM Trombe wall

For this design the most relevant features are the adaptivity of the indoor environment and the reduction of the heat demand. This design consists of a PCM Trombe wall (figure 34) where the PCM functions as a self-adaptive thermal storage that stores heat at a constant temperature and releases it when necessary. This helps the indoor environment to remain comfortable and in balance. This wall functions the same way as the PV-Trombe wall, where cool air from the outside comes into the air space through the lower vent absorbing the heat within the space that is being released by the PCM. This helps with the regulation of the temperature and the release time. The pre-heated air then travels to the indoors decreasing the heating demand. When the air within the indoor space cools down, it will travel again to the cavity through the lower indoor air vent. In this way there is a constant flow of air and air (heat) exchange helping the indoor environment to remain comfortable and healthy. The wall also has a top air vent on top that opens when the temperature inside the cavity space is too high, for example during summer. This allows a continues flow of air in order to avoid overheating. During the night, the PCM Trombe wall will cool the indoor space helping it remain cool and in this way decreasing the cooling demand. The window to wall ratio is of 43%, which is the maximum allowable WWR for this orientation giving the users sufficient view to the outside. In addition, the chosen PCM is a salt-hydrate with a phase change of 23°C. This is a type of PCM that becomes transparent when in liquid form. The windows are operable and consists of triple glazing.

The permanent shading features are designed taking the sun's position and angle on the location, into account. The lamellas are also placed against the sun taking its angle into account, making it seem as if the whole system is twisting. They provide sufficient shading in order to avoid overheating and allow for sufficient daylight without having glare discomfort. The rest of the wall is composed as can be seen in figure 35 and table 19.

Figure 34: PCM Trombe wall. Image by author.

Table 19: PCM Trombe wall properties. Table by author.

Façade design Passive measures	**Thickness m**	**Thermal Conductivity W/m·K**	**Rc-value m^2·K/W**
Air outside			0,043
Float glass	0,004	1,060	0
PCM S23	0,019	0,540	0,04
Float glass	0,004	1,060	0
Ventilated cavity	0,100	0,400	0,25
VIP insulation	0,040	0,006	6,67
Aerogel-based plaster	0,010	0,014	0,71
Air inside			0,13
Total	0,177		7,85
U-value (W/m^2·K) opaque			0,13
U-value (W/m^2·K) transparent (window)			0,75

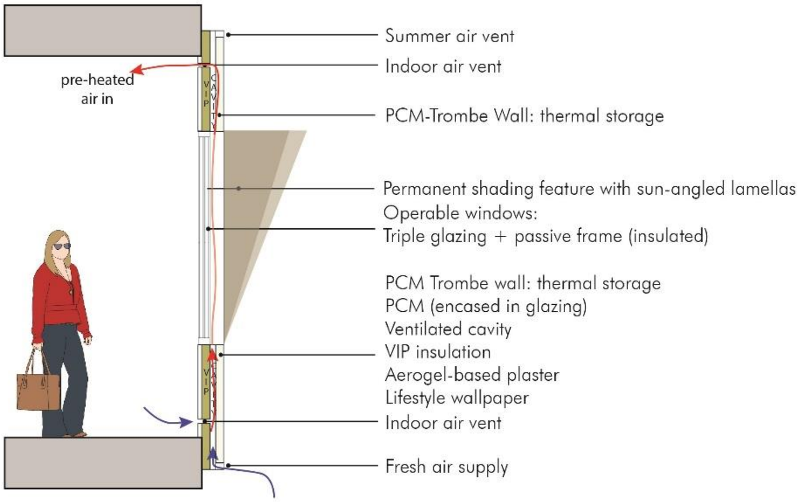


Figure 35: PCM Trombe wall section. Image by author.

Dynamic design – PCM Living wall

For this design the most relevant features are the adaptivity of the indoor environment and the reduction of the energy demand. This design consists of a PCM Living wall (figure 36) where again the PCM functions as a self-adaptive thermal storage that stores heat at a constant temperature and releases it when necessary. This wall functions exactly the same way as the PCM Trombe wall, but it disperses the air (heat) in a different manner. After the fresh is pre-heated by the PCM, this air goes into another air layer which is the Living wall. This is a thin transparent polymer surface (silicone) which adapts according to the human presence in the space and to the indoor conditions. When the CO_2 levels are too high and also when the temperature reaches a certain degree, the living wall opens its "gills" in order to allow fresh pre-heated air to go into the indoor space. The system consists of temperature sensor, an infrared sensor, a CO_2 sensor, a microcontroller for the data reasoning, and shape memory alloy as actuator for the opening and closing of the "gills".

Figure 36: PCM Living wall. Image by author.

The façade has a solar controlled shading feature which has PV-cells on top for at least its own energy production. This system can open or close and go up or down in order to provide extra shading, better PV-performance and help bounce daylight deeper into the space. The window to wall ratio is also of 43%, which is the maximum allowable WWR for this orientation, giving the users sufficient view to the outside. The windows are operable and consists of triple glazing. The rest of the wall is composed as can be seen in figure 37 and table 20.

Table 20: PCM Living wall properties. Table by author.

Façade design Passive measures	Thickness m	Thermal Conductivity W/m·K	Rc-value m²·K/W
Air outside			0,043
Float glass	0,004	1,060	0
PCM S23	0,019	0,540	0,04
Float glass	0,004	1,060	0
Ventilated cavity	0,100	0,400	0,25
VIP insulation	0,040	0,006	6,67
Air gap	0,010	0,400	0,71
Air inside			0,13
Total	0,177		7,85
U-value (W/m²·K) opaque			0,13
U-value (W/m²·K) transparent (window)			0,75

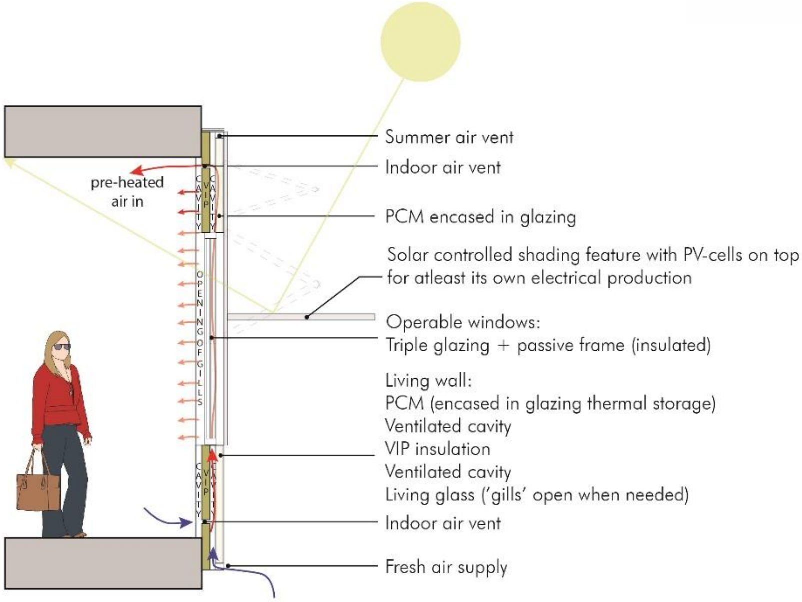


Figure 37: PCM Living wall section. Image by author.

4.1.3 Design configuration archetype Full Control (FC)

Static design – Interactive Wall++

For this design the most relevant features are the ability to control the indoor environment and the reduction of the energy demand. This design consists of an interactive Wall++ (figure 38), which responds to human touch, human presence and understands and responds to patterns. The wall is connected to a microcontroller which allows it to send information to the web. Based on patterns or simply by giving a sign to the wall, the indoor comfort of the space can be regulated. The system is composed out of two layers of water base nickel paint to allow for high conductivity, copper tape as insulation for the transmitter electrodes placed in a diamond pattern, and its finished with regular latex paint. For the heating, cooling, and ventilating of the indoor environment, an integrated building service system is used, which is the NEXT Active Façade. This system is placed in the wall and can self-adapt the environment according to set-values and can also be fully controlled by the user. Connected with the Wall++, the system can start when there is presence in the room or when the user gives a sign to the wall. The façade itself is simple on the outside, due to the fact that this archetype has a low external control factor. Nevertheless, there is sufficient space on the outdoor layer for energy production which can be used for the controllable components.

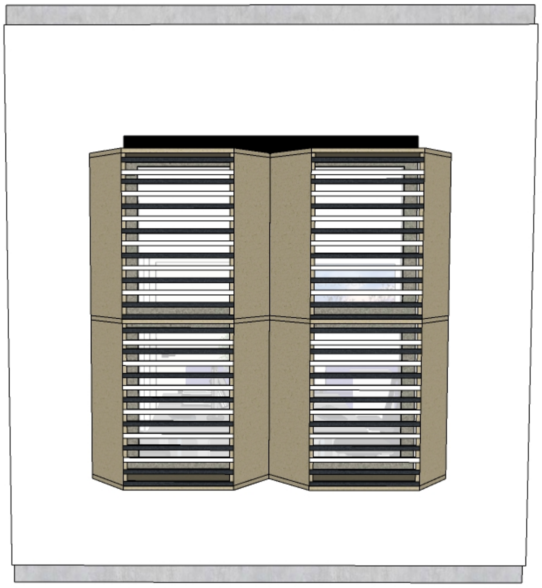


Figure 38: Interactive Wall++. *Image by author.*

Table 21: Interactive Wall++ properties. *Table by author.*

Façade design Passive measures	Thickness m	Thermal Conductivity W/m·K	Rc-value m²·K/W
Air outside			0,043
BIPV's	0,003	1,800	0
Concrete	0,100	0,700	0,14
Ventilated cavity	0,050	0,400	0,13
VIP insulation	0,040	0,006	6,67
Gypsum plasterboard	0,010	0,250	0,04
Air inside			0,13
Total	0,203		7,15
U-value (W/m²·K) opaque			0,14
U-value (W/m²·K) transparent (window)			0,75

The permanent shading features are designed as boxes in order to give the users their own privacy, taking the sun's position and angle on the location, into account. The sides of the boxes and the lamellas are both placed against the sun taking its angle into account. They provide sufficient shading in order to avoid overheating and allow for sufficient daylight without having glare discomfort. The window to wall ratio is of 37%, which is the minimum allowable WWR for this orientation. The windows are operable and consists of triple glazing. The rest of the wall is composed as can be seen in figure 39 and table 21.

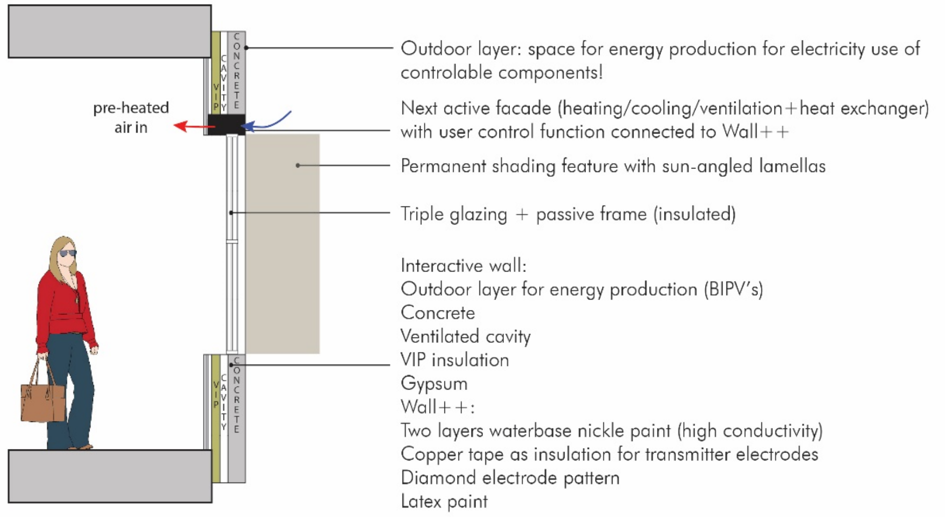


Figure 39: Interactive Wall++ section. *Image by author.*

Dynamic design – Controllable wall

For this design the most relevant features are also the ability to control the indoor environment and the reduction of the heat demand. This design consists of a controllable wall (figure 40), which is a concrete lightweight buffer for thermal storage and two PCM layers that work as insulation layers determining when the stored heat/cold will be absorbed or released by the concrete buffer. The storing of energy takes place depending on the season. For the summer example, this means that during the night, the cold outside will be allowed to the indoor helping the indoor space to remain cool for the next day while also storing cold in the buffer. During the day, the PCM on the outside makes sure to keep the warm out and the indoor PCM releases the stored cooling when necessary. In the winter it works the other way around, by storing the heat during the day into the buffer, and releasing this to the inside when necessary.

The window area is designed to allow more space for the users to have their own privacy and still have sufficient view to the outside. The window to wall ratio is also of 37%, which is the minimum allowable WWR for this orientation. The windows are operable and consists of electrochromic glazing, giving the users the freedom to change the state of the glazing when desired. The indoor wall has indoor pods which allows the users to have freedom of their own space. The façade itself is simple on the outside, due to the fact that this archetype has a low external control factor. It is possible to use the top part of the façade for energy production, but due to the fact that the window box sticks out, the lower part is less suitable for the production of energy. However, this could intervene with the function of the PCM within the façade. A most suitable position could be to place them on top of the box. The rest of the wall is composed as can be seen in figure 41 and table 22.

Figure 40: controllable wall. Image by author.

Table 22: controllable wall properties. Table by author.

Façade design Passive measures	Thickness m	Thermal Conductivity W/m·K	Rc-value $m^2 \cdot K/W$
Air outside			0,043
Float glass	0,004	1,060	0
Ventilated cavity	0,015	0,400	0,04
VIP insulation	0,020	0,006	3,33
PCM S23	0,019	0,540	0,04
Lightweight concrete	0,160	0,170	0,94
PCM S23	0,019	0,540	0,04
Gypsum plasterboard	0,010	0,250	0,04
Air inside			0,13
Total	0,247		4,60
U-value ($W/m^2 \cdot K$) opaque			0,22
U-value ($W/m^2 \cdot K$) transparent (window)			0,75

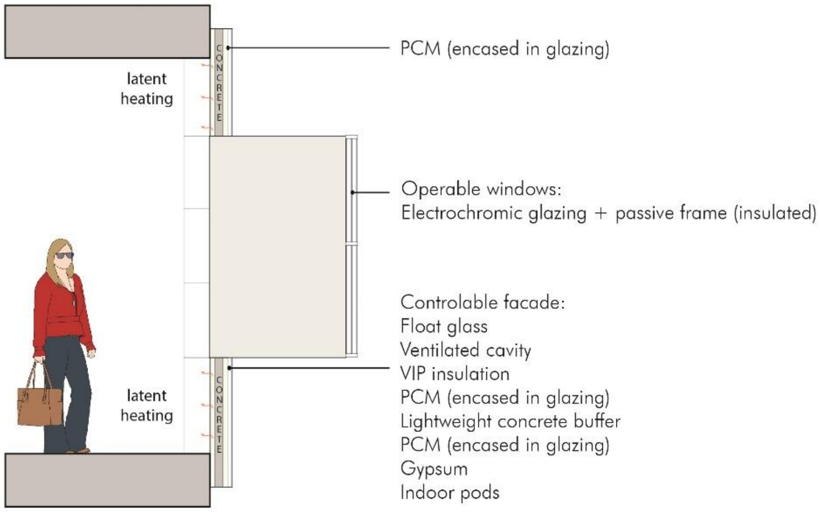


Figure 41: controllable wall section. Image by author.

4.2 Design performance evaluations (simulations)

The evaluation of the design configurations will be conducted using the software DesignBuilder which is a tool for checking building designs' energy, carbon, lighting, and comfort performances. The results of each of the design configurations will be assessed against their comfort values and energy performance, taking into account that the comfort of the users is the primary objective and the energy performance of the design is the secondary objective. Before the simulations, the necessary hand calculations were conducted in order to be able to ensure the performance of the design configurations.

4.2.1 Stack effect calculations

Due to the fact that most of the design configurations presented use the stack effect within their cavity for the introduction of pre-heated fresh air to the indoor space, the necessary calculations were made.

The stack effect is the movement of air resulting from air buoyancy, where the greater the temperature difference and the greater the height, the greater the stack effect. Due to the fact that hot air is thinner and therefore lighter than cold air, this will rise. When cold air from outside goes in the cavity and the temperature in here is higher making the air hot, this hot air will then rise and go through an upper vent into the indoor space. After this pre-heated air becomes cold, this will go down due to the fact that cold air is heavy. The cold air will go into the lower vent of the space and then back into the cavity, where this air can be re-used and mixed with fresh air.

For the stack effect it is important to calculate the air flow through the top and bottom openings that go to the cavity (outside-cavity) and from the cavity (cavity-indoor). These flows need to be identical in order to avoid an implosion or explosion of air. It is also important to know how much fresh air is needed within the indoor space. This depends either on the size of the space or the amount of people within the space. According to the comfort limit values presented in table 1, the required airflow per person is 7 l/s. The traditional office of the Applied Physics building used for the simulations is intended for two people. This means that the indoor space requires at least 14 l/s or 50 m^3/h of fresh air. The results of the calculations of the airflow through the top and bottom openings, the pressure difference at different temperatures, the effective opening, and the amount of fresh air being provided to the indoor space, can be seen below. The additional values needed for the calculations can be found in table 23.

Airflow formula:

$$\mathrm{Q} = \mathrm{Aeff\ Cd}\sqrt{\frac{2\Delta P}{\rho}} =: \ \mathrm{Q} = \mathrm{Aeff\ Cd}\sqrt{\frac{2\Delta P}{\rho}} = 0{,}02 \ * \ 0{,}65\sqrt{\frac{2*1{,}77}{1{,}2}} = 0{,}022 \text{ m}^3\text{/s} = 79 \text{ m}^3\text{/h, sufficient fresh air.}$$

Pressure difference, different temperatures:

$$(\Delta\mathrm{P})(\mathrm{h}) = (\Delta\mathrm{P})(\mathrm{h}) = \frac{ghP0{,}0}{\mathrm{R}}\left(\frac{1}{Te} - \frac{1}{Ti}\right) = \frac{9{,}81*3{,}6*101000}{287}\left(\frac{1}{281{,}4} - \frac{1}{293{,}15}\right) = 1{,}77 \text{ Pa}$$

Effective opening (A_{eff}) for two similar size openings:

$$\mathrm{Aeff} = \frac{A}{\sqrt{2}} = \frac{0{,}028}{\sqrt{2}} = 0{,}02 \text{ m}^2$$

In order to ensure the stack effect, the width of the cavity cannot be smaller than the height of the openings, otherwise this will affect the airflow. Therefore, the width of the cavity of the design configurations has to be bigger than 55 mm.

Table 23: additional values for calculations.
Table by author.

Additional values	
Cd	0,65
ρ	1,2 KJ/m^3
g	9,81 m/s^2
h	3,6 m
P	101000 Pa
R	287 J/kgK
Te	281,4 K
Ti	293,15 K
A	0,028 m^2
A, height	0,055 m
A, width	0,50 m

4.2.2 Simulations model set up

For the simulations, the model was set up according to the technical aspects presented in table 15. The settings for all the design configurations have been set up in the software DesignBuilder as described in table 24.

Table 24: set up of design configurations. Table by author.

General settings	Values
Model options	
Model template	ASHRAE 90.1
Gains data	Early
Occupant latent gains	Dynamic calculation
Lighting gain units	W/m^2
Timing	Typical workday
HVAC	Simple
Sizing	Autosize
Method	EnergyPlus
Auxiliary energy calculations	Separate fans and pumps
Mechanical ventilation methods	Ideal loads
Natural ventilation	Calculated
Infiltration unit	ac/h
Advanced	
Natural ventilation	Model airflow through holes and virtual partitions
Scheduled	Airflow through internal openings
Airflow rate per opening area	0,1 m^3/s-m^2
Heating design	30 Sept – 30 April
Cooling design	30 April – 30 Sept
Temperature control	Operative temperature (for PCM: Air temperature)
Inside convection algorithm	TARP
Outside convection algorithm	DOE
Simulation	
Time steps per hour	4 (for PCM: 12)
Temperature control	Operative temperature
Solar distribution	Full exterior (for Trombe wall: full interior and exterior)
General solution algorithm	Conduction Transfer Function (for PCM: Finite Difference)
Inside convection algorithm	TARP (for PCM: Adaptive Convection Algorithm)
Outside convection algorithm	DOE (for PCM: Adaptive Convection Algorithm)
Site set up	
Location	Delft
Coordinates	Lat: 52 – Long: 4,22
Site orientation	67,5°
Office set up	
Block 1 – Occ	
Dimensions (LxWxH)	5,94 x 3,60 x 3,67
Office area	21,38 m^2
Adiabatic surfaces	Floor, ceiling, 2x side walls, 1x back wall
Activity tab	
Occupancy	
Occupancy density	0,1 (people/m^2)
Occupancy schedule	07:00 – 19:00
Days/week	5 (Monday – Friday)
Metabolic	

Activity	Light office work/Standing/Waking
Environmental control	
Heating	21 °C
Heating set back	18 °C
Cooling	24 °C
Cooling set back	26 °C
Natural ventilation setpoint	
Indoor min. temperature control	23 °C
Minimum fresh air	7 l/s-person
Mechanical ventilation per area	1 l/s-m^2
Office equipment	**ON**
Power density	5 W/m^2
Office schedule	07:00 – 19:00
Radiant fraction	0,2
Construction tab	
Airtightness	
Constant rate	0,050
Schedule	24/7
Condition	Excellent
Openings tab	
Free aperture	
Glazing area opens	100%
Discharge coefficient	0,65
Office schedule	07:00 – 19:00
Seasonal control	Summer only
Lighting tab	
General lighting	**ON**
Normalized power density	2,5 W/m^2-100 lux
Office schedule	07:00 – 19:00
Luminaire type	Suspended
Lighting control	**ON**
Working pane height	0,80 m
Control type	Linear/off
HVAC tab	
Mechanical ventilation	**ON**
Outside air definition method	Min. fresh air (max. per person and per area)
Office schedule	07:00 – 19:00
Seasonal control	All year
Days/week	5
Heat recovery	Sensible (for PCM: enthalpy)
Heating	**ON**
Fuel	Electricity from grid
COP	5
Seasonal control	Winter only
Days/week	5
Cooling	**ON**
Fuel	Electricity from grid
COP	4,5
Seasonal control	Summer only
Days/week	5
Natural ventilation	**ON**
Outside air definition	By zone
Outside air	5 ac/h
Outdoor min. temperature control	15 °C
Outdoor max. temperature control	24 °C

4.2.3 Simulation results

Current situation – Applied Physics office building

According to the information provided by TU Delft's Campus & Real Estate, the current offices in block IV of the Applied Physics building have heating provided by their own gas boilers, but have no cooling. It also consists of natural ventilation through the opening of windows and a mechanical air extraction unit. Due to the fact that it was not possible to measure the current comfort levels of the offices in this block, this situation was simulated. For this simulation, the previous model set up mentioned, was used. The heating and electricity performance of the building were obtained through the TU Delft energy monitor website (TU Delft, 2018). The intention was to use the values given by the building energy monitor as the heating and electricity consumption of the building. Since the shown values are too high for an office building, most probably due to the fact that there are multiple types of spaces within the building, such as laboratories, lecture rooms, and so on, it was decided not to use these values, but rather to take the values from the simulation into account. The results can be seen in table 25.

Table 25: comfort and energy performance of current situation office Applied Physics building. Table by author.

Current situation office - Applied Physics building	Values	Unit
Average operative temperature winter (Oct – April)	19,7	°C
Average operative temperature summer (May – Sept)	25,0	°C
Heating consumption (no cooling) winter (Oct – April)	125,90	kWh/m^2
Lighting and office equipment consumption winter (Oct – April)	17,84	kWh/m^2
Heating consumption (no cooling) summer (May – Sept)	0	kWh/m^2
Lighting and office equipment consumption summer (May – Sept)	9,09	kWh/m^2
Energy performance winter (Oct – April)	2810,77	kWh
Energy performance summer (May – Sept)	177,20	kWh

Even though these values are not an actual representation of the real conditions, they are an approximation based on gathered data and assumptions in order to be able to compare the current situation with the comfort and energy performance of the design configurations.

Façade design configurations – Applied Physics office building

The results of the comfort and energy performance of the design configurations are going to be first illustrated and then evaluated on their ability to reach the comfort levels (figures 42-44), heating/cooling/lighting/office equipment consumption (figures 45-46), and the nearly energy neutral values (figures 47-51) stated in paragraph 3.1.

Operative temperatures per season

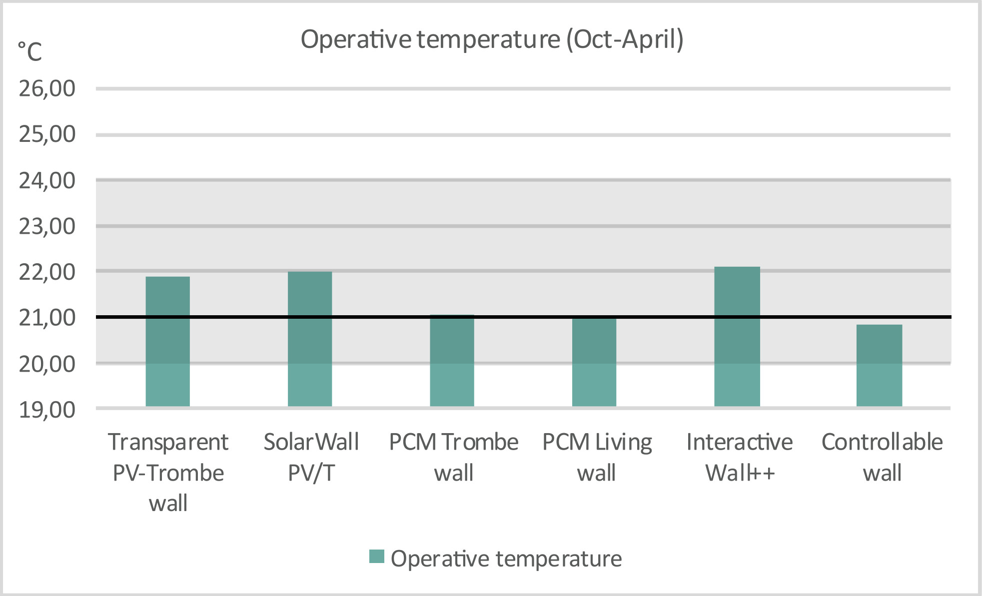


Figure 42: operative temperature winter season. Image by author.

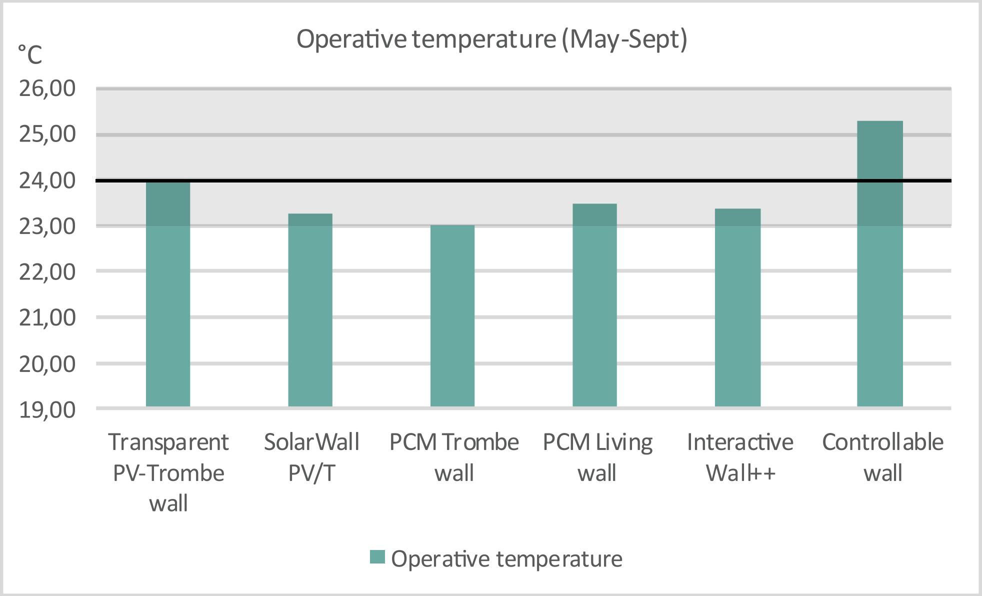


Figure 43: operative temperature winter season. Image by author.

Daylight factor (annual)

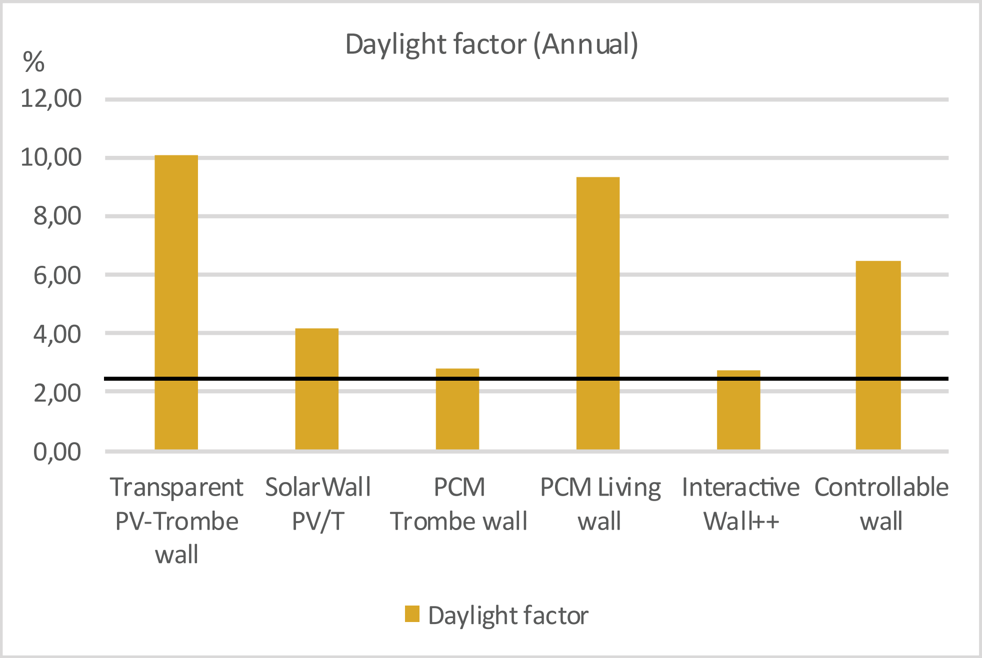


Figure 44: daylight factor annual. Image by author.

