



Multi-functional Facade Module

for different climate
conditions

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Sustainable Design Graduation Studio
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Abstract

The building sector is responsible for more than one third of resource consumption globally. Concerning the new construction, new regulations have been set, which impose that by 2020 all new buildings constructed within the EU should reach nearly zero-energy levels. The building envelope plays a strategic role in the energy and environmental performance of the building, significantly affecting the levels of indoor comfort. The increasing necessity of sustainability in built environments is leading to the need of the adaptive façade adoption. The façade is no longer a mere static element offering just a shelter for users. The future building skin is required to respond dynamically, being able to react to non-continuous, ever-changing climatic conditions, occupant comfort and energy efficiency requirements. It is apparent that building facades need to be transformed to fulfill adapted roles of high performance integration and façade elements need to be designed to provide the necessary flexibility needed in terms of energy flow and thermal comfort.

Companies like “Rollecate”, which is a facade construction company in the Netherlands with worldwide projects have grasped this change and are interested in creating new products, which reflect the current trend of adaptivity. This graduation project started with the existing research project “Future Adaptive Facades and Components” with the question from “Rollecate” about the direction the facade industry is heading to. “Rollecate” wants to know what the future of adaptive facades is and how this is translated into

a new product or a modification of an existing one that could be developed soon and be relevant for the building sector in the next five years and on.

The aim of the research project is the development of a Multi-functional Façade Module (MFM) that consists of several functionalized layers that could be separately assembled depending on the architectural design of the building and the corresponding climate. Moreover, the proposed design is modular, which gives the possibility to be altered easily throughout its lifecycle, thus being also adaptive to future technological innovations. In order to evaluate it, this facade system is tested for an office building in Amsterdam, Netherlands with the main objective of providing thermal comfort to the occupants, whilst minimizing the energy consumption.

In the framework of a decade-long research activity on Advanced Integrated Façades (AIF), MFMs show a considerable potential for building envelopes, being one of the most promising Responsive Building Elements (RBE) in terms of energy reduction potential. In addition, the results of this research project prove that MFMs are performing well, offering considerable energy savings. They are a promising facade concept for future applications, offering not only an adaptive but also a sustainable solution to the construction of office buildings. Nevertheless, there is still space for future improvement, as well as further research and development as explained at the end of this research project.

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Introduction

The building sector is responsible for more than one third of resource consumption globally. Concerning the new construction, new regulations have been set, which impose that by 2020 all new buildings constructed within the EU should reach nearly zero-energy levels. Traditional buildings were built by means of passive systems lacking flexibility so as to respond to climate change and temperature fluctuations in order to provide thermal comfort, resulting in an unpleasant indoor environment. Current high energy consumption in buildings is attributable to non-optimal architectural choices, low performance of the building envelope, low efficiency of HVAC and lighting systems, as well as a still low utilization of renewable energy sources (Casini, 2016).

The building envelope plays a strategic role in the energy and environmental performance of the building, significantly affecting the levels of indoor comfort. Over the past few decades, facade design has evolved significantly through the application of environmental simulations and genetic algorithms. This evolution indicates the growing importance of sustainable considerations in facade design. The use of parametric studies for building performance which promises optimised systems has become common. However, facade optimisation does not address effectively the variety of external conditions, such as sunlight, precipitation and changing occupancy, that affect both a building and its users.

In reality, the factors that affect a building, its envelope and its ability to serve as an effective system of climate control are multi-dimensional. When designing a facade or an effective building system, one of the most important aims is to balance conflicting goals of environmental control,

financial costs, client needs and occupant comfort. An equally dispersed favorability among competing parameters is optimal, however, an unfortunate compromise between the different objectives is also possible. For this reason, in every situation the goals should be set from the beginning with hierarchical order of importance according to context. As architect Jean Nouvel has said:

“Constructing generic buildings, to be placed anywhere, not specific to urban areas, is doing things with no value”.

The increasing necessity of sustainability in built environments is leading to the need of the adaptive facade adoption. The facade is no longer a mere static element that forms a barrier between indoor and outdoor environment by offering just a shelter for users. The future building skin is required to respond dynamically, being able to react to non-continuous, ever-changing climatic conditions, occupant comfort and energy efficiency requirements. Like the skin of the human body, it should be able to adapt fully to the environmental conditions in a dynamic way, ensuring efficient, continuous, and automatic management of energy flows in accordance to climate, user behavior, and market conditions of energy.

In conclusion, it is apparent that building facades need to be transformed to fulfill adapted roles of high performance integration. Several different types of adaptive facade concepts have already been developed and an increase in emerging, innovative solutions is expected for the near future.

RESEARCH FRAMEWORK

I. Problem statement

The regulations on energy performance and sustainability are growing constantly. Facades have undeniably great effect on the inner climate and therefore the demands of façades in terms of energy, user comfort and geometrical possibilities are getting higher. In order to meet these new requirements, new innovative systems, materials and technologies are researched or even some are already being used and the building sector has shown a considerable progress throughout the years.

Serious environmental concerns like global warming and the greenhouse effect have shown the way towards “adaptivity” of the building skin, since the façade is the main parameter that influences the buildings’ energy performance. Façade elements need to be designed to provide the necessary flexibility needed in terms of energy flow and thermal comfort. There are already quite a lot examples of adaptive facades showing great potential in energy savings and surely there is much more to be discovered and applied in architectural projects. Computational design, environmental simulations, integrated facade systems and smart materials have already been used in order to construct adaptive building envelopes and offer great challenges for future developments.

Companies like “Rollecate”, which is a facade construction company in the Netherlands with worldwide projects have grasped this change and are interested in creating new products, which reflect the current trend of adaptivity. “Rollecate” wants to know what the future of adaptive facades is and how this is translated into a product that could be developed soon and be relevant for the building sector in the next five years and on.

II. Objectives

The aim of the research project is the development of a Multi-functional Façade Module (MFM) that consists of several functionalized layers that could be separately assembled depending on the architectural design of the building and the corresponding climate. The modular elements will be able to be assembled and placed with different geometric configurations, different types of materials and different colors in order to guarantee customization. In other words, this facade system must offer the possibility to integrate other building functions, it must be technically upgradeable, it must be flexible in terms of functionality and all these should be accomplished while offering different geometrical possibilities and thus architectural design freedom.

MFMs show a considerable potential for building envelopes, being one of the most promising Responsive Building Elements (RBE) in terms of energy reduction potential. They take advantage of the positive features of integrated facades and layered facades. This research design aims to investigate the advantages and disadvantages of these innovative facade concepts for the buildings’ energy efficiency and the user comfort and assess their implementation in the market in the near future.

III. Sub-objectives

The main objective will be pursued by dividing it into the following sub-objectives:

- ◊ to research the state-of-the-art adaptive facades that already exist and gain knowledge on their functions, materialization and systems used

- ◊ to determine the future trends and market needs according to this research

- ◊ to gain knowledge on integral, modular and layered product architecture

- ◊ to define the facade requirements that should be fulfilled in the Netherlands

IV. Research question

How can an adaptive system of multi-functional façade modules be designed taking advantage of integral and layered product architecture in order to respond to different climate conditions and provide thermal comfort whilst minimizing the energy demand of an office building in the Netherlands?

V. Sub-questions

The main question will be answered through the following sub-questions:

- ◊ What types of adaptive facades have already been built and how are they materialized, detailed and constructed?

- ◊ What are the future trends according to the state-of-the-art built adaptive facades, the current research projects and their technology readiness levels?

- ◊ What is modularity and how can it be applied on the design in order to ensure standardization and flexibility?

- ◊ What has integral product architecture to offer and how can the extra functions be incorporated in the façade module?

- ◊ What are the requirements of an adaptive

integrated façade in the Netherlands and how can these values be translated to a concept and design?

- ◊ How can such a multi-functional system provide all the functional requirements while preserving the aesthetic values of the architectural design?

- ◊ Which is the best configuration of the modules to reduce the overall energy demand (heating, cooling and lighting) in the Netherlands?

VI. Methodology

i. Literature study

The first part of the project consists of a literature study concerning the various types of façade systems available in the market and their characteristics. Focus is put on materialization, assembly, performance and costs. This is done together with studying the general building envelope functions, which are multi-dimensional.

In addition, the term “adaptivity” and what it means for a building is studied. A research is conducted on adaptive facades that have already been built, on adaptive materials and components, on new experimental products as well as research projects concerning adaptive envelopes with the aim of gathering the state-of-the-art and gaining knowledge on their characteristics.

Furthermore, the market driven process is studied so as to understand how the decisions on new products are made and how much power the client has to influence those decisions.

Lastly, research is being done on what is

indoor comfort and by which parameters it is influenced with the aim of determining the façade requirements.

ii. Analysis and conclusions

After the completion of the literature review, different classifications of the gathered data are made. Firstly, a classification is made of the functions which a façade performs and all the parameters that are directly and strongly connected with them and which functions of the building envelope they can influence.

Moreover, a classification of adaptive materials, components and elements is done in order to gain knowledge on their way of function. Gathering them in a table makes it easier to make comparisons and highlight the most common characteristics in order to draw conclusions.

Then, a classification is made of the reference projects. They are divided in existing buildings, available products and research projects and are put in chronological order. It needs to be emphasized that the chosen reference projects are representative and focus was put on variety in order to show the different potentials adaptive facades have. In terms of specific time restrictions when the classification was made, it may be possible that examples of the same value were excluded. In addition, it is important to mention that information about some criteria have been deduced from existing knowledge because it was not found from a source.

The reference projects are examined by the following parameters: type of control, exterior and interior agents of adaptation, response to adaptation agent, purpose of adaptation, response

time, type of control and degree of adaptability. The aim is to conclude to the most common which will also be the most important features of each category which will show why and how adaptive facades are used. Right after the classification, a conclusion is made concerning the future trends on the short and long run in order to understand what is relevant for “Rollecate” to develop the next years. Some projects may show great potential but may also need a lot of years until they are ready to be implemented in the market, however, “Rollecate” is interested in the direction it should follow according to where the facade industry is heading to in the near future.

At the same time an interview form is developed and interviews with architects from the Department of Architecture and the Built Environment in TU Delft are conducted face to face. The interviews were recorded if allowed by the interviewee, otherwise, notes were taken. The goal of the questionnaire is to understand what the actual relationship is between the available products and the design requirements of the architects. Moreover, through these interviews an attempt is made to get the architects’ opinion about the available products and if architects consider them satisfactory according to the current design needs. In addition, it is considered important to hear the architects’ vision about the future of adaptive facades and how they think the market should orient itself from a product development point of view. However, the amount of interviews conducted is small and it is just to give an impression at the kick-off of this thesis project and not to draw global conclusions.

iii. Design phase

After evaluating the case studies and in accordance

with Rollecate’s requirements, the facade design is formulated. The design becomes more detailed and hand calculations are conducted as well in order to predict each module’s performance. Right after, the efficiency of the system is tested for an open plan office in Amsterdam, Netherlands, which is also “Rollecate’s” main market. In addition, simulation models are used to check the energy performance of the façade system. The procedure has an experimental character as digital tools are used to investigate the energy performance. The software used is “Design Builder” and different configurations are tested in order to conclude to the façade composition with the best performance for offices in the Dutch climate. Finally, conclusions about this proposal are drawn in order to assess the implementation of the façade system in the market and suggestions are made for further developments and in order to avoid possible mistakes and failures in the future.

A graphical representation of the way this thesis is structured can be found in Figure 1 and the Time Planning in Figure 2.

VII. Societal and scientific relevance

In developed countries people spend on average 90% of their time indoors (Bougdah and Sharples, 2010). This situation can explain the fact that buildings globally account for a very big part not only of the final energy consumption but also of CO₂ emissions. As the global population is increasing and the living standards are improving, it can be easily predicted that these numbers are expected to increase substantially in the following decades. Therefore, new regulations have been set concerning the new construction, which impose that by 2020 all new buildings constructed within

the EU should reach nearly zero-energy levels.

The building envelope plays a strategic role in the energy and environmental performance of the building, significantly affecting the levels of indoor comfort. Advanced integrated building envelopes are one of the most promising adaptive façade systems and components in terms of energy reduction potential. Adaptive building envelopes can provide improvements in the building energy efficiency and economics through their capability to change their behavior in real time according to indoor-outdoor parameters, by means of materials, components and systems, while preserving the thermal and visual comfort of occupants. Therefore, adaptive facades can make a significant and viable contribution to meeting the EU’s 2020 targets.

In the framework of a decade-long research activity on Advanced Integrated Façades (AIF), the new concept which has been developed, namely the Multifunctional Facade Module (MFM) shows a considerable potential for building envelopes, being one of the most promising Responsive Building Elements (RBE). Except for the energy efficiency, MFMs provide a high architectural design freedom since they require no or extremely limited connections with other elements and technical installations, allowing easy installation on building site. In addition, they can be placed with different geometric configurations, different types of materials and different colours in order to guarantee customization. (Favoino et al., 2014 & Favoino et al., 2015)

The value of this research aims to investigate the advantages of these innovative facade concepts for the building’s energy efficiency and the user comfort and assess their implementation in the market in the near future.

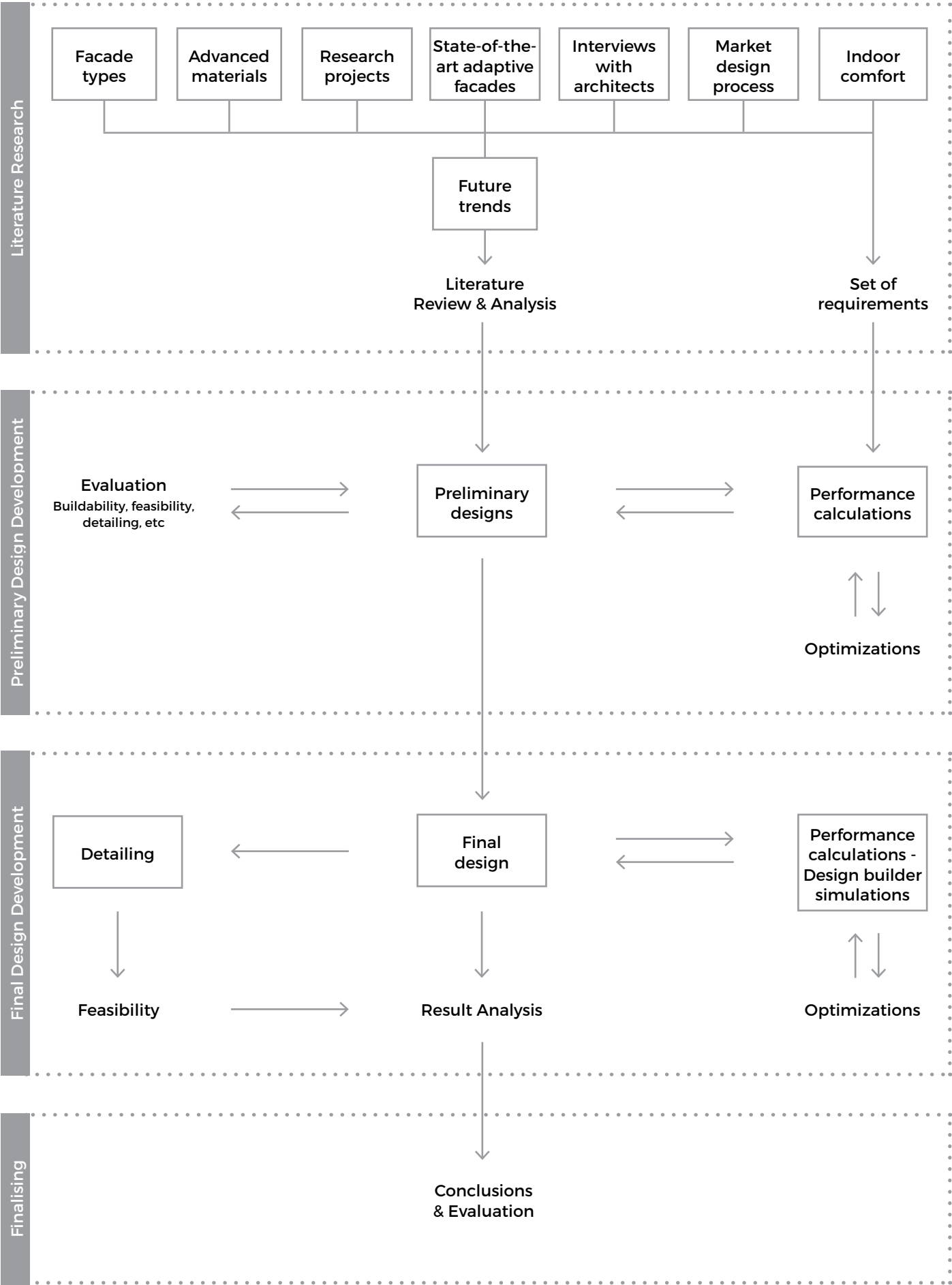


Figure 1: Graduation Methodology and Approach

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Figure 2: Time Planning

ADAPTIVITY & THE BUILDING ENVELOPE

I. What is an adaptive building skin?

Building envelopes are one of the most important design parameters determining the indoor environment, thus affecting energy usages in buildings. They act as intermediary filters between external environmental conditions and the desired interior requirements and therefore play a very important role in regulating and controlling energy waste (López et al., 2017). Architectural designers have taken an important step towards responsive solutions that can react situationally by developing adaptive facade systems.

The etymology of the word adapt stems from the Latin *adapto*, from *ad* (“to, towards, at”) + *apto* (“adjust, adapt; prepare”). In simple terms, adapt means to “adjust toward.” There are quite a few different categories except for “adaptive” like interactive, dynamic, kinetic or responsive architecture that have been used loosely and cause a confusion even to professionals. These categories are closely related domains within architecture that may or may not contribute to adaptation in the long run. Nowadays, the idea of adaptive architecture is misused in a number of projects that aim to be adaptive, however they fall in another category and contribute only slightly towards the long-term adaptation.

Throughout the years some people have tried to explain the term “adaptive facades”. Some of these explanations are the following:

“The ability of a system to adjust by itself in relation to a changing environment. An adaptive system, as in the case of building skins, has the ability to adapt the features, behaviour or configuration of the external environment.” (Dewidar et al., 2013)

“A climate adaptive facade has the ability to repeatedly and reversibly change some of its functions, features or behavior over time in response to changing performance requirements and variable boundary conditions, and does this with the aim of improving overall building performance.” (Loonen et al., 2013)

“The ability to respond or benefit from external climatic conditions to meet efficiently and more important effectively occupant comfort and wellbeing requirements.” (Luible, 2014)

From these explanations it becomes clear that adaptability grants a systematic flexibility that allows the optimal data to fluctuate given specific changes in stimuli. In another sense, adaptive systems are essentially self-optimising; they allow a facade to compensate for climatic fluctuations and changing occupant needs depending on the transient conditions they detect. Within an adaptive scenario, optimisation occurs situationally rather than globally. The system has the ability to adapt continuously offering optimal performance in relation to specific points in time rather than static points predetermined prior to implementation. Adaptation grants a versatility that can account for seasonal variability, daily weather pattern fluctuation or even future climatic drift. At any time, no matter the conditions of its initial conception, a building can be optimised for its surrounding environmental conditions.

The future building skin is required to respond dynamically, being able to react to non-continuous, ever-changing climatic conditions, occupant comfort and energy efficiency requirements. Like the skin of the human body, it should be able to adapt fully to the environmental conditions in a dynamic way, ensuring efficient, continuous,

and automatic management of energy flows in accordance to climate, user behavior, and market conditions of energy (Casini, 2016). A key characteristic of an effective intelligent building skin is its ability to modify energy flows through the building envelope by regulation, enhancement, attenuation, rejection or entrapment. In addition, an adaptive facade system can continually optimise its form to withstand the environmental conditions by utilising dynamic mechanics. It follows that these systems must maintain a certain flexibility and intelligence to respond actively to fluctuations in environmental stimuli.

After investigating the basic principle ideas of what is an adaptive facade and how it works, a scheme was made with the parameters that are directly related to the creation and function of adaptive facades. This was done taking into account the importance of general facade requirements, but also the interests of a company like “Rollecate”. Thus, the following scheme was created which can be seen in Figure 3. These parameters would be of an interest while researching the future of adaptive facades from a product development point of view.

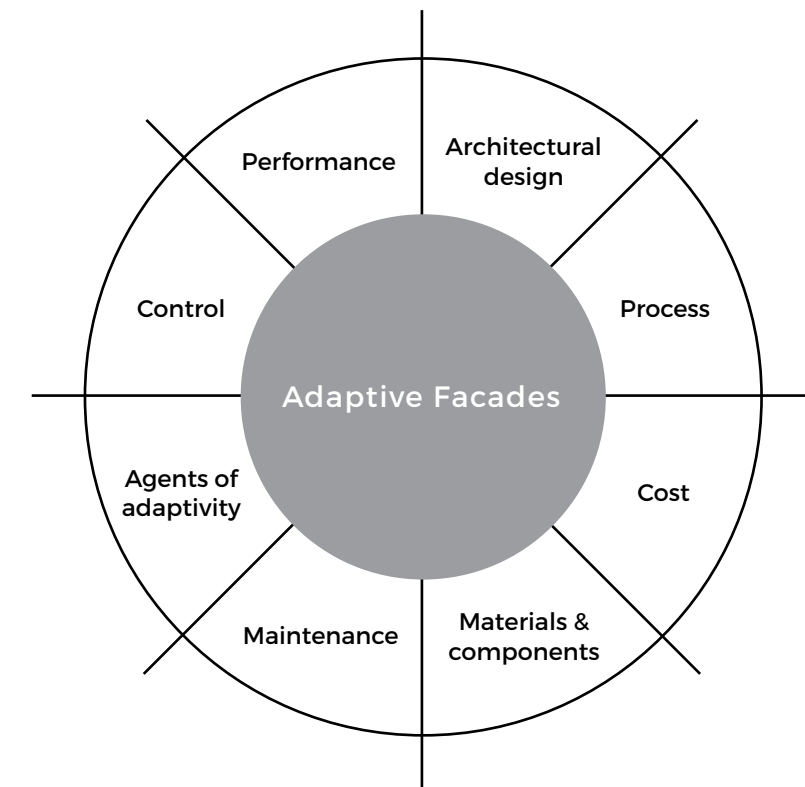


Figure 3: Parameters directly related with the creation and function of adaptive facades
Scheme created in collaboration with Shirin Masoudi

i. Classification of adaptive materials, components and elements

In this section, a classification of adaptive materials, components and elements is presented with the aim of putting forward their characteristics and gain knowledge on them. The final goal is to show the novel adaptive technologies regardless of how much developed or widely used they are. Therefore, the examples shown in Table 1 vary from the traditional ever used window to nanomaterials like graphene, which are still being tested. In order to achieve this goal, every example presented is analysed based on specific parameters which will be explained in this section and which are based on existing classification approaches. Many of those parameters are common with the ones used for the classification of adaptive buildings, products and research projects, which is presented in the next section. These parameters define most of the design variables and are the following:

Type of control: This criterion demonstrates how adaptation is achieved and therefore what type and how much control someone has over it. Adaptation can be realised manually, mechanically or neither of the two which means it is a smart material that responds by itself and is thus self-adjusting.

Agent of adaptation: Adaptive mechanisms are supposed to respond to a trigger. This is what is called agent of adaptation and it can be either a human, the environment, exterior or interior, or an object (Basarir and Altun, 2017). Exterior and interior environment can be further divided in more specific parameters as shown in Table 1.

Response to adaptation agent: A facade responds to the trigger of adaptation either in a static or in a dynamic way. The static way can be for example

a change in a material's form [property changing, energy exchanging materials] whereas the dynamic way is referred to facades which involve movement. (Basarir and Altun, 2017)

Purpose: This criterion refers to the change that occurs in the characteristics of a material/ component/element after the trigger of adaptation has taken place. (Loonen et al., 2015)

Response time: Adaptivity is realised through time and in different time scales. The response time until the adaptation has occurred can last from seconds, minutes, hours, days to even seasons. This can be justified if we translate motion in nature. Swift variations in wind occurs in seconds, clouds move in minutes, the sun requires hours to move through the sky and weather conditions change according to seasons.

Control of adaptivity: There are two types with which an adaptive facade responds to changing conditions: the closed-loop control and the open-loop control. Their distinction can be drawn by the fact that a closed-loop system is "automated", whereas an open-loop system is "automatic". (Loonen, 2010)

In the closed-loop system there are three basic elements involved as shown in Figure 4[a]: sensors, processors and actuators. There is also a possible fourth component, the controller, which is not always present. A sensor can detect ambient conditions, the processor collects this data from all sensors and the actuator translates this data into a mechanical, chemical or physical action. Closed-loop systems always imply the use of feedback control action, which is what distinguishes it from an open-loop system. Therefore, a closed-loop system is designed to automatically achieve

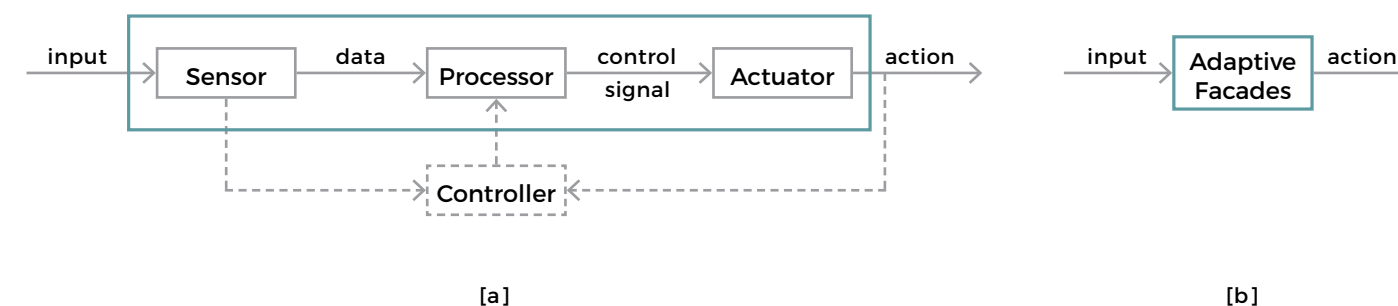


Figure 4: Adaptability control concepts: [a] closed-loop control & [b] open-loop control
Source: Loonen, R. C. G. M. (2010). Climate Adaptive Building Shells - What can we simulate? Architecture, Building & Planning Faculty. Eindhoven, The Netherlands, TU Eindhoven. MSc: 230.

and maintain the desired output condition by comparing it with the actual condition. (Loonen, 2010)

On the other hand, an open-loop system (Figure 4[b]) is an intrinsic feature of the adaptive facade's subsystem and therefore self-adjusting. The adaptive behaviour is caused automatically by an environmental stimuli and does not involve sensors and thus external power for its operation. For this reason, it also involves a limited number of components as can also be seen in the Figure ? and thus less complexity, which is undoubtedly an advantage. However, since it is self-controlled, there is no possibility for any intervention after it is built. (Loonen, 2010)

Degree of Adaptability: Adaptive change takes place either gradually, directly or a mix of both, which can be characterised as hybrid (Basarir and Altun, 2017). Opening a window causes a direct alteration in the indoor environment, whereas the use of PCM leads to gradual adaptation since it takes hours for the PCM to change its state from solid to liquid and reversibly. A hybrid system are the PV panels which start to absorb the sunlight

instantly when it reaches their surface but this procedure can last for as long as the sun reaches them which makes it a gradual procedure at the same time.

Classification parameters				Materials																	Components		Elements							
Product				Bimetal	Electrochromic	Fluorescent	Hydrogel	Liquid crystal	Mechanochromic	PCM	Photocatalytics (TiO2)	Photoelectric (graphene)	Photochromic	Phosphorescent	Piezoelectric	Shape memory	Silica gel	Suspended particle	Thermochromic	Thermoluminescent	Thermotropic	Air cavity	Photovoltaics	Vegetation	Window	Blinds	layered ETFE	Register	Sun shading	
Type of Control	Manual																								x	x	x	x	x	
	Mechanical																					x			x	x		x	x	
	Smart material			x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x		x			x				x		
Agent of Adaptation	Inhabitants										x				x												x		x	x
	Environment	Exterior Environment	Solar radiation	x	x	x							x	x	x								x	x	x	x	x			x
			Temperature		x					x						x				x		x								
			Humidity				x											x												
			Wind						x						x											x	x			
			Precipitation																							x			x	
			Noise																											
		Interior Environment	Temperature						x																		x			x
			Humidity				x																				x			
			Light		x																									x
			Air exchange rate																								x		x	
			Air velocity																											
			Sound level																											
Objects							x										x													
Response to Adaptation Agent	Static				x	x		x	x	x	x	x	x	x		x	x	x			x	x	x				x	x		
	Dynamic			x			x									x										x	x		x	
Purpose	Thermal comfort			x	x		x	x		x			x			x			x			x			x	x				x
	IAQ			x							x						x					x			x	x		x		
	Visual and Lighting Performance				x	x		x	x				x	x				x	x								x	x		x
	Acoustic Performance																						x							
	Energy Performance			x	x	x	x			x		x	x	x	x	x							x	x	x	x				x
Response time	Seconds				x	x		x				x	x		x	x	x	x			x				x	x			x	x
	Minutes			x			x		x	x	x			x	x	x						x						x		
	Hours									x												x								
	Days																								x					
	Season																									x				
Control of Adaptivity	Closed Loop				x			x										x								x	x		x	x
	Open Loop			x		x	x		x	x	x	x	x	x	x	x			x			x	x	x						
Degree of Adaptability	On-off				x			x					x					x								x	x		x	x
	Gradual			x		x	x		x	x	x			x	x	x	x		x			x			x					
	Hybrid											x												x						

Table 1: Classification of adaptive materials, components and elements
Table created in collaboration with Shirin Masoudi

ii. Classification of adaptive buildings, products and research projects

In this section, a classification of adaptive buildings, products and research projects is presented with the aim of putting forward the characteristics of these systems and gain knowledge on them. The final goal is to define the future trends of adaptive facade design and development of novel adaptive technologies according to the evaluation of the state-of-the-art existing adaptive buildings and mainly of the research currently conducted. In order to achieve this goal, every example presented is analysed based on specific parameters which will be explained in this section and which are based on existing classification approaches. In addition, another purpose of this classification is to reveal the strengths, weaknesses as well as the efficiency of each project.

The classification of the chosen projects with a small description for each of them can be found in Appendix A. Right after the classification, the results were counted, which can be found in tables in Appendix B and additionally graphs (Graph 1 - 8) were created which are presented in this section, in order to draw conclusions. Moreover, some categorizations of these projects were made in order to highlight the future trends. These can be found in this section as well.

The parameters based on which the examples are classified intend to examine mainly motivations and drivers, elements of adaptation, method and effect. The choice of these specific parameters was made based on the report "A Classification Approach for Adaptive Facades" by Basarir, B. and Altun, M. C. from Department of Architecture in Istanbul, Turkey published in 2017. This report presents an analysis of existing classification

approaches and then proposes a new approach. The final choice of parameters for this report was made according to the information that needed to be derived from each project with the aim of defining the current and consequently the future trends. These parameters define most of the design variables and are the following:

Response to adaptation agent: see section "Classification of adaptive materials, components and elements"

Exterior agent of adaptation: When studying adaptive architectural examples it is not only interesting to know what is actuated but also how that actuation is produced. In other words what is the trigger of adaptation. (Basarir and Altun, 2017) Exterior agents of adaptation can be solar radiation, temperature, humidity, wind, precipitation and noise.

Interior agent of adaptation: While the most common situation is the trigger to be exterior, it is also likely to be interior. Such agents of adaptation can be temperature, humidity, light, air exchange rate, air velocity and sound level.

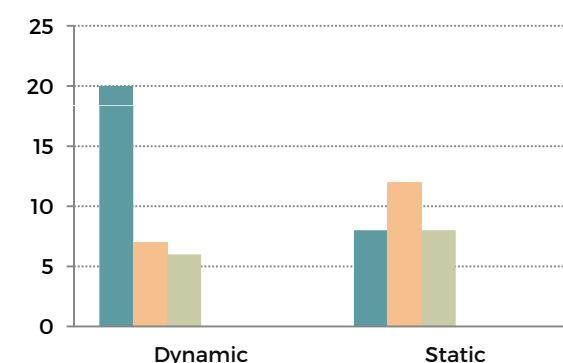
Purpose: This criterion refers to the change that occurs in the characteristics of a facade after the trigger of adaptation has taken place (Loonen et al., 2015). Purpose can be thermal comfort, indoor air quality, visual comfort and lighting, acoustic and energy production.

Control of adaptivity: see section "Classification of adaptive materials, components and elements"

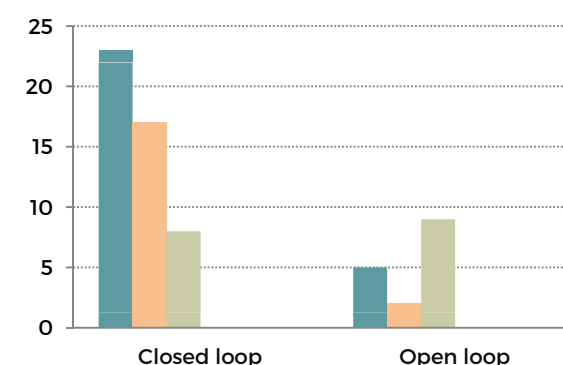
Energy: The system is evaluated according to its independency on external power. The ones that produce energy are classified as "+" like for example facades with integrated PV panels. Likewise, a

system that does not need energy to work nor does it produce energy is classified as "0" like for example facades with shape memory alloys. Finally, systems that need external power to work are classified as "-" like for example kinetic facades because kinetics is mediated by use of a computer.

Highest cost: The project is evaluated according to cost which is of high interest not only for a company like "Rollecate" which constructs facade systems but also for the client. According to the available information about each project, an assumption is made of which part of the facade set-up [materials, production, assembly, maintenance] involves the highest cost. This does not necessarily mean that it is expensive at the same time, just that this aspect has the highest cost.



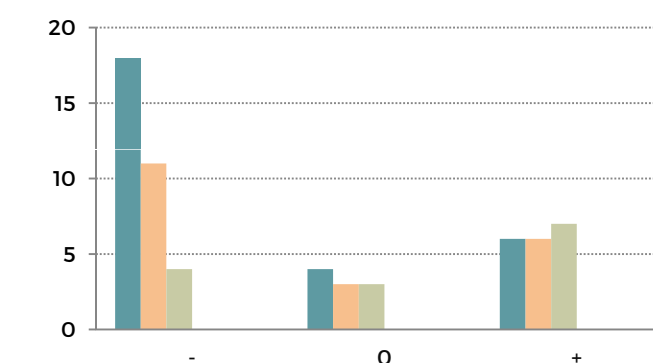
Graph 1: Response to Adaptation Agent
Graph created in collaboration with Shirin Masoudi



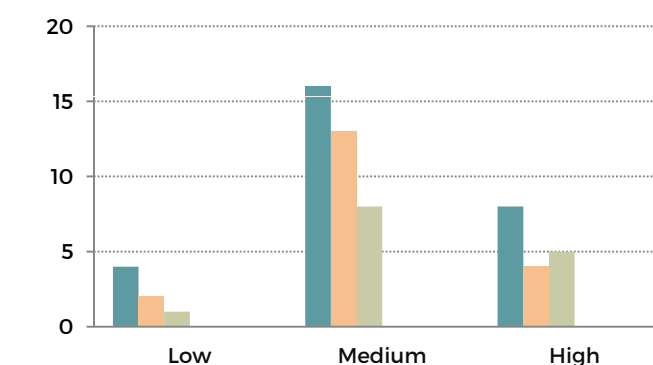
Graph 3: Control of Adaptivity
Graph created in collaboration with Shirin Masoudi

Architecture design freedom: Design criteria are also very important and especially of high interest for the architect, who wants to be given design flexibility and to not feel dependant on product or material constraints.

After the classification was made according to these parameters, the results were gathered in Tables, which can be found in Appendix B. In total, 61 examples were studied; 28 buildings, 19 products and 14 research projects. The results are presented in this section in Graphs 1 - 8, one for each parameter. This was done because it is considered important to see the differences between built and research projects. This difference will make clear which are the real trends and which ones are mostly in the research phase.

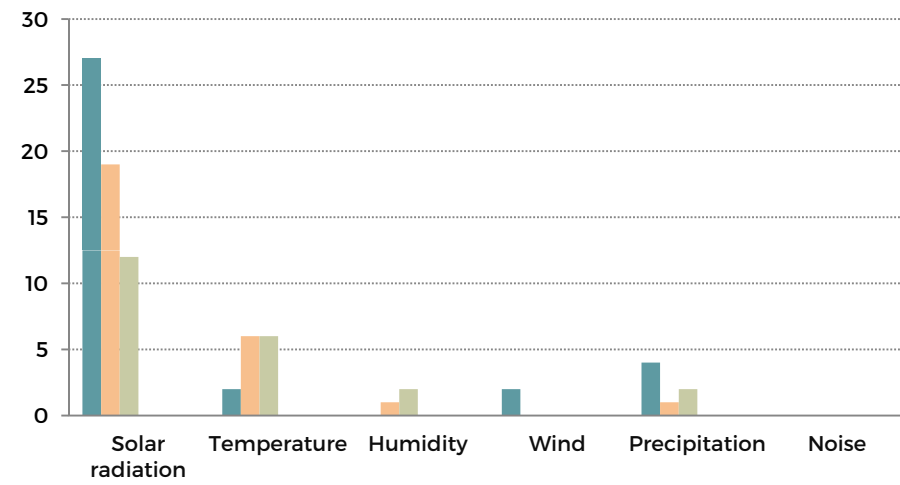


Graph 2: Energy
Graph created in collaboration with Shirin Masoudi

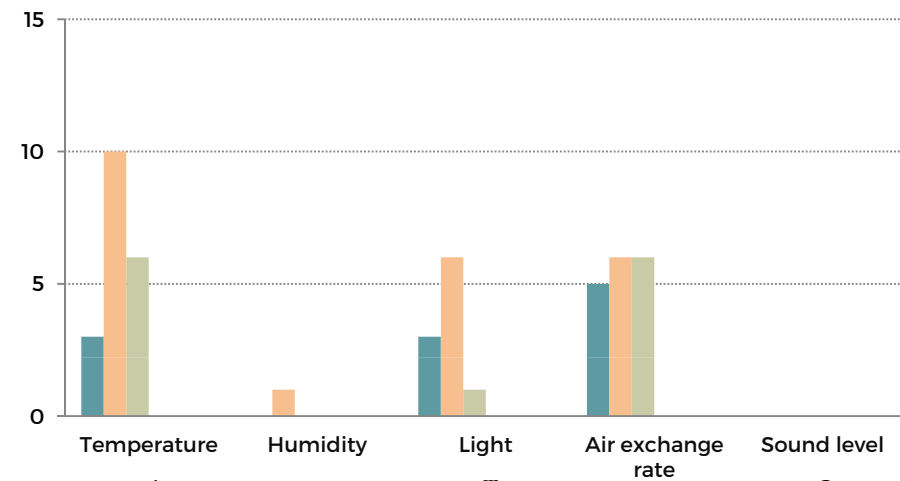


Graph 4: Architecture design freedom
Graph created in collaboration with Shirin Masoudi

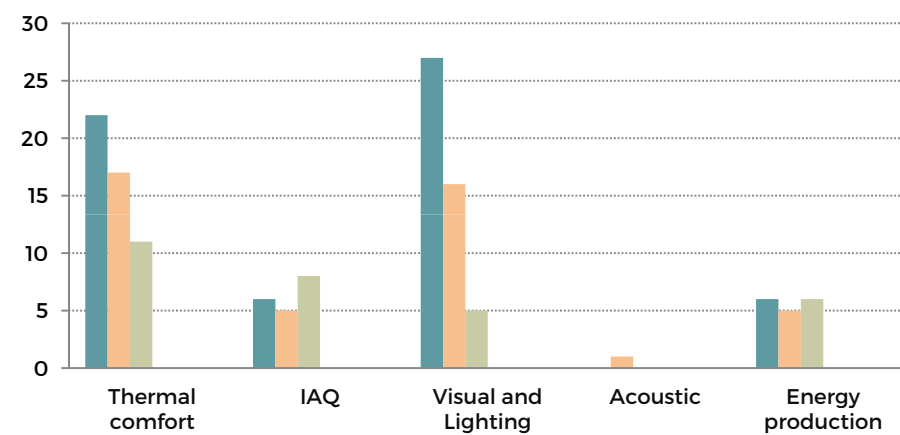




Graph 5: Exterior Agent of Adaptation
Graph created in collaboration with Shirin Masoudi

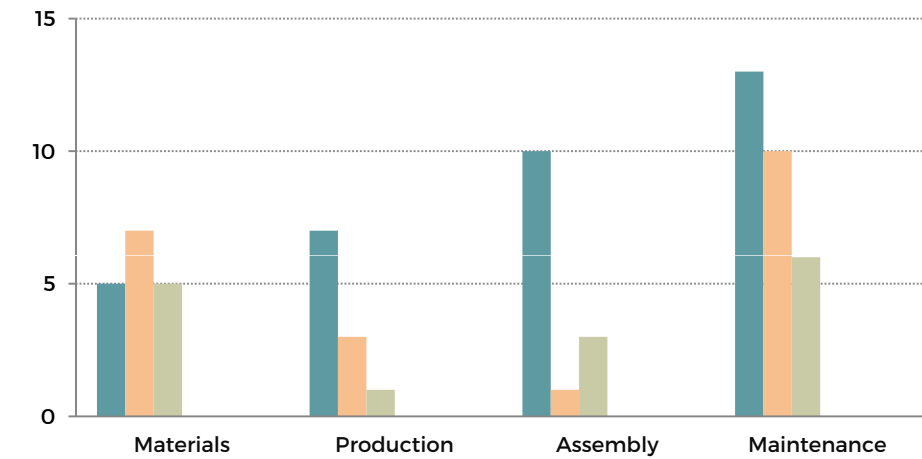


Graph 6: Interior Agent of Adaptation
Graph created in collaboration with Shirin Masoudi



Graph 7: Purpose
Graph created in collaboration with Shirin Masoudi

Buildings Products Research Projects



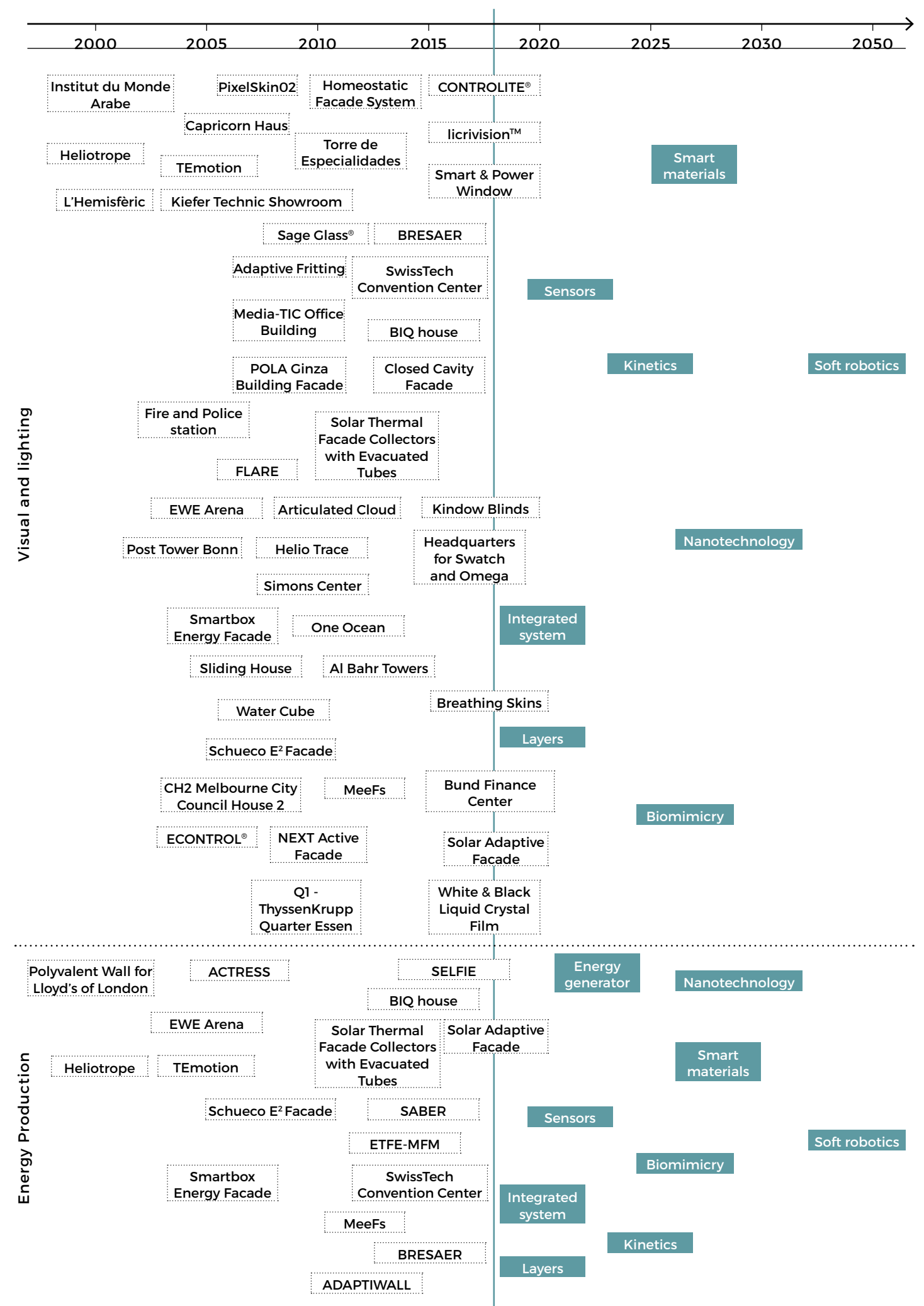
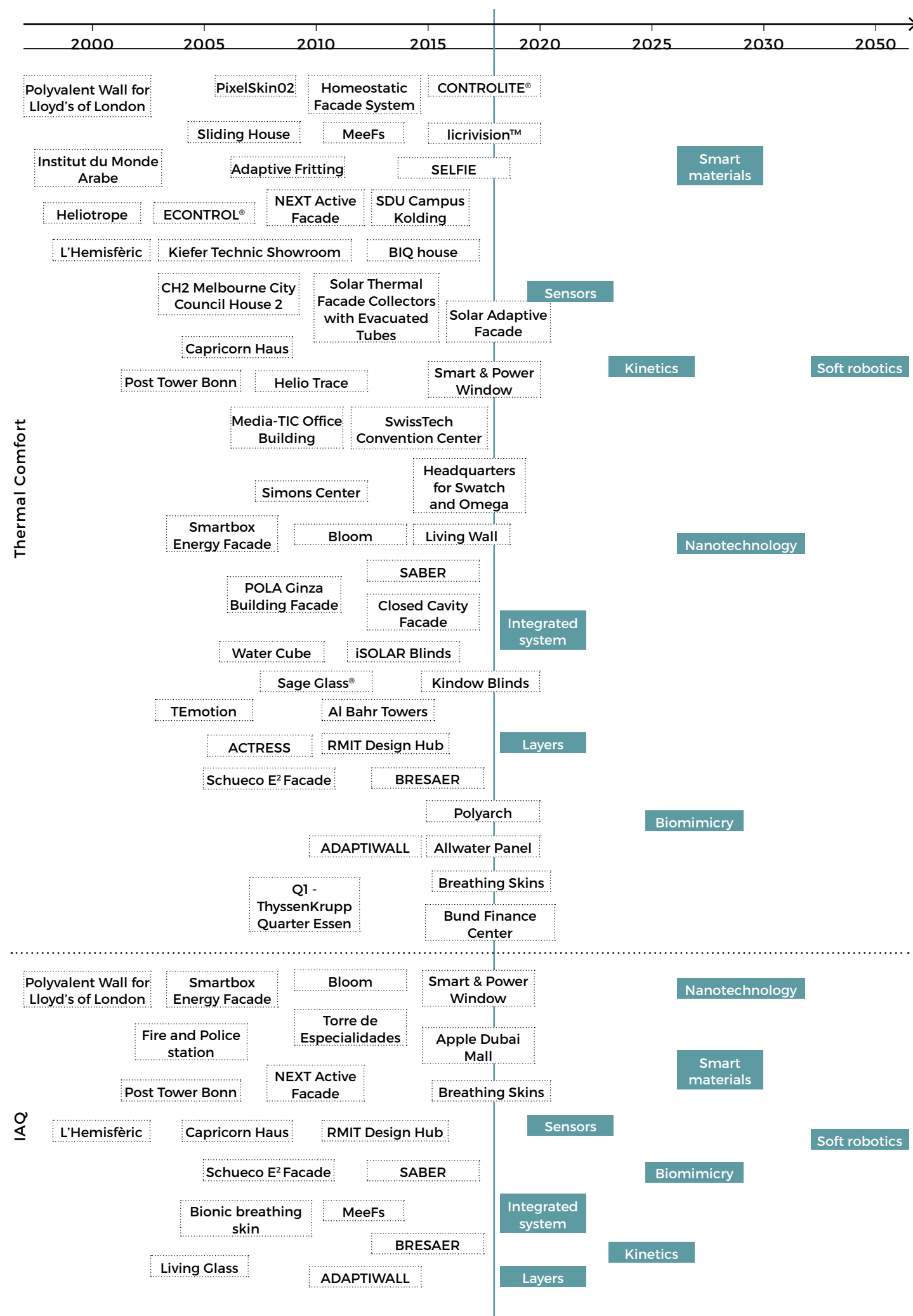
Graph 8: Highest cost
Graph created in collaboration with Shirin Masoudi

Buildings Products Research Projects

There are some conclusions to be drawn from these tables. First of all, the most common external agent of adaptation is by far solar radiation in all categories. Moreover, in most cases there exist only exterior agents and not interior ones. The most common interior agents are temperature or air exchange rate. The most common purpose of adaptation in buildings is visual and lighting with thermal comfort coming second, whereas the research projects focus more on the thermal comfort. In addition, the control of adaptivity happens in most cases of buildings with sensors, which means that closed-loop control is used, whereas research projects show a balance between close and open loop control which could mean that more research on smart materials is starting to be conducted. What's more, maintenance seems to be an issue in quite a lot of the reference projects showing the highest cost involved compared with the rest of the parameters. As far as energy is concerned, in real applications most of the projects require an external power to work, whereas in a considerable part of research projects production

of energy is provided by a part of the system. Last but not least, the architectural design freedom is medium in most cases, since most of the projects involve limitations but could be also adjustable in other geometric configurations.

In the following two pages, the chosen reference projects can be found divided according to the purpose of adaptation and put in a timeline. The timeline was created including the decades up until 2050 in order to show the assumed future trends based on the results of the classifications made. These future trends will be explained in the next section together with some additional concepts which were observed but are not considered as a trend.



II. Emerging adaptive concepts

Following the literature study on adaptive facades and after the classification of the reference projects was made, there were clearly some common concepts that were encountered frequently or on the other hand were unknown and had only recent and limited applications. The most common ones were gathered in Table 2, in order to see which of them are encountered the most. Important was also to distinguish which ones are most common in buildings, meaning in real applications, and which are found mostly in research projects and

then assess this frequency with the Technology Readiness Level of the project, an evaluation criterion which will be explained later in this report.

i. Biomimicry

Biomimicry is an innovative approach and an emerging field in architecture. Similarities can be observed in the way nature's devices and the architectural design work, which can be seen in Figure 5. There are already quite a few buildings, for which architects derived inspiration through the

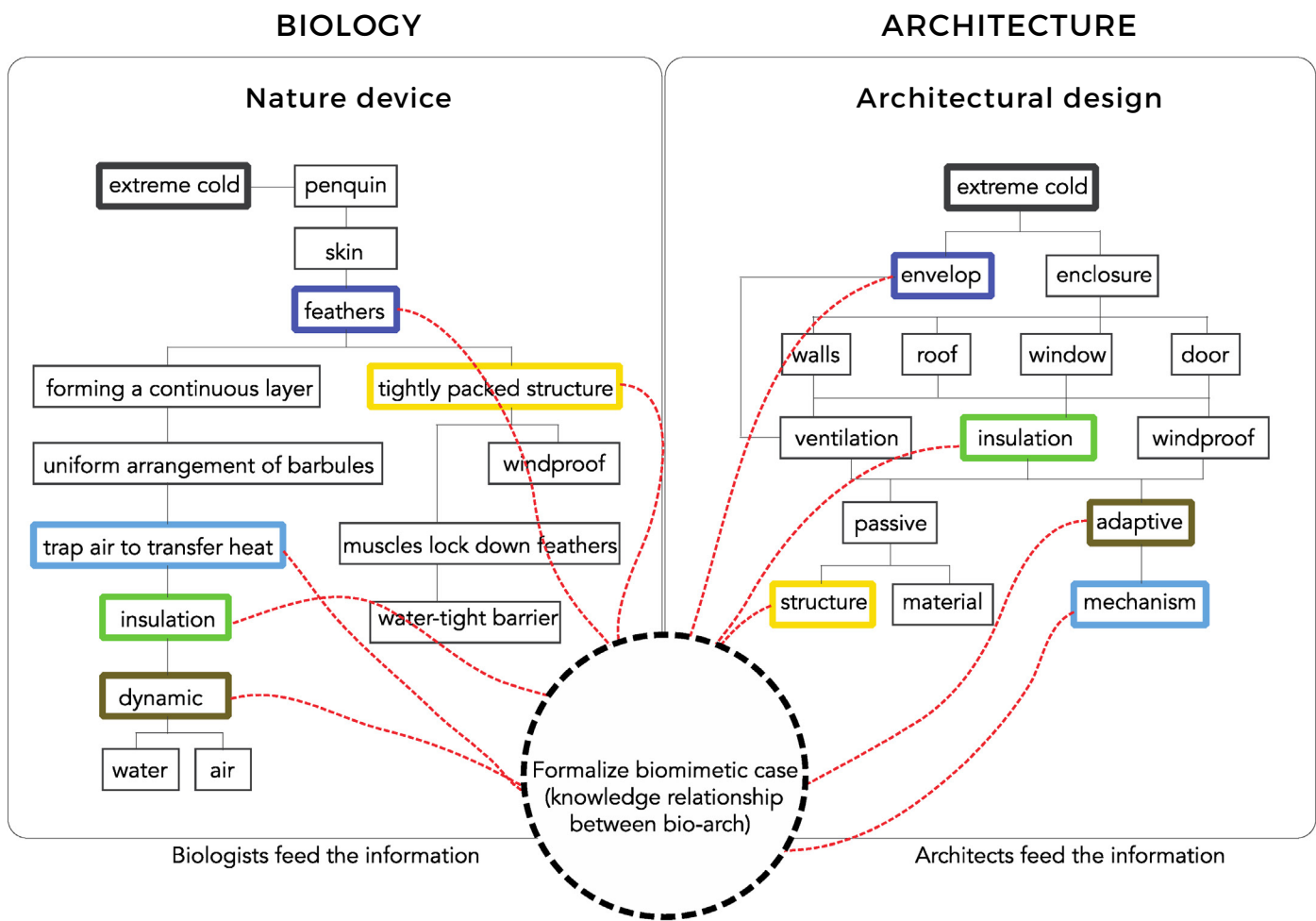


Figure 5: Relationship between biology and architecture
Source: Chayaamor-Heil, N. and N. Hannachi-Belkadi (2017). "Towards a Platform of Investigative Tools for Biomimicry as a New Approach for Energy-Efficient Building Design." Buildings 7(1): 19.

	Reference projects	Concepts											
		Biomimicry	Smart materials	Nanotechnology	Sensors	Integrated system	Layers	Low-tech	Aesthetics	Kinetics	Soft Robotics	High Transparency	Energy generator
Buildings	Institute du Monte Arabe (1987)	x			x		x		x	x			
	Heliotrope (1994)	x			x					x		x	x
	L'Hemisfèric (1998)	x			x				x	x		x	
	Post Tower Bonn (2003)				x	x	x	x				x	
	Fire and Police station (2004)					x		x	x				
	Ewe Arena, Germany (2005)	x			x					x		x	x
	Sliding House (2005)	x			x		x	x	x	x			
	CH2 Melbourne City Council House 2 (2006)	x			x			x		x			
	Kiefer Technic Showroom (2007)	x			x					x			
	Capricorn House (2008)					x	x	x					
	Water Cube (2008)						x		x				
	Media-TIC Office Building (2009)			x	x		x						
	POLA Ginza Building Facade (2009)	x			x				x	x		x	
	Q1 - ThyssenKrupp Quarter Essen (2010)	x			x			x		x		x	
	Helio Trace (2010)	x			x		x			x		x	
	Simons Center (2010)	x			x		x		x	x			
	Articulated Cloud (2011)							x	x	x			
	Torre de Especialidades (2012)			x					x				
	One Ocean (2012)	x			x				x	x			
	Al Bahr Towers (2012)	x			x				x	x			
	RMIT Design Hub (2012)					x	x					x	x
	Homeostatic Facade System (2013)	x	x				x		x	x			
	SAHMRI (2013)	x						x	x				
	BIQ House (2013)				x		x						x
Swiss Tech Convention Center (2014)								x			x	x	
SDU Campus Kolding (2014)	x			x					x				
Headquarters for Swatch and Omega (2017)						x		x					
Apple Dubai Mall (2017)	x			x			x	x	x		x		
Bund Finance Center (2017)				x		x		x	x				
Products	Polyvalent Wall for Lloyd's of London (1981)				x	x	x						x
	TEmotion (2005)				x	x	x						x
	Smartbox Energy Façade (2006)				x	x	x						x
	Schueco E2 Facade (2007)					x	x						x
	Flare - Kinetic Membrane Facade (2008)				x				x	x			
	PixelSkin02 (2008)		x						x	x			
	NEXT Active Facade (2010)					x	x	x					
	Solar Thermal Facade Collectors with Evacuated Tubes (2013)						x						x
	Smart Window & Power Window (2014)				x	x	x			x		x	x
	licrivisionTM - Liquid Crystal Window (2015)			x			x					x	
CONTROLITE® - Intelligent Daylighting System (2016)				x		x			x				
Research Projects	Living Glass (2005)	x	x							x		x	
	Bionic Breathing Skin (2007)	x		x			x		x	x			
	ACTRESS (2007)		x		x	x	x						x
	Adaptive Fritting (GSD) (2009)						x		x	x			
	Bloom (2011)	x	x							x			
	SABER (2014)	x	x							x			
	Adaptive Solar Facade (2015)	x			x					x	x		x
	Breathing Skins (2015)	x					x		x	x			
	SELFIE (2016)		x	x	x	x	x						x
	Allwater Panel (2017)						x					x	

Table 2: Most commonly encountered concepts in adaptive reference projects
Table created in collaboration with Shirin Masoudi

study of natural designs' principles. This means that the building mimics a specific organism or the way an organism behaves or relates to its environment. This correlation to nature can be expressed by the building's form, material, construction, process or function.

The closest approach is the one of the adaptations to the environment by plants, since they are bonded to a specific location just like buildings. Being unable to move, they have developed special characteristics in order to respond to ever changing environmental issues over time and protect themselves. The plants' leaves possess multi-functional properties providing more than one solutions for different environmental conditions at the same time. (López et al., 2017) In addition, as stated in the journal article of Knippers J. and Speck T. (2012): "An important characteristic of natural systems is a multi-layered, finely tuned and differentiated combination of basic components, which lead to structures that feature multiple networked functions".

However, since biomimicry is a new paradigm, there are some issues in implementing it in the built environment. First of all, its development is limited only on certain scales as can be seen in Figure 5. In addition, the biggest drawback is the lack of a clear systematic methodology, since the ecosystem does not involve the presence of design methods. Moreover, many projects have failed because of mimicking nature without adjustments, thus creating conflicts with integrated parts of the design concept. (Al-Obaidi et al., 2017)

ii. Smart materials

In the last decades, emerging ecological demands

have been the driving force in the development of highly evolved building technologies, such as material development. Smart materials is one of the advancements and show a dynamic behaviour in response to external stimuli, however, their application is still limited. They are used as bulk materials or more often in form of coatings. There are five characteristics that distinguish smart from traditional materials (Loonen, 2010 & Casini, 2016):

- ◊ transiency - response to multiple environmental states
- ◊ selectivity - discrete and predictable response
- ◊ immediacy - real-time response
- ◊ self-actuation - internal response of the material or system
- ◊ directness - local response.

Moreover, smart materials can be divided in two categories (Casini, 2016):

- ◊ property-changing materials - one of their mechanical, chemical, optical, electrical, magnetic or thermal properties is autonomously and reversibly changed in response to a stimuli
- ◊ energy-exchanging materials - an input energy is converted to into another form of energy by means of the first law of thermodynamics.

iii. Nanotechnology

Nanomaterials fall in the same category as smart materials, namely "advanced materials" with the difference that they respond in a different way. They show a high-fixed response, introducing new functionalities and improved properties while adding value to existing products and processes in a sustainable way (Casini, 2016). The fundamental difference of nanomaterials in comparison to

traditional ones is the nanoscale property, which improves the performance of bulk materials significantly.

The word "Nanotechnology" was first used back in 1974, however, their application is still limited although they hold great promise for future innovation. There are still issues to be addressed before their full commercial application regarding costs and health and environmental aspects

iv. Sensors

The majority of the reference projects involves the use of sensors, which detect events or changes in the environment and send the information to other electronics, frequently a computer processor. A sensor's output changes when the measured input changes as well. After the input is processed, the actuator translates this data into a mechanical, chemical or physical action.

The presence of sensors in almost all reference projects can be justified by the need of the adaptivity to respond to ambient conditions which should be measured in real time in order to give continuous feedback. In this way, the system can respond when specific predetermined requirements have been met.

v. Integrated system

Many of the reference projects consist of an integrated facade system, which means that all functions from building services installations are integrated in the facade. This approach offers flexibility of the layout, the possibility of all functions' synchronization and the advantage of premanufacturing for later on-site installation

(Knaack et al., 2011). Possible drawbacks could be the complexity of the system and the maintenance costs. The fact that all responsible advisors need to get involved at a very early stage of the design process can be either an advantage since communication lapses will be avoided or a disadvantage since they are forced to not only coordinate but also to ensure common quality and cost levels.

vi. Layers

According to Knaack U. (2011): "Examples such as space suits, Gore-Tex jackets and milk containers prove that the combination of layers with different properties can lead to remarkable performance". Studying the reference projects, it was noticed that a big part of them use different layers in order to achieve the desirable adaptivity. Layers were used in two different ways. First, there are reference projects where layers of the same material were used with the purpose for visual and lighting control or in order to take advantage of the material's properties in layers. The second way is the use of different functionalized layers to facilitate different purposes at the same time.

vii. Low-tech

Another characteristic noticed while doing the classification of adaptive buildings was that quite a few of them achieve the concept of adaptivity without the use of novel technologies. On one hand, low-tech solutions are in their nature simple and reliable which would be a benefit for the usually complex design of adaptive facades, but on the other the definition of their characteristics is ambiguous. In terms of this research the reference

projects were assigned as “low-tech” according to the three following criteria (Basarir, 2017):

◊ Material - use of simple, raw or non-processed, locally produced materials

◊ Simplicity - simple facade design constructed through simple processes

◊ Knowledge - use of traditional, non-mechanical kind of technology and unsophisticated equipment and production techniques; specialisation is not required. In this category, it is important to mention that the level of technical maturity matters because widely applied techniques which are not considered cutting edge anymore are being used by low-tech creators.

viii. Aesthetics

Except for meeting functional requirements, building envelopes should also be aesthetically pleasant reflecting each period's qualities and technological improvements. Nevertheless, a good design is technically driven and is strongly related to a building's performance, so aesthetics and performance are strongly combined. However, in many cases architects go for aesthetics sacrificing the maximum performance that could be achieved. In the case of adaptive facades, form and morphology are currently trends to mimic nature in architecture. Therefore, it is important to distinguish buildings that show an adaptive behaviour and approach contributing considerably to overall building performance and the ones promoted as adaptive, but in reality just resemble a mechanism only as a design concept.

ix. Kinetics

Adaptive facades with moving parts show a great potential over conventional building envelopes,

whose static properties are not the most optimal efficiency solution. In most cases, kinetics are involved in order to provide adaptive facade shading systems, however, they are also used to follow the sun in order to absorb sunlight or even just for aesthetics. In addition, in most cases the movement is bio-inspired and in some engineers try to question geometrical and structural limits.

x. High Transparency

In recent decades there was clearly a fashion of using large glazed surfaces, which were excessive with respect to the need for daylighting. Such facade configurations cause on one hand significant transmission heat losses during the winter and on the other huge solar heat gains in the summer period. In quite a few cases of the reference projects though, adaptive facades which involve movable parts take advantage of large glazed surfaces in buildings, while offering the possibility of a protected version by the movement of opaque surfaces. In this way, they maximize the solar heat gains while limiting the energy demand for space heating.

xi. Energy generator

Nowadays, the increasing necessity of sustainability in built environments has led to a new demand expressed by society, which expects from the building system to make a transition from its consumer role to that of an energy producer (Casini, 2016). A considerable amount of the reference projects consists of Photovoltaic systems which are able to absorb sunlight and convert it to electric power. The mount of PV installations is either fixed or in more recent developments,

solar trackers are used in order for the PV panels to follow the sun with the aim of maximizing the direct exposure time. In this latter case three of the previous mentioned concepts are involved as well, namely, sensors, biomimicry and kinetics.

Recent developments involve research of materials in order to lower costs, increase their efficiency as well as offer more design flexibility in terms of different colors and integration in the facade.

xii. Soft Robotics

Soft robotics is a field in robotics that is growing rapidly nowadays. The basic idea behind this field in mechanics is the design of robots from highly compliant materials, similar to those found in living organisms. Such a soft material is for example silicone rubber. These materials are activated pneumatically by simply altering the levels of air pressure in the air channels of the robots. In this way, they can perform various different movements.

The research field is still in a nascent stage, and the main efforts are currently invested onto the exploration of unconventional materials and their implementation in robotic systems. Therefore, only one of the reference projects, namely the research project “Adaptive Solar Facade” from ETH University involves the use of soft robotic pneumatic actuators in order for the individual facade modules to be actuated.

xiii. Media

Architecture tends to use media facades more and more as a stylistic feature. What used to be applied to facades after construction more in the way of an addition is now part of the planning process.

Recent developments in LED dynamic lighting technologies are empowering new approaches for visionary design. Innovative tools are available to architects and designers to develop a more dynamic concept of architecture by integrating lighting and media applications into architectural façades. Media façades are layers of individually controllable lights, attached to or even woven into the exterior surface of a building to function as a dynamic screen. Media facades set new standards for the fusion of architecture, media, and art by broadcasting projections, animations, or messages into the urban space.

Although media facades are considered a trend following the literature study, they were not included in the table of the most commonly encountered concepts since their purpose is not related to climate conditions.

III. Technology Readiness Levels

The research projects presented in the framework of this thesis report are in a different research level meaning that their effectiveness is not proven yet in an extent so as to guarantee their application in real projects. Therefore, it is considered important to evaluate their distance from the full commercial application. This should be done because the goal of this thesis is to seek a possible future product or system that “Rollecate” could evolve and implement in its products in the near future.

A valid way to do this evaluation is to assign these research projects to the so called Technology Readiness Levels (TRLs). By evaluating a technology project against the parameters for each TRL, one can assign a TRL rating to the project based on its stage of progress. TRL is a new development in “Horizon 2020”, which is the biggest funded EU Research and Innovation Programme with the aim of securing Europe’s global competitiveness. TRLs are indicators of the maturity level of particular technologies. They are a measurement system that provides a common understanding of technology status and addresses the entire innovation chain.

There are nine technology readiness levels; TRL 1 being the lowest and TRL 9 the highest. It is worth mentioning that the completion of a level does not automatically mean that a project has moved to the next TRL number. This will be accomplished when a project will manage to obtain the next number according to the description in the diagram (Figure 6). Information about the parameters of each level’s evaluation can be found in Figure 6. The nine Technology Readiness Levels were retrieved from the General Annexes of “Horizon 2020” Work Programme 2016-2017 and are the following:

- ◊ TRL 1 – basic principles observed
- ◊ TRL 2 – technology concept formulated
- ◊ TRL 3 – experimental proof of concept
- ◊ TRL 4 – technology validated in lab
- ◊ TRL 5 – technology validated in relevant environment (industrially relevant environment in the case of key enabling technologies)
- ◊ TRL 6 – technology demonstrated in relevant environment (industrially relevant environment in the case of key enabling technologies)
- ◊ TRL 7 – system prototype demonstration in operational environment
- ◊ TRL 8 – system complete and qualified
- ◊ TRL 9 – actual system proven in operational environment (competitive manufacturing in the case of key enabling technologies; or in space)

The products and research projects presented in Appendix A have been evaluated by comparing the available information about their research level with the nine Technology Readiness Levels and the results are shown in Table 3.