Heating, cooling, lighting, and office equipment consumption per season

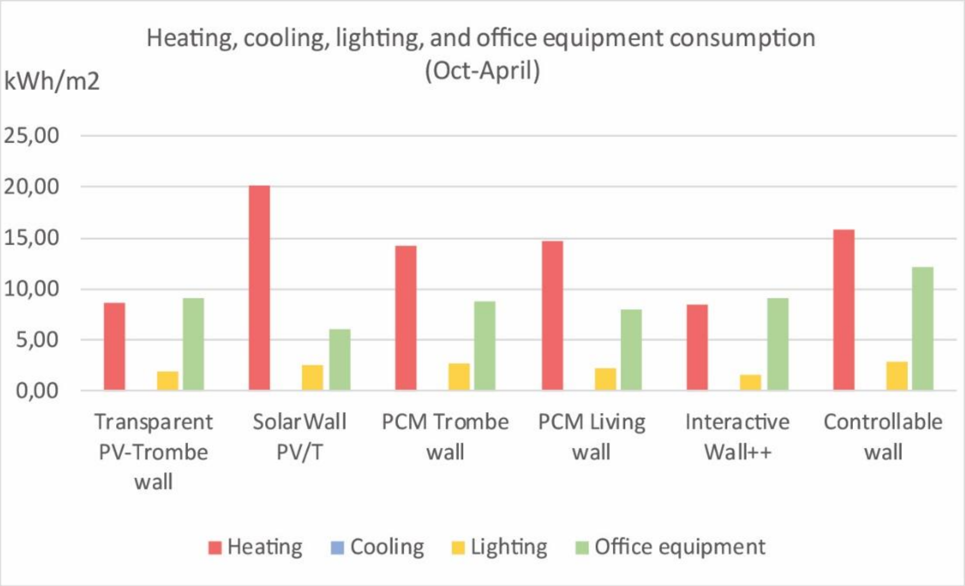


Figure 45: heating/cooling/lighting/office equipment consumption winter season. Image by author.

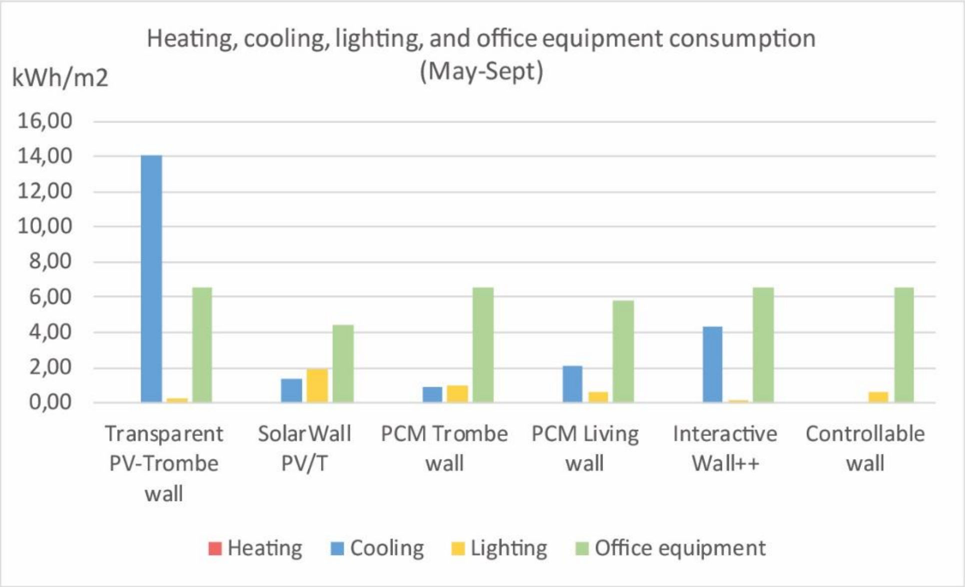


Figure 46: heating/cooling/lighting/office equipment consumption summer season. Image by author.

Energy performance per season

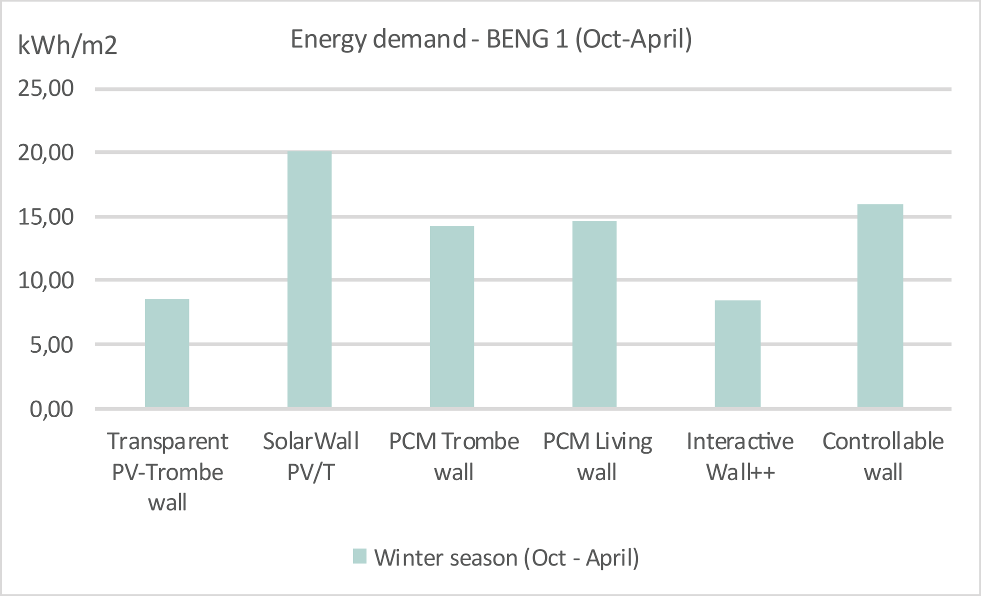


Figure 47: energy demand – BENG 1 winter season. Image by author.

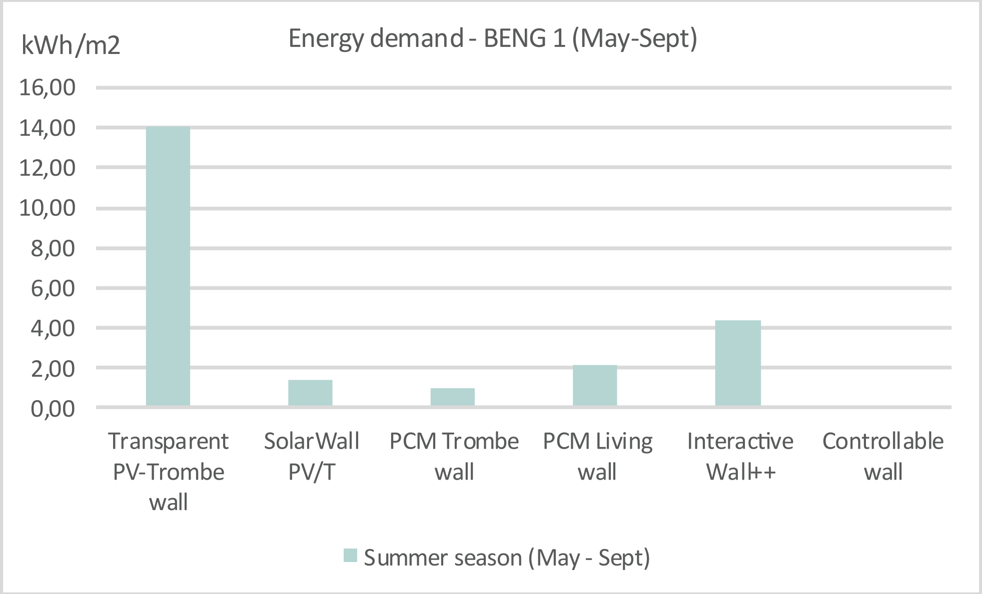


Figure 48: energy demand – BENG 1 summer season. Image by author.

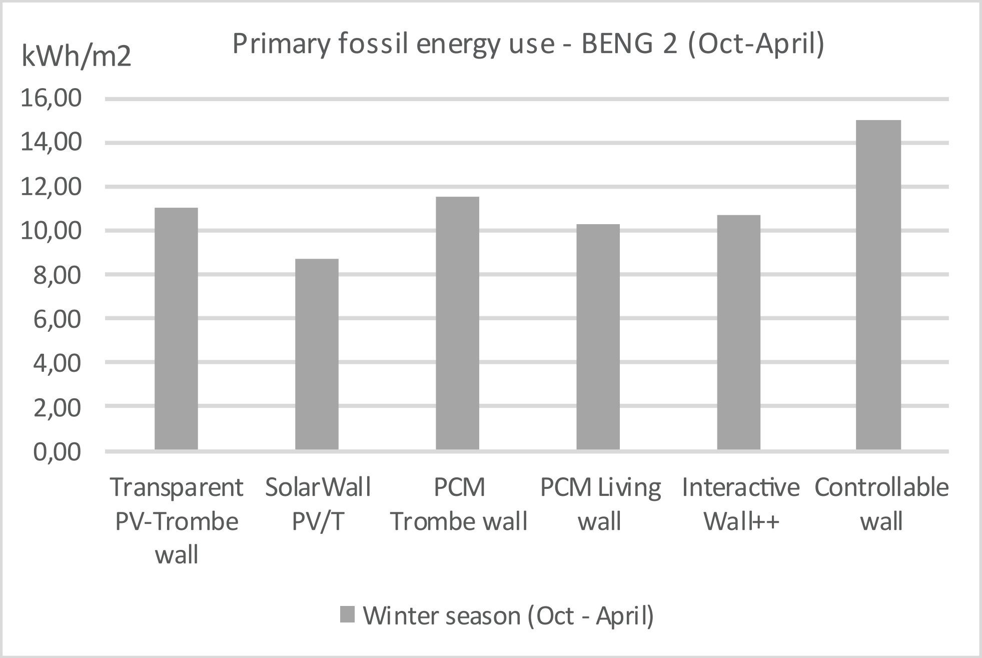


Figure 49: primary fossil energy use – BENG 2 winter season. Image by author.

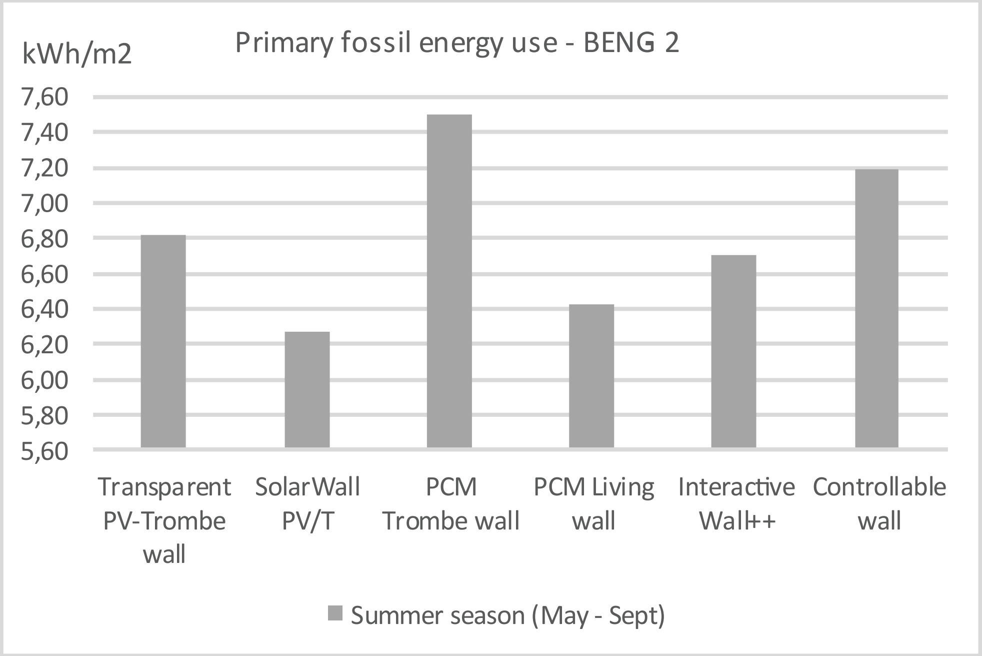


Figure 50: primary fossil energy use – BENG 2 winter season. Image by author.

Energy production (annual)

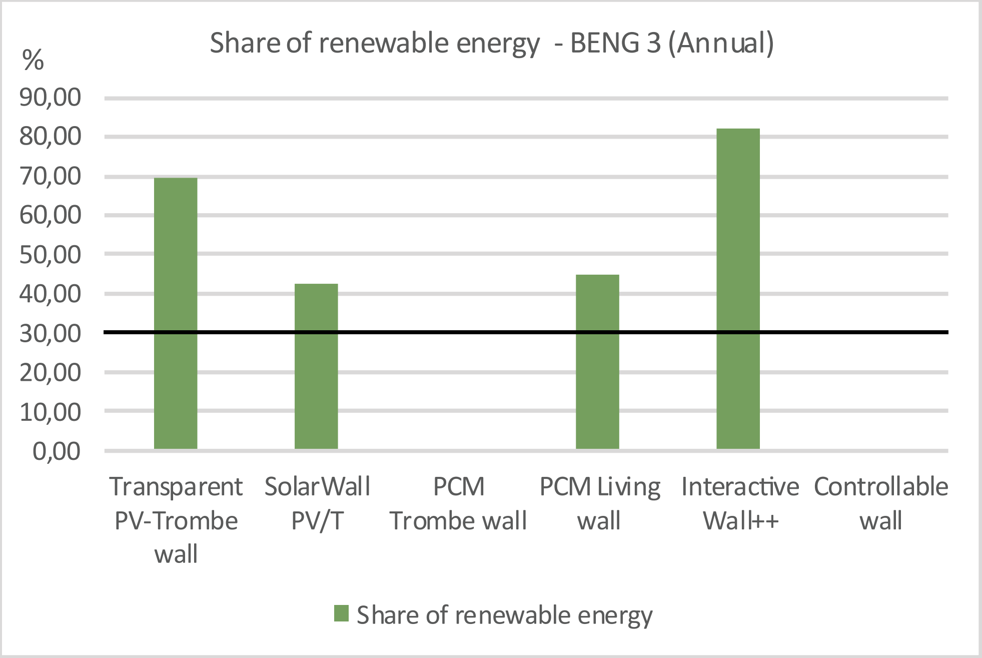


Figure 51: share of renewable energy annual. Image by author.

4.2.4 Conclusion

Table 26 shows the comparison in numbers between the current situation and between the design configurations together with the comfort values and the nearly energy neutral values.

Table 26: comparison between current situation and between design configurations + comfort and energy values. Table by author.

Design configurations	Rc-value	Avg. Winter temp. °C	Avg. Summer temp. °C	Daylight %	(BENG 1) kWh/m^2.yr	(BENG 2) kWh/m^2.yr	(BENG 3) %
Comfort and NZEB values	**4,5 - 7,0**	**20 - 24°C (21°C)**	**23 - 26°C (24°C)**	**≥2,5%**	**≤115**	**≤ 40**	**≥ 30**
Current situation	0,65	19,7	25,0	N.A.	126	193	0
Energy Efficient (EF)							
PV-Trombe wall	8,15	21,9	24,0	10,1	23	18	70
SolarWall PV/T	7,95	22,0	23,3	4,20	21	15	42
Self-Adaptive (SA)							
PCM Trombe wall	7,85	21,0	23,0	2,81	15	19	0
PCM Living wall	7,85	21,0	23,5	9,32	17	17	45
Full Control (FC)							
Interactive Wall++	7,15	22,1	23,4	2,76	13	17	82
Controllable wall	4,60	20,8	25,3	6,47	16	22	0

N.A.= Not available

The values above show how well each design configuration performs regarding comfort and energy. For the nearly energy neutral values, the BENG-values were taken into account. BENG 1 refers to the annual energy demand for heating and cooling. BENG 2 refers to the sum of the primary energy consumption for heating, cooling, and fans. For office buildings, the primary energy consumption for lighting also counts. The energy generated by PV-panels can be subtracted from the primary energy consumption. Even though the office equipment energy use does not fall into this category, for the design configurations, this will be added to the BENG 2 value. BENG 3 refers to the share of renewable energy in percentage, which is determined by dividing the amount of self-generated renewable energy by the total of renewable energy plus primary fossil energy use.

These values show an approximation to the BENG-values and can be used as an indication whether the designs meet up with the BENG requirements. However, these values were not obtained or calculated with the BENG calculation software, due to the fact that this is still not available. In order to be sure that the design configurations really do meet up with the BENG requirements, these will have to be calculated again when the BENG calculation tool becomes available. Nevertheless, these values show a real approximation and will therefore be used to evaluate the design configurations.

Analyzing the results of the simulations, it can be concluded that all of the design configurations comply with the comfort and nearly energy neutral requirements. BENG-3 can be somewhat disregarded due to the fact that the building is still able to produce energy by other means than on the façade. Nevertheless, it will be taken into account for choosing a design configuration per Archetype, but only as a tiebreaker.

Looking at the results of the Energy Efficient Archetype design configurations, the PV-Trombe wall has better values than the SolarWall PV/T in the Rc-value, both the average temperature per season, and in daylight factor. Only in the energy demand (BENG 1) value and the primary energy consumption (BENG 2) value, the SolarWall PV/T scored better. Even though the PV-Trombe wall has a higher value in those, it is still within the range of nearly energy neutral. If taking the energy production (BENG 3) value into account, the PV-Trombe wall performs almost two times better. Therefore, for the Energy Efficient Archetype, the design configuration PV-Trombe wall is chosen as the better performing design configuration.

Looking at the results of the Self-Adaptive Archetype design configurations, the PCM Living wall has either the same values or better values than the PCM-Trombe wall. In addition, with this design configuration, it is possible to produce energy, achieving a significantly good energy production (BENG 3) value. Also, the design has the possibility to bounce daylight to the inside in an effort to help reduce lighting costs, the PV-panels can self-adjust according to the most efficient sun angle and in this way helping reduce the energy costs even more. It was not possible to take these measures into account for the simulation, therefore they are not reflected in the results meaning that the design configuration should perform better than the results stated above in table 26. With this in mind, for the Self-Adaptive Archetype, the design configuration PCM Living wall is chosen as the better performing design configuration.

Looking at the results of the Full Control Archetype design configurations, the Interactive Wall++ scored the best on Rc-value, average summer temperature, energy demand (BENG 1), and the primary energy consumption (BENG 2) value. The Controllable wall on the other hand has better values for the average winter temperature and the daylight factor. In addition, with the Interactive Wall++ it is possible to produce energy and not with the Controllable wall. Therefore, due to the fact that the Interactive Wall++ has overall the better values, for the Full Control Archetype, the design configuration Interactive Wall++ is chosen as the better performing design configuration.

In general, all of the design configurations perform better than the current situation of the office spaces of the Applied Physics building and therefore can be considered as an enhancement of the comfort and energy levels of the office spaces. With a new façade that complies with the users comfort, user control, user preferences, and a façade that is also energy efficient, the users should definitely feel satisfied and this should reflect in their work productivity.

Chapter 5 – Final design

This chapter shows the implementation of the chosen design configurations within the case study. It also shows their technical drawings and winter and summer systems.

Energy Efficient (EF) Archetype

Transparent PV-Trombe wall

- Neutral comfort

- Outside view
- Contact with nature

- High external control
- Low internal control

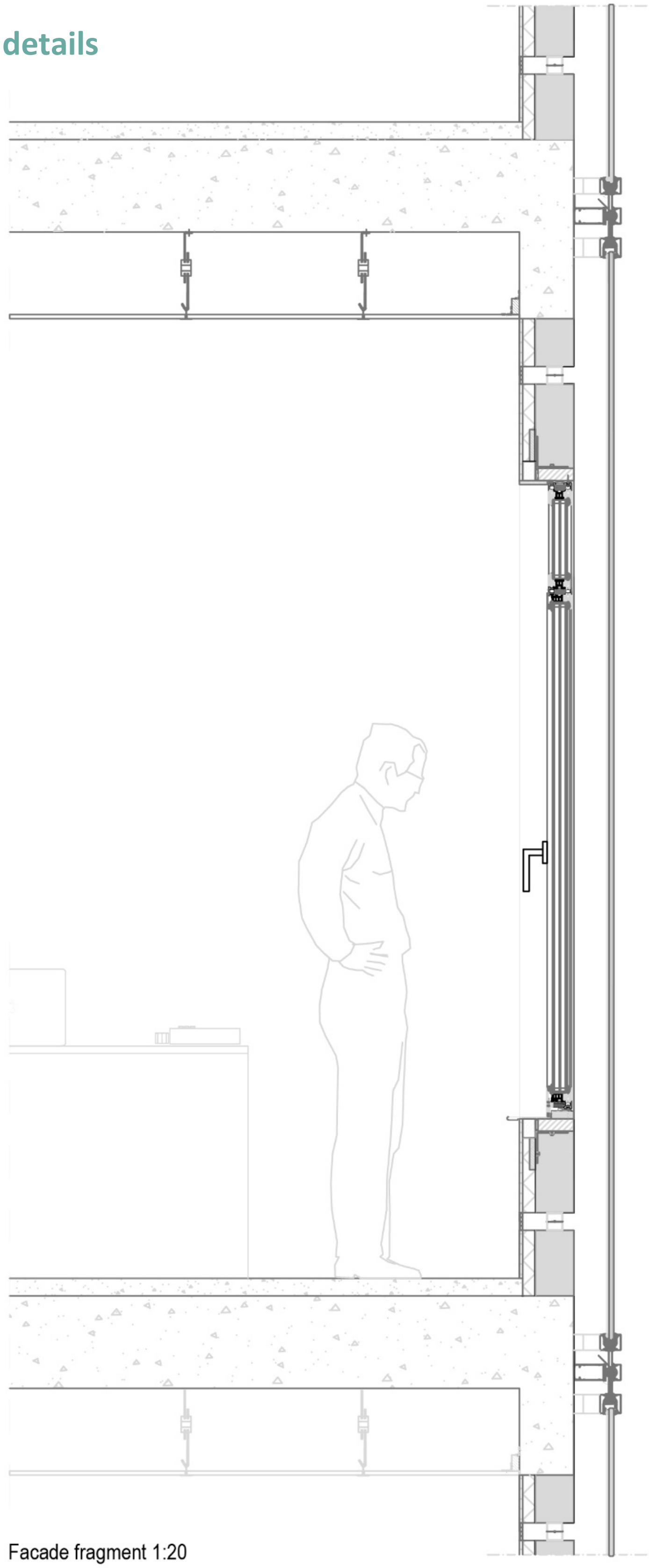
- Highly energy efficient

Implementation into case study

Figure 52: transparent PV-Trombe wall exterior view. Image by author.

Figure 53: transparent PV-Trombe wall interior view. Image by author.

Fragment and details



Facade fragment 1:20

Figure 54: transparent PV-Trombe wall façade fragment. *Image by author.*

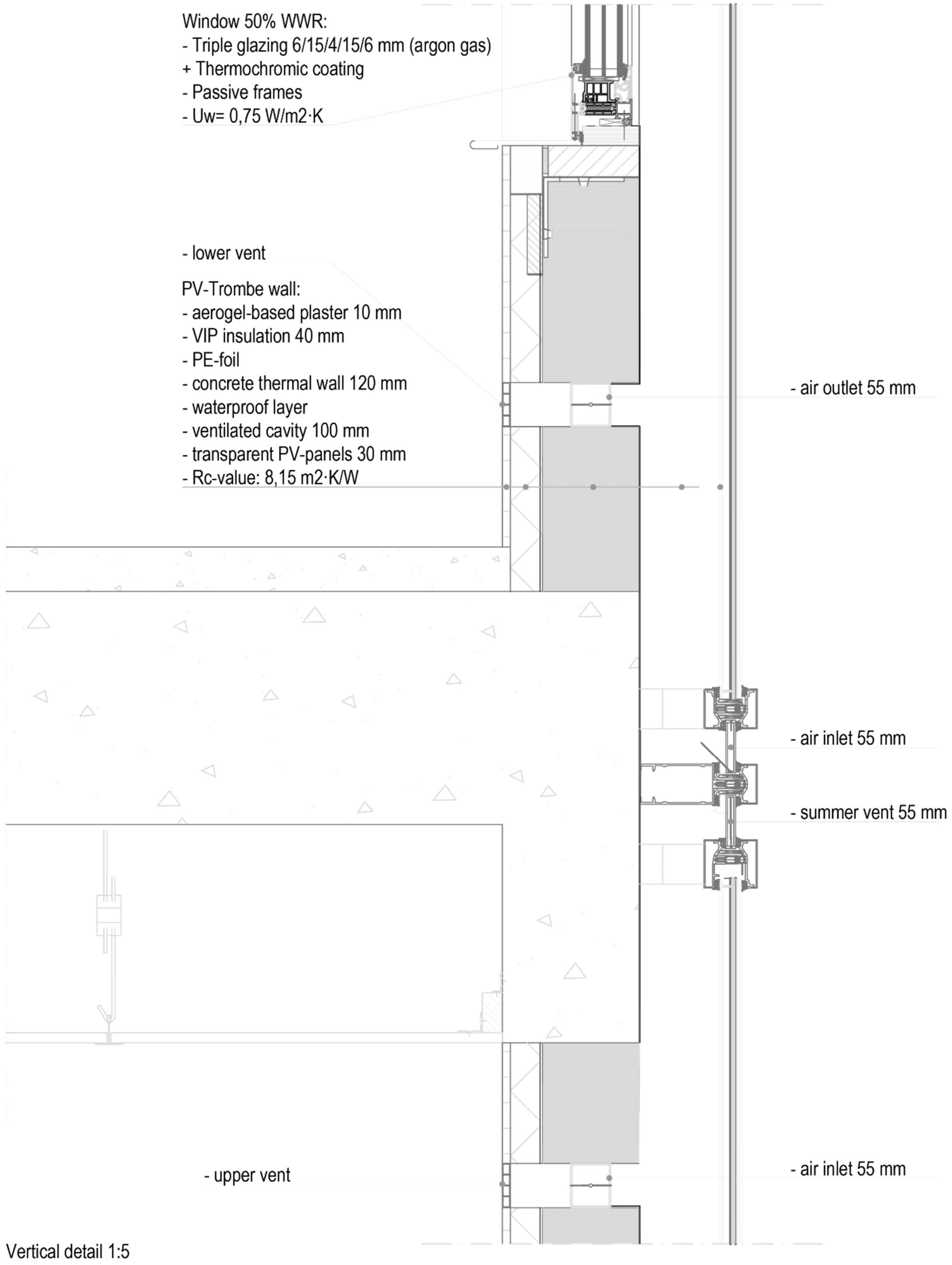


Figure 55: transparent PV-Trombe wall vertical detail. *Image by author.*

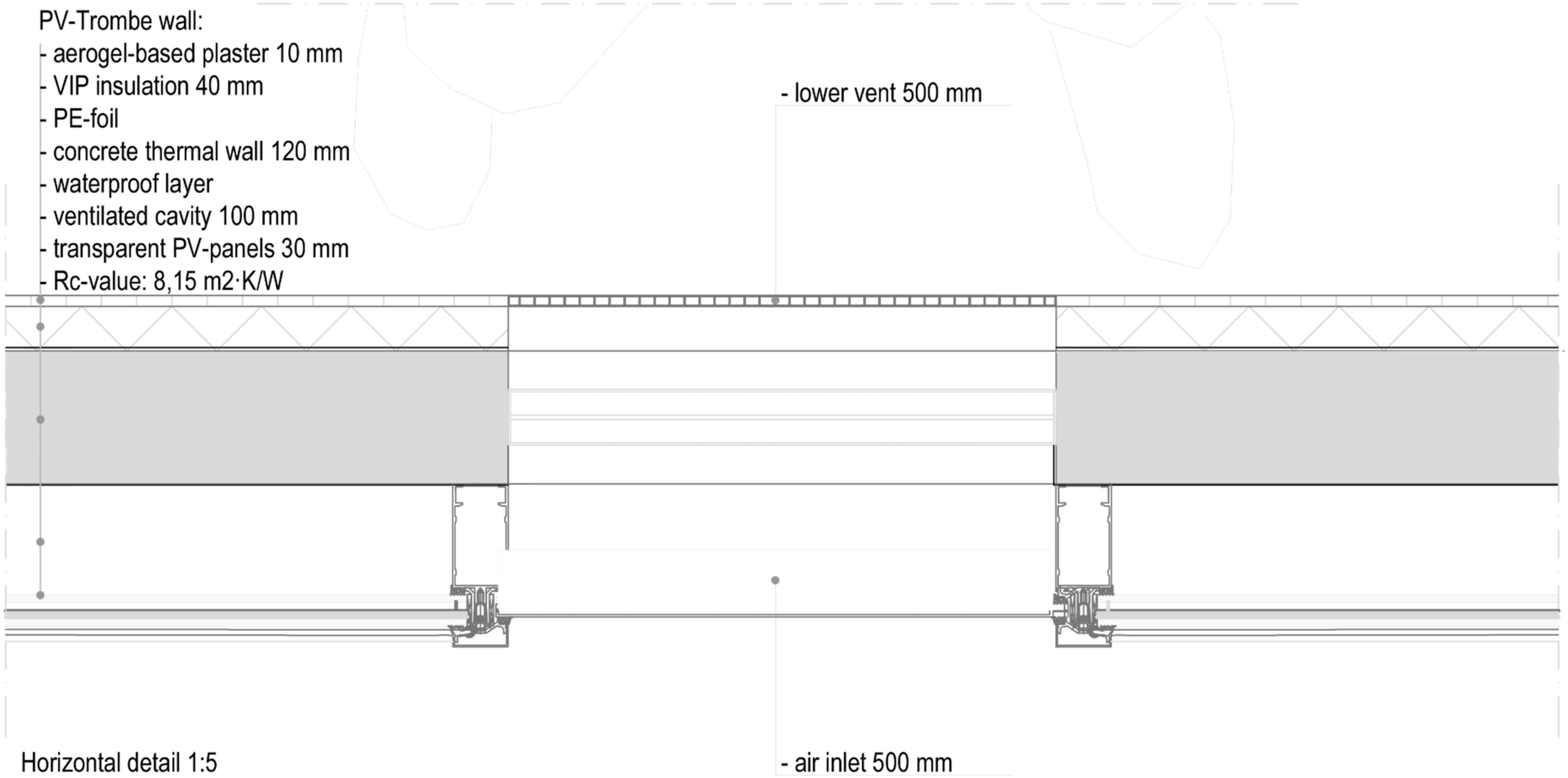
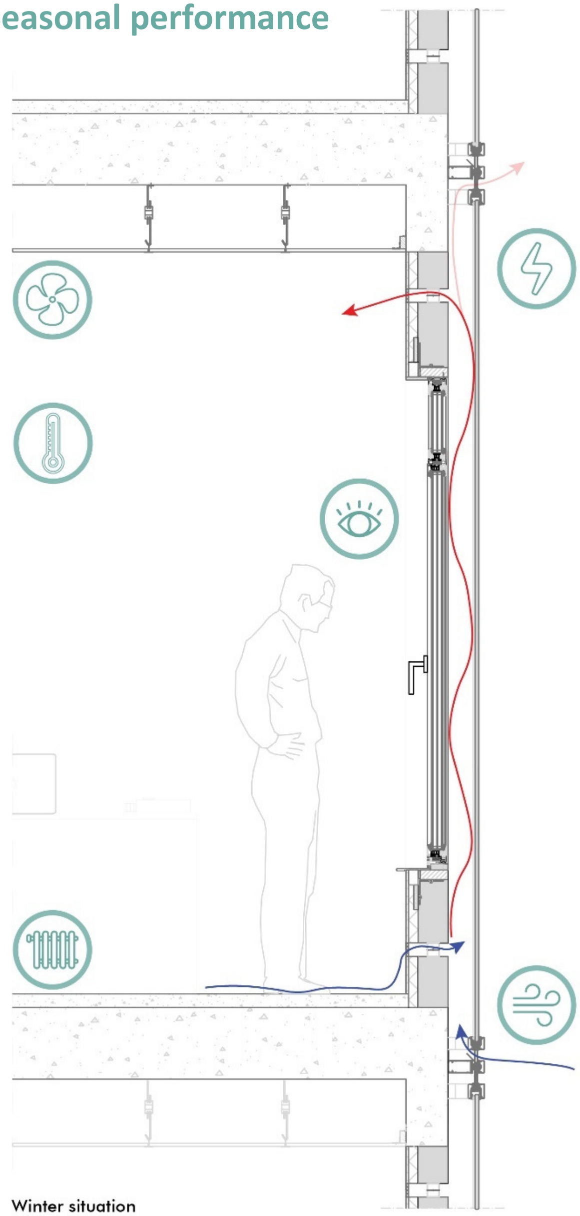


Figure 56: transparent PV-Trombe wall horizontal detail. Image by author.

Seasonal performance



Transparent PV-Trombe wall
Winter situation (Oct-April)

Fresh air supply through facade.
Supply: 80 m3/h (max. 3 people).

Air heating through facade.
Additional low temperature heating if necessary with heat pump (COP=5) with supply from aquifer thermal energy storage.
Summer air vent opens in case of overheating.

Mechanical ventilation exhaust if necessary.

Average winter temperature 21,9°C (Oct-April).

50% window-to-wall-ratio.
10,1% daylight factor.
Thermochromic glazing in order to avoid glare.
500 lux LED lighting with occupancy sensors.

Onyx Solar transparent PV-panels.
Winter electricity production: 316 kWh (Oct-April).

PV-Trombe wall:
Rc-value: 8,15 m2·K/W opaque areas.
Thermochromic glazing + passive frames:
U-value: 0,75 W/m2·K translucent areas.

Figure 57: winter situation EF-design. Image by author.

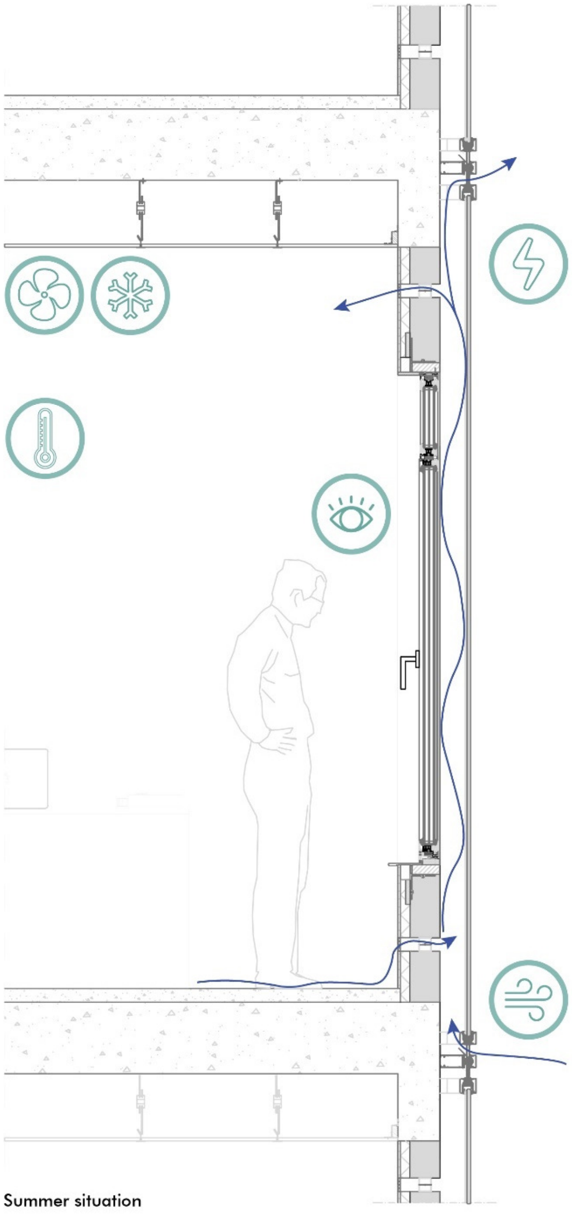


Figure 58: summer situation EF-design. *Image by author.*

Transparent PV-Trombe wall
Summer situation (May-Sept)

Fresh air supply through facade.
Supply: 80 m3/h (max. 3 people).

Air cooling through facade.
Operable windows for extra cooling/ventilation.
Additional low temperature cooling if necessary with heat pump (COP=5) with supply from aquifer thermal energy storage.
Summer air vent opens for continuous flow or air.

Mechanical ventilation exhaust if necessary.

Average summer temperature 24,0°C (May-Sept).

50% window-to-wall-ratio.
10,1% daylight factor.
Thermochromic glazing in order to avoid glare.
500 lux LED lighting with occupancy sensors.

Onyx Solar transparent PV-panels.
Summer electricity production: 497 kWh (May-Sept).

PV-Trombe wall:
Rc-value: 8,15 m2·K/W opaque areas.
Thermochromic glazing + passive frames:
U-value: 0,75 W/m2·K translucent areas.

Self-Adaptive (SA) Archetype

PCM Living Wall

- Positive about comfort

- Use of technologies is main experience
- Technologies improves standard of living
- Space matches lifestyle

- High external control
- Low internal control

- Conflicted about energy use

Figure 59: PCM Living wall exterior view. Image by author.

Figure 60: PCM Living wall interior view. Image by author.

Fragment and details

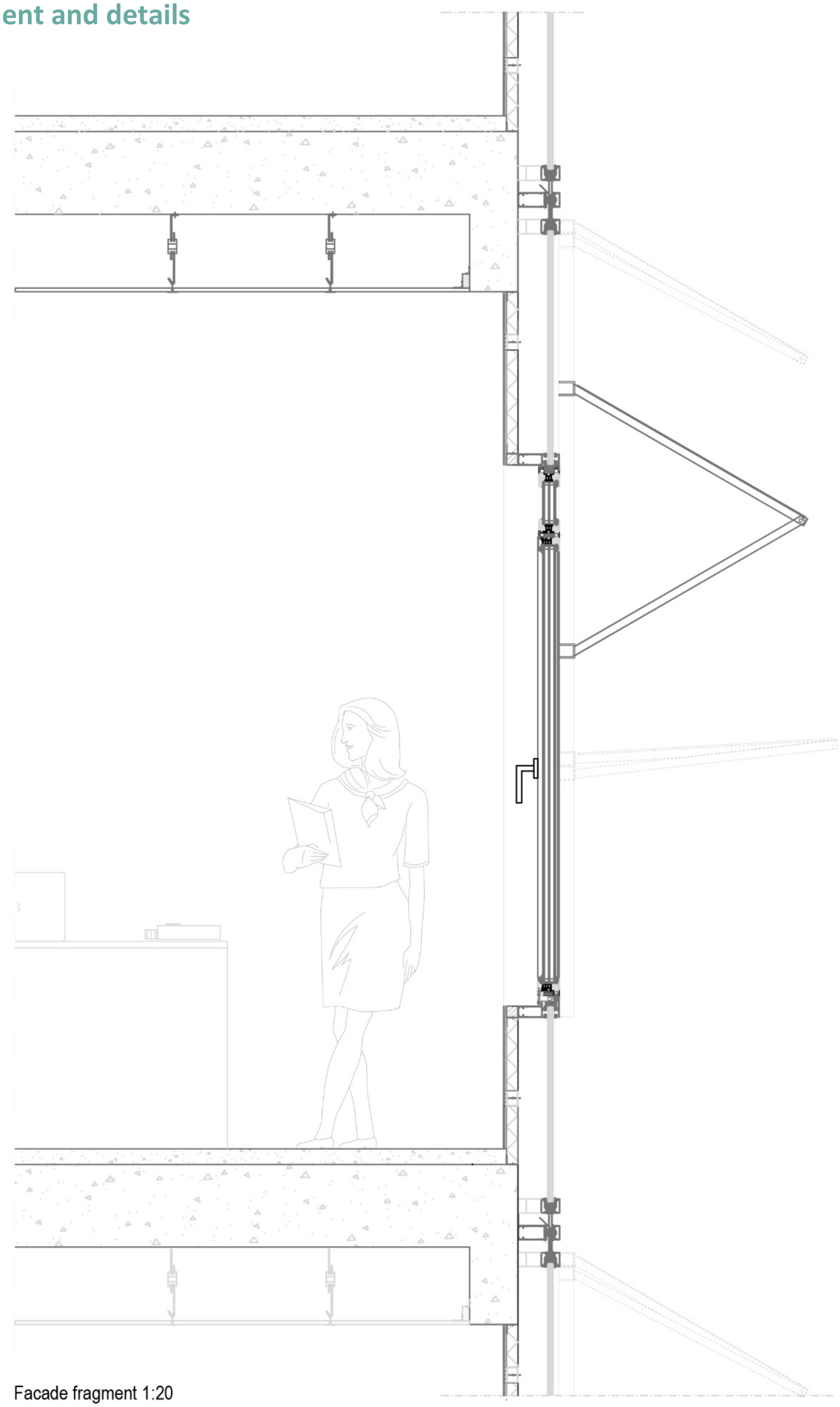


Figure 61: PCM living wall façade fragment. Image by author.

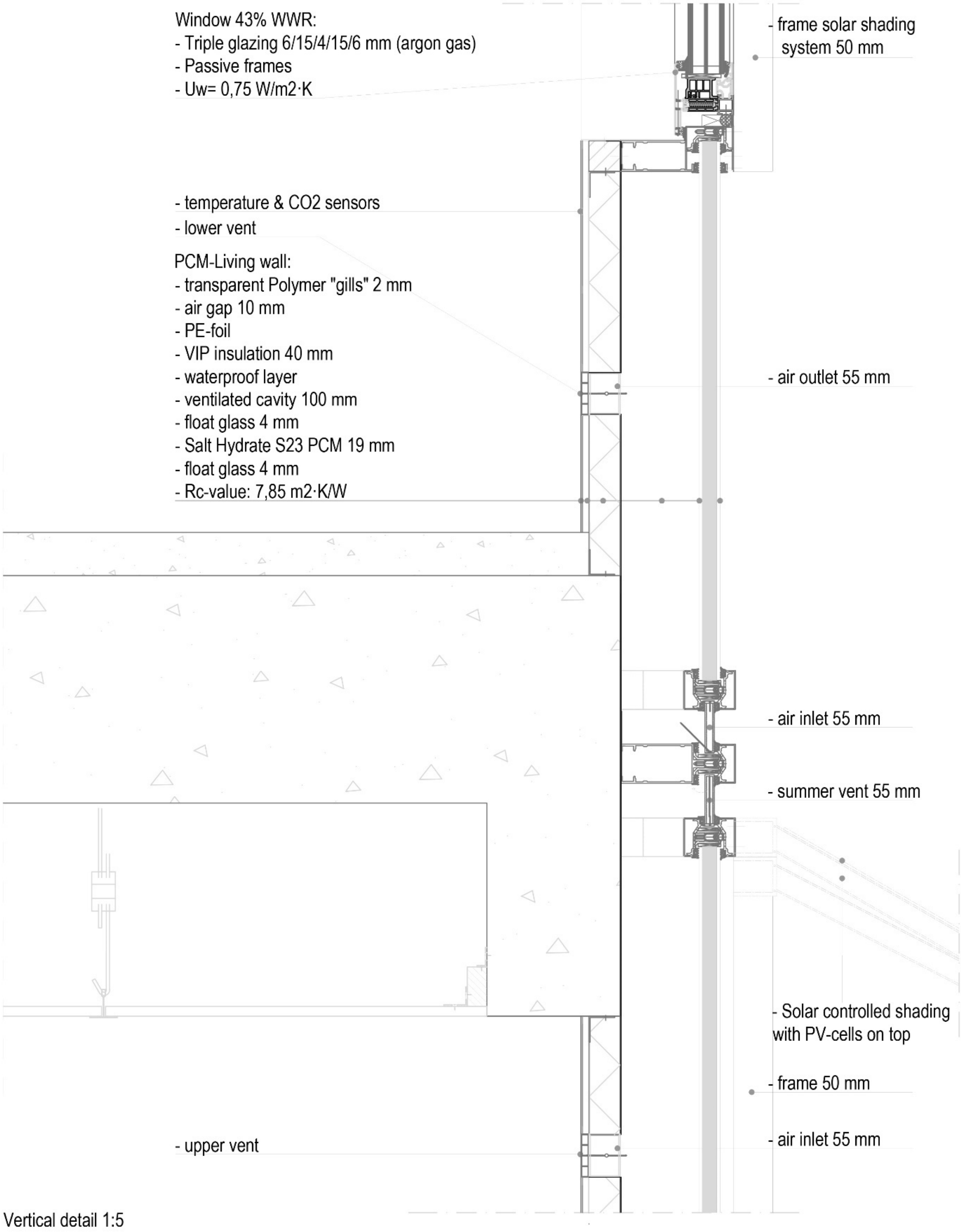


Figure 62: PCM living wall vertical detail. *Image by author.*

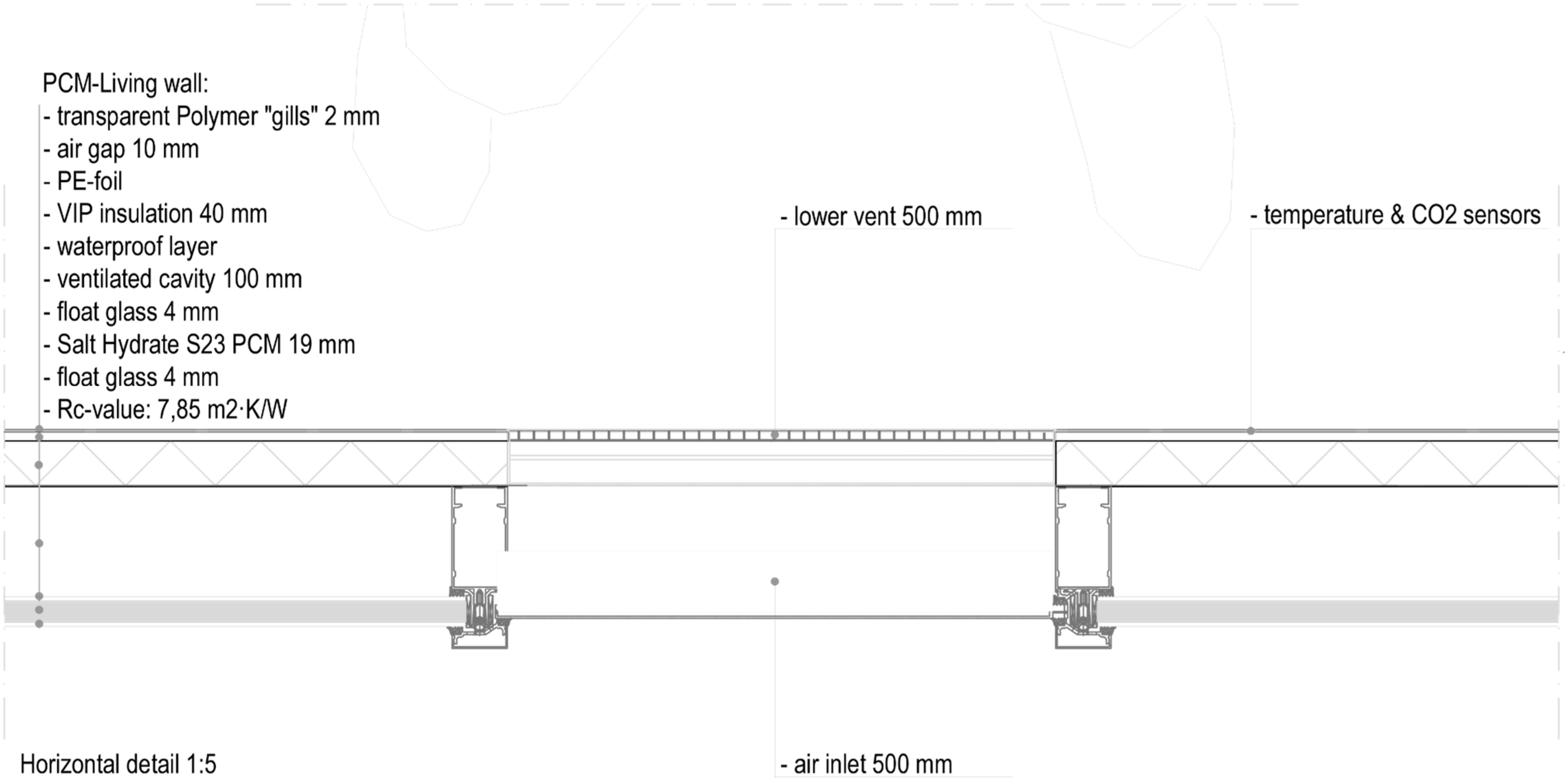
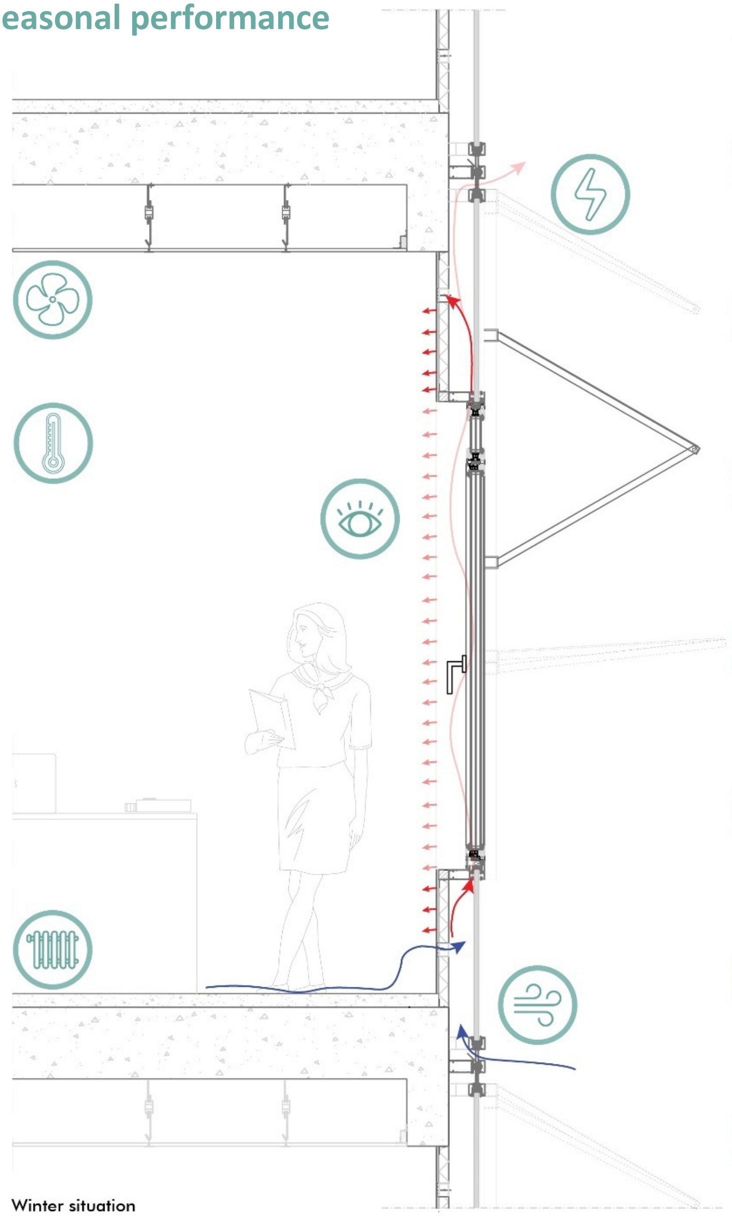


Figure 63: PCM living wall horizontal detail. Image by author.

Seasonal performance



PCM living wall
Winter situation (Oct-April)

Fresh air supply through facade.
Supply: 80 m3/h (max. 3 people).

Air heating through facade by self-adaptive PCM thermal storage, supplied by opening of gills.
Additional low temperature heating if necessary with heat pump (COP=5) with supply from aquifer thermal energy storage.
Summer air vent opens in case of overheating.

Mechanical ventilation exhaust if necessary.

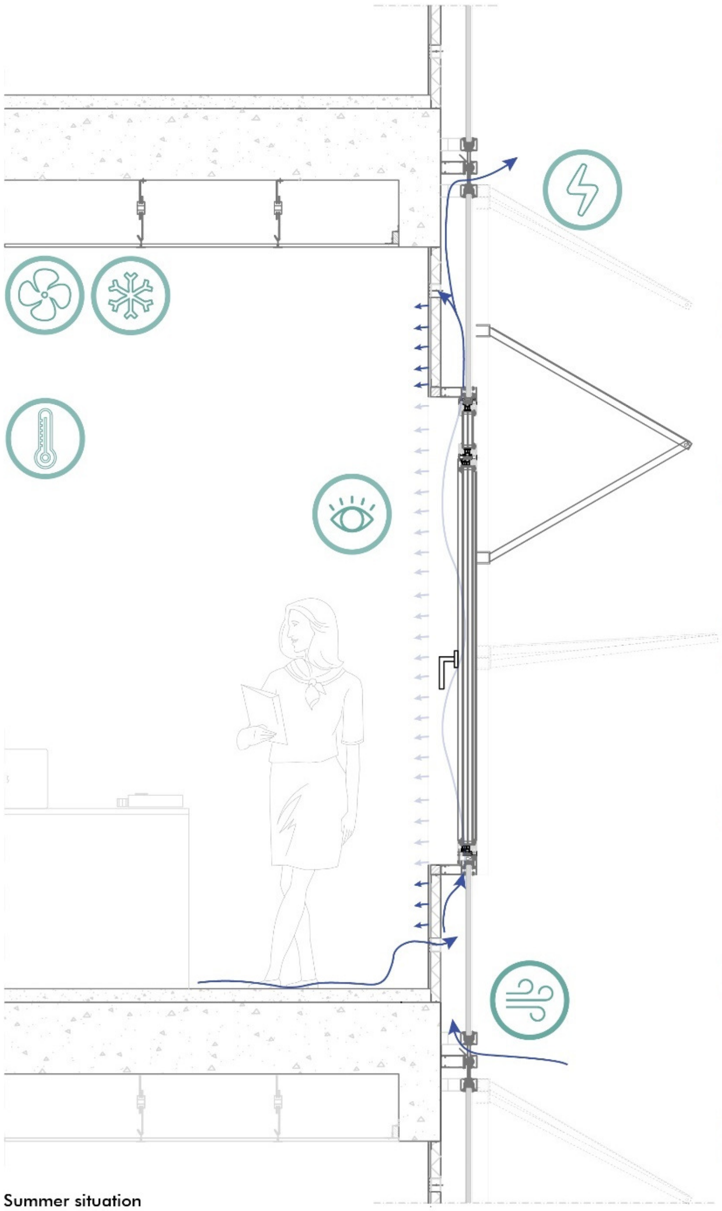
Average winter temperature 21,0°C (Oct-April).

43% window-to-wall-ratio.
9,3% daylight factor.
Bouncing of daylight by solar controlled shading feature.
500 lux LED lighting with occupancy sensors.

Solar controlled PV-panels on top of shading feature.
Winter electricity production: >110 kWh (Oct-April).

PCM living wall:
Rc-value: 7,85 m2·K/W opaque areas.
Triple glazing + passive frames:
U-value: 0,75 W/m2·K translucent areas.

Figure 64: winter situation SA-design. Image by author.



PCM living wall
Summer situation (May-Sept)

Fresh air supply through facade.
Supply: 80 m3/h (max. 3 people).

Air cooling through facade by self-adaptive PCM thermal storage, supplied by opening of gills.
Operable windows for extra cooling/ventilation.
Additional low temperature cooling if necessary with heat pump (COP=5) with supply from aquifer thermal energy storage.
Summer air vent opens for continuous flow or air.

Mechanical ventilation exhaust if necessary.

Average summer temperature 23,5°C (May-Sept).

43% window-to-wall-ratio.
9,3% daylight factor.
Bouncing of daylight by solar controlled shading feature.
500 lux LED lighting with occupancy sensors.

Solar controlled PV-panels on top of shading feature.
Summer electricity production: >199 kWh (May-Sept).

PCM living wall:
Rc-value: 7,85 m2·K/W opaque areas.
Triple glazing + passive frames:
U-value: 0,75 W/m2·K translucent areas.

Figure 65: summer situation SA-design. Image by author.

Full Control (FC) Archetype

Interactive Wall++

- High comfort

- Own privacy
- High freedom

- Low external control
- High internal control

- Negative emotions about energy awareness

Figure 66: interactive Wall++ exterior view. Image by author.

Figure 67: interactive Wall++ interior view. Image by author.