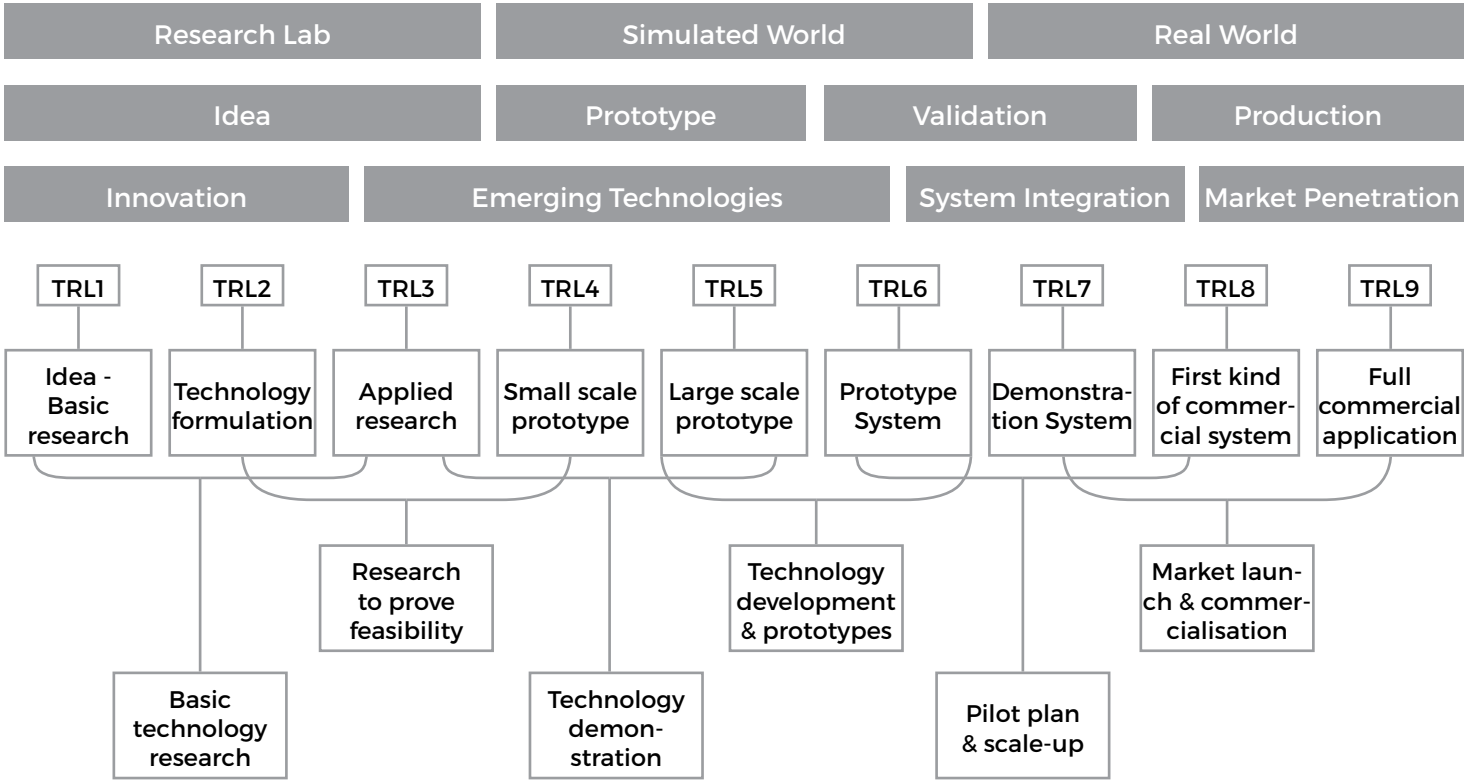


Figure 6: Technology Readiness Levels
Source: https://www.nasa.gov/pdf/458490main_TRL_Definitions.pdf

Reference projects		TRL
Products	Polyvalent Wall for Lloyd's of London (1981)	2
	TEmotion (2005)	9
	Smartbox Energy Façade (2006)	5
	Schueco E2 Façade (2007)	9
	Flare - Kinetic Membrane Façade (2008)	4
	PixelSkin02 (2008)	4
	NEXT Active Façade (2010)	9
	Solar Thermal Façade Collectors with Evacuated Tubes (2013)	5
	Smart Window & Power Window (2014)	8
	licrivationTM - Liquid Crystal Window (2015)	8
Research Projects	CONTROLITE® - Intelligent Daylighting System (2016)	9
	Living Glass (2005)	3
	Bionic Breathing Skin (2007)	3
	ACTRESS (2007)	5
	Adaptive Fritting (GSD) (2009)	8
	Bloom (2011)	4
	SABER (2014)	4
	Adaptive Solar Façade (2015)	6
	Breathing Skins (2015)	4
	SELFIE (2016)	5
	Allwater Panel (2017)	5

Table 3: Assessment of the research projects and products according to TRLs
Table created in collaboration with Shirin Masoudi

IV. Market design process

Another step of the literature research was to gain knowledge on how the market works and how it drives the engineering design process. This aspect is especially interesting because of the architect, who plays a strategic role being between the manufacturers and the clients (Figure 7).

There are two ways of marketing approaches, the push and the pull marketing. The main distinction between the two lies in the way the consumers are approached. The idea behind the push marketing is to push customers towards the product and that is why it is referred to mass production products. On the other hand, the pull marketing aims at establishing a loyal following and draw customers to the products. The way the push-pull relationship works, can be seen in Figure 8 and will be explained in detail later in this section.

i. The architect

When a new product is implemented in the market, it is very important that the potential users are aware of its existence, especially when it is about new innovative technologies. In the field of the building sector, the clients hire and trust architects as experts of coming up with the best solution in terms of design, environmental and thus financial interest for them. An appropriate design which takes advantage of new technological systems can ensure better energy performance of buildings and thus lower costs. Architects have strong repulsions and preferences for specific products. Therefore, it is considered of high importance that when a company like “Rollecate” is researching new products to implement in the market, the architects’ opinion is taken into consideration. In

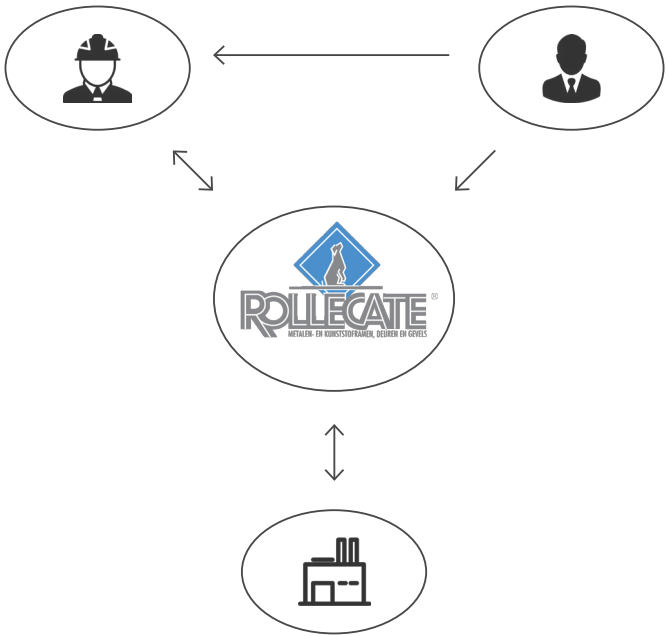


Figure 7: Supplier-Architect-Client Relationship

the building sector the architect is the one that will pull the customers to the products and will make them avoid the pushing, promotional products.

For this reason, in the beginning of this research project, a few interviews with architects from the Department of Architecture and the Built Environment of TU Delft were conducted. This was done in order to get an idea about their opinions regarding adaptivity, the existing systems and their knowledge about those systems. The interviews can be found in Appendix C, whereas the most important results are summarised here. First of all, From the three architects interviewed, noone had used a more technologically advanced adaptive system except for sunshading and

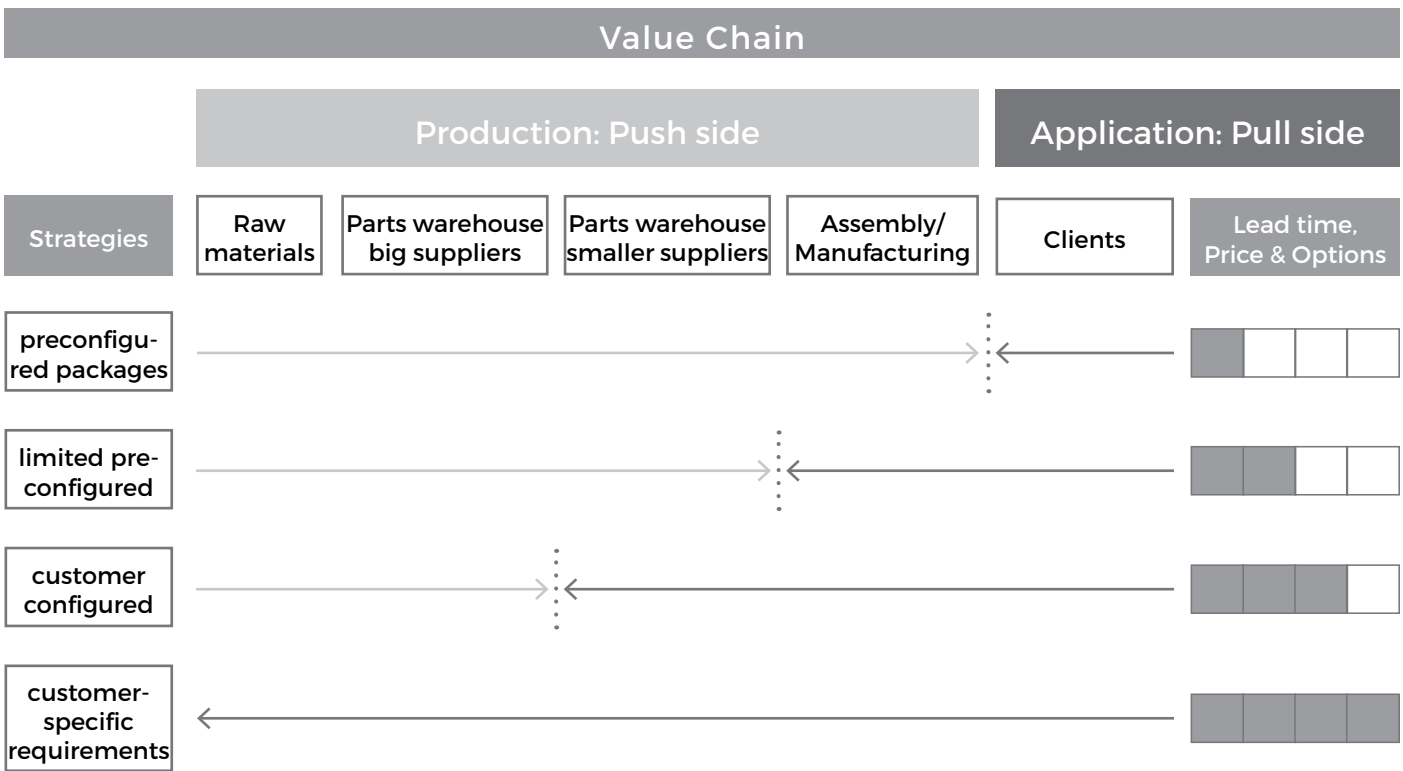


Figure 8: Push-Pull Relationship
Source: JDA Software Group Inc.

operable windows, nor have they ever monitored the performance. However, they do believe in the potential of adaptive systems and that a good design its technically driven, so a high performance should coexist with aesthetics. A few proposals for the future were the consideration of thermal mass and night-time cooling andf that the complexity and maintenance should be kept low, while durability and performance remain high.

ii. The client

It is believed that customers require from one single product to fulfill an enormous amount of needs, while at the same time be as visually appealing as possible. In addition, they also need to be given

freedom of choice and therefore, products need to provide the necessary flexibility. Cost, time and quality are the main variables that drive customer needs. These values can be seen in Figure 8 in relation to the influence of pull and push sides. From this scheme it is understood that the more the client pulls, the further he/she has to search in the supply chain, since the product he/she seeks for is custom. This procedure offers more options but requires of course more money and longer lead times. On the other hand, readily available products can be easily accessed without the need to get in contact with suppliers or any other stakeholders of the supply chain and therefore they are cheaper. However, the options of the client are limited to the preconfigured packages offered by the market.

iii. Product development

A new product development can be triggered by different parameters as can be seen in Figure 9 with the aim of satisfying newly defined customer wants or market niches. It can start from a crazy idea or just be an evolvement or modification of an existing product. In any case the problem development is of great importance in order for the final product to have societal and market relevance. The stages of product development follow more or less the logic of the Technology Readiness Levels presented in previous section.

An interesting remark is the importance of the market pull as explained in the previous section in

the procedure of product development. It can be a trigger itself, however, as seen in Figure 9, two other triggers lead also back to market pull. Thus, it is apparent that product development requires an understanding of customer needs, the competitive environment, and the nature of the market. It is very important to understand the customer's preliminary requirements which formulate the problem definition and the functional requirements of the new product. This procedure will lead to a complete product specification. In many cases the client does not really know what he/she asks for and therefore has ambiguous requirements which sometimes are also in conflict. In this stage, critical thinking of the designer is highly needed in order

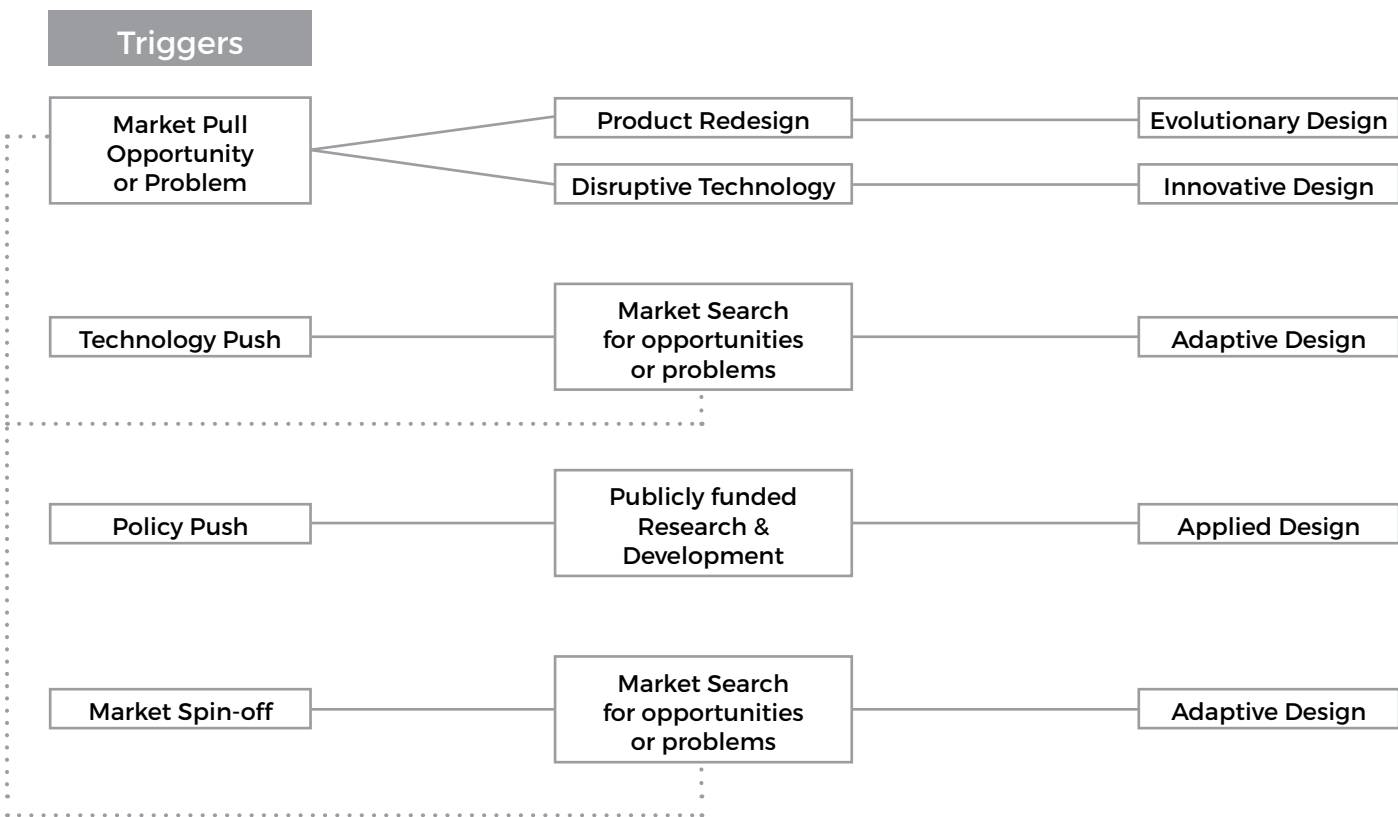


Figure 9: Triggers of the design process
Source: Devon, R. and Jablolkow K. (2010). Teaching Front End Engineering Design (FEED). Mid-Atlantic ASEE Conference, Villanova University.

to assess these requirements and not presume that they represent maturation.

Another important aspect are the costs involved in the new product development. It is important that costs related to production, manufacture and use are determined at an early stage of the design as expenses increase substantially through the various development stages. For this reason, it is easier and cheaper to make changes at the conceptual stage.

iv. Design as a market driven process

In the case of "Rollecate", the driver to investigate the future of adaptive facades is the market pull, since there were clients asking about it. Therefore, it was considered important to research what the procedure of the product development is from the trigger and the initial idea until the final design proposal and the actual construction. This procedure can be seen in Figure 10 and involves

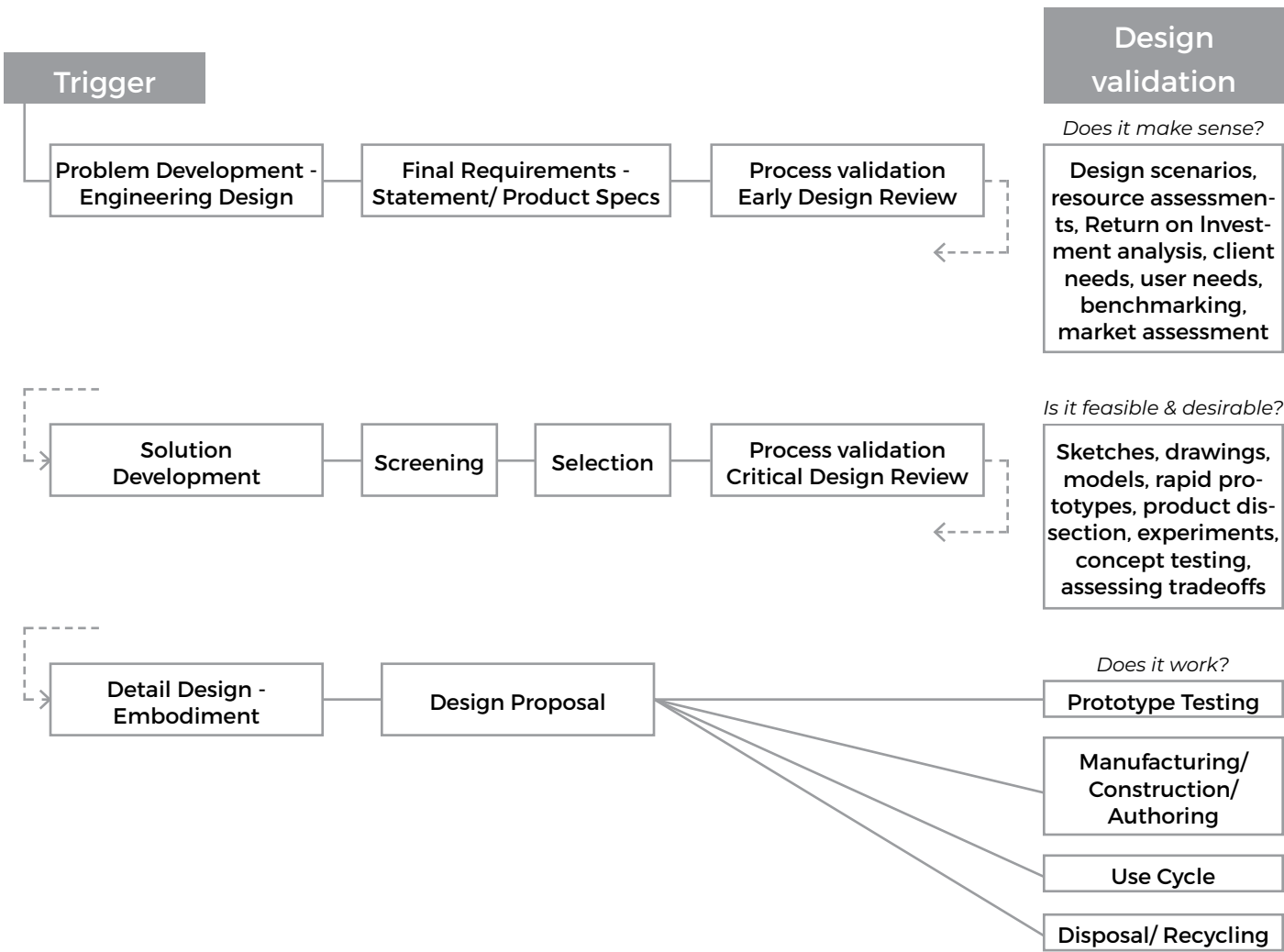


Figure 10: The Engineering Design: A market driven process
Source: Devon, R. and Jablolkow K. (2010). Teaching Front End Engineering Design (FEED). Mid-Atlantic ASEE Conference, Villanova University.

three stages: the input (trigger), the process and the output (the design proposal) (Devon and Jablokow, 2010). First, the final requirements are being set and validated, then a solution is developed which is assessed and reviewed, again validated with the aim to reach the final design proposal to be manufactured and tested as final validation. This is also the methodology approach followed in this research design.

v. Product Architecture

When designing a new product, it is of great importance to know the possible ways, in which the components can be arranged and connected because it influences considerably the behaviour and function of a product. Therefore, it is also of great importance to consider the arrangement of the components at an early stage when a new product is specified and developed in order to be implemented in the market. For this reason, it is useful to know the history of a product development until today, what configurations have been already applied and what are their advantages and disadvantages. For this reason, the evolution of facade types will be presented in a following section.

Product architecture involves the arrangement of functional elements, mapping of these elements to physical components and the specification between these interfaces. Product architecture is divided in two categories, integral and modular architecture, although most products exhibit a combination of the characteristics. It is important to assess which functional elements should be treated in a modular way and which in an integral one. Modular architecture requires a better management of the systems and their interfaces,

whereas integral architecture involves a closer collaboration between all responsible advisors at an early stage of the design process.

vi. Integral architecture

At integral architecture, there is a many-to-one mapping of functions and components, which means that the components are multi-functional. In addition, the interfaces between components are well coupled and this is why components of fully integral products cannot be changed without changing other components, in order for the system to keep working properly. Integral products are often designed to maximize a certain performance, however, an extensive redesigning is required if a modification is made to one of the components. An example of integral architecture is the laptop because it combines all functional elements in one component. (Klein, 2013)

vii. Modular architecture

At modular architecture, there is an one-to-one mapping of functions and components and the interfaces between components are de-coupled. This enables modular architecture of products to allow for separate changes that cannot happen in the integral logic, a fact which gives them the advantage of being technically upgradeable and flexible in use. An example of modular architecture is the desktop computer because for every functional element a certain component is needed. (Klein, 2013)

The term modularity describes the use of same units in order to create different product variants. The aim of this product architecture is to create

identification between independent, standardized or interchangeable units to fulfill the variety of functions. Potential benefits of modularity include:

- ♦ increased product variants
- ♦ cost savings in inventory and logistics
- ♦ economy of scale in component commonality
- ♦ increased feasibility of product/ component change
- ♦ independent product development
- ♦ flexibility in component reuse
- ♦ upgradeability, easy add-ons and adaptations
- ♦ reduced order lead-time
- ♦ decoupling risk
- ♦ easy maintenance and disposal

There are three types of modular architecture, which will be explained shortly:

- ♦ slot
- ♦ bus
- ♦ sectional

The three of them share the same characteristics described already, however, their difference lies in the way the component interactions are organised (Klein, 2013). In the case of “slot” architecture, every component has its connection. A good example is the keyhole, which can be opened by only one key. The characteristic of “bus” architecture is that it provides one element to which multiple different components can be connected. A well-known example is the usb port, where components of different functions can be connected. In the case of “sectional” architecture, all interfaces are of the same type, which means that alone but also in

combination they form a whole product. The Lego blocks are designed with this logic.

viii. Facade types evolution

In terms of better understanding the history of facade product architecture, the different facade types were studied. In the following pages, a short reference will be made on the different facade types and their main characteristics, advantages and drawbacks as well as a reference building will be presented, where the specific facade type was applied. Most of the information was retrieved from the book "Façades: Principles of Construction" by Knaack U. et al. published in 2007 in Germany.

There is a large variety of ways that a building envelope can be constructed. Some are load bearing like the solid wall or walls with a skeletal structure whereas some others are non-load bearing like curtain walls. The latter ones depend on an interior structure to bear the load and serve only as skins for

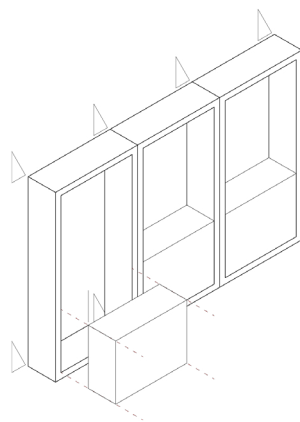
protecting the inside from the outside environment. Moreover, there is a distinction between types that are assembled on-site and others that are completely fabricated off-site and assembled in units. The development of the latter system led to fast and economic installation with limited use of resources in manpower and tooling compared to traditional systems. In addition, there are types that are only a mere static element that forms a barrier between indoor and outdoor environment by offering just a shelter for users and others that integrate a lot more functions. A development like that is the component facade which offers the integration of mechanical components in the facade to substitute the central HVAC system.

Curtain wall Facade

1. suspended from above with the aid of tie rods
2. large degree of independence from the main structure
3. the façade can be partitioned almost at will
4. cladding or glazing meet the various aesthetic or functional requirements
5. vertical and lateral loads are generally led to ground floor by floor
6. longer spans can be bridged by adding special loadbearing elements



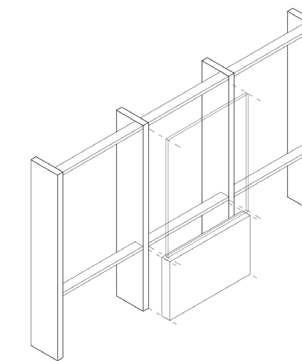
Federal Center, Chicago
Ludwig Mies van der Rohe, 1964
Source: chicagoarchitecture.info



Source: Knaack et al., 2007



TU Delft Library, Delft
Mecanoo, 1998
Source: www.mecanoo.nl



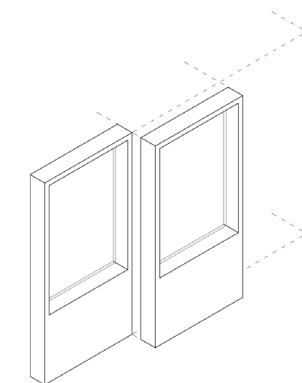
Source: Knaack et al., 2007

Post-and-beam Facade

1. storey-high posts linked by horizontal beams
2. functions are put in the spaces between these members
3. posts serve for loads transfer and support of the cladding and other functions



Westhafen Haus, Frankfurt
Schneider + Schumacher, 2005
Source: www.schreiber-sicken.de



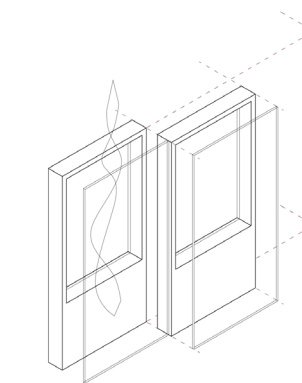
Source: Knaack et al., 2007

System Facade

1. off-site prefabrication of wall elements
2. mounted on-site
3. guaranteed production quality, rapid assembly and low labour requirements on site
4. still limited to special applications such as high-rise buildings
5. high level of logistical investment required



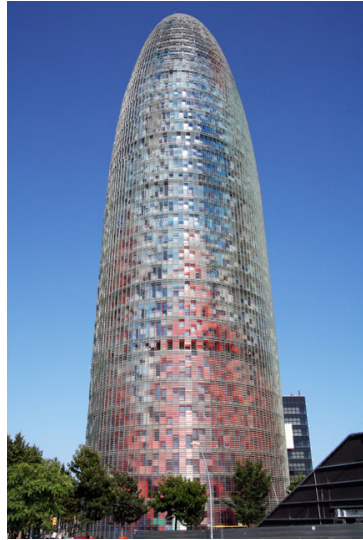
Triangle Building, Cologne
Gatermann + Schossig, 2006
Source: www.skyscrapercenter.com



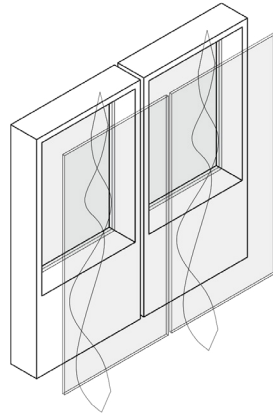
Source: Knaack et al., 2007

Double Facade

1. extra layer of glazing outside the façade to provide ventilation or additional soundproofing
2. may be realised in various ways, depending on the functions desired and the facade requirements



Torre Agbar, Barcelona
Jean Nouvel, 2004
Source: www.aviewoncities.com



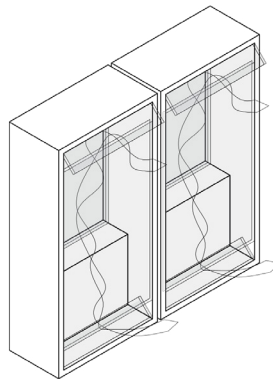
Source: Knaack et al., 2007

Second-skin Facade

1. second layer of glass over the entire outer surface of the building
2. technical and structural simplicity
3. does not involve a large number of moving parts
4. the outer layer of glass is simply mounted on the inner façade structure
5. easy construction
6. ventilation mechanisms only have to be provided at the top and bottom zones of the façade
7. limited control possibilities of the interior environment - risk of overheating



ARAG Tower, Düsseldorf
Foster + Partners & RKW, 2001
Source: www.skyscrapercenter.com



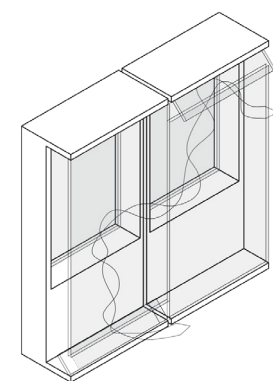
Source: Knaack et al., 2007

Box-window Facade

1. storey-high façade elements with ventilation flaps at top and bottom
2. ventilation flaps can be opened by individual users
3. freedom of the users to control their own internal environment
4. the freedom given to one occupant may have an adverse effect on the conditions experienced by another



Stadttor, Düsseldorf
Petzinka Pink und Partner, 1998
Source: de.wikipedia.org



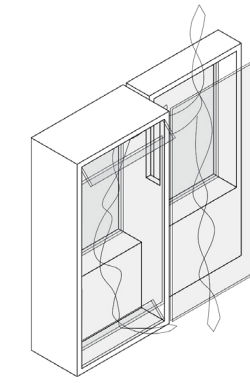
Source: Knaack et al., 2007

Corridor Facade

1. connection of neighbouring double façade elements
2. staggered ventilation of the space between the two skins
3. horizontal flow of air is prevented by vertical baffles in the space between the two skins



Photonics Centre, Berlin
Sauerbruch Hutton Architects, 1998
Source: www.sauerbruchhutton.de



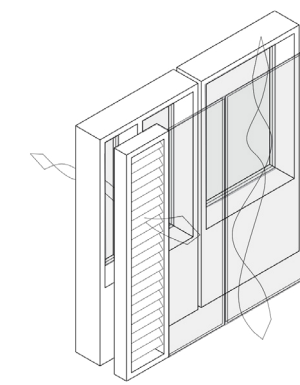
Source: Knaack et al., 2007

Shaft-box Facade

1. the most effective version of the double façade
2. the greatest constructional and control-engineering effort involved
3. the air of box windows is exhausted into a shaft mounted on the façade that extends over several floors
4. a stack effect ensures vertical motion of the air in the shaft



Debitel, Stuttgart
RKW Architektur + Städtebau, 2002
Source: wikivisually.com



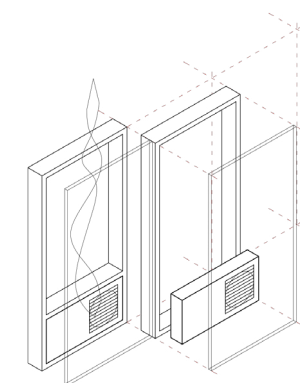
Source: Knaack et al., 2007

Alternating Facade

1. single-skin façade constructions converted locally to double façades by the addition of a second skin
2. benefits of the buffering effect of the double façade



Post Tower, Bonn
Helmut Jahn, 2003
Source: www.archdaily.com



Source: Knaack et al., 2007

Integrated Facade

1. integration of functions other than ventilation like active environmental-control or lighting components
2. generally called a "modular façade" or "hybrid façade"

CONTEXT & REQUIREMENTS

I. Facade functions

A building envelope serves simultaneously many different functions as shown in the figure while the main one is most often to provide a shelter for the occupants. The main purpose is to offer a comfortable space for the users of the building to work or live undisturbed. This space needs to be protected from outside parameters like wind, rain, snow, heat, cold and sound. Thus, a building skin protects the building from direct external environmental factors like sunlight, rain and wind and helps in maintaining comfortable interiors along with providing structure and stability to the building.

In 1963, Hutcheon proposed a widely accepted list of principle functional requirements which should be considered in the design process of building envelopes. These are the following:

- ◇ control heat flow
- ◇ control air flow
- ◇ control water vapor flow
- ◇ control rain penetration
- ◇ control light, solar and other radiation
- ◇ control noise
- ◇ control fire
- ◇ provide strength and rigidity
- ◇ be durable
- ◇ be aesthetically pleasing
- ◇ be economical

The outer barrier or envelope of the building, is the part that provides the protection (Knaack, 2011). Nevertheless, the façade performs more functions.

Taking Hutcheon’s list into account and considering some additional aspects that have arisen from then on like sustainability, the scheme shown in Figure 12 has been created which shows the main facade functions and the aspects directly connected with them. Building envelopes need to deal with all the parameters presented, however, some facades excel at certain points more than others. The three of the five main purposes of the facade shown in the scheme are directly related to climate. These aspects need to be considered thoroughly since current demands on sustainability have increased their value. Therefore, it was decided that this research will be evaluated with a focus on thermal comfort and minimising energy demand. For this reason, in the next section indoor comfort is defined according to an analysis of influential parameters.

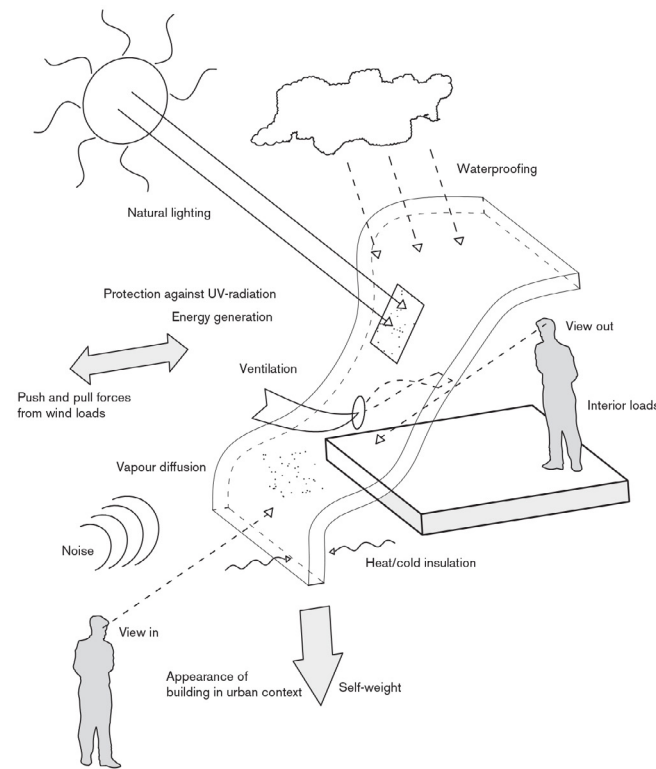


Figure 11: Facade functions
Source: Knaack et al., 2007

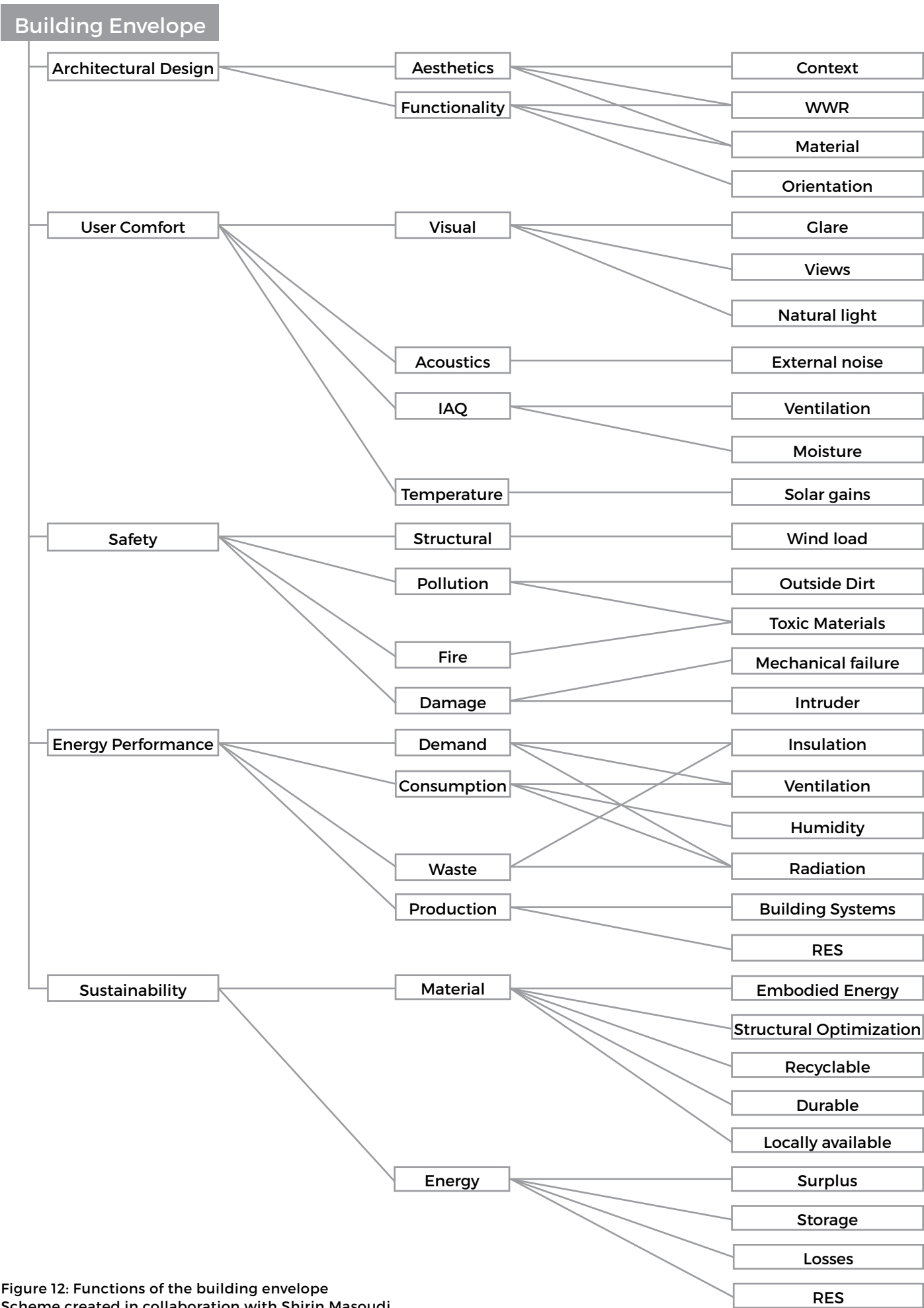


Figure 12: Functions of the building envelope
Scheme created in collaboration with Shirin Masoudi

II. Indoor Comfort

Our lives are surrounded by constantly changing forces of nature and environment. The spaces we inhabit are constantly changing as well, although the change is slow and occurs through non-physical conditions. These changes justify the fact that our perception about comfort change all the time. For this reason, buildings should be able to adapt and vary their configuration in relation to the changing environment and consequently the changing user's preferences.

In developed countries, most people spend on average 90% of their time indoors (Bougdah and Sharples, 2010), whereas in the past the indoor environment catered mostly as a place for shelter, sleeping and eating. Therefore, it is very important that the buildings provide inhabitants with the desirable well-being, which is largely affected by health, comfort and safety. Comfort is when an individual is satisfied in his/her well-being and surrounding climate (Boerstra et al., 2015). The comfort can be divided in different categories (Bluyssen, 2009), which will be explained in this section. These categories are:

- ♦ Thermal comfort
- ♦ Auditory comfort
- ♦ Visual comfort
- ♦ Olfactory comfort
- ♦ Hygienic comfort

Adaptive building skins are a vital component to resolve the issues of indoor comfort as they are a medium through which the intelligence can be imparted to the building system to respond to

an environmental stimulus. The construction of adaptive buildings means not only a more demanding design process, but also more complexity for the building's operation phase. The mere addition of adaptive features to the building envelope does not directly guarantee successful operation. The adaptive behavior has to balance competing objectives related to indoor comfort, which means that it has to satisfy simultaneously multiple, interdependent performance requirements (Rivard et al., 1995). These are often competitive, and sometimes even conflicting in nature like daylight vs. glare, views vs. privacy, fresh air vs. draught risk, solar shading vs. artificial lighting, passive solar gains vs. potential overheating. For this reason, it is of great importance that the various subsystems in the façade cooperate, together and with other building services, to resolve conflicts and handle trade-offs.

In order to determine these performance requirements and design comfortable and sustainable buildings, the exterior climate is of utmost importance. It is once again apparent that context has a great influence on design decisions. The context of each project determines the relative importance of the various functional requirements (Loonen, R., 2010). Not only the climate is different, but also the inhabitants. Their culture, habits, preferences personal accessories and living standards vary all over the world determining different habitable ways and thus different building structures and solutions. These parameters impose that each individual has its own preferences related to its own comfort standards. This is why it is inherently hard to achieve comfort in each of the five mentioned categories for every person. Nevertheless, except for the cultural aspects and the individual preferences, there are also two

other aspects to be considered. First, the client's wishes and second the building standards, which impose certain minimum requirements to be met. However, not every aspect is directly dependant on the exterior façade. The most critical aspects will be considered in this research.

All these drivers, either external or internal, which influence the indoor environmental aspects are summarised in Figure 13. Regulatory, technological, societal and economical parameters have to be

the ability to maintain a constant core temperature, which can be achieved when his/her body heat gains and losses are in equilibrium (Boerstra et al., 2015).

Thermal comfort is mainly controlled by the heating, ventilating and air-conditioning (HVAC) system. This system can be designed either as central or as decentralised units integrated in the facade. In addition, adaptive systems like sun-shading can also control considerably the thermal comfort,

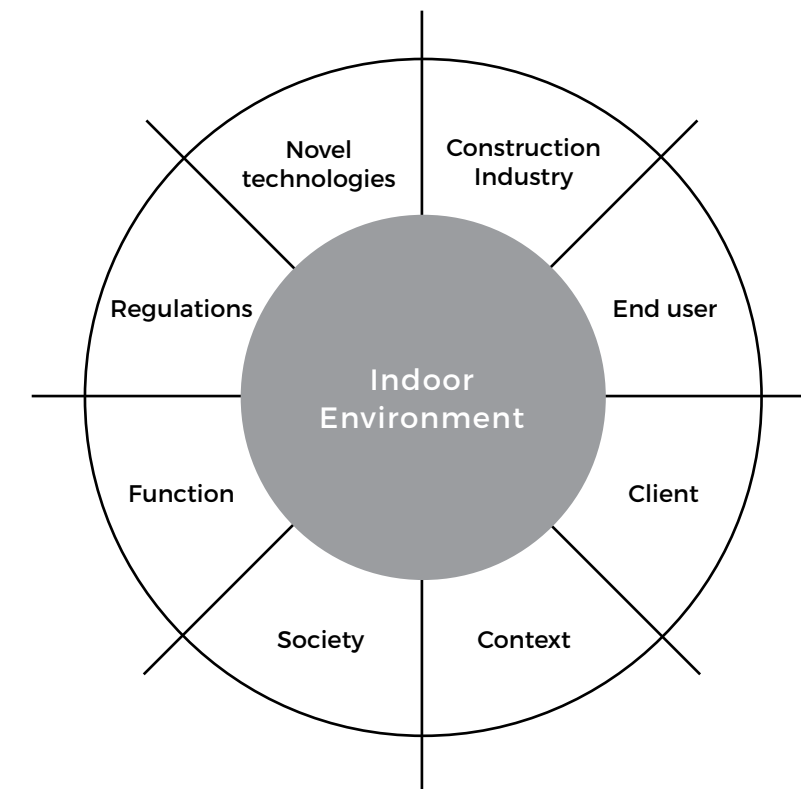


Figure 13: Drivers of indoor environmental aspects

met and form the final decisions.

i. Thermal Comfort

The thermal comfort of an individual is in principle

since the sun has a very big impact on the radiant temperature. At a building scale, adaptive envelope systems can improve thermal comfort in real time since they are able to change their functions,

features and behaviour in response to external environmental stimuli. This would be the optimum approach since predetermined settings of the HVAC system according to simulations of weather data and user behaviour fail to accommodate unpredictable changes. With adaptive facades, the desirable comfort is achieved much quicker by improving the overall building performance at the same time, since less or no energy is required for the HVAC system to work.

Thermal comfort is determined by the following parameters (Bluyssen, 2009):

♦ Temperature (air and radiant)

Temperature driven heat is transferred through conduction by the contact of materials, through convection by the movement of gases and liquids and through radiation. Air temperature is measured by the dry bulb temperature, whereas radiant temperature is measured by the mean radiant temperature.

♦ Relative humidity

Relative humidity is the ratio of the mole fraction of water vapour in a given moist air sample to the mole fraction in an air sample saturated at the same temperature and pressure. This means practically that the higher the relative humidity is, the closer the saturation conditions are reached. On the other hand, a lower relative humidity would facilitate evaporative cooling. Relative humidity is measured in percentages.

♦ Air velocity

Air velocity is defined as the rate of position change over time and it is measured in meters per second (Bluyssen, 2009). Air movement can cause local cooling of the body described as draught. Moreover,

a faster air movement can result in a quicker heat exchange through convection.

♦ Turbulence intensity

♦ Activity and clothing

ii. Auditory Comfort

Auditory comfort is achieved when sound levels are kept low enough in order for people to be able to concentrate and communicate properly with others without other auditory disturbances (Bluyssen, 2009). Sound can travel via three different transmission paths: direct transmission, flanking transmission and indirect airborne transmission. Therefore, a construction should be able to provide sound insulation and block the excessive sound energy, in order for the acceptable sound standards to be maintained.

Human hearing is between the frequencies of 20 and 20000 Hertz, which are created through waves of compression of air detected by the human ear. The loudness of the sound is determined by the sound pressure level, expressed in decibel(dB). Humans can hear sounds as low as 0 dB and even higher than 130 dB, but that could cause the hearing organ to be permanently damaged.

Auditory comfort is determined by the following parameters (Bluyssen, 2009):

♦ Sound levels

♦ Frequencies

♦ Duration

♦ Absorption characteristics

♦ Sound insulation

♦ Reverberation time

iii. Visual Comfort

Day lighting has always been a major consideration when designing a building. The invention of artificial lighting provided independency from the exterior natural lighting which led to more design freedom. Visual comfort is largely influenced by the amount of light in a room, its color quality, the glare and the view. The quality and amount of light in buildings are considered of great importance since insufficient or bad lighting conditions may contribute to anxiety or even depression of individuals. In addition, the light amount has been related to aspects like alertness and productiveness of individuals. What's more, light is also strongly connected to thermal qualities, since it is energy and is converted to heat as soon as it falls on a surface.

Visual comfort is determined by the following parameters (Bluyssen, 2009):

♦ Luminance and illuminance

♦ Reflectance(s)

♦ Color temperature and color index

♦ View and daylight

♦ Frequencies

iv. Olfactory & Hygienic Comfort

Both olfactory and hygienic comfort are related to indoor air quality. High concentration levels of carbon dioxide or a clogged filter, which would cause bad smells to remain in the interior space are responsible for user dissatisfaction. The desirable

comfort can be achieved by sufficient ventilation and a constant air exchange rate. Another parameter related to indoor air quality, which has negative effects on human health are materials that generate substantial amounts of pollution not only during manufacturing but also during use, like VOCs, HCFCs, etc.

Olfactory and hygienic comfort are determined by the following parameters (Bluyssen, 2009):

♦ Pollution sources and air concentrations

♦ Types of pollutants (allergic, irritational, carcinogenic, etc.)

♦ Ventilation rate and efficiency

III. The Climate

i. The Netherlands climate

The Netherlands have a temperate maritime climate influenced by the North Sea and Atlantic Ocean. According to Köppen-Geiger classification the climate of The Netherlands can be classified as Cfb Climate; a warm temperate humid climate with the warmest month lower than 22°C over average and four or more months above 10°C over average.

People in the Netherlands experience cool summers and moderate winters. During the winter the daytime temperatures vary between 2°C-6°C, whereas during summer they vary between 17°C-20°C. The annual average temperature is approximately 10°C and the average rainfall in a year is 76.5cm, which is considered a lot. In Figure 14, an average of the monthly temperature and rainfall for The Netherlands over the period 1991-2015 can be seen. In addition, high wind speeds are also an issue especially in fall and winter, when strong atlantic low-pressure systems can bring gales and uncomfortable weather.

ii. Amsterdam Weather Data Analysis

The facade system for an office building was chosen to be located in Amsterdam. It is interesting to mention that the average monthly rainfall and especially the temperatures in Amsterdam differ a lot from the ones of The Netherlands as a whole as shown in Figure 15. The average temperatures in Amsterdam are much lower and the rainfall is substantially more especially in autumn and winter. For this reason, specific climate data for Amsterdam was considered important to be found.

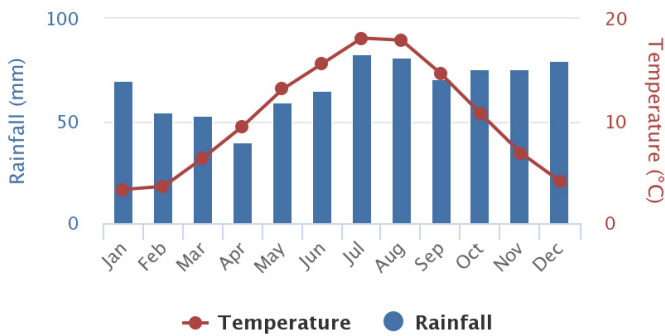


Figure 14: Average Monthly Temperature and Rainfall for The Netherlands from 1991-2015
Source: sdwebx.worldbank.org

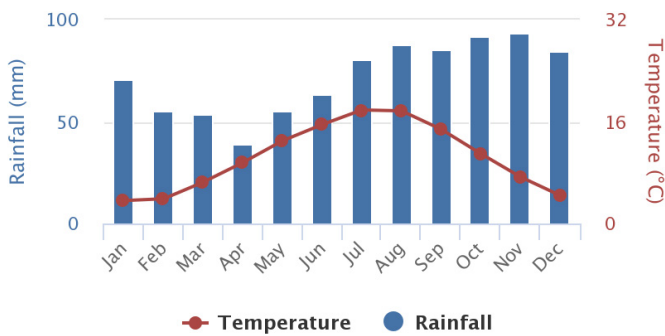


Figure 15: Average Monthly Temperature and Rainfall for Amsterdam (52.3702° N, 4.8952° E) from 1991-2015
Source: sdwebx.worldbank.org

In order to have more accurate climate data for Amsterdam with the purpose to determine design parameters that are going to affect the facade design and set design requirements, the plug-in Ladybug in Rhino software was used. During the winter the mean temperature is 4°C and the high mean temperature is 5°C, whereas during summer they are 16°C and 19°C respectively. Autumn and spring have a relatively pleasant weather with autumn being a bit warmer but having larger wind speeds than spring. The annual average

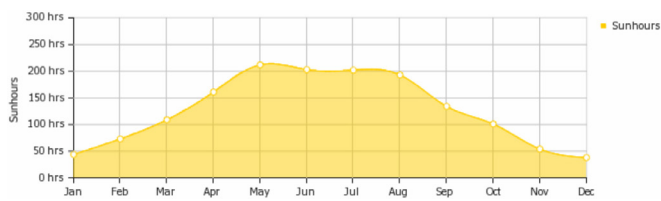


Figure 16: Average Monthly Sunhours in Amsterdam, The Netherlands
Source: www.weather-and-climate.com

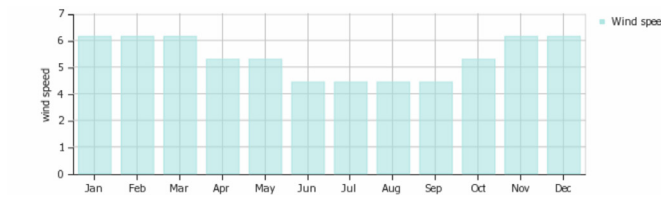


Figure 17: Average Wind Speeds in Amsterdam, The Netherlands
Source: www.weather-and-climate.com

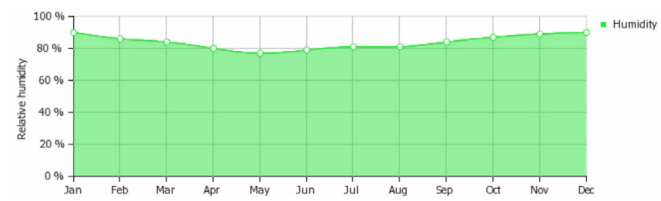


Figure 18: Average Relative Humidity in Amsterdam, The Netherlands
Source: www.weather-and-climate.com

temperature is approximately 10°C, same as for the whole country. The average monthly sunhours, wind speeds and relative humidity percentages can be seen in Figures 16, 17 and 18 respectively. May is the sunniest month, while December has the lowest amount of sun hours. Wind speeds are high with August and December the least and most windy months respectively. The relative humidity percentages remain high throughout the whole year with an annual average of 84%.



Figure 19: Global Horizontal Irradiation Map, The Netherlands
Source: solargis.com

Another value which is of importance especially for photovoltaic installations is the Global Horizontal Irradiance (GHI), which is the total amount of shortwave radiation received by a surface horizontal to the ground. This value includes both the Direct Normal Irradiance (DNI) and Diffuse Horizontal Irradiance (DIF). As shown in Figure 19, Amsterdam has an annual average sum of around 1025-1050kWh/m².

IV. Comfort guidelines for offices in The Netherlands

Spaces should be designed in order to deliver the desirable comfort to the building's users. For this reason, guidelines have been created, which differ according to the building function. Such guidelines are ISO, which is an international guideline or ASHRAE, which is the guideline created by the United States of America.

Apart from these widely known standards and guidelines, Netherlands has made its own contribution in the development of the thermal comfort guidelines (Boerstra et al., 2015), which are of course based on the international ones. These standards are revised and reviewed every 10 years and the most updated ones were published in 2014. This updated version of ISSO 74 guideline is intended for use in offices and related buildings in The Netherlands and is a hybrid of non-adaptive and adaptive approaches.

Class (bandwidth)	Explanation	PPD	PMV analogy (bandwidth)
A	High level of expectation. Select this category as a reference when designing spaces for people with limited load capacity (for instance, sensitive people or persons who are diseased) or when there is a higher demand for comfort	Max. 5%	–
B	Normal level of expectation. Select this category as a reference when designing or measuring new buildings or in the case of substantial renovations	Max. 10%	$-0.5 < PMV < +0.5$
C	Moderate level of expectation. Select this category as a reference in the case of limited renovations or when measuring older existing buildings	Max. 15%	$-0.7 < PMV < +0.7$
D	Limited level of expectation. Select this category as a reference in the case of temporary buildings or limited use (for instance, one to two hours of occupation per day)	Max. 25%	$-1.0 < PMV < +1.0$

Figure 20: Description of the four classification levels
Source: Boerstra, A. C., et al. (2015). "A new hybrid thermal comfort guideline for the Netherlands: background and development." Architectural Science Review 58(1): 24-34.

There are two important aspects based on which the temperature limits are determined (Boerstra et al., 2015). These are:

◊ Type α or Type β situation (room, building)

This aspect has to do with differences between spaces even in the same building. Type α is related to free-running situations with informal clothing policies, which involve adaptation aspects like operable windows. Type β , on the other hand, is related to a centrally controlled HVAC system. This criterion is also mentioned in the NVBV (Nederlands Vlaamse Bouwfysica Vereniging - Netherlands-Flanders Association of Building Physics) Handbook, which contains Building Physics quality requirements for buildings.

◊ Classification level (Class A, B, C or D)

There are four Class types: high, normal, moderate and limited level. The description of the four classification levels can be seen in Figure 20.

The requirements of the indoor operative temperatures for each of the Class types for summer and winter can be seen in Figure 21 and depend also on the situation Type α or β . According to the guidelines, these requirements have to be met 0.6m above the floor level in the zone of occupancy.

The situation Type chosen for the specific office building is Type β because a central HVAC system will be used together with the adaptive facade system. The facade system is supposed to lower the heating and cooling energy demands but it does

not itself provide the heating and cooling.

The Class type chosen for the specific office building is B because it is the normal level of expectation for a new building or a substantial renovation. The requirements of the indoor operative temperatures for this Class type can be seen on the graph in Figure 22. The operative temperature should remain within the range given between the black bold lines, whereas the potential set temperatures for winter and summer in case of using active heating or cooling are illustrated with the dashed lines and are 21°C and 24.5°C respectively.

		Winter	Intermediary seasons	Summer
General	Set-point line	21		24.5
Class A	Upper limit Lower limit		See class B (+ occupant control requirement, ± 2 K) See class B (+ occupant control requirement, ± 2 K)	
Class B	Upper limit Lower limit	24 ^a 20 ^a	$18.8 + 0.33 \cdot \theta_{rm} + 2^b$ $20 + 0.2 \cdot (\theta_{rm} - 10)^c$	Type β spaces: 26 ^a Type α spaces: $18.8 + 0.33 \cdot \theta_{rm} + 2$
Class C	Upper limit Lower limit	25 ^a 19 ^a	$18.8 + 0.33 \cdot \theta_{rm} + 3^b$ $19 + 0.2 \cdot (\theta_{rm} - 10)^c$	Type β spaces: 27 ^a Type α spaces: $18.8 + 0.33 \cdot \theta_{rm} + 3$
Class D	Upper limit Lower limit	26 ^d 18 ^d	$18.8 + 0.33 \cdot \theta_{rm} + 4^b$ $18 + 0.2 \cdot (\theta_{rm} - 10)^c$	Type β spaces: 28 ^d Type α spaces: $18.8 + 0.33 \cdot \theta_{rm} + 4$

^aBased upon the standard classes B and C winter limits mentioned in ISO 7730 (ISO 2005).
^bBased upon the SCATs database comfort temperature equation EN 15251 (CEN 2007) and the *P*-equations presented in CIBSE (2013) and Nicol and Humphreys (2010); with an added 5–10% dissatisfied correction.
^cLower limits summer are derived by extrapolation; with starting point $x = \theta_{rm}$ of 10°C and $y =$ lower limit winter (ISO 7730 (ISO 2005)) (different for each class) and end point $x = \theta_{rm}$ of 25°C (maximum value x -axis given the Dutch outdoor climate) and $y =$ lower limit summer (ISO 7730 (ISO 2005)) (also different for each class).
^dNew (non-adaptive) limit values for the new class D, in line with the limits mentioned by National Standard of the People's Republic of China (2012).

Figure 21: Requirements indoor operative temperature (°C)
Source: Boerstra, A. C., et al. (2015). "A new hybrid thermal comfort guideline for the Netherlands: background and development." Architectural Science Review 58(1): 24-34.

According to NVBV (Nederlands Vlaamse Bouwfysica Vereniging) Handbook, the required values of the room temperatures for offices in winter and summer are as shown in Table 4. They are divided in three quality levels: basic, good and excellent. Taking both sources into consideration, “A new hybrid thermal comfort guideline for the Netherlands: Background and development.” (Boerstra et al., 2015) and the NVBV Handbook, the indoor operative temperature should be at a good or excellent quality level.

In addition, according to NVBV Handbook, the thermal insulation of the different building parts should be according to the values given in Table 5.

Apart from determining the thermal comfort requirements, it is important to know for how long and under which weather conditions, measurements should be conducted, in order to ensure that these requirements are met (Boerstra et al., 2015). Figure 23 shows these conditions in more detail and is based on average outdoor weather conditions in The Netherlands.

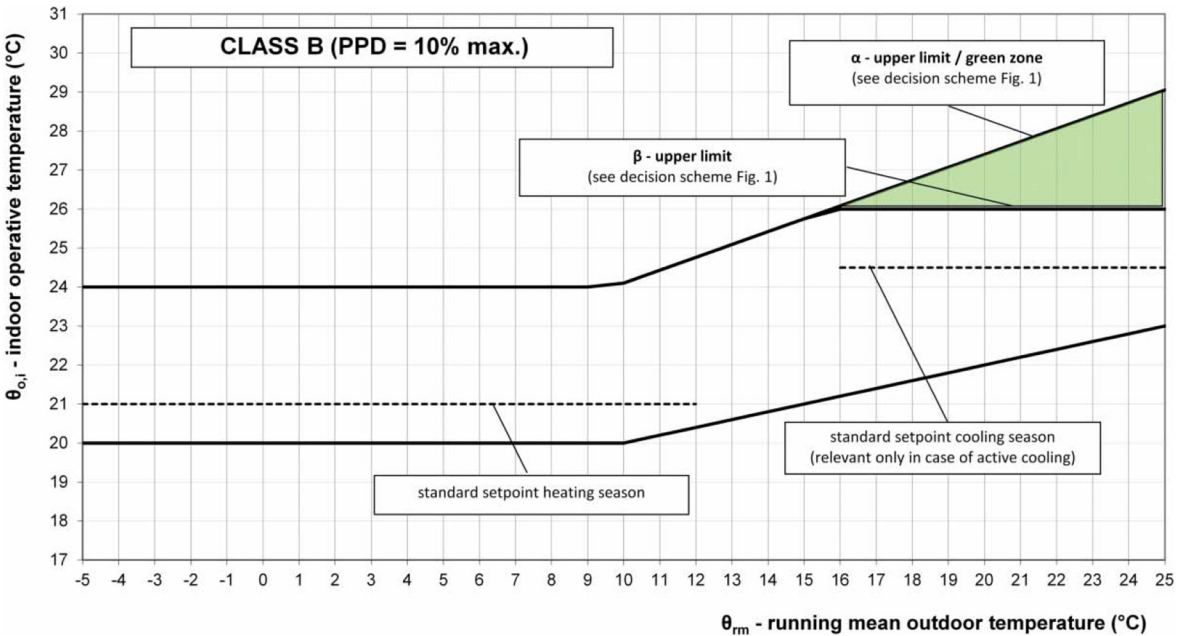


Figure 22: ISSO 74: 2014 Class B requirements for the operative temperature indoors in relation to the running mean outdoor temperature
Source: Boerstra, A. C., et al. (2015). “A new hybrid thermal comfort guideline for the Netherlands: background and development.” Architectural Science Review 58(1): 24-34.

		Quality Level		
		Basic	Good	Excellent
		activity: mainly sitting (1,2 met)		
Operative Temperature	winter (1,0 clo)	19-25°C	20-24°C	20-24°C + IB
	summer (0,5 clo)	22-27°C	23-26°C	23-26°C + IB

* IB: possibility of influencing the temperature individually

Table 4: Required values of the room temperatures for offices in winter and summer
Source: NVBV Handboek by the Nederlands Vlaamse Bouwfysica Vereniging [www.nvbv.org]

Thermal Insulation	Quality Level		
	Basic	Good	Excellent
Closed parts	$R_{c, \text{floor}} = 3,5 \text{ W/m}^2\text{K}$ $R_{c, \text{facade}} = 4,5 \text{ W/m}^2\text{K}$ $R_{c, \text{roof}} = 6,0 \text{ W/m}^2\text{K}$	$R_{c, \text{floor}} = 4,5 \text{ W/m}^2\text{K}$ $R_{c, \text{facade}} = 5,0 \text{ W/m}^2\text{K}$ $R_{c, \text{roof}} = 7,0 \text{ W/m}^2\text{K}$	$R_{c, \text{floor}} = 6,5 \text{ W/m}^2\text{K}$ $R_{c, \text{facade}} = 6,5 \text{ W/m}^2\text{K}$ $R_{c, \text{roof}} = 8,0 \text{ W/m}^2\text{K}$
Windows & Doors	$U_{w, \text{max}} = 2,20 \text{ m}^2\text{K/W}$ $U_{w, \text{average}} = 1,65 \text{ m}^2\text{K/W}$	$U_{w, \text{max}} = 1,65 \text{ m}^2\text{K/W}$ $U_{w, \text{average}} = 1,20 \text{ m}^2\text{K/W}$	$U_{w, \text{max}} = 1,20 \text{ m}^2\text{K/W}$ $U_{w, \text{average}} = 0,80 \text{ m}^2\text{K/W}$

Table 5: Performance levels of thermal insulation
Source: NVBV Handboek by the Nederlands Vlaamse Bouwfysica Vereniging [www.nvbv.org]

Type	Duration	Running mean outdoor temperature ^a	Wind force	Hours of sunshine
Winter measurement	Minimum 21 days	– 5 to + 5°C during at least 14 days of the measurement period	Minimum 3 Bft (3.4 m/s) during at least 50% of the measurement period	No requirements
Spring/autumn measurement	Minimum 21 days	7–13°C during at least 14 days of the measurement period	No requirement	Minimum 4 hours per day during at least 50% of the measurement period
Summer measurement	Minimum 21 days	16–22 °C during at least 14 days of the measurement period	No requirement	Minimum 6 hours per day during at least 50% of the measurement period

^aRunning mean outdoor temperature as measured at the nearest official weather station.

Figure 23: Measurement durations and conditions as required by ISSO 74: 2014
Source: Boerstra, A. C., et al. (2015). “A new hybrid thermal comfort guideline for the Netherlands: background and development.” Architectural Science Review 58(1): 24-34.

A more detailed quality level classification (Figure 25) is provided by “PIANOO”, Expertise Center Procurement of the Ministry of Economic Affairs and Climate. In their latest August 2017 version of the document “Environmental criteria for sustainable public procurement of Office Buildings New Construction”, the minimum requirements are provided according to which an office can be assigned to the different quality levels. Besides that, information is also provided in relation to which guideline should be used for the calculation of each quality criterion and how the performance

	Theme	Calculation method for new construction
Energy	Energy performance	NEN7120*, including NVN7125 (April 2011)
	Own generation of sustainable energy	x% = (Eownparcel/Ep.adm,tot,nb) *100% according to NEN 7120*
Materials	Environmental Performance	Calculation method for Environmental Performance Buildings and Groundwork, Road and Hydraulic Engineering works, with associated environmental database [SBK]
	Wood	www.inkoopduurzaamhout.nl/ and specifically www.inkoopduurzaamhout.nl/bestektekst.pdf
	Flexible fit-out package	prevent and limit extra environmental impact from the use of materials that are not easily adaptable or replaceable
Health	Noise in workspaces	Quality levels according to the NVBV Handbook of Building-Physical Quality of Office Space with reference to NEN 5077
	Indoor Air Quality, ventilation capacity	NEN 1087 and NVBV Handbook of Building-Physical Quality of Office Space
	Thermal Comfort	In accordance with ISSO 74 and ISSO 32
	Natural lighting incidence	Daylight factor [DF] = Eroom/Eopen field *100% -Design phase: calculation using daylight simulation programmes with a CIE-overcast sky.

Figure 24: Performance levels of thermal insulation
Source: NVBV Handboek by the Nederlands Vlaamse Bouwfysica Vereniging [www.nvbv.org]

levels of the thermal insulation should be calculated (Figure 24).

The thermal comfort, which is of interest for this research project should be in accordance with ISSO 74, which has already been mentioned in detail and ISSO 32.

Health in buildings									
Energy	Level A1	100 % better than base value x points	50 % independent generation x points	25 % independent generation x points	10 % independent generation x points	35 % better than base value 0 points	No level specified	Buildings Decree (*)	Basic level
	Level A2	80 % better than base value x points							
	Level B1	65 % better than base value x points							
	Level B2	50 % better than base value x points							
Materials	Environmenta l performance	30 % better than level C x points	25 % better than level C x points	20 % better than level C x points	15 % better than level C x points	Calculation in accordance with the explanatory notes to calculation method: Max. €0.90 /m GFA 100% Sustainable Procurement of wood Flexible fit-out package (in accordance with explanatory notes) 0 points	No level specified Calculation required in Buildings Decree	No level specified	Buildings Decree
	Noise in work areas, workspaces	Class A (in accordance with explanatory notes) x points	Class B (in accordance with explanatory notes) x points	Class C (in accordance with explanatory notes) 0 points					
Indoor Air Quality, ventilation capacity		No higher level specified				8.3 dm³/s, pp 0 points	Buildings Decree	No level specified	Buildings Decree
	Airflow ventilation		6 dm³/s per m² of working area x points			3 dm³/s per m² of working area Or: 6 dm³/s per m² of working area 0 points	No level specified	No level specified	
	Thermal comfort		No higher level specified			Class A, in accordance with new ISSO 74 0 points	No level specified	No level specified	
	Natural light incidence in workspace for long-term use > 2 hours	100% of workspaces designated for long-term occupancy min. DF > 3.0% x points	100% of workspaces designated for long-term occupancy min. DF > 2.0% x points			100% of workspaces designated for long-term occupancy min. DF > 1.0% 0 points			

Figure 25: Details of minimum requirement, award criterion and contract clauses
Source: “Environmental criteria for sustainable public procurement of Office Buildings New Construction Version August 2017” [https://www.pianoo.nl/]

* As from 1 January 2019, all Central Government buildings must be built in an energy-neutral manner. This means that this must be factored in with the invitation. An application for an integrated environmental permit will be regarded as the start time.

V. Facade Requirements

Following the literature study of the facade functions, the outdoor climate and the desirable indoor climate according to official guidelines, facade requirements can be set to which the design of the Multi-functional Facade Module should be held. They will be explained in four parts: comfort, energy, materials and practical requirements.

i. Comfort

The following requirements should be followed according to the guidelines:

R-value for closed parts: $R_{c, \text{facade}} = 5,0 \text{ W/m}^2\text{K}$ or more

U-value for windows and doors: $U_{w, \text{max}} = 1,65 \text{ m}^2\text{K/W}$
 $U_{w, \text{average}} = 1,20 \text{ m}^2\text{K/W}$ or lower

Temperature range during winter: 20-24°C

General set-point temperature for winter: 21°C

Temperature range during summer: 23-26°C

General set-point temperature for summer: 24.5°C

Heating, cooling and lighting are the primary parameters for regulation, leading to energy efficiency and dynamic spatial effects. For this reason, the aim of this research project is to prove that the Multi-functional Facade Module can contribute to minimizing the energy consumption substantially, while keeping a constant indoor comfort based on the regulations' requirements.

ii. Energy

According to the Life Cycle Analysis (LCA) of energy consumption of existing low-energy buildings,

the overall lifetime energy consumption is largely influenced by the embodied energy. This influence is much higher in low-energy buildings compared to inefficient ones (Casini, 2016). It is apparent that in order to achieve the net zero-energy goal of the future, energy has to be put in the forefront. For this reason, a primary aspect of the proposed facade system is energy production from renewable sources. In addition, in terms of a comprehensive approach of rational energy use, the choice of good insulating materials and of high-efficiency systems will contribute to energy sufficiency and efficiency.

iii. Materials

The choice of materials is important to ensure the safety and well-being of the occupants and should contribute to the overall sustainability of every new construction concerning the 2020 zero-energy buildings regulations. Materials should be processed with eco-friendly ways, should be reusable and recyclable, should not contain volatile substances and should be easily disposed. All these factors contribute to keeping the embodied energy of materials low.

iv. Practical

◊ Facade type

The system used is a unitised curtain wall system and should function appropriately, providing the necessary airtightness and watertightness. In addition, the components are modular, thus requiring limited connections with other elements. In addition, the unitised system provides the advantages of easy maintenance and technical upgradeability.

◊ Safety

The facade system should guarantee safety by offering robustness, fire resistance and protection from the outdoor weather conditions.