Fragment and details

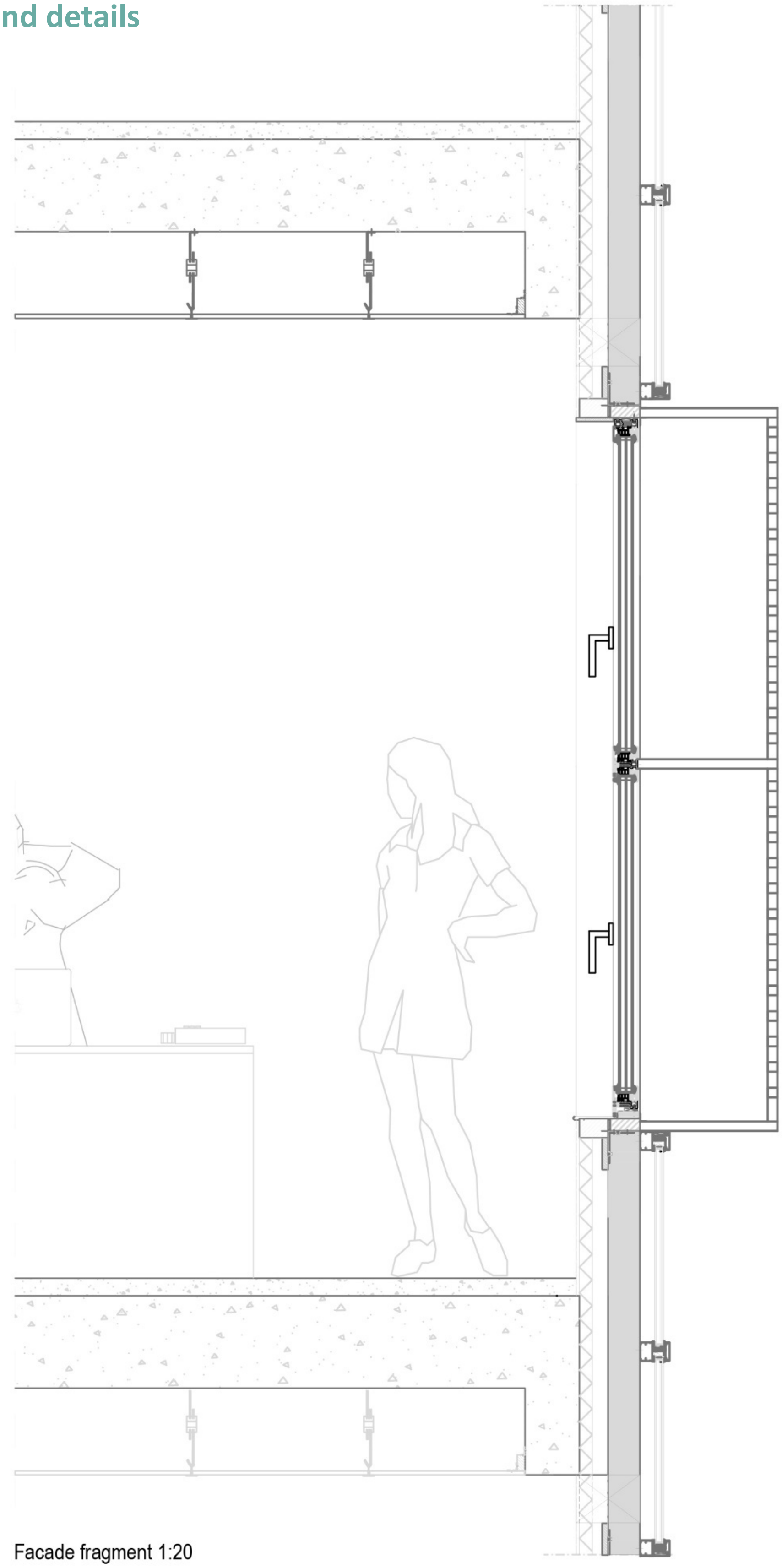


Figure 68: interactive Wall++ façade fragment. *Image by author.*

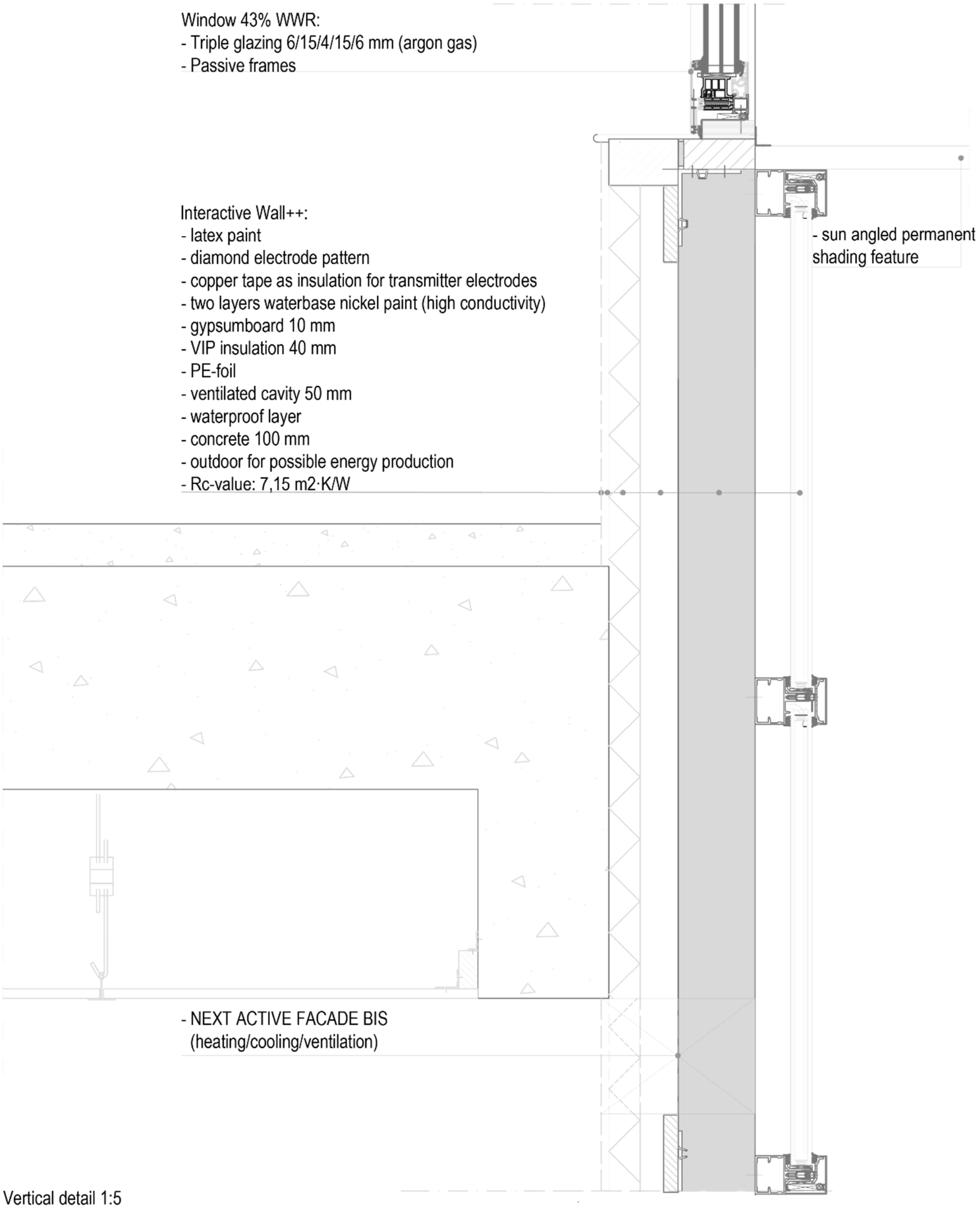
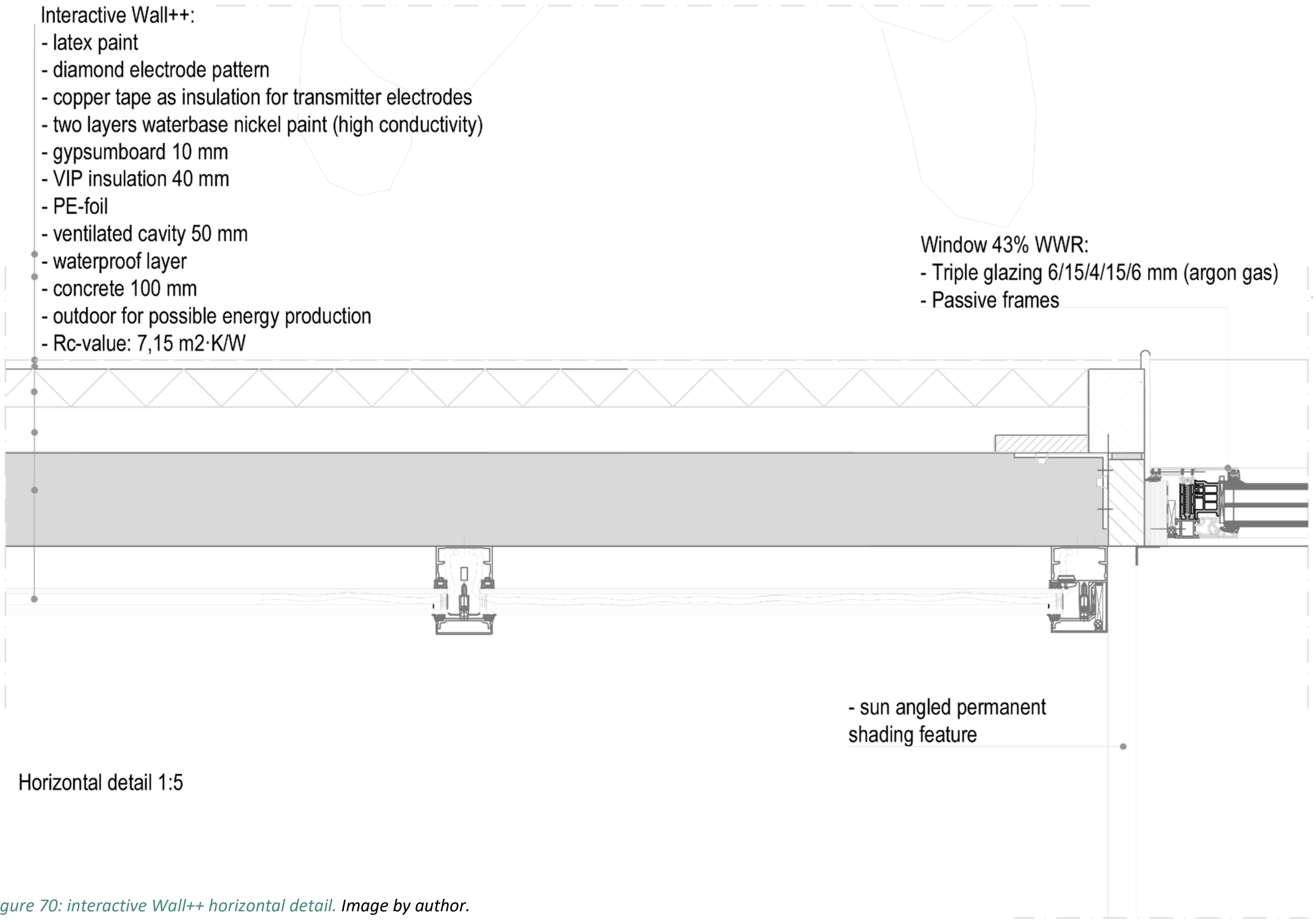


Figure 69: interactive Wall++ vertical detail. *Image by author.*



Interactive Wall++:
- latex paint
- diamond electrode pattern
- copper tape as insulation for transmitter electrodes
- two layers waterbase nickel paint (high conductivity)
- gypsumboard 10 mm
- VIP insulation 40 mm
- PE-foil
- ventilated cavity 50 mm
- waterproof layer
- concrete 100 mm
- outdoor for possible energy production
- Rc-value: 7,15 m2·K/W

Window 43% WWR:
- Triple glazing 6/15/4/15/6 mm (argon gas)
- Passive frames

- sun angled permanent shading feature

Horizontal detail 1:5

Figure 70: interactive Wall++ horizontal detail. *Image by author.*

Seasonal performance

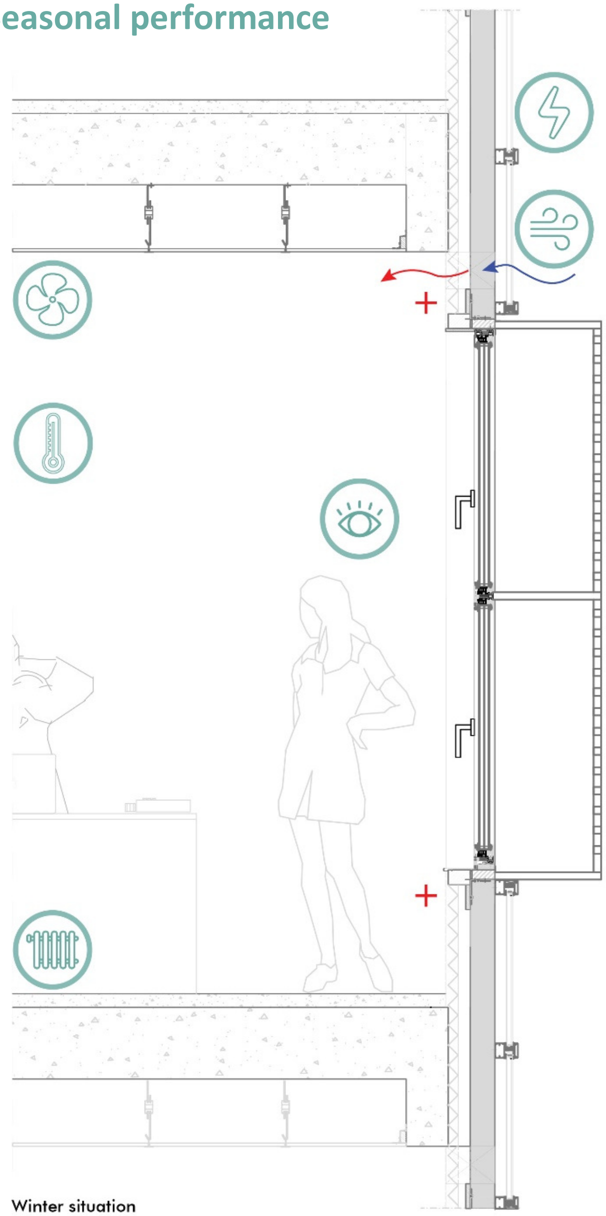


Figure 71: winter situation FC-design. Image by author.

Interactive Wall++
Winter situation (Oct-April)

Fresh air supply by NEXT Active Facade Building Integrated System (BIS) and heat exchanger.
Supply: 80 m3/h (max. 3 people).

Air heating through NEXT Active Facade BIS with user control function connected to Wall++. Wall++ reacts to human presence, patterns, and signs.
Additional low temperature heating if necessary with heat pump (COP=5) with supply from aquifer thermal energy storage.

Air exhaust by NEXT Active Facade BIS.
Mechanical ventilation exhaust if necessary.

Average winter temperature 22,1°C (Oct-April).

37% window-to-wall-ratio.
2,8% daylight factor.
Sun-angled shading feature with sun-angled lamellas.
500 lux LED lighting with occupancy sensors.

Possibility to place Building Integrated PV-Panels (BIPV's) on outer facade without influencing the performance of the facade.
Possible winter electricity production: 235 kWh (Oct-April).

Interactive Wall++:
Rc-value: 7,15 m2·K/W opaque areas.
Triple glazing + passive frames:
U-value: 0,75 W/m2·K translucent areas.

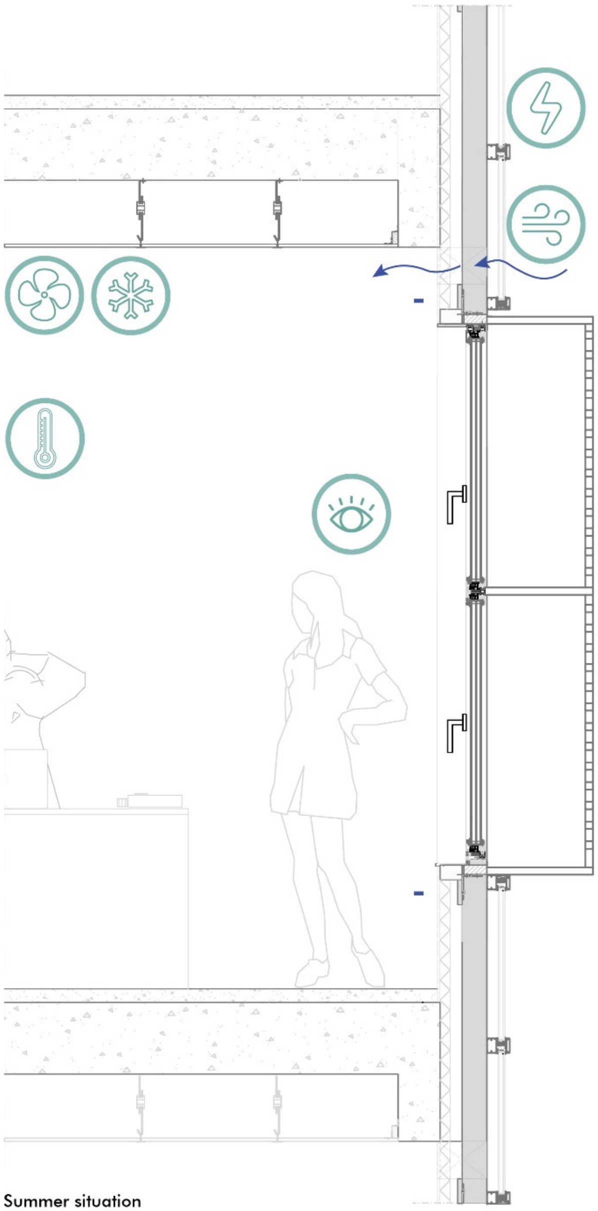


Figure 72: summer situation FC-design. Image by author.

Interactive Wall++
Summer situation (May-Sept)

Fresh air supply by NEXT Active Facade Building Integrated System (BIS) and heat exchanger.
Supply: 80 m3/h (max. 3 people).

Air cooling through NEXT Active Facade BIS with user control function connected to Wall++. Wall++ reacts to human presence, patterns, and signs.
Operable windows for extra cooling/ventilation.
Additional low temperature cooling if necessary with heat pump (COP=5) with supply from aquifer thermal energy storage.

Air exhaust by NEXT Active Facade BIS.
Mechanical ventilation exhaust if necessary.

Average summer temperature 23,4°C (May-Sept).

37% window-to-wall-ratio.
2,8% daylight factor.
Sun-angled shading feature with sun-angled lamellas.
500 lux LED lighting with occupancy sensors.

Possibility to place Building Integrated PV-Panels (BIPV's) on outer facade without influencing the performance of the facade.
Possible summer electricity production: 371 kWh (May-Sept).

Interactive Wall++:
Rc-value: 7,15 m2·K/W opaque areas.
Triple glazing + passive frames:
U-value: 0,75 W/m2·K translucent areas.

Chapter 6 – Discussion

This chapter discusses the findings of this research by interpreting what the results mean, why the results matter, and what the results cannot tell us. It also reflects on how an optimal “all users” façade should function.

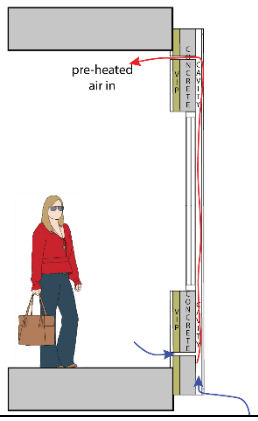
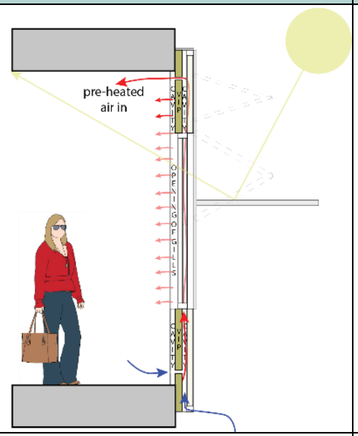
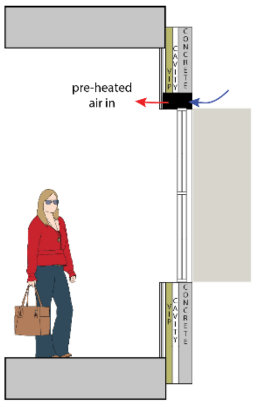
6.1 Interpretations

The office-user oriented interactive/adaptive façade designs presented in this research, only focuses on three different types of users, namely the Energy Efficient type of users, the Self-Adaptive environment type of users, and the Full Control of their environment type of users. However, it is known that more different types of users exist than only the three types of users presented in this research. Also, this research took into account that all of the employees within the office space are the same archetype and therefore have the same user preferences. However, this is not always the case.

The results of this research show that due to the fact that every type of user has different preferences, it is almost impossible to have one interactive/adaptive façade design that complies with all of the user preferences of all types of users, because for example some of the user preferences might contradict each other. However, it is possible to make a design combining the most important characteristics of the design configurations that have a high influence on the indoor comfort and on the energy performance of the space. In this way, a façade can be designed which can comply and serve the most relevant preferences of all existing type of user's, while also providing a comfortable indoor environment and helping its building become nearly energy neutral.

Table 27 shows the characteristics of the design configurations per façade component, their range of investment costs, the similarities and differences of these characteristics, and reflects on which of these characteristics are relevant enough in order to provide an optimal "all users" façade design.

Table 27: characteristics of the designs. Table by author.

Archetypes	**Energy Efficient (EF)**	**Self-Adaptive (SA)**	**Full Control (FC)**
Designs	**PV-Trombe wall**	**PCM Living wall**	**Interactive Wall++**
Characteristics			
State of the art technologies	✓	✓	✓
Comfort	✓	✓	✓
Building regulations	✓	✓	✓
Nearly energy neutral	✓	✓	✓

Façade components	**Shading features**		
Investment	-	€ € €	€
Similarities	The solar controlled and sun angled shading features of the SA and FC designs help with glare discomfort, avoids overheating, and helps reduce the energy demand.		
Differences	The EF design does not have a shading feature in order for it not affect the performance of the PV-panels on the outer layer of the Trombe wall. If this was not the case, the choice would have gone to place preferably a passive shading feature, if possible, or otherwise an active shading feature, depending on the expected performance of the façade design.		
Optimal "all users" design	For the optimal "all users" design, the option of a solar controlled or sun angled shading features helps increase indoor comfort and decreases the energy demand. This seems to be more significant than the energy that can be produced by the façade due to the fact that there are other places in buildings where this can take place. It would indeed be more optimal if the façade could also produce energy, but a shading feature has more direct influence on the indoor comfort and energy demand of the space and therefore should be considered a priority. If with a shading feature there is still the possibility of producing energy on the façade without influencing the performance of it, than this would be considered the most optimal design.		
	Ventilation		
Investment	-	-	€ € €
Similarities	Both the EF and the SA designs provide ventilation through the façade by redirecting the air and in this way pre-heating the incoming air within the cavity, reducing the temperature discomfort during winter and the energy demand.		
Differences	The FC design has a façade integrated ventilation system which allows the user to have complete control of their environment.		
Optimal "All users" design	For the optimal "all users" design, the ventilation through façade method of the EF and SA designs can be used which is a passive method for introducing ventilation to the indoor space and also the façade integrated ventilation system of the FC design can be used as additional ventilation in case needed, providing the users with control of their environment.		
	Window glazing		
Investment	€ € €	€ €	€ €
Similarities	Both the SA and FC designs have triple glazing in order to reduce the amount of heat gain from outside and heat loss from inside.		
Differences	The EF design has a thermochromic triple glazing window in order to avoid overheating and glare discomfort. This is because a shading feature could not be placed on this design without obstructing the performance of the PV-panels and of the heat produced within the Trombe wall.		
Optimal "all users" design	For the optimal "all users" design, triple glazing can be used when the window has a solar controlled or sun angled shading feature. If this is not the case, then a thermochromic triple glazing window is the best option. However, there are other options for window glazing than the previously named ones. Electrochromic glazing also helps reducing the amount of heat gain from outside and heat loss from inside, avoids overheating, and also avoids glare discomfort. The difference is that this type of window glazing can be controlled by the users, giving them the freedom to adapt the state of the window glazing, from translucent to opaque, at any moment in time.		
	Window frame		
Investment	€ €	€ €	€ €
Similarities	All of the three designs have passive window frames.		
Differences	-		

Optimal "all users" design	For the optimal "all users" design, passive window frames can be used. However, there are other options for window frames than passive frames. There are some frames that produce electricity from the sun's intensity on the window glazing. This type of frame was not used for the designs, because of the constant shadow on the glazing produced by the shading features. Depending on the design, this electricity production frame can be used as an enhancement of the design.		
	Window-to-wall-ratio (WWR)		
Investment	€	€ €	€ € €
Similarities	-		
Differences	Each archetype design has a different WWR. EF=50%, SA=43%, and FC=37%. The costs range of the WWR presented above reflects on the investment costs between the opaque and translucent areas. However, the results of this research show that the designs with a higher WWR also presented a higher energy demand value meaning that at the end the costs for maintaining the space with the lower investment costs, will be higher than the costs for maintaining the space with the higher investment costs. Even so, the results show that all of the designs meet up with the nearly energy neutral values.		
Optimal "all users" design	For the optimal "all users" design, it is advised to first follow the guidelines mentioned in this research for WWR per orientation. Second, to take into consideration most of the users preferences linked to WWR, such as outside view, privacy, and so on. Third, to find the right balance between the preferable amount of WWR per orientation and the user preferences linked to WWR.		
	Façade technology		
Investment	€ € €	€ € €	€
Similarities	The EF and SA designs both use the Trombe wall method for passive heating/cooling. The difference between these two is that the EF design uses a massive concrete wall for static heat storage and the SA design uses PCM for adaptive heat storage. Both designs work efficiently, but because the PCM self-adapts to the current outdoor conditions quicker than the massive concrete wall, it allows a more comfortable indoor environment and also uses less energy.		
Differences	The FC design has a standard airtight façade with state of the art technologies which allows the users to directly control their environment by interacting with the wall. The façade understands patterns, reacts to signs, and also self-adapts according to the users' behavior. Therefore, it allows for a more comfortable indoor environment and also uses less energy.		
Optimal "all users" design	For the optimal "all users" design, the Trombe wall method of the SA design with adaptive heat storage can be used together with the user control technologies of the FC design. In this way the indoor environment would self-adapt according to the outdoor conditions and also to the users' preferences at any moment in time.		
	Insulation		
Investment	€ €	€ €	€ €
Similarities	All of the three designs have Vacuum Insulated Panels (VIP's) for thermal insulation, which is a high performing insulation with exceptional insulation values and slim thickness ultimately providing more office usage area.		
Differences	-		
Optimal "all users" design	For the optimal "all users" design, VIP can be used for thermal insulation. However, there are other options for thermal insulation than VIP. Some are less expensive, but have less better insulation values with a higher thickness (PUR) and others which have good insulation values with slim thickness (Aerogel) and are as expensive as the VIP.		

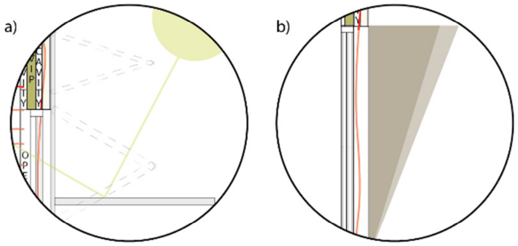
	Heating/Cooling		
Investment	€ €	€ €	€ € €
Similarities	Both the EF and SA designs regulate heating and cooling by pre-heating/pre-cooling the air within the cavity of the façade and redirecting it to the indoor environment by stack effect. If additional heating or cooling is necessary, the indoor environment is then regulated by low temperature heating/cooling systems.		
Differences	The FC design regulates heating and cooling with the use of the Next Active Façade system, integrated within the façade. Connected to the interactive state of the art technologies, the indoor environment self-adapts according to the users' behavior and can be controlled by the user at any moment in time by giving signs to the wall.		
Optimal "all users" design	For the optimal "all users" design, the pre-heating/pre-cooling of the air within the cavity of the façade and redirecting it to the indoor environment by stack effect can be used together with the the Next Active Façade system, integrated within the façade, for additional heating or cooling that can be used only when necessary, or by implementing low temperature heating/cooling systems.		
	Interior design		
Investment	€	€	€
Similarities	The EF, SA, and FC designs all have different type of interior design preferences.		
Differences	The EF Archetype prefers to have contact with nature in the indoor environment, while the SA Archetype prefers to have a space that matches the lifestyle, and the FC Archetype prefers privacy and the freedom to adapt the indoor environment at any time.		
Optimal "all users" design	Due to the fact that every type of user has different interior design preferences, for the optimal "all users" design it is advised to give the user the possibility to adapt the indoor space to their own preference and taste. This refers to office design and layout (desk location and furniture), color use in offices, and contact with nature (indoor plants, biomimicry, biophilic).		

Optimal "all users" design

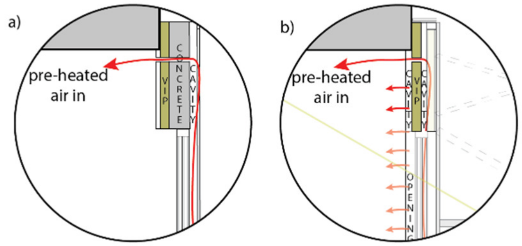
This research shows what are the relevant factors to take into account when designing a façade in order to ensure user satisfaction while also designing a façade that can help its building become nearly energy neutral. For the optimal "all users" design, it is important to follow the design criteria of user comfort, user control, energy efficiency, and user preferences. For user preferences, the preferences mentioned in table 27 for the optimal "all users" design can be taken into account. Another method would be doing a review of the preferences of all of the possible existing Archetypes and analyzing and evaluating these and making a selection depending on the type of office building being created/renovated. With the right criteria being set, the design of the façade can be done by looking for solutions for the "all users" preferences within state of the art technologies together with some traditional technologies. It would be ideal to start with the design looking for solutions within passive measures and when necessary implementing active technologies. It is very important to test the design from the beginning in order to determine if the design meets up with the set up criteria of user satisfaction and energy efficiency. In this phase, the design can be continuously optimized in order for it to meet up with the expectations. At the end of this evaluation phase, the design can be further developed into a final design. Following these steps for the design of the office-user oriented façade for "all users" will ensure user satisfaction for different types of users and will help its building become nearly energy neutral. Regarding the possible investment costs of realizing such a façade, it can be said that not all of the technologies mentioned in table 27 for the optimal "all users" façade are that expensive. It is a combination of traditional technologies together with state of the art technologies, which can be expensive, but should repay themselves in a short period of time due to their high impact on the reduction of the energy demand of the office space. Figure 73 shows the possible variations for the optimal "all users" façade design according to the results of table 27.

Optimal "all users" facade design guideline

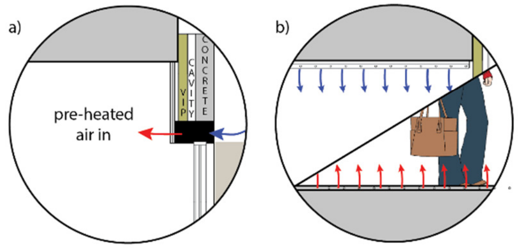
Shading feature:
Heat protection by solar controlled (a) or sun angled shading feature(s).



Ventilation through facade:
Supply of natural ventilation through facade to the indoor space by one opening (a) or by multiple openings (b).

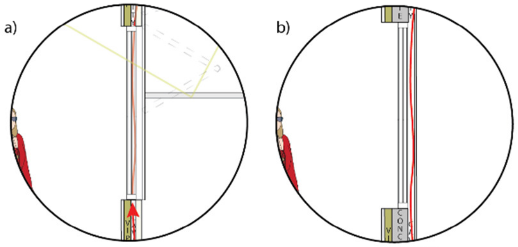


Additional ventilation + heating/cooling:
Supply of additional ventilation + heating/cooling, in case needed, by using the user controlled Next Active Facade system integrated in the facade (a) or by using low temperature heating/cooling systems (b) integrated in the floor and ceiling.



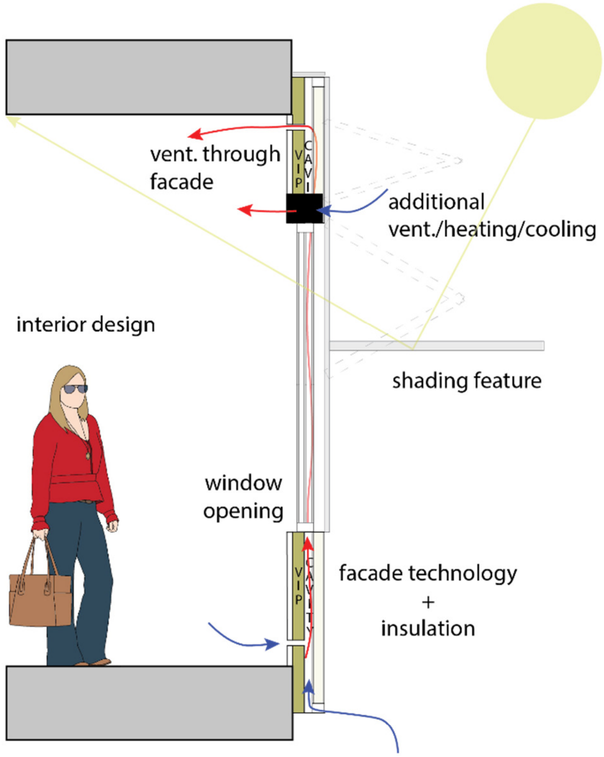
Interior design:
User freedom on adapting the indoor space to user's preference and taste, because of the different interior design preferences of every type of user (a/b/c).

WWR:
WWR percentage depending on orientation (a), taking into consideration most of the users preferences linked to WWR (b), such as outside view, privacy, and so on, and finding the right balance between the preferable amount of WWR per orientation and the user preferences linked to WWR.

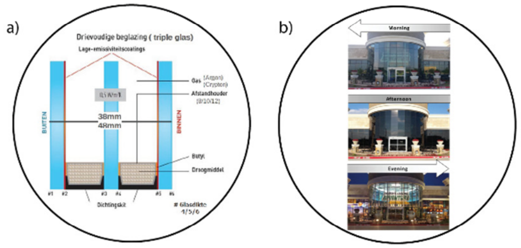


e.g.
West 37-43%

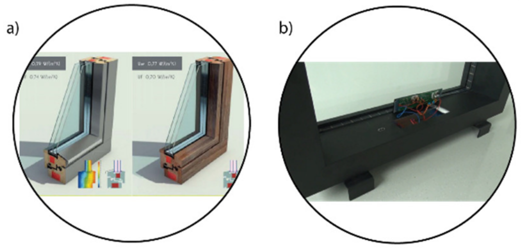
e.g.
West >43%
due to user preferences



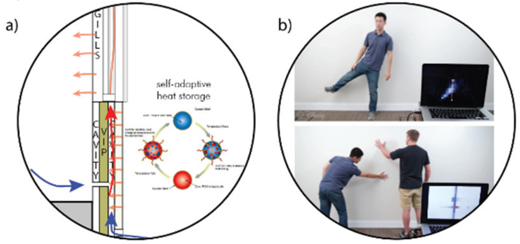
Window glazing:
For heat gain/heat loss through window openings, triple glazing (a) can be used when the window has a solar controlled or sun angled shading feature. If this is not the case, then a thermochromic triple glazing (b) window is the best option or the user controlled option of electrochromic glazing.



Window frame:
For window frame, passive (insulative) window frames (a) can be used or the option of electricity producing window frames (e.g. Physee SmartWindow) (b).



Facade technology:
For the optimal "all users" design, the Trombe wall method of the SA design with adaptive heat storage (a) can be used together with the user control technologies of the FC design (b). In this way the indoor environment would self-adapt according to the outdoor conditions and to the users' preferences at any moment in time.



Facade insulation:
For facade thermal insulation, the Vacuum Insulated Panel (VIP) is a high performing thermal insulation (a) (λ=0,006 W/m·K) with slim thickness giving the users more office area. Another very good thermal insulation is the Aerogel (silica) nano-insulation (b) (λ=0,013 W/m·K).

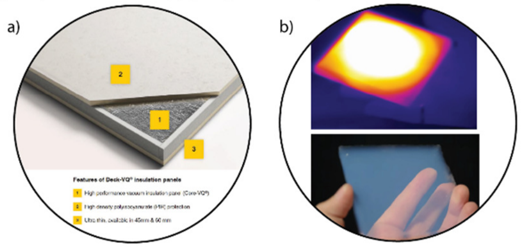


Figure 73: possible variations for the optimal "all users" façade design. Image by author.

6.2 Implications

The results of the office-user oriented interactive/adaptive façade design affirms, adds to, and also challenges some of the findings of previous studies mentioned in chapter 2, literature study.

The literature states some influential office design factors which can ensure employees' satisfaction. For façade design these are the amount of WWR depending on the orientation of the façade (Kwon, Remøy, & van den Bogaard, 2019). Each of the archetypes' designs have different percentages of window-to-wall-ratio (WWR). These were chosen based on the design preferences of each archetype and on information found in literature. For example, due to the fact that the Energy Efficient archetype has outside view as an important user preference, a bit more than the maximum preferable WWR for the orientation of the façade was used for the design. Due to the fact that the Full Control archetype has own privacy as an important user preference, the minimum amount of preferable WWR for the orientation of the façade was used for the design. The Self-Adaptive archetype did not have specific preferences that could be linked to the WWR of the façade, but because having sufficient view to the outside was mentioned as a very important preference in the interview with the office user of the case study, for this design the maximum preferable WWR for the orientation of the façade was used.

The amount of WWR is directly linked to user satisfaction, because this has a high influence on the amount of daylight to the indoors, on the heat gain/loss through the window, and on the outside view. Besides user satisfaction, WWR is also directly linked to the energy demand of the space. Looking at the results of the evaluation of the designs of this research, it can be seen that the energy demand of the designs ranged from high to low for the designs which have a high WWR to a low WWR. This affirms the findings of the study of Goia (2016) which states that an optimal WWR per orientation in office buildings has high implications on the total energy saving potential and that the optimal WWR value is the one that minimizes, on an annual basis, the sum of the energy used for heating, cooling and lighting. Looking at the designs and the results, it can be said that all of them provide sufficient view to the outside, sufficient daylight to the inside, and show energy savings that can help the building become nearly energy neutral. Therefore, the optimal WWR for the orientation of these designs indeed lies between 37%-43%, as mentioned in Goia's (2016) study.

An interesting fact of the results of the archetypes' designs is that the Energy Efficient archetype seems to be the least energy efficient of all the designs. This can be due to the users' preferences, but also possibly because the system does not self-adapt according to the current climate conditions and to user presence and/or because the users do not have control of their indoor environment meaning that more energy is being used in total. This shows that having and indoor environment that self-adapts and where the users have control over their environment at all times, could be more beneficial in terms of energy use. These results challenges the findings of the study of Dr. Ortiz's (2019), where it is stated that the Energy Efficient archetype (Restrained Conventionals in his study) is ranked as the second most energy saver supposedly saving more energy than the Self-Adaptive archetype (Vulnerable Pessimists in his study) and the Full-Control archetype (Sensitive Wasters in his study).

Overall this study sheds some light into what does it mean to design a façade for specific types of users and how could an optimal "all users" façade look like and function in order to suffice office users needs of comfort and to help its building become nearly energy neutral. It adds relevant information on office-user oriented façade design guidelines and tries to bridge the gap between façade design, office users satisfaction factors, and state of the art interactive/adaptive technologies, which adapts according to users satisfaction factors and to outdoor conditions, while also being as energy efficient as possible in order for the façade to help the building become nearly energy neutral.

6.3 Limitations

Through the course of this research, several limitations were encountered. For the literature, the restrictions faced were on the availability of substantial information on some of the interactive/adaptive technologies, due to the fact that these were still in their experimental phase. Therefore, these were disregarded from the research. For the evaluation, the restrictions faced were the simulation possibilities of the chosen evaluation software, DesignBuilder. Some of the design configurations were too complex for the simulation software and therefore some of the key components of these design configurations could not be taken into account in the results of the simulations. In addition, the current COVID-19 pandemic made it not possible to measure the current indoor conditions of the case study's offices in order to establish the comfort levels and in this way conclude on whether the design configurations really do perform better than the current situation. Nevertheless, due to the one user experience interview that was still possible to be completed, it was concluded that the current indoor conditions are experienced as being poor and unacceptable. In this way, it was concluded that all of the design configurations provided a better indoor condition than the current situation. For the evaluation of the energy performance, the results of the simulations were translated into BENG values and in this way the design configurations were evaluated. Initially, it was intended to use the new BENG calculation tool called the NTA 8800, but unfortunately this was not available during the time that the evaluation took place. Nevertheless, due to the fact that the results of the simulations were translated to BENG values, it was concluded that all of the design configurations meet up with these values and can be considered as being nearly energy neutral.

The current COVID-19 pandemic also prohibited the opportunity to evaluate the design configurations based on the case study's current office users preferences. This would have taken place in a workshop/interview form were the office users were going to experience the design configurations in Virtual Reality and in this way express their preferences for a specific design configuration. With this approach, one design configuration was going to be chosen for this research's final design. Therefore, this research now concludes on three possible design configurations for specific types of users and on a possible optimal "all users" façade design guideline based on the most relevant characteristics of the presented design configurations. These façade design configurations and guideline should help increase user satisfaction and therefore work productivity and also help its building become nearly energy neutral. In order to establish which design configuration would be the preferred one by the current office users, the workshop/interview with the office users could be done as further research.

This research refers to office buildings and is designed taking the case study's current situation. Nevertheless, it is believed that the design configurations can be implemented in other office buildings as well as other types of buildings.

Chapter 7 – Conclusions

This chapter concludes on the research and gives an answer to the main research question stated in the research framework. It also gives advice on possible further research.

7.1 Conclusions

The aim of this research was to investigate the relevant factors of user satisfaction that could be implemented into façade design, while also investigating state of the art interactive/adaptive façade technologies (passive and active) and energy efficient façade design methods, in order to provide design solutions which optimally satisfies office users needs of comfort, and therefore increases work productivity, and also supports nearly energy neutrality of office buildings. Based on the research objectives, the research question was formulated. This was divided into categories followed by sub-questions in order to assess the problem as thorough as possible. Therefore, the main question will be answered in this way.

User satisfaction – *"How does employees' surroundings affect office users' work productivity, which are the user satisfaction factors that can affect work productivity, and what are the comfortable limit values of these factors?"*

1. What is the impact of the employees' surroundings on their work productivity?

The literature study shows that physical conditions, such as temperature and office appliances, and also psychological conditions, such as privacy, territoriality, and communication within an employees' work environment, can affect work productivity. Poor quality of these conditions can lead to an unhealthy work environment which ultimately can lead to health problems, such as stress and anxiety. Among other things, stress at work is related to substantial economic consequences, including absenteeism, increased worker turnover, decreased employees satisfaction and therefore decrease in work productivity. Due to the fact that physical factors of the work environment, such as temperature, air quality, lighting, and noise, have been linked to office users' satisfaction, this means that these factors are directly implicated in the effects of work induced stress on health. Examples of employees' work environment are office aesthetics, such as desk location, furniture, color use, contact with nature, and designing with nature as inspiration (biomimicry).

2. Which factors affect users' satisfaction and therefore work productivity?

User satisfaction can be affected by thermal comfort, indoor air quality, intelligible speech, visual comfort, user control, and office & building aesthetics. According to the literature study, there are some influential office design factors which can ensure employees satisfaction. These are spatial office design, such as layout and position of workplaces, and façade design, such as window-to-wall ratio (WWR) and orientation, which are the ones who have the most influence on user satisfaction and therefore work productivity.

3. What are the comfortable limit values for user satisfaction?

The comfortable limit values consists of values regarding temperature, indoor air quality, and daylight & artificial light levels. For cellular offices without mechanical cooling systems, the comfortable limit values of indoor temperature, lies between 20–24°C for the winter season and between 23-26°C for the summer season. For indoor air quality, the minimal airflow per person is of 7 l/s with ventilation rates of 0,35 l/s/m^2 for very low polluting spaces with the use of very low polluting finishing building materials (low VOC's), and an advised relative humidity between 30%-70%. For daylight, the minimum allowable levels are at least an equivalent daylight area of 2,5% of the whole office area with a minumum absolute equivilant daylight area of 0,5 m^2. For artificial lighting, this means a maintained illuminance of 500 lux.

Façade design – *"How to design a façade, what are passive and active design measures, and how and which of the users satisfaction factors can be implemented into façade design?"*

4. How to design a façade according to The New Stepped Strategy?

The translation of The New Stepped Strategy to façade design consists of the same methods. First, multiple designs for the façade can be developed according to different orientations, taking the local climate into account. Also, selecting materials and systems for the thermal and visual comfort of the façade which helps it reduce the heat losses and increase heat gains respectively in order to reduce the energy demand, while also incorporating user control into these systems and selecting materials which help with maintaining comfortable noise levels (step 1). Second, incorporating systems and technologies which helps re-use waste streams, such as heat recovery of the indoor air (step 2). Third, using the façade's surface for sufficient energy production in order for the façade to help the building become nearly energy neutral (step 3).

5. What are passive and active design measures?

Passive façade design consists of reducing the energy demand of a façade. This can be done by taking consideration of the local climate and environmental elements, building layout, and material properties. Some passive measures can also help re-use heating. There are three mayor functions that play a key role on the passive design of a façade, which are heat protection, heat gain from the sun, and heat rejection.

Active measures are introduced when the passive design measures alone cannot completely eliminate the total energy demand of a façade. These active measures consists of design measures for heat generation, heat dissipation, and electricity and are related to the use (systems) and generation of heat and electricity and the re-use of heating and cooling. Also, the use of smart technologies (automated computer-based controls) falls in this category.

6. Which of the factors that affect user satisfaction can be implemented into façade design and how can this be done?

The factors affecting user satisfaction that can be implemented into façade design are window-to-wall ratio, orientation, office aesthetics, thermal comfort, visual comfort, user control, and energy. There are no passive or active measures that could be implemented in a façade which benefits the user satisfaction factor of colors. This is the same for intelligible speech. These two factors can still be implemented in the façade design, but will not have any effect on the reduce, re-use, and produce measures of the new stepped strategy.

The implementation of the user satisfaction factors into façade design can be done through state of the art interactive/adaptive technologies in order to optimally satisfy users' needs of comfort.

Interactive/adaptive technologies – *"Which state of the art interactive/adaptive projects and technologies (passive and active) are of relevance for this research and how can these technologies be integrated into a façade along with the user satisfaction factors?"*

7. What are the state of the art passive and active façade technologies and what are their challenges and potentials?

During this research, an extensive amount of state of the art passive and active façade technologies were investigated an evaluated on their comfort levels, user control possibilities, office aesthetics, and energy performance. These range from interactive/adaptive buildings and research projects to materials, methods and systems. The most relevant projects used in this research are the AdaptiWall (the concept), BRESAER (some components), and Double Face 2.0 (the concept). Regarding materials, methods and systems, the most relevant used in this research are Salt hydrated Phase Change Materials (PCM) and Trombe wall method as thermal storage, Vacuum Insulated Panel (VIP) insulation with exceptional thermal conductivity, aerogel based plaster with very good thermal conductivity, solar controlled shading with integrated PV-panels and daylight expansion, SolarWall & NightSolar for thermal energy production, color changing and transparent PV-panels for electricity production, triple glazing with Thermochromic and Electrochromic coatings, NEXT Active Façade as building integrated services, Living glass for ventilation with human detection, and Wall++ for adapting the indoor environment due to human presence, behavior, and patterns.

These projects and technologies make it possible to design state of the art façades that comply with the user satisfaction factors and are energy efficient.

8. How to integrate users satisfaction factors into a façade along with passive and active technologies?

The integration of the user satisfaction factors within a façade along with interactive/adaptive technologies can happen in static layers, in dynamic features (moving parts), or an integration of both static layers and dynamic features. Besides using passive and active measures, also the use of intelligent technologies, such as sensors and data analysis, can be used in order for the actuators to respond to the current needs of the users.

Energy – *"How can an energy efficient façade be designed in order to help a building achieve nearly energy neutrality?"*

9. How can a façade support the energy neutrality of office buildings?

Façades can support the energy neutrality of office building by being energy efficient and in this way helping reduce the energy demand more than what is required. For example, by applying materials and systems which help achieve a higher Rc-value for opaque parts and a lower U-value for translucent parts than what is normally required. Also, the façades' surface can be used for the production of energy, by either producing thermal heat or electricity. In addition, façades can be designed by taking the BENG values into account. These measures would help with the overall energy reduction of office buildings.

10. How to design an energy efficient office façade?

For the design of an energy efficient façade, the local climate conditions that the façade is going to be exposed to, need to be taken into account. These are the fluctuations of outdoor temperatures, the amount of sun hours and sun intensity on the façade, the angle of the sun during different seasons, and the wind direction, amount and speed. Also, the façade's orientation is important, the mass of the façade to solar position, the WWR depending on the climate type and orientation, the protection of façades from direct solar radiation (shading) during warm seasons, the collection of solar heat through the façade during cold seasons, storing the collected heat in the façade's mass, providing natural ventilation as cooling through the façade, and providing sufficient natural light to the inside by either having sufficient glazing area or using light shelves to redirect light to the indoor spaces. It is also important to understand the building which the façade is being designed for and the occupancy patterns in order to know what the users would need during this time and what the façade should therefore provide.

Design, validation, and evaluation – *"Which criteria fits for the purpose of this research, how to have multiple façade designs which influence the facades' performance and user satisfaction, and which of the design configurations is the most suitable to be further developed in this research?"*

11. What is the most relevant criteria for the design in order for the façade to fit the purpose of this research?

For this research, the most relevant design criteria for the office-user oriented façade are user comfort, user control, user preferences, and energy efficiency. User preferences is the most subjective criteria and therefore should be handled separately when designing a façade. For a successful façade design, it is always important to take into consideration whom you are designing it for. For offices this is difficult due to employees turnover. Even so, it should be taken into consideration. Literature shows multiple archetypes regarding user preferences. For the development of the design configurations of this research's office-user oriented façade, the user preferences of the archetypes Energy Efficient, Self-Adaptive, and Full Control were taken into account.

It is also important to make a distinction between technologies which fit the best to the specific design principles of an archetype. Therefore, a generic façade design guideline was generated. This shows the relation of the technologies to the archetypes' design principles and are scored on their possible applicability. Taken these criteria into consideration, the façade designs will fit the purpose of this research.

12. How do different design configurations influence the performance of the facade and the satisfaction of the office users?

For the Energy Efficient, Self-Adaptive, and Full Control archetypes, one static and one dynamic design configuration were made in order to assess their comfort and performance. The research shows that each façade component has a different effect on the performance of the façade and the users' comfort. Therefore, the components chosen do not only meet up with the design principles, but also go well together and positively influence each other. Some of the façade components chosen are applicable for multiple purposes, such as the solar controlled dynamic shading feature with PV-panels on top in the dynamic design configuration of the Self-Adaptive archetype. This component not only provides heat protection, but also produces energy and helps bounce daylight to the inside. Other examples are the static and dynamic designs of the Energy Efficient archetype, which are the transparent PV-Trombe wall and the SolarWall. Both, use the heat produced by the PV-panels for the pre-heating of the incoming air, helping the PV-panels to not overheat and in this way increasing their efficiency.

The evaluation of the design configurations showed that the higher the user comfort, the higher the energy demand. Also, that the design principles have a significant impact on the energy demand of the designs. The results of the evaluation showed that the design configurations of the Energy Efficient archetype have a higher energy demand than the designs of the Self-Adaptive and Full Control archetype. This is because the design principles of this archetype are directly related to the energy performance of the façade. Even so, the performance of all of the design configurations are well within the range of nearly energy neutral.

It is possible that a combination of the static and dynamic designs of each archetype could give a better performance and user comfort. It is also possible that having one design that provides enough comfort, has a good performance, and also suffice all of the three archetypes preferences, could enhance the users' satisfaction even more.

13. Which design configuration meets up with the user satisfaction limit values, preferences, and does it help support nearly energy neutrality?

The design configuration which meets up with all of the set requirements is the transparent PV-Trombe wall for the Energy Efficient archetype, the PCM-Living wall for the Self-Adaptive archetype, and the Interactive Wall++ for the

Full Control archetype. These designs provide comfortable indoor temperatures during all seasons, sufficient amount of daylight, and show significantly great values in order to be considered nearly energy neutral.

Due to the fact that every type of user has different preferences, it is almost impossible to have one interactive/adaptive façade design that complies with all of the user preferences of all types of users. The previously mentioned design configurations are only focused on the user preferences of these three types of users, assuming that all of the employees within the office space are the same archetype and therefore have the same user preferences, which in reality is not always the case. However, it is possible to make a design combining the most important characteristics of the previously mentioned design configurations that have a high influence on the indoor comfort and on the energy performance of the office space. In this way, a façade can be designed which can comply and serve all of the type of user's preferences, to some extent, while also providing a comfortable indoor environment and helping its building become nearly energy neutral.

The combination of characteristics for the user preferences of the optimal "all users" façade design is done by analyzing the similarities and differences between the characteristics of the design configurations of the Energy Efficient, Self-Adaptive, and Full Control archetypes, per façade component, and reflecting on the impact of these characteristics on the user satisfaction and energy demand of the office space. Taking these user preferences for the optimal "all users" design or making a review of the preferences of all of the possible archetypes that can be encountered in the type of office building being created/renovated and analyzing them, evaluating them, and making a selection between these, can provide an office-user oriented façade for "all users" that will ensure user satisfaction for different types of users and will help its building become nearly energy neutral.

Main research question

"How can an interactive/adaptive office building façade element be designed to optimally satisfy its users in order to increase work productivity and to support nearly energy neutrality of office buildings?"

The research shows that an interactive/adaptive office building façade element that optimally satisfies its users, in order to increase work productivity, and also supports its building to become nearly energy neutral, can be design by investigating and understanding what affects work productivity, what enhances user satisfaction and what are the comfortable limit values according to literature. Also, by analyzing how to design a façade taking passive and active measures into account, and by analyzing how to implement user satisfaction factors within the façade design. Furthermore, by analyzing state of the art interactive/adaptive technologies (projects, materials, and systems) on their possible applicability for this research's façade design and also by analyzing how to implement user satisfaction factors within these technologies. In addition, by understanding how to design an energy efficient office façade and what does it mean for a façade to be nearly energy neutral in terms of values.

Based on all of this information, design considerations were stipulated, which consists of the design criteria. One of the most important design criteria, and one which was very leading for this research, were the user preferences of the archetypes, which refer to different design principles. Besides the user comfort design principles, these archetypes' design principles, highly impacted the results of the design configurations.

The recommended design configurations for each archetype were obtained by following a generic façade guideline which shows which passive and active, static and dynamic, technologies per façade component fit the best per archetype design. First, solutions within passive measures were investigated and then, where passive measures were not possible or did not fit the criteria, active measures were applied. These technologies were also evaluated on their advantages and disadvantages regarding user satisfaction and energy performance. In addition, for the evaluation, these design configurations were implemented into a case study which is the Applied Physics Building on the TU Delft's Campus. This is a building within the Campus which is in serious need for a renovation and which's façade does not perform according to the current requirements. Also, by means of an interview regarding user experience, one of the office user of this building described the comfort levels of the indoor environment as being more than unacceptable.

During the evaluation, a continuous iteration between the design configurations, the climate and energy calculations, and the results of the simulations, existed. The designs were therefore continuously optimized in order to meet up with the design requirements. After concluding with the evaluation, the results of design configurations were weighted against each other on their comfort level and energy performance and in this way, the best design per archetype was chosen.

In conclusion, this research shows different possible design configurations for three different types of users which can help increase user satisfaction and therefore work productivity, and also help its building become nearly energy neutral. With the generic façade guideline, the research has shown a path that can be followed in order to make a façade design for specific type of people while also taking user satisfaction and energy performance into account. Due to the fact that multiple types of users can be encountered in an office space and that every type of user has different preferences, it is almost impossible to have one interactive/adaptive façade design that complies with all of the user preferences of all types of users. However, it is possible to make a design combining the most important characteristics of the previously mentioned design configurations that have a high influence on the indoor comfort and on the energy performance of the office space. With this combination of similar façade component characteristics, an optimal “all users” façade can be designed. Another possibility is by reviewing the preferences of all of the possible archetypes that can be encountered in the type of office building being created/renovated and analyzing them, evaluating them, and making a selection between these. This would provide an office-user oriented façade for “all users” that will ensure user satisfaction for different types of users and will help its building become nearly energy neutral.

7.2 Further research on office-user oriented façade design

As mentioned in the limitations paragraph, that due to the current COVID-19 pandemic, the indoor conditions of the case study's offices could not be measured in order to establish the comfort levels and in this way conclude on whether the design configurations really do perform better than the current situation. Also, the evaluation of the design configurations on whether they can really be considered as nearly energy neutral could not be performed with the new BENG calculation tool called the NTA 8800, due to the fact that this was still not available during the time that the evaluation took place. In addition, the evaluation of the design configurations based on the case study's current office users preferences could not be performed in a workshop/interview form in order to establish which of the design configurations is the one preferred by the current office users. Because of this, this research now concludes on three possible design configurations for specific types of users and on a possible optimal "all users" façade design guideline based on the most relevant characteristics of the presented design configurations. These façade design configurations and guideline should help increase user satisfaction and therefore work productivity and also can help its building become nearly energy neutral. Therefore, the measurements of the current indoor conditions for the evaluation, the calculation of the design configurations with the NTA 8800 software, and the workshop/interview with the current office users for the preferred design configuration, could be done as further research.

As mentioned in the conclusions paragraph, it is possible that a combination of the static and dynamic designs of each Archetype, could give a better energy performance and user satisfaction. It is also possible that having one design that provides enough comfort, has a good performance, and also suffice all of the three Archetypes' preferences, could enhance the users' satisfaction even more. Therefore, further research on this could also be done.

Regarding the formed generic façade guideline, further research could be done on how the decisions made using this guideline for the designs, measure to the results of the design configurations. This could help establish other possible optimizations and combinations between static and dynamic designs for each archetype.

Chapter 8 – Reflection

This chapter reflects on the research process, its societal impact, and the personal reflection of the author.

8.1 Graduation process

Position of graduation topic within the graduation studio

Due to the current gap between façade design, office users satisfaction factors, and state of the art interactive/adaptive technologies, this research focuses on the designing of an interactive/adaptive office façade which adapts according to users satisfaction factors and to outdoor conditions, while also being as energy efficient as possible in order for the façade to help the building become nearly energy neutral. This topic fits perfectly within the tracks Climate design and Façade design of the graduation studio. Regarding Climate design, this research focuses on the indoor conditions office users are exposed to. More specifically, on their thermal comfort, visual comfort, and overall quality of the indoor space. Also, this research highlights different approaches on how to meet up with the future climate and sustainable goals, such as the nearly energy neutrality of buildings. Regarding Façade design, this research focuses on translating the users' needs of comfort into façade design and shows ways on how to integrate these in different façade designs, along with interactive/adaptive technologies, while also being energy efficient. This research also shows a guideline on how to design office-user oriented and energy efficient façades for specific types of users and concludes on how to design the best possible optimal "all users" façade that will ensure user satisfaction for different types of users and will help its building become nearly energy neutral. These designs and guidelines are applicable for the retrofitting of buildings and also for new buildings.

Regarding the position of the graduation topic within the MSc Building Technology track, this graduation topic highlights all the key features that form this track. This research's topic, office-user oriented façade design, emphasizes on designing innovative, future orientated, and sustainable building components (façades) that are integrated into the built environment. It tackles the integration of architectural designs with technical disciplines using advanced digital designing and evaluating tools. It shows the contribution to buildings to make them more sustainable, comfortable, and environmentally intelligent.

Evaluation of the research methodology and aimed results

The research methodology for the development of the office-user oriented façade design, highly influenced the obtained results. Even though the current COVID-19 pandemic made it not possible to fully follow the research methodology as initially intended, this was adapted as much as possible in order to obtain reliable and justifiable results.

The research methodology consists of four phases, namely, the literature study phase, the research through design phase, the validation phase, and the finalization phase. Even though all of the phases influenced the results, the phase that influenced the results the most, was the research through design phase. Using a generic façade guideline, multiple design configurations were made. The technologies presented within this generic façade guideline have the most influence on the presented designs. It is possible that making the designs using another guideline, could have presented different results. Nevertheless, the results presented highlight the key features of this research and shows the incorporation of user satisfaction factors, along with interactive/adaptive technologies integrated in energy efficient façade designs. The evaluation part of this phase also had a great impact on the results presented, because this influenced the choice for the three design configurations which were ultimately selected. Even so, it is believed that choosing another evaluation method than evaluating the results through simulations and calculations, still would have led to the same design configurations being selected. The most affected phases by the current COVID-19 pandemic, were the validation and finalization phases. For these phases, it was initially intended to validate the design configurations in a workshop/interview form were the office users of the selected case study were going to experience the design configurations in Virtual Reality and in this way express their preferences for a specific design configuration. With this approach, one design configuration was going to be chosen for the finalization of this research. Therefore, this research now concludes on three possible design configurations for specific types of users, instead of only one preferred design, and on a possible optimal "all users" façade design guideline based on the most relevant characteristics of the presented design configurations.

Even though the initial research methodology was afflicted by the current COVID-19 pandemic and therefore the aimed results could not be fully achieved, the adapted research methodology provided the research with substantially good design results.

Relation of research and design

For the development of the designs of this research, the research through design method was applied. This method reflects on designing by understanding the current state of façade designs based on gathered information, and reflecting on this by the means of generating new knowledge and suggesting improved states for façade designs. These are façade designs that provide optimal user satisfaction with the use of interactive/adaptive technologies and which are energy efficient in order to help its building become nearly energy neutral. This research method allows for continuous iteration between evaluation and design in order to ultimately present optimal designs.

This method helped with identifying the current issues within office user satisfaction and its relation to façade design, the potentials of state of the art technologies for façade design, and the implementation of these within an energy efficient façade that should help its building achieve nearly energy neutrality.