◊ Maintenance

Maintenance is a very important aspect for the building in order to achieve a long lasting quality for the facade. It prevents degradation and corrosion of the surface materials and maintains aesthetics. For this reason, access to the facade is important in order to be easily maintained and cleaned at a regular basis.

**APPLICATIONS
& MATERIALISATION**

I. Case studies

In this section, a few of the reference projects presented in Appendix A will be analysed more in depth because they are directly connected with the main objective of this report. In other words, these are the ones that led to the choice of the final topic and on which the final design and main outcome of this report will be based. Right after, these projects plus a few more that are relevant are gathered in a table to highlight the advantages and disadvantages as well as to evaluate the cost involved in each one of them.

i. ACTRESS

ACTRESS (ACTIVE RESponsive and Solar) is a Multi-functional Facade Module (MFM) developed by TEBE group of the Polytechnic University of Turin. It incorporates different technologies with the aim of improving the building's energy efficiency and converting energy from renewable energy sources (RES). It has a "standalone attitude", which means that it requires no or extremely limited connections with other elements and it is comprised of an opaque (OSM) and a transparent sub-module (TSM) which consist of various different material

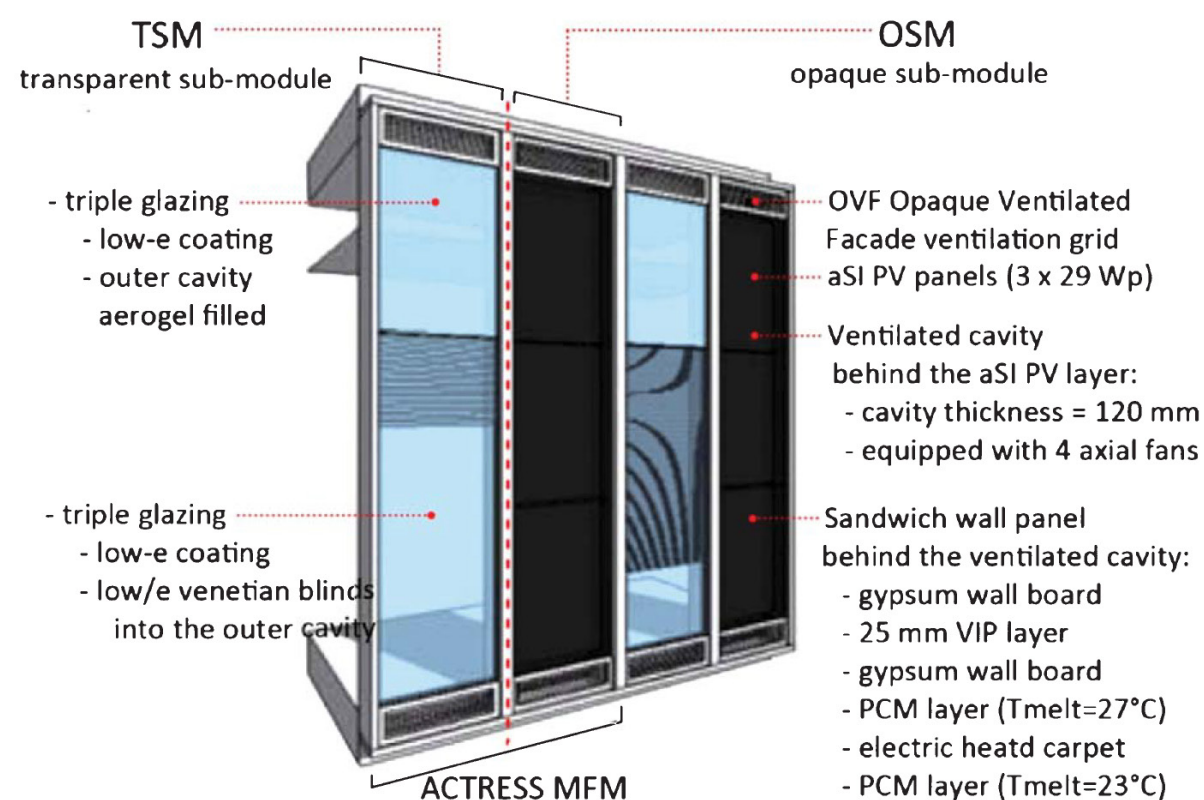


Figure 26: Overview of the ACTRESS project and composition of the modules
Source: Perino, M. and V. Serra (2015). "Switching from static to adaptable and dynamic building envelopes: A paradigm shift for the energy efficiency in buildings." *Journal of Facade Design and Engineering* 3(2): 143-163.

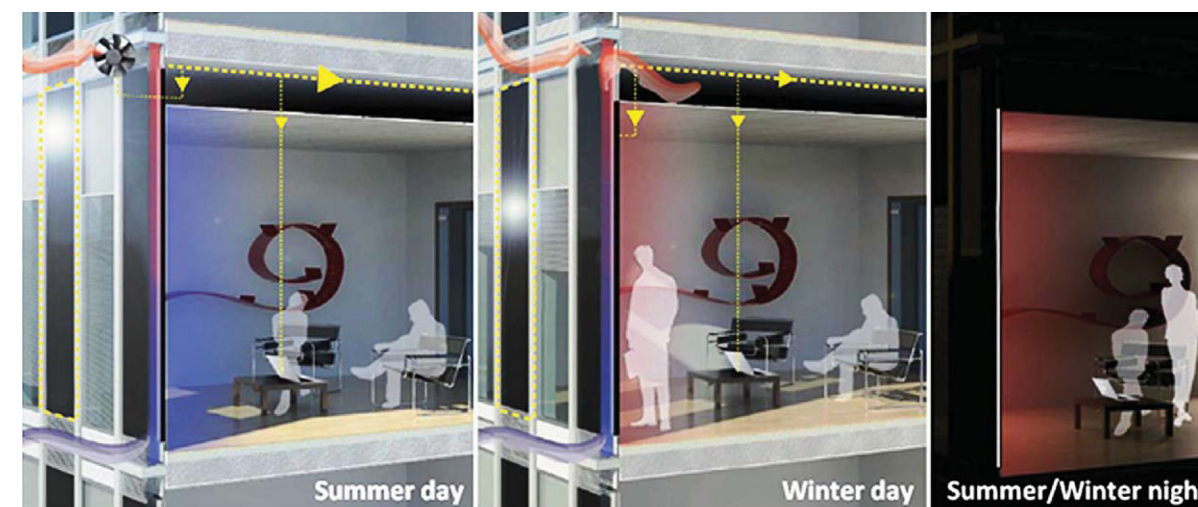


Figure 27: ACTRESS operating modes
Source: Favoino, F., et al. (2015). "Assessing the performance of an advanced integrated facade by means of simulation: The ACTRESS facade case study." *Journal of Facade Design and Engineering* 3(2): 105-127.

layers. The opaque sub-module can be operated as a thermal buffer or as a supply air facade in the winter and as an outdoor air curtain facade during summer (Favoino et al., 2014). These operating modes of the ACTRESS MFM can be seen in Figure 27. The transparent sub module is made up of two different triple glazing systems. The composition of the modules can be seen in Figure 26.

An ACTRESS module was tested in Torino for almost two years and the conclusions showed that it is "energy positive" and that more than 50% of the total primary energy can be saved. Moreover, the obtained thermal insulation was excellent and the "passive activation" of PCM showed a satisfactory thermal inertia, however, the performance of the LHTES (Latent Heat based Thermal Energy Storage) coupled with the PV system was partially disappointing because it did not meet the high expectations of reduced heat losses. Nevertheless, the heat gains were always higher than the heat losses. In addition, the glazing with aerogel had a very good performance, however it was concluded

that it is not suitable for an MFM because it did not show any possibility of adaptation, raising some worries about overheating during the summer period. On the other hand, the triple glass unit with the low-e venetian blinds was highly performing, extremely flexible and adaptable (Favoino et al., 2014).

ii. ADAPTIVALL

ADAPTIVALL (Multi-functional light-weight WALL panel based on ADAPTive Insulation and nanomaterials for energy efficient buildings) project is a climate adaptive multi-functional lightweight prefab panel suitable for the construction of cost-efficient, rapid and energy efficient facades, conceived by TNO Delft & Partners. This facade is able to reduce heating and cooling demand by 50-80% compared to typical highly insulating solutions and it is also able to almost eliminate auxiliary heat recovery and ventilation installations. Besides the validated energy savings,



Figure 28: Overview of the ADAPTIWALL project and arrangement of layers
Source: www.adaptiwall.eu

ADAPTIWALL offers a high architectural flexibility, being able to be adjusted for different types of buildings and climatic regions.

The core element of the panel is a load-bearing, lightweight concrete layer with nano-additives and impregnated with PCMs, which is used as a buffer to store heat and cold. Moreover, adaptive insulation consisting of non-traditional polymer materials is installed on both sides of the buffer, in order to control the heat flows. In addition, a total heat exchanger with nanostructured membrane is used to provide compact ventilation and an energy recovery system leading to temperature, moisture and anti-bacterial control. The cladding and windows are not considered as key components, however, a glass cladding and a solar collector are used to harvest energy. The composition of the facade layers can be seen in Figure 28.

iii. SELFIE

SELFIE (Smart and Efficient Layers for Innovative Envelopes) facade is a unitized curtain wall system that allows not only easy on-site installation but also customization through the possibility of the modular components to be placed with different geometric configurations, different types of materials and different colors. Besides, the choice of using modular elements guarantees an isolated action of maintainability, meaning that in case of repair the global performance of the facade is not influenced.

SELFIE facade consists of three modular components with a size 0,90x1,40m, two opaque and one transparent with various different material layers. Such layers are PCM, special innovative-coupled glass with internal IR treatment, visible

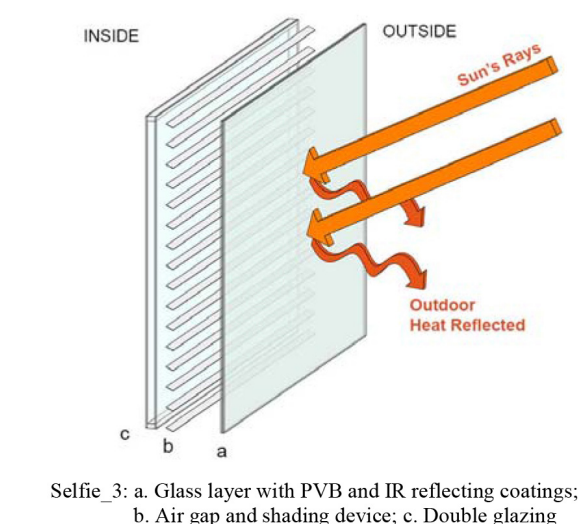
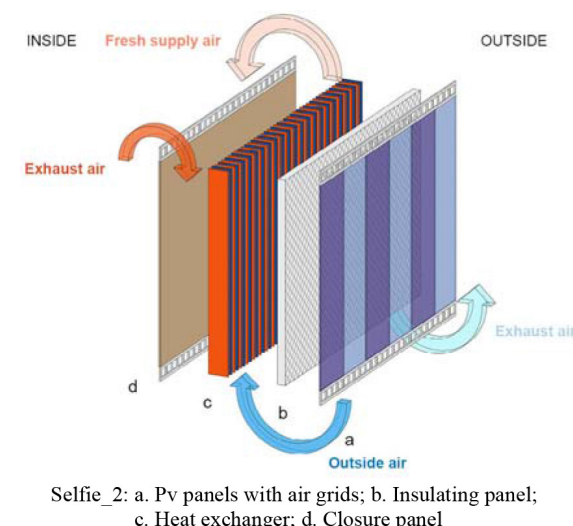
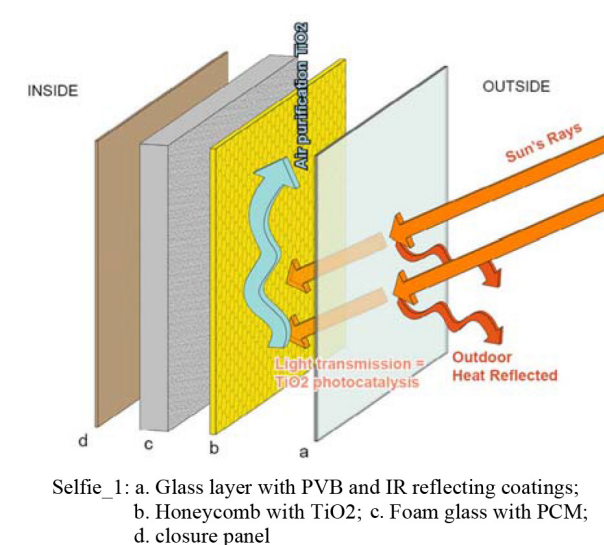


Figure 29: Composition of the modules of the SELFIE project
Source: Romano, R. and P. Gallo (2016). 'The SELFIE Project Smart and efficient envelope' system for nearly zero energy buildings in the Mediterranean Area."

photoactivable ceramic and/or metals and/or special paints devoted to the treatment of air. The composition of the modules can be seen in Figure 29. All three components have integrated sensors and equipment for data management, in order to guarantee a smart control of energy flows inside the building envelope and to ensure the ability of changing their energy performance according to external climatic conditions. However, the system offers to the users also the possibility to manage the facade themselves even in the absence of an automated system of control.

iv. BRESAER

BRESAER (BREAkthrough Solutions for Adaptable Envelopes in building Refurbishment) project (Figure 30) is an innovative envelope system conceived by Acciona Infraestructuras & Partners, that combines active and passive components, integrating them into a lightweight structural mesh. It is composed of multifunctional and multilayer insulation panels made of Ultra High Performance Fibre Reinforced Concrete, multifunctional lightweight ventilated facade



Figure 30: Visualisation of the BRESAER project
Source: www.bresaer.eu

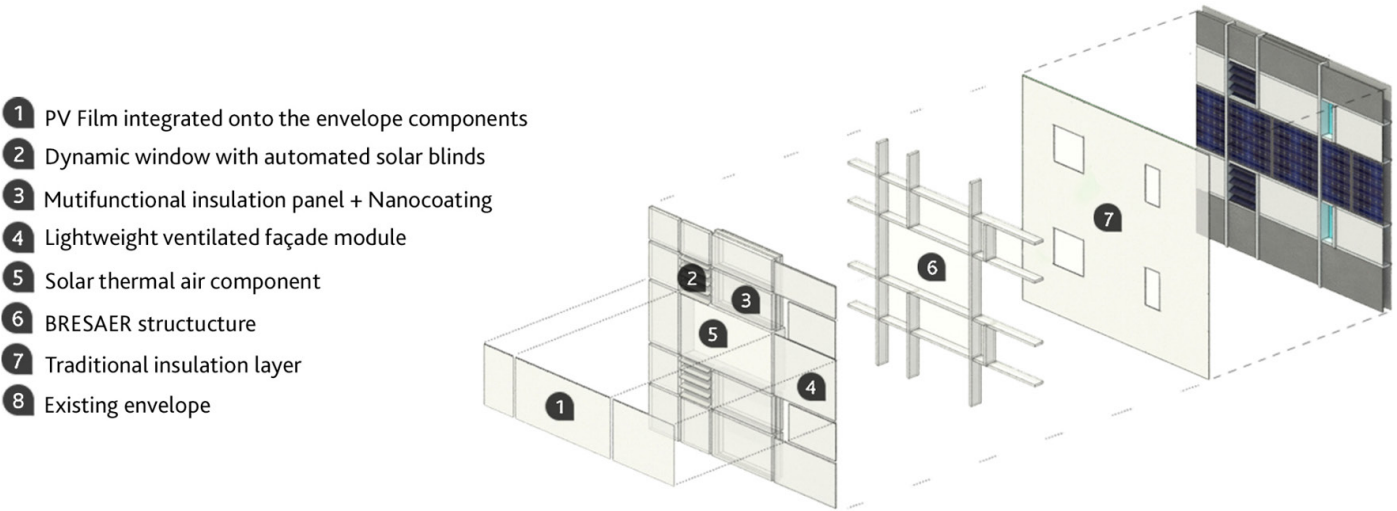


Figure 31: Overview of the BRESAER project and arrangement of panels
Source: www.bresaer.eu

modules and dynamic automated windows with insulated solar blinds, which adjust automatically according to the position of the sun and the occupants comfort. In addition, Combined Solar Thermal Air and PV envelope components are used for indoor space heating and ventilation, thermal insulation and electricity generation. Moreover, preheated air can be used for indoor space heating and dehumidification. The composition of the facade layers can be seen in Figure 31.

The project is tested in four virtual demonstrations located in different European climate zones and a real one in Ankara, Turkey, expecting to record a reduction by at least 60% of the total primary building's energy consumption and to reach a near zero energy building.

v. MeeFS

MeeFS (Multifunctional Energy Efficient Facade System) project is a multifunctional energy efficient façade system for building retrofitting developed by Acciona Infraestructuras. This new system will

allow a 27% reduction of the total energy demand, in order to increase energy efficiency and indoor comfort of residential buildings in European climate zones. It will incorporate innovative solutions by means of active and passive technologies solutions combination.

The MeeFS project consists of seven technological units - insulation, green façade, ventilated façade, solar protection, building-integrated photovoltaics (BIPV), an advanced passive solar protector/energy absorption auto mobile unit, and an advanced passive solar collector/ventilation module. These technological units have both opaque and transparent properties and are integrated into modules and then into structural panels and into existing facades, as shown in Figure 32. In addition, the modules also include multiple sensors, which enable real-time monitoring, in order to optimise energy consumption. The project was demonstrated in a real building in Spain, which can be seen in Figure 33 and passed successfully not only the performance tests, but also the detailed technical assessments.

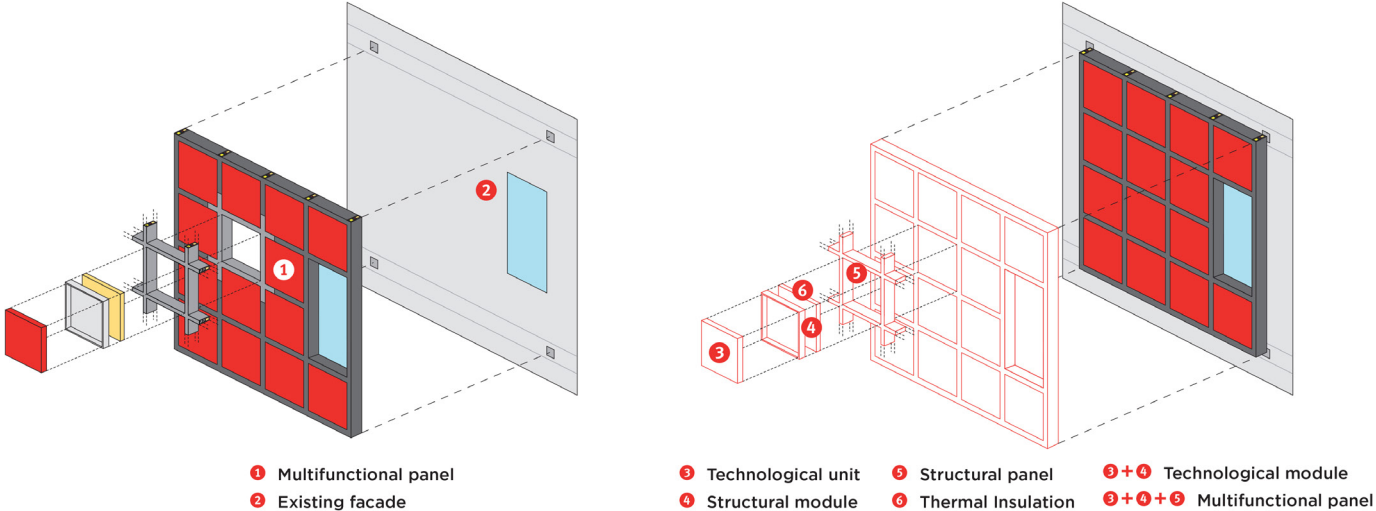


Figure 32: Overview of the MeeFS project and arrangement of panels
Source: www.meeFS-retrofitting.eu



Figure 33: Demonstration of the MeeFS project in Spain
Source: www.meeFS-retrofitting.eu

II. Case studies evaluation

In the following pages in Tables 6.1-6.5, the previously described projects are presented in tables, in order to evaluate them and get a clearer overview of their advantages and disadvantages, which is a crucial step before determining the system of this research project. While creating these tables, the criteria set together with “Rollecate” were taken into account. These are the following:

- the complexity of the system should not be high
- the dimensions and the thickness of materials used are preferred to be kept to the minimum

- the weight should be kept low
 - the use of liquids is preferred to be avoided
 - the wiring if required should be well integrated
 - the costs involved should be reasonable and kept as low as possible
- These criteria were set and were carefully considered in order to ensure that “Rollecate” as a company will benefit and potentially make a profit in the future, which is always an important aspect for new products and systems and for a company that wants to succeed and be competent in the market.

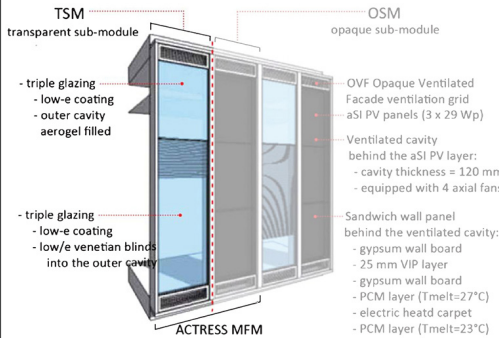
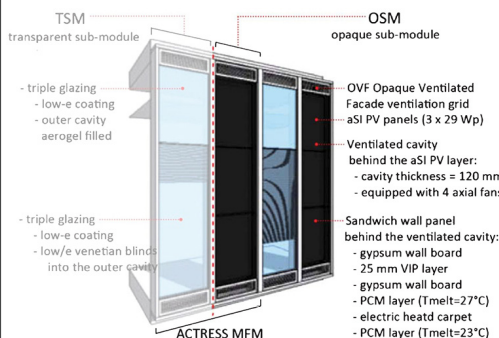
Project	Advantages	Disadvantages	Cost
ACTRESS	 <p>very good thermal insulation, remarkably low heat losses, accounts for more than 90% of the overall daily gains, glazing with low-e venetian blinds is highly performing, extremely flexible and adaptable</p>	aerogel glazing overheating - very high surface temperatures - no possibility of adaptation	
	 <p>harvesting energy, various ventilation strategies (supply air, outdoor air curtain, exhaust air) and different ventilation modes for winter and summer (natural, hybrid, mechanical, thermal buffer), remarkably low heat losses, “passive activation” of PCM provides satisfactory thermal inertia, while keeping the module weight low</p>	difficult to operate, complex behavior of PCM, use of liquid, thickness	

Table 6.1: Case studies evaluation


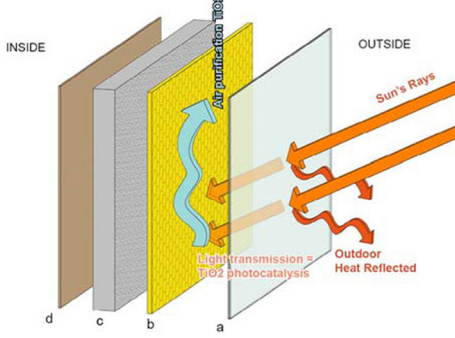
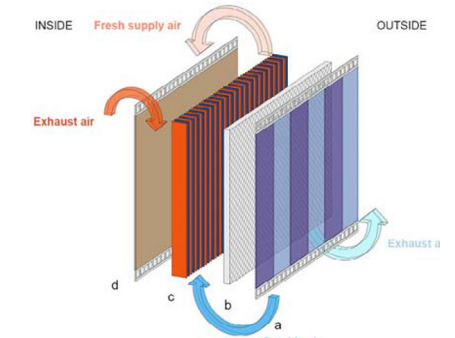
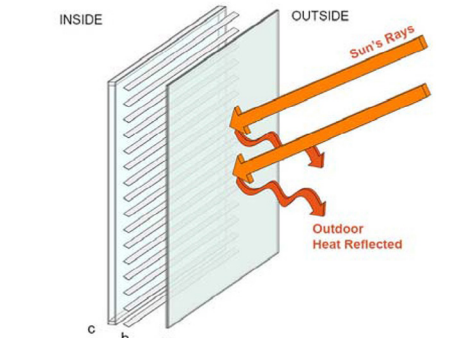
Project	Advantages	Disadvantages	Cost
Adaptiwall	 <p>harvesting energy, adaptive insulation, lightweight concrete buffer, compact ventilation and energy recovery</p>	all-in-one component - complexity, thickness, use of liquid	+
SELFIE	 <p>Selfie_1: a. Glass layer with PVB and IR reflecting coatings; b. Honeycomb with TiO2; c. Foam glass with PCM; d. closure panel</p> <p>self-cleaning treatment, indoor air purification, PCM: thermal inertia increase, foam glass: lightweight, good thermo-hygrometric performance, high strength, grid vents deliver different ventilation modes which allow: reduction of energy consumption for heating, reduction of overheating phenomena honeycomb: minimize quantity, weight and cost of material</p>	complex behavior of PCM, use of liquid	
	 <p>Selfie_2: a. Pv panels with air grids; b. Insulating panel; c. Heat exchanger; d. Closure panel</p> <p>photovoltaic panels DSSC (Dye Sensitized Solar Cells) produce renewable energy, energy savings</p>	use of liquid	
	 <p>Selfie_3: a. Glass layer with PVB and IR reflecting coatings b. Air gap and shading device; c. Double glazing</p> <p>possibility of integrating DSSC (Dye Sensitized Solar Cells) photovoltaic cells in the external layer in order to produce electricity, reduction of thermal transmittance, control of solar radiation, improvement of acoustic performance</p>		

Table 6.2: Case studies evaluation





	Project	Advantages	Disadvantages	Cost
BRESAER	 <p>Combined solar thermal and PV envelope component</p>	provides thermal energy, heats building ventilation air, improves indoor air quality, no maintenance required over its 30+ year lifespan, energy savings, displace 20-50% of heating fuel consumption and corresponding greenhouse gas emissions	use of liquid	
	 <p>Multifunctional lightweight ventilated façade module</p>	elimination of auxiliary HVAC installations, improvement of indoor air quality, integrated photovoltaic system for electricity generation		
	 <p>Dynamic window with controlled air-tightness and insulated solar blinds</p>	insulated solar blinds, automatic adjustment according to the position of the sun	view restriction, cleaning - maintenance - repair, appearance - aesthetics	
	 <p>Multifunctional UHPFRC panels for envelope</p>	lightweight, maximized heat exchange and heat storage capacity	considerably more expensive than conventional concrete	

Table 6.3: Case studies evaluation

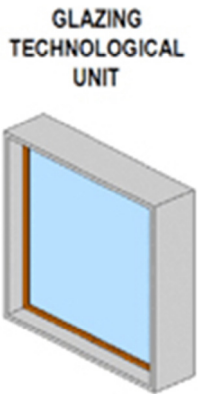
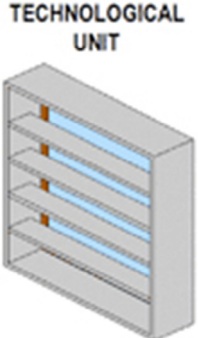

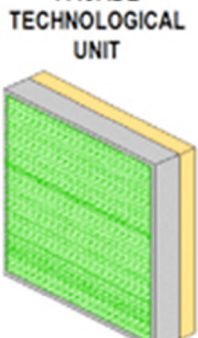
	Project	Advantages	Disadvantages	Cost
MeeFS	 <p>GLAZING TECHNOLOGICAL UNIT</p>	views, solar gains		
	 <p>SOLAR PROTECTION TECHNOLOGICAL UNIT</p>	adjustable movable slats, energy savings, improve thermal and visual comfort, very effective against solar heat gains	view restriction, cleaning - maintenance - repair, appearance - aesthetics	
	 <p>SOLAR THERMAL TECHNOLOGICAL UNIT</p>	semitransparent external layer, lightweight high inertia internal wall, controllable cladding system, lower and upper opening gaps with adjustable louvers for ventilation of the cavity		
	 <p>GREEN FACADE TECHNOLOGICAL UNIT</p>	improve thermal comfort, mitigation of urban heat island effect, protect from direct solar radiation, cooling effect through evaporation, noise absorption, energy savings, no ground soil needed	maintenance issues	+

Table 6.4: Case studies evaluation

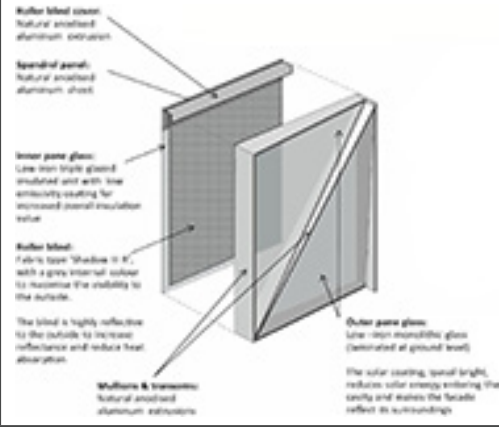
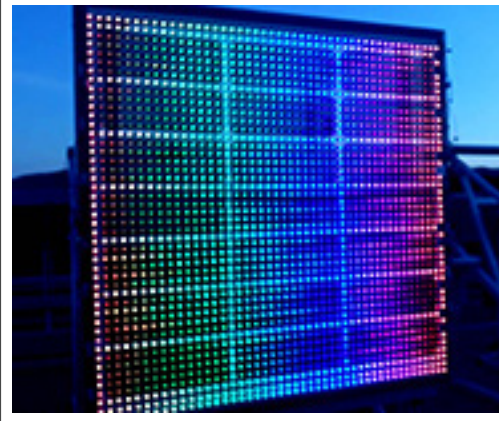
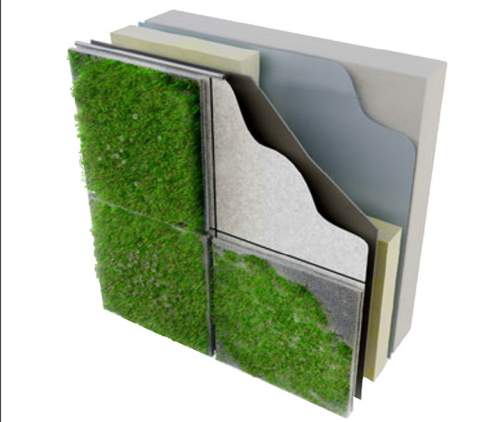
Project	Advantages	Disadvantages	Cost
Closed Cavity Facade -CCF 	energy savings, visual comfort, highly transparent glazing, less prone to damage and thus low maintenance requirements, no cavity condensation risks, no cavity dust/dirt from outside	should remain completely sealed, constant need of dry and clean air to be fed into the façade cavity in order to prevent the formation of condensation on the glazing	
ETFE Multi-functional Module 	energy harvesting, integrated photovoltaics and lighting function with LED, acts as glazing system, self-contained module providing the power for the LED		
Living Wall Facade 	lightweight - zero earth system, 90% reduction in water consumption - hydroponics used for nutrient and water delivery, resilient growth - seeds grow on-site, visually appealing even without the green	takes up to 2 months until full growth, higher costs than a green facade, need of irrigation, drainage control and nutrients to be delivered and organized vertically, maintenance	+

Table 6.5: Case studies evaluation

III. Classification and evaluation of applied materials according to function

In the following pages in Tables 7.1-7.3, the materials encountered in the previously described projects plus a few more found in other projects presented in Appendix A, which were considered interesting for future applications according to the presented

literature are gathered in tables according to their function and are evaluated again focusing on their advantages, disadvantages and cost depending on "Rollecate's" preferences.

Function	Materials	Advantages	Disadvantages	Cost
Solar protection	exterior blinds	energy savings, improve thermal comfort, heat, glare and light control, very effective against solar heat gains	view restriction, high visual impact, appearance - aesthetics, cleaning - maintenance - repair	
	interior blinds	glare and light control, do not affect building aesthetics	view restriction, high visual impact, lower thermal performance than exterior blinds	
	blinds/louvers in window cavity	energy savings, heat, glare and light protection, lower risk for damage and thus maintenance requirements	view restriction, appearance - aesthetics	
Energy production	High Concentration Photovoltaics - HCPV	double the efficiency of PVs, low temperature coefficients, increased and stable energy production throughout the day due to tracking	need of solar tracking - must be perpendicular to the sun, specific geometry - lack of standardization, appearance - aesthetics, works best in certain sunny areas with high Direct Normal Irradiance (DNI)	
	Building Integrated Photovoltaics - BIPV	can be transparent, can function as shading	lower efficiency than PVs	
	Building Integrated Photovoltaics/Thermal - BIPV/T	both electricity and thermal energy		
	Building Integrated Solar Thermal - BIST	air	anti-freezing or anti-boiling, non-corrosive, simple structure, low cost	low heat capacity, potential leakage and noise, lower efficiency, large mass or volume, high in heat loss
		water	non-toxic, cost effective, perform well in cold climates	possible leakage, freezing, corrosion and overheating, unstable heat removal effectiveness
		refrigerant	small fluid volume, stable performance, high efficiency	environmental behavior, requirement to be recharged
		heat pipe	compact and super high heat exchange ability, constant liquid flow, versatility, scalability and adaptability of the design, small weight, easy assembly and installation	difficult in maintenance and replacement
	PCM	improve thermal comfort, diversity in building integration	difficult to operate, complex behavior, use of liquid	+

Table 7.1: Classification and evaluation of materials

Function	Materials	Advantages	Disadvantages	Cost
Glazing	triple glazing filled with granular aerogel	aerogel: low thermal conductivity	possibility of glazing overheating - very high surface temperatures, low light transmissibility	+
	triple low-e coated glazing with argon in the outer air gap	highly reflective		+
	ETFE	90-95% transparent, solar control, lightweight, durable - does not degrade, sustainable - easily recyclable, self-cleaning properties, cost-effective	offers better performance only in a multi-layered (usually 2-3) pneumatic system - need of power for the inflated cushions	
Insulation	Ultra High Performance Concrete - UHPC	lightweight, high strength, longer life cycle, less maintenance	considerably more expensive than conventional concrete, very long mix times and high energy mixers required	+
	Phase Change Material - PCM	improve thermal comfort, diversity in building integration	difficult to operate, complex behavior, use of liquid	
	Vacuum Insulation Panel - VIP	outstanding thermal conductivity, better insulation performance can be achieved with much thinner insulation than conventional insulation materials	lower thicknesses reduce lifetime and require a higher gas pressure	
Ventilation	total heat exchanger	compact ventilation and energy recovery	use of liquid	
	ventilated chamber	elimination of thermal bridges and condensation problems, excellent thermo-hygrothermal performance		
	cavity wall	hybrid ventilation with different modes for winter and summer, different airflow paths, thermal and sound insulation	cold spots on the inside walls can be caused - condensation, limitation of insulation that is able to be installed	-
Green facade	vertical garden	improve thermal comfort, mitigation of urban heat island effect, protect from direct solar radiation, cooling effect through evaporation, noise absorption, energy savings, no ground soil needed	attached character, view restriction - visual impact, maintenance, irrigation, care issues	+

Table 7.2: Classification and evaluation of materials

Function	Type	Advantages	Disadvantages	Cost
Coating	antireflection coating applied on PV cells	reduction of light reflection, increase of light transmission	no adaptivity	
	low-e	reduce the total SHGC - reflect the solar near-infrared radiation, high levels of daylight transmission, low U-factor, solar control	reduce the beneficial solar gain that could be used to offset heating loads	
	IR reflective	reduce SHGC - reflects the wavelengths of the sun's radiation that cause surfaces to become hot - keep surfaces cool, glare control, uniform exterior appearance	reduces visible transmittance, usually for hot climates, no adaptivity	
	passive	titanium dioxide - TiO2	self-cleaning, anti-bacterial, photocatalytic, hydrophobic properties, fire retardant, increased durability, lower maintenance need, reflects visible and infrared spectrum	
		thermochromic	infrared light reflection, high energy savings, no activation electricity	
	active	electrochromic	energy savings, low-voltage power needed, power only required at the switch time, spectral transmission is maintained during changing transparency levels, gradual transmission change is advantageous for the occupant's eyes	switching speed is tied to the size and temperature of the window, activation electricity is required
		liquid crystal	very quick change (~1sec), control privacy	activation electricity is required - whenever light is needed, no energy savings, no outside visibility
		suspended particle	instantaneous control of light (<1sec), outside visibility, wide range of transmittance, UV protector, reduction of infrared light, energy savings	limited in size, activation electricity is required, optical direct transmittance in the clear state is poor

Table 7.3: Classification and evaluation of materials

DESIGN PHASE

After the evaluation of the case studies and of the applied materials, the system to be tested for this research project was determined as shown in Table 8. This was done based on the advantages and disadvantages presented, however, in a few cases where the potential of a specific material was considered important to be considered, the risk was taken to try and prove that the aspect seen as problem from “Rollecate’s” point of view is in reality a great potential. The results of the hand calculations and simulations would show the performance of the system, showcasing the potential of the chosen materials and modules.

I. Multi-functional Facade Module

The Facade System comprises of three main types of modules: transparent, semi-transparent and opaque. These three types were chosen, in order to provide the necessary architectural design freedom because all the case studies presented consist only of opaque and transparent ones. An overview of the multi-functional modules can be seen in Table 8. The logic of the system is that it consists of modules that deliver different functions, being able to change their behavior and adapt to different environmental conditions. A selection of them creates a whole facade according to the needs of the concept and context of each project. In addition, the layers could theoretically be incorporated in any module size in order to suit different projects with different floor heights, providing again the required architectural design freedom. For this research project the module size chosen is 0.90x0.90m, which suits a typical office facade with concrete structure and floor height 3.60m. In general, it is preferred to keep the module size small with a maximum of 1.40x1.40m since it

should remain low in weight and be transported easily.

i. Transparent Modules

Transparent modules should maximize thermal insulation, light transmission and protection from summer solar radiation. Therefore, the functions chosen are the following:

- ◊ Solar protection
- ◊ Smart Glazing

ii. Semi-transparent Modules

Semi-transparent modules should provide the advantage of combining daylight with energy efficiency. Therefore, the functions chosen are the following:

- ◊ Energy production
- ◊ Insulation

iii. Opaque Modules

Opaque modules should maximize inertia and thermal insulation characteristics. In addition, they are a good option to incorporate energy production, since it has a higher efficiency than in semi-transparent modules. Therefore, the functions chosen are the following:

- ◊ Energy production
- ◊ Insulation
- ◊ Green

A more detailed description of each module is provided in the following section.

Multi-functional Facade Module - MFM		synergetic effect, customized layout of the facade in order to fit different buildings and climates	
Modules		Materials	Specifications (1. being the innermost layer)
Transparent Modules	Solar protection	blinds in window cavity [53mm]	1. glass [4mm] 2. air gap [14mm] 3. glass [4mm] 4. air gap with blinds [27mm] 5. spectrally selective coating 6. glass [4mm]
	Smart glazing	electrochromic window [29mm]	1. glass [4mm] 2. low-e coating 3. argon gas filled gap [16mm] 4. glass 5. transparent conductive coating 6. electrochromic layer 7. ion-conducting electrolyte layer 8. ion storage layer 9. transparent conductive coating 7. glass [4-10: 9mm]
Semi-transparent Modules	Energy production	Building Integrated Photovoltaics - BIPV [28mm]	1. glass [4mm] 2. air [16mm] 3. glass [3mm] 4. encapsulant [0.38mm] 5. electrical conductor 6. solar cells with antireflection coating 7. encapsulant [4-7: 2mm] 8. glass [3mm]
	Insulation	Translucent PCM [128mm]	1. glass [3mm] 2. aerogel [16mm] 3. glass [3mm] 4. air cavity [70mm] 5. glass [3mm] 5. PCM [30mm, type S23] 6. glass [3mm] (air inlet and outlet for ventilation)
Opaque Modules	Energy production	Building Integrated Photovoltaics/Thermal - BIPV/T [121mm]	1. aluminium panel [d=1.5mm] 2. Vacuum Insulated Panel (VIP) [d=40mm] 3. aluminium panel [d=1.5mm] 4. ventilated cavity 70mm 5. laminated PV cells [8mm] (air inlet and outlet for ventilation)
	Insulation	Wall panel with PCM [149mm]	1. aluminium panel [d=1.5mm] 2. Vacuum Insulation Panel (VIP) [d=40mm] 3. aluminium panel [d=1.5mm] 4. air cavity [70mm] 5. glass [3mm] 6. PCM [30mm, type S23] 7. glass [3mm] (air inlet and outlet for ventilation)
	Green Facade	Living Wall Facade [206mm]	1. aluminium panel [d=1.5mm] 2. Vacuum Insulation Panel (VIP) [d=30mm] 3. aluminium panel [d=1.5mm] 4. substructure & irrigation system [90mm] 5. backplate [3mm] 6. aquanappe - root mat [4mm] 7. aluminium foam [6mm] 8. plant growth [70mm]

Table 8: Overview of the Multi-functional Facade Module (MFM)

II. Application principles

For this research project, a typical office construction with concrete used in European countries is chosen to visualise the final design and to conduct the simulations, in order to test the performance of the proposed system. The floor-to-ceiling height is 2.70m and the floor-to-floor height is 3.60m. The chosen module size is 0.90x0.90 for two main reasons, first because it divides the floor-to-floor height in exactly four parts and second because in this way the facade profiles do not affect the view to the outside while occupants are sitting and working or while standing.

As already stated, the modules can be combined and applied on a facade as the client wishes and as required by the needs of each project and climate. However, within this research project a proposal is made of how they could be applied according to the function of each module and the needs of an office facade. This proposal is directly related to the need of each facade part to be transparent, semi-transparent or opaque and it can be seen in Figure 34. For the top part, which essentially covers the structure of the building and the suspended ceiling, the use of BIPV/T is proposed because there is no need of transparency and thus this part can be used for the maximum potential of

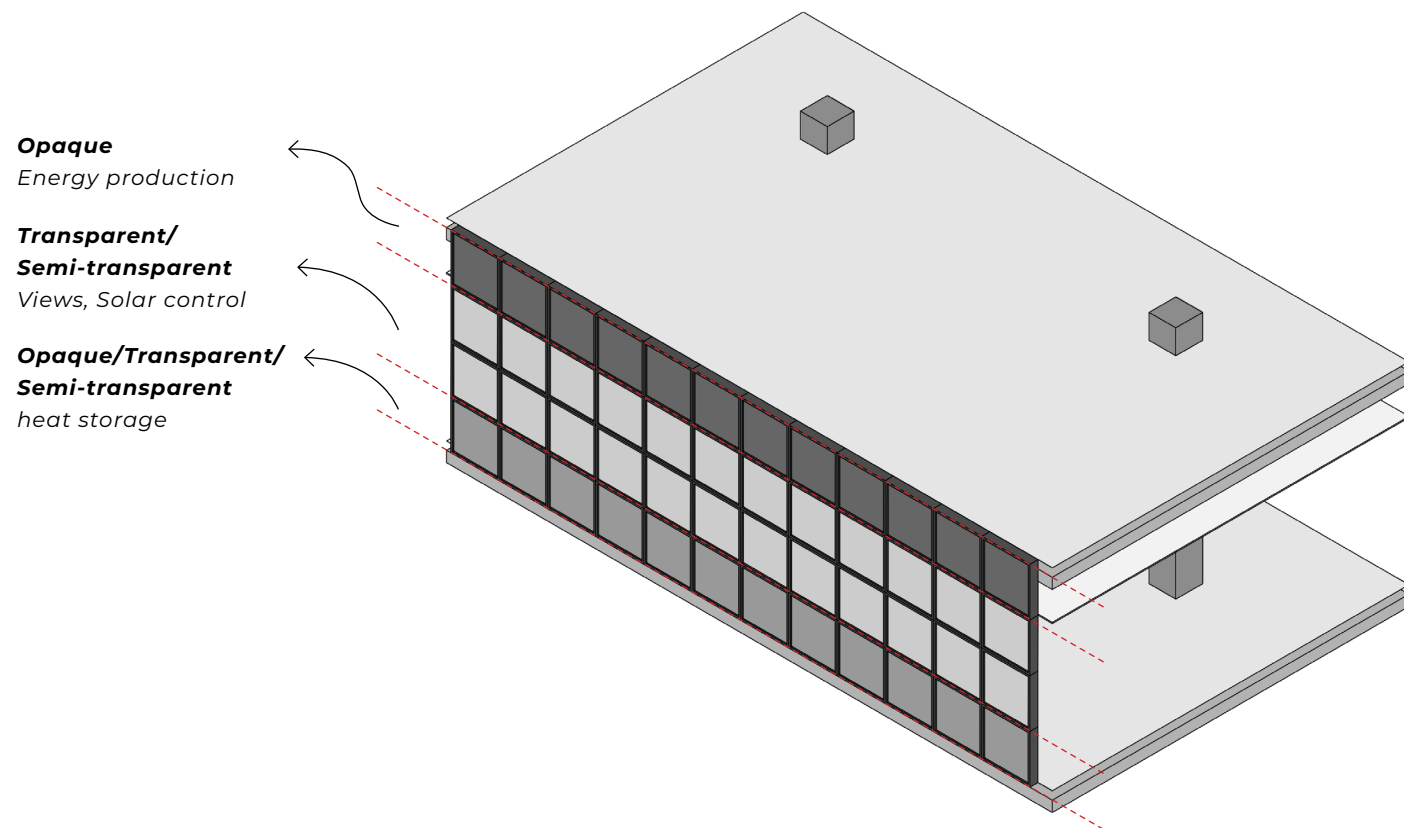


Figure 34: Facade division according to the Multi-functional Facade Modules functions and the needs of an office facade

energy generation. For the two middle parts, either the transparent modules or the semi-transparent modules would be ideal according to the privacy needs of the corresponding office area. The transparent modules provide views and natural light while also protecting from the sun and the semi-transparent ones provide the required privacy, while also enabling partly daylight to enter. For the lower facade part, all modules could be used depending on preferences. According to this logic, a few combinations are made to be simulated and are presented later in this report.

A representation of how the facade system could look like according to the proposed arrangement can be seen in Figure 35. This facade segment consists of BIPV/T modules on the top part for energy production, electrochromic glazing modules in the two middle ones to provide views, natural light but also solar control and PCM modules in the lower part for insulation and heat storage. In addition, the green module could cover a full part of the facade as shown in Figure 35.

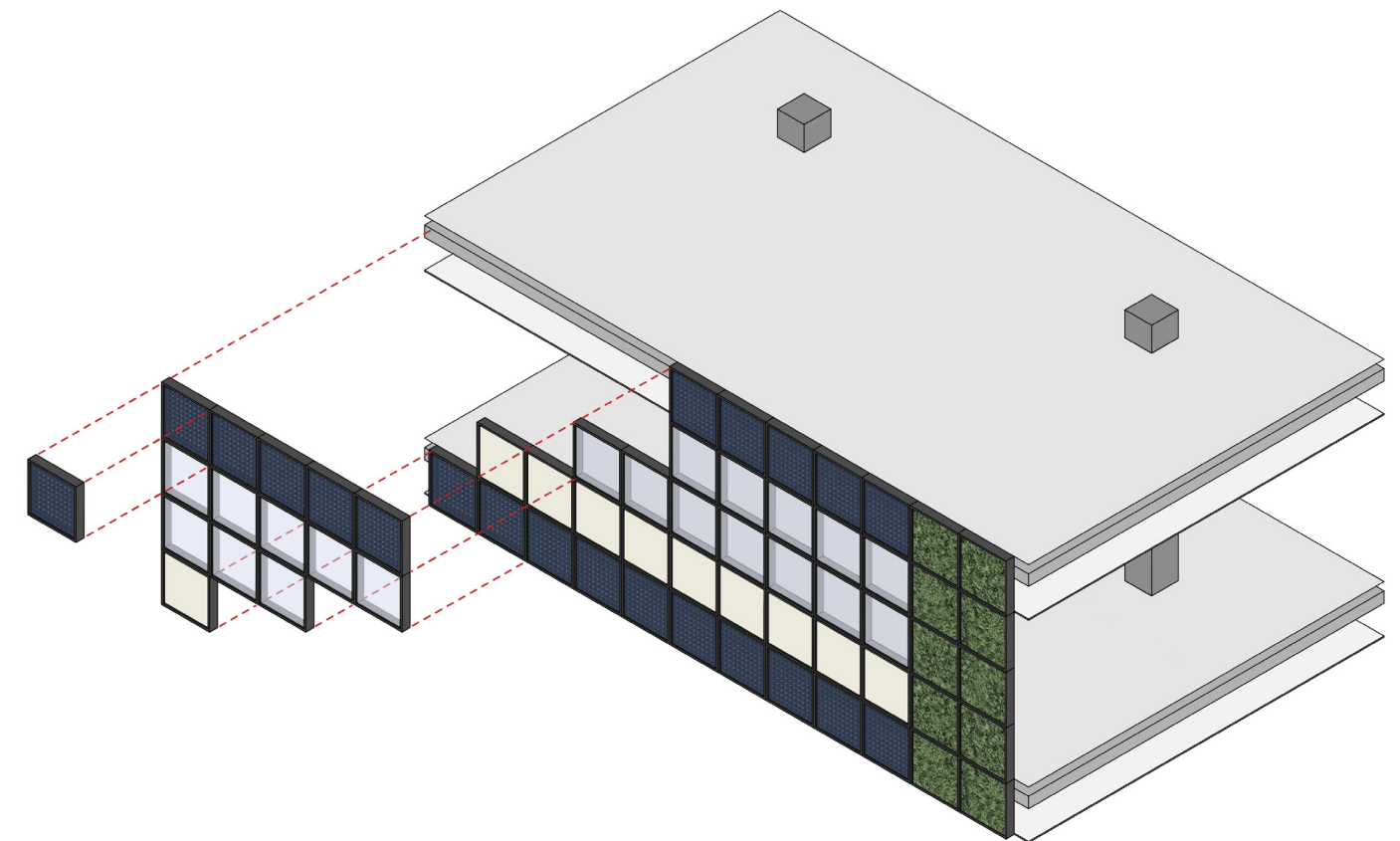


Figure 35: Example of a facade composition constructed with a possible combination of Multi-functional Facade Modules

II. Transparent Modules

i. Glazing unit with integrated blinds

Solar shading systems are important in order to favor solar gain in winter and reduce it in summer. Nevertheless, exterior shadings are in many cases not preferred due to architectural concepts and maintenance costs. Therefore, for this module blinds were chosen to be integrated in the window cavity. The composition of the module can be seen in Table 9 and Figure 37. This module offers the functions of slat tilting and blind raising/lowering, which are achieved by a motor that permits a constant speed resulting in a synchronized function for multiple blinds. A comprehensive drawing of the integrated blinds layer can be seen in Figure 38. The Venetian blind operation could also be powered using the photovoltaic cells of the energy production modules. This module offers heat, glare and light protection leading to energy savings. In addition, since the blinds are enclosed in the window cavity, there is much lower risk for damage and consequently maintenance requirements.

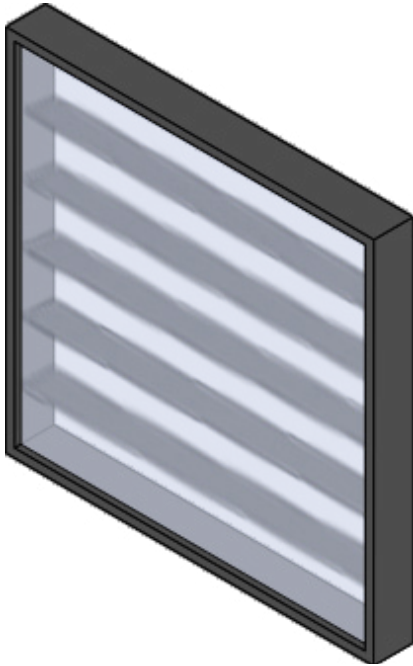


Figure 36: Glazing unit with Integrated blinds

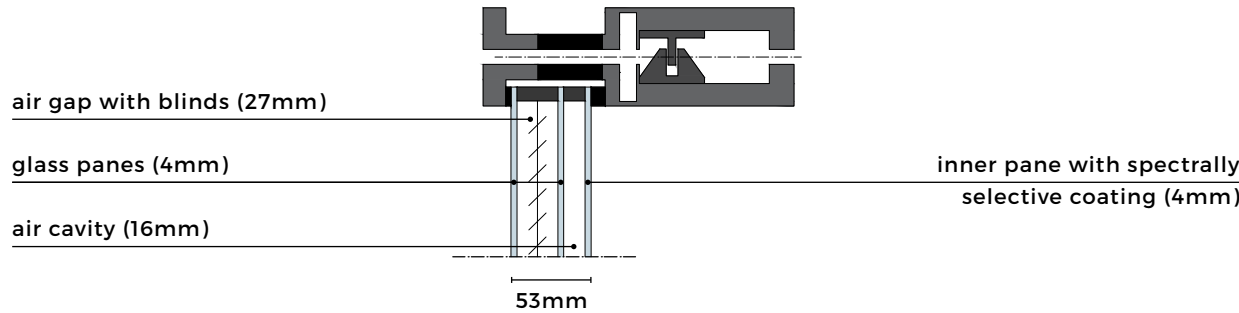


Figure 37: Concept detail of the glazing unit with Integrated blinds

Module	Transparent						
Function	Solar protection						
Type	blinds in window cavity						
Layers & properties		thickness		R-value		g-value	T _v
	1. glass	0,004	m	0,004	m²K/W		
	2. air gap	0,014	m	0,17	m²K/W		
	3. glass	0,004	m	0,004	m²K/W		
	4. air gap with blinds	0,027	m	0,36	m²K/W		
	5. spectrally selective coating	0	m				
	6. glass	0,004	m	0,004	m²K/W		
Tot		0,053	m	0,71	m²K/W	0,28	0,40
U-value				1,4	W/m²K		

Table 9: Properties of the glazing unit with Integrated blinds

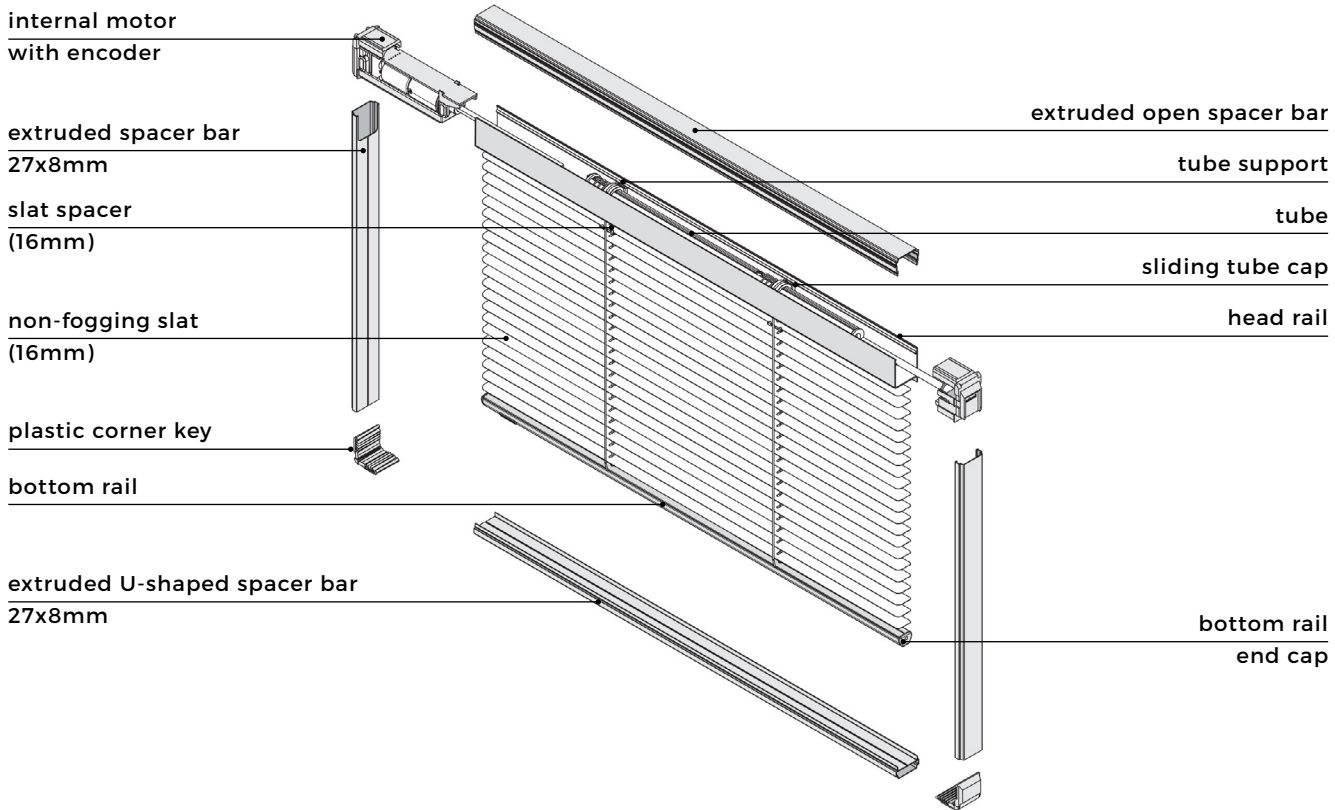


Figure 38: Comprehensive drawing with the components of the “ScreenLine SL27M integrated venetian blinds”
Source: www.pellini.net

ii. Unit with electrochromic glazing

For the glazing parts, a smart window was chosen and specifically an electrochromic window, which is made by sandwiching certain materials between two glass panes. The layers of the electrochromic composite panel can be seen in Figure 41, whereas the composition of the module can be seen in Table 10 and Figure 40. This module is an active solar control device, whose glazing switches between a clear and transparent blue-gray tinted state by the application of a low voltage (typically 1-5V DC) with the advantage that no power is needed to maintain this desired state. One complete switching cycle takes about 15-20 min and requires less than 2Wh/m². In order to supply the individual glass panels with electricity, a wiring circuit is needed which can be embedded into the structural façade elements, preferably posts. Another advantage of electrochromic glazing is that it has the ability to maintain spectral transmission during changing transparency levels and therefore it has become one of the most used chromogenic technologies for building facades. In addition, this module could be powered using the photovoltaic cells of the energy production modules.

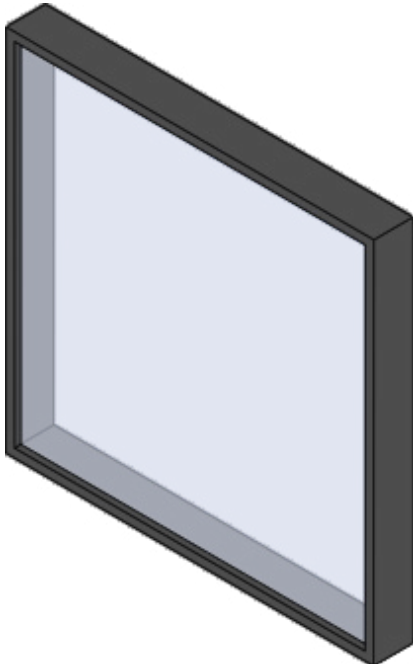


Figure 39: Unit with electrochromic glazing

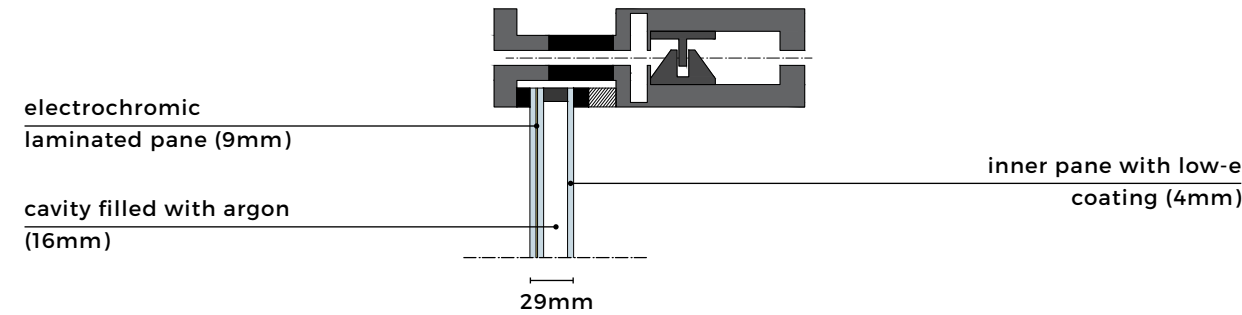


Figure 40: Concept detail of the unit with electrochromic glazing

Module	Transparent								
Function	Smart glazing								
Type	electrochromic window								
Layers & properties		thickness		R-value		g-value		Tv	
	1. glass	0,004	m	0,41	m²K/W	off	on	off	on
	2. low-e coating	0,016	m		m²K/W				
	3. argon filled gap		m²K/W						
	4. glass	0,009	m	0,3	m²K/W				
	5. electrochromic layer								
	6. glass								
Tot		0,029	m	0,88	m²K/W	0,42	0,1	0,56	0,1
U-value				1,1	W/m²K				

Table 10: Properties of the unit with electrochromic glazing

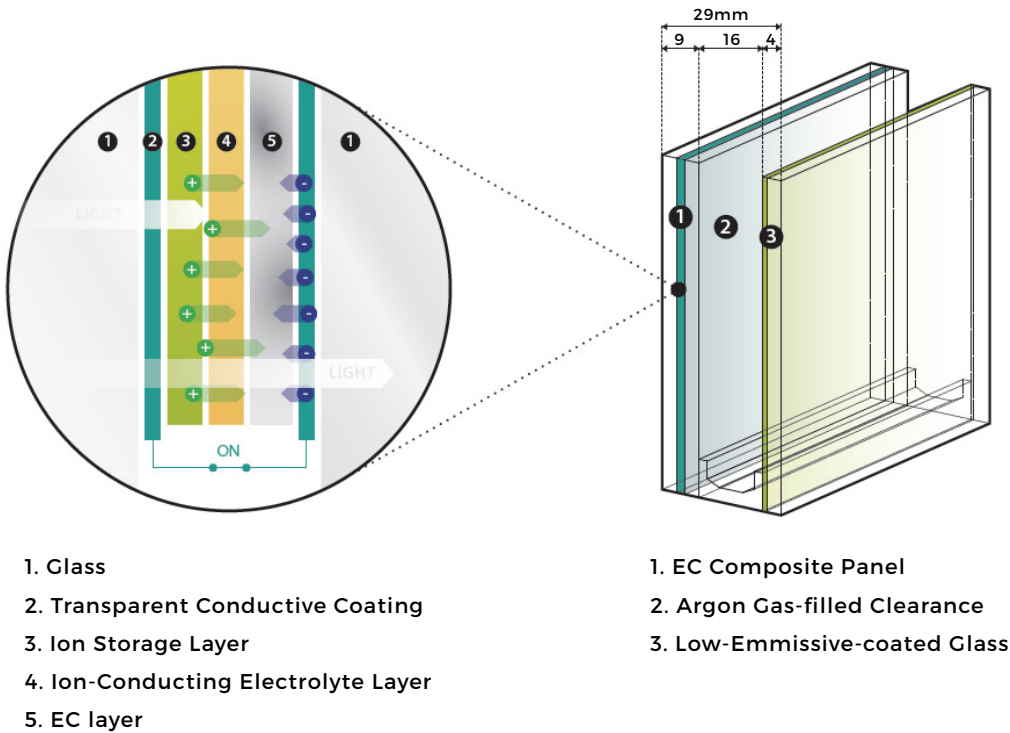


Figure 41: Detailed interpretation of "ECONTROL smart glass II" and of the electrochromic composite panel's layers
Source: www.econtrol-glas.de/en

II. Semi-transparent Modules

i. Glazing unit with BIPV

For this module, BIPVs (Building Integrated Photovoltaics) are used as renewable energy source to provide electrical energy. The PV glazing reduces incoming solar radiation, while producing energy and providing 36% of transparency. This level of transparency is achieved due to the choice of a big distance between the cells, but at the same time it causes a lower energy performance in comparison to the opaque BIPV/T module. In addition, the PV cells are covered with antireflection coating because it reduces light reflection and increases light transmission. The layers of the laminated PV cells can be seen in Figure 44, whereas the composition of the module can be seen in Table 11 and Figure 43.

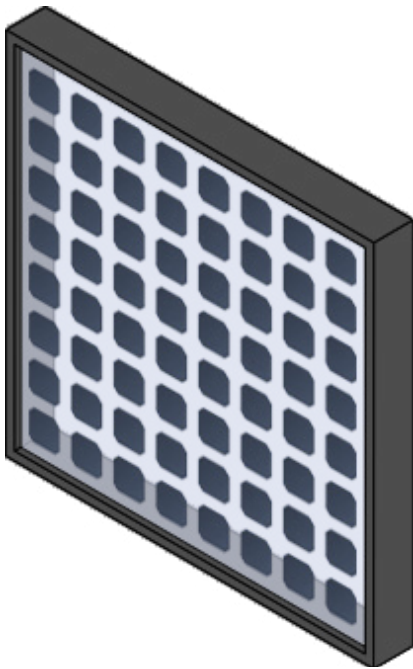


Figure 42: Glazing unit with BIPV

Module	Semi-transparent						
Function	Energy production						
Type	BIPV						
Layers & properties		thickness		R-value		g-value	Tv
	1. glass	0,004	m	0,41	m²K/W	0,68	0,79
	2. low-e coating	0,016	m				
	3. argon filled gap						
	4. glass	0,003	m	0,07	m²K/W	0,40	0,40
	5. PV cells (130kWh/y)	0,002	m				
	6. antireflection coating	0	m				
	7. glass	0,003	m	0,003	m²K/W		
Tot		0,028	m	0,65	m²K/W	0,27	0,32
U-value				1,5	W/m²K		

Table 11: Properties of the glazing unit with BIPV

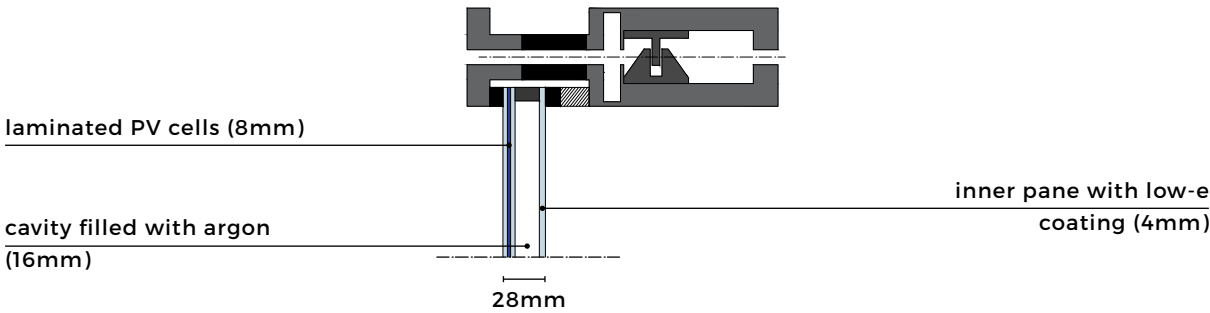


Figure 43: Concept detail of the glazing unit with BIPV

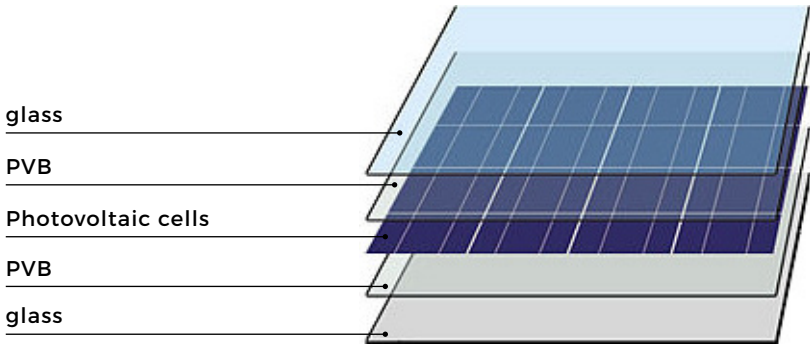


Figure 44: Composition of laminated glass with PV cells

ii. Unit with translucent PCM

For this module, translucent PCM (Phase Change Material) is used in order to store heat energy in a latent form, which means that heat is released when it is really needed. PCM undergoes a phase change from fluid to solid and vice versa, providing a big potential for temperature control of the indoor space. This module works basically like a thermal mass wall and PCM offers the advantage of solar passive heating without increasing mass. An air cavity is also put behind the PCM in order to regulate better its temperature and thus the release time. The ventilation modes for winter and summer period during day and night can be seen in Figure 47. During the winter, the incoming air is preheated by the PCM and enters to the inside, decreasing the heating loads and contributing to the users comfort. During the summer, night-time cooling is used, in order to take advantage during the day keeping the interior air cooler. As a result, the use of PCM cuts off-peak cooling loads while stabilizing the interior temperature. The composition of the module can be seen in Table 12 and Figure 46.