8.2 Societal impact

Applicability of results in practice

The design configurations presented in this research were designed taking into account their feasibility on being applied in real conditions. Even though most of the technologies used for the design configurations are state of the art, they have already been either applied in a wide range or have been through their validation process and show good outcomes. The concept on how to do energy efficient façade design has already been known for quite some time and has been applied in many cases. Even though, designing for nearly energy neutrality is still somewhat in its transition phase, it also has been done on multiple occasions. Regarding user satisfaction, the relevance of designing for user satisfaction has become increasingly popular over the years with the introduction of smart systems. It is now in its stage of being applied in office buildings and show great interest. Although incorporating all of these factors within a façade can be complex, it is not impossible. The presented design configurations make use of concepts which can now be considered standard for their purpose and takes them to their next level in life by innovating them and implementing state of the art technologies.

Contribution of project to sustainable development and achievement of projected innovation

The results of this research helps with bridging the gap between façade design, office users satisfaction factors, and interactive/adaptive technologies. Furthermore, it provides multiple innovative façade designs by following a guideline of a wide range of state of the art technologies linked to Archetypes, that makes it possible to design a façade for specific type of users while also being energy efficient and helping its building become nearly energy neutral. The optimal “all users” façade design guideline makes it possible to design the best possible façade for “all types of users” using the most relevant characteristics of the proposed user specific façade designs.

Impact of project on sustainability - people, planet, profit

Regarding sustainable impact on people, this research proposes solutions for façade design in order to enhance user satisfaction with façades that are designed for a specific type of user and also proposes a design guideline for an optimal “all users” façade design . User satisfaction consists of comfort and health. An unsatisfied user will miss work more often than usual, take longer than usual to finish the tasks assigned, and will complain constantly about their environment affecting the satisfaction of other users. Poor quality of indoor conditions can lead to an unhealthy work environment which ultimately can lead to health problems, such as stress and anxiety. Research has suggested that stress at work is a major public health risk due to the fact that it is associated with cardiovascular morbidity and with substantial economic consequences, including absenteeism, increased worker turnover, decreased employees satisfaction and has associated decreases in worker productivity. Therefore, it is essential to provide a comfortable and healthy place of work. The solutions presented in this research can help increase user satisfaction and therefore work productivity and can help provide a healthy environment for users.

Regarding sustainable impact on the planet, the presented façade design configurations are designed in an energy efficient manner in order to help decrease the energy consumption in office buildings. The building sector in Europe is responsible for an energy consumption of 40% of Europe's final energy use, where office buildings consume 26% of this amount. High energy use means high carbon emissions and dependence on fossil fuels. Therefore, it is crucial to find solutions within the buildings' envelope in order to help decrease or completely remove this amount. The façade is one of the buildings' components which is responsible for this high energy use. By designing façades which are not only energy efficient, but that also helps its building become nearly energy neutral, can definitely decrease the high energy use in buildings and also helps decrease carbon emissions and dependence on fossil fuels.

Regarding sustainable impact on profit, by applying façades which are energy efficient and help its building become nearly energy neutral, the energy consumption of buildings decreases, saving money. By applying façades which helps increase the indoor conditions office users are exposed to, user satisfaction will therefore increase, increasing work productivity and providing a healthy environment to users. In such an environment, users will miss work less than usual and their health, regarding indoor conditions, can be guaranteed. Healthy people also means less health care issues, which ultimately saves money.

Social-cultural and ethical impact

Some of the presented solutions require the collection of data of the office users' indoor behavior in order to establish a pattern for self-adaptivity of the indoor conditions. This can raise the issue of privacy and confidentiality of office users. Even though the gathered data would only be used in order to provide a better indoor environment, some people do not like the idea of their behavior being constantly monitored and recorded. Therefore, this should always happen taking the wishes of the users into consideration.

8.3 Personal reflection

The topic of this research was chosen due to my affinity to climate design and interest in indoor environmental quality and façade design. Also, due to the fact that I have experienced indoor discomfort on multiple occasions in in the offices of my previous employments. Most of the times, the offices I worked in where open plan offices and I was always the one who found the indoor environment to be cold. The only solution that I had was putting on a sweater. This provided me with comfort, but I did not find it to be an optimal solution, because it still affected my concentration. Therefore, for my graduation thesis, I wanted to focus on user satisfaction within office buildings by using the façade as the main comfort provider.

From the beginning I have enjoyed the process of working on the graduation studio. I liked working on the research framework and methodology and gathering information for the literature study. This shed light on the issue of office user discomfort and highlighted the main causes. Also, it provided information on the possibilities of providing user satisfaction within a façade using state of the art interactive/adaptive technologies. It was interesting to get to know so many projects and technologies and it impressed me that even though some of these technologies were not that new, they were not all largely known or largely being implemented. The challenge arrived when it was time to put all of the literature into designs. For me this was a big challenge, due to the fact that I do not possess much experience in designing, and for this thesis, I had to develop at least six designs. In order to be able to do this, I followed the methodology, as supposed, and tried to find the right balance between the methodology and my own personal interests. In the beginning, this was still difficult to do, but in moments of desperation, I always went back to the methodology and research question and this helped me to get to the designs. Finally, I could enjoy the designing process and I was able to come up with the six designs which meet up with the requirements. After this, it was time to start performing the evaluation of the designs in order to establish their comfort and energy performance. I knew that this would also be a challenge, but I was looking forward to do this. This seemed to be more challenging than expected, due to the complexity of the designs and the possibilities within the chosen simulation software. Therefore, the simulations took more time than planned to perform. The current COVID-19 pandemic also made it difficult to reach experts in the manner we are normally used to. It was difficult to establish communication and it was also difficult to clarify some uncertainties through the virtual channels. Nevertheless, the simulations were successfully conducted and the results of the performance of the design configurations were analyzed. Based on their comfort and energy performance, the best designs per Archetype were chosen. As already mentioned, it was the intention to choose the best design configuration by interviewing the current office users of the case study in a workshop/interview where the users were going to experience the design configurations in Virtual Reality and give their preference for a certain design. I was looking forward to do this and to listen to what the current users thought about the designs and to get their feedback. Sadly, this had to be cancelled due to the current COVID-19 pandemic. Therefore, this research now concludes on three possible design configurations for specific types of users, instead of only one preferred design, and on a possible optimal “all users” façade design guideline based on the most relevant characteristics of the presented design configurations. The current situation changed the outcome of the research as was initially intended in the methodology. Nevertheless, it gives a good outcome on three possible façade designs for the specific type of users selected and on a design guideline for a possible optimal “all users” façade design which can ensure user satisfaction and can help its building become nearly energy neutral by the means of interactive/adaptive technologies.

Overall the graduation experience was a very enriching one, where I learned many things, from how to ensure office user satisfaction through façade design, to learning how to share my screen in skype.

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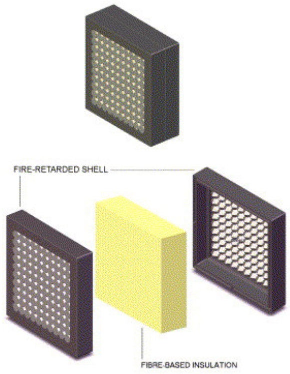
Appendix A – State of the art materials and systems

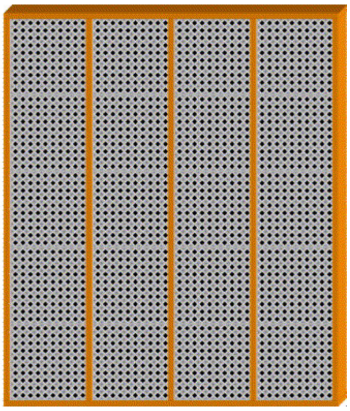
State of the art interactive/adaptive materials and systems – **Heat protection**

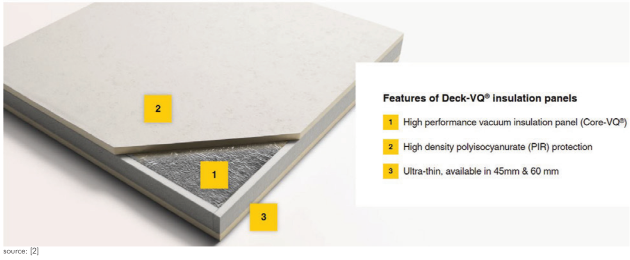
Dynamic insulation

Dynamic insulation, consist of a perforated encasing of insulation which allows for air through the facade picking up heat from the insulation fibres. It helps reducing the heat loss and provides pre-warmed, draught free air to the indoors. This makes the facade's U-value not constant anymore, but variable to the speed of the air allowing for an adaptable indoor environment.



source: [1]





Features of Deck-VQ® insulation panels

1 High performance vacuum insulation panel (Core-VQ®)

2 High density polyisocyanurate (PIR) protection

3 Ultra-thin, available in 45mm & 60 mm

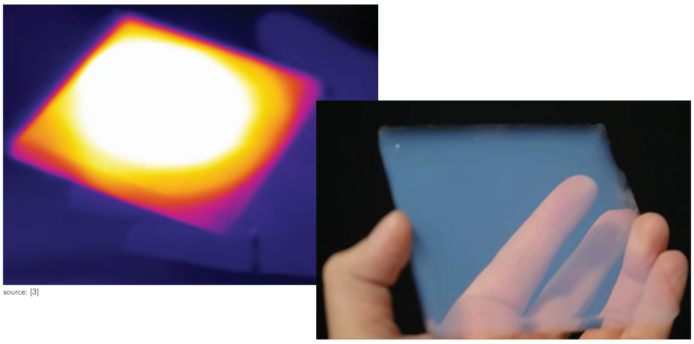
source: [2]

Vacuum Insulated Panels (VIP)

Vacuum insulated panels (VIP) is a high performing insulation that consists of a rigid silica core wrapped within a high barrier envelope where the air inside is complete vacuumed. It provides exceptional insulation values with slim thickness (λ=0,006 W/m·K) which allows for more indoor surface.

Aerogel insulation

Aerogel (silica) nano-insulation is an ultra-porous material which is full of air filled holes, despite being solid. They consist of over more than 90% of air. Because its a nano-material, it makes it difficult for heat to pass through. Thus, it makes them a very good insulation material. It can reach high insulation values (λ=0,013 W/m·K) with a slim thickness.



source: [3]

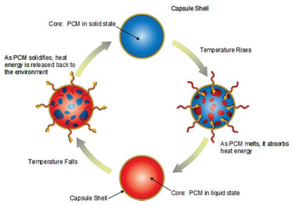
source: [4]

Aerogel based plaster

Aerogels can also be integrated in plasters. By mixing aerogel with natural plaster, the thermal conductivity of the plaster is enhanced. Research shows that by mixing the natural plaster with 90% of granular aerogel, the thermal conductivity can go from 0,50 W/m·K to 0,050 W/m·Km, decreasing the value by 10 times. If the volume of the granular aerogel is increased, values up to λ= 0,015 W/m·K can be achieved with a thickness of 30 mm.

Phase Change Material (PCM)

Phase Change Material (PCM) is a material which is able to absorb or release large quantiaties of 'latent' heat when going through the Phase Change, from liquid to solid and vice versa, and in this way providing heating/cooling. It can be used as a thermal storage within the facade or as extra insulation. It performs better than a standard concrete massive wall, because it constantly adapts to the conditions it is exposed to.



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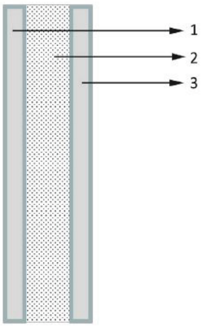
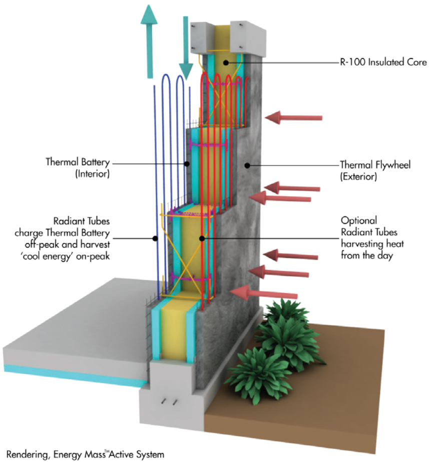


LAYER	DESCRIPTION
1	GLASS SHEET
2	PCM
3	GLASS SHEET

Energy Mass Wall (EMW)

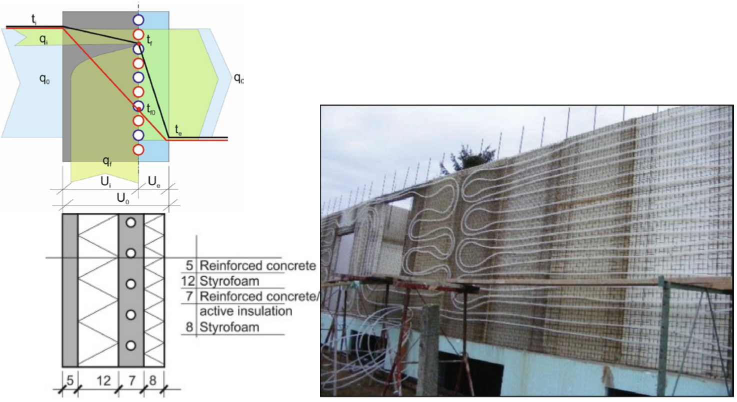
Energy Mass Wall (EMW) is a super insulated core filled with an expanding closed cell foam. This core becomes formwork for slim concrete skins, pneumatically placed on both sides. One or both of the shotcrete "skins" has embedded radiant tubing turning the entire wall into a radiantly active surface. The exterior concrete envelope dampens thermal flow into the building and the interior concrete envelope stores thermal energy that can be used when necessary (or vice versa in the winter).



Rendering, Energy Mass™Active System
source: [6]

Active thermal insulation

Active thermal insulation, reduces heat loss through external walls. Its a system of pipes inside the structure of an external building envelope in which a heating and cooling medium circulates, supplied with low temperature energy from the ground. Its not based on the direct transmission of low temperature energy to the room, but is related to the increase/decrease of temperature inside the external envelope. The basic principle of active insulation is that it uses the energy of the medium at a temperature lower than the temperature of the internal room, but at a higher than that of the outside air.



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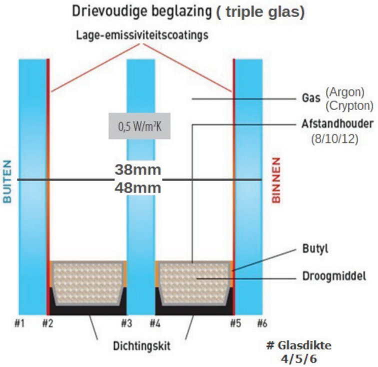


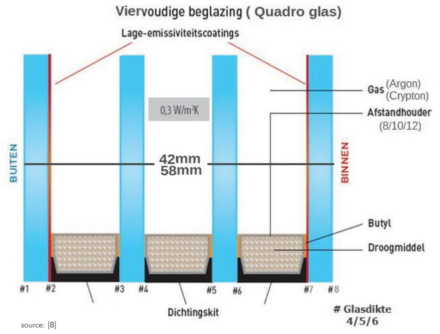
source: [8]

Triple glazing

HR+++ or triple glazing provides a high insulation value for transparent surfaces (Ugl=0,5 W/m2·K). It helps with indoor heat losses and outdoor heat gains. Its popularity is increasing due to the fact that it rapidly returns its investment. The insulation value depends on whether the cavities are filled either with air, argon gas, or krypton gas. The latter being the most insulative one.

Quadruple glazing

HR++++ or quadruple glazing provides an even higher insulation value for transparent surfaces (Ugl=0,3 W/m2·K) than triple glazing. The insulation value for this type of glazing also depends on whether the cavities are filled either with air, argon gas, or krypton gas. Because of the extra glazing an cavity, it is thicker than triple glazing, varying from 42mm to 58mm.



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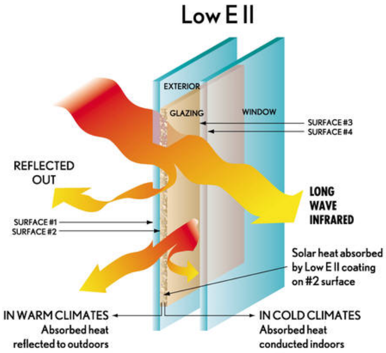


source: [9]

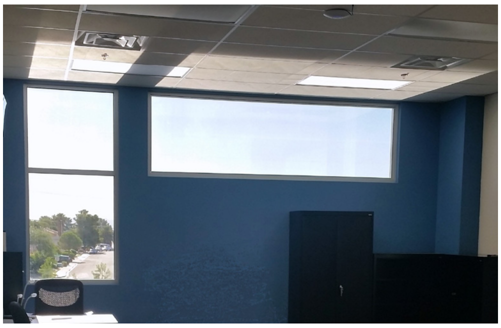
Low–e glazing

Low-emittance coating provides glazings with a reflective layer placed in the gap, which helps reflect solar heat during summer and traps radiant indoor heat during winter and in this way avoiding heat losses and heat gains.

Polaroid glazing

Polaroid glazing consists of a laminated glass with a film placed between the glass layers which consists of suspended particles of liquid crystals. When solar radiation hits the glass, the liquid crystals block the whole surface and the glass becomes opaque. When there is no solar radiation on the surface, the liquid crystals align allowing view to the outside. From the inside the window glazing looks darker than normal, but it still provides sufficient view to the outside.

source: [10]



source: [11]

Prismatic glazing

Prismatic glazing consists of a film which helps improve the daylight distribution to the indoor space helping reduce the demand for artificial lighting. From the inside the window glazing looks normal, distributing the light in a certain angle helping the dimmer parts of the indoor space to look brighter.

State of the art interactive/adaptive materials and systems – **Heat protection**

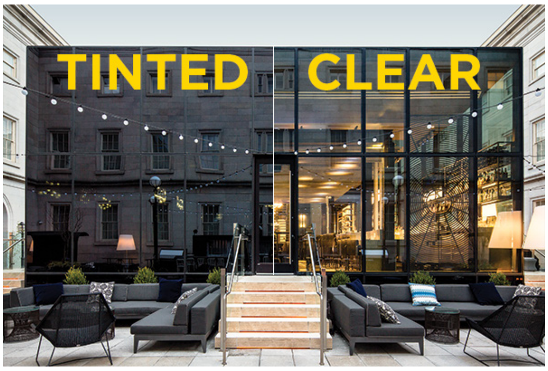
Thermochromic glazing – Photochromic glazing

Thermochromic and Photochromic glazing consists of a materials being extruded into polyvinyl butyral (PVB) laminated between tempered glass and placed into an insulative glass unit with low emissivity coating. It changes from translucent to opaque due to infrared rays from the sun. The darkness of the tint, depends on the intensity of the sun on the glass surface. This helps reducing the heat gains in a adaptive manner.

source: [12]

Electrochromic glazing

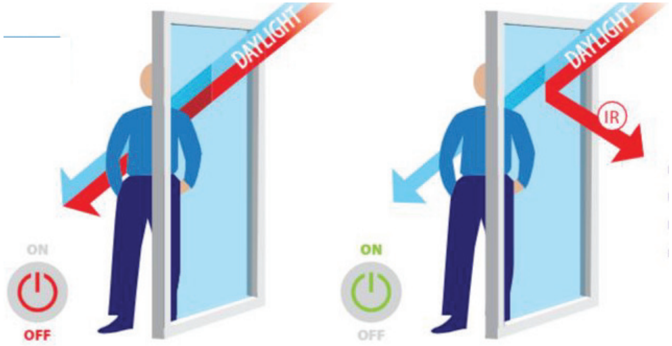
Electrochromic glazing consists of a coating of five layers (transparent conductor, electrochromic, ion conductor, counter electrode). This coating is applied in the glass and then its manufactured into the insulative glass unit. The glass changes its state by an induced electronic charge, either scheduled or user controlled.



source: [13]

PolyArch window

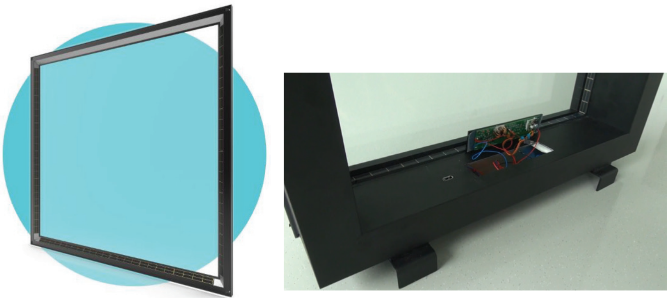
PolyArch window consists of an adaptive/responsive coating of liquid crystals placed between the glass layers which allows the transmittance of infrared radiation depending on the season. The responsive coating allows for the adaptation of the degree of reflection and the shifting of the position of the reflection in response to light or temperature without affecting transparency. Ultimately, the glass regulates whether the solar heat is being transmitted or reflected. Future concepts contain the possibility of being user controlled.



source: [14]

Physee Power window

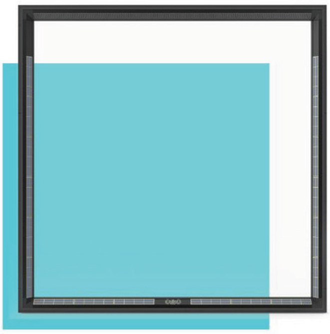
Physee Power window is a fully transpaernt colorless window which converts sunlight into green electricity. The coating on the glazing absorbs the sunlight, converts it into invisible light and sends it to the window frame which consists of solar cells which converts this light to electricity.



source: [15]

Physee Smart window

Physee Smart window works in the same way as the Power window, but also has sensors integrated within the frame that measure light intensity, temperature, pressure and air quality. Besides collecting internal data, it also collects external environment data and adapts according to this.



source: [15]

source: [15]

Physee Eesy window

Physee Eesy window works in the same way as the Smart window, but includes the possibility of power storage, user control systems and self-adaptation according to behaviour.

Trespa panels (Hassfurt town's school center)

The Trespa Meteon panels placed in this project allow for elastic deformation of lthe ouvres by induced bending stress by sensors and motors. From different angles, the louvres can seem either open or closed. The panels can be solar controlled in order to provide windows shading when necessary.

source: [16]

Flectofin

source: [17]

Flectofin is a hingeless louvre system that can open or close either by induced bending stress that can be caused by displacement within the core or by change of temperature in the lamina. This louvre system can provie sufficient shading when necessary by being solar controlled.

Green wall

Green wall as an outer layer can help improve the indoor thermal comfort as it provides and extra insulation layer. It does not require soil and it also is aesthetically appealing. It helps the facade to remain cool and also helps against the heat island effect.

source: [18]

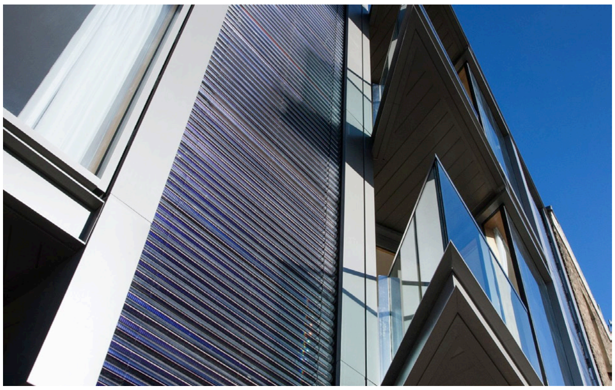
source: [19]

Breathing skins

Breathing skin consists of pneumatic muscles which open and close helping to regulate the amount of light, views, temperature, and air through the skin. They adapt according to the indoor and outdoor environment and to set requirements.

Thermal collector cladding

Thermal collectors cladding absorb solar heat generating energy that can be used as heating. They prevent the outdoor layer of the facade to heat up and in this way it helps increase the indoor thermal comfort while also helping reduce the energy costs of the building.



source: [20]

source: [21]

source: [22]

Integrated PV in shading features

PV-cells integrated in shading features or blinds help generating electricity while also providing sufficient shading in order to decrease the indoor heat gains. In this way, the indoor thermal comfort is increased and the electricity costs are decreased.

State of the art interactive/adaptive materials and systems – **Heat protection**

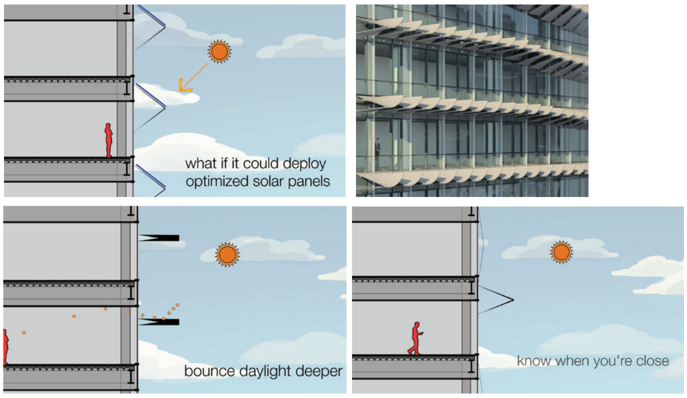
Thermal collectors as blinds

Thermal collectors as blinds absorb solar heat generating energy that can be used as heating. They provide shading and in this way helping increase the indoor thermal comfort while also helping reduce the energy costs of the building. Even though they are placed in front of the window, the still allow for sufficient view to the outside.

source: [23]

Sunbreak

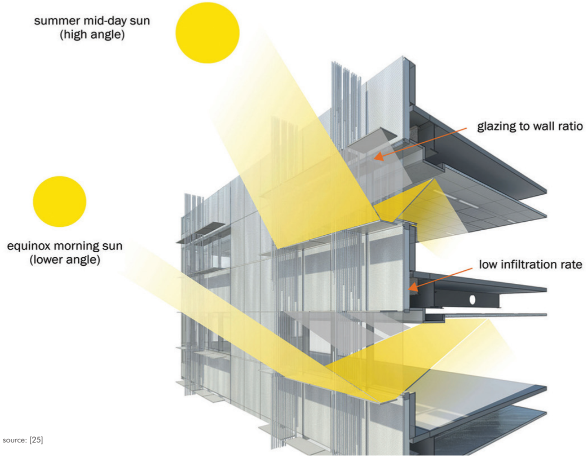
Sunbreak is a dynamic user controlled high tech shading system, which also provides solar controlled shading, daylight expansion, while also producing electricity. The system can recognize user behavior and self adapt. It can also place the PV-panels on top of the shading feature, in a more efficient angle. Besides this, it helps bouncing daylight to the inside. With these features, the system helps decrease overall energy costs and increases thermal comfort.



source: [24]

Daylight reflection (EGWW–building)

The shading feature of this building is designed in such a way that it helps bounce daylight to the indoor space, depending on the angle, while also providing sufficient shading. This helps reduce solar heat gains and minimizes the need for artifical light. Therefore, it reduces both heating and electricity costs.

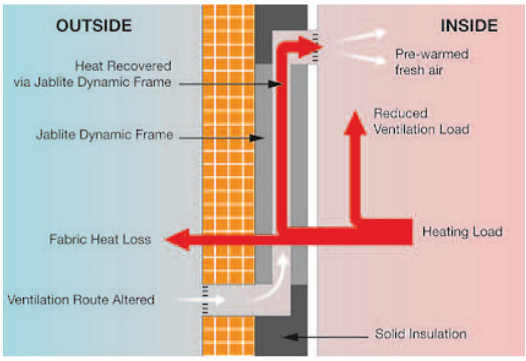


source: [25]

State of the art interactive/adaptive materials and systems – **Heat rejection**

Air alternation through facade

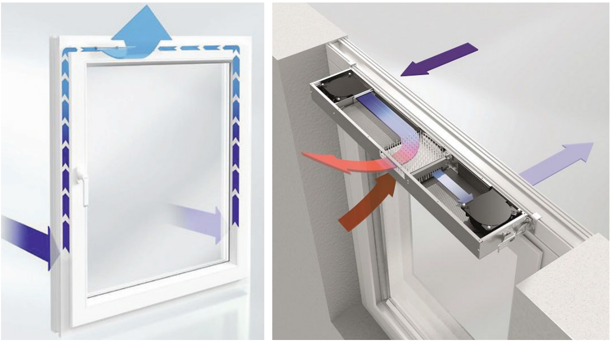
This system helps recovering the heat that goes lost through the facade. The openings in the facade allow for natural ventilation to go through the facade in order to ventilated the indoor space. While the air is going through the facade, it is being pre-heated. In this way, fresh warm air is being supplied in a passive manner, reducing energy costs. Due to the constant flow of air, this systems also helps with avoiding overheating during warm periods.



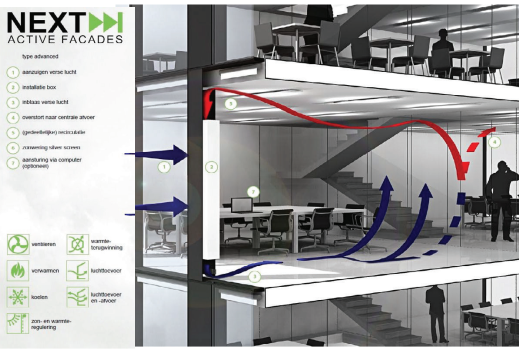
source: [26]

Decentralized ventilation

Schüco's decentralized ventilation, the VentoAir+ and VentoTherm Twist, help providing ventilation through the window frame. The latter also acquires a heat exchanger for the pre-heating of the incoming air and air quality sensors that allows it to self-adapt according to the indoor conditions.



source: [27]



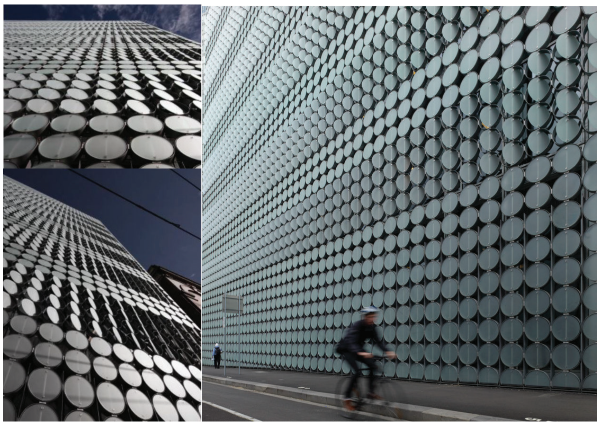
source: [28]

Next Active Façade

Next active facade is a Building Intergrated Service (BIS) system which provides ventilation to the indoor space. It also provides heating, cooling and acquires a heat exchanger. Besides this, it provides users with control of their environment.

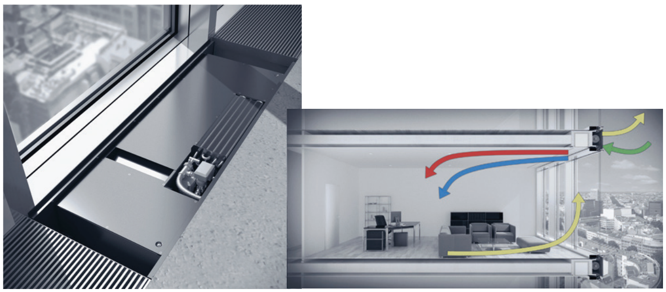
Operable disks (RMIT Design Hub)

The operable "disk" facade design of this building is a shading device which consists of sandblasted glass disks. Some of these are fixed while others are operable. Perimeter air intakes and fine mist sprinklers, which are incorporated into the facade's double glazed inner skin, provide passive (evaporative) cooled air through the floor and to the indoor space. Some of the disks also have PV-cells in order to generate electricity.



source: [29]

Schüco E2 system

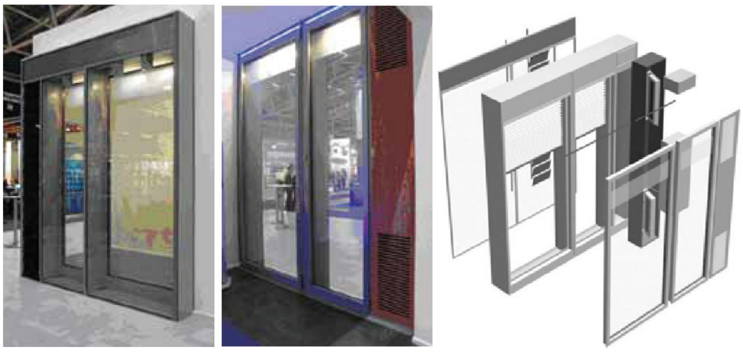


source: [30]

Schüco E2 system is a Building Integrated Service (BIS) system that provides decentralized ventilation, heating, and cooling through the facade. It is positioned between the floor and the window frame and is most suitable for curtain walls. It also includes a shading system which rolls in or out when shading is required. It acquires a heat recovery system adding on the reduction of the energy use.

TE motion

TE motion is a Building Integrated Service (BIS) system that integrates heating, cooling, ventilation, and artificial light all in one system. It also helps with the redirection of natural light to the indoor space. In addtion, it has PV-cells for on the outer layer for energy production. This helps with the overall energy reduction of buildings.



source: [31]

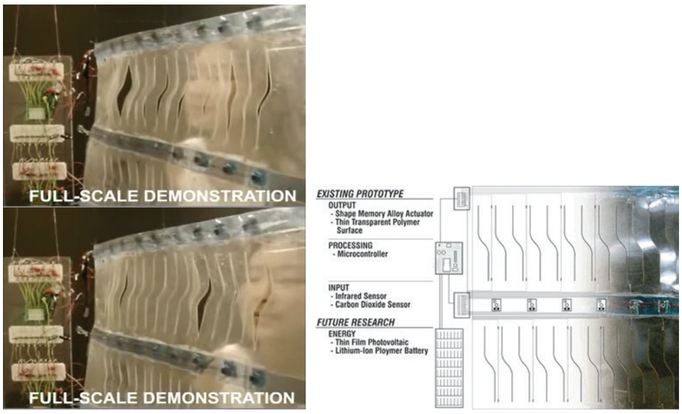
Smartbox

Smartbox is a Building Integrated Service (BIS) which provides decentralized heating, cooling, and ventilation through the facade. The system is situated between the floor and the curtain wall window frame. It also has a heat exchanger which adds to the energy reduction.

source: [32]

Living glass — responds to human presence

Living glass is a thin transparent silicone surface which opens its “gills” for air when their is human presence in the space and when the temperature and CO2-levels are too high. Flexinol wires within the silicone surface contract due to induced electricity which is triggered by the data collected through the sensors and where its analyzed by the microcontroller which then responds when necessary. In this way, ventilation is provided to the indoor space.



source: [33]

Capricorn Haus

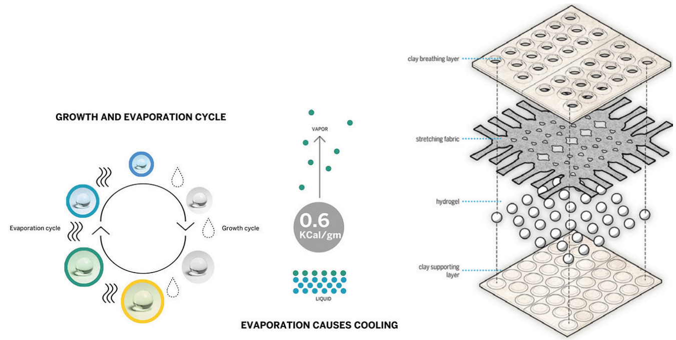
Capricorn Haus has a Building Integrated Service (BIS) system developed by Trox and Schueco which has heating, cooling, and ventilation system and also acquires a heat-exchanger. It consists of both opaque and translucent components.

source: [34]

State of the art interactive/adaptive materials and systems – **Heat rejection**

Hydroceramic hydrogel

Hydroceramic consist of hydrogel pellets and ceramic clay layers. The hydrogel pellets absorbs large quantities of water to provide a cooling effect by evaporation helping to decrease the temperature and increase the humidity in the surrounding air and in this way helping the indoor environment to remain in balance.



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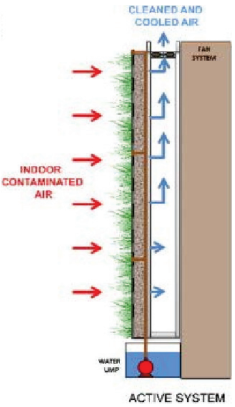


source: [36]

Active Living Wall System (ALWS)

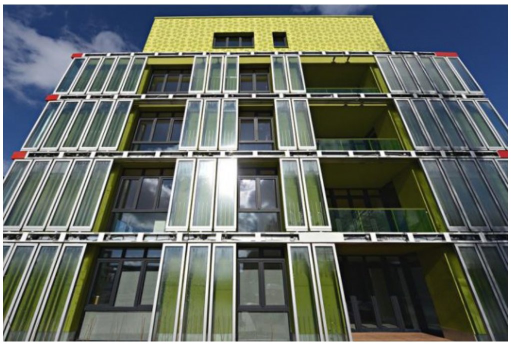
Active Living Wall System (ALWS) helps remove pollutants from the indoor air providing a healthy indoor environment. Depending on its position, it can act as an extra insulation layer. The plants can be plant in soil or in a hydroponic manner. It does acquire a high maintenance, but provides a very appealing look.

State of the art interactive/adaptive materials and systems – **Heat generation**

SolarWall PV/T

The solar active thermal envelope or Solarwall system consists of a perforated metal sheet façade which draws the excess heat of PV-panels which can be connected to the HVAC system of the building. The design allows for maximum energy contribution through heat accumulation in the air chamber that produces an air stream which travels to the inlet of the air handling unit (AHU) in order to help heat or cool the building. The amount of air in it depends on the building and the environment conditions.

source: [37]



source: [38]

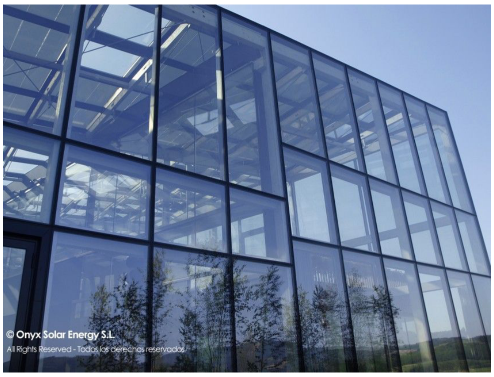
Algae bio–reactive façade (biomass)

The Algae bio-reactive facade produces renewable energy from algal biomass and solar thermal heat. This produced heat is transported to the building's energy management in order to harvest the biomass and the heat, to be used when necessary through the building services.

Color changing Building integrated PV–panels (BIPV)

Color changing BIPV's are integrated within the building's facade in order to produce electricity. The PV-panels change color due to the intensity of the sun on the panels. Their efficiency is lower than regular PV-panels, but they provide a more appealing look while still producing electricity.


source: [39]



source: [40]

Transparent PV–panels

Transparent PV-panels are PV-panels which can be used for translucent facades, such as curtain walls. They provide sufficient outside view while also generating electricity and avoiding heat gains. Ultimately reducing energy costs. However, their efficiency is lower than regular PV-panels.

Semi–transparent PV–panels

Semi-transparent PV-panels are another solution for translucent facades which generate electricity. These provide less view to the outside than when using complete transparent PV-panels, but their efficiency is higher.


source: [41]


source: [42]

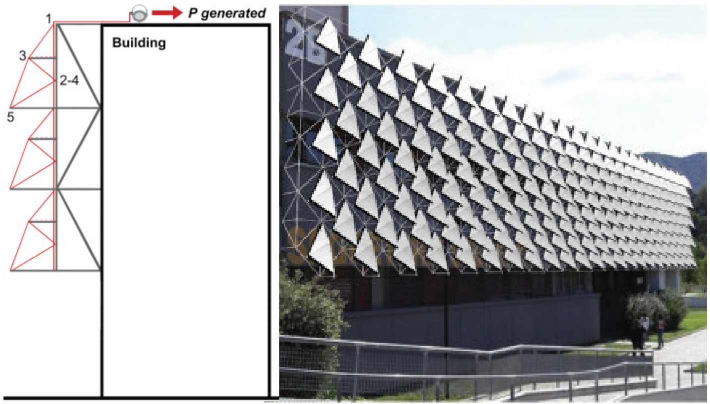
Wind energy (COR building)

The facade of this building consists of small facade integrated wind turbines. This helps with the generation of electricity to run the building. The wind turbines are only placed on the upper part of the building.

State of the art interactive/adaptive materials and systems – **Electricity**

Wind energy (blinking sail energy harvester)

The blinking sail energy harvester consists of a system of foldable modules which makes it possible to convert wind-induced motion into electricity. This energy can be used directly by the building or stored for later use.



source: [43]

source: [42]

Kinetic energy (terminal car park)

The shading for the facade of the garage of this building consists of 250 thousand aluminium plates which produces power by kinetic wind energy. The plates move with passing wind creating a spectacular and dynamic effect that looks like a disturbed water surface.

Wall++

Wall++ is an interactive indoor wall that uses high conductivity paint, electrodes, and microcontrollers which allows the wall to read human behavior and to respond to human touch, human pressence and to understands patterns. The wall analysis the data and sends the information to the actuactors in order to adapt the indoor environment. The system can also be user controlled.

source: [43]

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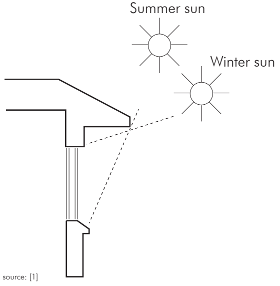
Appendix B – Matrix of solutions and Archetypes

Component: Shading features – **Static**

Passive

Type of Archetype

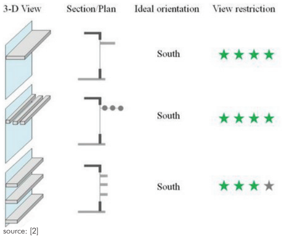
overhang



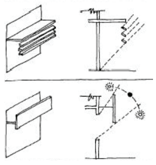
source: [1]

EF	+
SA	+
FC	-

horizontal blades



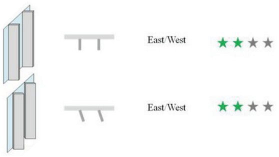
source: [2]



source: [3]

EF	++
SA	+
FC	-

vertical blades

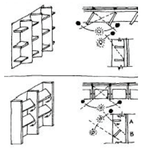


source: [2]

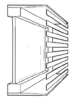
EF	+
SA	+
FC	+

horizon & vertical blades

source: [2]



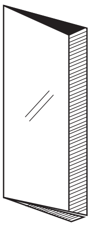
source: [3]



source: [4]

EF	+
SA	+
FC	+

one sided vertical blade with air openings



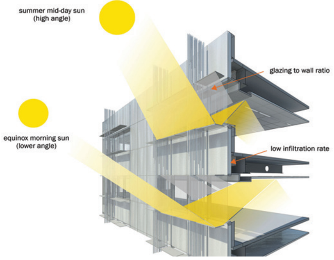
source: [5]

EF	+
SA	+
FC	-

Active

Type of Archetype

reflection of daylight on shading feature



source: [6]

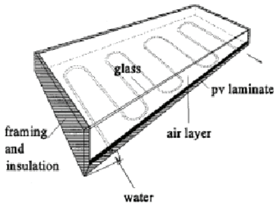
EF	++
SA	+
FC	-

thermal collectors as blinds

source: [7]

EF	+
SA	-
FC	-

thermal collector on top of shading feature



source: [8]

EF	++
SA	-
FC	-

integrated PV's on blinds

source: [9]

EF	+
SA	-
FC	-

integrated PV's on top of shading feature

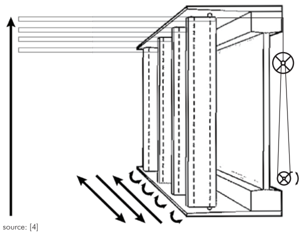
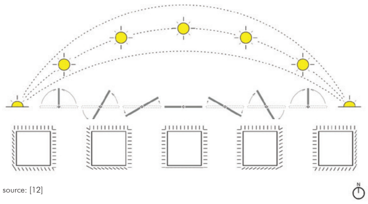
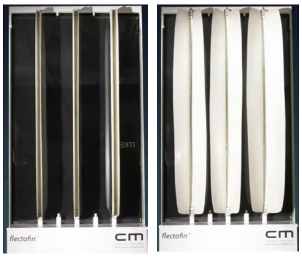
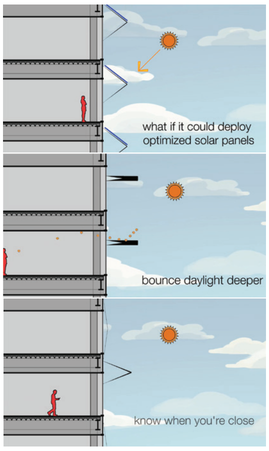
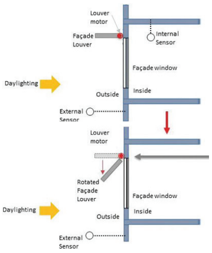
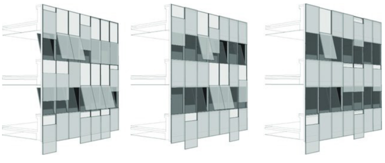
source: [10]

EF	++
SA	-
FC	-

Archetype Energy Efficient (EF): outside view/ contact with nature/ high external control/ low internal control
Archetype Self–Adaptive (SA): use of technologies is main experience/ space matches lifestyle/ high external control/ low internal control
Archetype Full Control (FC): own privacy and high freedom/ comfort above energy use/ low external control/ high internal control

++	very applicable
+	applicable
-	not applicable

Component: Shading features – **Dynamic**

Passive	Type of Archetype		Active	Type of Archetype
manually rotating shading systems  source: [4]	EF + SA - FC ++		solar and user controlled shading  source: [12]	EF + SA + FC +
louvres open and close by change of temperature  source: [11]	EF + SA + FC -		elastic deformation of louvres by induced bending stress by sensors and motors  source: [13]	EF + SA + FC -
			solar controlled shading + daylight expansion & energy production  source: [14]	EF ++ SA ++ FC -
			solar controlled shading louvre with sensors  source: [15]	EF + SA ++ FC -
			solar controlled shading panels  source: [16]	EF + SA + FC -

Archetype Energy Efficient (EF): outside view/ contact with nature/ high external control/ low internal control
Archetype Self–Adaptive (SA): use of technologies is main experience/ space matches lifestyle/ high external control/ low internal control
Archetype Full Control (FC): own privacy and high freedom/ comfort above energy use/ low external control/ high internal control

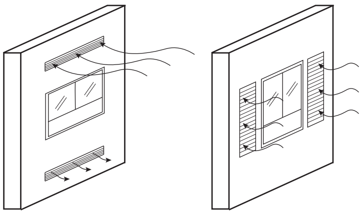
++ very applicable
\+ applicable
\- not applicable

Component: Facade openings – Air openings – **Static**

Passive

Type of Archetype

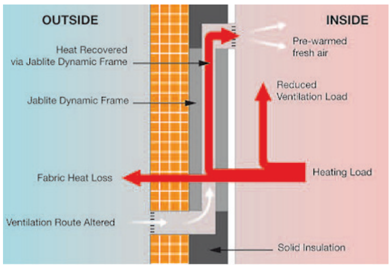
openings in facade for ventilation



source: [1]

EF -
SA +
FC -

altering route of ventilation



source: [17]

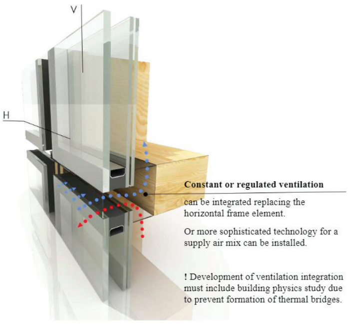
EF +
SA +
FC -

ventilation grilles on window

source: [18]

EF +
SA +
FC -

ventilation through gap between glazing



Constant or regulated ventilation can be integrated replacing the horizontal frame element.

Or more sophisticated technology for a supply air mix can be installed.

! Development of ventilation integration must include building physics study due to prevent formation of thermal bridges.

source: [19]

EF -
SA +
FC -

decentralized ventilation through window frame

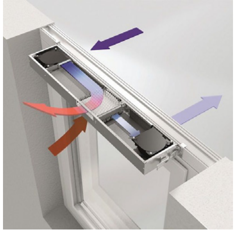
source: [20]

EF +
SA +
FC -

Active

Type of Archetype

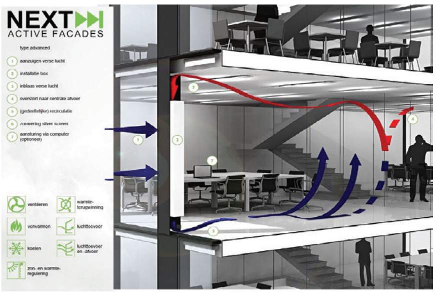
decentralized ventilation with heat exchanger for pre-heating of air



source: [20]

EF +
SA +
FC -

ventilation+heat exchanger integrated in facade



source: [21]

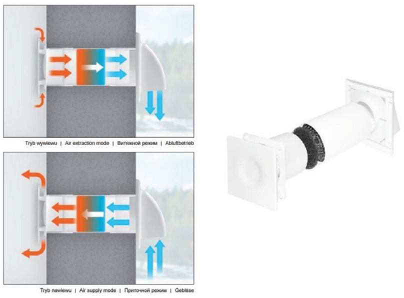
EF +
SA +
FC +

hybrid ventilation

source: [22]

EF +
SA +
FC -

air supply and extraction unit in facade



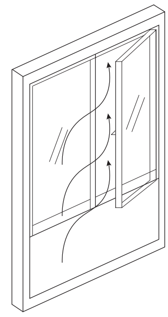
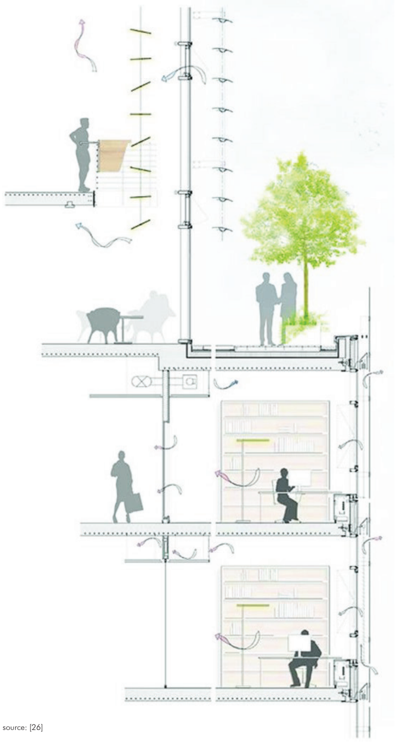
source: [23]

EF +
SA +
FC -

Archetype Energy Efficient (EF): outside view/ contact with nature/ high external control/ low internal control
Archetype Self–Adaptive (SA): use of technologies is main experience/ space matches lifestyle/ high external control/ low internal control
Archetype Full Control (FC): own privacy and high freedom/ comfort above energy use/ low external control/ high internal control

++ very applicable
\+ applicable
\- not applicable

Component: Facade openings – Air openings – **Dynamic**

Passive	Type of Archetype		Active	Type of Archetype
operable windows  source: [1]	EF + SA - FC +		windows open and close automatically for ventilation  source: [25]	EF + SA + FC -
operable windows grilles  source: [24]	EF + SA - FC +		windows open automatically for ventilation through double skin facade where the air is pre-heated.  source: [26]	EF + SA + FC -

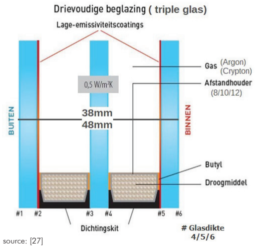
Archetype Energy Efficient (EF): outside view/ contact with nature/ high external control/ low internal control
Archetype Self–Adaptive (SA): use of technologies is main experience/ space matches lifestyle/ high external control/ low internal control
Archetype Full Control (FC): own privacy and high freedom/ comfort above energy use/ low external control/ high internal control

++ very applicable
\+ applicable
\- not applicable

Component: Facade openings – Window glazing

Passive

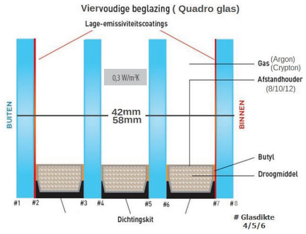
triple glazing (Uw=0,5 W/m2·K)



source: [27]

Type of Archetype	
EF	++
SA	-
FC	-

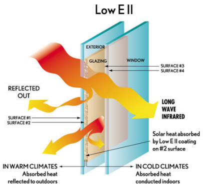
quadruple glazing (Uw=0,3 W/m2·K)



source: [27]

Type of Archetype	
EF	++
SA	-
FC	-

low-e glazing, reflects solar heat during summer and traps radiant indoor heat during winter



source: [28]

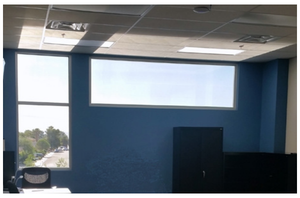
Type of Archetype	
EF	++
SA	+
FC	-

polaroid glazing, blocks intense reflected light reducing glare and discomfort.

source: [29]

Type of Archetype	
EF	+
SA	+
FC	-

prismatic glazing, daylight distribution indoors.



source: [30]

Type of Archetype	
EF	++
SA	+
FC	-

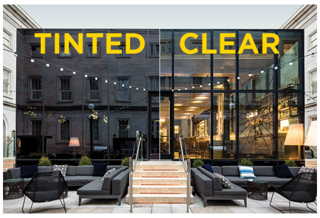
thermochromic/photochromic glazing, glazing transparency changes according to sun intensity or amount of UV-light.

source: [31]

Type of Archetype	
EF	+
SA	+
FC	-

Active

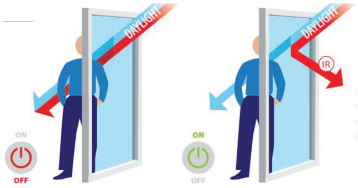
electrochromic glazing, change of state by induced electronic charge



source: [32]

Type of Archetype	
EF	+
SA	-
FC	+

polyArch, allowing the transmittance of infrared radiation depending on the season.



source: [33]

Type of Archetype	
EF	+
SA	+
FC	+

physee power window, converts sunlight into green electricity.

source: [34]

Type of Archetype	
EF	++
SA	-
FC	-

semi-transparent PV's

source: [35]

Type of Archetype	
EF	+
SA	-
FC	-

transparent PV's

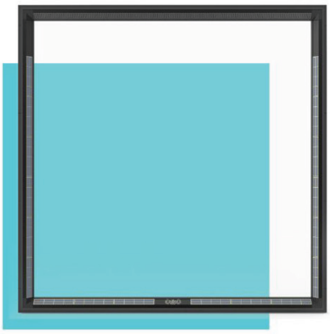
source: [36]

Type of Archetype	
EF	++
SA	-
FC	-

Archetype Energy Efficient (EF): outside view/ contact with nature/ high external control/ low internal control
Archetype Self–Adaptive (SA): use of technologies is main experience/ space matches lifestyle/ high external control/ low internal control
Archetype Full Control (FC): own privacy and high freedom/ comfort above energy use/ low external control/ high internal control

++	very applicable
+	applicable
-	not applicable

Component: Facade openings – Window frame

Passive	Type of Archetype		Active	Type of Archetype
insulated window frames (Uf=0,8 W/m2·K)  source: [37]	EF ++ SA - FC -		physee smart, frame with integrated sensors that measure light, temperature, pressure and air quality.  source: [34]	EF ++ SA ++ FC -
passive window frames (Uf=0,7 W/m2·K)  source: [38]	EF ++ SA - FC -		physee eesy, frame with, besides integrated sensors, power storage, user control systems and self-adaptation according to behaviour.  source: [34]	EF ++ SA ++ FC +

Archetype Energy Efficient (EF): outside view/ contact with nature/ high external control/ low internal control
Archetype Self–Adaptive (SA): use of technologies is main experience/ space matches lifestyle/ high external control/ low internal control
Archetype Full Control (FC): own privacy and high freedom/ comfort above energy use/ low external control/ high internal control

++ very applicable
\+ applicable
\- not applicable

Component: Facade layers – outdoor layer – **Static**

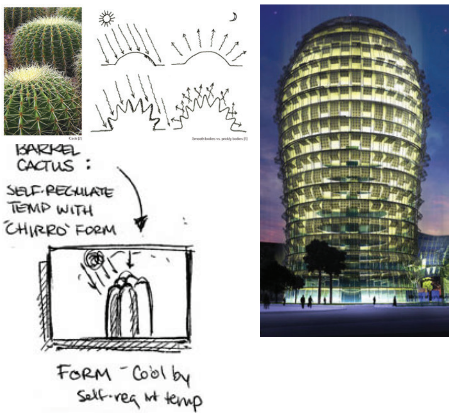
Passive

green wall as outer insulation layer

source: [39]

Type of Archetype	
EF	+
SA	-
FC	-

biomimicry: cactus shape cladding, absorbs less heat by day and emits this heat during night.



source: [40]

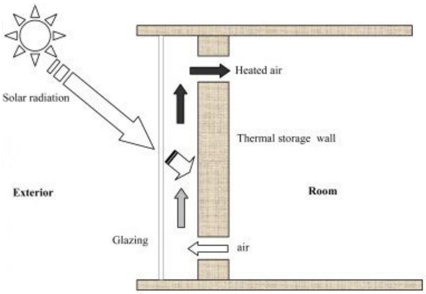
Type of Archetype	
EF	+
SA	-
FC	-

double-skin facade

source: [41]

Type of Archetype	
EF	+
SA	+
FC	-

trombe wall, heat between glass and wall is absorbed and stored in wall and released when necessary.



source: [42]

Type of Archetype	
EF	+
SA	+
FC	-

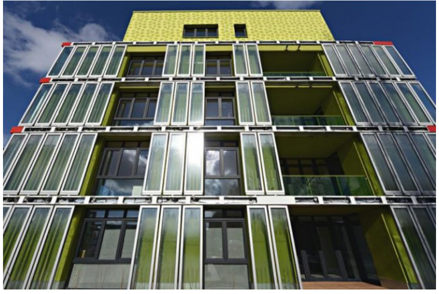
Active

color changing BIPV's according to sun intensity

source: [43]

Type of Archetype	
EF	+
SA	+
FC	-

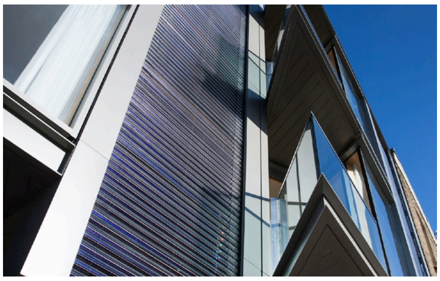
algae bio-reactive facade, produces renewable energy from algal biomass and solar thermal heat.



source: [44]

Type of Archetype	
EF	+
SA	-
FC	-

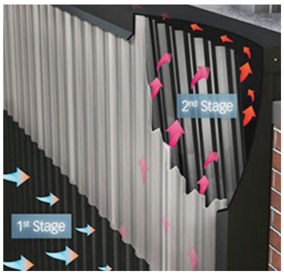
thermal collectors as facade cladding



source: [45]

Type of Archetype	
EF	+
SA	-
FC	-

SolarWall PV/T & NightSolar, thermal collector for heating and cooling. Pre-heating of fresh air by the solar radiation on the SolarWall panel and behind PV-panel.



source: [46]

Type of Archetype	
EF	+
SA	+
FC	-

Archetype Energy Efficient (EF): outside view/ contact with nature/ high external control/ low internal control
Archetype Self–Adaptive (SA): use of technologies is main experience/ space matches lifestyle/ high external control/ low internal control
Archetype Full Control (FC): own privacy and high freedom/ comfort above energy use/ low external control/ high internal control

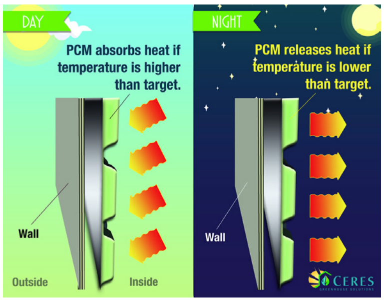
++	very applicable
+	applicable
-	not applicable

Component: Facade layers – outdoor layer – **Dynamic**

Passive

Type of Archetype

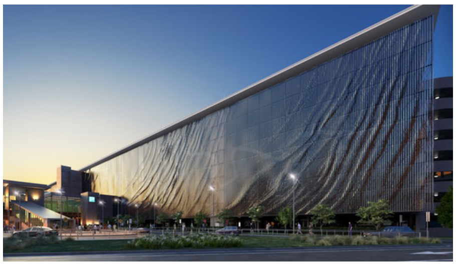
PCM as heat storage and extra insulation. PCM absorbs heat and releases it when necessary.



source: [47]

EF +
SA +
FC -

aluminum panels move with passing wind creating rippling pattern of a disturbed water surface.



source: [48]

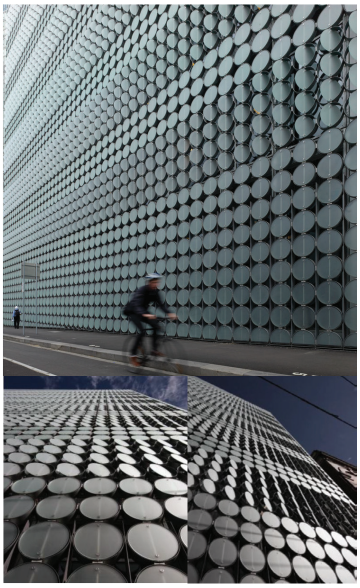
EF -
SA +
FC -

breathing skin, its pneumatic muscles regulate the amount of light, views, temperature, and air through the skin.

source: [49]

EF +
SA +
FC -

operable “disk” facade which includes PV-cells, evaporative cooling, and fresh air intakes.