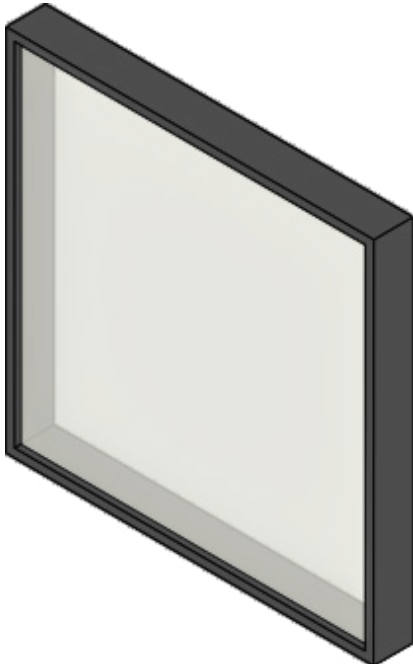


Figure 45: Unit with translucent PCM

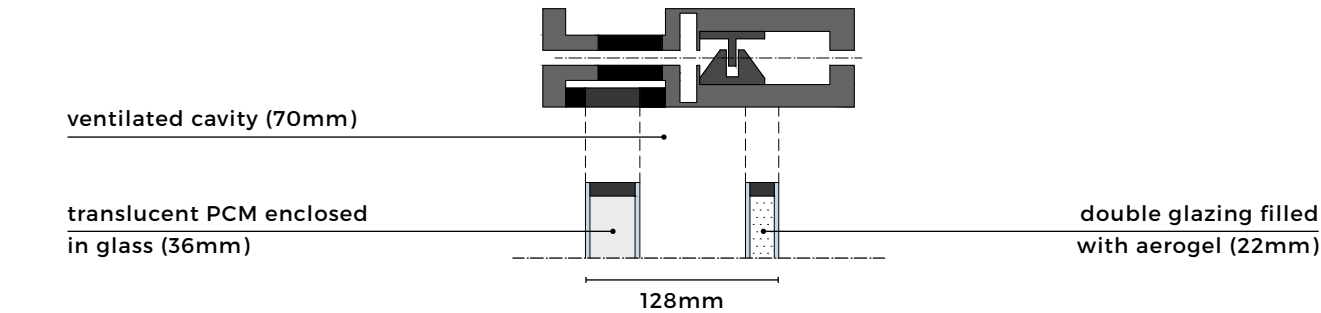


Figure 46: Concept detail of the unit with translucent PCM

Module	Semi-transparent								
Function	Insulation								
Type	Translucent PCM								
Layers & properties		thickness		R-value		g-value		Tv	
	1. glass	0,003	m	0,003	m²K/W	0,55	0,55	0,62	0,62
	2. aerogel	0,016	m	1,4	m²K/W				
	3. glass	0,003	m	0,003	m²K/W				
	4. air cavity	0,07	m	0,17	m²K/W	-	-	-	-
	5. glass	0,003	m	0,003	m²K/W	0,9	0,86	0,9	0,86
	6. PCM	0,03	m	0,15	m²K/W	0,33 solid	0,37 liquid	0,38 solid	0,55 liquid
	7. glass	0,003	m	0,003	m²K/W	0,9	0,86	0,9	0,86
Tot		0,128	m	1,90	m²K/W	0,15	0,15	0,19	0,25
U-value				0,5	W/m²K				

Table 12: Properties of the unit with translucent PCM

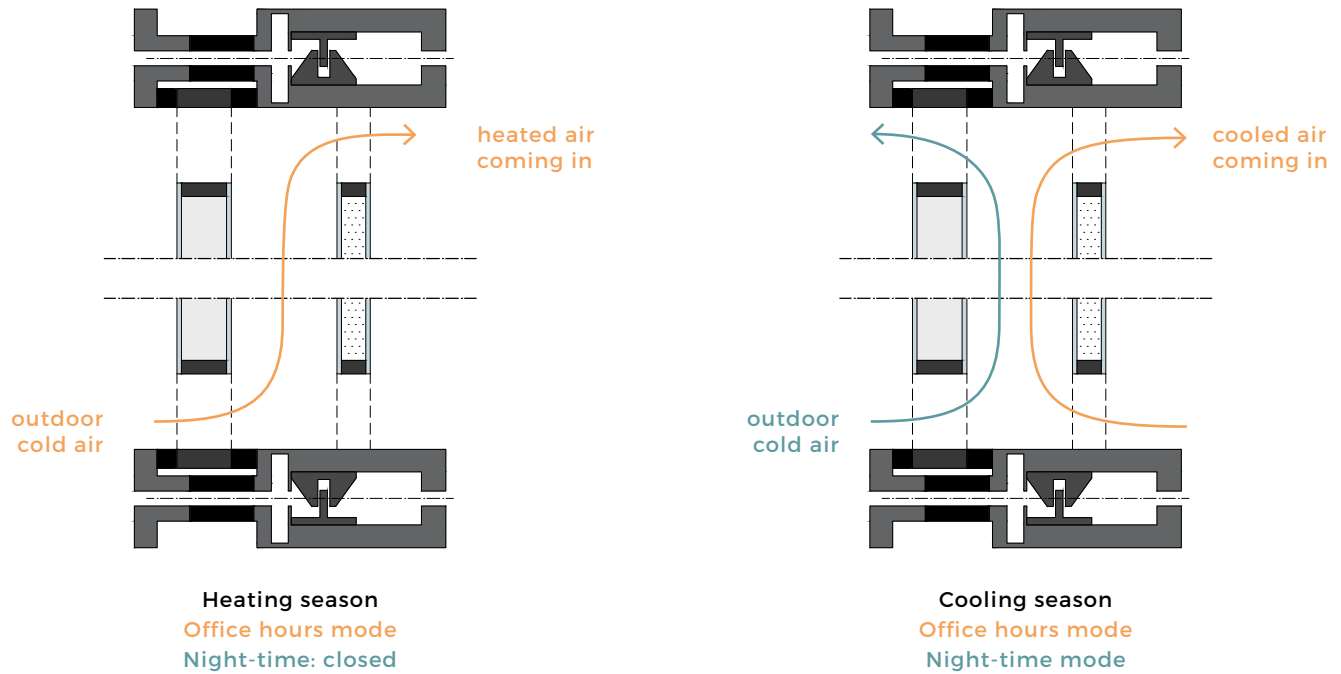


Figure 47: Ventilation modes for the translucent PCM unit during day and night for heating and cooling season

III. Opaque Modules

i. Unit with BIPV/T

For this module, BIPV/Ts (Building Integrated Photovoltaics/Thermal) are used again as renewable energy source to provide electrical and thermal energy. This module incorporates an air cavity of 70mm right behind the PVs with the purpose of reducing their temperature, which results in an improvement in their efficiency and lifetime. Moreover, during winter the heated air is drawn through this cavity in the room reducing heating loads as can be seen in Figure 50. During the summer the air grids are only opened to the outside, in order to reduce the PVs temperature. In addition, in this case of the BIPV/T module, the PV glazing provides 15% of transparency because the distance between the cells is smaller since the module is opaque and there is no light coming in the building. For this reason, the cells that can fit in the module are more than the ones of the semi-transparent module and thus the energy performance is better than of the semi-transparent one. In addition, the PV cells are covered with antireflection coating because it reduces light reflection and increases light transmission. The composition of the module can be seen in Table 13 and Figure 49.

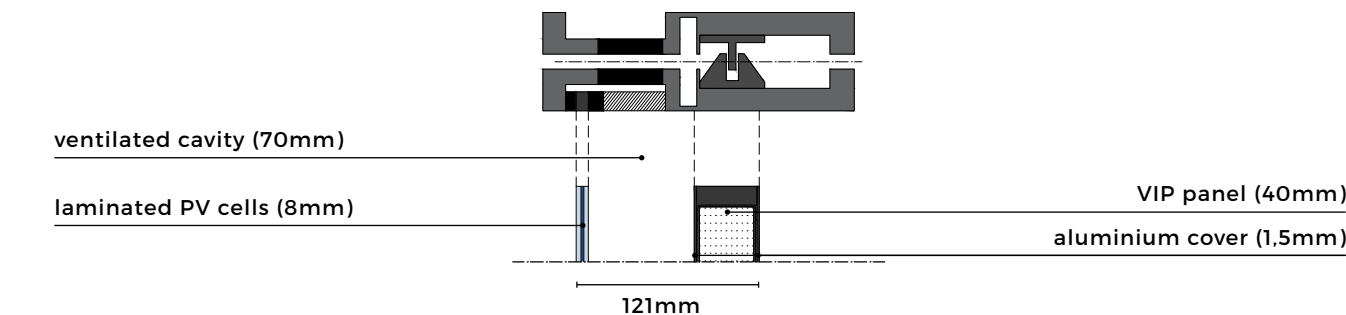


Figure 49: Concept detail of the unit with BIPV/T

Module	Opaque						
Function	Energy production						
Type	BIPV/T						
Layers & properties		thickness		R-value		g-value	Tv
	1. aluminium panel	0,0015	m	0,1	m²K/W		-
	2. VIP	0,04	m	5,714	m²K/W		-
	3. aluminium panel	0,0015	m	0,1	m²K/W		-
	4. ventilated cavity	0,07	m	0,17	m²K/W		-
	5. glass	0,003	m	0,003	m²K/W	0,11	0,17
	6. PV cells (179kWh/y)	0,002	m	0,05	m²K/W		
	7. antireflection coating	0	m				
	8. glass	0,003	m	0,003	m2K/W		
Tot		0,121	m	6,31	m²K/W	0,005	-
U-value				0,2	W/m²K		

Table 13: Properties of the unit with BIPV/T

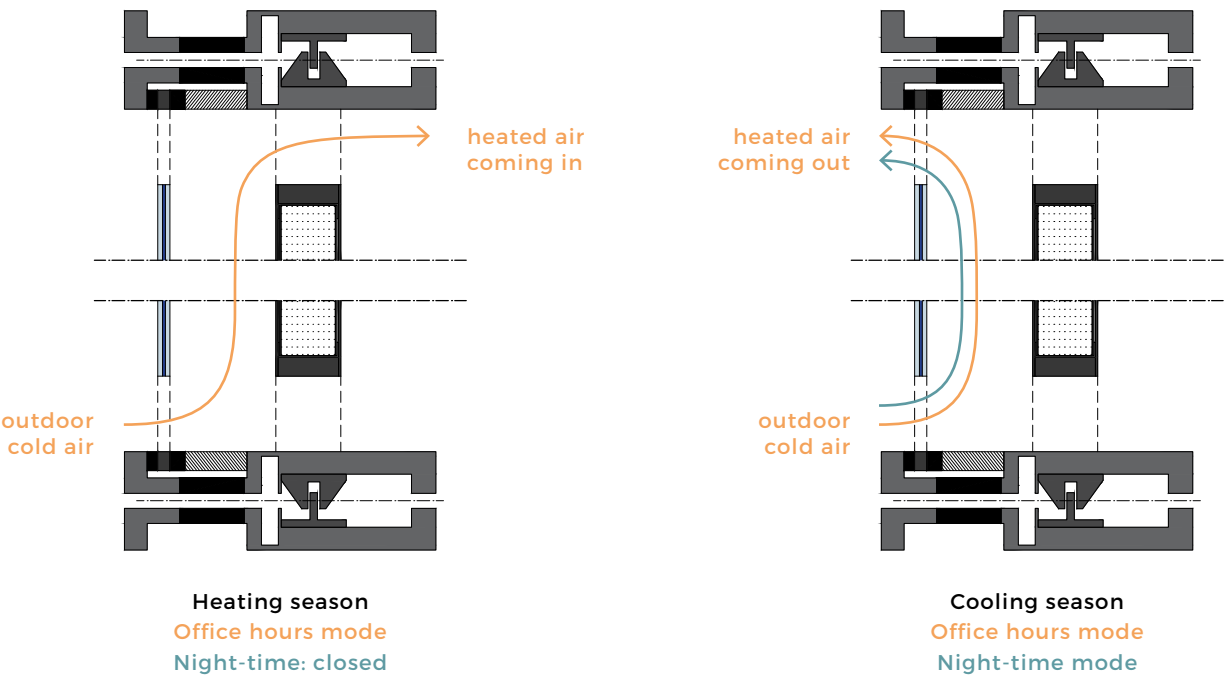


Figure 50: Ventilation modes for the BIPV/T unit during day and night for heating and cooling season

ii. Unit with opaque PCM

For this module, PCM (Phase Change Material) is used again but this time in its opaque form. The principle is again that of the thermal mass wall and It works the same way as the semi-translucent module. In addition, Vacuum Insulating Panels (VIPs) are used, which are advanced insulating materials able to achieve better insulation performances with extremely reduced thickness in comparison to conventional insulating materials. This is especially important because heat losses and consequently heating loads are reduced. The composition of the module can be seen in Table 14 and Figure 52. The ventilation modes for winter and summer period during day and night can be seen in Figure 53 and essentially they work the same way as already explained for the unit with translucent PCM.

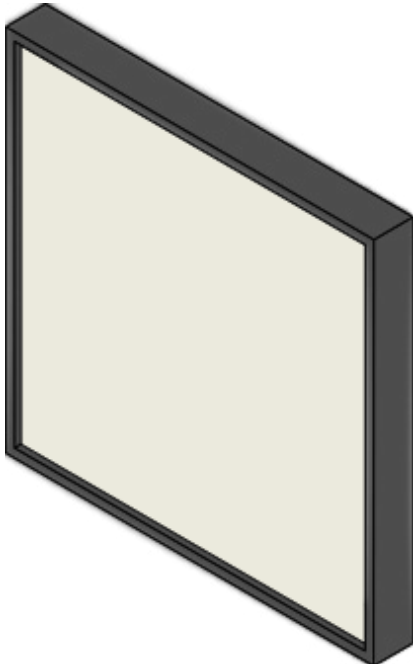


Figure 51: Unit with opaque PCM

Module	Opaque								
Function	Insulation								
Type	Wall panel with PCM								
Layers & properties		thickness		R-value		g-value		Tv	
	1. aluminium panel	0,0015	m	0,1	m²K/W			-	-
	2. VIP	0,04	m	5,714	m²K/W			-	-
	3. aluminium panel	0,0015	m	0,1	m²K/W			-	-
	4. air cavity	0,07	m	0,17	m²K/W			-	-
	5. glass	0,003	m	0,003	m²K/W	0,9	0,86	0,9	0,86
	6. PCM	0,03	m	0,15	m²K/W	0,33 solid	0,37 liquid	0,38 solid	0,55 liquid
	7. glass	0,003	m	0,003	m²K/W	0,9	0,86	0,9	0,86
Tot		0,149	m	6,41	m²K/W	0,002	0,003	-	-
U-value				0,2	W/m²K				

Table 14: Properties of the unit with opaque PCM

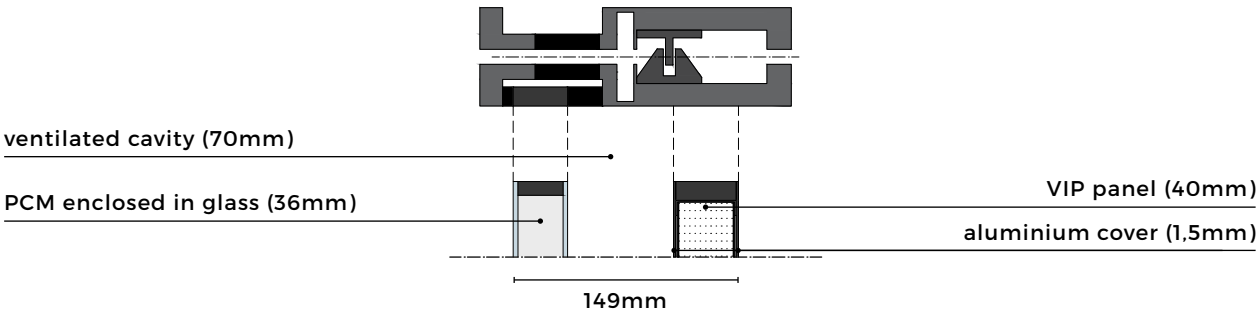


Figure 52: Concept detail of the unit with opaque PCM

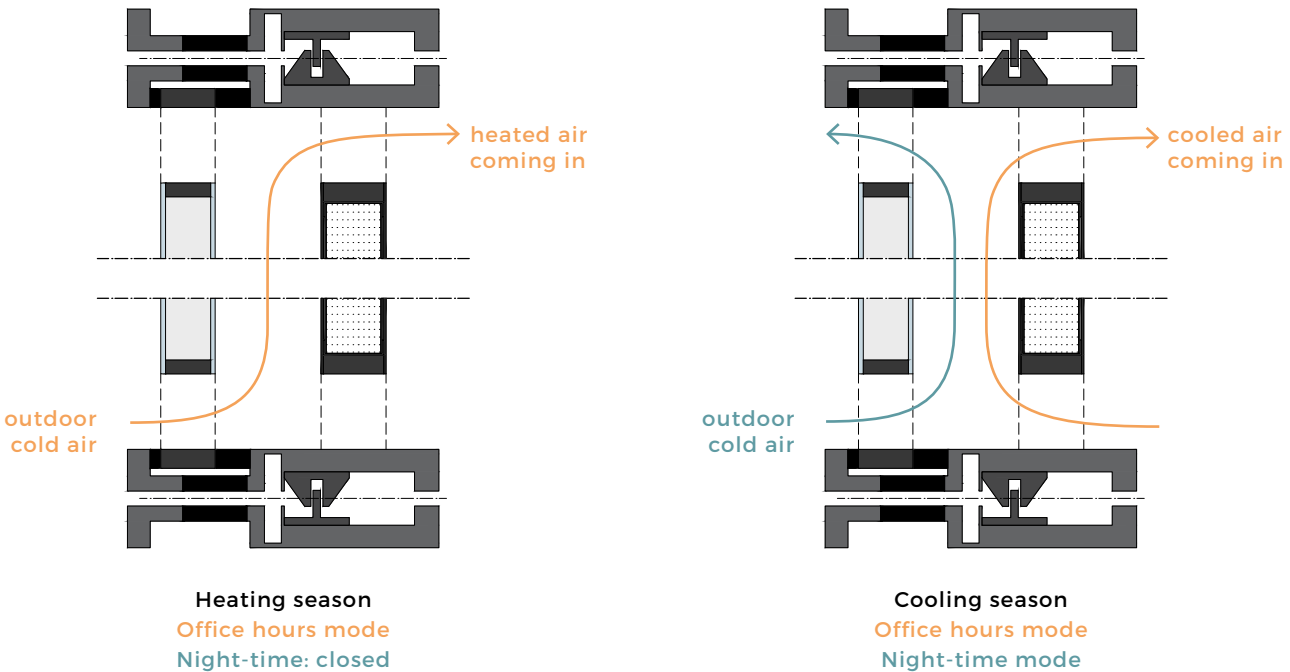


Figure 53: Ventilation modes for the opaque PCM unit during day and night for heating and cooling season

iii. Living Wall unit

For this module, an innovative living green wall is used. The advantage is that it is a zero-earth system and therefore lightweight. Moreover, instead of ground, hydroponics are used for nutrient and water delivery, which leads to 90% reduction in water consumption. The composition of the module can be seen in Table 15 and Figures 55 and 56. This module has a high energy potential that can be used for cooling, since evapotranspiration reduces substantially the incoming heat flow. Evaporative cooling works in the same way as phase change materials with the only difference that the phase change is not happening from fluid to solid and vice versa but from liquid to air. As a result, the incorporation of such a module in a facade means that especially during summer the cooling loads can be reduced considerably, not to mention the improvement of the urban air quality.

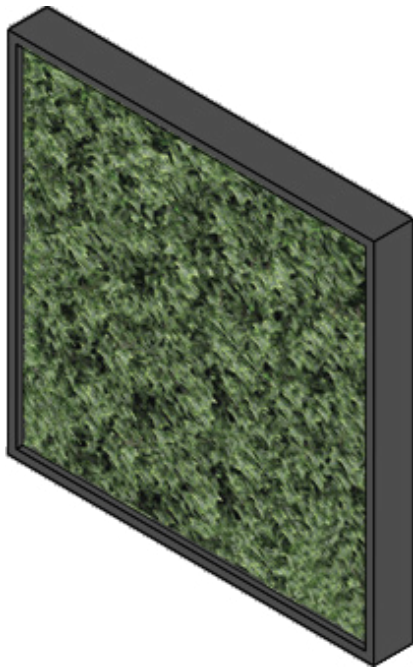


Figure 54: Living wall unit

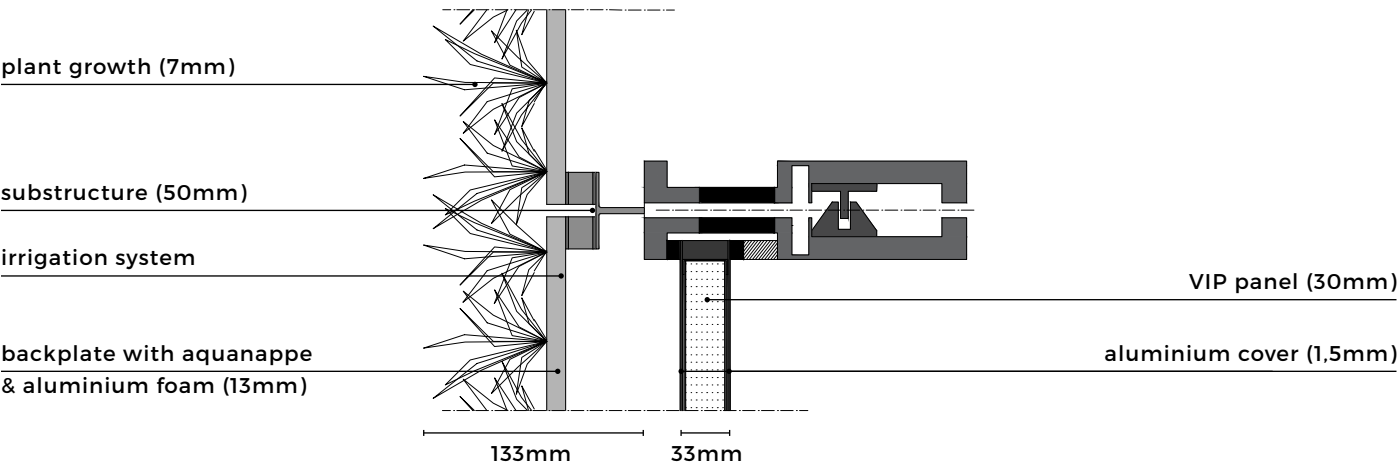


Figure 55: Concept detail of the Living wall unit

Module	Opaque						
Function	Green Façade						
Type	Living Wall Façade						
Layers & properties		thickness		R-value		g-value	Tv
	1. aluminium panel	0,0015	m	0,1	m²K/W		-
	2. VIP	0,03	m	4,285	m²K/W		-
	3. aluminium panel	0,0015	m	0,1	m²K/W		-
	4. substructure	0,05	m	-	-	-	-
	5. backplate & irrigation system	0,003	m	0,107	m²K/W		-
	6. aquanappe-root mat	0,004	m	0,075	m²K/W		-
	7. aluminium foam	0,0056	m	0,62	m²K/W		-
	8. plant growth	0,07	m	-	-		-
Tot		0,166	m	5,46	m²K/W	0,01	-
U-value				0,2	W/m²K		

Table 15: Properties of the living wall unit

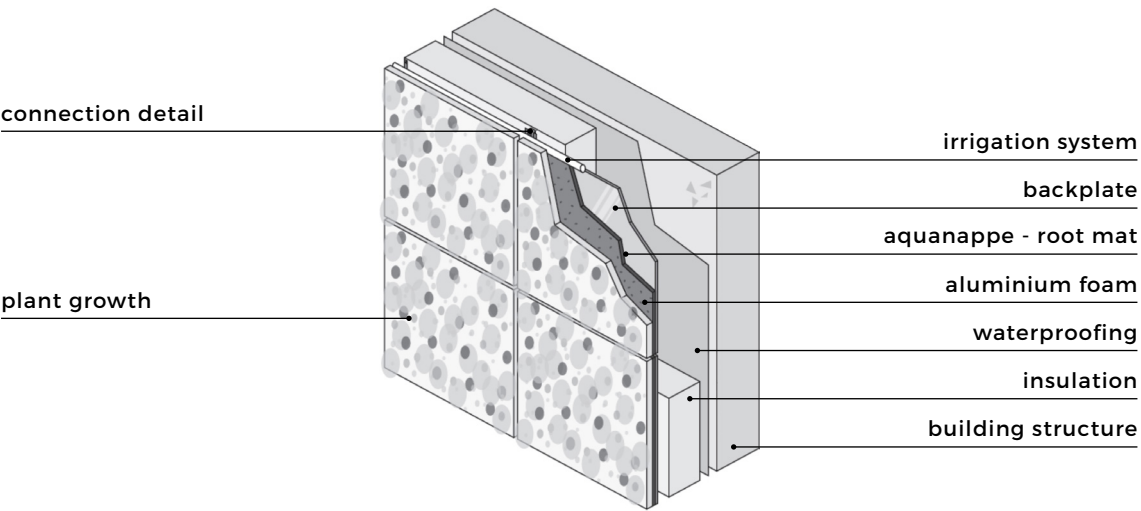


Figure 56: Comprehensive drawing of "Living Wall"
Source: http://greeninitiatives.cn/pdfdoc/presentation/1411885320333Innovative%20and%20Intelligent%20Facades_Jeff%20Tsai_Arup_rev.pdf

HAND CALCULATIONS

Having chosen the final units and their layering and type of materials, their performance had to be taken into account. For this reason, two methods were used. First, hand calculations were conducted and then Design Builder software was used to run simulations. The hand calculations are considered really important for this research project, because they show the performance of each module separately, whereas with the simulations just a final result is given which represents the performance of a combination of different modules. Thus, the results of the hand calculations would be able to give an indication of which modules would perform better.

In order to do the hand calculations, values such as the R-values, U-values and the g values of the different modules were important to be determined. These were retrieved by products already existing in the market that were similar. These properties are already presented in the previous section, where each module is introduced and presented separately. Some additional values, that were needed are the dimensions of each module, the specific heat of air (c), the density of air (ρ), the heat resistances for inside (r_e) and outside (r_i) based on Dutch regulations and the latent heat of water (E_{water} - water of 100°C to water vapour of 100°C). Moreover, the amount of days ($t_{\text{heatingseason}}$) and hours of the heating season and the sun's gross heat gain (q_{sol}) were needed as well. These values can be seen in Tables 16, 17 and 18.

For the calculation of the q_{sol} , the values presented in Table 18 were used, which are according to the Nederlandse norm NEN 2916. The south orientation was chosen as it has the highest values and thus seems to have the highest potential for solar gains. For the heating season, the values of the months

Module's Dimensions		
length	0,9	m
width	0,9	m
Surface	0,81	m ²

Table 16: Dimensions of units

Other values		
$\rho \cdot c =$	1200	J/Km ³
$q_{\text{sol}} =$	58	W/m ²
$\Delta T_{\text{avg}} =$	13	K
$t_{\text{heatingseason}} =$	210	days
hours per season =	5040	h
$r_e =$	0,04	m ² K/W
$r_i =$	0,13	m ² K/W
$E_{\text{water}} =$	2257000	J/kg

Table 17: Additional values needed

October to April were added and then converted to W/m² ending up with the value $q_{\text{sol}} = 58 \text{ W/m}^2$. The same was done for the whole year, since the solar power of the PV modules would be calculated annually as well. In this case, all months were added ending up with the value $q_{\text{sol}} = 83 \text{ W/m}^2$. These values can be seen in Tables 19 and 20.

q_{sol} (MJ/m ²)									
Month	Vertical								Horizontal
	South	South-east	East	North-east	North	North-west	West	South-west	
January	41	40	39	39	39	39	39	41	43
February	143	105	58	48	48	49	73	126	117
March	265	199	130	93	89	100	167	243	254
April	307	256	194	139	123	161	244	305	373
May	309	302	275	213	184	269	353	355	503
June	315	319	297	236	229	343	417	381	574
July	290	285	261	209	192	277	348	339	504
August	366	349	287	196	161	238	334	374	489
September	273	212	153	110	107	162	248	294	295
October	203	152	87	65	64	66	104	175	166
November	73	58	36	33	33	33	40	64	63
December	22	22	22	22	22	22	22	22	35

Table 18: Gross Heat Gain q_{sol} in MJ/m² by solar irradiation per month, depending on the orientation
Source: Nederlandse norm NEN 2916 (nl) "Energy performance of non-residential buildings - Determination method"

$q_{\text{annual}} =$	2607	2299	1839	1403	1291	1759	2389	2719	3416
-----------------------	------	------	------	------	------	------	------	------	------

$q_{\text{annual}} =$	724	kWh/m ²
	83	W/m ²

Table 19: Annual South Gross Heat Gain by solar irradiation per month

$q_{\text{heatingseason}} =$	1054	832	566	439	418	470	689	976	1051
------------------------------	------	-----	-----	-----	-----	-----	-----	-----	------

$q_{\text{heatingseason}} =$	293	kWh/m ²
	58	W/m ²

Table 20: Heating Season South Gross Heat Gain by solar irradiation per month

I. Calculation of the solar PV energy

After calculating the Gross Heat Gain by solar irradiation, the solar PV energy could be calculated. In order to do that, the dimensions and the efficiency of the PV cells were essential to be specified. The dimensions of the PV cells for the semi-transparent and the opaque PV modules can be found in Tables 21 and 22 respectively. In addition, the properties of each PV cell can be seen in Figure 58 and the relation of the distance chosen between the PV cells to the power and the transparency levels for the two different modules can be seen in Figure 57. Then, the solar PV energy could be calculated as shown in Table 23 using the following values:

E = Energy (kWh)

A = Total solar panel area (m²)

r = solar panel yield (%)

H = Annual average irradiation on tilted panels

PR = Performance ratio, Coefficient of losses

A*r = Total power of the system

semi-transparent module : cell dimensions		
length	0,125	m
width	0,125	m
distance	0,025	m
surface	0,016	m ²
cells per module	36	
Tot surface	0,56	m ²

Table 21: PV cells dimensions of the semi-transparent module

opaque module : cell dimensions		
length	0,125	m
width	0,125	m
distance	0,003	m
surface	0,016	m ²
cells per module	49	
Tot surface	0,77	m ²

Table 22: PV cells dimensions of the opaque module

E = A * r * H * PR	heating season (Oct-Apr)				annually			
	semi-transparent		opaque		semi-transparent		opaque	
A =	0,56	m ²	0,77	m ²	0,56	m ²	0,77	m ²
r =	22%		22%		22%		22%	
H =	293	kWh/m ² .hs	293	kWh/m ² .hs	724	kWh/m ² .an	724	kWh/m ² .an
PR =	1,00		1,00		1,00		1,00	
A*r =	0,1	kWp	0,2	kWp	0,1	kWp	0,2	kWp
E =	36	kWh/hs	50	kWh/hs	90	kWh/y	123	kWh/y

Table 23: Solar PV Energy calculation

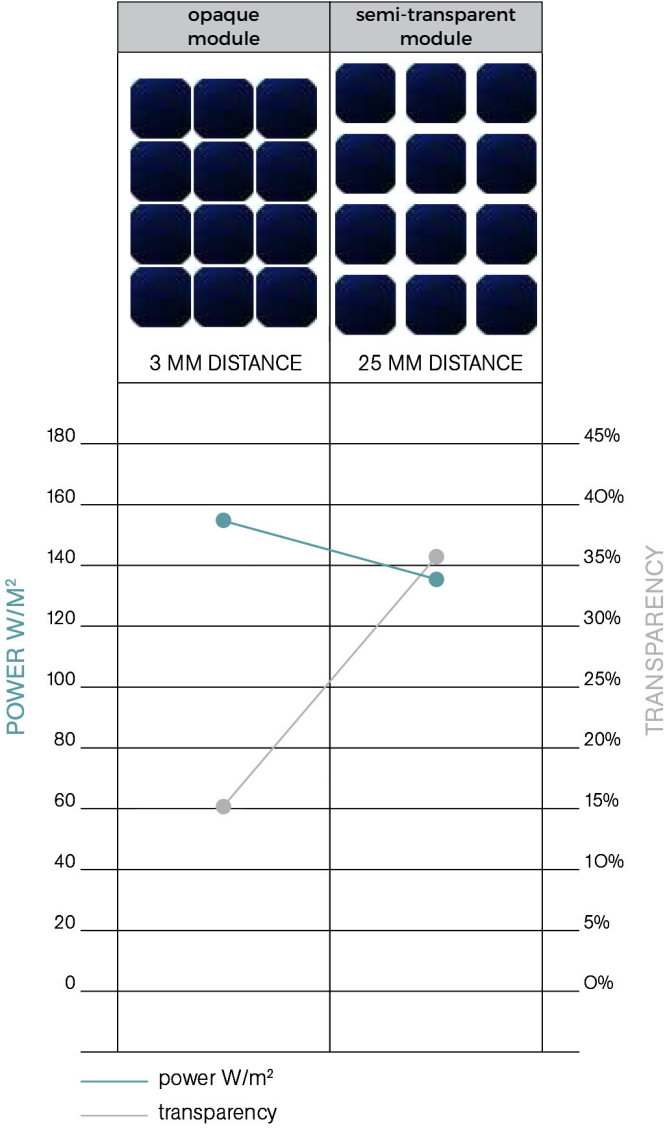


Figure 57: Relation of cell distance to power and transparency levels


	DIMENSIONS	EFFICIENCY	Wpeak/m ²	Wpeak/cell
	MONOCRYSTALLINE – HIGH EFFICIENT			
	125X125	22%	155	2.90 - 3.11

Figure 58: PV cells properties

Using the formula $E = A * r * H * PR$, the results obtained were that the semi-transparent module can produce 36kWh of electricity per heating season and 90kWh per year and that the opaque module can produce 50kWh of electricity per heating season and 90kWh per year.

II. Determination of air inlet, outlet and cavity dimensions

Another calculation that is necessary to be conducted is the amount of heat that each module absorbs depending on what type of module it is, because it is essential to be verified that the chosen width of the cavity and the height of the ventilation openings are enough, in order for the incoming air to remove the excessive heat. This calculation needed to be made for the opaque modules with the PV cells and the PCM.

The first step is to calculate the amount of heat absorbed by each module. This calculation is made assuming a time with a very high solar irradiation ($q_{sol}=600\text{W/m}^2$), in order to consider the case of the highest heat absorbed. For the opaque module with the PVs, first the amount converted to electricity is calculated, which depends on the 22% efficiency of the PV cells. Then from the 78% left, it is assumed that around 40% is absorbed, which gives as result the value of 152W/module as can be seen in Table 24. In the case of PCM, the volumetric heat capacity (MJ/m^3) of the specific type S23 is used and converted according to the volume of the module's PCM to kWh. This results to 75 W/day and 151W/cycle as can be seen in Table 25.

PVs,opaque module		
length (l)	0,9	m
width (w)	0,9	m
height (h)	0,9	m
Surface	0,81	m ²
Cavity Volume	0,057	m ³
PV cells efficiency	22	%
electricity production	132	W/m ²
heat absorbed(40%) $Q_H=$	187	W/m ²
	152	W/module

Table 24: Calculation of heat absorption by the opaque module with PV cells

PCM module		
length (l)	0,9	m
width (w)	0,9	m
height (h)	0,9	m
Surface	0,81	m ²
Cavity Volume	0,057	m ³
PCM thickness	0,03	m
PCM Volume	0,024	m ³
Volumetric Heat Capacity (S23)	268	MJ/m ³
	1,8	kWh
	75	W/day
	151	W/cycle

Table 25: Calculation of heat absorption by the PCM module

Then, these amounts of heat absorbed are used as inputs, in order to calculate the temperature difference between the cavity and the outside air, the air flux for a temperature difference (T_e) of 10°C (283K), which is the average temperature in Amsterdam, and at last the heat that is able to be removed. These calculations were conducted for different air inlet opening heights, because the temperature difference should be small and at the same time the height of the air inlet opening has to be as much so as to prevent the speed of air in that point to be lower than in the cavity. This is important otherwise the stack driven ventilation effect will not be working. The influence of the air inlet opening height to the temperature difference can be seen in Figure 59 and it is similar for all modules, since the absorbed heat values do not have a big difference and the values tested for the air inlet opening height were the same. A few additional values that were needed for these calculations can be seen in Table 26 and the results for each module can be seen in Tables 27 and 28.

Other values		
$C_d =$	0,7	
$g =$	9,8	m/s
$q_{sol} =$	600	W/m ²
$T_e =$	283	K
$\rho \cdot c =$	1200	J/Km ³

Table 26: Additional values needed for the calculations

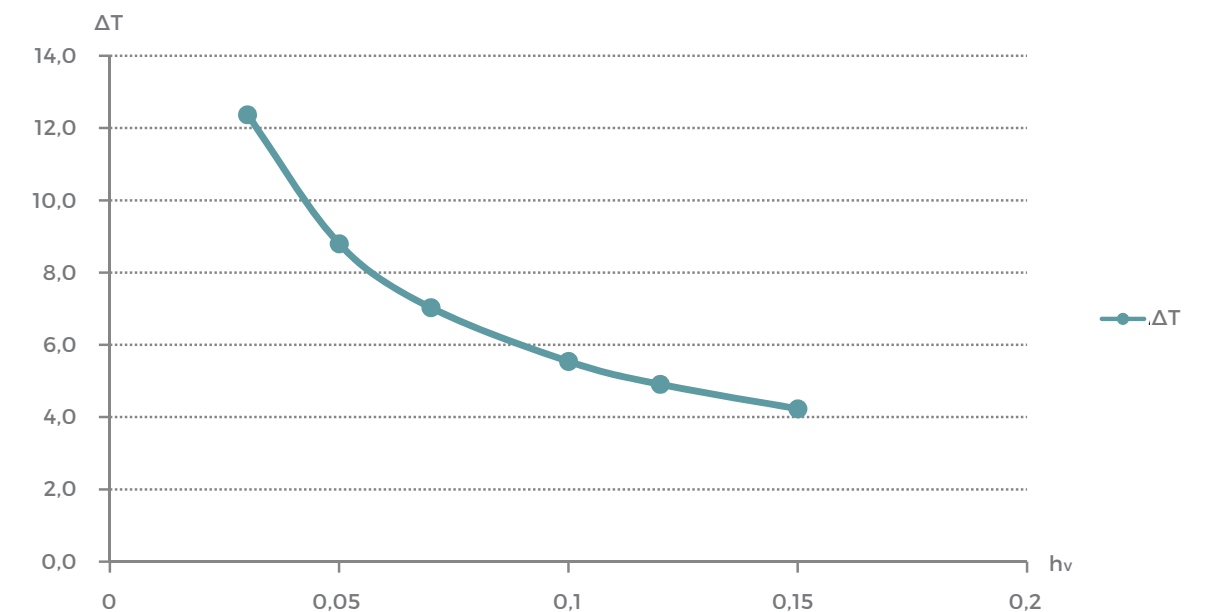


Figure 59: Relation of the air inlet opening height (h_v) to the temperature difference (ΔT) between the cavity and the outside air.

According to the results, the heat removed from each module (Q) is a bit more than the heat absorbed. In reality though, this amount should be the same and the difference can be justified because of formulas simplifications.

After evaluating the results, the air inlet opening height chosen is 5cm, because of two main reasons; first, the temperature difference ΔT should be lower than 10°C, because for every 10°C rise in temperature of a PV panel, its efficiency drops by 5% and second since the module has a height of

90cm and the air openings are 2 for each module, an inlet and an outlet, the total height taken for the openings should remain small. After determining the height of the air inlet and outlet, the cavity width was needed to be determined as well. Since the air speed at the inlet point should be higher than in the cavity, the width cavity should be at least equivalent with the air opening. For this reason, a cavity width of 7cm is chosen, which is a bit more than the opening and ensures the stack driven ventilation.

vents height (h _v)		A _{in} = h _v *w		A _e = A _{in} /√2		Stack-driven ventilation $\Delta T \approx 0,03 * (((Q_H \wedge 2) / (h * (A_e \wedge 2))) \wedge (1/3))$		Air flux $V = C_d * A_e * \sqrt{2 * g * h * \Delta T / T_e}$		removed heat $Q = \rho * c * V * \Delta T$	
0,03	m	0,03	m²	0,02	m²	12,4	K	0,01	m³/s	174	W
0,05	m	0,05	m²	0,03	m²	8,8	K	0,02	m³/s	174	W
0,07	m	0,06	m²	0,04	m²	7,0	K	0,02	m³/s	174	W
0,1	m	0,09	m²	0,06	m²	5,5	K	0,03	m³/s	174	W
0,12	m	0,11	m²	0,08	m²	4,9	K	0,03	m³/s	174	W
0,15	m	0,14	m²	0,10	m²	4,2	K	0,03	m³/s	174	W

Table 27: Calculations for the opaque module with the PV cells

vents height (h _v)		A _{in} = h _v *w		A _e = A _{in} /√2		Stack-driven ventilation $\Delta T \approx 0,03 * (((Q_H \wedge 2) / (h * (A_e \wedge 2))) \wedge (1/3))$		Air flux $V = C_d * A_e * \sqrt{2 * g * h * \Delta T / T_e}$		removed heat $Q = \rho * c * V * \Delta T$	
0,03	m	0,03	m²	0,02	m²	12,3	K	0,01	m³/s	173	W
0,05	m	0,05	m²	0,03	m²	8,8	K	0,02	m³/s	173	W
0,07	m	0,06	m²	0,04	m²	7,0	K	0,02	m³/s	173	W
0,1	m	0,09	m²	0,06	m²	5,5	K	0,03	m³/s	173	W
0,12	m	0,11	m²	0,08	m²	4,9	K	0,03	m³/s	173	W
0,15	m	0,14	m²	0,10	m²	4,2	K	0,03	m³/s	173	W

Table 28: Calculations for the module with the PCM

III. Heat balance equations

In order to calculate the potential heat gains or losses of each module, a heat balance equation was determined for each of them. For every module the transmissions and the solar gains were calculated. For the modules with the PV cells, the additional energy produced by them was also added to the heat balance equation. Moreover, in the case of the green module the evapotranspiration of the plants was taken into account. In addition, in the case of PCMs and electrochromic glazing the change of phase was considered and for this reason two different calculations were conducted for each of those modules. In the following pages, the formulas used and the results obtained can be seen in Tables 29 - 35.

Glazing unit with integrated blinds		
H _{transmission} = $\sum U * A$		
H _{transmission} =	1,14	W/K
Q _{heat,trans} = H*ΔT _{avg} *t _{heatingseason}		
Q _{heat,trans} =	74,64	kWh
Q _{sun} = n* $\sum g * A * q_{sol}$		
Q _{sun} =	40,25	kWh
Q _{tot} = Q _{sun} - Q _{heat,trans}		
Q _{tot} =	-34,39	kWh

Table 29: Heat balance equation for the glazing unit with integrated blinds

i. Transparent Modules

For the glazing unit with integrated blinds and the electrochromic glazing, first the transmissions were calculated, then the solar gains and then according to balance equations, both modules exhibit losses, which is logical since they are transparent parts. In the case of the electrochromic glazing, there is a big difference in losses between the clear and the colored state, since the heat gains in the clear state are much higher than in the colored one, which is justified because of the different g values.

Unit with electrochromic glazing				
off	H _{transmission} = $\sum U * A$			
	H _{transmission} =	0,92	W/K	
	Q _{heat,trans} = H*ΔT _{avg} *t _{heatingseason}			
	Q _{heat,trans} =	60,31	kWh	
	Q _{sun} = n* $\sum g * A * q_{sol}$			
	Q _{sun} =	58,01	kWh	
	Q _{tot} = Q _{sun} - Q _{heat,trans}			
	Q _{tot} =	-2,30	kWh	
on	H _{transmission} = $\sum U * A$			
	H	H _{transmission} =	0,92	W/K
	Q _{heat,trans} = H*ΔT _{avg} *t _{heatingseason}			
	Q	Q _{heat,trans} =	60,31	kWh
	Q _{sun} = n* $\sum g * A * q_{sol}$			
	Q	Q _{sun} =	11,84	kWh
	Q _{tot} = Q _{sun} - Q _{heat,trans}			
	Q	Q _{tot} =	-48,47	kWh

Table 30: Heat balance equation for the glazing unit with electrochromic glazing

ii. Semi-transparent Modules

In the case of the glazing unit with BIPV, the same steps were followed with the only difference that in the heat balance equation the energy produced by the BIPVs was added. However, the final result for this module ended up having losses as well. In the case of the module with the transparent PCM, the results for the liquid and solid state did not show big difference in the losses, since the difference of the g value for the different states is very small.

Glazing unit with BIPV			
Htransmission = ∑ U*A			
Htransmission =	1,24	W/K	
Qheat,trans = H*ΔTavg*theatingseason			
Qheat,trans =	81,27	kWh	
Qsun= n*∑ g*A*qsol			
Qsun =	34,81	kWh	
Seasonal solar energy per module			
QPVs,semi-transparent =	36	kWh	
Qtot = Qsun + QPVs,semi-transparent - Qheat,trans			
Qtot=	-10,24	kWh	

Table 31: Heat balance equation for the glazing unit with BIPV

Unit with translucent PCM				
liquid	Htransmission = ∑ U*A			
	Htransmission =	0,43	W/K	
	Qheat,trans = H*ΔTavg*theatingseason			
	Qheat,trans =	27,90	kWh	
	Qsun= n*∑ g*A*qsol			
	Qsun =	23,84	kWh	
	Qtot = Qsun - Qheat,trans			
solid	H	Qtot=	-4,06	kWh
	Htransmission = ∑ U*A			
	Q	Htransmission =	0,43	W/K
	Qheat,trans = H*ΔTavg*theatingseason			
	Q	Qheat,trans =	27,90	kWh
	Qsun= n*∑ g*A*qsol			
	Q	Qsun =	20,00	kWh
	Qtot = Qsun - Qheat,trans			
	H	Qtot=	-7,90	kWh

iii. Opaque Modules

In the case of the opaque unit with BIPV/T, the same steps were followed as for the glazing unit with BIPV. The results for this module exhibited considerable gains, since it is opaque and also able to produce more energy than the semi-transparent BIPV module. In the case of the opaque PCM, again the difference of the results of the liquid and solid state is small, however, this time the losses are much lower than in the case of the translucent PCM.

Unit with BIPV/T			
Htransmission = ∑ U*A			
Htransmission =	0,13	W/K	
Qheat,trans = H*ΔTavg*theatingseason			
Qheat,trans =	8,41	kWh	
Qsun= n*∑ g*A*qsol			
Qsun =	0,57	kWh	
Seasonal solar energy per module			
QPVs,opaque =	50	kWh	
Qtot = Qsun + QPVs,opaque - Qheat,trans			
Qtot=	41,91	kWh	

Table 33: Heat balance equation for the unit with BIPV/T

Unit with opaque PCM				
liquid	Htransmission = ∑ U*A			
	Htransmission =	0,13	W/K	
	Qheat,trans = H*ΔTavg*theatingseason			
	Qheat,trans =	8,28	kWh	
	Qsun= n*∑ g*A*qsol			
	Qsun =	0,38	kWh	
	Qtot = Qsun - Qheat,trans			
solid	H	Qtot=	-7,90	kWh
	Htransmission = ∑ U*A			
	Q	Htransmission =	0,13	W/K
	Qheat,trans = H*ΔTavg*theatingseason			
	Q	Qheat,trans =	8,28	kWh
	Qsun= n*∑ g*A*qsol			
	Q	Qsun =	0,19	kWh
	Qtot = Qsun - Qheat,trans			
	H	Qtot=	-8,09	kWh

Table 34: Heat balance equation for the unit with opaque PCM

Last but not least, in the case of the green module, the energy potential of the evapotranspiration was also calculated and added to the heat balance equation. First the cooling power of water was calculated using the formula $Q_{\text{evaporation}} = 0,2 \cdot E_{\text{water}} / 3600$. Then interior (Y_i) and exterior (Y_e) resistances were also needed and calculated as follows: $Y_e = 1/0,1$ and $Y_i = 1/R_{\text{wall}}$ with $R_{\text{wall}} = 4,49 \text{ m}^2\text{K/W}$. These additional values can be seen in Table 36. In the end, the result of the heat balance equation for this module shows also losses, but in this case it is favourable, since the living wall unit is intended to contribute for reducing the cooling loads.

Green unit		
$H_{\text{transmission}} = \sum U \cdot A$		
$H_{\text{transmission}} =$	0,15	W/K
$Q_{\text{heat,trans}} = H \cdot \Delta T_{\text{avg}} \cdot t_{\text{heatingseason}}$		
$Q_{\text{heat,trans}} =$	9,73	kWh
$Q_{\text{sun}} = n \cdot \sum g \cdot A \cdot q_{\text{sol}}$		
$Q_{\text{sun}} =$	0,66	kWh
$Q_{\text{int}} = (Y_i/Y_e + Y_i) \cdot Q_{\text{evaporation}}$		
$Q_{\text{evaporation}} =$	125,4	W
$Q_{\text{int}} =$	13,78	kWh
$Q_{\text{tot}} = Q_{\text{sun}} - Q_{\text{int}} - Q_{\text{heat,trans}}$		
$Q_{\text{tot}} =$	-22,85	kWh

Table 35: Heat balance equation for the green unit

Other values		
$E_{\text{water}} =$	2257000	J/kg
$Y_e =$	10	W/m²K
$Y_i =$	0,22	W/m²K

Table 36: Additional values needed for the calculation of the heat balance equation for the green unit

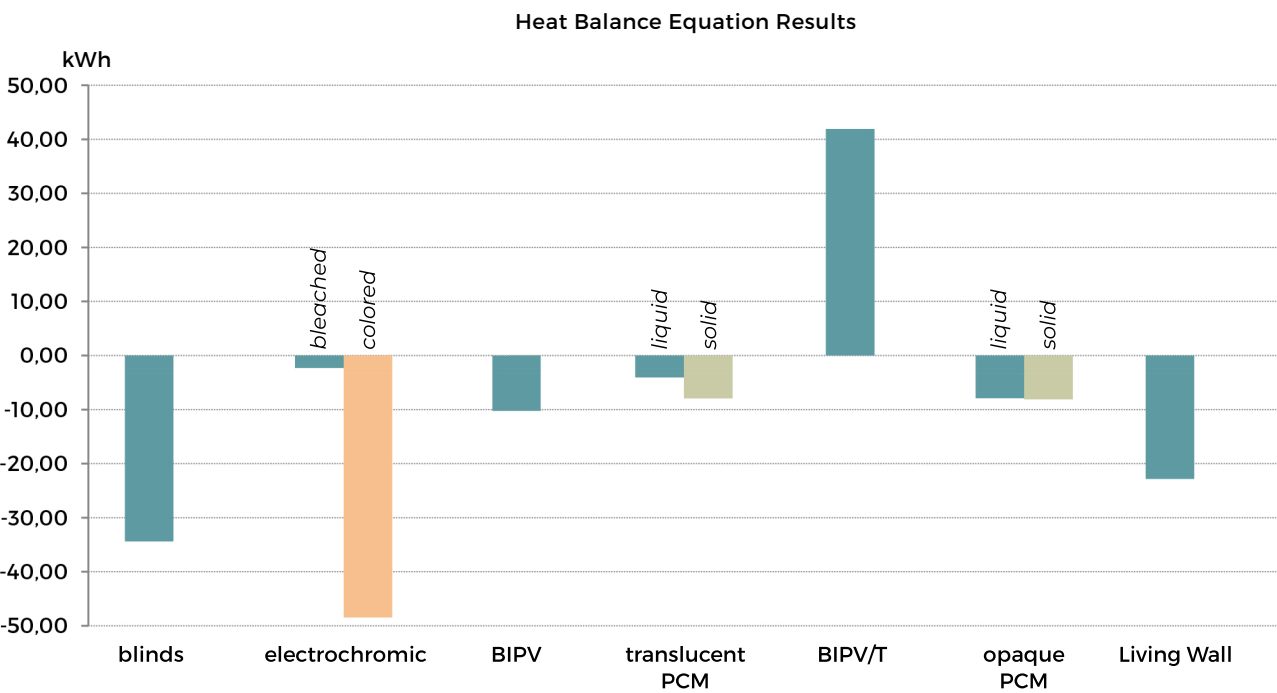
IV. Conclusions

The heat balance equations were the final goal of the hand calculations and other side calculations were made to provide inputs for them, except for the determination of the air inlet, outlet and cavity dimensions. The final results for each module, which can be seen together in Graph 11, showed that all units except for the BIPV/T one have a negative heat balance meaning that they have losses.

For the transparent units this was expected, since transparency means higher heat transmissions to the outside, even though very low U-values were achieved. Especially in the case of the electrochromic glazing unit the losses are very high when bleached but surprisingly close to zero while being on its colored mode, which is a very advantageous combination. The semi-transparent units were also not expected to be positive but at

least the losses are lower especially for the BIPV unit, that produces an amount of solar energy, which is an extra contribution to the heat balance equation counteracting substantially the losses. For the opaque units, the results are much better than for the rest of the units because being opaque they have high R-values. On the other hand, the green module was supposed to contribute to the cooling so the losses are beneficial in this case.

The hand calculations were made for each module separately. However the logic of the project is to have a combination of units, since each of them delivers a different function and thus altogether are supposed to reach a balance of heat losses and gains and consequently an exceptional energy performance compared to a typical construction. The next step with the simulations would prove if this assumption is right.



Graph 11: Hand calculations - Heat Balance Equations Results

**DESIGN BUILDER
SIMULATIONS**

After the hand calculations for each module were completed, simulations were conducted with the aid of “Design Builder” software. The dimensions of the open-plan office building’s segment that is simulated can be seen in Table 37. Before starting the simulations, it was decided that the translucent PCM unit and the green unit would not be used because of two reasons; first, Design Builder is not able to simulate translucent PCM so the performance of this unit would be far from real. Besides, its losses were similar to the ones of the transparent units and the heat provided by its ventilated cavity would be added manually, since the software cannot take it into account. Second, the green module was not included in the simulations because it would require a much more detailed analysis to be designed properly. It could even be a research project itself.

First, simulations were run for each of the modules separately, meaning that the full facade of the tested segment was covered with one type of modules. This was done, in order to compare the simulation results with the ones of the hand calculations, in order to find out if the assumed performance of each module was right.

Then, simulations were conducted for the reference project and for six different combinations of modules. These simulations were run twice; once for a WWR (Window-to-Wall Ratio) of 40% and once for a WWR of 50%. According to some preliminary research conducted with EnergyPlus software, it has been shown that a 1:1 ratio between the transparent and opaque modules is the most beneficial for temperate climates, in order to minimize the energy consumption (Favoino et al., 2015). This is why a WWR of 50% was chosen and then the WWR of 40% was also tested so that

comparisons could be made and conclusions could be drawn of what works better specifically for the Netherlands. The goal of the simulations was to test the performance of the façade and its influence in the total energy performance of the building.

Segment's Dimensions		
length	14	m
width	7,2	m
height	2,7	m
floor-to-ceiling height	3,6	m
Volume	272,16	m ³
Area	100,8	m ²
Façade surface	50,4	m ²

Table 37: Dimensions of the simulated segment

I. Reference project

Before the simulations of the MFM project, a reference project with the same dimensions was simulated, in order for the multi-functional facade system to be compared with a typical construction.

i. Settings

A number of settings were realised and will be described in this section. Firstly, the weather data file for Amsterdam was loaded and then the orientation of the simulated facade was set to the south. The floor, the ceiling and the rest of the walls were considered adiabatic, in order to avoid any heat gains or losses.

The case study constitutes of an open-plan office building and thus the Activity Template chosen is Office Building-Office-Open Plan and the schedule wherever it is needed is set to 6:00-18:00 Mon-Fri. Furthermore, the density/occupancy had to be set according to the requirement of minimum fresh air 50m³/h/person. The segment’s volume is approximately 282m³, which gives as a result 6 persons per office (=282/50). The segment’s floor area is approximately 100m² which means that 16.7m² (=100/6) correspond to one person and the density can be calculated to 1/16.7 =0.06. Furthermore, the metabolic activity was set to Light office work/Standing/Walking with a value of 1,00 as clothing insulation level for winter and 0,50 for summer. In addition, an infiltration rate of 0.2 ac/h was set (Construction tab > Airtightness > Model infiltration > Constant rate > 0.3 and Schedule > On 24/7), according to building regulations for new constructions.

As far as the amount of energy consumed for the

office equipment, the computers were turned on with 5 W/m² gain (Activity tab). As far as the lighting is concerned, LED was chosen as template and general lighting was turned on with recessed as luminaire type and a normalised power density of 2.0 W/m² per 100 lux (Lighting tab). Moreover, the lighting control was turned on for a more sustainable use.

ii. Construction & Openings

For the opaque parts, a typical wall reference was chosen, consisting of gypsum wall board, insulation and lightweight metal cladding, which has an R-value > 5W/m²K as required by the regulations, in order to obtain a good quality level.

For the transparent parts, an HR⁺⁺ window was chosen with U-value < 1,65 m²K/W as required by the regulations, in order to obtain a good quality level. This means a double glazing low-e window with a cavity filled with argon.

iii. HVAC

The following settings were chosen for cooling and heating. In the Activity tab > Environmental control the heating setpoint was set to 21°C with a heating set back to 18°C and the cooling setpoint to 24.5°C with a cooling set back to 26°C. These temperatures were chosen as explained in the previous section “Comfort guidelines for offices in The Netherlands” according to the updated version of ISSO 74 guideline, which is intended for use in offices and related buildings in The Netherlands (Boerstra et al., 2015).

In the HVAC tab, the template was set to None, so

that a custom HVAC system could be determined. The mechanical ventilation was activated with the Outside air definition method set to Min fresh air (per person), which takes into account the data from the Activity tab. In addition, heat recovery was turned on to enthalpy type, because it recovers not only sensible but also latent heat. Moreover, heating and cooling were activated with natural gas as fuel for the first and electricity from grid as fuel for the latter one.

In addition, natural ventilation was added to the system, since the MFM project has as well and the comparison should be made having the same parameters. The settings that were made for the natural ventilation are the following. Firstly, in the Model Data tab the natural ventilation was turned on with schedule control. In the Activity tab > Ventilation Setpoint Temperature> Indoor min. temperature control was set to 23°C. This value should be at least 2 degrees higher than the heating setpoint temperature (21°C) so as to prevent simultaneous heating and venting. Moreover, the minimum fresh air was set to 7l/s per person. In the HVAC tab, the natural ventilation is set by zone with 5 ac/h and with operation schedule ASHRAE 90.1 HVAC Availability-Office. Moreover, the outdoor max. temperature control is set to 24°C, in order to prevent outside air hotter than 24°C to enter the building and the outdoor min. temperature control is set to 15°C, in order to prevent natural ventilation when the outside air temperature is lower than 15°C. The minimum number was set taking into account the summer night-time cooling, because the temperature in a summer night is usually not lower than 15°C. Lastly, the Delta T limit is set to -50, because when the difference of the indoor temperature minus the outdoor is bigger than the Delta T the ventilation is not allowed.

iv. Simulation Results

The simulations were run for the cases of WWR of 40% and 50% and also for the heating season (Oct-Apr) and cooling season (May-Sep) separately. The operative temperature was set as control temperature, since the required setpoint temperatures correspond to the indoor operative temperatures. The results can be seen in Graphs ?? together with the results of the MFM simulations, so that direct comparisons can be made.

II. Multi-functional Facade Module

Several simulations were conducted for the Multi-functional Facade System, in order to test different facade compositions. As already stated, first, a simulation was run for each module separately assuming the whole facade fragment is composed of one type of modules. This scenario is not in accordance with the logic of the project, but it was needed in order to find out how the modules behave separately and compare the results with the hand calculations. Then, following the logic of the research project of combining different modules, which deliver different functions, several combinations of modules were determined and simulated.

i. Settings

The same settings were chosen as for the reference project.

ii. Construction & Openings

The materials and layers of each module were chosen as already explained in the chapter “Design Phase”, where all units are presented in detail. The only difference was that for the module with the integrated blinds, Design Builder offered only the choice for the blinds to be placed in the inner cavity and not in the outer cavity as initially proposed. In addition, since the windows are operable so that the user is also given the choice to control the system, free aperture is chosen for the top of the windows (glazing unit with integrated blinds, unit with electrochromic glazing and unit with BIPV glazing).

iii. HVAC

The settings in the Activity tab for the heating and cooling set temperatures are the same as for the reference project. The same applies for the settings in the HVAC tab for mechanical ventilation, heating and cooling system and natural ventilation. The only difference in the case of the Multi-functional Facade Module is the schedule of the natural ventilation, which is needed to change modes according to the season simulated. For this reason, a new custom schedule was created, in order to distinguish the heating season from the cooling season. This was done because the fresh air provided by the ventilated cavities of the PVs and the PCMs modules needed to be taken into account. During the winter period a hybrid ventilation is chosen, which combines mechanical with natural ventilation and enables preheated air, either by the PV cells or the PCM, to enter the office space. During the summer, the vents of the PCM modules are open to the inside during the day and to the outside during the night, in order to enable night-time cooling to take place. This strategy has the potential of lowering the peak daytime temperatures by 2°-3°C. As for the vents of the PV modules, during summertime they open only to the outside during the night, in order to keep the temperature of the PVs low.

The settings that were made for the natural ventilation are the same as the ones of the reference project with the only difference the customized schedule, which was created according to the ventilation modes explained, which were translated to a schedule as follows:

Through: 30 Apr
For: Weekdays, WinterDesignDay
Until: 06:00, Off

Until: 18:00, On
Until: 24:00, Off
For: Saturday
Until: 24:00, Off
For: Sunday
Until: 24:00, Off
For: AllOtherDays
Until: 24:00, Off
Through: 30 Sep
For: Weekdays, SummerDesignDay
Until: 18:00, On
Until: 24:00, Off
For: Saturday
Until: 08:00, On
Until: 24:00, Off
For: Sunday
Until: 08:00, On
Until: 24:00, Off
For: AllOtherDays
Until: 24:00, Off
Through: 31 Dec
For: Weekdays
Until: 06:00, Off
Until: 18:00, On
Until: 24:00, Off
For: Saturday
Until: 24:00, Off
For: Sunday
Until: 24:00, Off
For: AllOtherDays
Until 24:00 Off

iv. Heat provided by cavity ventilation

As already mentioned, during the heating season heat is provided to the interior space by air that is preheated by the PV panels and the PCM in the corresponding modules. This parameter was not able to be taken into account by Design Builder and for this reason it was calculated and added manually to the results. In order to calculate this amount of heat for the PCM module, its volumetric heat capacity was used once again as was done for the calculation of the air inlet's, outlet's and cavity's dimensions. This time it was converted to kWh/ heating season by multiplying with 5040 hours giving a result of 16kWh/hs/module as can be seen

in Table 38. Then, this value was multiplied by the amount of PCM modules used in each simulation case and divided by the simulated segment's floor surface, in order to get the kWh provided during the heating season per m². The results can also be found in Table 38. In the case of the BIPV/T, the heat absorbed per module was calculated assuming 40% as was done for the calculation of the air inlet's, outlet's and cavity's dimensions and then a 40% of this amount was assumed to be able to be used for heating the interior space ending up with a value of 36kWh/hs/module as can be seen in Table 39. As last step, like in the PCM case, this value was multiplied by the amount of BIPV/T modules used in each simulation case and divided by the simulated segment's floor surface, in order to get the kWh provided during the heating season per m². The results can also be found in Table 39.

Heat provided per PCM module in heating season		
Volumetric Heat Capacity (S23)	268	MJ/m³
	1,8	kWh
	75	W/day
	151	W/cycle
heat provided by the ventilated cavity	16	kWh/hs

Heat provided by PCM modules in heating season		
total heat provided (60 modules)	950	kWh/hs
total heat provided per m² (60 modules)	9,42	kWh/hs/m²
total heat provided (36 modules)	570	kWh/hs
total heat provided per m² (36 modules)	5,65	kWh/hs/m²
total heat provided (30 modules)	475	kWh/hs
total heat provided per m² (30 modules)	4,71	kWh/hs/m²
total heat provided (21 modules)	332	kWh/hs
total heat provided per m² (21 modules)	3,30	kWh/hs/m²
total heat provided (15 modules)	237	kWh/hs
total heat provided per m² (15 modules)	2,36	kWh/hs/m²

Table 38: Calculation of heat provided by the PCM module

Heat provided per BIPV/T module in heating season		
energy production (22%)	50	kWh/hs
heat absorption (40%)	91	kWh/hs
heat provided by the ventilated cavity (40%)	36	kWh/hs

Heat provided by BIPV/T modules in heating season		
total heat provided (60 modules)	2182	kWh/hs
total heat provided per m² (60 modules)	21,65	kWh/hs/m²
total heat provided (36 modules)	1309	kWh/hs
total heat provided per m² (36 modules)	12,99	kWh/hs/m²
total heat provided (30 modules)	1091	kWh/hs
total heat provided per m² (30 modules)	10,82	kWh/hs/m²
total heat provided (15 modules)	545	kWh/hs
total heat provided per m² (15 modules)	5,41	kWh/hs/m²

Table 39: Calculation of heat provided by the BIPV/T module

v. Simulated cases

The simulations were run for the cases of each unit separately and for a few cases of combination of units with a WWR (Window-Wall-Ratio) of 40% and 50%. Each case was simulated twice, once for the heating season (Oct-Apr) and once for the cooling

season (May-Sep). The cases simulated and the combination, type and amount of modules used can be found in Tables 40-44.

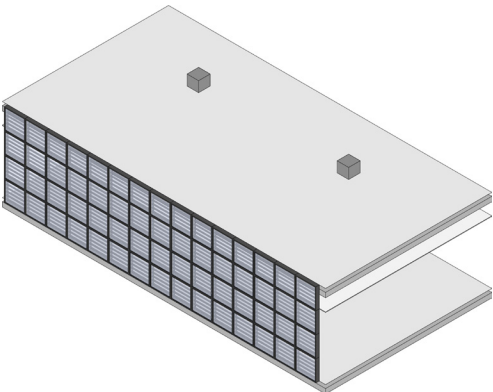
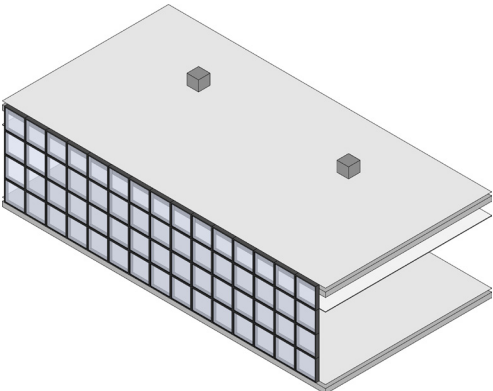
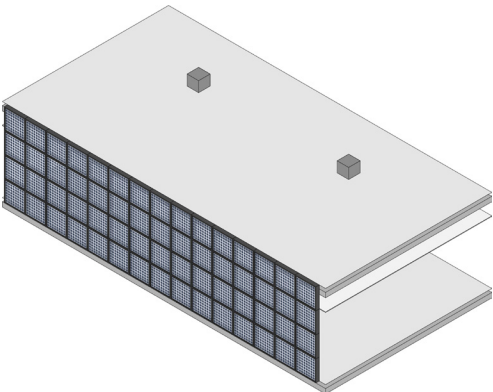
Facade composition		Transparent surface	Opaque surface
Blinds WWR=100%		60 modules Blinds A = 48,6 m²	-
EC WWR=100%		60 modules EC A = 48,6 m²	-
BIPV WWR=100%		60 modules BIPV A = 48,6 m²	-

Table 40: Overview and module composition of simulated facades

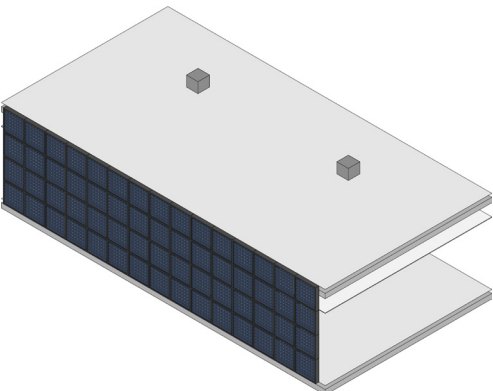
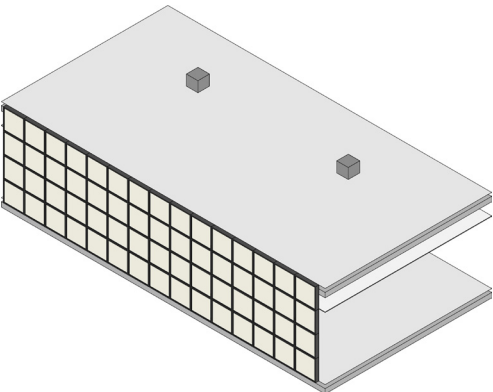
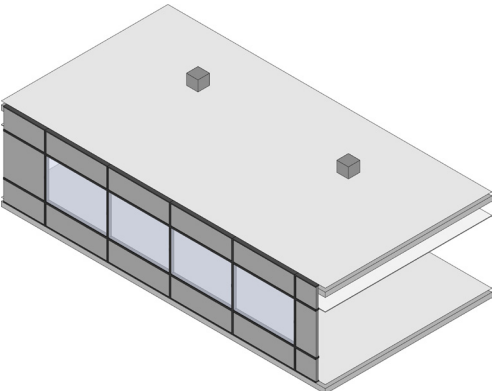
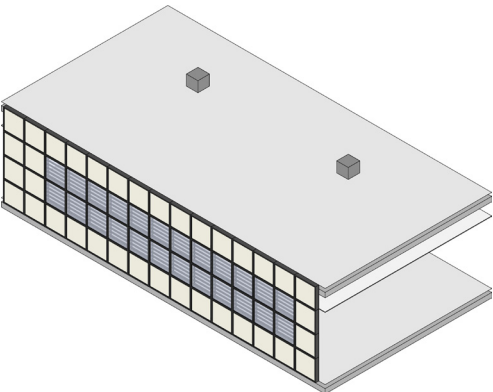
Facade composition		Transparent surface	Opaque surface
BIPV/T WWR=0%		-	60 modules BIPV/T A = 48,6 m²
PCM WWR=0%		-	60 modules BIPV/T A = 48,6 m²
reference project WWR=40%		windows: HR++ A = 19,44 m²	gypsum wall board, insulation, lightweight metal cladding A = 29,16 m²
PCM + blinds WWR=40%		24 modules Blinds A = 19,44 m²	36 modules PCM A = 29,16 m²

Table 41: Overview and module composition of simulated facades

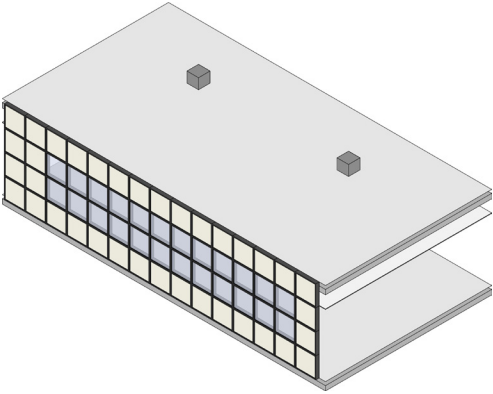
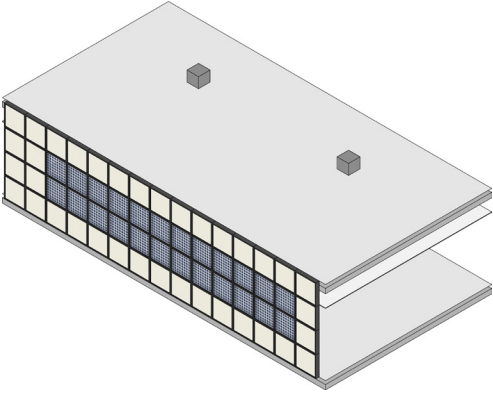
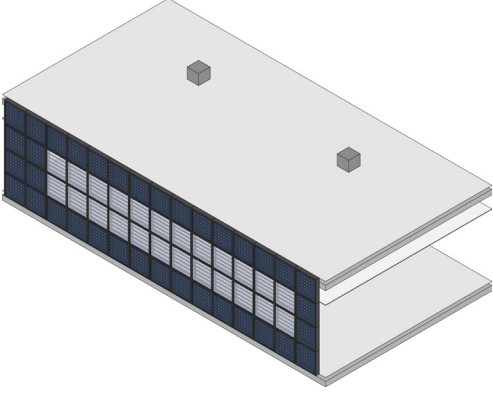
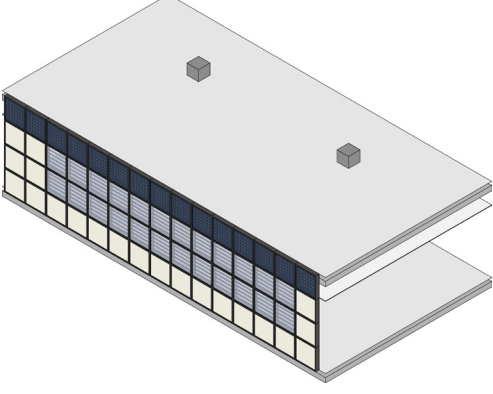
	Facade composition	Transparent surface	Opaque surface
PCM + EC WWR=40%		24 modules EC A = 19,44 m²	36 modules PCM A = 29,16 m²
PCM + BIPV WWR=40%		24 modules BIPV A = 19,44 m²	36 modules PCM A = 29,16 m²
BIPV/T + Blinds WWR=40%		24 modules Blinds A = 19,44 m²	36 modules BIPV/T A = 29,16 m²
PCM + BIPV/T + Blinds WWR=40%		24 modules Blinds A = 19,44 m²	15 modules BIPV/T A = 12,15 m² 21 modules PCM A = 17,01 m²

Table 42: Overview and module composition of simulated facades

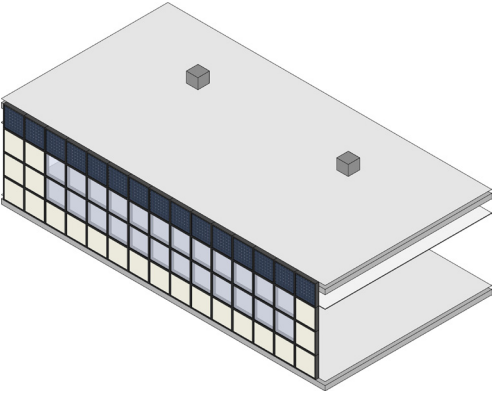
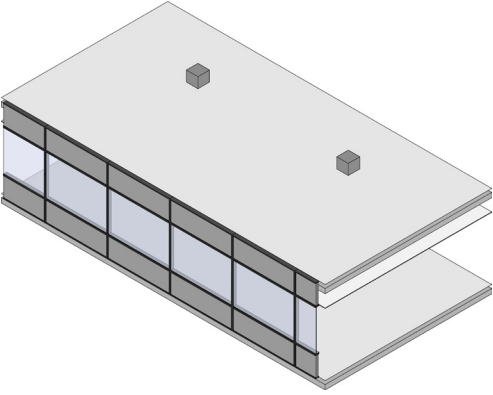
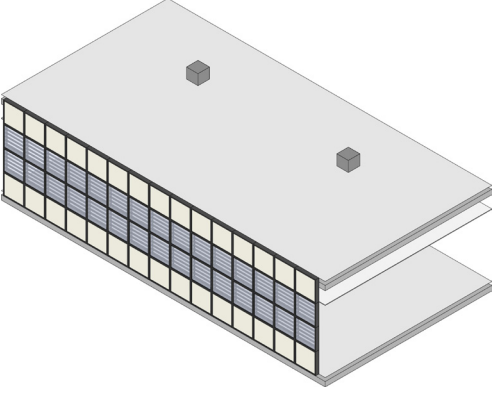
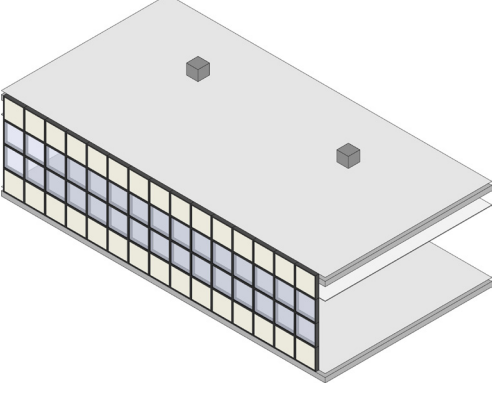
	Facade composition	Transparent surface	Opaque surface
PCM + BIPV/T + EC WWR=40%		24 modules EC A = 19,44 m²	15 modules BIPV/T A = 12,15 m² 21 modules PCM A = 17,01 m²
reference project WWR=50%		windows: HR++ A = 24,30 m²	gypsum wall board, insulation, lightweight metal cladding A = 24,30 m²
PCM + blinds WWR=50%		30 modules Blinds A = 24,30 m²	30 modules PCM A = 24,30 m²
PCM + EC WWR=50%		30 modules EC A = 24,30 m²	30 modules PCM A = 24,30 m²

Table 43: Overview and module composition of simulated facades

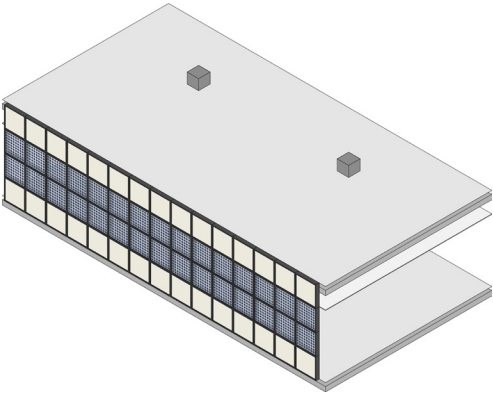
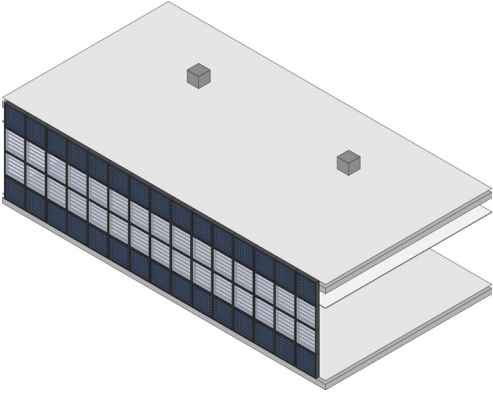
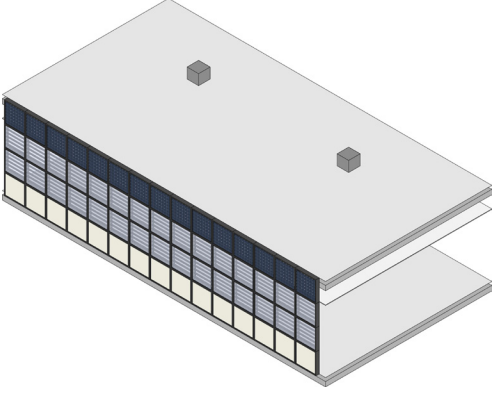
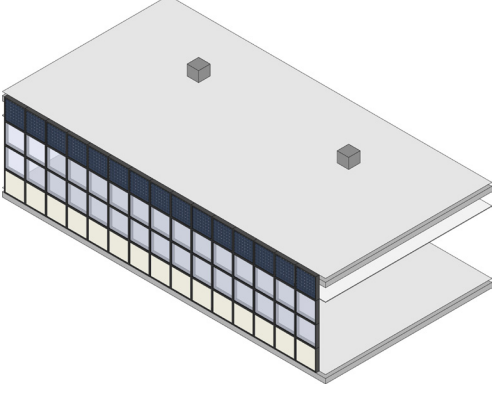
Facade composition		Transparent surface	Opaque surface
PCM + BIPV WWR=50%		30 modules BIPV A = 24,30 m ²	30 modules PCM A = 24,30 m ²
BIPV/T + Blinds WWR=50%		30 modules Blinds A = 24,30 m ²	30 modules BIPV/T A = 24,30 m ²
PCM + BIPV/T + Blinds WWR=50%		30 modules Blinds A = 24,30 m ²	15 modules BIPV/T A = 12,15 m ² 15 modules PCM A = 12,15 m ²
PCM + BIPV/T + EC WWR=50%		30 modules EC A = 24,30 m ²	15 modules BIPV/T A = 12,15 m ² 15 modules PCM A = 12,15 m ²

Table 44: Overview and module composition of simulated facades

vi. Simulation Results

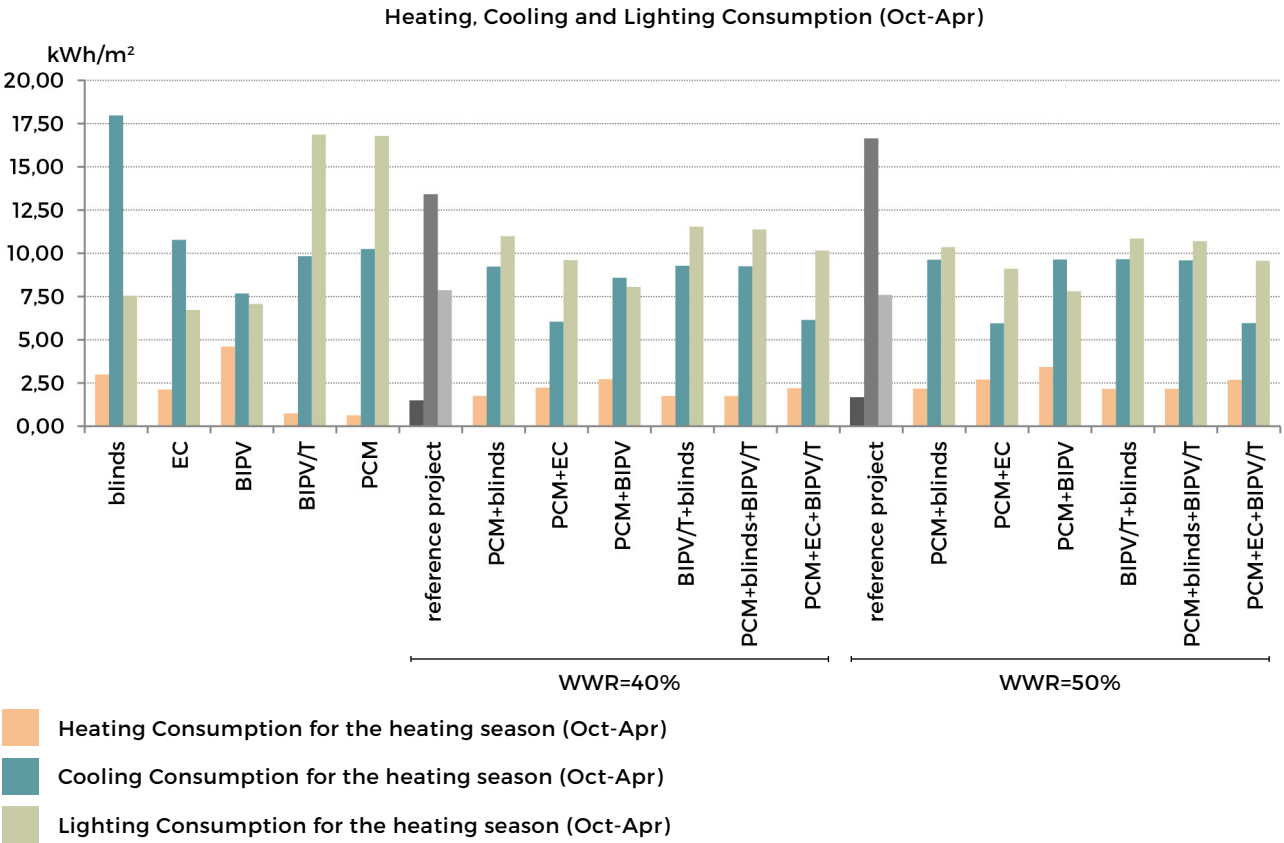
In total, the cases simulated were 19, five for each module separately, two for the reference project with the different Window-Wall-Ratios (1casex2) and 12 for different combinations of the MFM units with the different Window-Wall-Ratios (6casesx2). The operative temperature was set as control temperature, since the required setpoint temperatures correspond to the indoor operative temperatures. The reason why they were run separately was first because it was considered important to see the heating, cooling and lighting loads for the different periods and second because the average operative temperatures and the comfort and discomfort hours were also important, since the setpoints are different for every season. The results can be seen in Graphs 9, 10, 13, 14, 15, 16 and 17, whereas the detailed results with accurate numbers can be found in Appendix D.

After the simulations were conducted, the energy performance of each case was calculated as well for the heating and cooling season separately but also for the whole year. This calculation was made assuming a new construction with a COP (Coefficient of Performance) of 5 for the heating, 4 for the cooling, 1 for the lighting and 1 for the energy production. For the simulated cases that heat was provided by the ventilated cavities, which was calculated by hand, this was also added to the calculation. The results can be seen in Graphs 11, 12 and 18, whereas the detailed results with accurate numbers can again be found in Appendix D.

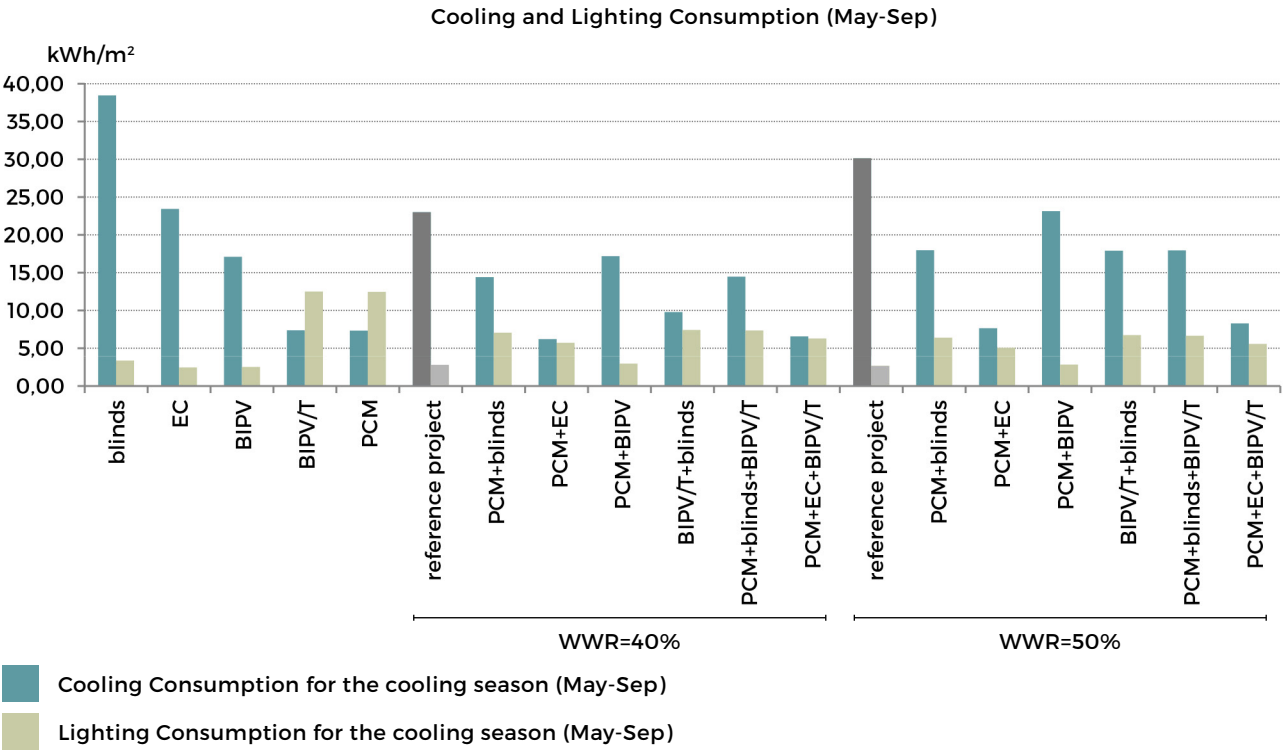
The graphs were made using the Design Builder results because in this way the comparison between them is immediately visible and thus easier. Each graph includes all 19 cases and contain

the following information:

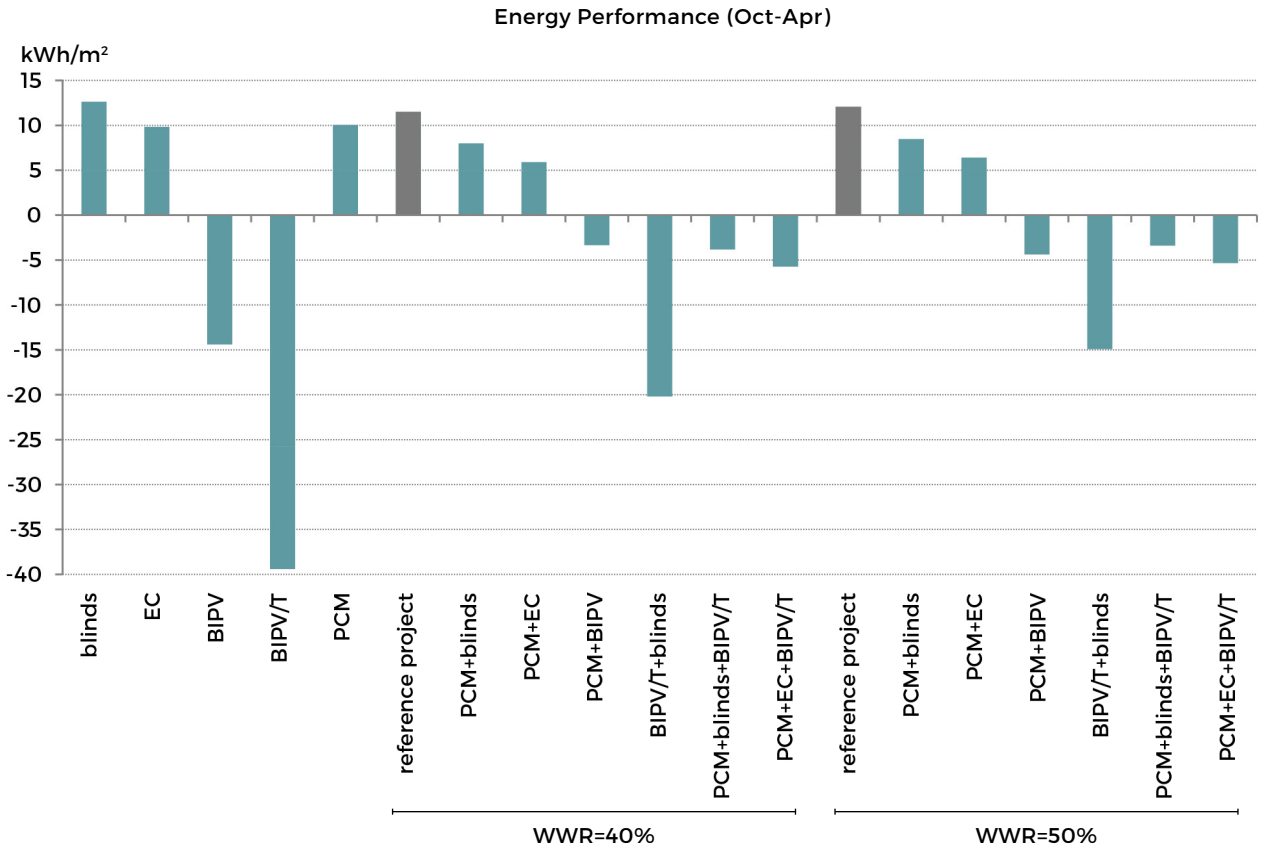
- ◊ heating, cooling and lighting consumption during the heating season (Graph 9)
- ◊ cooling and lighting consumption during the cooling season (Graph 10)
- ◊ energy performance during the heating season (Graph 11)
- ◊ energy performance during the cooling season (Graph 12)
- ◊ average operative temperature during occupation hours (08:00-18:00) for the heating season (Graph 13)
- ◊ average operative temperature during occupation hours (08:00-18:00) for the cooling season (Graph 14)
- ◊ discomfort hours during occupation hours (08:00-18:00) for the heating season (Graph 15)
- ◊ discomfort hours during occupation hours (08:00-18:00) for the cooling season (Graph 16)
- ◊ annual comfort during occupation hours (08:00-18:00) (Graph 17)
- ◊ annual energy performance (Graph 18)



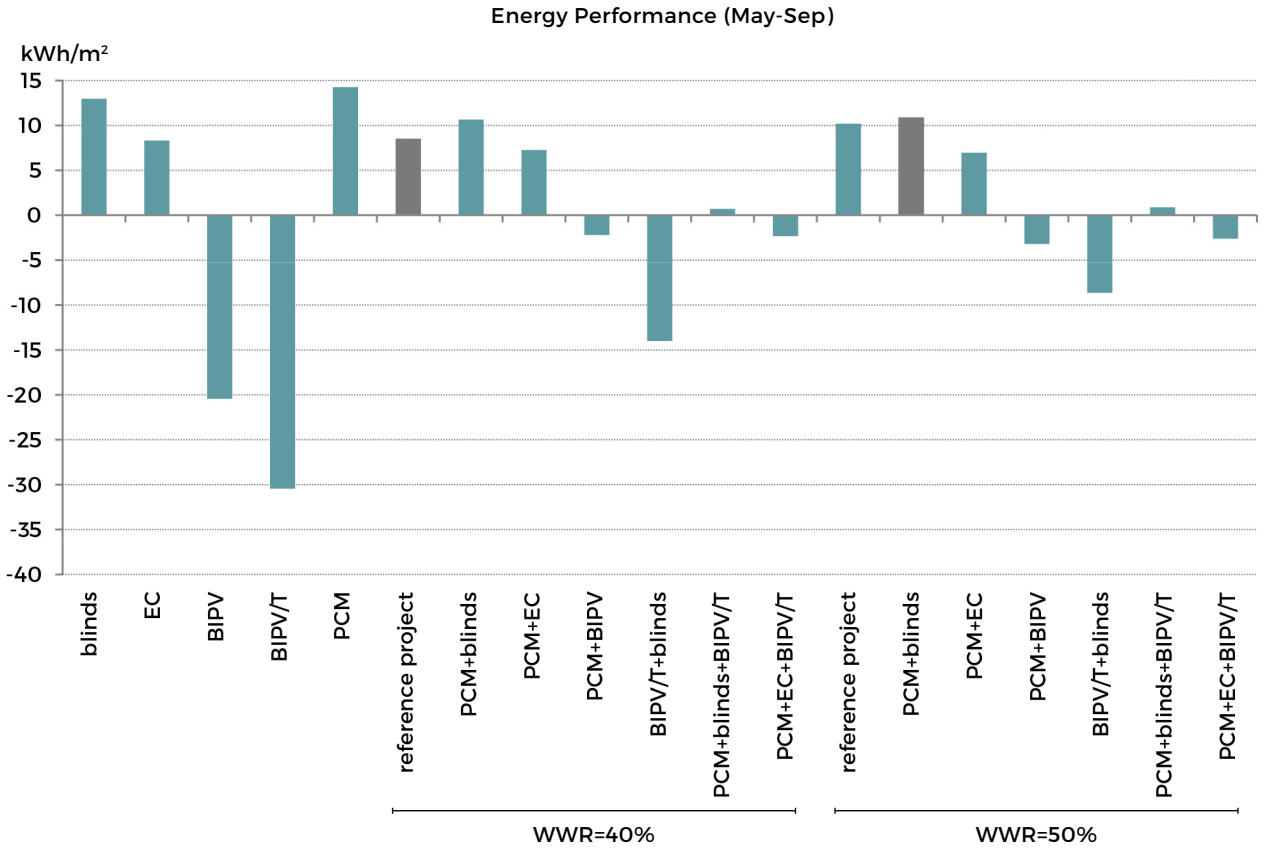
Graph 9: Heating, Cooling and Lighting Consumption for the heating season (Oct-Apr)



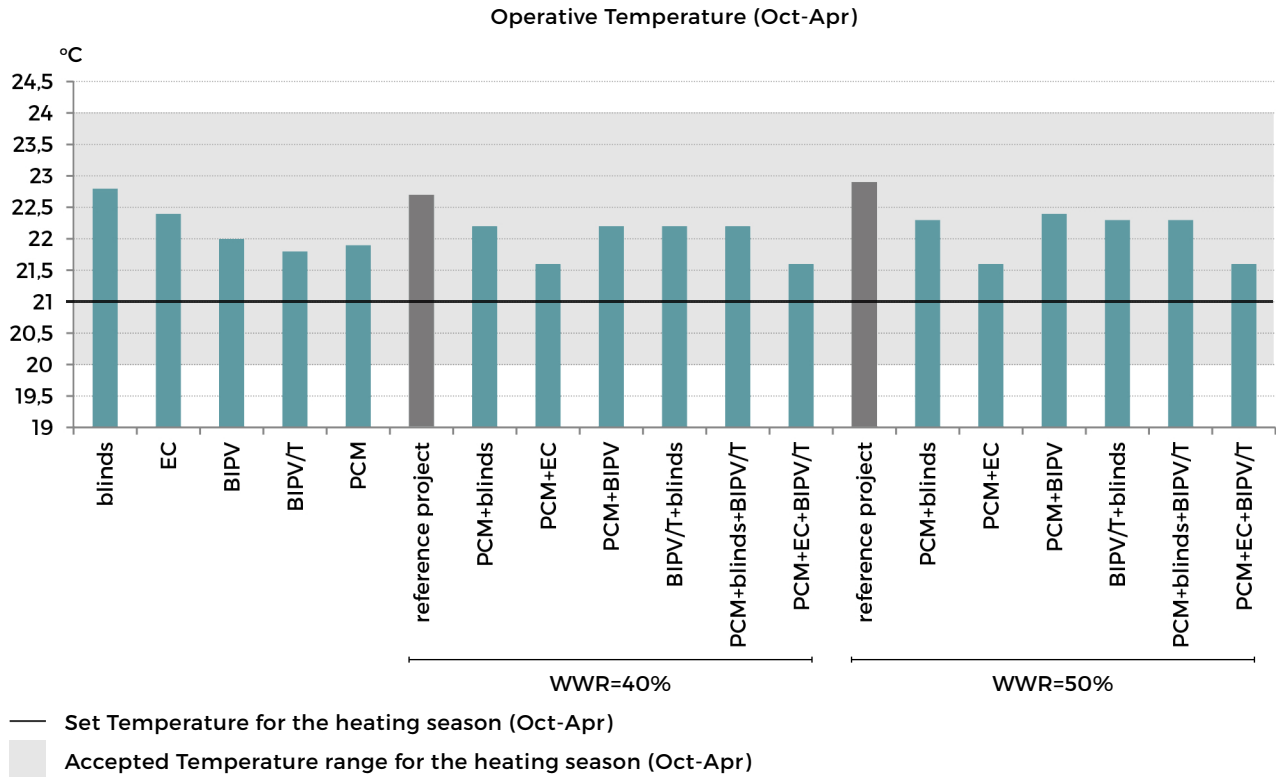
Graph 10: Cooling and Lighting Consumption for the cooling season (May-Sep)



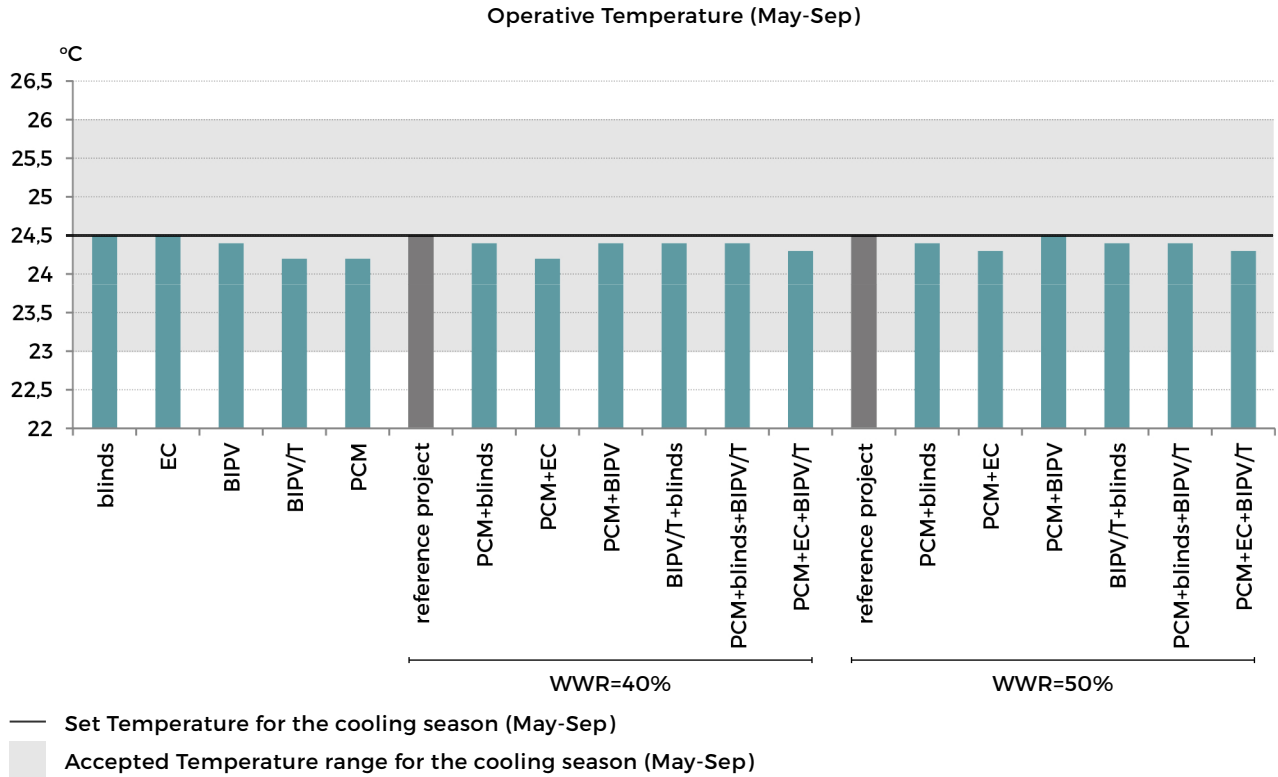
Graph 11: Energy Performance of the simulated cases for the heating season (Oct-Apr)



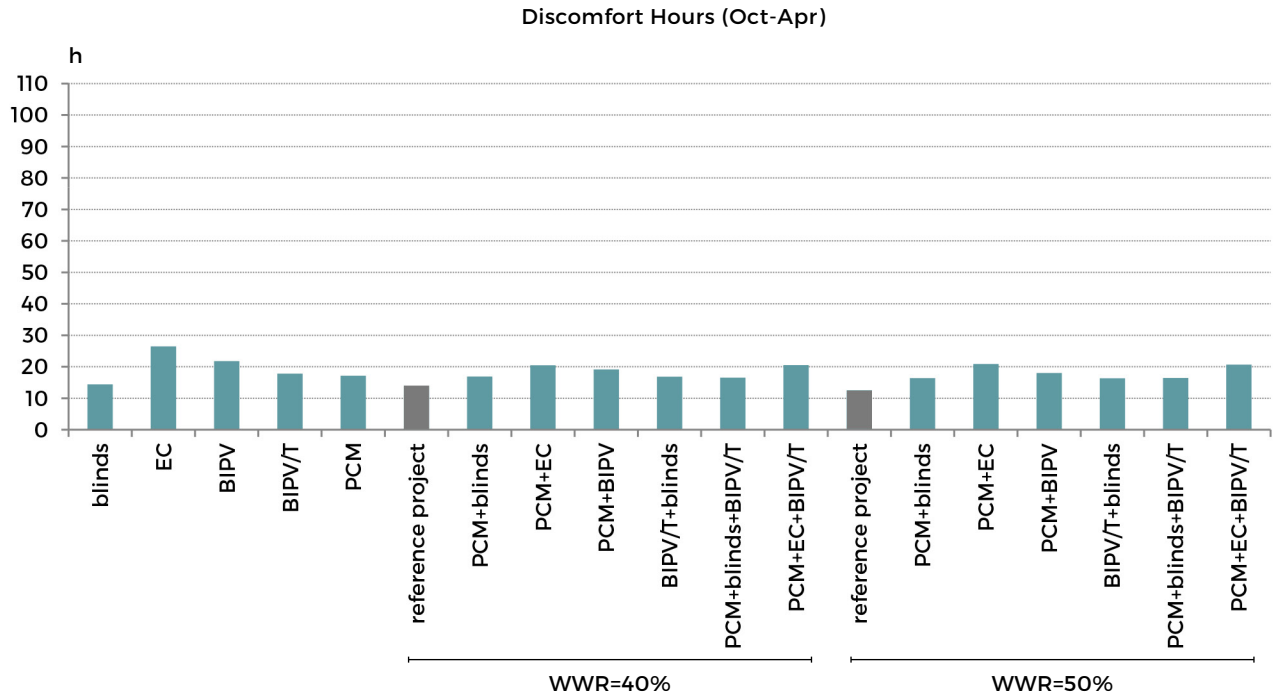
Graph 12: Energy Performance of the simulated cases for the cooling season (May-Sep)



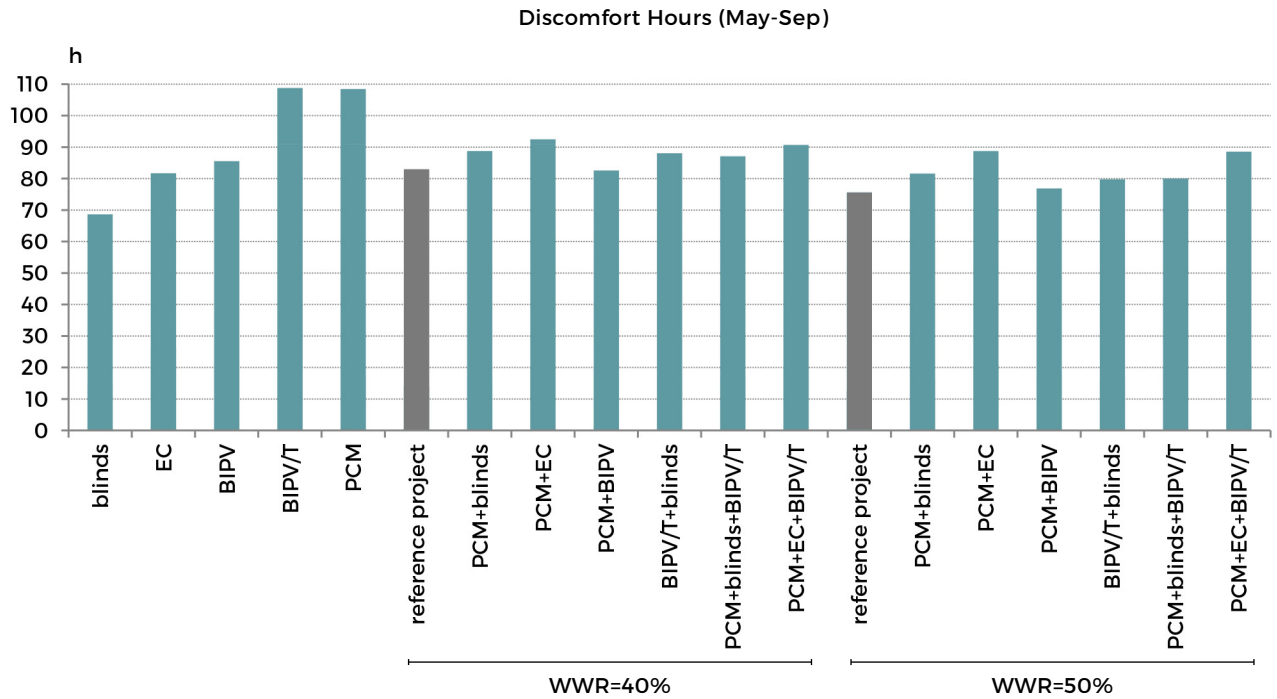
Graph 13: Operative Temperature of the simulated cases for the heating season (Oct-Apr)



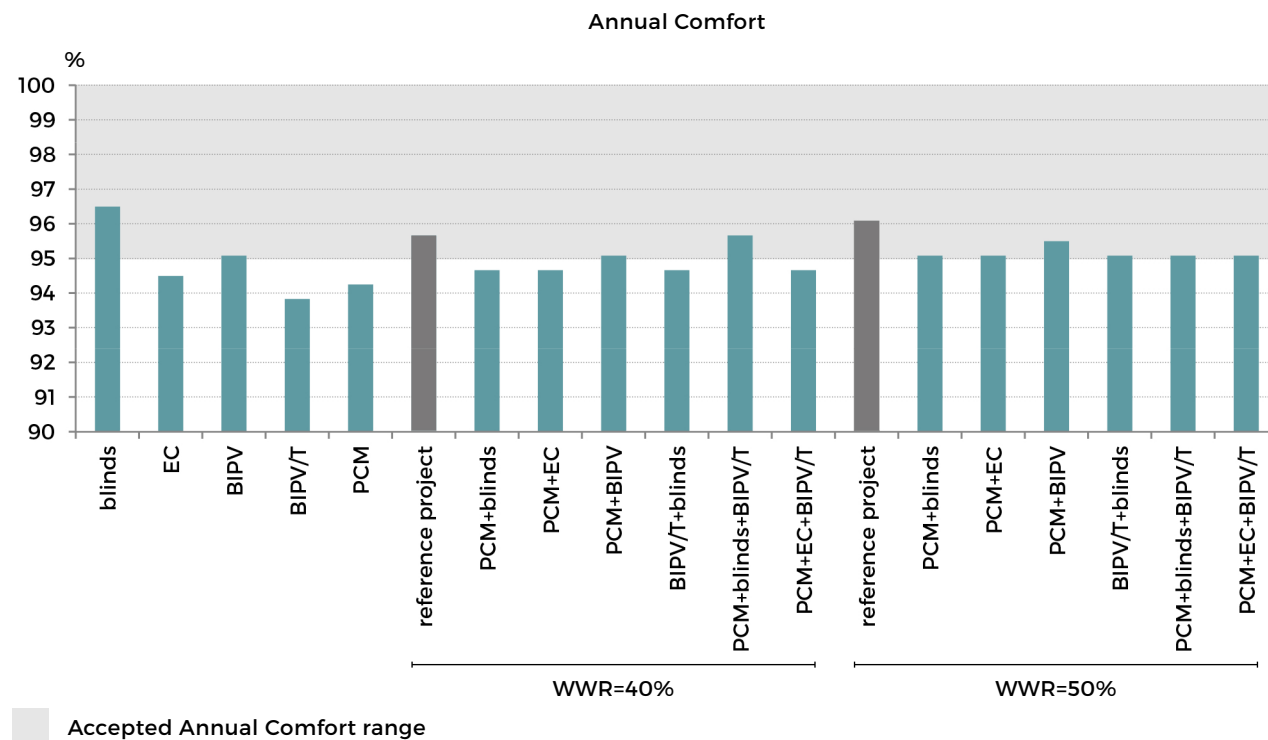
Graph 14: Operative Temperature of the simulated cases for the cooling season (May-Sep)



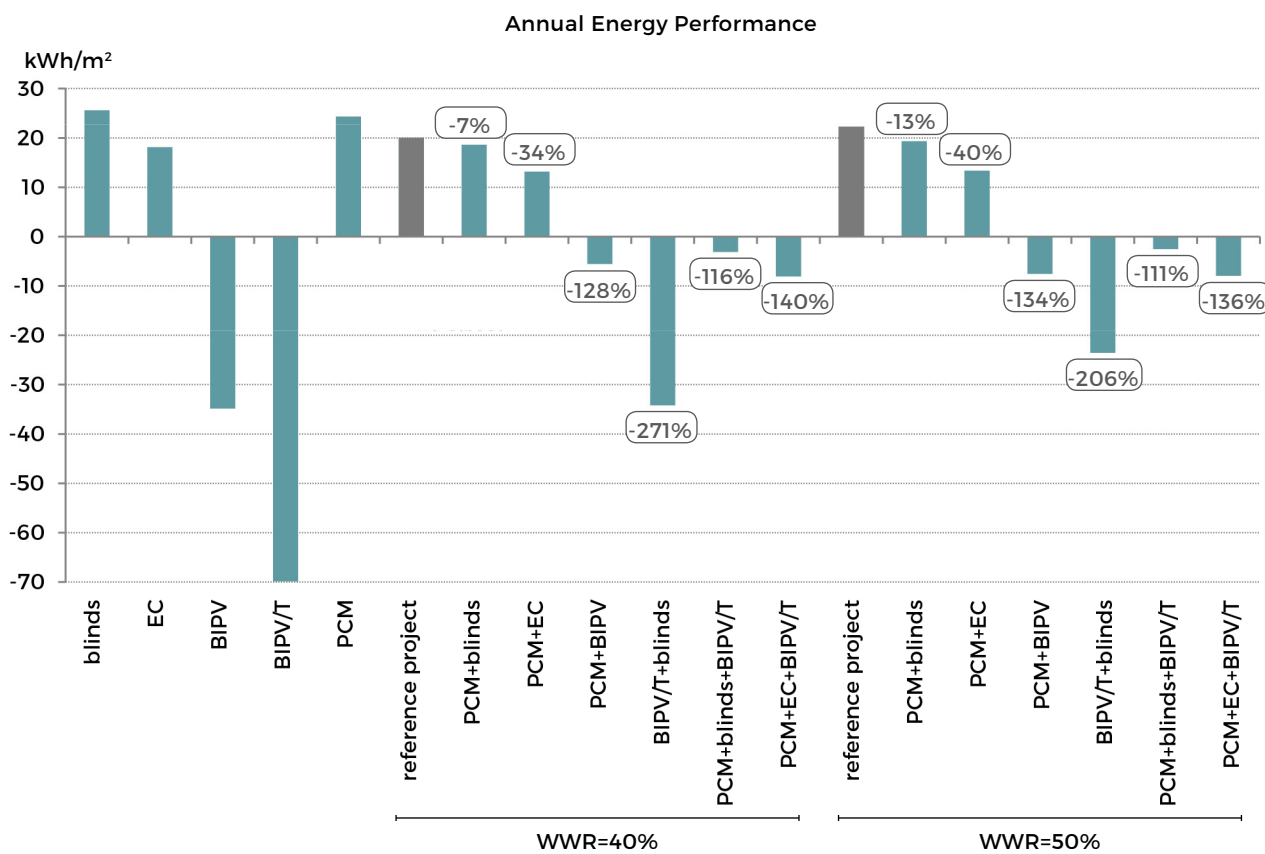
Graph 15: Discomfort hours of the simulated cases for the heating season (Oct-Apr)



Graph 16: Discomfort hours of the simulated cases for the cooling season (May-Sep)



Graph 17: Annual Comfort of the simulated cases



Graph 18: Annual Energy Performance of the simulated cases

vii. Conclusions

There are some interesting conclusions to be made for the simulations conducted for different combinations of units. First of all, the operative temperatures achieved for all simulated cases are within the accepted range. An interesting result is that the proposed design has a much higher impact on cooling loads showing considerable reduction compared to the reference project than on heating loads, which are actually slightly higher. This aspect is particularly beneficial, since cooling is more difficult to reduce in office buildings. Furthermore, the lighting consumption is higher for the MFM because the transparent parts have always a shading system to control the solar radiation and heat gains. Even though this is disadvantageous for the overall energy performance, the final results showed that all simulated cases of MFM have a better energy performance than the reference project as shown in Graph 18.

As far as the Window-Wall-Ratio is concerned, the 40% WWR shows a better energy performance than the 50%, which is logical since a bigger surface is opaque, however the difference is very small. For the case of 50% WWR, there is a higher heating and cooling demand and a lower lighting demand since the transparent surface is bigger. The operative temperatures of the 40% and 50% WWR have a very small difference being almost same or slightly higher for the case of 50%WWR and maybe this is why the comfort seems to be slightly better as well than in the case of 40%. The comfort has reached accepted percentages ($\geq 95\%$) for all simulated cases of 50% WWR whereas a few of the respective percentages in the cases of the 40% are slightly lower (only around 0,5%) than the minimum 95%. According to these facts we could conclude, that

although the literature suggests that 50% WWR is the best option in the case of temperate climates, the results of the different percentages are very close and do not make a big difference neither in terms of energy performance nor in terms of comfort.

In general, the results obtained were beneficial and showed a much better energy performance in comparison to that of the reference project with the typical office construction as shown in Graph 18. MFMs show more controlled solar gains, thus leading to lower needs for heating and cooling, and offer additionally the benefit of energy production. Nevertheless, the comfort percentage obtained in the cases of the reference projects is around 1% higher than the one achieved by the cases with the MFM. As far as the transparent units are concerned, the electrochromic one shows a better annual performance, whereas the integrated blinds offer a bit higher comfort.

The most important conclusion is that the logic of the design with modules delivering different functions and performing better as a whole was validated to be working since the more modules were combined and simulated, the better results of energy performance and comfort were achieved. As can be seen from the previous graphs, the cases where only one module was simulated covering the whole facade, show much worse results than the ones where different modules are combined. In particular, the heating, cooling and lighting loads (Graphs 9 & 10) and the discomfort hours (Graphs 15 & 16) are much higher, whereas the required annual comfort percentage is not achieved for all cases.

viii. Comparison of Hand Calculations with Simulation Results

After completing the simulations, the results of the ones conducted for each unit separately were compared to the hand calculations and as it can be seen in Tables 45-47, the results are matching proportionally in comparison with each other. The proportion is logical since the hand calculations were made for one module each time, whereas every simulation contains 60 modules of the same type.

From the hand calculations it was found out that the unit with the electrochromic glazing has the highest solar gains, next comes the glazing unit with the integrated blinds and at last the glazing with the BIPV. The same order is also followed if the simulation results of the solar gains are compared. In addition, the same logic of proportion applies for the electricity generation with the BIPV/T showing the highest amount of energy produced, both for the hand calculations and the simulations. Finally, if the transmitted heat of the hand calculations is compared with the heating required shown by the simulations, the units that have higher transmissions have also a higher heating consumption, which is logical.

For these reasons, It can be concluded that the hand calculations are proven to have given the right indication of performance for each module. However, the ratio of the proportions between the results of the hand calculations and the simulations are not always the same. This can be justified by the following aspects; first of all, the formulas used for the hand calculations are simplified versions, since the behavior of a construction in reality is much more complex. This complexity is even higher in cases of integration of adaptive materials, which respond to exterior triggers like the electrochromic glazing and the PCMs. In addition, for the hand calculations, the frames of the units were not taken into account since the focus was put on the layers used and their properties, whereas in simulations an aluminium frame with thermal break was chosen.

Transparent Units								
heating season	blinds				EC			
	simulation	Unit	hand calculation	Unit	simulation	Unit	hand calculation	Unit
solar gains windows	2642,13	kWh	40,25	kWh	2929,48	kWh	58,0	kWh
zone sensible heating	301,02	kWh	-	-	213,56	kWh	-	-
$Q_{\text{heat,trans}}$	-	-	74,64	kWh	-	-	60,31	kWh

Table 45: Hand calculations - Simulation results comparison for the Transparent units

Semi-transparent Unit				
heating season	BIPV			
	simulation	Unit	hand calculation	Unit
solar gains windows	2298,72	kWh	34,81	kWh
electricity generation	2450,29	kWh	36,23	kWh
zone sensible heating	464,79	kWh	-	-
$Q_{\text{heat,trans}}$	-	-	81,27	kWh

Table 46: Hand calculations - Simulation results comparison for the Semi-transparent unit

Opaque Units								
heating season	BIPV/T				PCM			
	simulation	Unit	hand calculation	Unit	simulation	Unit	hand calculation	Unit
electricity generation	3752,26	kWh	49,76	kWh	-	-	-	-
zone sensible heating	74,73	kWh	-	-	63,41	kWh	-	-
$Q_{\text{heat,trans}}$	-	-	8,41	kWh	-	-	8,28	kWh

Table 47: Hand calculations - Simulation results comparison for the Opaque units

FINAL DESIGN

I. Application examples - Interior



Figure 60: Visualisation of office interior with electrochromic glazing units (bleached state)



Figure 62: Visualisation of office interior with opaque units (PCM or BIPV/T) and electrochromic glazing units (bleached state)



Figure 61: Visualisation of office interior with electrochromic glazing units (colored state)



Figure 63: Visualisation of office interior with opaque units (PCM or BIPV/T) and electrochromic glazing units (colored state)



Figure 64: Visualisation of office interior with opaque units (PCM or BIPV/T) and glazing with BIPV units



Figure 65: Visualisation of office interior with opaque units (PCM or BIPV/T) and glazing units with integrated blinds



Figure 66: Visualisation of office interior with glazing with BIPV units



Figure 67: Visualisation of office interior with translucent PCM units



Figure 68: Visualisation of office interior with opaque units (PCM or BIPV/T), electrochromic glazing and translucent PCM units



Figure 69: Visualisation of office interior with opaque units (PCM or BIPV/T), integrated blinds and translucent PCM units

II. Application examples - Exterior



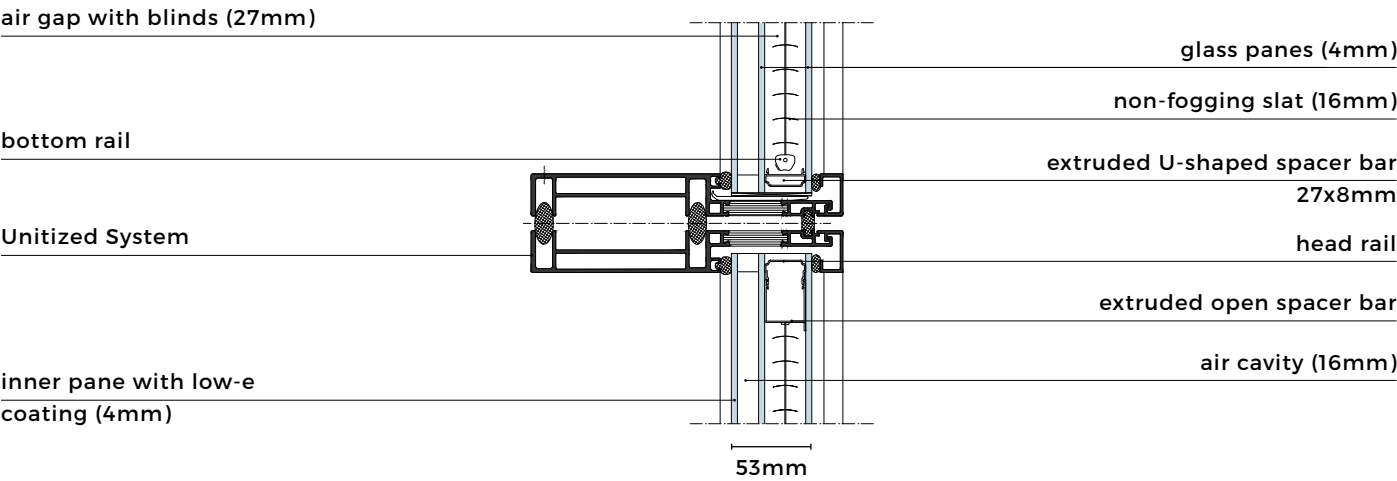
Figure 70: Visualisation of office building with MFM application



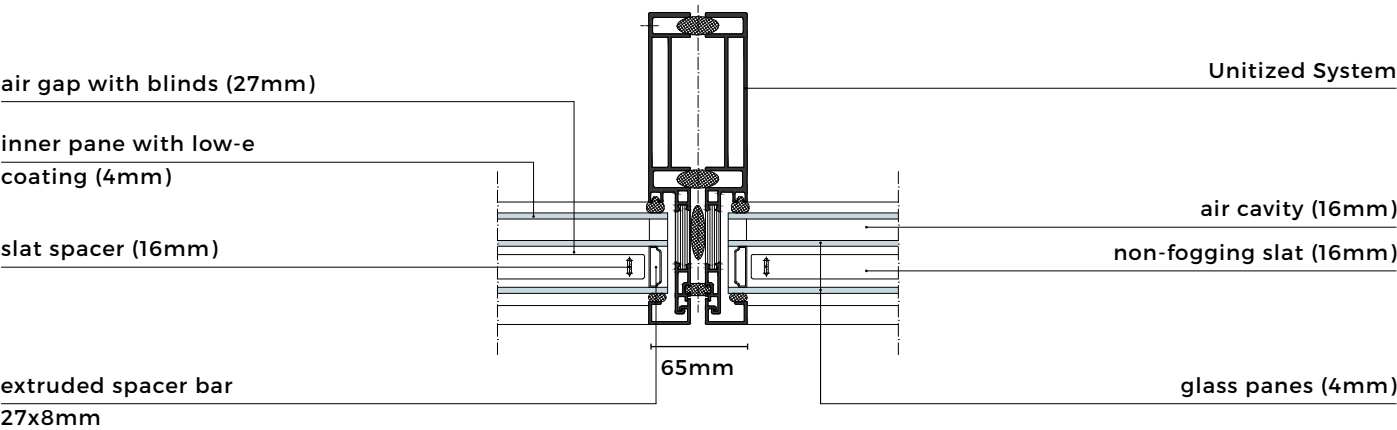
Figure 71: Visualisation of office building with MFM application

III. Technical Drawings

i. Glazing unit with integrated blinds

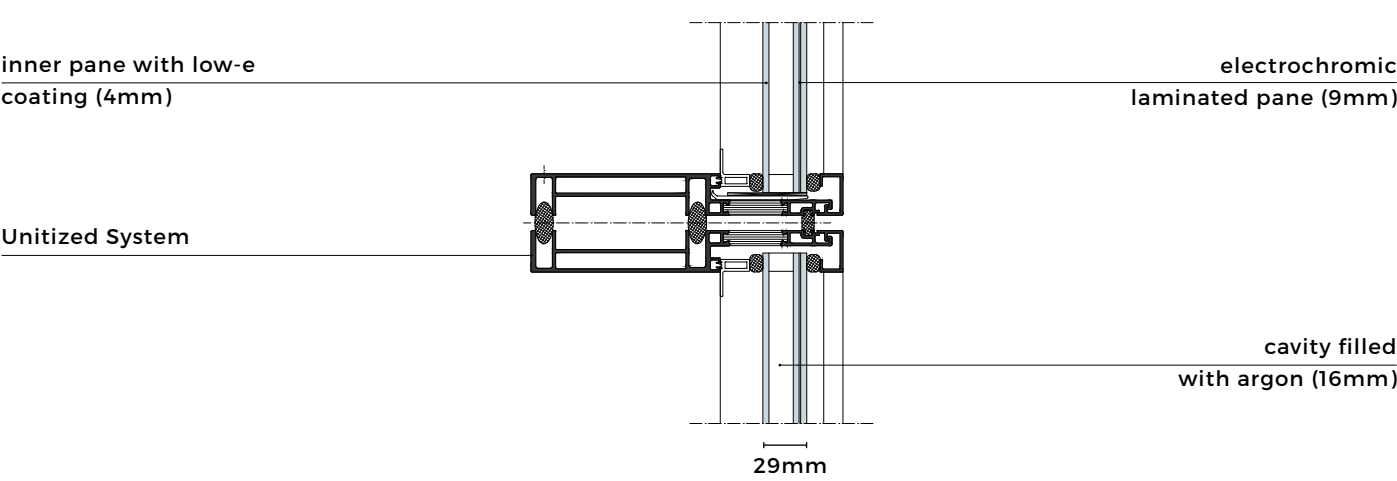


Section - Scale 1:5

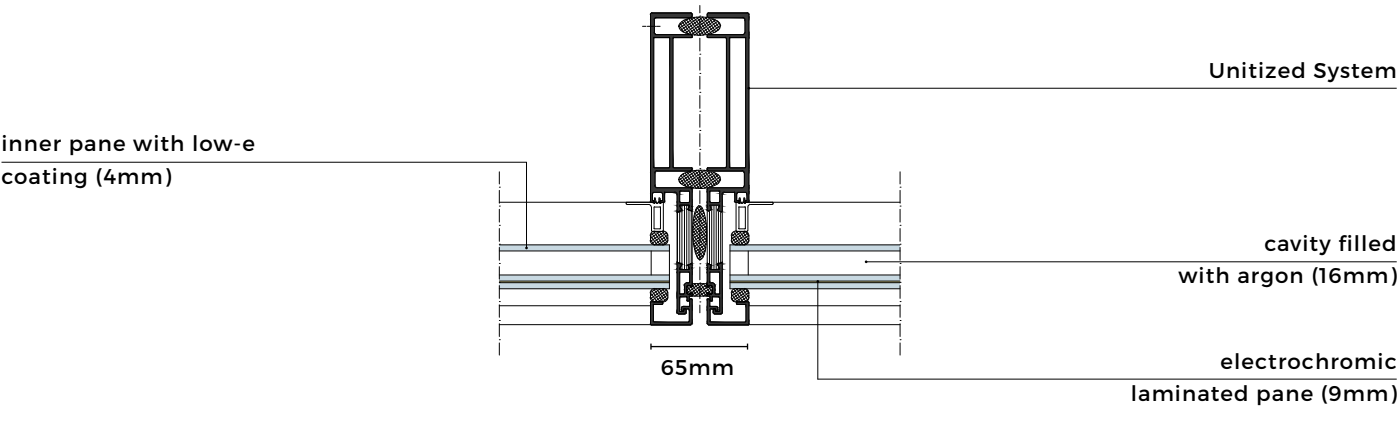


Plan - Scale 1:5

ii. Unit with Electrochromic glazing



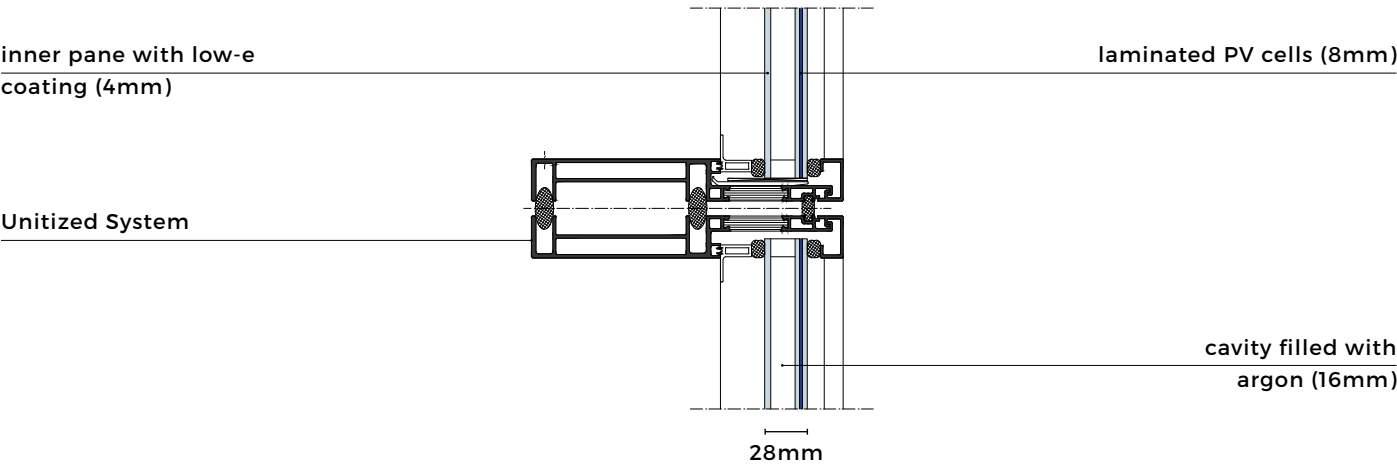
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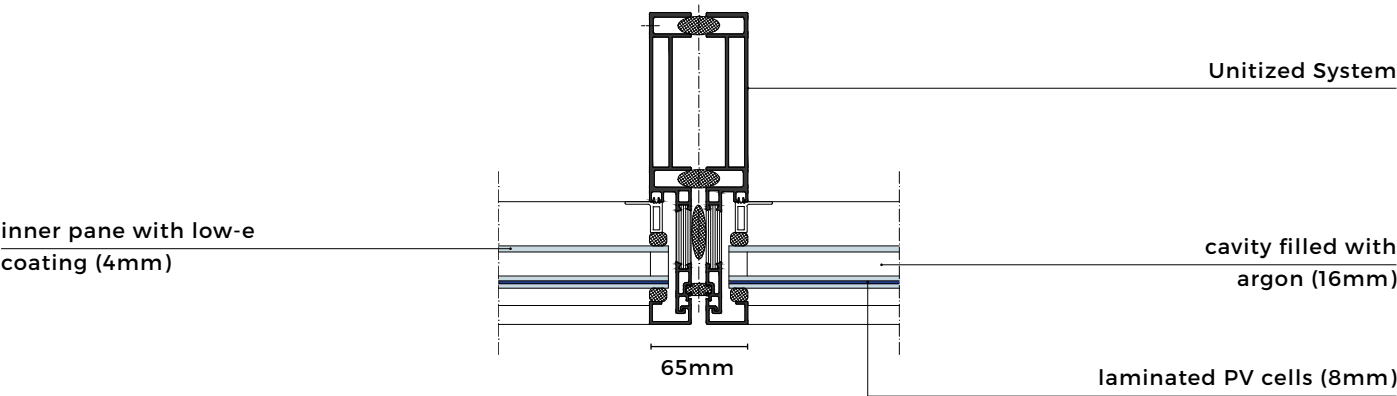
Plan - Scale 1:5

* From outermost to innermost layer:
1. Glass
2. Transparent Conductive Coating
3. Ion Storage Layer
4. Ion-Conducting Electrolyte Layer
5. EC layer
6. Transparent Conductive Coating
7. Glass

iii. Glazing unit with BIPV

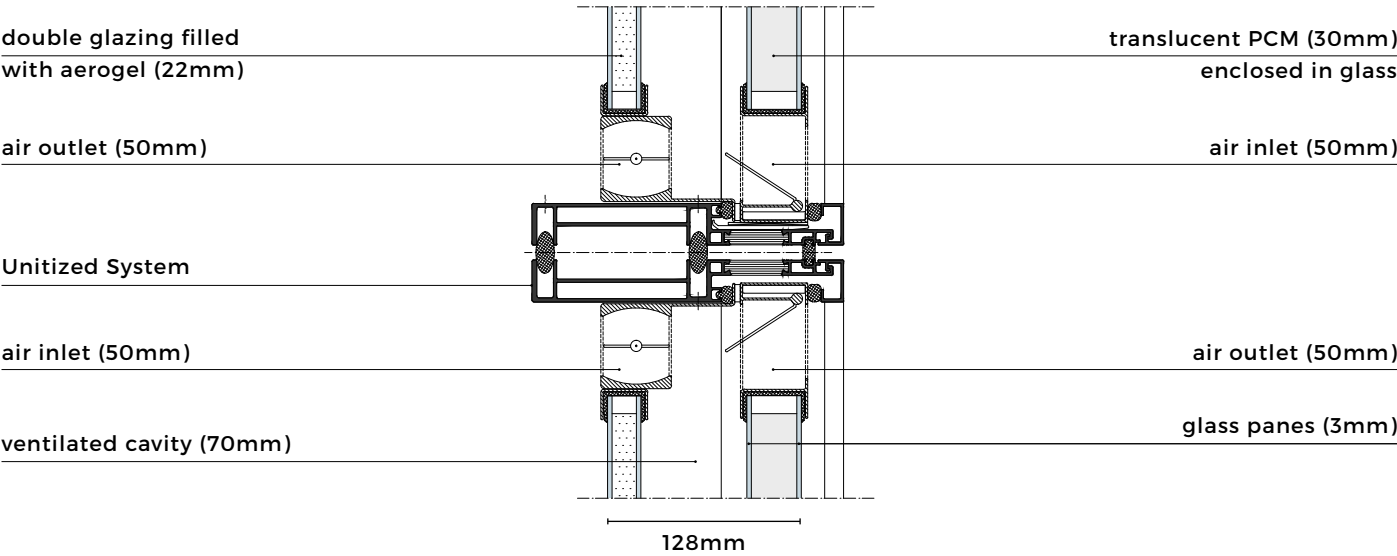


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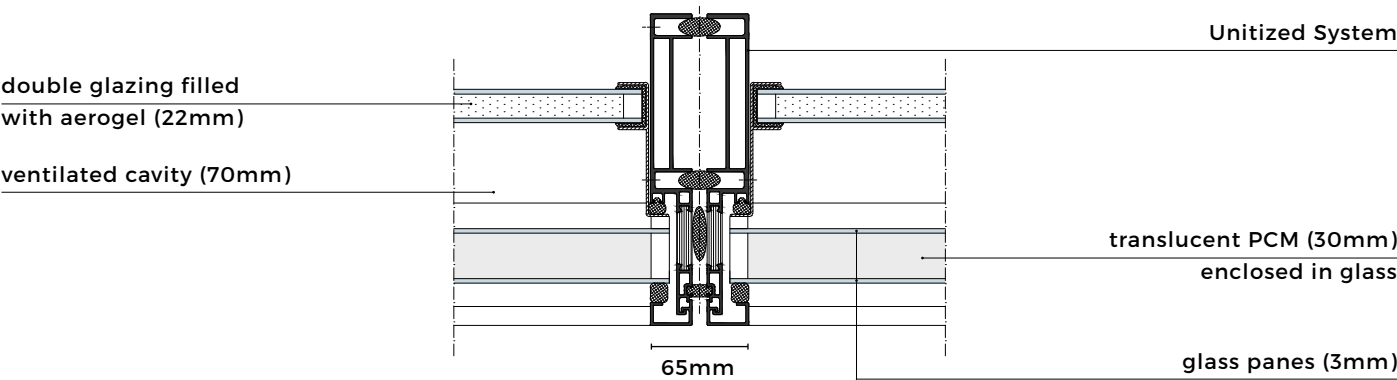


Plan - Scale 1:5

iv. Unit with translucent PCM

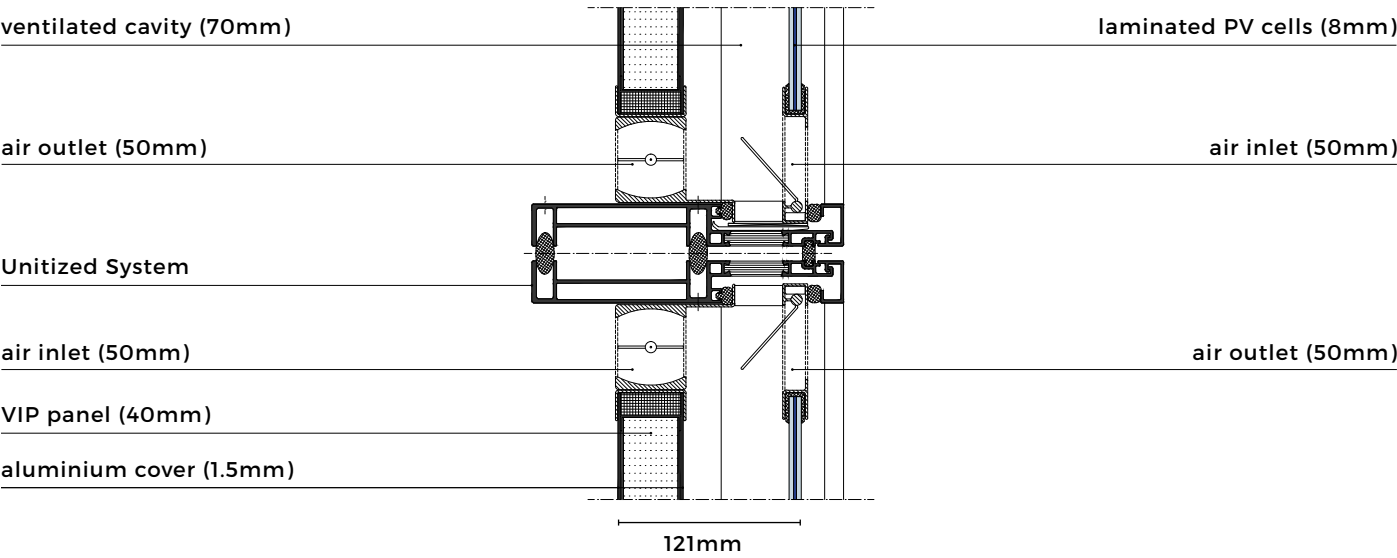


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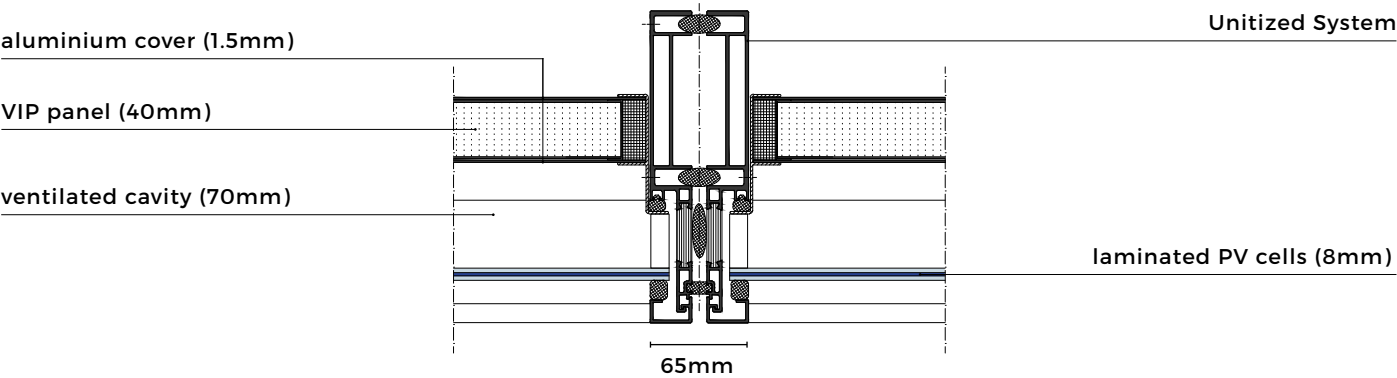