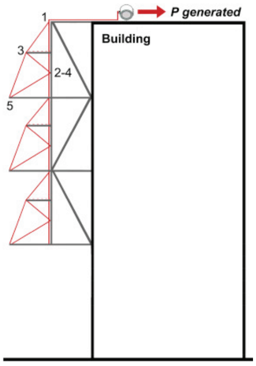
source: [50]

EF +
SA +
FC -

Active

Type of Archetype

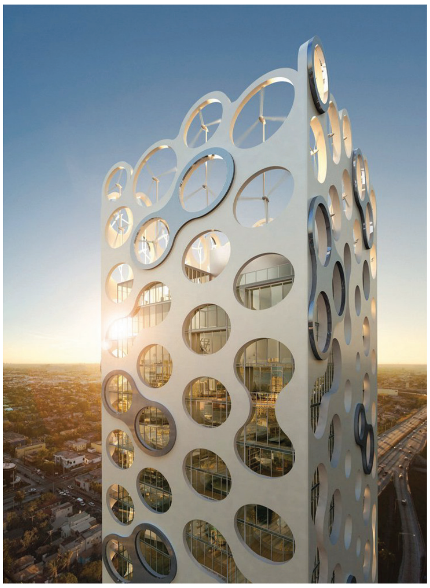
wind-energy harvesting facade, converting wind-induced motion of a membrane into electrical energy.



source: [51]

EF +
SA -
FC -

the COR building, producing power from wind turbines.



source: [52]

EF +
SA -
FC -

Archetype Energy Efficient (EF): outside view/ contact with nature/ high external control/ low internal control
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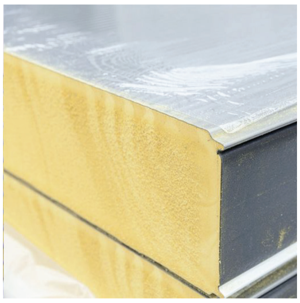
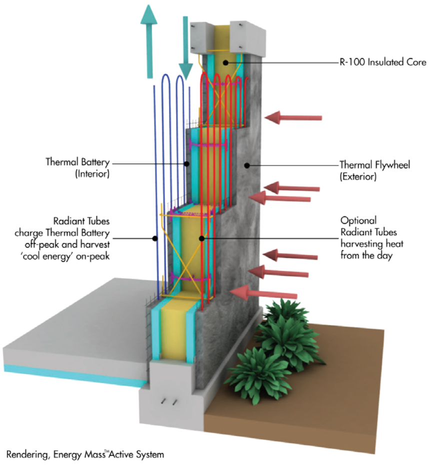
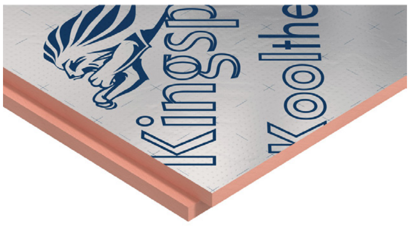
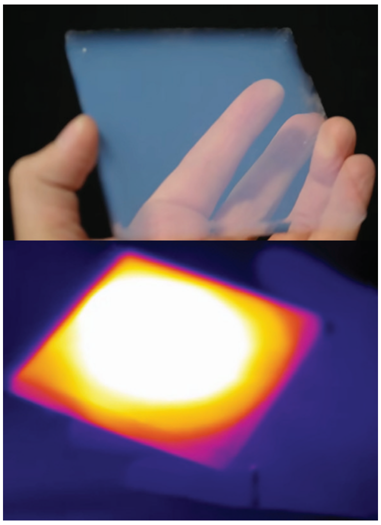
Archetype Full Control (FC): own privacy and high freedom/ comfort above energy use/ low external control/ high internal control

++ very applicable
+ applicable
- not applicable

Component: Facade layers – mid layer – **Static**

Passive	Type of Archetype		Active	Type of Archetype
PUR insulation ((λ=0,026 W/m·K)  source: [53]	EF + SA - FC -		Energy Mass Wall (EMW) is a super insulated core filled with an expanding closed cell foam. This core becomes formwork for slim concrete skins, pneumatically placed on both sides. One or both of the shotcrete "skins" has embedded radiant tubing turning the entire wall into a radiantly active surface. The exterior concrete envelope dampens thermal flow into the building and the interior concrete envelope stores thermal energy that can be used when necessary (or vice versa in the winter).  Rendering, Energy Mass™Active System source: [57]	EF + SA + FC -
resol rigidfoam insulation (λ=0,018 W/m·K)  source: [54]	EF + SA - FC -			
aerogel (silica) nano-insulation (λ=0,013 W/m·K)  source: [55]	EF + SA - FC -			
vacuum insulated panels (VIP), high insulation panels with slim thickness (λ=0,006 W/m·K)  source: [56]	EF + SA - FC -			

Archetype Energy Efficient (EF): outside view/ contact with nature/ high external control/ low internal control
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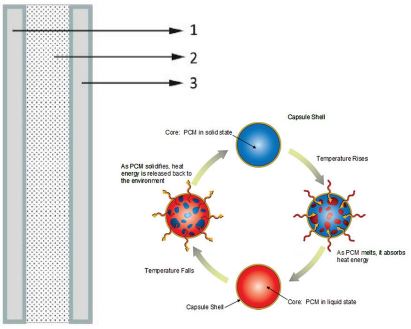
Archetype Full Control (FC): own privacy and high freedom/ comfort above energy use/ low external control/ high internal control

++	very applicable
+	applicable
-	not applicable

Component: Facade layers – mid layer layer – Dynamic

Passive

PCM as heat storage and extra insulation. PCM absorbs heat and releases it when necessary.

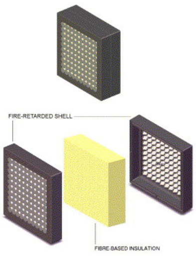


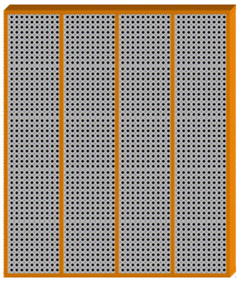
LAYER	DESCRIPTION
1	GLASS SHEET
2	PCM
3	GLASS SHEET

source: [58]

Type of Archetype	
EF	+
SA	+
FC	-

dynamic insulation, perforated encasing of insulation allows for air through the facade making the U-value not constant anymore, but it varies with the speed of the air.



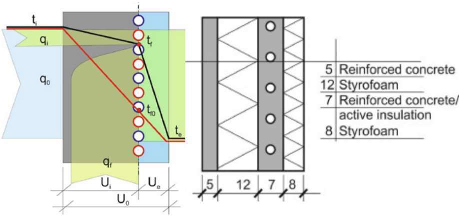


source: [59]

Type of Archetype	
EF	+
SA	+
FC	-

Active

active thermal insulation, reduces heat loss through external walls. Its a system of pipes inside the structure of an external building envelope in which a heating and cooling medium circulates, supplied with low temperature energy from the ground. Its not based on the direct transmission of low temperature energy to the room, but is related to the increase/decrease of temperature inside the external envelope. The basic principle of active insulation is that it uses the energy of the medium at a temperature lower than the temperature of the internal room, but at a higher than that of the outside air.



source: [60]

Type of Archetype	
EF	+
SA	+
FC	-

Archetype Energy Efficient (EF): outside view/ contact with nature/ high external control/ low internal control
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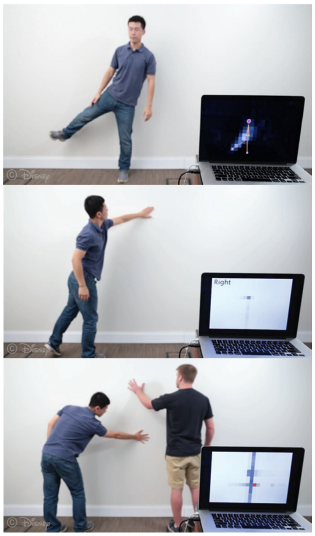
Archetype Full Control (FC): own privacy and high freedom/ comfort above energy use/ low external control/ high internal control

++	very applicable
+	applicable
-	not applicable

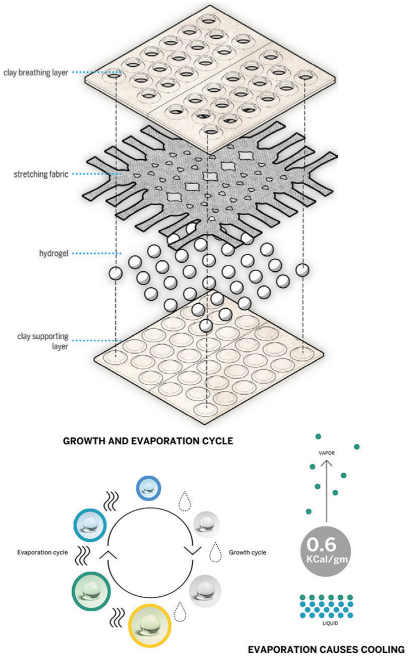
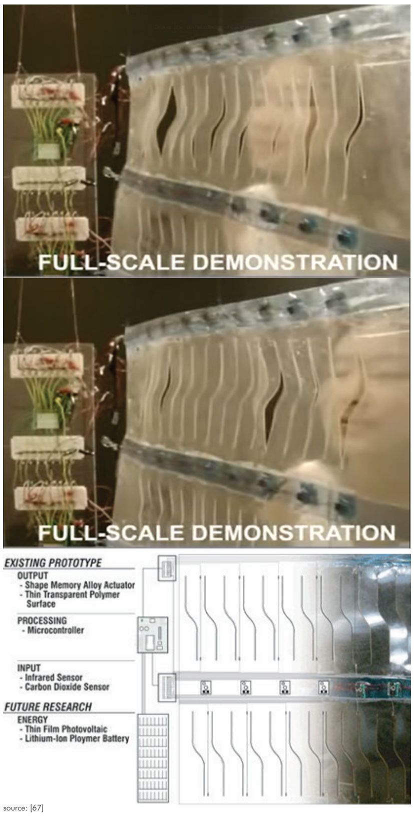
Component: Facade layers – indoor layer – **Static**

Passive	Type of Archetype		Active	Type of Archetype
green pods, allows users to arrange the wall to their preferences and it also serves as an extra insulation layer.  source: [61]	EF ++ SA + FC +		active living wall system (ALWS), removes pollutants from the air providing a healthy indoor environment. Depending on its position, it can act as an extra insulation layer.  source: [63]	EF ++ SA - FC -
aerogel-based plaster, combination of natural lime coat with 90% granular aerogel decreases the thermal conductivity of the plaster by 10 times reaching an insulation value of λ=0,015 W/m·K with 30 mm thickness.  source: [62]	EF + SA - FC -		aesthesis, provides an interactive working surface.  source: [64]	EF - SA - FC +
			wall++, reacts to human touch, pressence and understands patterns or signs to adapt indoor comfort.  source: [65]	EF + SA ++ FC ++

Archetype Energy Efficient (EF): outside view/ contact with nature/ high external control/ low internal control
Archetype Self–Adaptive (SA): use of technologies is main experience/ space matches lifestyle/ high external control/ low internal control
Archetype Full Control (FC): own privacy and high freedom/ comfort above energy use/ low external control/ high internal control

++ very applicable
\+ applicable
\- not applicable

Component: Facade layers – indoor layer layer – **Dynamic**

Passive	Type of Archetype		Active	Type of Archetype
hydroceramic, consist of hydrogel pellets and ceramic clay layers. The hydrogel pellets absorbs large quantities of water to provide a cooling effect by evaporation helping to decrease the temperature and increase the humidity in the surrounding air and in this way helping the indoor environment to remain in balance.  source: [66]	EF + SA + FC -		living glass, thin transparent silicone which opens its "gills" for air when their is human presence in the space and when the temperature and CO2-levels are too high.  source: [67]	EF + SA ++ FC -

Archetype Energy Efficient (EF): outside view/ contact with nature/ high external control/ low internal control
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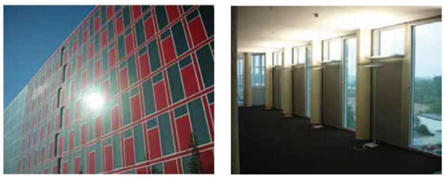
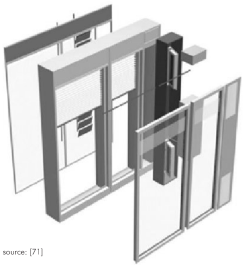
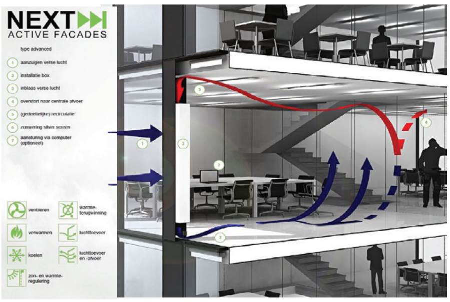
++	very applicable
+	applicable
-	not applicable

Component: Building services integrated (BIS) in facade & User Control

BIS	Type of Archetype	User Control	Type of Archetype
smartbox: heating, cooling, and ventilation + heat exchanger.  source: [68]	EF ++ SA + FC -	voice control to adapt indoor environment  source: [1]	EF - SA - FC +
Schüco E2 system: heating, cooling, and ventilation + heat recovery  source: [69]	EF ++ SA + FC -	activity recognition: sensors, data management, and actuators  Perception Data analysis and reasoning Response source: [1]	EF + SA + FC +
Capricorn Haus: heating, cooling, and ventilation + heat-exchanger.  source: [70]	EF + SA + FC +		
TE motion: heating, cooling, ventilation, redirection of natural light, artificial lighting, and PV-cells  source: [71]	EF ++ SA + FC +		
Next active facade: heating, cooling, and ventilation+heat exchanger.  source: [21]	EF ++ SA + FC +		

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Archetype Full Control (FC): own privacy and high freedom/ comfort above energy use/ low external control/ high internal control

++ very applicable
\+ applicable
\- not applicable

References

[1]: diagram by author
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Appendix C – Interview user experience

General information

*Vereist

1. Are you a full-time or a part-time employee? *

Markeer slechts één ovaal.

☒ Full-time employee (minimum 36 hours)
○ Part-time employee

2. In what type of spaces do you work the most? *

Markeer slechts één ovaal.

☒ Own desk
○ Shared desk
○ Can choose randomly

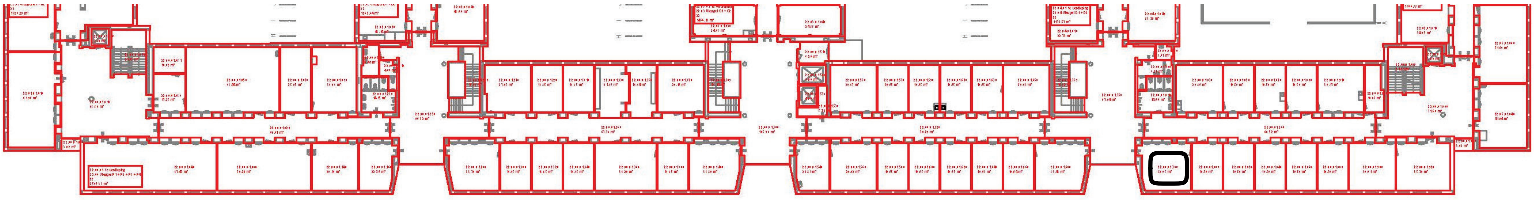
3. How many people are you sharing your workspace with?

Depending on the day of the week, 1 to 3

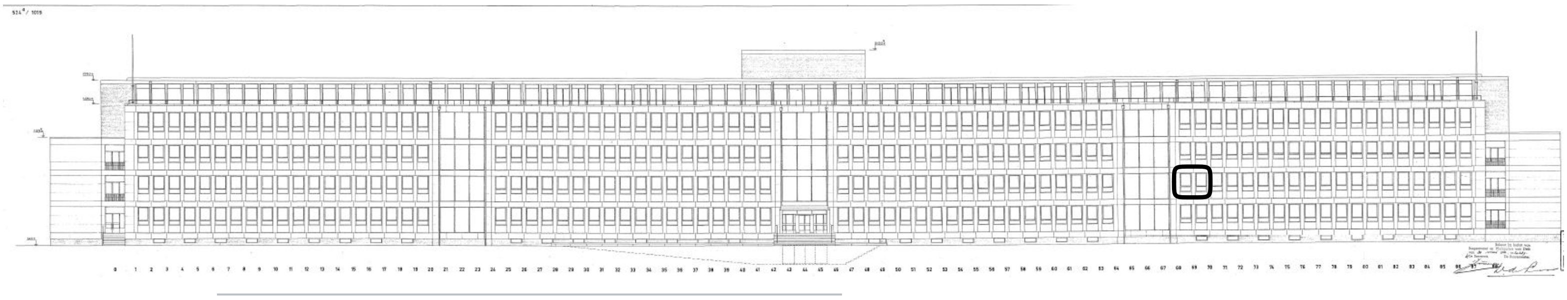
4. Where is your office located? Which block in wing F and which floor?

F4 second floor (1st story)

5. Please make a circle where your office is located *



6. Please make a circle where your office is located *



7. Where do you work the most? *

Markeer slechts één ovaal.

(4 days a week) ☒ Work at the office (write how many times a week?)
(0,5 day a week) ☒ Work at home (write how many times a week?)
☐ Visiting other third parties (write how many times/hours a week?)
☐ Visit and work in other offices or building (write how many times/hours a week?)

8. How many hours do you spend in the office per week? *

Markeer slechts één ovaal.

☐ 8 hours or less
☐ 8 - 16 hours
☒ 16 - 24 hours
☐ 24 - 32 hours
☐ 32 - 36 hours
☐ 36 - 40 hours
☐ more than 40 hours

9. How many hours do you work away from your desk per day (for teamwork, meetings, breaks, etc)? *

2 hours on average

10. How many times do you break each day? *

1 to 0 times a day

11. How long is each break for one time? *

Markeer slechts één ovaal.

- ○ Around 10 min.
- ○ Around 15 min.
- ☒ Around 20 min.
- ○ Around 25 min.
- ○ Around 30 min.

12. In which space do you mainly spend time for breaks? (multiple answers possible) *

Vink alle toepasselijke opties aan.

- ☐ Outside of building
- ☒ Coffee lounge
- ☐ Breakout area (informal meeting spaces)
- ☐ Canteen
- ☐ Own desk

Indoor Environmental Quality

13. Can you indicate how satisfied you have been with your work environment during winter? *

	Extremely dissatisfied	Somewhat dissatisfied	Neither satisfied nor dissatisfied	Somewhat satisfied	Extremely satisfied
Temperature	X				
Artificial light	X				
Daylight	X				
Air quality	X				
View to outside					X
Noise	X				
Humidity			X		
Overall comfort	X				

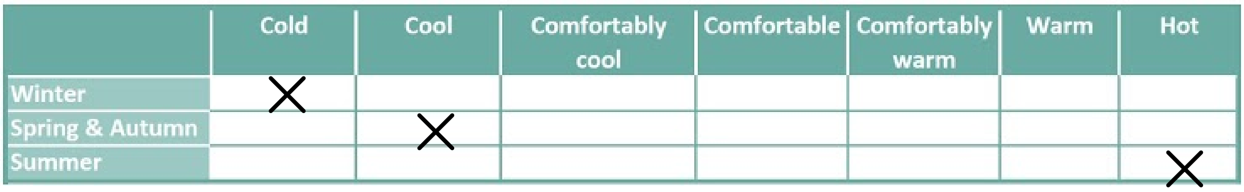
14. Can you indicate how satisfied you have been with your work environment during spring/autumn? *

	Extremely dissatisfied	Somewhat dissatisfied	Neither satisfied nor dissatisfied	Somewhat satisfied	Extremely satisfied
Temperature		X			
Artificial light	X				
Daylight		X			
Air quality	X				
View to outside					X
Noise	X				
Humidity			X		
Overall comfort		X			

15. Can you indicate how satisfied you have been with your work environment during summer? *

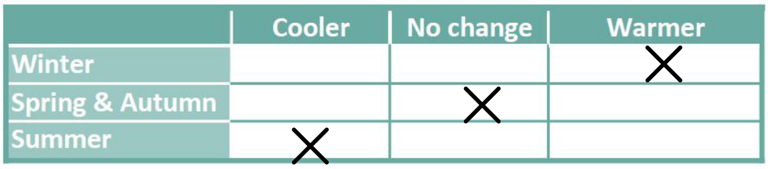
	Extremely dissatisfied	Somewhat dissatisfied	Neither satisfied nor dissatisfied	Somewhat satisfied	Extremely satisfied
Temperature	X				
Artificial light	X				
Daylight	X				
Air quality	X				
View to outside					X
Noise	X				
Humidity			X		
Overall comfort	X				

16. How do you sense the indoor temperature of your workspace? *



	Cold	Cool	Comfortably cool	Comfortable	Comfortably warm	Warm	Hot
Winter	X						
Spring & Autumn		X					
Summer							X

17. Would you like it to be? *



	Cooler	No change	Warmer
Winter			X
Spring & Autumn		X	
Summer	X		

18. Where is your desk located? *

Markeer slechts één ovaal.

☒ 0-2 m away from windows
☐ 2-4 m away from windows
☐ 4-6 m away from windows
☐ No window

19. Does natural light interfere your PC screen or desk (glare)? *

Markeer slechts één ovaal.

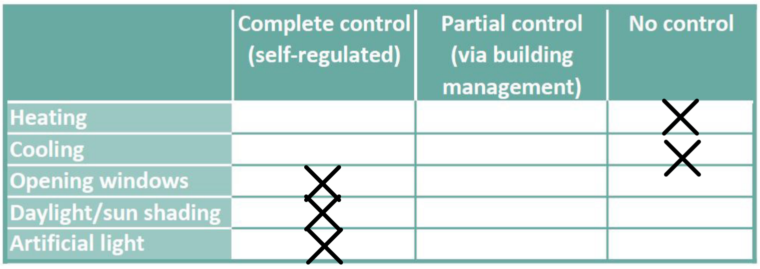
☒ Yes
☐ Sometimes
☐ No

20. Does your office have openable windows? *

Markeer slechts één ovaal.

☒ Yes
☐ No

21. To what extent can you control the following aspects of your workspace? *



	Complete control (self-regulated)	Partial control (via building management)	No control
Heating			☒
Cooling			☒
Opening windows	☒		
Daylight/sun shading	☒		
Artificial light	☒		

daylight is limited. Artificial light, only on and off is possible.

22. If your control goes via building management, how many times a day do you feel like you need them to adapt the indoor environment? *

Not available

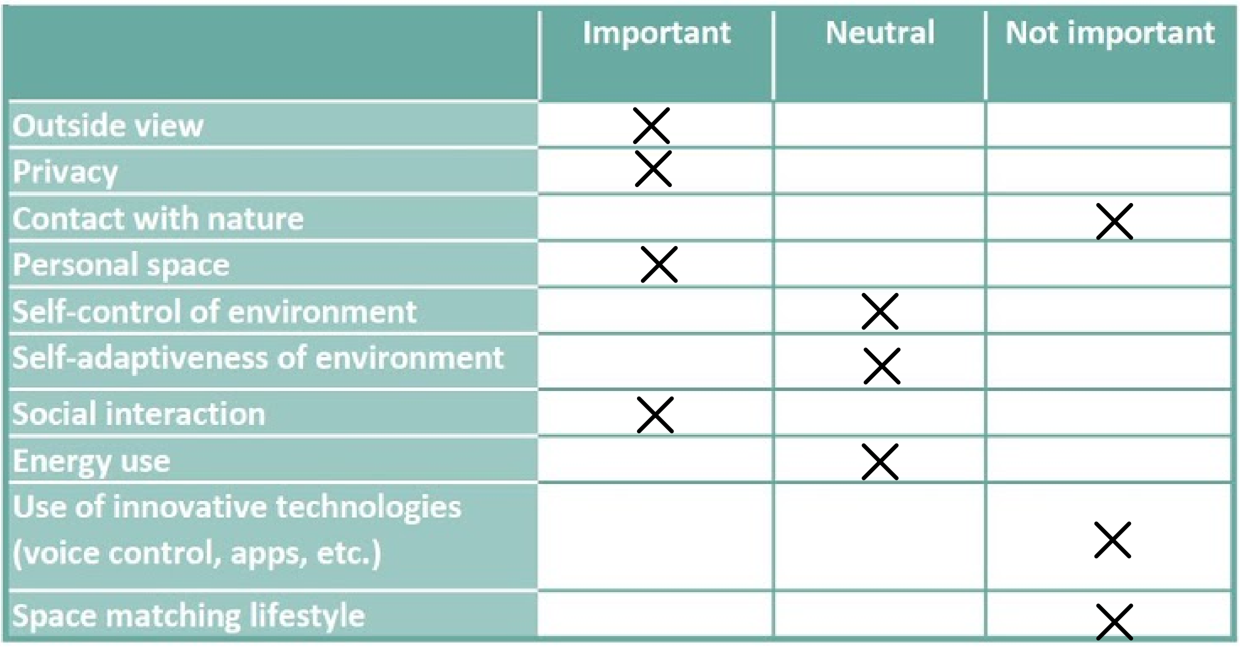
23. How many times a day do you actually contact building management to adapt the indoor environment? *

Not available

24. When building management adapts the indoor environment, how long does it take for you to feel comfortable again? (X minutes, X hours, still not comfortable?) *

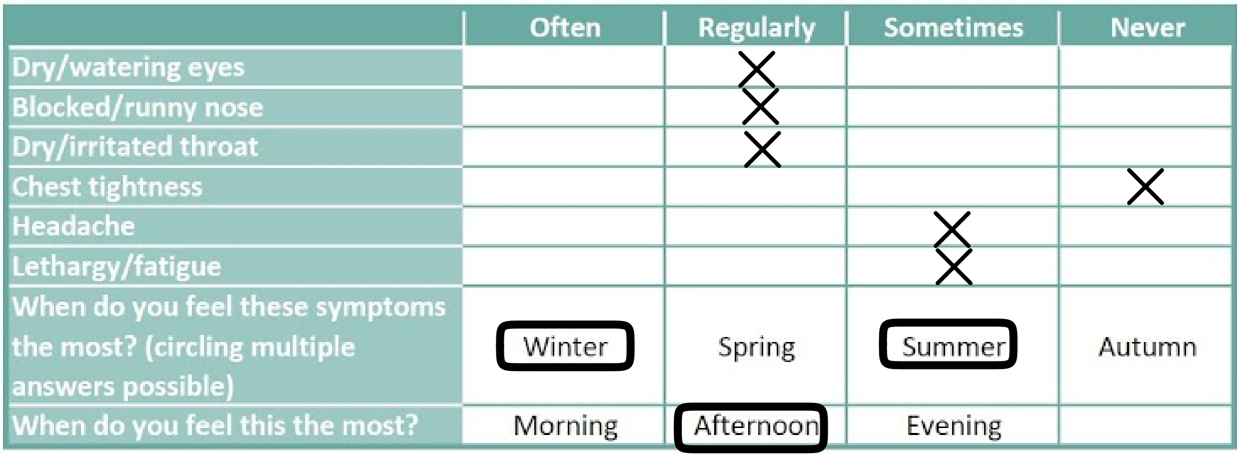
Not available

25. Which of the following is important for you to have in your workspace? *



	Important	Neutral	Not important
Outside view	X		
Privacy	X		
Contact with nature			X
Personal space	X		
Self-control of environment		X	
Self-adaptiveness of environment		X	
Social interaction	X		
Energy use		X	
Use of innovative technologies (voice control, apps, etc.)			X
Space matching lifestyle			X

26. Have you experienced any of the following? *



	Often	Regularly	Sometimes	Never
Dry/watering eyes		X		
Blocked/runny nose		X		
Dry/irritated throat		X		
Chest tightness				X
Headache			X	
Lethargy/fatigue			X	
When do you feel these symptoms the most? (circling multiple answers possible)	[✓ Winter]	Spring	[✓ Summer]	Autumn
When do you feel this the most?	Morning	[✓ Afternoon]	Evening	

27. If there are any further remarks about your workspace or environment that you have not yet addressed, please write them down. Thank you! *

The indoor climate is largely determined by the outside conditions. Windy and cold outside conditions means cold and unpleasant inside conditions. Warm outside means warm inside.