Plan - Scale 1:5

v. Unit with BIPV/T

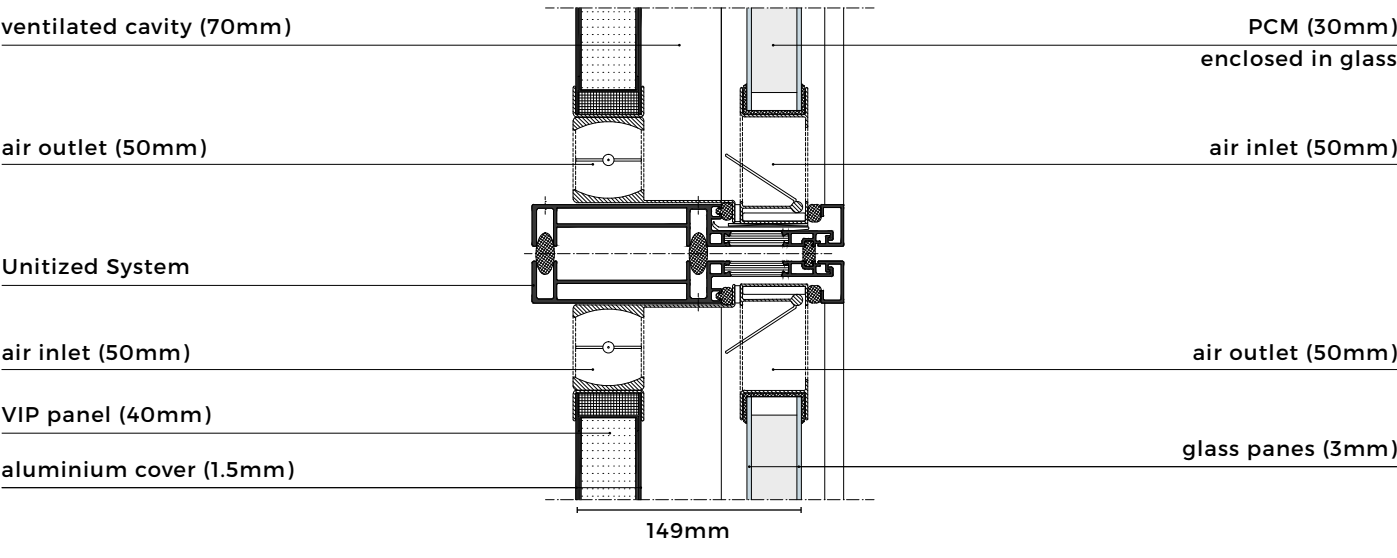


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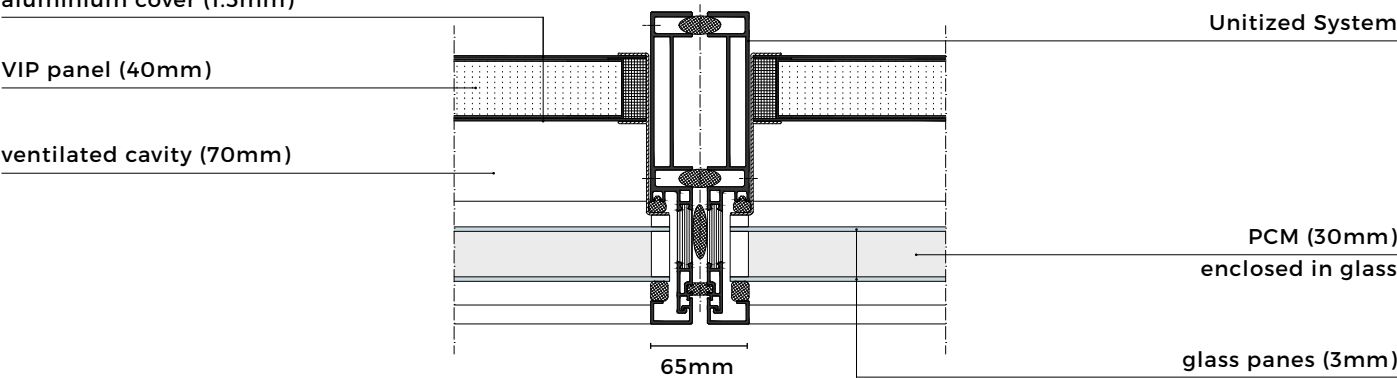


Plan - Scale 1:5

vi. Unit with opaque PCM

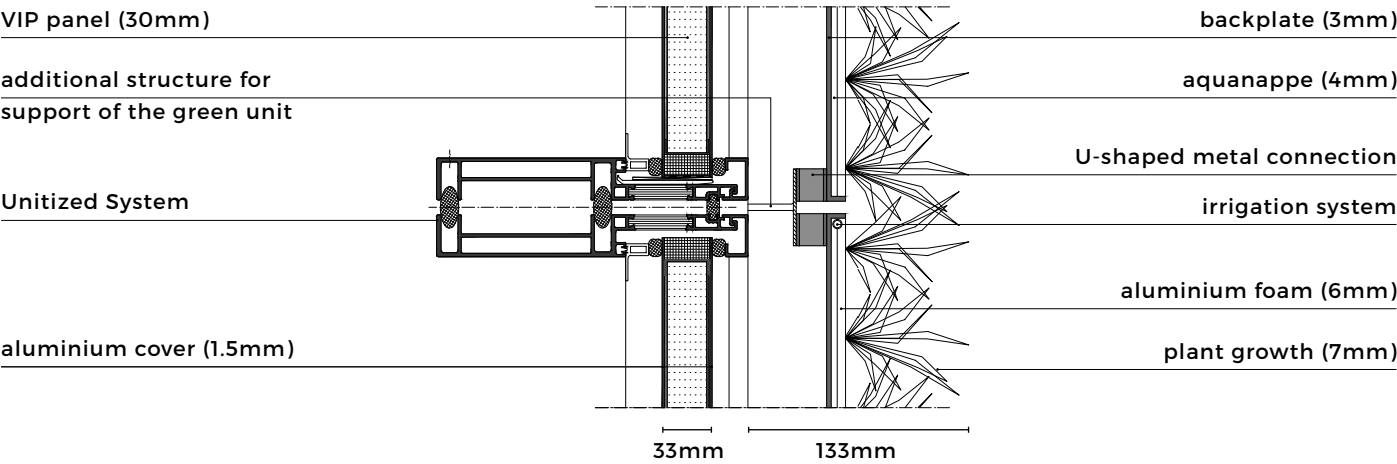


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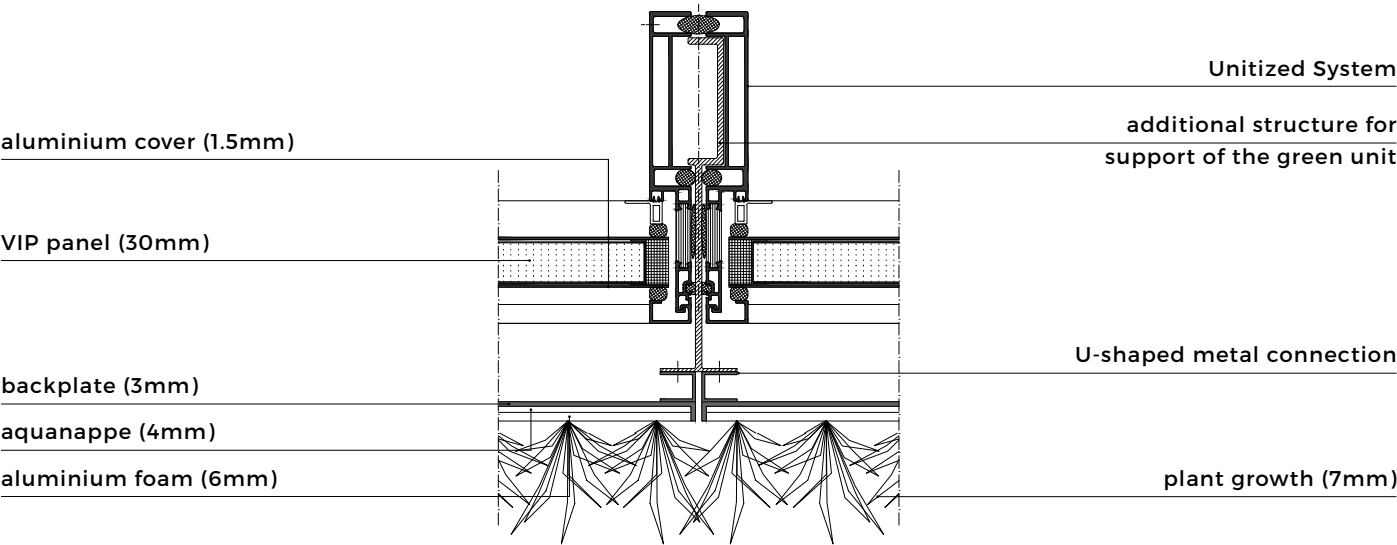


Plan - Scale 1:5

vii. Living Wall Unit

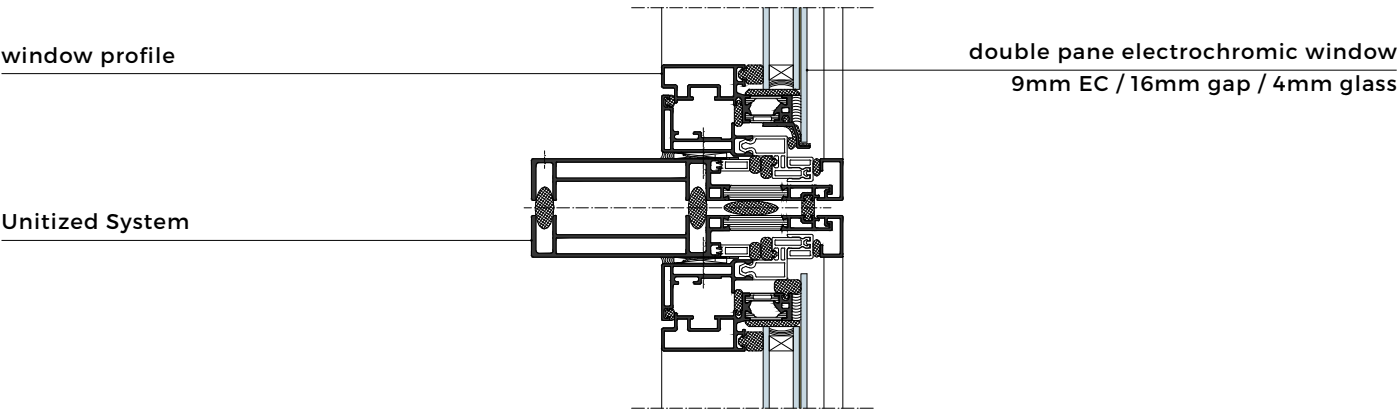


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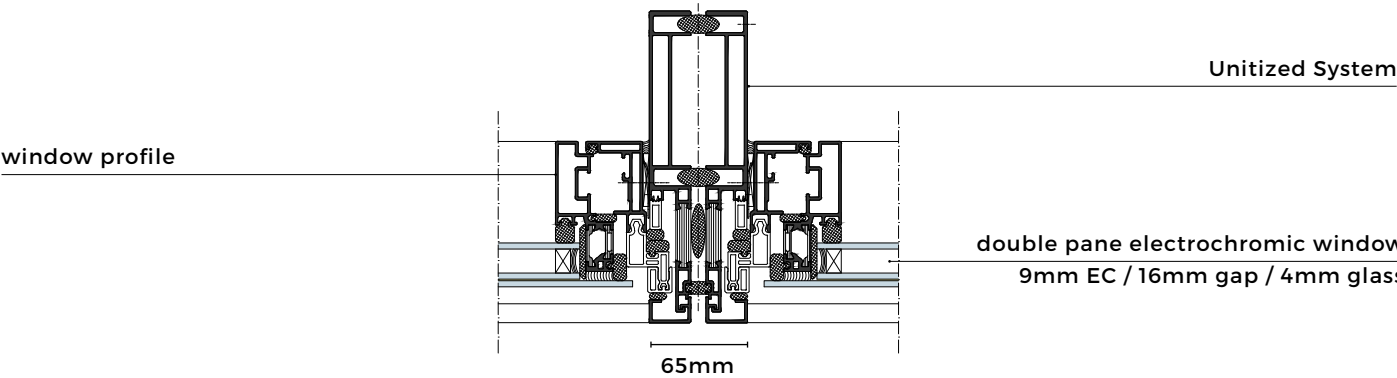


Plan - Scale 1:5

viii. Detail of operable windows



Section - Scale 1:5



Plan - Scale 1:5

* The choice of electrochromic window is exemplary. The same window profile and attachment is used for the glazing unit with integrated blinds and the glazing unit with BIPV

ix. Installation of unitized system

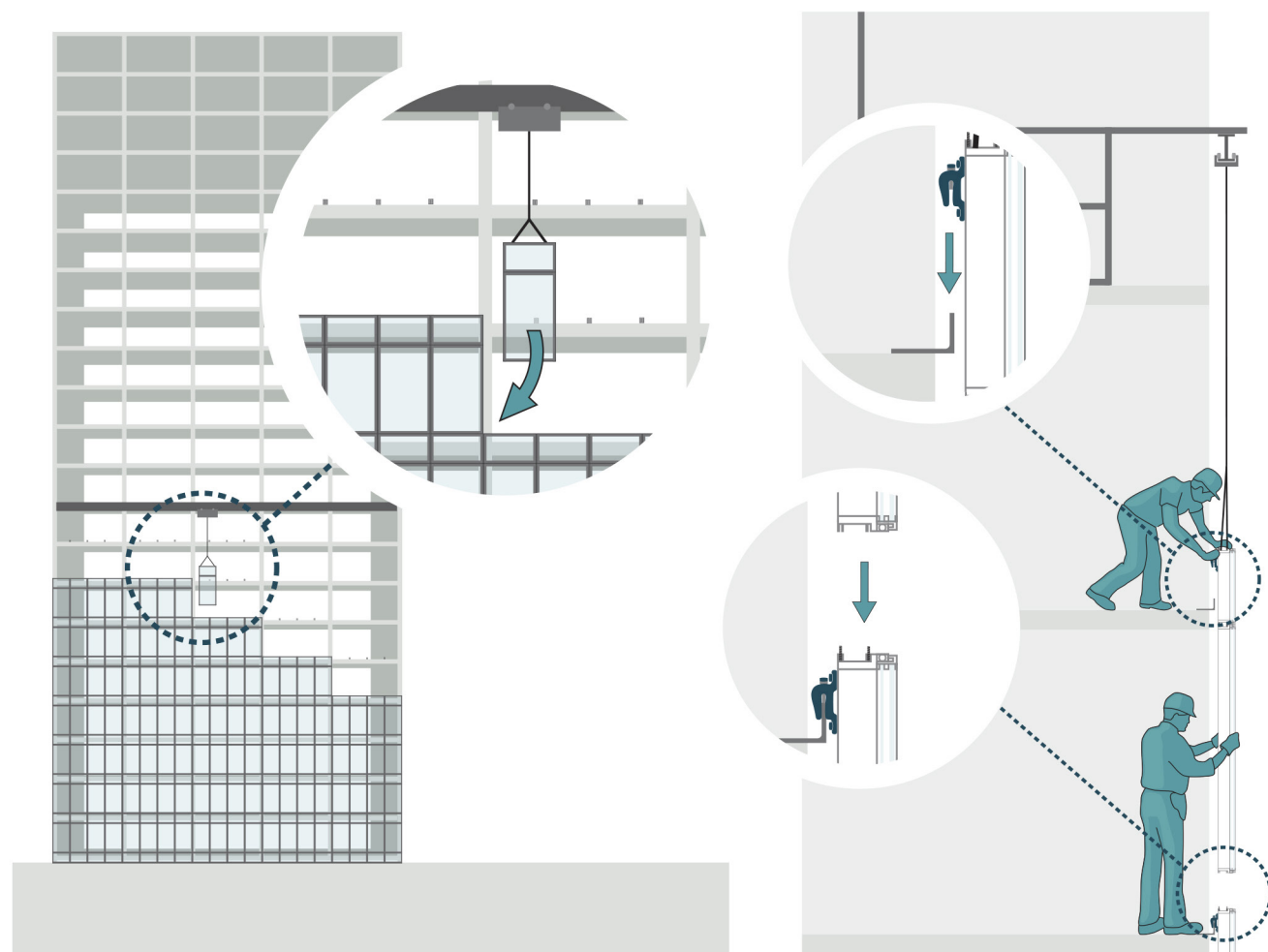


Figure 72: Standard element installation
Source: www.reynaers.ie

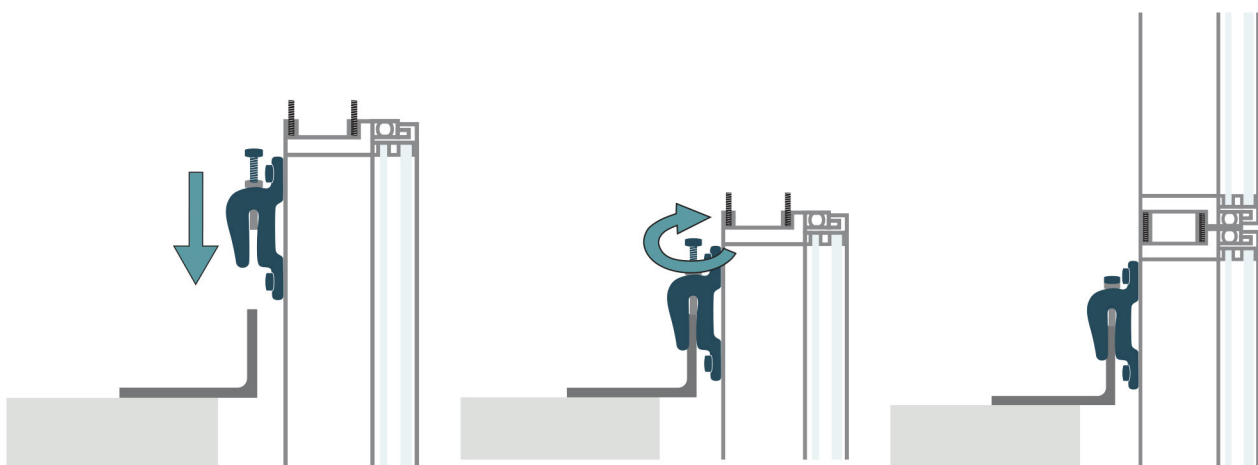
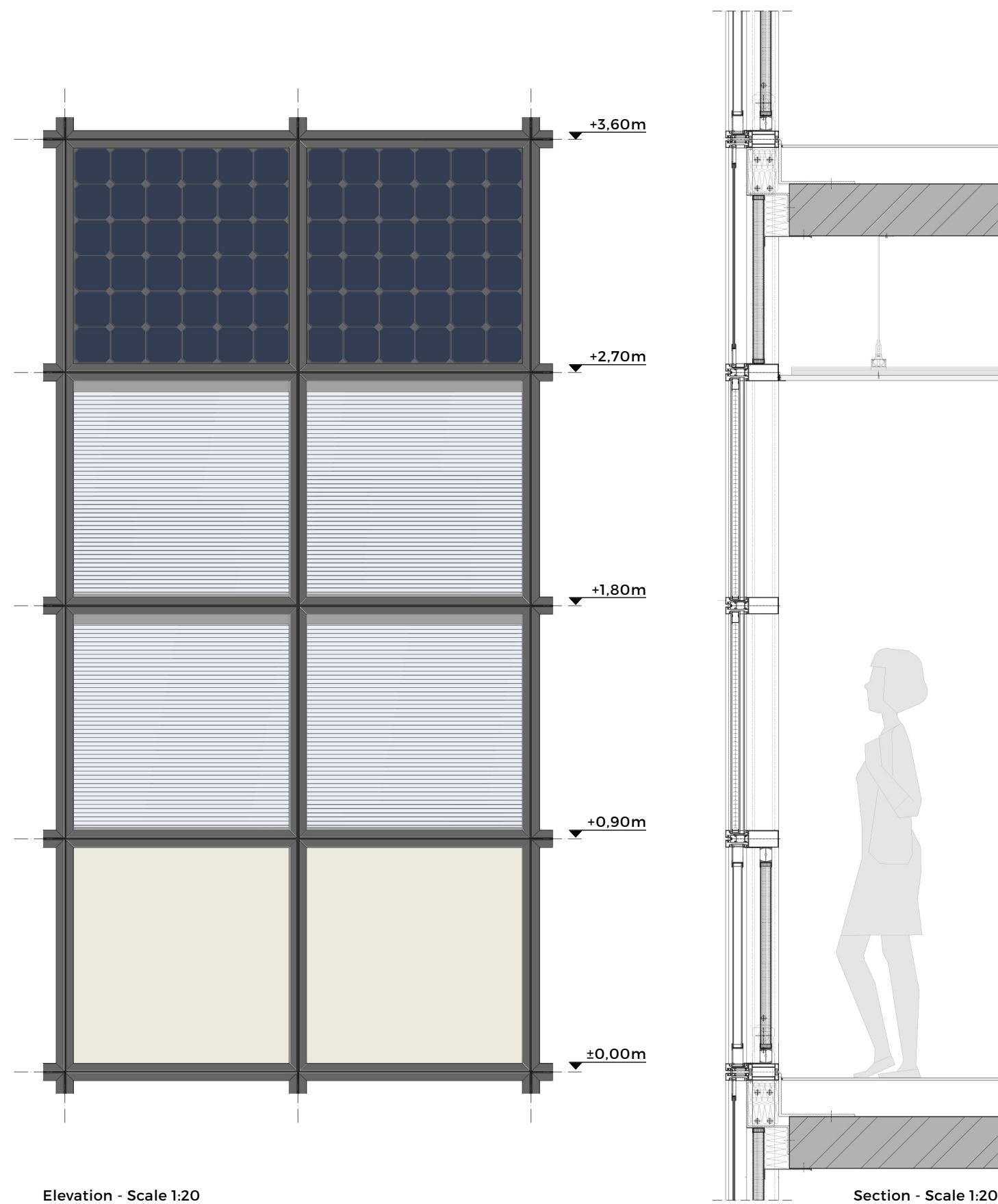


Figure 73: Detail of standard bracket functionalities
Source: www.reynaers.ie

x. Application example - Elevation & Section



CONCLUSIONS

I. Limitations

Research projects conducted for the purpose of a Master's thesis are usually marked with several restrictions, since they are experimental and completed within a short-term period. Moreover, the available means for testing in terms of required software or lab equipment are sometimes according to the nature of the project limited. The completion of this thesis project could not be an exception to this rule.

The most important restriction was at the transition of the literature study to the design/experimental phase. While studying the relevant literature, a lot of new, smart and innovative materials showing great potential were found. However, most of them were not possible to be integrated to the design because there was no access to the required means to test them. Besides, smart, adaptive materials show a unique response to real environmental conditions, which is almost impossible to be simulated by a software. These materials are still in experimental phase and although it would be interesting to explore their capabilities, it was concluded that they still have a long way before real applications and even wide application in research projects. Besides, the project was realised in collaboration with "Rolocate" seeking for new facade concepts and systems applicable in the near future.

Nevertheless, a few materials with self-regulating behavior like the PCM and the electrochromic glazing which have been applied in real projects are already included in software options and were incorporated to the design. However, in the case of the translucent PCM, it is still not able to be simulated so it was excluded from this phase of the testing and only hand calculations were made.

In addition, this research project is focused on office buildings and all results and conclusions are applicable for that type of function. Nevertheless, it is believed that in reality it can be applied to other types of buildings as well with similar advantages in terms of energy efficiency.

II. Overall assessment

The review on properties of the materials chosen together with Rolocate's guidance, the climate responsive aspects of the facade design and relevant researches done in the field of the MFMs contributed to define facade strategies taking into account both their negative and positive aspects.

The simulations that have been performed on the open-plan office in Amsterdam and the comparison with the reference project confirm the potential of the climate adaptive multifunctional building elements. The results of this research project together with the conclusions of similar projects, like the case studies presented in the research framework, can strongly support the view that the concept works in different climates with considerable energy savings.

More specifically, from the simulations conducted it was proved that the units offer the required annual comfort, while achieving a nearly zero-energy or positive annual energy performance. The thermal insulation of each unit is in accordance with the official guidelines and the operative temperatures are both for winter and summer in the required range. However, these results apply for a south facade which has the highest solar irradiation, a fact that is very beneficial in terms of the energy production. Consequently, the facades of the other orientations would perform worse with the

same combinations tested and maybe a different arrangement would be required.

As overall conclusion about the near future of adaptive facades after the completion of this research project, it was deduced that it does not lie on the integration of smart, innovative materials but on traditional ones with the difference that layering and combinations matter. The adaptability and thus the higher energy efficiency depend a lot on the sequence of layers chosen for a facade but also on the combination of different elements with different layering. Consequently, "Rolocate" is not needed to change the way facade systems are constructed but it should consider collaborating with other stakeholders with knowledge on material science and building physics, in order to achieve synchronisation of these functions and offer systems with long-term cost savings for the client.

III. Research Question

How can an adaptive system of multi-functional facade modules be designed taking advantage of integral and layered product architecture in order to respond to different climate conditions and provide thermal comfort whilst minimizing the energy demand of an office building in the Netherlands?

The proposed design of the Multi-functional Facade Module (MFM) incorporates a variety of different materials and climate strategies applied in different units of the same size, which can be combined at will in relation to the context and the project's needs. The concept of integrating different type of units, which deliver different functions is multi-functional as a whole and

reaches its highest performance when units function in combination and not separately. The aspect of energy production is essential, in order to reach zero energy performance or even being energy positive.

The concept of MFMs have been proven to be rather successful for temperate climates by the completion of this research project and the simulation results achieved. However, there are a few parameters that should be taken into account while applying the system to a new project. These parameters can be established as guidelines for the designers and contribute to create an energy efficient facade system which will provide thermal comfort in the indoor space of offices.

Several considerations should be made according to the climate, to which this facade system is applied. First of all, the optimal Window-Wall-Ratio should be defined. The 50% is supposed to be the most beneficial for temperate climates, however, if applied in a Mediterranean climate for example this ratio will have to be different because of the higher solar gains and temperatures reached. Then, another aspect to consider is which combination of units is optimal for the specific location and project and for which orientation.

The proposed composition of modules can remain the same for different climates except for one. In the case of PCM, the type and thickness should be chosen according to the corresponding operative temperature. In this way, the phase change of PCM will be achieved at the most optimal time, providing the biggest potential for temperature control of the indoor space. Last but not least, the different natural ventilation strategies for summer and winter that can be applied with the aid of the ventilated cavities integrated in specific units

of the MFM should be redefined according to the climate's needs. It is essential to consider not only winter and summer modes but also day and night ones, in order to take advantage of the natural ventilation to the maximum.

So according to the above aspects the system is applied according to the following steps as illustrated in Figure 74:

1. Define the Window-Wall-Ratio according to the climate
2. Choose which modules will be applied according to the context and the building function
3. Define the size and geometry of the modules if there is a need for custom design
4. Define the ventilation strategy of the building according to the climate and consequently how the ventilated cavities of the respective modules will be used
5. Define the type and thickness of PCM according to the climate

How is the adaptive system of the Multi-functional Facade Module designed?

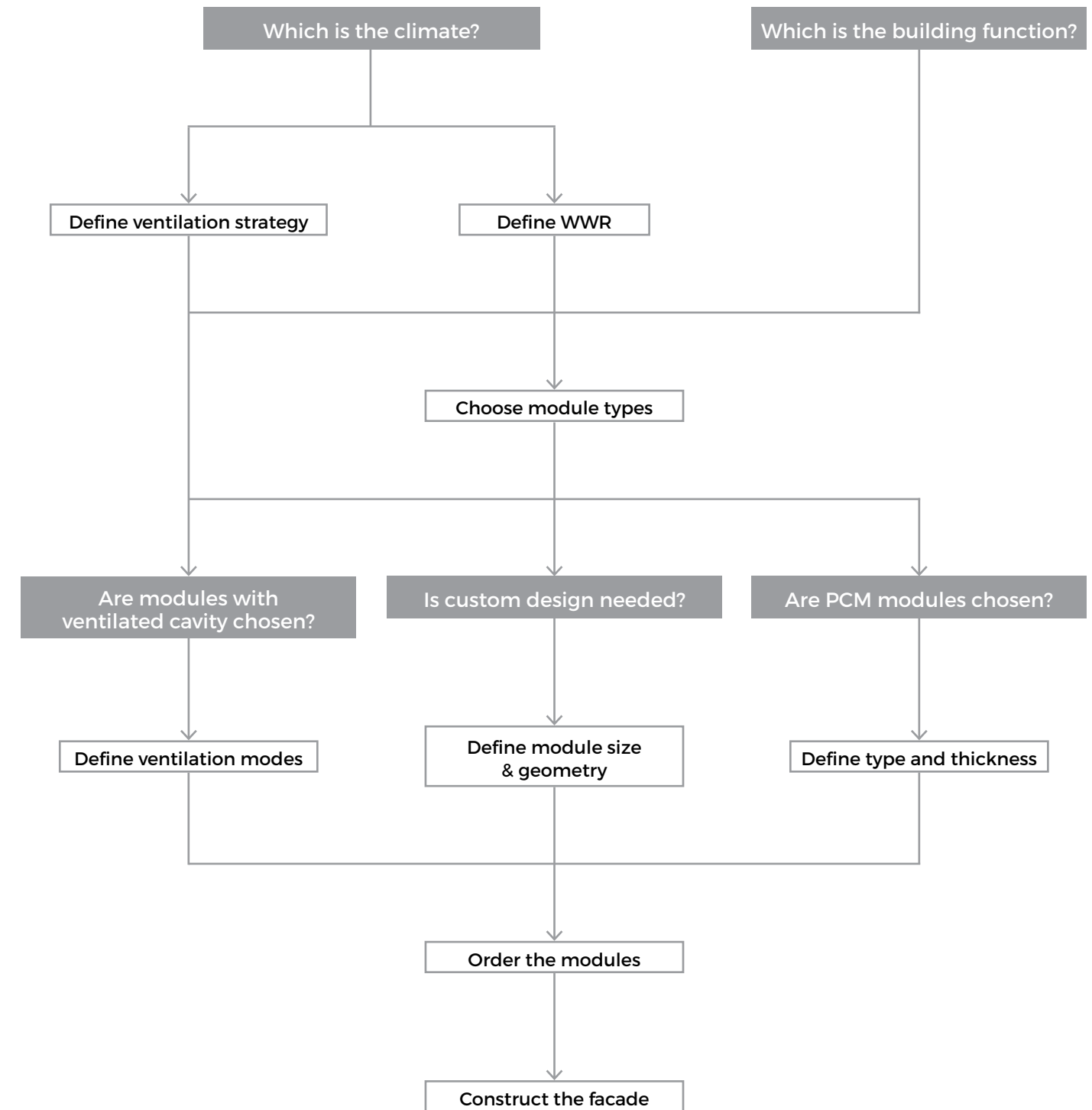


Figure 74: Step-by-step choices for the construction of a facade with the Multi-functional Facade Module

IV. Sustainability Review

According to the simulation results, it can be concluded that the proposed design of the Multi-functional Facade Module is rather successful offering considerable energy savings. However, the improved thermal performance and comfort and the money savings on utility bills are not alone enough for the proposed facade system to be considered sustainable. Other factors like the type and quantity of materials, their cost and the lifecycle of the components, including the raw material production, the fabrication processes, the phase of use and their disposal should be taken into account as well.

Long-term performance of building materials as estimated for the length of a service lifetime is usually considered as one of the key building component characteristics. This is because aging-based deterioration of performance characteristics may influence thermal performance of a building envelope. However, except for the lifespan of the materials themselves, the life expectancies of building envelope components depend also on used material configuration, on the installation quality, the maintenance level, climatic conditions, and the intensity of use. The useful life of a building component is dependent on its context and should always be related to the particular combination of environmental factors to which it is subjected. In the Netherlands, office buildings have an average life of 40 years and therefore the nominal life span for the building envelope materials has to be at least as long as this expected service time. For the materials that have an even longer life span, the aspect of reuse is also important because of the embodied energy that is within the production, manufacture, transportation and construction

of the new material. Except for that, the reuse also discourages the production of new products and reduces the raw material extraction, which contributes to the minimization of the negative impacts of embodied energy. In case the reuse is not an option, recyclable recovered resources should be redirected back to the manufacturing process, but in any case materials should not end up in landfills and incinerators.

Windows play a major role in controlling solar heat gains and controlling a building's energy usage. The proposed design offers two different choices of windows, one with integrated blinds and one incorporating smart glazing, namely electrochromic. Glass itself is environmentally friendly in production terms and recyclability, since it is manufactured from silica which is one of the most abundant elements on earth. For the glazing unit with integrated blinds, the glass panes can be recycled or reused, whereas the integrated blinds are also recyclable and especially metal blinds, which is the type used for this research project, are the easiest type to recycle. More specifically the slats are made from aluminium, which is among the most recyclable materials.

However, the management of the laminated glass waste is a concern because the contamination (laminated and wired glazing) is considered as one of the main drawbacks preventing the recycling of architectural glazing (Papaefthimiou et al., 2009). Nevertheless, since its application in the building sector becomes more frequent, the disposal of wasted laminated glass gradually draws public attention. Scraps of the interlayers of laminated glass, which are usually PVB or EVA film could be recycled and disposed for various applications, whereas glass powder is also turned into usable

products. In the case of electrochromic glazing, it should be tested whether further development of the existing stabilization processes for the crushed glass shall be required, due to the raw materials incorporated in the thin film layers of an EC device (Papaefthimiou et al., 2009). It is apparent that EC windows disposal is a crucial issue, which should be further investigated especially in the case of their market expansion.

Smart windows offer a more precise system to prevent solar heat gains by avoiding the look of conventional blinds and providing blind-free views. It should be mentioned though that the electrochromic glazing has a higher initial cost compared to conventional windows, however, the feature of invisible improvement of building energy performance makes electrochromic technology particularly attractive for building preservation. This visual contact between indoors and outdoors has advantageous effects on the well-being and working efficiency and consequently can result in enhanced indoor comfort. At its bleached state the electrochromic window gives comparatively small need for artificial lighting but is disadvantageous with regard to cooling energy, while at its colored state it shows opposite results. Moreover, extensive testing on durability (EControl System Description 2010, p. 2) unveiled life-cycles of up to 105 switching procedures, which resemble 30 years within the temperature range of -30 to 600°C. However, according to Papaefthimiou et al. a lifetime of 20 years is more realistic and it is necessary to be extended in the future in order to compensate not only for the considerably higher initial costs but also for the higher energy required for its production compared to simple glazing systems. Taking into account that the average life of an office building in the Netherlands is

40 years as already mentioned, this aspect is disadvantageous because the electrochromic modules would need to be renewed. In addition, the weight of the electrochromic glazing is estimated to be 32kg/m², which is comparable to existing windows and therefore the existing facade systems prove to be structurally adequate. On the other hand, this technology is still developing, so there are still improvements to be made in research for architectural applications and as previously mentioned, there is an issue with cost, however, technology prices tend to fall as demand and availability increase, which means that in the future it may be more affordable.

One of the most significant contributors to a building's energy efficiency is the building's ability to control the heat transfer between the interior space and external environment. For the proposed facade system PCM is used in order to store heat energy in a latent form which is an innovative solution to reduce the building's energy consumption whilst maintaining an equivalent high thermal mass and providing a big potential for temperature control of the indoor space. Important factors for the successful application of PCMs in building envelopes are the evaluation of its stability and the potential of failure over a long period of application. The available service life data for building envelopes containing PCM are unfortunately limited and they also contain many limitations and contradictions due to the fact that a building's lifespan varies according to the country applied as already mentioned (Kosny, 2015). Long-term performance deterioration processes of PCMs are well investigated and widely acknowledged today, however, they have not been incorporated yet into numerical performance predictions of building envelope components, which is an aspect

to be researched in the future (Kosny, 2015). In addition, there is an issue with cost and the amount of material used, since the PCM layers in the proposed design are fairly thick because they are put in the outside. It should be mentioned that the placement of the PCM layer in the inside would give considerable material savings, estimated up to 30%. Another concern is PCMs high flammability (McLaggan et al., 2017) and apart from that paraffins evaporate creating highly toxic benzene and toluene when burnt, which are both known carcinogens.

The module with the translucent PCM consists also of a layer of aerogel to provide high thermal resistance while maintaining the desired translucent effect. Aerogel is one of the best insulators ever known, while being also breathable and fireproof. In general aerogels are pretty fragile, however by tailoring the production process, many of the properties like bulk density, thermal conductivity, transparency, color, mechanical strength, and susceptibility to water can be adjusted. Thus, aerogel can achieve an extreme low density being amazingly strong at the same time, which means that it offers maximal thermal protection with minimal weight and thickness. However, its production requires an extraordinary amount of time and money and this is the reason why it is not so widely applied. On the other hand, it is very durable and withstands mechanical abuse, while providing safe installations with sustained long term performance. In addition, aerogel is recyclable, since it is a silica-based substance and it is not known to be carcinogenic or toxic. Some aerogel particles can even be reused and are generally harmless to the environment even if released.

As far as the insulation material of the opaque PCM module is concerned, Vacuum Insulation Panels (VIPs) are used instead of conventional insulating materials. This new advanced form of insulating panels provide between 5 and 7 times the insulation capacity compared to conventional ones, with the added advantage that it does not require a modification of its thickness nor a reduction in the useful volume of the transport unit or storage element (Elhuyar, 2005). The better insulation performance with extremely reduced thickness is undeniably the biggest advantage offering substantial material savings. Apart from that, VIPs show a large potential to reduce the CO2 footprints of buildings (Alam et al., 2011). However, the application of VIPs is presently limited due to their susceptibility to damage during installation and development, uncertain useful life time, thermal bridging and high cost (Alam et al., 2011).

As far as the composition of the VIPs is concerned, the substances of greatest relevance are the filler materials used in the core of the panels with silicas being the most frequently used ones, while aluminium oxides, iron oxides and calcium oxides are less common. From a recycling perspective, VIPs are complex products as they have a multilayer film that is sealed to conserve the vacuum and a monomaterial block or panel (Elhuyar, 2005). As a number of the microporous filler materials used to manufacture vacuum insulated panels are essentially respirable dust, measures have to be taken to minimize the dust emissions from plants that treat VIPs. They can be handled in a sustainable way only in enclosed plants that not only capture all of the VHC blowing agents, but also retain the potentially harmful fine particulates so that these materials can be disposed of in a safe and proper way.

One of the biggest contributors to climate change is also energy production. Modern solar technologies harness solar energy to generate electrical power like the Building Integrated Photovoltaics (BIPVs), which are incorporated in two of the system's modules. The value of Building Integrated Photovoltaics in façade applications lies in the fact that these systems entirely replace façade-cladding systems that do not have the added benefit of generating power. On the other hand, BIPV have high initial investment capital costs, however, there are significant long-term benefits to be achieved for clients, end users and the entire society (Yang and Zou, 2016). In the case of the BIPV/T module, an improvement on the system efficiency is achieved due to the cooling effect of the air flowing through the air cavity incorporated behind the PV panels, hence obtaining a higher yield with lowering the panel temperature.

The type of cells used is monocrystalline with 22% of efficiency, which are produced by pouring hot, liquid silicon into molds that are manufactured according to the very complicated Czochralski process. From a recycling perspective, laminated glass can be recycled and disposed for various applications as already mentioned. Silicon based PV modules consist of approximately 80% of glass and therefore the flat glass recycling industry is able to treat this product in their current recycling line. Output fractions of this process are ferrous and non-ferrous metals, glass, silicon and plastics. The glass resulting from PV modules is mixed with standard glass cullet, and partially reintroduced in glass fiber or insulation products and partly in glass packaging products. The metals, silicon and plastics can be used for the production of new raw materials.

Assessing all the above mentioned factors about the life cycle of all different materials used for the proposed design, it can be concluded that the Multi-functional Facade Module is fairly sustainable as a system. Its biggest disadvantage is the high initial cost of many of the materials, however, taking into consideration the extremely high improvement of the energy performance that the simulations showed compared to the reference project, the MFM system is undoubtedly advantageous in the long-run providing a fair payback. In addition, the high initial costs can be justified for the present time since the system proposed is adaptive and most of the materials used are not conventional and still not widely applied. They are still being researched, however, in the future it is expected that the increase of their availability, application and demand will make them more affordable. Furthermore, another advantage of the facade system, which contributes to the overall sustainability aspect is that all the chosen materials of the Multi-functional Facade Module are not hazardous and do not pose any contamination risk to the building occupants. In addition, they are recyclable, which helps prevent the waste of potentially useful materials and reduces the potential consumption of fresh virgin materials. Apart from that, recycling lessens energy usage, reduces air pollution and the need for conventional waste disposal, while contributing to waste reduction. Last but not least, since the system is modular, it gives the opportunity to easily replace any module with another one in the future, an aspect which makes it extremely flexible. This way, either new technological improvements can be incorporated and upgrade an existing facade providing even better energy performance or the need for changing use of spaces can be achieved.

V. Future developments

The designed solution was proved to be rather successful, however further development can be made to improve certain features.

First of all, concerning the PCM module, an appropriate shading strategy should be considered, since these materials have a specific maximum operative temperature. For this reason, it is preferable to be protected by the sun during summer, in order to not exceed the maximum operative temperature. One solution could be to apply a coating to the glass that the PCM is enclosed to, however the most appropriate solution in order to be fully adaptable will be to choose electrochromic glazing. This aspect was not taken into account for this research project because it was tested in the Netherlands, where the solar irradiation is not very high. Consequently, extremely high temperatures cannot be reached in the facade and for this reason the use of shading in order to protect the PCM from excessive heat exposure is not needed.

Furthermore, an important aspect to be considered is the structural part, in order to achieve a higher level of the drawings detailing and ensure the ultimate safety of the system. This aspect was not studied in the framework of this research project because focus was put on the performance. Besides, a unitized system is used, which is rather standard and the size of units is small. However, calculations need to be made with the use of FEM analysis software, for instance, in order to obtain accurate results.

In addition, more simulations could be conducted with various glazing percentages and of course including the two modules that were not simulated

in this research project with the aim of creating a design tool box for architects, designers and engineers. This would be exemplary offering the possibility to check the respective performances of hundreds of different combinations in different climates quicker without the need of conducting the simulations every time. This database could be continuously updated according to new material developments and innovations added to the Multi-functional Facade Module.

Another future step, in order to further research the applicability of this concept, would be to test it for other parts of Europe. For this reason, simulations will need to be performed for reference cases in other countries. Under the condition that this step proves the efficiency of the Multi-functional Facade Module as well, a model could be converted in the future to a full scale building model for simulation.

In addition, a suitable design of an automated management system needs to be developed because the adaptation of the MFM has to happen continuously, driven by suitable control strategies. In this way, it will be possible to fully exploit the potential of the Multi-functional Facade Module.

Meanwhile, as these procedures take time in reality, material research, experiments and product development would be extremely useful to be executed, in order to progress in the field of the integrated materials and the chosen layers.

VI. Reflection

i. Graduation process

The graduation project started with the existing research project “Future Adaptive Facades and Components” with the question from “Rollecate” Facade Construction Company about the direction the facade industry is heading to. According to the Sustainable Design Graduation Studio, every research project has to fit within two of the four tracks of the Master Building Technology: Façade, Structural, Climate and Computational design. The chosen tracks for this graduation project were Facade and Climate design. In terms of Facade Design, the graduation project delivers a detailed facade system, which can be applied to new buildings or retrofitting projects. In terms of Climate design, the focus lays on sustainability, since the aim of the proposed facade system is to improve energy efficiency of office buildings while providing thermal comfort to the users.

For the current research project an innovative adaptive facade system for offices was developed, which delivers different functions at the same time and can be applied in different climate conditions. This Multi-functional Facade Module (MFM) consists of different units, being multi-functional as a whole, an aspect which is achieved by making a selection of modules to be used according to each project and its context. In addition, the proposed design is modular, which gives the possibility to be altered easily throughout its lifecycle, thus being also adaptive to future innovations. In order to evaluate it, this facade system is tested for an office building in Amsterdam, Netherlands with the main objective of providing thermal comfort to the occupants, whilst minimizing the energy

consumption.

The method used in order to define the type of units proposed and their materials was to research the existing adaptive methods applied in the construction industry and define the state-of-the-art. It needs to be emphasized that the chosen reference projects are representative and focus was put on variety in order to show the different potentials that adaptive facades have. In terms of specific time restrictions when the classification was made, it may be possible that examples of the same value were excluded. Through this research, knowledge was gained on the systems used, their functions and materialisation. Consequently, the future trends were defined in the near and far future according to their current level of development and application extent.

All decisions for the design of the façade system were based on the results of this research. In addition, the decision-making process was facilitated by evaluating the most relevant case studies and the conclusions they reached from simulations or if already demonstrated and tested. The products and projects that were studied led to the definition of the design principles that needed to be followed and also to the selection of materials and their position in the modules. This method appeared to be efficient because the whole scope of adaptive innovative systems were taken into consideration, both ready products already in the market as well as research projects with future potential. Nevertheless, it is important to be mentioned that not all case studies mention extensively how exactly they work or the exact materials used and thus it is possible that parameters and materials of similar importance and efficiency as of the ones chosen, were not considered. The selection was based not

only on the conclusions of these research projects but also taking into consideration the feasibility of their application in the near future as defined together with “Rollecate”.

As far as the testing is concerned, both hand calculations and simulations were conducted. The hand calculations preceded the simulations for three reasons; first to ensure that the specifications of each module reach the official requirements in terms of thermal insulation quality level for office buildings in the Netherlands, second to have an indication which modules are more effective in terms of providing the thermal comfort and third to have a first evaluation of the modules performance, ensuring that the approach is logical. Then the simulations would give more accurate results of the overall performance since there are materials tested, which behavior is very difficult to calculate by hand. Nevertheless, even in the simulations some simplifications are involved, since these materials are adaptive and thus almost impossible to be simulated by a software as they would act in reality. The composition of the chosen units materials were all possible to be made with a small difference just for one of them, which is considered negligible to be able to influence the results. However, the only aspect which was not included to the simulations was the heat provided by the natural ventilation modes because of software restrictions and thus calculated by hand and added later to the results. If simulated, the results would be more accurate although the current calculations are considered to give a good approximation.

The results obtained were beneficial and showed a much better energy performance in comparison to that of a typical office construction, which were also the desired results. In addition, the logic

of the design with modules delivering different functions and performing better as a whole was validated to be working since the more modules were combined and simulated, the better results of energy performance and comfort were achieved.

ii. Societal impact

Nowadays, most offices facades are a typical, usually fully-glazed curtain wall, a quite standardized solution which leads to the creation of similar buildings although constructed in different countries with different climates. The proposed Multi-functional Facade Module (MFM) offers an adaptive solution for this standardized practice lowering the energy consumption, improving the indoor environment and offering more aesthetical variety. An additional advantage is that the facade system is not only applied for new projects but could also be used for retrofitting with the use of an additional substructure, leading to substantial improvements of the building's performance. Nevertheless, it should be mentioned that a higher level of complexity is involved in comparison to a widely used common curtain wall system, not in terms of the facade type used but of the materials and layers applied.

It is certain that the proposed project is applicable in practice for two main reasons; first there are quite a few similar projects currently under development as presented in the research framework of this report, which have reached positive conclusions, promising great potential in terms of energy performance and second the results of this research project also prove that MFMs are performing well offering considerable energy savings. Besides, the proposed design is incorporated in a unitized facade system, which is already widely applied.

Furthermore, this design leads to a much better and more efficient management of the indoor environment, since less energy is required in order to reach the official standards and requirements, which is undeniably a big advantage especially concerning the 2020 zero-energy buildings regulations.

Except for the climate considerations, in terms of technical benefits, the proposed system is modular, an aspect which offers several advantages. First of all, the units of the facade system are demountable offering flexibility in component reuse. Moreover, they are transportable by truck, since they are small in size and relatively lightweight. In addition, a single element can be easily replaced with another one offering the advantage of upgradeability. This is extremely beneficial because it gives the possibility of improving the facade even more in the future according to new innovations and developments of the system or to the changing wishes of the building's users. In addition, unitized facades are composed out of individual off-site prefabricated elements leading to a fast and economic installation with limited use of resources in manpower and tooling compared to traditional curtain walls. Last but not least, maintenance is also easy to be performed since the system used is unitized.

In conclusion, taking all these factors into consideration, it is obvious that the Multi-functional Facade Module is a promising facade concept for future applications. MFMs offer not only an adaptive but also a sustainable solution to the construction of office buildings ensuring the new EU building regulations are met, which impose that by 2020 all new buildings should reach nearly zero-energy levels.

APPENDIX A

IN COLLABORATION WITH SHIRIN MASOUDI

Classification of adaptive buildings, products and research projects

i. Buildings

- | | |
|--|---|
| 1. Institute du Monte Arabe (1987) | 32. Smartbox Energy Facade (2006) |
| 2. Heliotrope (1994) | 33. Schueco E ² Facade (2007) |
| 3. L'Hemisfèric (1998) | 34. Flare - Kinetic Membrane Facade (2008) |
| 4. Post Tower Bonn (2003) | 35. PixelSkin02 (2008) |
| 5. Fire and Police station (2004) | 36. Adaptive Fritting (GSD) (2009) |
| 6. Ewe Arena, Germany (2005) | 37. SageGlass® (2010) |
| 7. Sliding House (2005) | 38. NEXT Active Facade (2010) |
| 8. CH2 Melbourne City Council House 2 (2006) | 39. Solar Thermal Facade Collectors with Evacuated Tubes (2013) |
| 9. Kiefer Technic Showroom (2007) | 40. Smart Window & Power Window (2014) |
| 10. Capricorn House (2008) | 41. iSolar Blinds (2014) |
| 11. Water Cube (2008) | 42. Iicrivision™ - Liquid Crystal Window (2015) |
| 12. Media-TIC Office Building (2009) | 43. Closed Cavity Facade (2015) |
| 13. POLA Ginza Building Facade (2009) | 44. CONTROLITE® - Intelligent Daylighting System (2016) |
| 14. Q1 - ThyssenKrupp Quarter Essen (2010) | 45. White & Black Liquid Crystal Film (2016) |
| 15. Helio Trace (2010) | 46. Living Wall Facade (2016) |
| 16. Simons Center (2010) | 47. Kindow Blinds (2017) |
| 17. Articulated Cloud (2011) | |
| 18. Torre de Especialidades (2012) | |
| 19. One Ocean (2012) | |
| 20. Al Bahr Towers (2012) | |
| 21. RMIT Design Hub (2012) | |
| 22. Homeostatic Facade System (2013) | |
| 23. BIQ House (2013) | |
| 24. Swiss Tech Convention Center (2014) | |
| 25. SDU Campus Kolding (2014) | |
| 26. Headquarters for Swatch and Omega (2017) | |
| 27. Apple Dubai Mall (2017) | |
| 28. Bund Finance Center (2017) | |

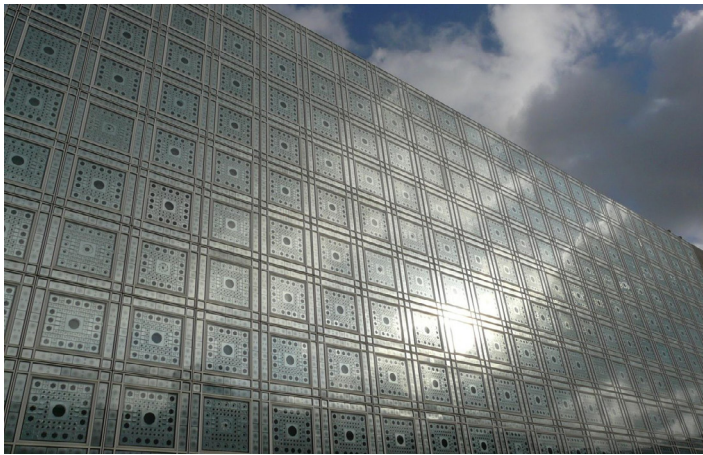
ii. Products

- 29. Polyvalent Wall for Lloyd's of London (1981)
- 30. TEmotion (2005)
- 31. ECONTROL® (2005)

iii. Research Projects

- 48. Living Glass (2005)
- 49. Bionic Breathing Skin (2007)
- 50. ACTRESS (2007)
- 51. Bloom (2011)
- 52. ADAPTIWALL (2012)
- 53. MeeFS (2012)
- 54. ETFE-MFM (2014)
- 55. SABER (2014)
- 56. BRESAER (2015)
- 57. Adaptive Solar Facade (2015)
- 58. Breathing Skins (2015)
- 59. SELFIE (2016)
- 60. Allwater Panel (2017)
- 61. Polyarch (2017)

BUILDINGS



Institut du Monde Arabe

Jean Nouvel, Architecture-Studio, Pierre Soria and Gilbert Lezenes

Paris, France

1987

Response to Adaptation Agent

☒ Dynamic ☐ Static

The south facade of The Institut du Monde Arabe is composed by advanced responsive metallic brise soleil that have been inspired by the mashrabiya, an archetypal element of Arabic architecture. The system has been used for centuries in the Middle East to protect the indoor environment from the sun radiation and to provide privacy. The amount of light that enters into the building is regulated by light sensitive diaphragms that shifting geometric pattern, regulate the dimension of transparency and opaque surface. The panels are composed by squares, circles and octagonal shapes that vary in their dimension and change configuration in a fluid motion.

Exterior Agent of Adaptation

- ☒ Solar radiation
- ☐ Temperature
- ☐ Humidity
- ☐ Wind
- ☐ Precipitation
- ☐ Noise

Interior Agent of Adaptation

- ☐ Temperature
- ☐ Humidity
- ☐ Light
- ☐ Air exchange rate
- ☐ Sound level

Purpose

- ☒ Thermal comfort
- ☐ IAQ
- ☒ Visual and Lighting
- ☐ Acoustic
- ☐ Energy production

Control of Adaptivity

- ☒ Closed loop
- ☐ Open loop

Energy

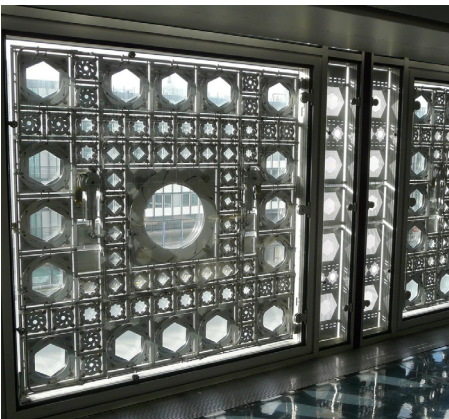
☒ - ☐ 0 ☐ +

Highest cost

- ☐ Materials
- ☒ Production
- ☒ Assembly
- ☐ Maintenance

Architecture design freedom

- ☒ Low
- ☐ Medium
- ☐ High



Sources: <https://www.archdaily.com/162101/ad-classics-institut-du-monde-arabe-jean-nouvel>



Heliotrope

Ralph Disch

Freiburg, Germany

1994

Response to Adaptation Agent

☒ Dynamic ☐ Static

Heliotrope is one of the first zero-energy houses in the world. It is mounted on a pole that allows it to rotate of 180 degrees during the day, taking advantage of the sun radiation, increasing the amount of daylight into the indoor space and assuring heat gain thanks to the solar thermal pipes on the facade. The PV panels and the solar thermal tubing provide both electricity and heating, transforming the project in a perfect example of sustainability.

Exterior Agent of Adaptation

- ☒ Solar radiation
- ☒ Temperature
- ☐ Humidity
- ☐ Wind
- ☒ Precipitation
- ☐ Noise

Interior Agent of Adaptation

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Control of Adaptivity

- ☒ Closed loop
- ☐ Open loop

Energy

☐ - ☐ 0 ☒ +

Highest cost

- ☐ Materials
- ☐ Production
- ☐ Assembly
- ☒ Maintenance

Architecture design freedom

- ☒ Low
- ☐ Medium
- ☐ High



Sources: <https://inhabitat.com/heliotrope-the-worlds-first-energy-positive-solar-home/>



L'Hemisfèric

Santiago Calatrava

Valencia, Spain

1998

Response to Adaptation Agent

☒ Dynamic ☐ Static

The building is composed by an IMAX theatre, a planetarium and a laserium. The design reminds to a human eye with the pupil, that hosts the planetarium, and the eyelid. The latter is the dynamic component of the building and it can open and close thanks to hydraulic lifts that move the shutters. The result is similar to an eye that coloses and opens. These are made out of steel and glass that provide daylight in the building and work as a glasshouse.

Exterior Agent of Adaptation

- ☒ Solar radiation
- ☒ Temperature
- ☐ Humidity
- ☐ Wind
- ☐ Precipitation
- ☐ Noise

Interior Agent of Adaptation

- ☒ Temperature
- ☐ Humidity
- ☒ Light
- ☒ Air exchange rate
- ☐ Sound level

Purpose

- ☒ Thermal comfort
- ☒ IAQ
- ☒ Visual and Lighting
- ☐ Acoustic
- ☐ Energy production

Control of Adaptivity

- ☒ Closed loop
- ☐ Open loop

Energy

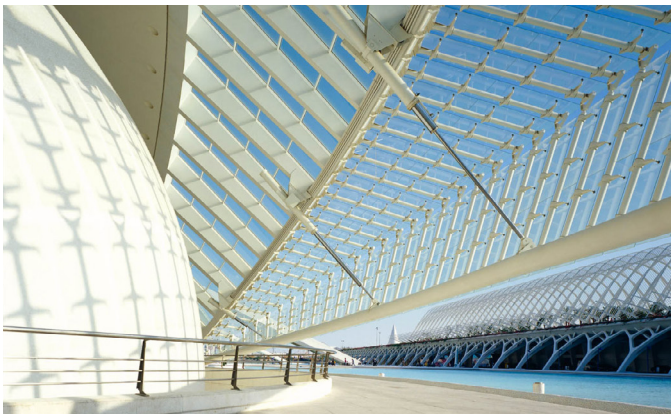
☒ - ☐ 0 ☐ +

Highest cost

- ☐ Materials
- ☐ Production
- ☐ Assembly
- ☒ Maintenance

Architecture design freedom

- ☒ Low
- ☐ Medium
- ☐ High



Sources: <http://www.idesignarch.com/lhemisferic-an-eye-catching-architectural-masterpiece-in-valencia/>



Post Tower Bonn

Helmut Jahn Architects

Bonn, Germany

2003

Response to Adaptation Agent

☐ Dynamic ☒ Static

Post Tower Bonn has a twin-shell facade with the outer shell being completely out of glass. The sytem used is a unitised curtain wall with custom designed exterior layer. The double-glazed facade compensates for heat gain, providing ventilation without a central mechanical system. The shades and operable windows facilitate climate control, while daylight sensors automatically adjust office light levels reducing energy costs. Post Tower offers to its occupants enormous control over their environments, being able to adjust both the shading system sandwiched between the two-layered curtain wall and the operable windows. The aim of the design is to integrate as essential component the idea that the skin of the building modulates its own climate and therefore decentralised installation units are located on the floor slab directly behind the facade layer.

Exterior Agent of Adaptation

- ☒ Solar radiation
- ☐ Temperature
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- ☒ Closed loop
- ☐ Open loop

Energy

☐ - ☒ 0 ☐ +

Highest cost

- ☐ Materials
- ☐ Production
- ☐ Assembly
- ☒ Maintenance

Architecture design freedom

- ☐ Low
- ☒ Medium
- ☐ High



Sources: http://www.archlighting.com/projects/a-facade-for-the-future_o
<https://www.archdaily.com/231521/flashback-post-tower-murphyjahn>



Fire and Police Station

Sauerbruch Hutton

Berlin, Germany

2004

Response to Adaptation Agent

☒ Dynamic ☐ Static

The Fire and Police Station in Berlin is an extension to a now free-standing 19th-century structure and its facade is built up from large-scale, red and green glass shingles. When closed, the glass shingles are slightly tilted, which causes the creation of sky reflections on the building volume. The ones that are placed in front of windows can be opened individually in order to provide sunshading and protect from glare. These movable glass louvres create variations of colors according to whether they are open or closed. The aim of the design was to decrease the reliance on mechanical systems and allow the building and its users to interact with the exterior environment by maximising natural ventilation and daylighting.

Exterior Agent of Adaptation

- ☒ Solar radiation
- ☐ Temperature
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- ☐ Energy production

Control of Adaptivity

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- ☐ Open loop

Energy

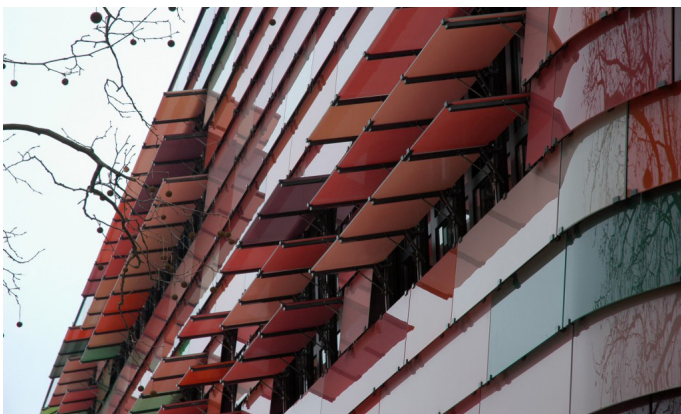
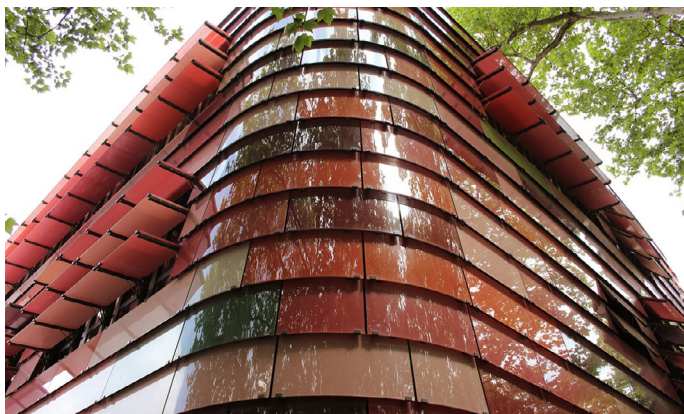
☐ - ☒ 0 ☐ +

Highest cost

- ☐ Materials
- ☐ Production
- ☒ Assembly
- ☒ Maintenance

Architecture design freedom

- ☐ Low
- ☒ Medium
- ☐ High



Sources: <http://architectuul.com/architecture/fire-and-police-station>
<http://www.talkitect.com/2008/11/fire-and-police-station-elizabeth-abegg.html>



EWE Arena

asp Architekten Stuttgart

Oldenburg, Germany

2005

Response to Adaptation Agent

☒ Dynamic ☐ Static

The facade of EWE Arena consists of a fully-glazed facade, in front of which a large mobile sunscreen is mounted. This mobile solar shade continuously tracks the sun at half-hour intervals, in 7,5° steps with the aim of generating green power, while reducing the amount of solar insolation and significantly reducing the costs of air conditioning. The approximately 240 m² brise soleil consists of 70 frameless monocrystalline PV modules, which generate 27200kWh of energy per year and can travel 200° around the perimeter of the building.

Exterior Agent of Adaptation

- ☒ Solar radiation
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- ☐ Wind
- ☐ Precipitation
- ☐ Noise

Interior Agent of Adaptation

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Control of Adaptivity

- ☒ Closed loop
- ☐ Open loop

Energy

☐ - ☐ 0 ☒ +

Highest cost

- ☐ Materials
- ☐ Production
- ☐ Assembly
- ☒ Maintenance

Architecture design freedom

- ☐ Low
- ☒ Medium
- ☐ High



Sources: http://www.solarfassade.info/en/project_examples/de/ewe_arena_oldenburg.php
Vogt, M. et al. (2010). MOVE: Architecture in Motion - Dynamic Components and Elements



Sliding House

dRMM Architects

Suffolk, East Anglia, GB

2005

Response to Adaptation Agent

☒ Dynamic ☐ Static

The Sliding House has a part of glass and aluminium construction while the rest is timber-frame with larch timber boarding. It consists of a second, sliding sleeve that envelopes the whole ensemble and therefore can be arranged in many different positions. In summer, the sliding roof shades against the sun while in winter it functions in reversed way, allowing passive solar gains during the day and shielding against heat losses during the night. The movable second-skin consists of a steel frame construction with an insulated and moisture-proofed timber infill. Railway tracks assist the sliding movement which is powered by four electric motors.

Exterior Agent of Adaptation

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- ☐ Temperature
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- ☐ Wind
- ☐ Precipitation
- ☐ Noise

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- ☒ Visual and Lighting
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- ☐ Energy production

Control of Adaptivity

- ☒ Closed loop
- ☐ Open loop

Energy

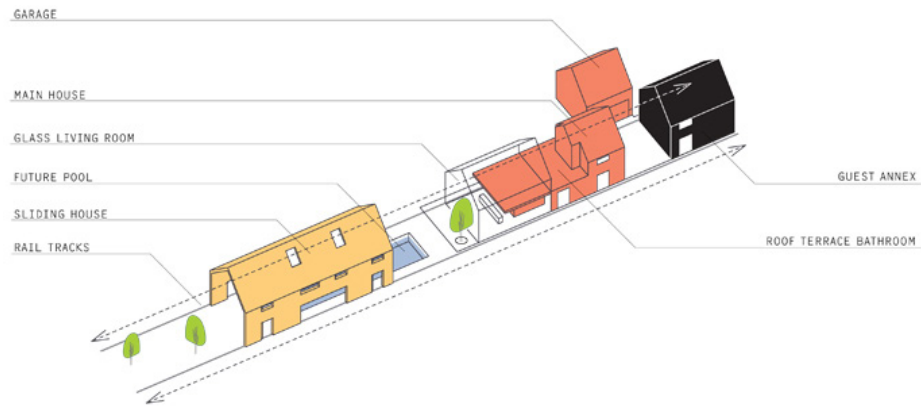
☒ - ☐ 0 ☐ +

Highest cost

- ☐ Materials
- ☐ Production
- ☐ Assembly
- ☒ Maintenance

Architecture design freedom

- ☐ Low
- ☒ Medium
- ☐ High



Sources: <https://www.dezeen.com/2009/01/19/sliding-house-by-drm-2/>
Vogt, M. et al. (2010). MOVE: Architecture in Motion - Dynamic Components and Elements



CH2 Melbourne City Council House 2

DesignInc

Melbourne VIC, Australia

2006

Response to Adaptation Agent

☒ Dynamic ☐ Static

The building is a high example of sustainability. it responds to sun and wind to optimize natural light and ventilation. Among the sustainable techniques applied in the design, just the adaptive facade strategies are considered. In particular, the western facade is protected by the sun thanks to a shading system made of recycled timber screens. Moreover, the daylight is integrated by tapered ventilaton ducts. Because of the orientation of the facade, the shading system rotates horizontally according to the position of the sun. The view is never completely obstructed because the panels do not close completely.

Exterior Agent of Adaptation

- ☒ Solar radiation
- ☐ Temperature
- ☐ Humidity
- ☐ Wind
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Control of Adaptivity

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- ☐ Open loop

Energy

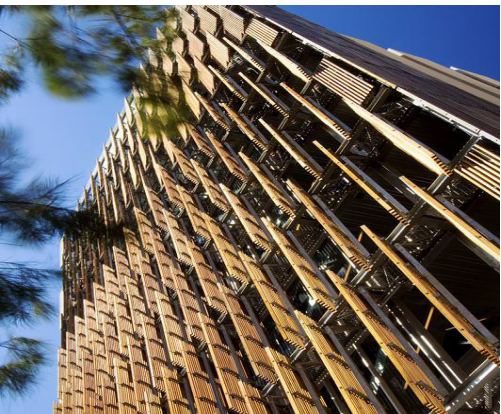
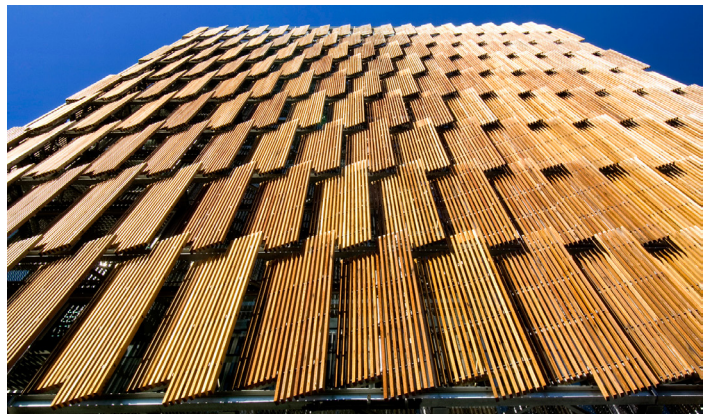
☒ - ☐ 0 ☐ +

Highest cost

- ☐ Materials
- ☐ Production
- ☐ Assembly
- ☒ Maintenance

Architecture design freedom

- ☐ Low
- ☒ Medium
- ☐ High



Sources: <https://www.designinc.com.au/portfolio/commercial-workplace/ch2-melbourne-city-council-house-2>



Kiefer Technic Showroom

Ernst Giselsbrecht and Partner

Bad Gleichenberg, Austria

2007

Response to Adaptation Agent

☒ Dynamic ☐ Static

The facade of Kiefer Technic Showroom consists of sun screen electronic shutters of preformed aluminum. These can be regulated automatically to optimize the indoor climate, or they can be personalized by the users according to their preferences. The facade changes during the day according to the sun location that determines the position of the shading system. Therefore, the building can change from a completely closed configuration, to an open transparent glazing facade.

Exterior Agent of Adaptation

- ☒ Solar radiation
- ☐ Temperature
- ☐ Humidity
- ☐ Wind
- ☐ Precipitation
- ☐ Noise

Interior Agent of Adaptation

- ☐ Temperature
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- ☐ Sound level

Purpose

- ☒ Thermal comfort
- ☐ IAQ
- ☒ Visual and Lighting
- ☐ Acoustic
- ☐ Energy production

Control of Adaptivity

- ☒ Closed loop
- ☐ Open loop

Energy

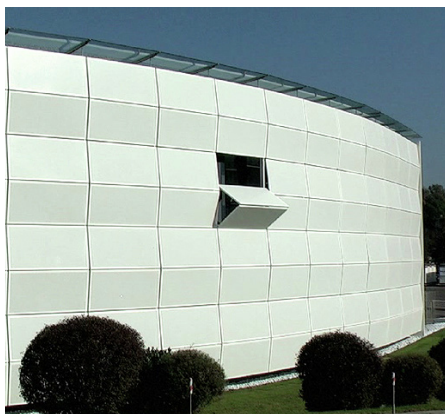
☒ - ☐ 0 ☐ +

Highest cost

- ☐ Materials
- ☐ Production
- ☐ Assembly
- ☒ Maintenance

Architecture design freedom

- ☐ Low
- ☒ Medium
- ☐ High



Sources: <https://www.archdaily.com/89270/kiefer-technic-showroom-ernst-giselbrecht-partner>



Capricorn Haus

Gatermann + Schossig

Dusseldorf, Germany

2008

Response to Adaptation Agent

☐ Dynamic ☒ Static

Capricorn Haus is built up from a multi-functional facade module which incorporates all the technology and equipment to regulate the indoor climate through a specially designed closed panel containing a decentralised service module. This unit provides heating, cooling, ventilation and heat exchange and requires an external power source and cold and hot water supply. The system can be controlled by each user individually. The façade is based on a unitised curtain wall system and each unit has a floor-high glazed part in form of a boxed window. Venetian blinds are used for sun-shading in the cavity of the boxed windows, while a light shelf is also used for light direction.

Exterior Agent of Adaptation

- ☒ Solar radiation
- ☐ Temperature
- ☐ Humidity
- ☐ Wind
- ☐ Precipitation
- ☐ Noise

Interior Agent of Adaptation

- ☐ Temperature
- ☐ Humidity
- ☐ Light
- ☒ Air exchange rate
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Purpose

- ☒ Thermal comfort
- ☒ IAQ
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Control of Adaptivity

- ☒ Closed loop
- ☐ Open loop

Energy

☒ - ☐ 0 ☐ +

Highest cost

- ☐ Materials
- ☒ Production
- ☐ Assembly
- ☐ Maintenance

Architecture design freedom

- ☐ Low
- ☒ Medium
- ☐ High



Sources: https://www.schneiderelectric.es/documents/buildings/capricorn_haus.pdf
http://www.gatermann-schossig.de/pages/de/alle_projekte/office/30.capricornhaus_duesseldorf.htm



National Aquatics Center / Water Cube

PTW Architects, Arup

Beijing, China

2008

Response to Adaptation Agent

☐ Dynamic ☒ Static

The organic form of the “Water Cube” is inspired by the natural formation of soap bubbles. On the one hand, it is a very simple regular building form with highly repetitive geometry but on the other hand the facade has a very unique complex geometry which appears random and organic. The facade consists of translucent ETFE (ethylene tetrafluoroethylene) bubble cladding, which allows high levels of natural daylight to into the building. The project has managed to achieve a reduction of in total 30% energy consumption, savings of 55% lighting energy and a capture of 20% solar energy, which is used for heating the interior space and the swimming pools.

Exterior Agent of Adaptation

- ☒ Solar radiation
☐ Temperature
☐ Humidity
☐ Wind
☒ Precipitation
☐ Noise

Interior Agent of Adaptation

- ☐ Temperature
☐ Humidity
☐ Light
☐ Air exchange rate
☐ Sound level

Purpose

- ☒ Thermal comfort
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Control of Adaptivity

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Energy

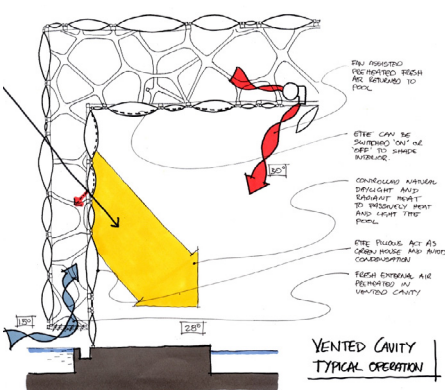
☐ - ☐ 0 ☒ +

Highest cost

- ☐ Materials
☐ Production
☒ Assembly
☐ Maintenance

Architecture design freedom

- ☐ Low
☐ Medium
☒ High



Sources: <https://www.arup.com/projects/chinese-national-aquatics-center>
<https://www.dezeen.com/2008/02/06/watercube-by-chris-bosse/>



Media-TIC Office Building

Enric Ruiz Geli

Barcelona, Spain

2009

Response to Adaptation Agent

☐ Dynamic ☒ Static

This digital technology hub uses distributed sensors to control solar shading by ETFE (ethylene tetrafluoroethylene) cladding. The ETFE cladding surface has two different configurations to match the building's orientation to the sun. The south-west facade filters solar radiation through a screen of vertical cushioned panels filled with nitrogen, which resembles a 'cloud' sunscreen. The south-east facade is arranged in convex and concave triangles, whereby three inflatable chambers within each triangular frame provide both shade and thermal insulation. In total, the Media-TIC technology hub achieves 20% of energy savings by using 2500m² of ETFE cladding.

Exterior Agent of Adaptation

- ☒ Solar radiation
☐ Temperature
☐ Humidity
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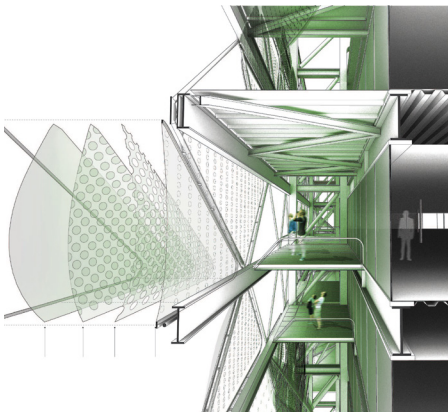
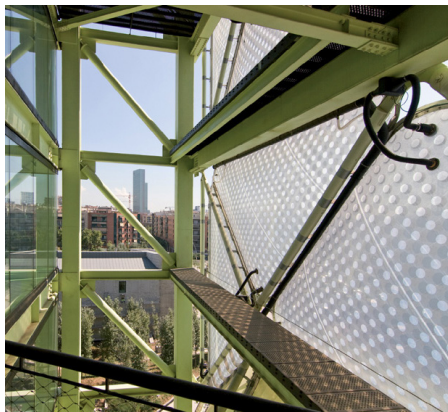
☒ - ☐ 0 ☐ +

Highest cost

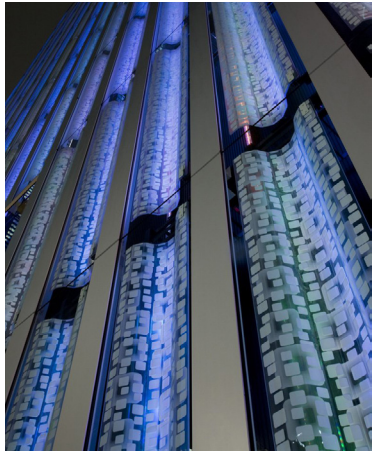
- ☐ Materials
☐ Production
☒ Assembly
☐ Maintenance

Architecture design freedom

- ☐ Low
☐ Medium
☒ High



Sources: <http://www.ruiz-geli.com/projects/built/media-tic>
<https://www.designbuild-network.com/projects/media-tic/>



POLA Ginza Building Facade

Hoberman, Yasuda Atelier and Nikken Sekkei

Ginza District, Tokyo, Japan

2009

Response to Adaptation Agent

☒ Dynamic ☐ Static

The facade of the building is characterized by around 185 shutters positioned between the double skin facade. Each shutter can be individually controlled and has a dimension of one by three meters. The shutters are made of an acrylic sheet that has been formed into a curved surface and provide shading.

Exterior Agent of Adaptation

- ☒ Solar radiation
- ☐ Temperature
- ☐ Humidity
- ☐ Wind
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- ☒ Medium
- ☐ High



Sources: <http://www.hoberman.com/portfolio/pola.php?rev=0&onEnterFrame=%5Btype+Function%5D&myNum=17&category=&projectname=POLA+Ginza+Building+Facade>



Q1 - ThyssenKrupp Quarter Essen

JSWD Architekten, Chaix & Morel et Associés

Essen, Germany

2010

Response to Adaptation Agent

☒ Dynamic ☐ Static

The building has two facade typologies: the first one is applied on two of the elevations and is fully transparent, acting as gigantic windows and the second one is applied on the rest of the building, which is covered by triangular panels made of stainless steel lamellas. The latter ones change orientation by rotating horizontally according to the sun position and, thanks to the lamellas, they redirect the light without blocking the view. When the triangular panels are perpendicular to the facade, the orthogonal view is completely free from obstructions.

Exterior Agent of Adaptation

- ☒ Solar radiation
- ☐ Temperature
- ☐ Humidity
- ☐ Wind
- ☐ Precipitation
- ☐ Noise

Interior Agent of Adaptation

- ☐ Temperature
- ☐ Humidity
- ☐ Light
- ☐ Air exchange rate
- ☐ Sound level

Purpose

- ☒ Thermal comfort
- ☐ IAQ
- ☒ Visual and Lighting
- ☐ Acoustic
- ☐ Energy production

Control of Adaptivity

- ☒ Closed loop
- ☐ Open loop

Energy

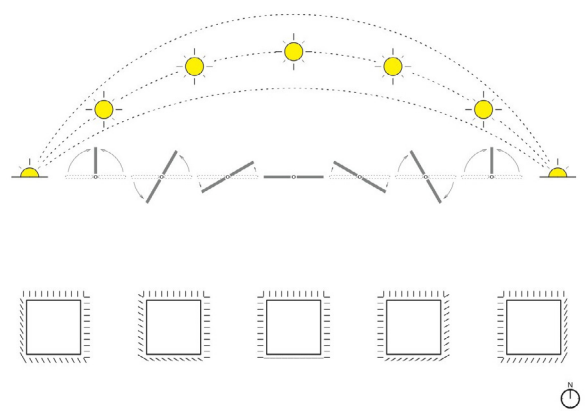
☒ - ☐ 0 ☐ +

Highest cost

- ☐ Materials
- ☐ Production
- ☐ Assembly
- ☒ Maintenance

Architecture design freedom

- ☐ Low
- ☒ Medium
- ☐ High



Sources: <https://www.archdaily.com/326747/q1-thyssenkrupp-quarter-essen-jswd-architekten-chaix-morel-et-associés>



Helio Trace

Skidmore, Owings, Merrill, Permasteelisa Group, Hoberman

Center of Architecture, New York, USA

2010

Response to Adaptation Agent

☒ Dynamic ☐ Static

The shading system is a prototype that responds to the solar radiation, by adjusting its position, regulating glare and amount of daylight. From the thermal point of view, it decreases the solar heat gain by the 81%, decreasing the cooling demand and therefore the energy consumption. During the day, the building gradually transforms from completely transparent to opaque, according to the incident solar radiation.

Exterior Agent of Adaptation

- ☒ Solar radiation
☐ Temperature
☐ Humidity
☐ Wind
☐ Precipitation
☐ Noise

Interior Agent of Adaptation

- ☐ Temperature
☐ Humidity
☐ Light
☐ Air exchange rate
☐ Sound level

Purpose

- ☒ Thermal comfort
☐ IAQ
☒ Visual and Lighting
☐ Acoustic
☐ Energy production

Control of Adaptivity

- ☒ Closed loop
☐ Open loop

Energy

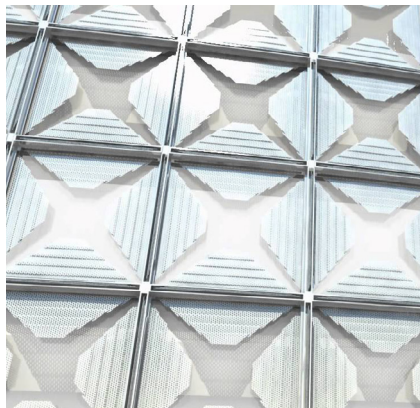
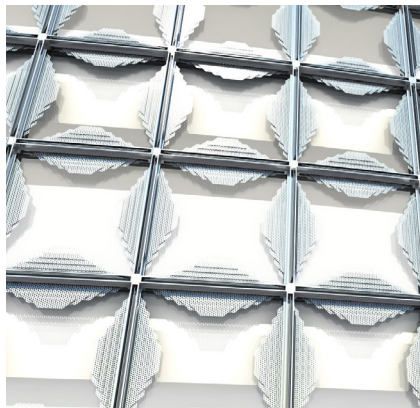
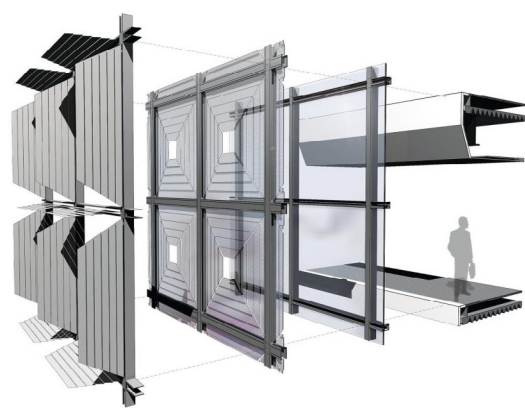
☒ - ☐ 0 ☐ +

Highest cost

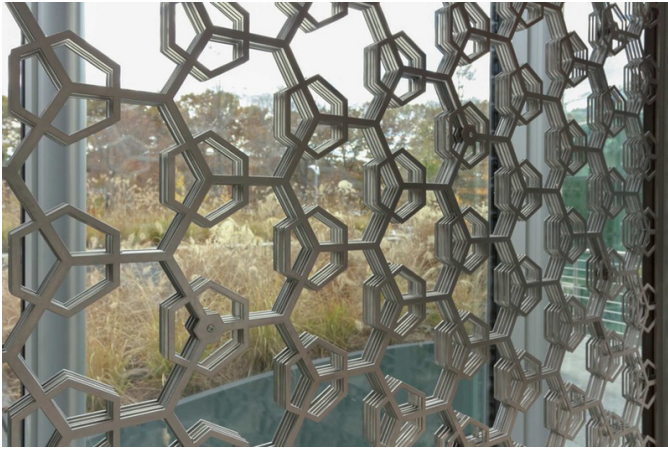
- ☐ Materials
☒ Production
☒ Assembly
☐ Maintenance

Architecture design freedom

- ☐ Low
☒ Medium
☐ High



Sources: <http://www.hoberman.com/portfolio/heliotrace.php?rev=0&onEnterFrame=%5Btype+Function%5D&myNum=11&category=&projectname=HelioTrace>



Simons Center

Hoberman

SUNY Stony Brook, New York, USA

2010

Response to Adaptation Agent

☒ Dynamic ☐ Static

This installation gives three possible artistic pattern for a dynamic shading system. The geometry has been designed in a way that can move creating different patterns according to the amount of transparency required. The system regulates daylight and solar heat gain, decreasing the energy demand needed for cooling.

Exterior Agent of Adaptation

- ☒ Solar radiation
☐ Temperature
☐ Humidity
☐ Wind
☐ Precipitation
☐ Noise

Interior Agent of Adaptation

- ☐ Temperature
☐ Humidity
☐ Light
☐ Air exchange rate
☐ Sound level

Purpose

- ☒ Thermal comfort
☐ IAQ
☒ Visual and Lighting
☐ Acoustic
☐ Energy production

Control of Adaptivity

- ☒ Closed loop
☐ Open loop

Energy

☒ - ☐ 0 ☐ +

Highest cost

- ☒ Materials
☒ Production
☐ Assembly
☐ Maintenance

Architecture design freedom

- ☒ Low
☐ Medium
☐ High



Sources: <http://www.hoberman.com/portfolio/simonscenter.php?rev=0&onEnterFrame=%5Btype+Function%5D&myNum=19&category=&projectname=Simons+Center>



Articulated Cloud

Ned Kahn

Children’s museum of Pittsburgh, Pennsylvania

2011

Response to Adaptation Agent

☒ Dynamic ☐ Static

Articulated Cloud is both a façade and an art installation, composed of thousands of translucent, white plastic squares that move in the wind. Natural conditions, such as shifting light and weather, change the optical qualities of the skin in unique and unpredictable ways. The articulated skin is supported by an aluminum space frame so it appears to float in front of the building. It modulates light reaching the main enclosure behind and produces visual and audio outputs according to the wind and light available.

Exterior Agent of Adaptation

- ☐ Solar radiation
- ☐ Temperature
- ☐ Humidity
- ☒ Wind
- ☐ Precipitation
- ☐ Noise

Interior Agent of Adaptation

- ☐ Temperature
- ☐ Humidity
- ☐ Light
- ☐ Air exchange rate
- ☐ Sound level

Purpose

- ☐ Thermal comfort
- ☐ IAQ
- ☒ Visual and Lighting
- ☐ Acoustic
- ☐ Energy production

Control of Adaptivity

- ☐ Closed loop
- ☒ Open loop

Energy

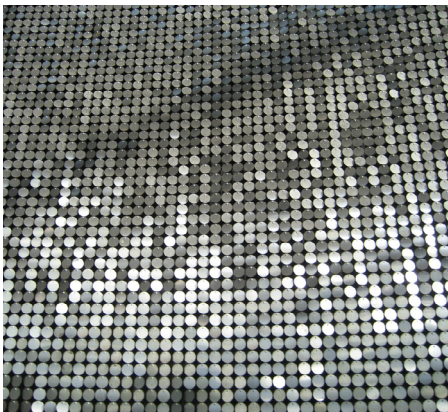
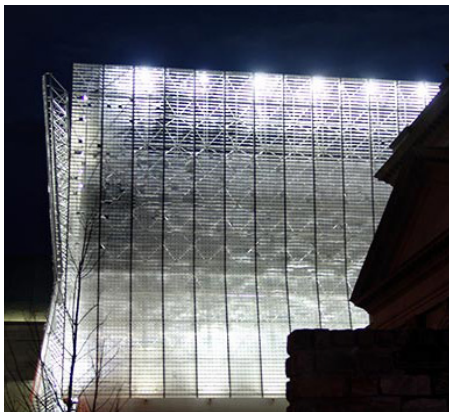
- ☐ - ☒ 0 ☐ +

Highest cost

- ☐ Materials
- ☐ Production
- ☒ Assembly
- ☐ Maintenance

Architecture design freedom

- ☐ Low
- ☒ Medium
- ☐ High



Sources: <http://nedkahn.com/portfolio/articulated-cloud/>
<http://ming3d.com/DAAP/ARCH713fall11/?tag=ned-kahn>



Torre de Especialidades, Hospital Manuel Gea Gonzales

Elegant Embellishments

Mexico City, Mexico

2012

Response to Adaptation Agent

☐ Dynamic ☒ Static

A hive-like double skinned facade is made of decorative architectural module that can effectively reduce air pollution. The facade is made up from Prosolve370e, a new type of ceramic developed by the office Elegant Embellishments. The specialized material is covered with superfine titanium dioxide (TiO2), a technology that neutralizes contamination when in contact with daylight and which is known for its self-cleaning, anti-microbial and de-polluting properties. The design is also important for this effect since it increases the capacity to receive and disperse ultraviolet light. The wind speed through the façade creates turbulence, causing a better distribution of the contaminants across the active surfaces. In addition, the facade skin acts as a natural light filtration system and solar gain blocker for the interior.

Exterior Agent of Adaptation

- ☒ Solar radiation
- ☐ Temperature
- ☐ Humidity
- ☒ Wind
- ☒ Precipitation
- ☐ Noise

Interior Agent of Adaptation

- ☐ Temperature
- ☐ Humidity
- ☐ Light
- ☐ Air exchange rate
- ☐ Sound level

Purpose

- ☐ Thermal comfort
- ☒ IAQ
- ☒ Visual and Lighting
- ☐ Acoustic
- ☐ Energy production

Control of Adaptivity

- ☐ Closed loop
- ☒ Open loop

Energy

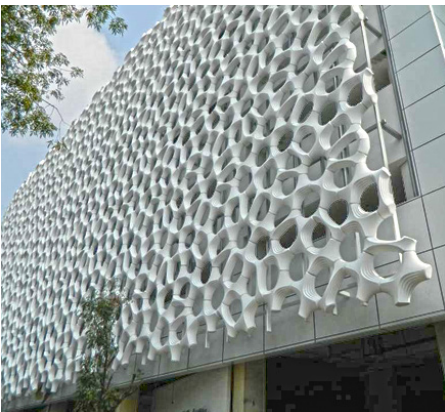
- ☐ - ☒ 0 ☐ +

Highest cost

- ☒ Materials
- ☐ Production
- ☐ Assembly
- ☐ Maintenance

Architecture design freedom

- ☐ Low
- ☐ Medium
- ☒ High



Sources: <https://inhabitat.com/mexico-citys-manuel-gea-gonzalez-hospital-has-an-ornate-double-skin-that-filters-air-pollution/>
<https://www.centreforpublicimpact.org/case-study/mexico-citys-manuel-gea-gonzalez-hospital-facade/>



One Ocean, Thematic Pavilion Expo 2012

Soma ZT GmbH

Yeosu, South Korea

2012

Response to Adaptation Agent

☒ Dynamic ☐ Static

The Thematic Pavilion is fully integrated into its urban context and natural environment and has become an iconic landmark for the area. The kinetic facade consists of glass fiber reinforced polymers (GFRP) creating various animated patterns in order to control the interior light conditions. The effect is achieved by continuous surfaces which twist from vertical to horizontal orientation creating a connection of interior and exterior space. The longer a lamella is, the wider the opening angle can become and the bigger the area affected by light that enters the building. After sunset, the visual effect of the moving lamellas is enhanced by LEDs.

Exterior Agent of Adaptation

- ☒ Solar radiation
☐ Temperature
☐ Humidity
☐ Wind
☐ Precipitation
☐ Noise

Interior Agent of Adaptation

- ☐ Temperature
☐ Humidity
☐ Light
☐ Air exchange rate
☐ Sound level

Purpose

- ☐ Thermal comfort
☐ IAQ
☒ Visual and Lighting
☐ Acoustic
☐ Energy production

Control of Adaptivity

- ☒ Closed loop
☐ Open loop

Energy

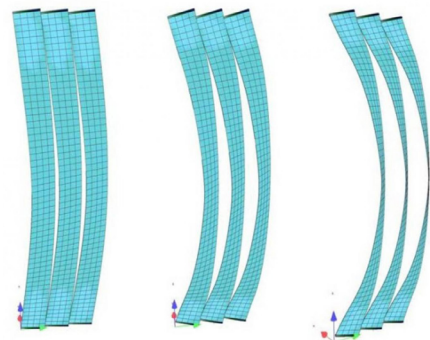
☒ - ☐ 0 ☐ +

Highest cost

- ☐ Materials
☐ Production
☒ Assembly
☒ Maintenance

Architecture design freedom

- ☐ Low
☐ Medium
☒ High



Sources: http://www.soma-architecture.com/index.php?page=theme_pavilion&parent=2
<http://compositesandarchitecture.com/?p=68>



Al Bahr Towers

Aedas Architects

Abu Dhabi, United Arab Emirates

2012

Response to Adaptation Agent

☒ Dynamic ☐ Static

Al Bahr Towers incorporate a “mashrabiya” inspired shading system, which operates as a curtain wall. The facade which is suspended on an independent frame consists of triangles. Each triangle is coated with fiberglass and is programmed to respond to the movement of the sun with the aim to reduce solar gain and glare. The screen was simulated by the computational team of the architectural office to test its response to sun exposure and the changing incidence angles throughout the year. In addition, it allowed the architects to use more naturally tinted glass which not only provides better views but also allows more light to enter the interior space thus leading to less need for artificial light.

Exterior Agent of Adaptation

- ☒ Solar radiation
☐ Temperature
☐ Humidity
☐ Wind
☐ Precipitation
☐ Noise

Interior Agent of Adaptation

- ☐ Temperature
☐ Humidity
☐ Light
☐ Air exchange rate
☐ Sound level

Purpose

- ☒ Thermal comfort
☐ IAQ
☒ Visual and Lighting
☐ Acoustic
☐ Energy production

Control of Adaptivity

- ☒ Closed loop
☐ Open loop

Energy

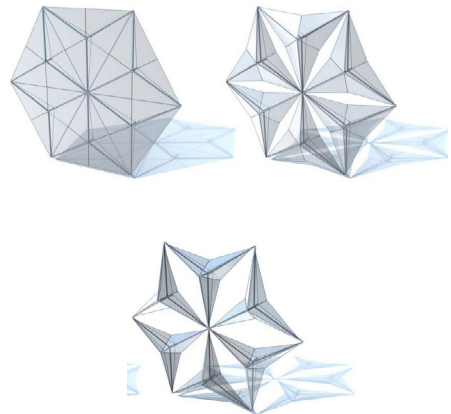
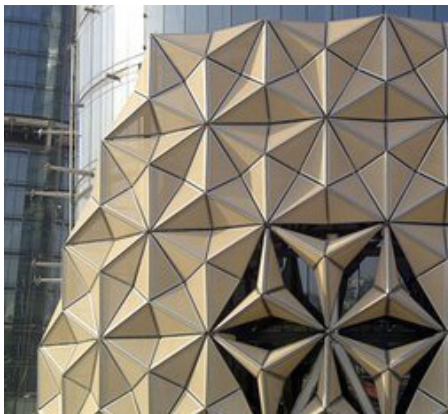
☒ - ☐ 0 ☐ +

Highest cost

- ☐ Materials
☐ Production
☒ Assembly
☐ Maintenance

Architecture design freedom

- ☐ Low
☐ Medium
☒ High



Sources: <https://www.arch2o.com/al-bahr-towers-aedas/>
<http://www.ahr-global.com/Al-Bahr-Towers>



RMIT Design Hub

Sean Godsell

RMIT University, Melbourne, Australia

2012

Response to Adaptation Agent

☒ Dynamic ☐ Static

RMIT Hub incorporates strategies of water, waste and recycling management. In particular, it consists of an automated operable second-skin sunshading system which includes photovoltaic cells, evaporative cooling and fresh air intakes with the aim of improving the indoor air quality and lowering running costs. The second skin is made up of sandblasted glass disks, which are fixed to either a horizontal or vertical aluminium axel. Every 21 disks, 12 operable and 9 fixed, compose one panel of the curtain wall face of the building. The entire facade is designed in such a way that can be easily replaced so that it can be upgraded as solar technology evolves with the possibility of being able one day to produce enough electricity to run the entire building.

Exterior Agent of Adaptation

- ☒ Solar radiation
- ☐ Temperature
- ☐ Humidity
- ☐ Wind
- ☐ Precipitation
- ☐ Noise

Interior Agent of Adaptation

- ☒ Temperature
- ☐ Humidity
- ☐ Light
- ☒ Air exchange rate
- ☐ Sound level

Purpose

- ☒ Thermal comfort
- ☒ IAQ
- ☐ Visual and Lighting
- ☐ Acoustic
- ☒ Energy production

Control of Adaptivity

- ☒ Closed loop
- ☐ Open loop

Energy

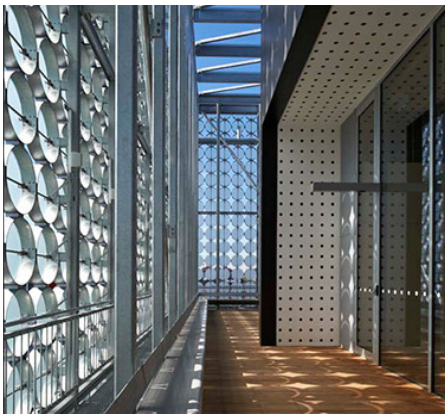
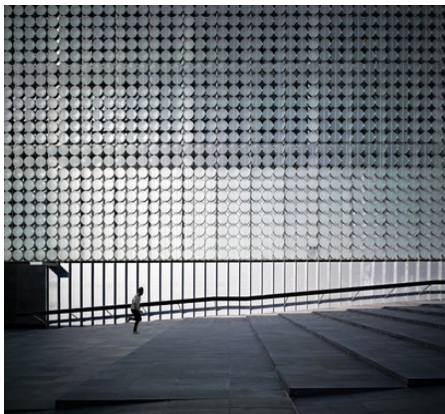
- ☐ - ☐ 0 ☒ +

Highest cost

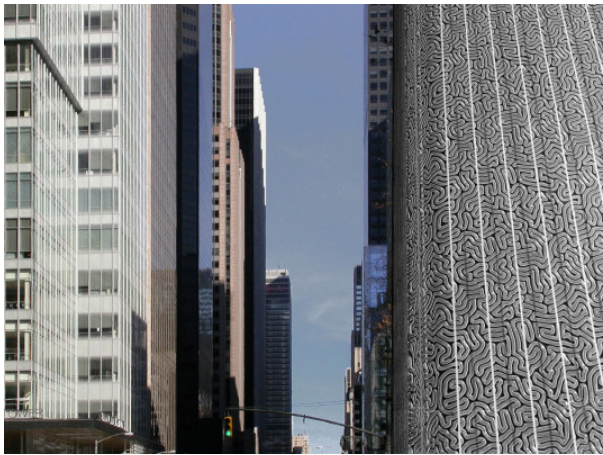
- ☐ Materials
- ☐ Production
- ☐ Assembly
- ☒ Maintenance

Architecture design freedom

- ☐ Low
- ☐ Medium
- ☒ High



Sources: <http://www.seangodsell.com/rmit-design-hub>
<https://www.archdaily.com/335620/rmit-design-hub-sean-godsell>



Homeostatic Facade System

Decker & Yeadon

New York, USA

2013

Response to Adaptation Agent

☒ Dynamic ☐ Static

Homeostatic Facade is a prototype system that regulates the solar radiation by changing shape. It is composed of ribbons made of dielectric elastomers, a polymer material, that polarizes when an electrical current is applied. It works as a muscle and consumes a little amount of energy. The ribbons are coated with silver electrodes that reflect light and distribute the electricity through the material. The ribbons expand or contract according to the environmental conditions, regulating both the solar heat gains and the amount of light.

Exterior Agent of Adaptation

- ☒ Solar radiation
- ☐ Temperature
- ☐ Humidity
- ☐ Wind
- ☐ Precipitation
- ☐ Noise

Interior Agent of Adaptation

- ☐ Temperature
- ☐ Humidity
- ☐ Light
- ☐ Air exchange rate
- ☐ Sound level

Purpose

- ☒ Thermal comfort
- ☐ IAQ
- ☒ Visual and Lighting
- ☐ Acoustic
- ☐ Energy production

Control of Adaptivity

- ☐ Closed loop
- ☒ Open loop

Energy

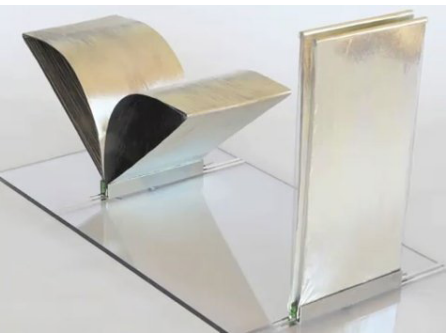
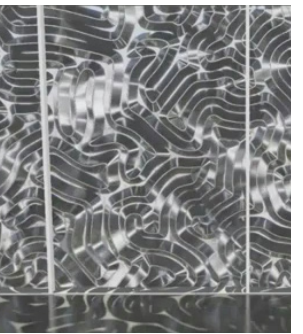
- ☒ - ☐ 0 ☐ +

Highest cost

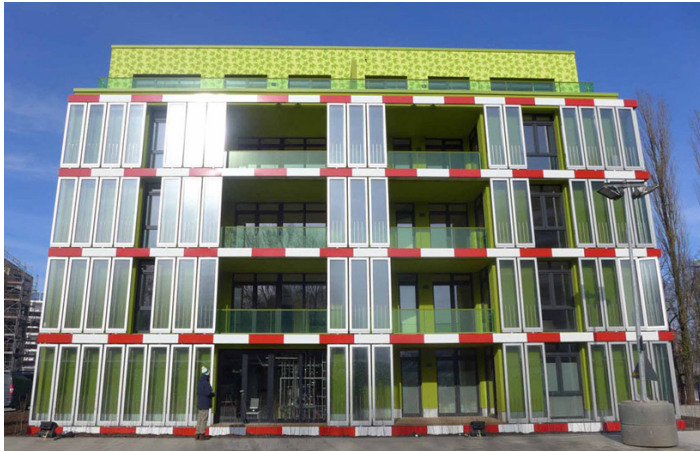
- ☒ Materials
- ☒ Production
- ☐ Assembly
- ☐ Maintenance

Architecture design freedom

- ☐ Low
- ☒ Medium
- ☐ High



Sources: <https://materia.nl/article/homeostatic-facade-system/>
<https://www.archdaily.com/101578/moving-homeostatic-facade-preventing-solar-heat-gain>



BIQ house

Splitterwerk Architects & Arup

Hamburg, Germany

2013

Response to Adaptation Agent

☐ Dynamic ☒ Static

The "bio-adaptive" facade consists of live microalgae which are used as bio-reactors and are growing in glass louvers that clad the southeast and southwest facades of the building in order to generate renewable energy and provide shade at the same time. The algae are continuously supplied with liquid nutrients and carbon dioxide via a water circuit running through the facade. The sun encourages the algae's growth to provide more shade, while at the same time heat is absorbed to warm the building's hot water tank. By growing, the algae are able to produce biomass, which is then converted into biofuel and consequently the process of photosynthesis is responsible for a dynamic response to the required solar shading. At the same time the algae creates harvestable energy, the excess of which can be stored in buffers or sold back to the local grid.

Exterior Agent of Adaptation

- ☒ Solar radiation
- ☐ Temperature
- ☐ Humidity
- ☐ Wind
- ☐ Precipitation
- ☐ Noise

Interior Agent of Adaptation

- ☐ Temperature
- ☐ Humidity
- ☐ Light
- ☐ Air exchange rate
- ☐ Sound level

Purpose

- ☒ Thermal comfort
- ☐ IAQ
- ☒ Visual and Lighting
- ☐ Acoustic
- ☒ Energy production

Control of Adaptivity

- ☐ Closed loop
- ☒ Open loop

Energy

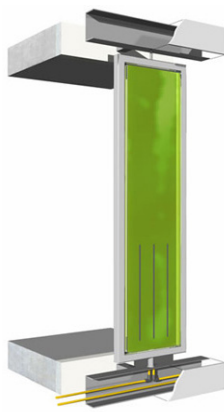
☐ - ☐ 0 ☒ +

Highest cost

- ☐ Materials
- ☐ Production
- ☒ Assembly
- ☐ Maintenance

Architecture design freedom

- ☐ Low
- ☒ Medium
- ☐ High



Sources: <https://www.arup.com/en/projects/s/SolarLeaf>
<http://www.iba-hamburg.de/en/themes-projects/the-building-exhibition-within-the-building-exhibition/smart-material-houses/biq/projekt/biq.html>



SwissTech Convention Center

Richter Dahl Rocha & Associés

University of Lausanne, Switzerland

2014

Response to Adaptation Agent

☐ Dynamic ☒ Static

The SwissTech Convention Center is the first large-scale convention hall to use EPFL's dye-sensitized solar cells. These are integrated in panels that constitute the building envelope. The EPFL's dye-sensitized solar cells have been invented by Michael Grätzel and, differently from the common solar cells, have the same performance independently from the angle of incidence of the light. A second advantage is that these solar cells are translucent and therefore they protect the building from solar radiation, allowing the passage of daylight, but reducing the solar gain and therefore the energy demand for cooling during summer.

Exterior Agent of Adaptation

- ☒ Solar radiation
- ☐ Temperature
- ☐ Humidity
- ☐ Wind
- ☐ Precipitation
- ☐ Noise

Interior Agent of Adaptation

- ☐ Temperature
- ☐ Humidity
- ☐ Light
- ☐ Air exchange rate
- ☐ Sound level

Purpose

- ☒ Thermal comfort
- ☐ IAQ
- ☒ Visual and Lighting
- ☐ Acoustic
- ☒ Energy production

Control of Adaptivity

- ☐ Closed loop
- ☒ Open loop

Energy

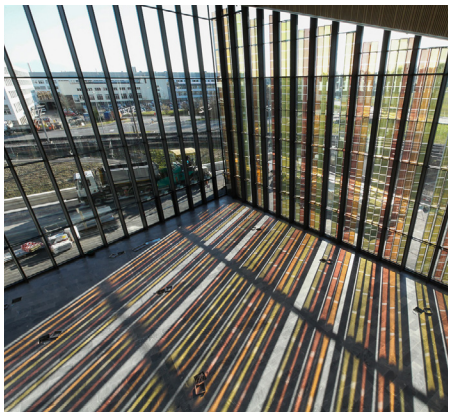
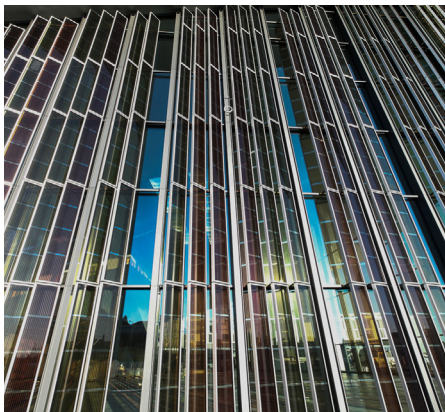
☐ - ☐ 0 ☒ +

Highest cost

- ☒ Materials
- ☐ Production
- ☐ Assembly
- ☐ Maintenance

Architecture design freedom

- ☐ Low
- ☐ Medium
- ☒ High



Sources: <https://www.archdaily.com/491135/richter-dahl-rocha-develop-innovative-facade-for-swisstech-convention-center>



SDU Campus Kolding

Henning Larsen Architects

Kolding Campus, Denmark

2014

Response to Adaptation Agent

☒ Dynamic ☐ Static

The facade modifies its composition according to the solar radiation in order to adjust daylight and thermal comfort. The facade is made up of 1600 triangular shape panels of perforated steel which change their position according to the amount of daylight. The latter is measured by some sensors that detect the light and the heat and modify the shutters position from flat along the facade, to open and perpendicular to the facade, providing daylight. In this way, the aspect of the building changes continuously.

Exterior Agent of Adaptation

- ☒ Solar radiation
- ☐ Temperature
- ☐ Humidity
- ☐ Wind
- ☐ Precipitation
- ☐ Noise

Interior Agent of Adaptation

- ☐ Temperature
- ☐ Humidity
- ☐ Light
- ☐ Air exchange rate
- ☐ Sound level

Purpose

- ☒ Thermal comfort
- ☐ IAQ
- ☒ Visual and Lighting
- ☐ Acoustic
- ☐ Energy production

Control of Adaptivity

- ☒ Closed loop
- ☐ Open loop

Energy

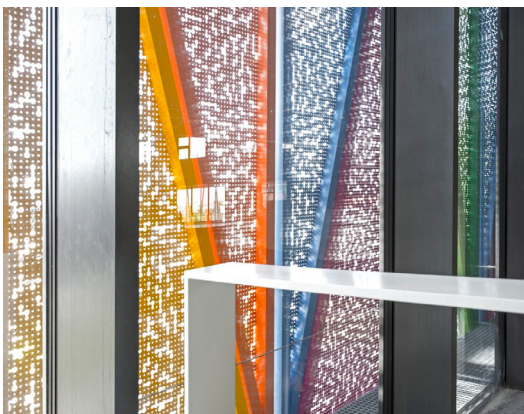
☒ - ☐ 0 ☐ +

Highest cost

- ☐ Materials
- ☐ Production
- ☐ Assembly
- ☒ Maintenance

Architecture design freedom

- ☐ Low
- ☒ Medium
- ☐ High



Sources: <https://www.archdaily.com/590576/sdu-campus-kolding-henning-larsen-architects>



Headquarters for Swatch and Omega

Shigeru Ban Architects

Biel, Switzerland

2017

Response to Adaptation Agent

☐ Dynamic ☒ Static

The Headquarters for Swatch and Omega consist of three buildings and the facade is a free form shell built with semi-circular timber frame structure. This shell is composed of different types of elements out of glass, ETFE and polycarbonate or timber. At the same time, all the elements are quadrangular which means that they follow the doubly curved shape of the building. The glass used is cold and warm bended, which works as a sun shading device. The polycarbonate is cold bended and is used as an internal layer of the ETFE cushions.

Exterior Agent of Adaptation

- ☒ Solar radiation
- ☐ Temperature
- ☐ Humidity
- ☐ Wind
- ☐ Precipitation
- ☐ Noise

Interior Agent of Adaptation

- ☐ Temperature
- ☐ Humidity
- ☐ Light
- ☐ Air exchange rate
- ☐ Sound level

Purpose

- ☒ Thermal comfort
- ☐ IAQ
- ☒ Visual and Lighting
- ☐ Acoustic
- ☐ Energy production

Control of Adaptivity

- ☒ Closed loop
- ☐ Open loop

Energy

☒ - ☐ 0 ☐ +

Highest cost

- ☐ Materials
- ☐ Production
- ☒ Assembly
- ☐ Maintenance

Architecture design freedom

- ☐ Low
- ☐ Medium
- ☒ High



Sources: [http://www.leichtonline.com/uploads/files/Swatch_eng_web\(1\).pdf](http://www.leichtonline.com/uploads/files/Swatch_eng_web(1).pdf)
<https://www.designboom.com/architecture/shigeru-ban-headquarters-for-swatch-production-buildings-for-omega/>



Apple Dubai Mall

Foster + Partners

Dubai, United Arab Emirates

2017

Response to Adaptation Agent

☒ Dynamic ☐ Static

The daylight is a significant element of this building. The amount of daylight is regulated by a shading system that has been reinterpreted by the traditional Arabic Mashrabiya. The shading system is called Solar Wings because it resembles wings that open and close according to the amount of light. These are made of multiple layers of tubes of lightweight carbon fibre that are more concentrated where the solar radiation is more intense. The dimension of the net allows to have a clear view to the outside environment.

Exterior Agent of Adaptation

- ☒ Solar radiation
- ☐ Temperature
- ☐ Humidity
- ☐ Wind
- ☐ Precipitation
- ☐ Noise

Interior Agent of Adaptation

- ☐ Temperature
- ☐ Humidity
- ☐ Light
- ☐ Air exchange rate
- ☐ Sound level

Purpose

- ☐ Thermal comfort
- ☐ IAQ
- ☒ Visual and Lighting
- ☐ Acoustic
- ☐ Energy production

Control of Adaptivity

- ☒ Closed loop
- ☐ Open loop

Energy

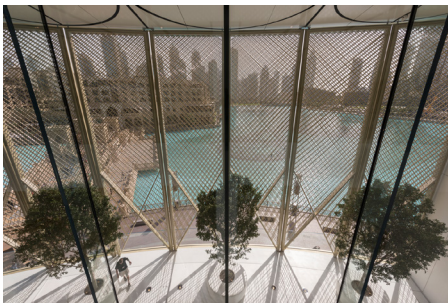
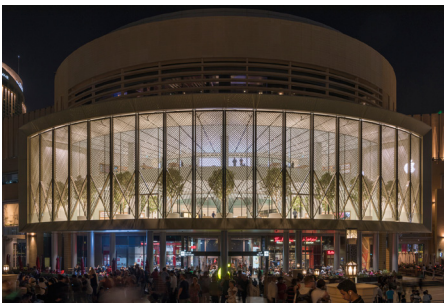
☒ - ☐ 0 ☐ +

Highest cost

- ☒ Materials
- ☐ Production
- ☐ Assembly
- ☐ Maintenance

Architecture design freedom

- ☐ Low
- ☒ Medium
- ☐ High



Sources: <https://www.archdaily.com/870357/apple-dubai-mall-foster-plus-partners>



Bund Finance Center

Foster + Partners and Heatherwick Studio

Shanghai

2017

Response to Adaptation Agent

☒ Dynamic ☐ Static

The building has been inspired by the traditional Chinese theatres. Its envelope is made by three layers of bronze tubes that work as shading system all around the building. According to the direction and amount of daylight, the three layers adjust their position changing the level of transparency of the facade. The effect is a dynamic envelope that seems to rotate around the building in a very fluid effect.

Exterior Agent of Adaptation

- ☒ Solar radiation
- ☐ Temperature
- ☐ Humidity
- ☐ Wind
- ☐ Precipitation
- ☐ Noise

Interior Agent of Adaptation

- ☐ Temperature
- ☐ Humidity
- ☐ Light
- ☐ Air exchange rate
- ☐ Sound level

Purpose

- ☒ Thermal comfort
- ☐ IAQ
- ☒ Visual and Lighting
- ☐ Acoustic
- ☐ Energy production

Control of Adaptivity

- ☒ Closed loop
- ☐ Open loop

Energy

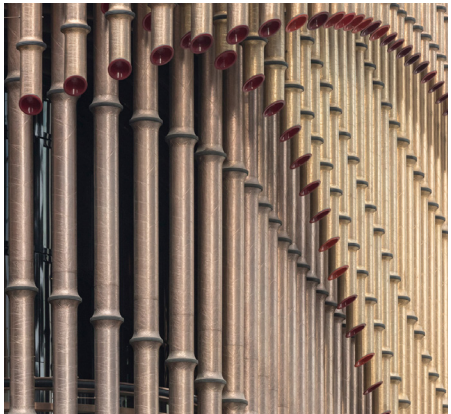
☒ - ☐ 0 ☐ +

Highest cost

- ☐ Materials
- ☒ Production
- ☐ Assembly
- ☒ Maintenance

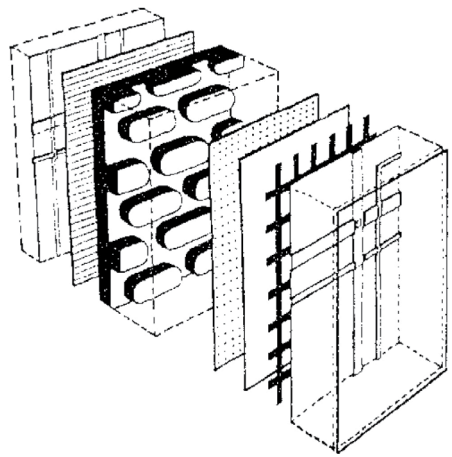
Architecture design freedom

- ☐ Low
- ☒ Medium
- ☐ High



Sources: <https://www.dezeen.com/2017/06/09/foster-heatherwick-complete-shanghai-arts-centre-curtain-like-facade-fosun-foundation-theatre-architecture/>

PRODUCTS



Polyvalent Wall for Lloyd's of London

Mick Davies

London, UK

1981

Response to Adaptation Agent

☐ Dynamic ☒ Static

The Polyvalent Wall is a layered, multifunctional and highly integral construction. The concept was to integrate all façade functions in one layer while incorporating energy collection and ventilation. The polyvalent wall would consist from different layers on top of a glass layer which would act as absorber, radiator, reflector, filter and transfer device at the same time. The necessary energy needed to be gained by the façade itself. In order for the façade to respond automatically to both the outer circumstances and the inside users, it needs to have sensors which contain information on usage schedules, habits and environmental performance data from the users of the building.

Exterior Agent of Adaptation

- ☒ Solar radiation
- ☒ Temperature
- ☐ Humidity
- ☐ Wind
- ☐ Precipitation
- ☐ Noise

Interior Agent of Adaptation

- ☒ Temperature
- ☐ Humidity
- ☐ Light
- ☒ Air exchange rate
- ☐ Sound level

Purpose

- ☒ Thermal comfort
- ☒ IAQ
- ☐ Visual and Lighting
- ☐ Acoustic
- ☒ Energy production

Control of Adaptivity

- ☐ Closed loop
- ☐ Open loop

Energy

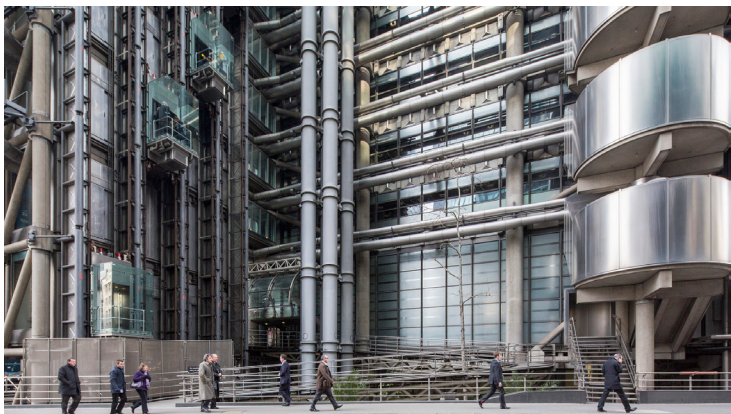
☐ - ☐ 0 ☒ +

Highest cost

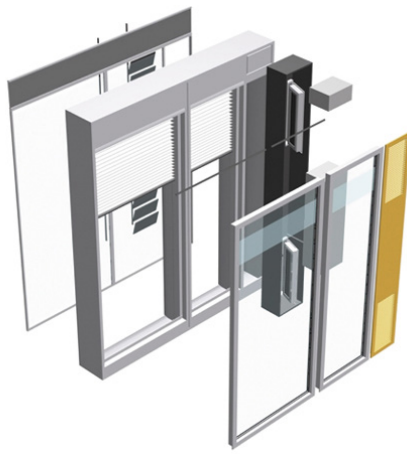
- ☐ Materials
- ☐ Production
- ☐ Assembly
- ☒ Maintenance

Architecture design freedom

- ☐ Low
- ☒ Medium
- ☐ High



Sources: <https://books.bk.tudelft.nl/index.php/press/catalog/download/600/693/499-1?inline=1>
Klein, T. (2013). Integral Facade Construction: Towards a new product for curtain walls.



TEmotion

Hydro Building Systems

WICONA global company & University of Dortmund

2005

Response to Adaptation Agent

☐ Dynamic ☒ Static

TEmotion is a synthesis of technology and emotion and it is actually a facade that responds to changes in outdoor and indoor conditions, such as light or temperature by incorporating technical components, sensors and control systems. The intelligent façade controls the integrated ventilation, air-conditioning and heating technology, adjusts the sun protection and prevents the interior from overheating. In addition, PV cells are used for generating energy in order to supply the building installations with electric current. All components of building services which are integrated in the functional element can be controlled through a central building services management system or by the user with the aim to achieve energy savings and a high level of well being for the users.

Exterior Agent of Adaptation

- ☒ Solar radiation
- ☒ Temperature
- ☐ Humidity
- ☐ Wind
- ☐ Precipitation
- ☐ Noise

Interior Agent of Adaptation

- ☒ Temperature
- ☐ Humidity
- ☐ Light
- ☒ Air exchange rate
- ☐ Sound level

Purpose

- ☒ Thermal comfort
- ☐ IAQ
- ☒ Visual and Lighting
- ☐ Acoustic
- ☒ Energy production

Control of Adaptivity

- ☒ Closed loop
- ☐ Open loop

Energy

☐ - ☐ 0 ☒ +

Highest cost

- ☐ Materials
- ☐ Production
- ☐ Assembly
- ☒ Maintenance

Architecture design freedom

- ☐ Low
- ☒ Medium
- ☐ High



Sources: <https://www.wicona.com/en/se/Aluminium/Sustainability/TEmotion/>



ECONTROL®

EControl-Glas GmbH & Co.

Plauen, Germany

2005

Response to Adaptation Agent

☐ Dynamic ☒ Static

ECONTROL® is a dimmable solar control glass developed by EControl-Glas that uses electrochromic glass to vary the tint of the glass and therefore its light transmittance and its solar factor. According to the shade of the glass, the light can be transmitted from 10 to 56%, maintaining a level of brightness even in its darkest state. As all the smart glazing, this solution protects the indoor climate during summer and reduces glare maintaining the view to the outside. It consumes electricity only when it changes the dimming level because the material has the capacity to memorize the information and maintain them until a new input is given. The dimming is of about 20-25 minutes. The control can be automated or controlled with the possibility for the users to adjust the diming level according to their preferences.

Exterior Agent of Adaptation

- ☒ Solar radiation
- ☐ Temperature
- ☐ Humidity
- ☐ Wind
- ☐ Precipitation
- ☐ Noise

Interior Agent of Adaptation

- ☒ Temperature
- ☐ Humidity
- ☒ Light
- ☐ Air exchange rate
- ☐ Sound level

Purpose

- ☒ Thermal comfort
- ☐ IAQ
- ☒ Visual and Lighting
- ☐ Acoustic
- ☐ Energy production

Control of Adaptivity

- ☒ Closed loop
- ☐ Open loop

Energy

☒ - ☐ 0 ☐ +

Highest cost

- ☒ Materials
- ☐ Production
- ☐ Assembly
- ☐ Maintenance

Architecture design freedom

- ☐ Low
- ☐ Medium
- ☒ High



Sources: www.econtrol-glas.de



Smartbox Energy Facade

Cepezed & Energy Research Center of Netherlands

2006

Response to Adaptation Agent

☐ Dynamic ☒ Static

Smartbox integrates building services components at the junction of the facade and the floor slab with the benefit of an unobstructed outside view since the floor to ceiling space remains free of obstacles. Smartbox Energy Facade contains a large amount of advanced climate-regulating equipment, such as a water pump, electrically driven ventilators and a heat exchanger. The project makes clever use of the sunlight in order to regulate the indoor environment and incorporates built-in photovoltaic solar cells to generate electricity. The project aimed to develop an 'active' façade concept that uses active and passive solar energy and intelligence in the façade. The result is a potential 50% reduction of building related energy use at market conformable prices, combined with improved comfort.

Exterior Agent of Adaptation

- ☒ Solar radiation
- ☒ Temperature
- ☐ Humidity
- ☐ Wind
- ☐ Precipitation
- ☐ Noise

Interior Agent of Adaptation

- ☒ Temperature
- ☐ Humidity
- ☐ Light
- ☒ Air exchange rate
- ☐ Sound level

Purpose

- ☒ Thermal comfort
- ☒ IAQ
- ☒ Visual and Lighting
- ☐ Acoustic
- ☒ Energy production

Control of Adaptivity

- ☒ Closed loop
- ☐ Open loop

Energy

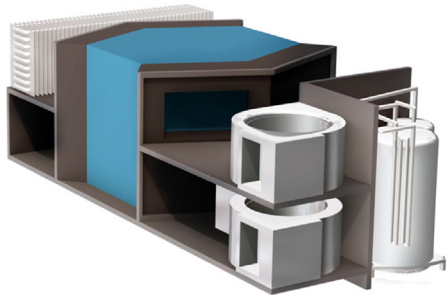
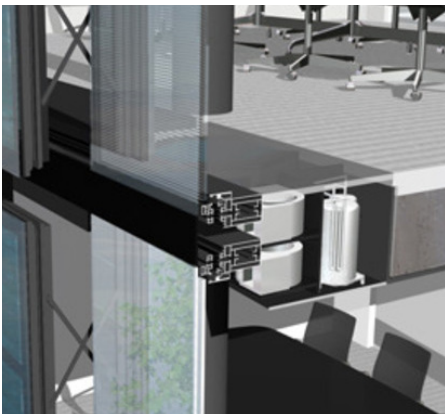
☐ - ☐ 0 ☒ +

Highest cost

- ☐ Materials
- ☐ Production
- ☐ Assembly
- ☒ Maintenance

Architecture design freedom

- ☐ Low
- ☒ Medium
- ☐ High



Sources: <https://www.cepezed.com/projects/51-smartbox>
<https://www.ecn.nl/news/newsletter-en/archive-2007/july-2007/smartbox/>



Schueco E² Facade

Prof. Stefan Behling

Schueco

2007

Response to Adaptation Agent

☐ Dynamic ☒ Static

Schueco E² Facade is a multifunctional facade with the aim of saving and generating energy by the technologies in real time. It is a revolutionary combination of facade and system technology which provides four different function modules that allow customization. These modules are: concealed decentralised ventilation, thin-film modules, integrated solar shading and flush integrated opening units. This facade provides transparency and offers at the same time protection from excessive solar radiation and permission of the optimum natural illumination while carrying out additional functions like generating electricity. The new facade system is a combination of curtain wall and structural glazing system and offers the possibility to integrate building services components at a designated space in front of the floor slab with the benefit of an unobstructed outside view.

Exterior Agent of Adaptation

- ☒ Solar radiation
- ☒ Temperature
- ☐ Humidity
- ☐ Wind
- ☐ Precipitation
- ☐ Noise

Interior Agent of Adaptation

- ☒ Temperature
- ☐ Humidity
- ☐ Light
- ☒ Air exchange rate
- ☐ Sound level

Purpose

- ☒ Thermal comfort
- ☒ IAQ
- ☒ Visual and Lighting
- ☐ Acoustic
- ☒ Energy production

Control of Adaptivity

- ☒ Closed loop
- ☐ Open loop

Energy

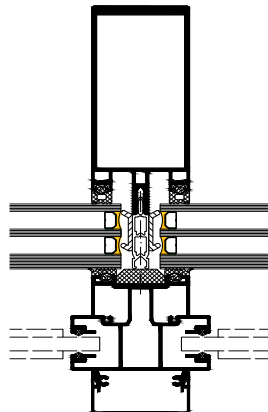
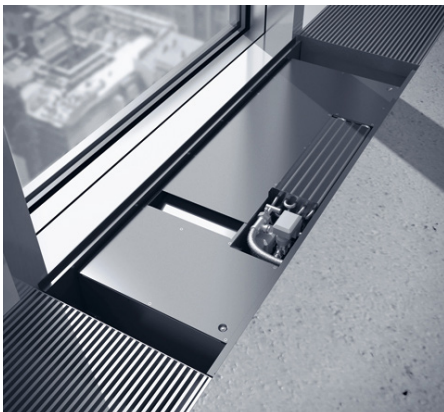
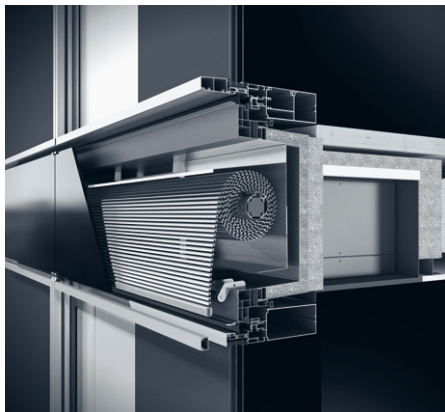
☐ - ☐ 0 ☒ +

Highest cost

- ☐ Materials
- ☐ Production
- ☐ Assembly
- ☒ Maintenance

Architecture design freedom

- ☐ Low
- ☒ Medium
- ☐ High



Sources: <http://www.geopetaluminium.com/E2.html>
http://www.creativealuminium.co.uk/downloads/Fasade_Saving_Energy_and_Generating_Energy.pdf



FLARE - Kinetic Membrane Facade

WHITEvoid interactive art & design

2008

Response to Adaptation Agent

☒ Dynamic ☐ Static

FLARE consists of a modular system acting like a living skin which is able to respond to the exterior environment. FLARE turns the building facade into a penetrable kinetic-flexible membrane while giving a visual effect at the same time. The facade is made of flake metal outlines which are moved by individually controllable pneumatic cylinders. Each metal flake can reflect ambient or direct sunlight, thus creating different images on the outer layer of the building. The building's activity is monitored by sensors which are inside and outside of the building and the system is controlled by a computer in order to create any kind of surface animation.

Exterior Agent of Adaptation

- ☒ Solar radiation
- ☐ Temperature
- ☐ Humidity
- ☐ Wind
- ☐ Precipitation
- ☐ Noise

Interior Agent of Adaptation

- ☐ Temperature
- ☐ Humidity
- ☐ Light
- ☐ Air exchange rate
- ☐ Sound level

Purpose

- ☐ Thermal comfort
- ☐ IAQ
- ☒ Visual and Lighting
- ☐ Acoustic
- ☐ Energy production

Control of Adaptivity

- ☒ Closed loop
- ☐ Open loop

Energy

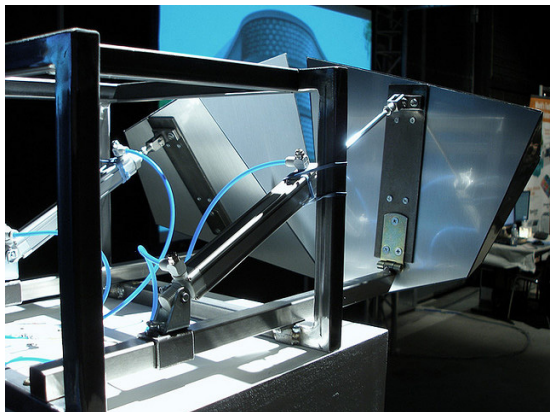
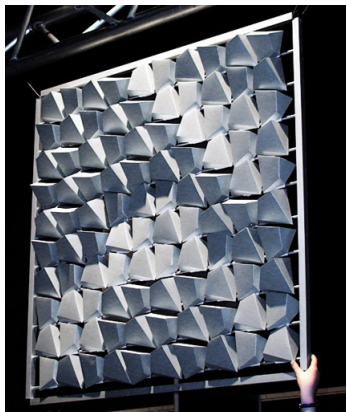
☒ - ☐ 0 ☐ +

Highest cost

- ☐ Materials
- ☐ Production
- ☐ Assembly
- ☒ Maintenance

Architecture design freedom

- ☐ Low
- ☒ Medium
- ☐ High



Sources: <http://www.mediaarchitecture.org/flare-kinetic-membrane-facade/>
http://www.whitevoid.com/#/main/architecture_spaces/flare_facade/description



PixelSkin02

Sachin Anshuman

United Kingdom

2008

Response to Adaptation Agent

☒ Dynamic ☐ Static

PixelSkin02 is a surface composed by pixel-tiles divided into four triangular panels of shape memory alloys (SMA). The panel creates a transparent visual field that can also generate low-resolution images and low-refresh-rate videos via electromechanical inputs by 200mA SMA wires. The panels regulate the light by opening or closing. The amount of light can vary thanks to the 255 possible states of adjustments of the triangular elements.

Exterior Agent of Adaptation

- ☒ Solar radiation
- ☐ Temperature
- ☐ Humidity
- ☐ Wind
- ☐ Precipitation
- ☐ Noise

Interior Agent of Adaptation

- ☐ Temperature
- ☐ Humidity
- ☐ Light
- ☐ Air exchange rate
- ☐ Sound level

Purpose

- ☒ Thermal comfort
- ☐ IAQ
- ☒ Visual and Lighting
- ☐ Acoustic
- ☐ Energy production

Control of Adaptivity

- ☒ Closed loop
- ☐ Open loop

Energy

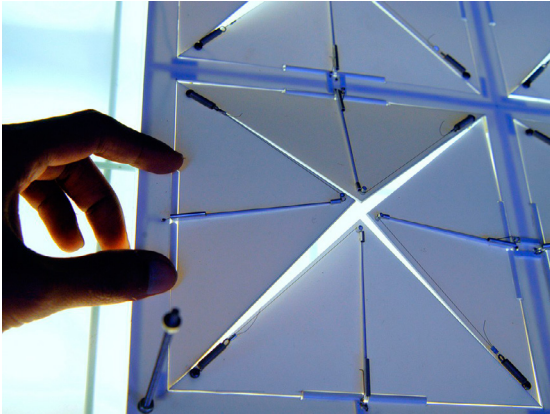
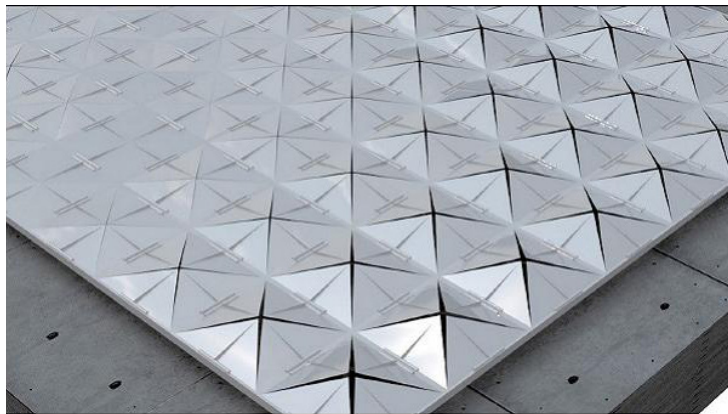
☒ - ☐ 0 ☐ +

Highest cost

- ☐ Materials
- ☒ Production
- ☒ Assembly
- ☐ Maintenance

Architecture design freedom

- ☐ Low
- ☒ Medium
- ☐ High



Sources: <http://transmaterial.net/pixelskin02/>



NEXT Active Facade

Kawneer

global company

2010

Response to Adaptation Agent

☐ Dynamic ☒ Static

Alcoa Architecture Systems, Somfy and Trox utilised the knowledge and expertise of the Cepezed Firm of Architects, Delft University of Technology, Hurks Facade Technology and Warema Nederland to develop a unique façade concept, which is an important link in the energy management of buildings. NEXT Active Facade has a modular set-up and offers fully integrated facilities such as climate cooling, heating, ventilation and regulation of sunlight. The facade can be freely divided and offers a low operating energy consumption. The facade filters and conditions sucked in outside air and brings it into the interior spaces draft-free. A heat exchanger regenerates the exhaust air, while night ventilation and automatic sun protection use natural resources.

Exterior Agent of Adaptation

- ☒ Solar radiation
- ☐ Temperature
- ☒ Humidity
- ☐ Wind
- ☐ Precipitation
- ☐ Noise

Interior Agent of Adaptation

- ☒ Temperature
- ☒ Humidity
- ☐ Light
- ☒ Air exchange rate
- ☐ Sound level

Purpose

- ☒ Thermal comfort
- ☒ IAQ
- ☒ Visual and Lighting
- ☐ Acoustic
- ☐ Energy production

Control of Adaptivity

- ☒ Closed loop
- ☐ Open loop

Energy

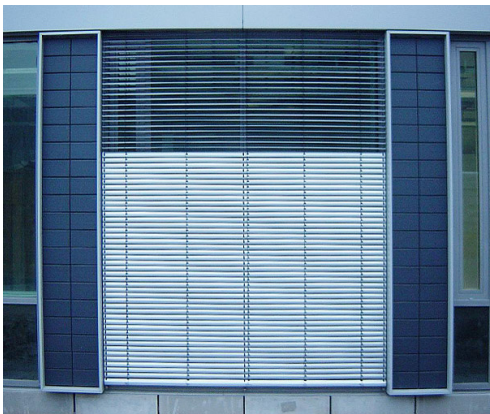
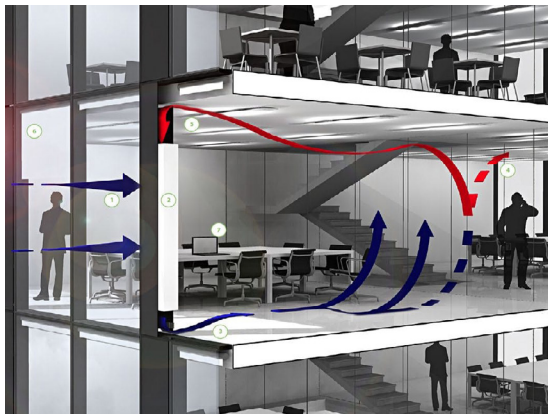
☐ - ☒ 0 ☐ +

Highest cost

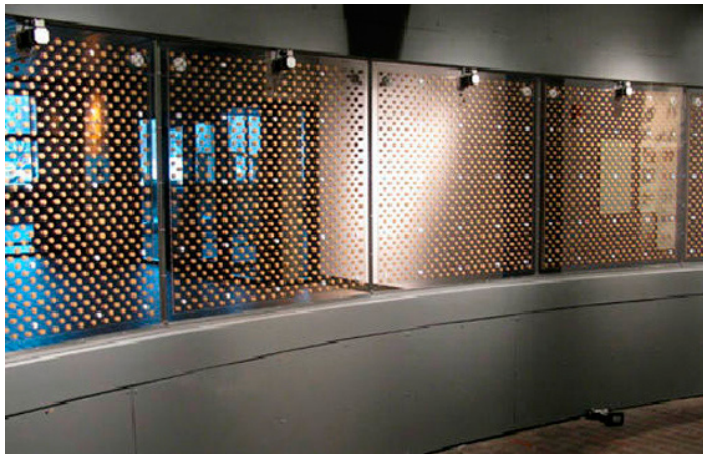
- ☐ Materials
- ☐ Production
- ☐ Assembly
- ☒ Maintenance

Architecture design freedom

- ☐ Low
- ☒ Medium
- ☐ High



Sources: <https://facadeworld.files.wordpress.com/2014/01/next-active-facades.jpg>
https://www.kawneer.com/bcs/architectuursystemen/catalog/pdf/brochures/NEXT%20Active%20Facades%20brochure_FINAL.pdf



Adaptive Fritting (GSD)

Hoberman

Harvard Graduate School of Design, Cambridge, Massachussetts, USA

2009

Response to Adaptation Agent

☒ Dynamic ☐ Static

The system is a prototype for a shading system that can control heat gains and the amount of daylight. The pattern allows different levels of transparency thanks to the adaptive fritting that, with a dynamic motion via motorized control, balances the opaque and transparent states. This effect is achieved by shifting a series of fritted glass layers, aligning or diverging the pattern.

Exterior Agent of Adaptation

- ☒ Solar radiation
- ☐ Temperature
- ☐ Humidity
- ☐ Wind
- ☐ Precipitation
- ☐ Noise

Interior Agent of Adaptation

- ☐ Temperature
- ☐ Humidity
- ☐ Light
- ☐ Air exchange rate
- ☐ Sound level

Purpose

- ☒ Thermal comfort
- ☐ IAQ
- ☒ Visual and Lighting
- ☐ Acoustic
- ☐ Energy production

Control of Adaptivity

- ☒ Closed loop
- ☐ Open loop

Energy

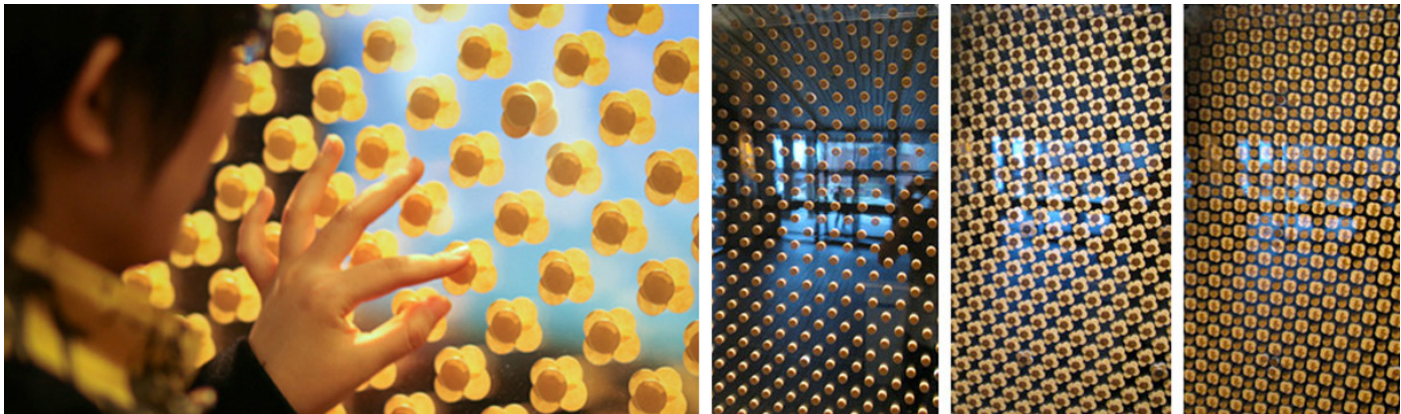
- ☒ - ☐ 0 ☐ +

Highest cost

- ☐ Materials
- ☒ Production
- ☐ Assembly
- ☐ Maintenance

Architecture design freedom

- ☐ Low
- ☒ Medium
- ☐ High



Sources: <http://www.hoberman.com/portfolio/gsd.php?rev=0&onEnterFrame=%5Btype+Function%5D&myNum=0&category=&projectname=Adaptive+Fritting+%28GSD%29>



SageGlass®

Saint-Gobain

Flamatt, Switzerland

2010

Response to Adaptation Agent

☐ Dynamic ☒ Static

SageGlass® is a smart window developed by Saint-Gobain that uses electrochromic glass as smart technology to maximize the daylight and minimize solar heat gain and glare. The window changes its tint, and therefore its light transmittance, with different shades of blue according to the amount of voltage that is applied. The application of the voltage can be automated thanks to light sensors, motion sensor, lighting control, thermostat or by the users. This solution allows the multi-zone: different portions of the glass can be tinted, independently from each other, with different shades without physically divide the facade with a frame.

Exterior Agent of Adaptation

- ☒ Solar radiation
- ☐ Temperature
- ☐ Humidity
- ☐ Wind
- ☐ Precipitation
- ☐ Noise

Interior Agent of Adaptation

- ☒ Temperature
- ☐ Humidity
- ☒ Light
- ☐ Air exchange rate
- ☐ Sound level

Purpose

- ☒ Thermal comfort
- ☐ IAQ
- ☒ Visual and Lighting
- ☐ Acoustic
- ☐ Energy production

Control of Adaptivity

- ☒ Closed loop
- ☐ Open loop

Energy

- ☒ - ☐ 0 ☐ +

Highest cost

- ☒ Materials
- ☐ Production
- ☐ Assembly
- ☐ Maintenance

Architecture design freedom

- ☐ Low
- ☐ Medium
- ☒ High



Sources: www.sageglass.com



Solar Thermal Facade Collectors with Evacuated Tubes

© Universität Stuttgart, IBK 2

Stuttgart, Germany

2013

Response to Adaptation Agent

☐ Dynamic ☒ Static

The solar thermal facade collector with evacuated tubes provides both thermal and lighting comfort. In particular, it collects the solar heat at high temperatures and, because of the semi-transparency of the elements, protects the indoor space from the glare and assures a light diffusion. The high-performance evacuated tubes are covered with perforated parabolic mirrors that direct the solar radiation onto the evacuated tubes. This helps reducing the solar gains and therefore, reduces the cooling demand in summer. From a visual comfort point of view, the system looks like venetian blinds, with the advantage of being more transparent, allowing to see the external environment.

Exterior Agent of Adaptation

- ☒ Solar radiation
- ☒ Temperature
- ☐ Humidity
- ☐ Wind
- ☐ Precipitation
- ☐ Noise

Interior Agent of Adaptation

- ☐ Temperature
- ☐ Humidity
- ☐ Light
- ☐ Air exchange rate
- ☐ Sound level

Purpose

- ☒ Thermal comfort
- ☐ IAQ
- ☒ Visual and Lighting
- ☐ Acoustic
- ☒ Energy production

Control of Adaptivity

- ☐ Closed loop
- ☒ Open loop

Energy

☐ - ☐ 0 ☒ +

Highest cost

- ☒ Materials
- ☒ Production
- ☐ Assembly
- ☐ Maintenance

Architecture design freedom

- ☒ Low
- ☐ Medium
- ☐ High



Sources: <http://www.bine.info/en/publications/publikation/fassadenkollektoren-mit-durchblick/>



Smart Window & Power Window

PHYSEE

Delft, Netherlands

2014

Response to Adaptation Agent

☒ Dynamic ☒ Static

PowerWindow is a patented product of Physee. It looks exactly as a common window, because it is transparent and colourless, but it has the advantage that converts light into electricity. The SmartWindow connects the inside and outside environment by smart sensors that measure light intensity, temperature, pressure and air quality, helping in the improvement of the indoor condition and in decreasing the energy demand for heating and cooling.

Exterior Agent of Adaptation

- ☒ Solar radiation
- ☒ Temperature
- ☐ Humidity
- ☐ Wind
- ☐ Precipitation
- ☐ Noise

Interior Agent of Adaptation

- ☒ Temperature
- ☐ Humidity
- ☒ Light
- ☒ Air exchange rate
- ☐ Sound level

Purpose

- ☒ Thermal comfort
- ☒ IAQ
- ☒ Visual and Lighting
- ☐ Acoustic
- ☒ Energy production

Control of Adaptivity

- ☒ Closed loop
- ☐ Open loop

Energy

☐ - ☒ 0 ☒ +

Highest cost

- ☐ Materials
- ☐ Production
- ☐ Assembly
- ☒ Maintenance

Architecture design freedom

- ☐ Low
- ☒ Medium
- ☐ High



Sources: <http://www.physee.eu/products/>



iSolar Blinds

LCC

Newcastle, United Kingdom

2014

Response to Adaptation Agent

☒ Dynamic ☐ Static

iSolar Blinds are transparent blinds that work as insulator. They allow natural daylight and control the solar heat gain. This is possible thanks to the design of this product that is made of an aluminium coated polyethylene sheet laminated to a sheet of carbon graphite, later perforated and laminated to a sheet of clear polyester. Each side of the material has a different benefit on the indoor climate: the aluminium reflects the solar radiation to the outside to decrease the solar heat gain in summer while it faces the indoor space during winter to maintain the heat into the building. The carbon graphite is a dark non-reflective layer that faces outwards during winter, absorbing the heat and releasing it into the indoor space.

Exterior Agent of Adaptation

- ☒ Solar radiation
- ☐ Temperature
- ☐ Humidity
- ☐ Wind
- ☐ Precipitation
- ☐ Noise

Interior Agent of Adaptation

- ☒ Temperature
- ☐ Humidity
- ☐ Light
- ☐ Air exchange rate
- ☐ Sound level

Purpose

- ☒ Thermal comfort
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- ☐ Visual and Lighting
- ☐ Acoustic
- ☐ Energy production

Control of Adaptivity

- ☒ Closed loop
- ☐ Open loop

Energy

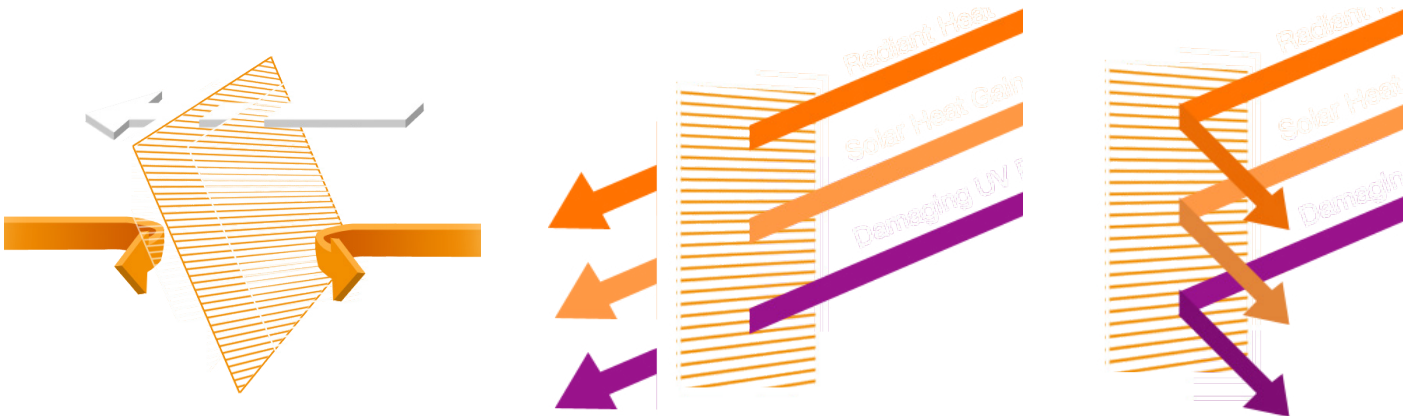
☒ - ☐ 0 ☐ +

Highest cost

- ☒ Materials
- ☐ Production
- ☐ Assembly
- ☐ Maintenance

Architecture design freedom

- ☐ Low
- ☒ Medium
- ☐ High



Sources: www.lcgenenergy.co.uk



licrivision™ - Liquid Crystal Window

Merck Window Technologies B.V.

Modular Innovation Center in Darmstadt

2015

Response to Adaptation Agent

☐ Dynamic ☒ Static

LCW solar control glazing allows to control the amount of daylight through the window. The glazing has a layer composed by liquid crystals that, in 2 seconds, can switch their orientation and therefore the window transmission. This is achieved with a change from bright to dark and it is possible to choose both greyscale or different colours. The transparency of the glazing does not change, but is just the colour that varies. The system is applicable to different sizes and shapes without changing its performance. Licrivision™ prevents the energy loss and controls solar heat, enhancing facade performance in terms of energy efficiency and sustainability.

Exterior Agent of Adaptation

- ☒ Solar radiation
- ☐ Temperature
- ☐ Humidity
- ☐ Wind
- ☐ Precipitation
- ☐ Noise

Interior Agent of Adaptation

- ☐ Temperature
- ☐ Humidity
- ☒ Light
- ☐ Air exchange rate
- ☐ Sound level

Purpose

- ☒ Thermal comfort
- ☐ IAQ
- ☒ Visual and Lighting
- ☐ Acoustic
- ☐ Energy production

Control of Adaptivity

- ☒ Closed loop
- ☐ Open loop

Energy

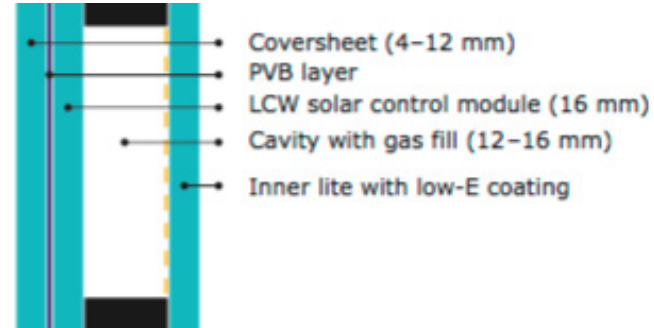
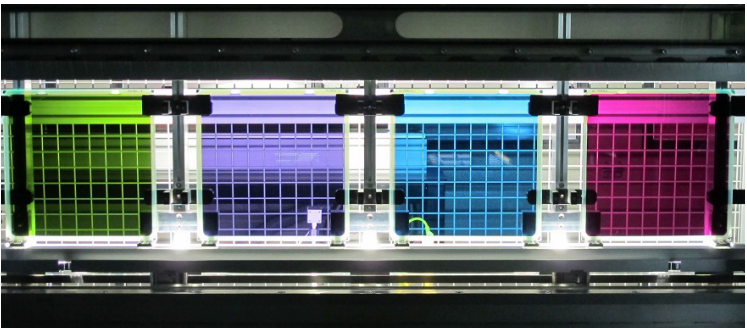
☒ - ☐ 0 ☐ +

Highest cost

- ☒ Materials
- ☐ Production
- ☐ Assembly
- ☐ Maintenance

Architecture design freedom

- ☐ Low
- ☐ Medium
- ☒ High



Sources: https://www.licrivision.com/en/LCW_solar_control_glazing.html



Closed Cavity Facade, JTI Headquarters

Josef Gartner GmbH

Geneva, Switzerland

2015

Response to Adaptation Agent

☐ Dynamic ☒ Static

The innovative Closed Cavity Facade system offers a new approach to the double skin facade system, where the cavity with a fabric roller blind in between the inner and the outer skin is completely sealed. Dry and clean air is constantly fed into the façade cavity in order to prevent the formation of condensation on the glazing. This facade is able to respond to external climatic conditions, while at the same time maintaining the visual qualities of an all-glass facade with a low g and U-value. The outside conditions are monitored electronically in order to make adjustments to the occupants comfort. As a result, energy consumption is reduced to a minimum and carbon emissions are reduced.

Exterior Agent of Adaptation

- ☒ Solar radiation
☐ Temperature
☐ Humidity
☐ Wind
☐ Precipitation
☐ Noise

Interior Agent of Adaptation

- ☒ Temperature
☐ Humidity
☐ Light
☐ Air exchange rate
☐ Sound level

Purpose

- ☒ Thermal comfort
☐ IAQ
☒ Visual and Lighting
☐ Acoustic
☐ Energy production

Control of Adaptivity

- ☒ Closed loop
☐ Open loop

Energy

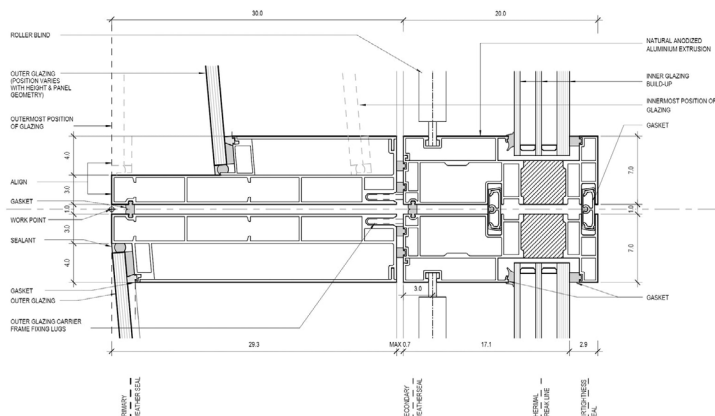
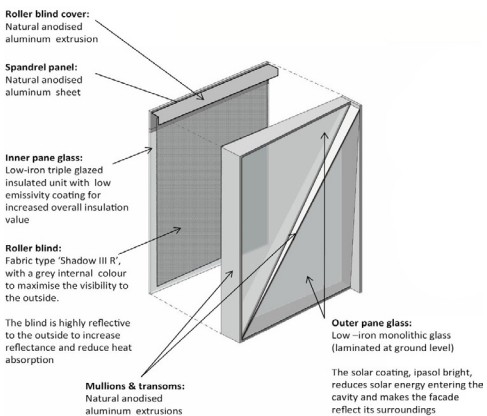
☒ - ☐ 0 ☐ +

Highest cost

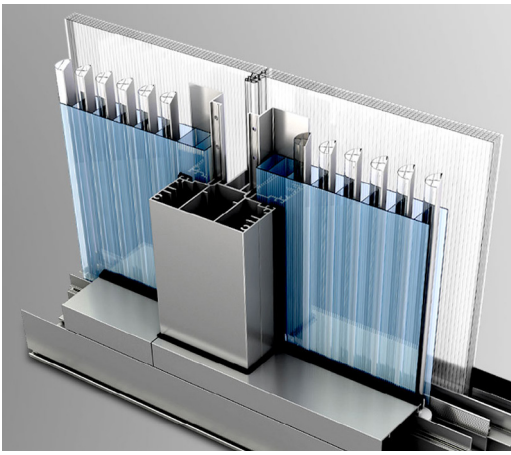
- ☐ Materials
☐ Production
☐ Assembly
☒ Maintenance

Architecture design freedom

- ☐ Low
☒ Medium
☐ High



Sources: <https://architizer.com/projects/closed-cavity-facade/>
<https://archpaper.com/2017/01/best-performing-glass-facade-system-soms-history/#gallery-0-slide-0>



CONTROLITE® - Intelligent Daylighting System

Danpal®

Global company

2016

Response to Adaptation Agent

☒ Dynamic ☐ Static

Controlite® is a modular system that regulates the amount of daylight, reduces the glare and the heating/cooling demand. Therefore, it significantly contributes to reduce the energy consumption. The panel is composed by translucent glazing boards that encase rotating louvers. These adjust their position throughout the day according to the amount of daylight that is desired in the indoor space. The mechanism is regulated by two sensors: one outside the building and a second one in the indoor environment. In this way, the system can optimize its function according to both the indoor and outdoor situation.

Exterior Agent of Adaptation

- ☒ Solar radiation
☐ Temperature
☐ Humidity
☐ Wind
☐ Precipitation
☐ Noise

Interior Agent of Adaptation

- ☐ Temperature
☐ Humidity
☒ Light
☐ Air exchange rate
☐ Sound level

Purpose

- ☒ Thermal comfort
☐ IAQ
☒ Visual and Lighting
☐ Acoustic
☐ Energy production

Control of Adaptivity

- ☒ Closed loop
☐ Open loop

Energy

☒ - ☐ 0 ☐ +

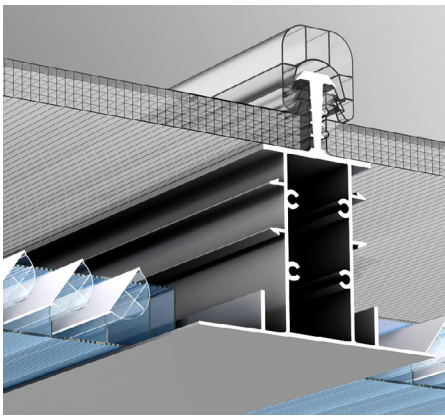
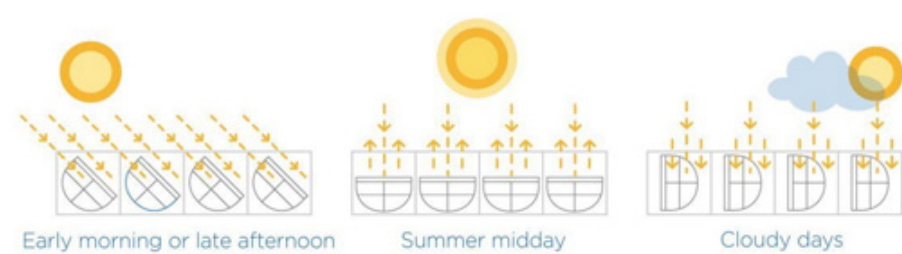
Highest cost

- ☐ Materials
☐ Production
☐ Assembly
☒ Maintenance

Architecture design freedom

- ☒ Low
☐ Medium
☐ High

LIGHT OPTIMISATION WITH THE CONTROLITE® SOLUTION



Sources: <http://www.danpal.com/products/controlite/>



White & Black Liquid Crystal Film

Gauzy

Tel Aviv - Yafo, Israel

2016

Response to Adaptation Agent

☐ Dynamic
 ☒ Static

Gauzy uses Polymer Dispersed Liquid Crystal Films for lighting control. The Company has developed different solutions that change transparency when a voltage is applied. The film has a white or dark dimming option that can be atomized or controlled by the users. A further option offered by this product is the possibility to project on the glass to have additional functions of advertisement or surface for office presentations.

Exterior Agent of Adaptation

- ☒ Solar radiation
- ☐ Temperature
- ☐ Humidity
- ☐ Wind
- ☐ Precipitation
- ☐ Noise

Interior Agent of Adaptation

- ☐ Temperature
- ☐ Humidity
- ☒ Light
- ☐ Air exchange rate
- ☐ Sound level

Purpose

- ☐ Thermal comfort
- ☐ IAQ
- ☒ Visual and Lighting
- ☐ Acoustic
- ☐ Energy production

Control of Adaptivity

- ☒ Closed loop
- ☐ Open loop

Energy

☒ -
 ☐ 0
 ☐ +

Highest cost

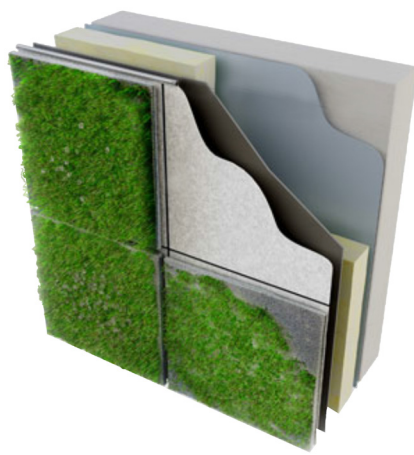
- ☒ Materials
- ☐ Production
- ☐ Assembly
- ☐ Maintenance

Architecture design freedom

- ☐ Low
- ☐ Medium
- ☒ High



Sources: www.gauzy.com



Living Wall Facade

Arup

Leeds, United Kingdom

2016

Response to Adaptation Agent

☐ Dynamic
 ☒ Static

The Living Wall Facade is an innovative zero earth system, which makes it really lightweight compared to typical green walls. In addition, hydroponics are used for the nutrients and the water delivery, thus leading to 90% reduction in water consumption. The seeds grow on site and it takes up to two months until full growth, however, it is also visually appealing without the green. The Living Wall facade improves thermal comfort due to evapotranspiration leading to energy savings, protects from direct solar radiation, dampens noise pollution, reduces air pollution and contributes substantially to the mitigation of the urban heat island effect.

Exterior Agent of Adaptation

- ☒ Solar radiation
- ☐ Temperature
- ☐ Humidity
- ☐ Wind
- ☒ Precipitation
- ☐ Noise

Interior Agent of Adaptation

- ☐ Temperature
- ☐ Humidity
- ☐ Light
- ☐ Air exchange rate
- ☐ Sound level

Purpose

- ☒ Thermal comfort
- ☐ IAQ
- ☐ Visual and Lighting
- ☒ Acoustic
- ☐ Energy production

Control of Adaptivity

- ☐ Closed loop
- ☒ Open loop

Energy

☐ -
 ☒ 0
 ☐ +

Highest cost

- ☐ Materials
- ☐ Production
- ☐ Assembly
- ☒ Maintenance

Architecture design freedom

- ☐ Low
- ☒ Medium
- ☐ High

Sources: http://greeninitiatives.cn/pdfdoc/presentation/1411885320333Innovative%20and%20Intelligent%20Facades_Jeff%20Tsal_Arup_rev.pdf



Kindow Blinds

Kindow BV

Delft, Netherlands

2017

Response to Adaptation Agent

☒ Dynamic ☐ Static

Kindow Blinds are indoor blinds that consist of vertical slats that rotate during the day thanks to a sun tracking system. The slats are made of two different materials: on one side a highly reflective material reflects the solar radiation back to the window in summer and on the other side a dark absorbing material contributes to heat gains during winter. The face exposed to the sunlight depends on the season and it is always perpendicular to the sunrays. The result is 25% of saved energy on lighting, heating and cooling.

Exterior Agent of Adaptation

- ☒ Solar radiation
- ☐ Temperature
- ☐ Humidity
- ☐ Wind
- ☐ Precipitation
- ☐ Noise

Control of Adaptivity

- ☒ Closed loop
- ☐ Open loop

Energy

- ☒ - ☐ 0 ☐ +

Interior Agent of Adaptation

- ☐ Temperature
- ☐ Humidity
- ☐ Light
- ☐ Air exchange rate
- ☐ Sound level

Highest cost

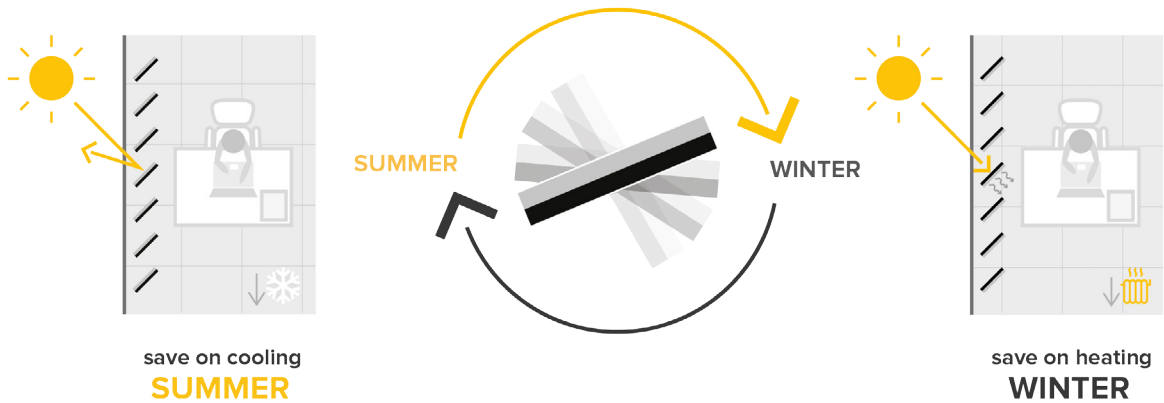
- ☒ Materials
- ☐ Production
- ☐ Assembly
- ☐ Maintenance

Purpose

- ☒ Thermal comfort
- ☐ IAQ
- ☒ Visual and Lighting
- ☐ Acoustic
- ☐ Energy production

Architecture design freedom

- ☐ Low
- ☒ Medium
- ☐ High



Sources: www.kindowblinds.com

RESEARCH PROJECTS



Living Glass

Soo-in Yang and David Benjamin

2005

Response to Adaptation Agent
☒ Dynamic ☐ Static

Living Glass is a material that monitors CO₂ concentration in the air by opening and closing in response to the human presence. This is a thin transparent element that does not require mechanical input to work, but its movement is regulated by a silicon surface embedded with Dynalloy Flexinol wires that contracts under electrical stimulus. This happens when the percentage of carbon dioxide is high and works like a breathing skin.

Exterior Agent of Adaptation

- ☐ Solar radiation
- ☐ Temperature
- ☐ Humidity
- ☐ Wind
- ☐ Precipitation
- ☐ Noise

Interior Agent of Adaptation

- ☐ Temperature
- ☐ Humidity
- ☐ Light
- ☒ Air exchange rate
- ☐ Sound level

Purpose

- ☐ Thermal comfort
- ☒ IAQ
- ☐ Visual and Lighting
- ☐ Acoustic
- ☐ Energy production

Control of Adaptivity

- ☒ Closed loop
- ☐ Open loop

Energy

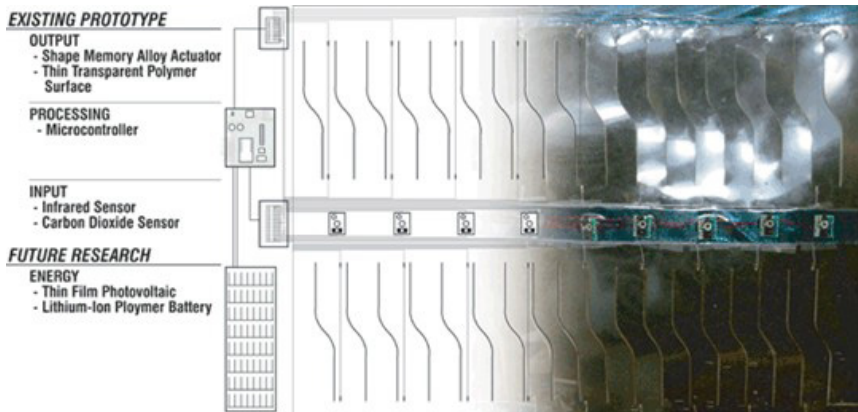
- ☒ - ☐ 0 ☐ +

Highest cost

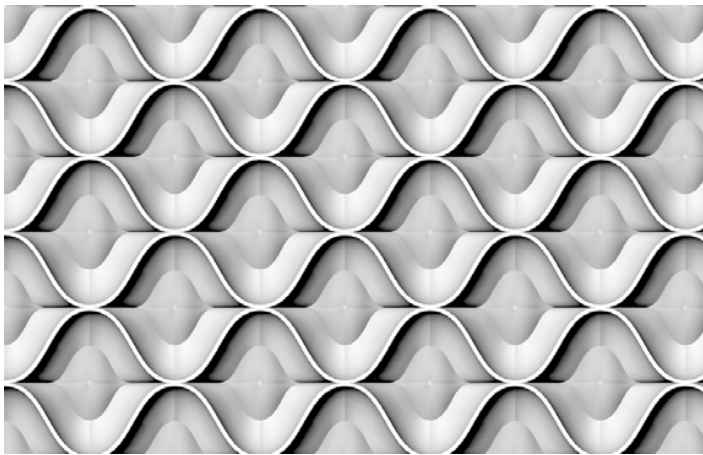
- ☒ Materials
- ☐ Production
- ☐ Assembly
- ☐ Maintenance

Architecture design freedom

- ☐ Low
- ☒ Medium
- ☐ High



Sources: <https://inhabitat.com/carbon-dioxide-sensing-living-glass/>:



Bionic breathing skin

L. Badarnah & U. Knaack

Department of Building Technology, Delft University of Technology, Delft, The Netherlands

2007

Response to Adaptation Agent
☒ Dynamic ☐ Static

The bionic breathing skin has been inspired by the sponge principle. It is composed by three layers assembled in a way that when they are deformed, a difference of pressure is created that allows the introduction and expulsion of air. The expansion and contraction of the layers is generated by piezoelectric wires and the amount of air exchanged is due to the velocity of the deformation. The air exchanged helps in the regulation of the indoor climate.

Exterior Agent of Adaptation

- ☐ Solar radiation
- ☐ Temperature
- ☐ Humidity
- ☐ Wind
- ☐ Precipitation
- ☐ Noise

Interior Agent of Adaptation

- ☐ Temperature
- ☐ Humidity
- ☐ Light
- ☒ Air exchange rate
- ☐ Sound level

Purpose

- ☐ Thermal comfort
- ☒ IAQ
- ☐ Visual and Lighting
- ☐ Acoustic
- ☐ Energy production

Control of Adaptivity

- ☒ Closed loop
- ☐ Open loop

Energy

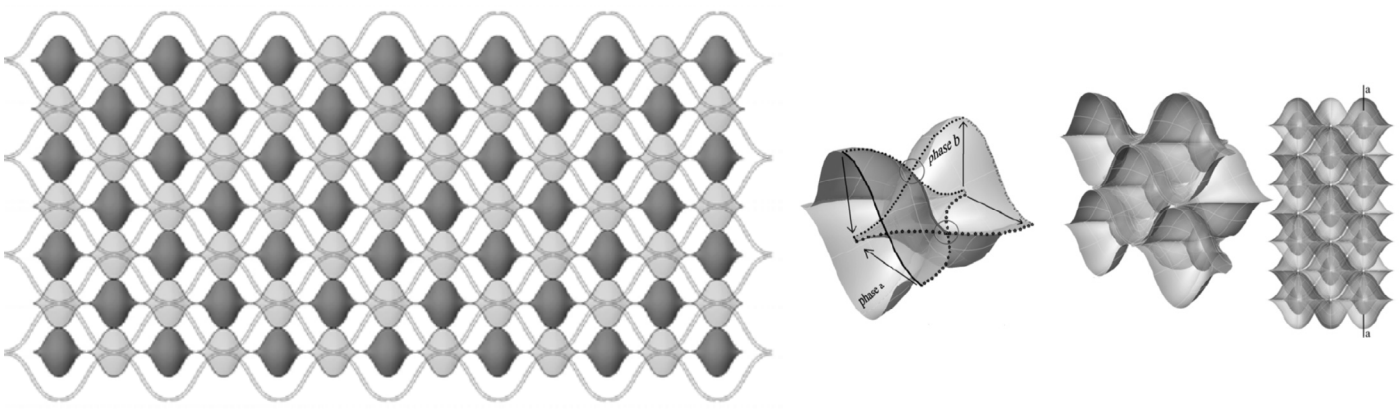
- ☒ - ☐ 0 ☐ +

Highest cost

- ☐ Materials
- ☐ Production
- ☒ Assembly
- ☐ Maintenance

Architecture design freedom

- ☐ Low
- ☒ Medium
- ☐ High



Sources: https://www.researchgate.net/publication/278667232_Bionic_breathing_skin_for_buildings



ACTRESS (Active RESponsive and Solar)

TEBE Research Group, Department of Energy

Politenico di Torino, Torino, Italy

2007

Response to Adaptation Agent

☐ Dynamic ☒ Static

ACTRESS is a multi-functional facade module (MFM) with “standalone attitude” which incorporates different technologies with the aim of improving the building’s energy efficiency and converting energy from renewable energy sources (RES). It is comprised of an opaque (OSM) and a transparent sub module (TSM) which consist of various different material layers. The opaque sub module can be operated as a thermal buffer or as a supply air facade in the winter and as an outdoor air curtain facade during summer. The transparent sub module is made up of two different triple glazing systems. An ACTRESS module was tested in Torino for almost two years and the conclusions showed that it is “energy positive”.

Exterior Agent of Adaptation

- ☒ Solar radiation
- ☒ Temperature
- ☐ Humidity
- ☐ Wind
- ☐ Precipitation
- ☐ Noise

Interior Agent of Adaptation

- ☒ Temperature
- ☐ Humidity
- ☐ Light
- ☒ Air exchange rate
- ☐ Sound level

Purpose

- ☒ Thermal comfort
- ☐ IAQ
- ☐ Visual and Lighting
- ☐ Acoustic
- ☒ Energy production

Control of Adaptivity

- ☐ Closed loop
- ☒ Open loop

Energy

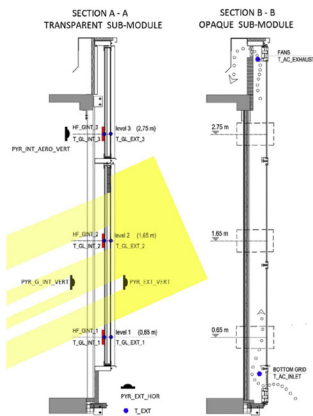
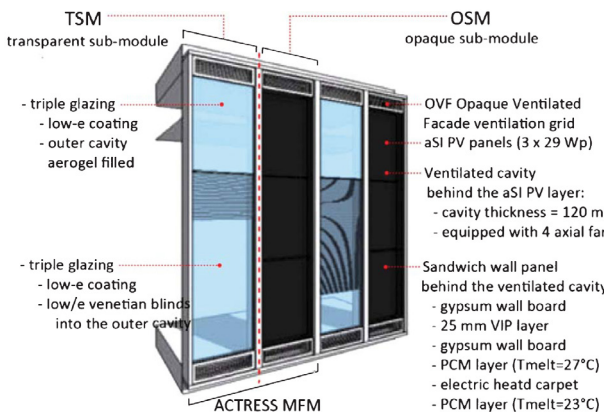
☐ - ☐ 0 ☒ +

Highest cost

- ☒ Materials
- ☐ Production
- ☐ Assembly
- ☐ Maintenance

Architecture design freedom

- ☐ Low
- ☐ Medium
- ☒ High



Sources: Favoino, F., et al. (2014). “Experimental assessment of the energy performance of an advanced responsive multifunctional façade module.” Energy and Buildings 68(Part B): 647-659.



Bloom

DO|SU Studio Architecture

Materials & Application Gallery, Los Angeles, California

2011

Response to Adaptation Agent

☒ Dynamic ☐ Static

Bloom is a temporary sun tracking installation inspired by mimicking the human body and it is not technically a facade but a similar technique could be applied in buildings in the near future. Bloom combines together material experimentation, structural innovation, and computational form and pattern resulting into an environmentally responsive form. The sun shade is made by thermobimetal, which is a laminated material composed of two different metals that react differently when exposed to sunlight, causing thus a curling effect. Consequently, specific areas of the shell are ventilated when the sun heats up its surface. The structure is self-supporting and it is composed of 414 hyperbolic paraboloid-shaped stacked panels, which combine a double-ruled surface of bimetal tiles with an interlocking, folded aluminum frame system.

Exterior Agent of Adaptation

- ☒ Solar radiation
- ☒ Temperature
- ☐ Humidity
- ☐ Wind
- ☐ Precipitation
- ☐ Noise

Interior Agent of Adaptation

- ☐ Temperature
- ☐ Humidity
- ☐ Light
- ☐ Air exchange rate
- ☐ Sound level

Purpose

- ☒ Thermal comfort
- ☒ IAQ
- ☐ Visual and Lighting
- ☐ Acoustic
- ☐ Energy production

Control of Adaptivity

- ☐ Closed loop
- ☒ Open loop

Energy

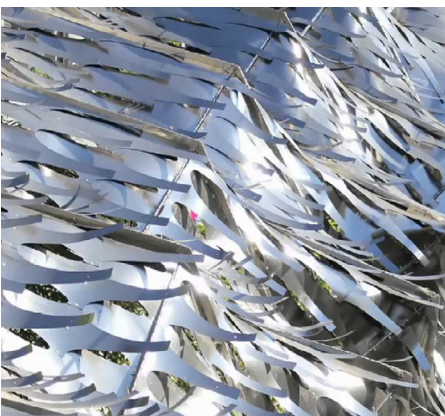
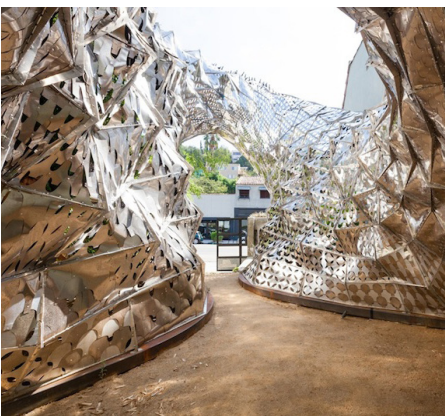
☐ - ☒ 0 ☐ +

Highest cost

- ☐ Materials
- ☐ Production
- ☒ Assembly
- ☐ Maintenance

Architecture design freedom

- ☐ Low
- ☐ Medium
- ☒ High



Sources: <http://dosu-arch.com/bloom.html>
<https://www.archdaily.com/215280/bloom-dosu-studio-architecture>



ADAPTIWALL (Multi-functional light-weight WALL panel based on ADAPTive Insulation and nanomaterials for energy efficient buildings)

TNO Delft & Partners

Delft, The Netherlands

2012

Response to Adaptation Agent

☐ Dynamic ☒ Static

ADAPTIWALL project is a climate adaptive multi-functional lightweight prefab panel suitable for the construction of cost-efficient, rapid and energy efficient facades. This facade is able to reduce heating and cooling demand by 50-80% compared to typical highly insulating solutions and it is also able to almost eliminate auxiliary heat recovery and ventilation installations. The core element of the panel is a load-bearing, lightweight concrete layer, which is used as a buffer to store heat and cold. Moreover, adaptive insulation consisting of non-traditional polymer materials is installed on both sides of the buffer, in order to control the heat flows. In addition, a total heat exchanger is used to provide compact ventilation and an energy recovery system. The cladding and windows are not considered as key components, however, a glass cladding and a solar collector are used to collect energy.

Exterior Agent of Adaptation

- ☒ Solar radiation
- ☐ Temperature
- ☐ Humidity
- ☐ Wind
- ☐ Precipitation
- ☐ Noise

Control of Adaptivity

- ☒ Closed loop
- ☒ Open loop

Energy

☐ - ☐ 0 ☒ +

Interior Agent of Adaptation

- ☒ Temperature
- ☐ Humidity
- ☐ Light
- ☐ Air exchange rate
- ☐ Sound level

Highest cost

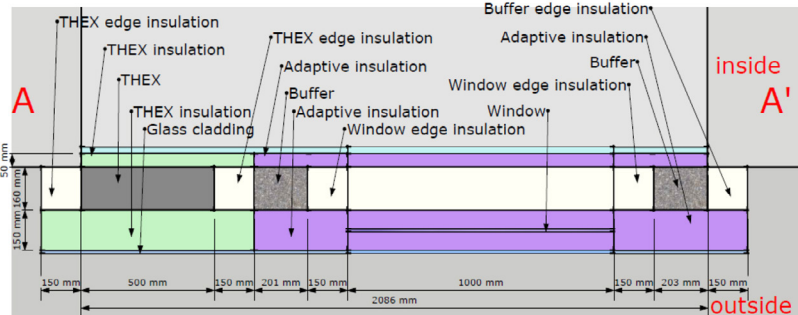
- ☐ Materials
- ☐ Production
- ☐ Assembly
- ☒ Maintenance

Purpose

- ☒ Thermal comfort
- ☒ IAQ
- ☐ Visual and Lighting
- ☐ Acoustic
- ☒ Energy production

Architecture design freedom

- ☐ Low
- ☒ Medium
- ☐ High



Sources: <http://www.adaptiwall.eu/mainmenu/home/>



MeeFS (Multifunctional energy efficient Facade System for building retrofitting)

Acciona Infraestructuras

Spain

2012

Response to Adaptation Agent

☐ Dynamic ☒ Static

The MeeFS project is a multifunctional energy efficient façade system for building retrofitting. This new system will allow a 27% reduction of the total energy demand, in order to increase energy efficiency and indoor comfort of residential buildings in European climate zones. It will incorporate innovative solutions by means of active and passive technologies solutions combination. The MeeFS project consists of seven technological units - insulation, green façade, ventilated façade, solar protection, building-integrated photovoltaics (BIPV), an advanced passive solar protector/energy absorption auto mobile unit, and an advanced passive solar collector/ventilation module. These technological units have both opaque and transparent properties and are integrated into modules and then into structural panels and into existing facades. The project was demonstrated in a real building in Spain.

Exterior Agent of Adaptation

- ☒ Solar radiation
- ☐ Temperature
- ☐ Humidity
- ☐ Wind
- ☒ Precipitation
- ☐ Noise

Control of Adaptivity

- ☒ Closed loop
- ☒ Open loop

Energy

☐ - ☐ 0 ☒ +

Interior Agent of Adaptation

- ☐ Temperature
- ☐ Humidity
- ☐ Light
- ☐ Air exchange rate
- ☐ Sound level

Highest cost

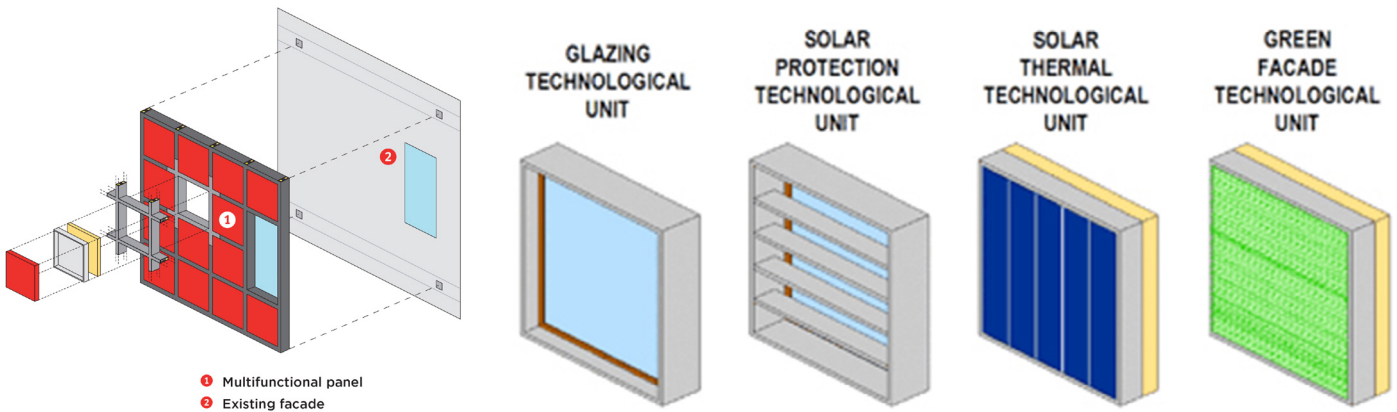
- ☐ Materials
- ☐ Production
- ☐ Assembly
- ☒ Maintenance

Purpose

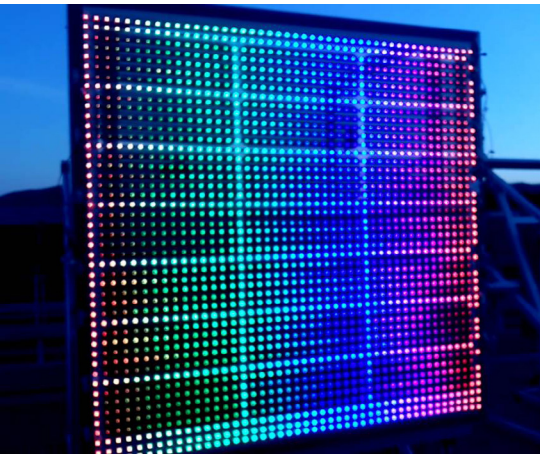
- ☒ Thermal comfort
- ☒ IAQ
- ☒ Visual and Lighting
- ☐ Acoustic
- ☒ Energy production

Architecture design freedom

- ☐ Low
- ☒ Medium
- ☐ High



Sources: <http://www.meeFS-retrofitting.eu/>



ETFE Multifunctional Modules

European Commission department

Europe

2014

Response to Adaptation Agent

☐ Dynamic ☒ Static

The ETFE-MFM project project is developing a multifunctional ETFE (Ethylene TetraFluoroEthylene) module with integrated photovoltaics and LED technologies, for sustainable architectural facade lighting. The ETFE multifunctional module will generate electricity during the day, in order to power its LEDs at night, giving a boost to the emerging field of Building Integrated Photovoltaics. Moreover, this module acts as a glazing system and has external battery storage, while it also includes flexible integrated control devices and a high architectural flexibility.

Exterior Agent of Adaptation

- ☒ Solar radiation
- ☐ Temperature
- ☐ Humidity
- ☐ Wind
- ☐ Precipitation
- ☐ Noise

Interior Agent of Adaptation

- ☐ Temperature
- ☐ Humidity
- ☐ Light
- ☐ Air exchange rate
- ☐ Sound level

Purpose

- ☐ Thermal comfort
- ☐ IAQ
- ☐ Visual and Lighting
- ☐ Acoustic
- ☒ Energy production

Control of Adaptivity

- ☐ Closed loop
- ☒ Open loop

Energy

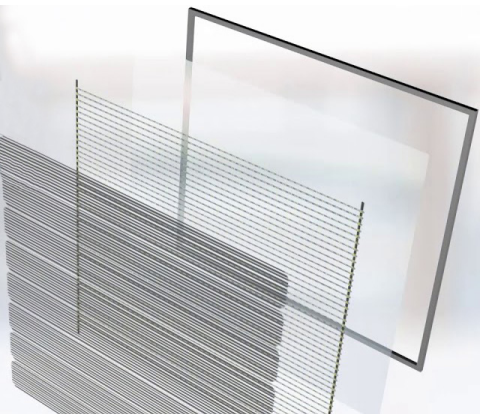
☐ - ☐ 0 ☒ +

Highest cost

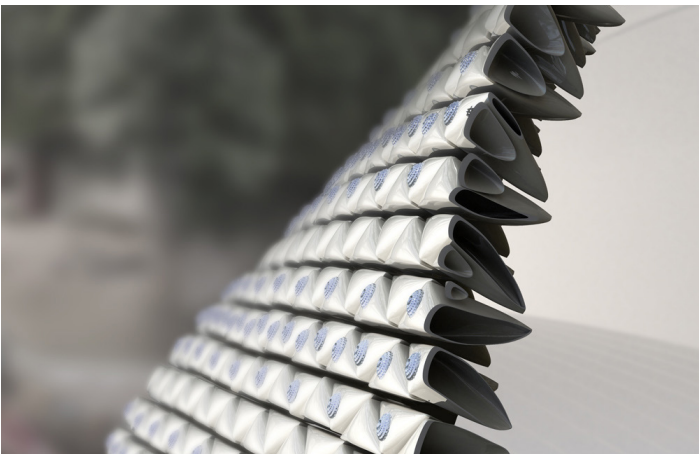
- ☐ Materials
- ☐ Production
- ☐ Assembly
- ☒ Maintenance

Architecture design freedom

- ☐ Low
- ☐ Medium
- ☒ High



Sources: <http://www.etfe-mfm.eu/>



SABER (Self-Activated Building Envelope Regulation)

BIOMS team of researchers

University of California, Berkeley

2014

Response to Adaptation Agent

☒ Dynamic ☐ Static

SABER is a new membrane that wraps around a building and it is inspired by the human skin that is able to breathe with the aim of a fully self-regulating system. Resembling the pores of the skin, the membrane is filled with micro-scale valves and lenses that open and close as they sense light, heat, and humidity. It works with a geometrical network of a temperature-responsive phase-change hydrogel capable of swelling or shrinking at a given temperature, releasing or absorbing water vapour. The facade does not require an external power and it offers hygrothermal and light transmission control. This membrane is a net zero cooling option, which doesn't actually cool the air, but it makes buildings in hot, humid tropical countries more comfortable.

Exterior Agent of Adaptation

- ☒ Solar radiation
- ☒ Temperature
- ☒ Humidity
- ☐ Wind
- ☐ Precipitation
- ☐ Noise

Interior Agent of Adaptation

- ☒ Temperature
- ☐ Humidity
- ☐ Light
- ☐ Air exchange rate
- ☐ Sound level

Purpose

- ☒ Thermal comfort
- ☒ IAQ
- ☒ Visual and Lighting
- ☐ Acoustic
- ☐ Energy production

Control of Adaptivity

- ☐ Closed loop
- ☒ Open loop

Energy

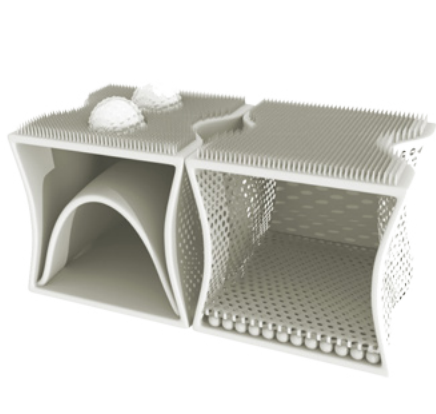
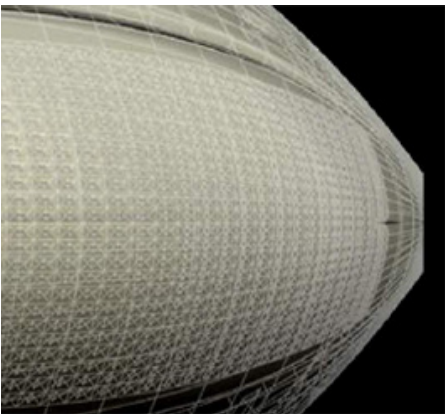
☐ - ☒ 0 ☐ +

Highest cost

- ☐ Materials
- ☒ Production
- ☐ Assembly
- ☐ Maintenance

Architecture design freedom

- ☐ Low
- ☒ Medium
- ☐ High



Sources: Casini, M. (2016). 6 - Advanced building skin. Smart Buildings, Woodhead Publishing: 219-245.
<https://materia.nl/article/saber-self-cooling-material/>



BRESAER (BREakthrough Solutions for Adaptable Envelopes in building Refurbishment)

Acciona Infraestructuras & Partners

Spain

2015

Response to Adaptation Agent

☐ Dynamic ☒ Static

BRESAER project is an innovative envelope system that combines active and passive components, integrating them into a lightweight structural mesh. It is composed of multifunctional and multilayer insulation panels made of Ultra High Performance Fibre Reinforced Concrete, multifunctional lightweight ventilated facade modules and dynamic automated windows with insulated solar blinds, which adjust automatically according to the position of the sun and the occupants comfort. In addition, Combined Solar Thermal Air and PV envelope components are used for indoor space heating and ventilation, thermal insulation and electricity generation. Moreover, preheated air can be used for indoor space heating and dehumidification. The project is tested in four virtual demonstrations located in different European climate zones and a real one in Ankara, Turkey, expecting to record a reduction by at least 60% of the total primary building's energy consumption and to reach a near zero energy building.

Exterior Agent of Adaptation

- ☒ Solar radiation
- ☐ Temperature
- ☐ Humidity
- ☐ Wind
- ☐ Precipitation
- ☐ Noise

Interior Agent of Adaptation

- ☐ Temperature
- ☐ Humidity
- ☒ Light
- ☐ Air exchange rate
- ☐ Sound level

Purpose

- ☒ Thermal comfort
- ☒ IAQ
- ☒ Visual and Lighting
- ☐ Acoustic
- ☒ Energy production

Control of Adaptivity

- ☒ Closed loop
- ☒ Open loop

Energy

☐ - ☐ 0 ☒ +

Highest cost

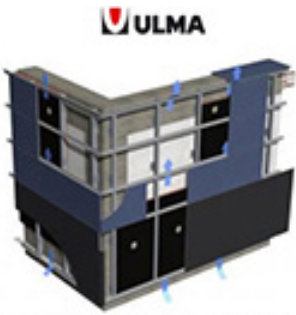
- ☒ Materials
- ☐ Production
- ☐ Assembly
- ☐ Maintenance

Architecture design freedom

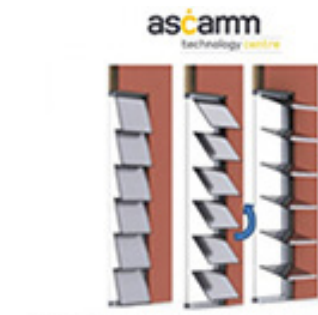
- ☐ Low
- ☒ Medium
- ☐ High



Combined solar thermal and PV envelope component



Multifunctional lightweight ventilated facade module

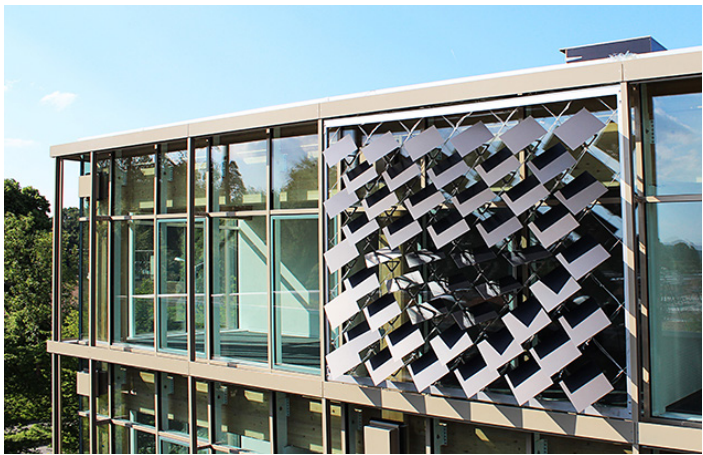


Dynamic window with controlled air-tightness and insulated solar blinds



Multifunctional UHPFRC panels for envelope

Sources: <http://www.bresaer.eu/about/>



Adaptive Solar Facade

ETH Foundation

House of Natural Resources (HoNR), Zurich, Switzerland

2015

Response to Adaptation Agent

☒ Dynamic ☐ Static

The ETH House of Natural Resources (HoNR) develops, implements and monitors in-situ novel façade elements and innovative structural elements made of wood at original scale. The facade includes several new technologies: adaptive solar facade, facade control and user interaction, soft robotic actuators, wooden solar trackers. The building envelope allows for active shading and glare reduction, daylight distribution, and sun tracking and energy generation. It is conceived as a modular system, which allows these functions to be distributed and mixed across the envelope and even across a window in the most optimal way. This results in a dynamic multifunctional envelope, which increases the building's energy performance and the user's comfort.

Exterior Agent of Adaptation

- ☒ Solar radiation
- ☐ Temperature
- ☐ Humidity
- ☐ Wind
- ☐ Precipitation
- ☐ Noise

Interior Agent of Adaptation

- ☐ Temperature
- ☐ Humidity
- ☐ Light
- ☐ Air exchange rate
- ☐ Sound level

Purpose

- ☒ Thermal comfort
- ☐ IAQ
- ☒ Visual and Lighting
- ☐ Acoustic
- ☒ Energy production

Control of Adaptivity

- ☒ Closed loop
- ☐ Open loop

Energy

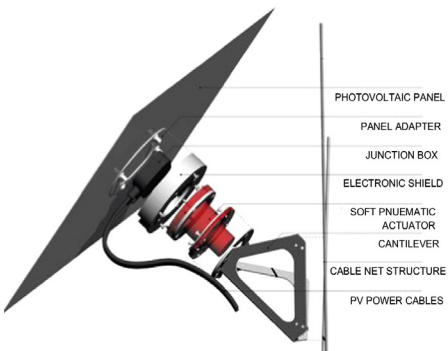
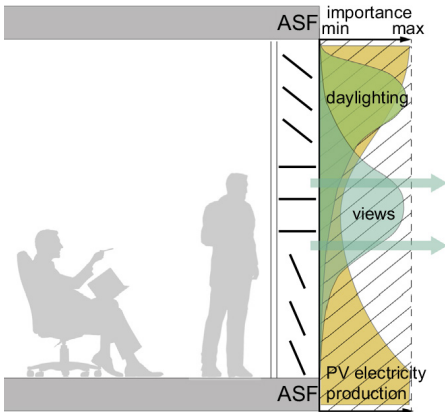
☐ - ☐ 0 ☒ +

Highest cost

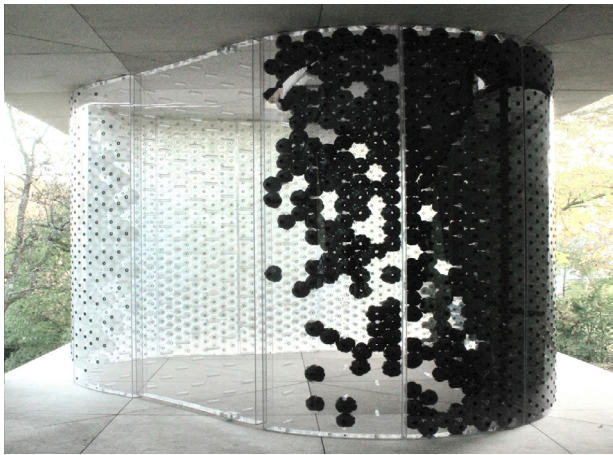
- ☐ Materials
- ☐ Production
- ☐ Assembly
- ☒ Maintenance

Architecture design freedom

- ☒ Low
- ☐ Medium
- ☐ High



Sources: <http://www.honr.ethz.ch/en/the-group/facade/solar-facade.html>
Nagy, Z., et al. (2016). "The Adaptive Solar Facade: From concept to prototypes." Frontiers of Architectural Research 5(2): 143-156.



Breathing Skins

Tobias Becker

Mandelbachtal, Germany

2015

Response to Adaptation Agent

- ☒ Dynamic ☐ Static

The project “Breathing Skins” is based on the concept of biomimicry. Like the skin’s pores open and close, the organic skins of this pneumatic facade technology adjust their permeability to control the necessary flow of light, matter and temperature between the inside and the outside. This way, the building skin “breathes” by changing constantly its appearance and thus providing an interesting interplay between the interior and exterior environment. On every square meter of breathing skin there are placed 140 air channels, described by Tobias Becker as “pneumatic muscles”, which are sandwiched between two glass surfaces. In order for these muscles to open, a small energetic input is required to create a slight underpressure so as to provide the desirable indoor conditions according to the users’ preferences. The project offers customization since the glass panels can have different geometric configurations and the “peumatic muscles” offer different color possibilities.

Exterior Agent of Adaptation

- ☒ Solar radiation
☒ Temperature
☒ Humidity
☐ Wind
☐ Precipitation
☐ Noise

Interior Agent of Adaptation

- ☒ Temperature
☐ Humidity
☐ Light
☒ Air exchange rate
☐ Sound level

Purpose

- ☒ Thermal comfort
☒ IAQ
☒ Visual and Lighting
☐ Acoustic
☐ Energy production

Control of Adaptivity

- ☒ Closed loop
☐ Open loop

Energy

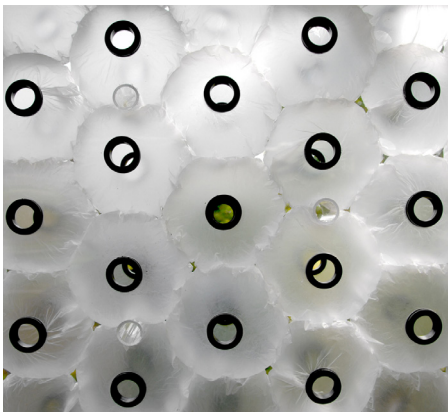
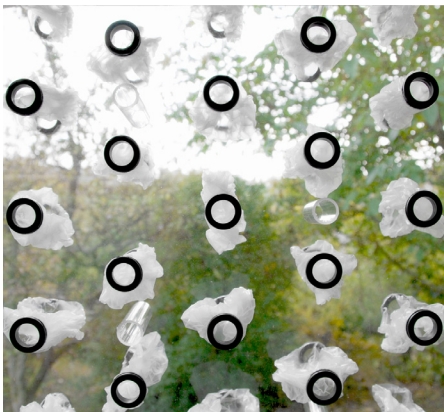
- ☒ - ☐ 0 ☐ +

Highest cost

- ☐ Materials
☐ Production
☒ Assembly
☒ Maintenance

Architecture design freedom

- ☐ Low
☒ Medium
☐ High



Sources: <https://www.breathingskins.com/>



SELFIE (Smart and Efficient Layers for Innovative Envelopes)

Italian Ministry of University and Research & Regional Administration of Tuscany

University of Florence, Florence, Italy

2016

Response to Adaptation Agent

- ☐ Dynamic ☒ Static

SELFIE facade is a unitized curtain wall system that allows not only easy on-site installation but also customization through the possibility of the modular components to be placed with different geometric configurations, different types of materials and different colors. SELFIE facade consists of three different components, two opaque and one transparent with various different material layers. All three components have integrated sensors and equipment for data management, in order to guarantee a smart control of energy flows inside the building envelope and to ensure the ability of changing their energy performance according to external climatic conditions.

Exterior Agent of Adaptation

- ☒ Solar radiation
☒ Temperature
☐ Humidity
☐ Wind
☒ Precipitation
☐ Noise

Interior Agent of Adaptation

- ☒ Temperature
☐ Humidity
☐ Light
☒ Air exchange rate
☐ Sound level

Purpose

- ☒ Thermal comfort
☐ IAQ
☐ Visual and Lighting
☐ Acoustic
☒ Energy production

Control of Adaptivity

- ☐ Closed loop
☒ Open loop

Energy

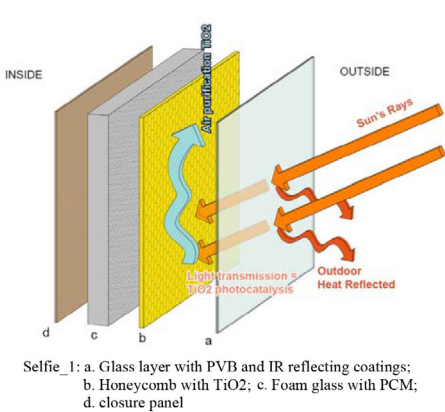
- ☐ - ☒ 0 ☐ +

Highest cost

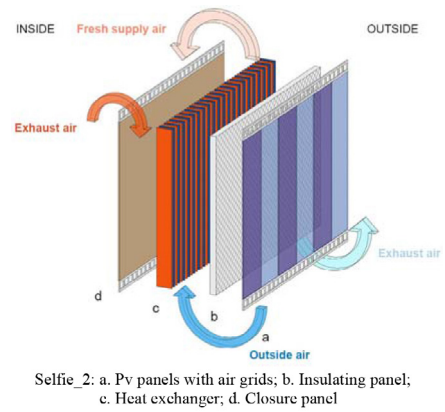
- ☒ Materials
☐ Production
☐ Assembly
☐ Maintenance

Architecture design freedom

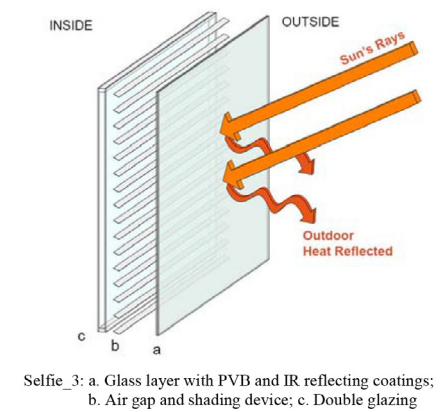
- ☐ Low
☐ Medium
☒ High



Selfie_1: a. Glass layer with PVB and IR reflecting coatings; b. Honeycomb with TiO₂; c. Foam glass with PCM; d. closure panel



Selfie_2: a. Pv panels with air grids; b. Insulating panel; c. Heat exchanger; d. Closure panel



Selfie_3: a. Glass layer with PVB and IR reflecting coatings; b. Air gap and shading device; c. Double glazing

Sources: Romano, R. and P. Gallo (2016). “The SELFIE Project Smart and efficient envelope’ system for nearly zero energy buildings in the Mediterranean Area.”



Allwater Panel

Allwater Ltd

Kecskemét, Hungary

2017

Response to Adaptation Agent

☐ Dynamic ☒ Static

The product is a panel composed of two layers of glass and a cavity filled with water. The element works as a thermal mass thanks to the property of water to store heat. The heat collected can be transported by the water into a storage system and used later in winter. The same process can be applied in winter to cool down the temperature during summer. Because the water is free to move in the facade, a uniform thermal balance is assured. A positive aspect is that the panel can be built and assempled empty and later filled with water, making the production and construction process easier. Moreover, because of the transparency of water, the outside view is not obstructed and the natural light can almost entirely enter into the building.

Exterior Agent of Adaptation

- ☒ Solar radiation
- ☒ Temperature
- ☐ Humidity
- ☐ Wind
- ☐ Precipitation
- ☐ Noise

Interior Agent of Adaptation

- ☐ Temperature
- ☐ Humidity
- ☐ Light
- ☐ Air exchange rate
- ☐ Sound level

Purpose

- ☒ Thermal comfort
- ☐ IAQ
- ☐ Visual and Lighting
- ☐ Acoustic
- ☐ Energy production

Control of Adaptivity

- ☐ Closed loop
- ☒ Open loop

Energy

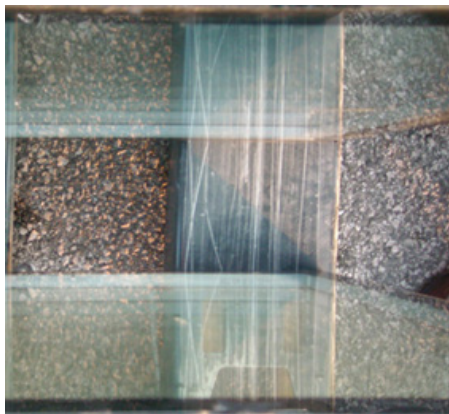
☐ - ☐ 0 ☒ +

Highest cost

- ☐ Materials
- ☐ Production
- ☐ Assembly
- ☒ Maintenance

Architecture design freedom

- ☐ Low
- ☒ Medium
- ☐ High



Sources: http://allwater.hu/?page_id=278



Polyarch

TU Delft and TU/e

Delft and Eindhoven, Netherlands

2017

Response to Adaptation Agent

☐ Dynamic ☒ Static

Polyarch is a project developed by TU Delft in collaboration with the Department of Functional Organic Materials and Devices at the TU/e. The goal is the production of a responsive coating of Cholesteric Liquid Crystals. This technology operates on the Infrared spectrum, resulting invisible to the human eye. The result is an adaptive coating that controls the amount of solar heat gain entering the building, working as a thermal regulator and reducing the energy required for heating and cooling. The product has still to be further developed to eliminate some drawback like the dependency on the light angle that can cause a colour disturbance at some incident light angles.

Exterior Agent of Adaptation

- ☒ Solar radiation
- ☐ Temperature
- ☐ Humidity
- ☐ Wind
- ☐ Precipitation
- ☐ Noise

Interior Agent of Adaptation

- ☒ Temperature
- ☐ Humidity
- ☐ Light
- ☐ Air exchange rate
- ☐ Sound level

Purpose

- ☒ Thermal comfort
- ☐ IAQ
- ☐ Visual and Lighting
- ☐ Acoustic
- ☐ Energy production

Control of Adaptivity

- ☒ Closed loop
- ☐ Open loop

Energy

☒ - ☐ 0 ☐ +

Highest cost

- ☒ Materials
- ☐ Production
- ☐ Assembly
- ☐ Maintenance

Architecture design freedom

- ☐ Low
- ☐ Medium
- ☒ High



Sources: <https://www.4tu.nl/bouw/en/LHP2015/Polyarch/>

APPENDIX B

CLASSIFICATION RESULTS OF APPENDIX A
IN COLLABORATION WITH SHIRIN MASOUDI

Response to adaptation agent	
Dynamic	20
Static	8

External Agent of Adaptivity	
Solar radiation	27
Temperature	2
Humidity	0
Wind	2
Precipitation	4
Noise	0

Interior Agent of Adaptivity	
Temperature	3
Humidity	0
Light	3
Air exchange rate	5
Sound level	0

Purpose	
Thermal comfort	22
IAQ	6
Visual and Lighting	27
Acoustic	0
Energy production	6

Control od Adaptivity	
Closed loop	23
Open loop	5

Highest Cost	
Materials	5
Production	7
Assembly	10
Maitenance	13

Architectural Design Freedom	
Low	4
Medium	16
High	8

Energy	
-	18
0	4
+	6

Table B1: Classification Summary of Buildings

Response to adaptation agent	
Dynamic	7
Static	12

External Agent of Adaptivity	
Solar radiation	19
Temperature	6
Humidity	1
Wind	0
Precipitation	1
Noise	0

Interior Agent of Adaptivity	
Temperature	10
Humidity	1
Light	6
Air exchange rate	6
Sound level	0

Purpose	
Thermal comfort	17
IAQ	5
Visual and Lighting	16
Acoustic	1
Energy production	5

Control od Adaptivity	
Closed loop	17
Open loop	2

Highest Cost	
Materials	7
Production	3
Assembly	1
Maitenance	10

Architectural Design Freedom	
Low	2
Medium	13
High	4

Energy	
-	11
0	3
+	6

Table B2: Classification Summary of Products

Response to adaptation agent	
Dynamic	6
Static	8

External Agent of Adaptivity	
Solar radiation	12
Temperature	6
Humidity	2
Wind	0
Precipitation	2
Noise	0

Interior Agent of Adaptivity	
Temperature	6
Humidity	0
Light	1
Air exchange rate	6
Sound level	0

Purpose	
Thermal comfort	11
IAQ	8
Visual and Lighting	5
Acoustic	0
Energy production	6

Control od Adaptivity	
Closed loop	8
Open loop	9

Highest Cost	
Materials	5
Production	1
Assembly	3
Maitenance	6

Architectural Design Freedom	
Low	1
Medium	8
High	5

Energy	
-	4
0	3
+	7

Table B3: Classification Summary of Research Projects

APPENDIX C
INTERVIEWS WITH ARCHITECTS
IN COLLABORATION WITH SHIRIN MASOUDI

Questionnaire Introduction

The façade accounts for the biggest part of energy consumption of a building. Therefore, a major challenge is to design the façade for minimum energy demand for heating, cooling, ventilation and lighting through maximum exploitation of the natural energy flows. By 2020 there is the requirement of ZEB or nZEB and adaptive facades seem to be a promising solution to achieve this goal towards the objective of a “smart, sustainable and inclusive” building industry.

The goal of the first research and the questionnaire is to understand what the actual relationship is between the available products and the design requirements of the architects. Do the architects think that the products available are satisfactory according to the current design needs? What do the architects consider as state-of-the-art nowadays?

The following questionnaire intends to get an insight to the architect’s opinion on this topic.

1st interview

Name: *Stephan Verkuijen*
Architect at wv studio & TU Delft Lecturer

Q1: What is your opinion about adaptive facades? Do you believe that adaptive façades really improve the performance of a building or a passive design would be adequate?

A1: *I think it is obvious that adaptive facades could really improve performance of a building*

Q2: Have you already applied adaptive solutions in your designs and in what extent? If so, do you calculate and monitor the performance of adaptive facades and how does this influence your decisions? What do you calculate and how do you monitor it if you do so?

A2: *Of course, opening windows and sun shading are very basic forms of adaptive facades and I have used these techniques many times. I have never used a more technologically advanced adaptive façade system.*

Q3: Are you aware of the adaptive facade systems that are already available in the market and do you think they would be prone to restrict your design freedom or contribute to the design quality of the project?

A3: *Again, opening windows (automatic or manual) and sun shading (automatic or manual) are readily available. These are basic forms of adaptive facades. Making use of a system restricts design freedom, but this doesn't make the design*

of a façade worse. A design restriction or design parameter (which is actually the same thing) can improve design.

Q4: Would you sacrifice performance in virtue of design purposes and how do you think they should be combined?

A4: *I do not understand the question, do you mean aesthetics instead of design? For me a well designed façade performs well. If it doesn't, it is not designed very well. When designing a building you have to take many design parameters into account. There is always a bit of give and take between the different parameters.*

Q5: Put the following aspects that an adaptive façade should regulate in order of importance (1 being the most important and 5 being the least)

___ thermal performance

___ energy production

___ visual and lighting

___ acoustic

___ indoor air quality

A5: *All equally important although air quality can also be dealt with by other systems in the building.*

Q6: Which of the above parameters would you like to be combined in a product?

Q6: *All of them*

Q7: Where do you think the market should orient itself from a product production point of view? Do you think there are aspects that are being neglected?

A7: *Adaptive facades usually focus on office buildings. Residential buildings are just as important. Consider what an adaptive façade can do for the design of the building interior. Make sure the adaptive façade is not just a bolt-on machine but an integral part of the building.*

Q8: Adaptive façades are strongly connected with customization but there are also already studies about Multi-functional Façade Modules (MFM). MFM is a category of Advanced Integrated Facades (AIF) and it is a development of integrated and modular multifunctional systems which incorporate different technologies with the aim of energy efficiency. They consist of prefabricated units with several functionalized layers which can be assembled with several combinations depending on the architectural design. Would you consider that a unitized system is adaptive?

A8: *It can be designed to be adaptive.*

Q9: What is in your opinion the future of adaptive facades?

A9: *An adaptive façade with high performance, low maintenance and durability will have a future. Use movable mechanical parts as little as possible as they can break.*

2nd interview

Name: Frank Schnater
Architect owner of RSW Architecten & TU Delft
Lecturer

Q1: What is your opinion about adaptive facades?
Do you believe that adaptive façades really improve the performance of a building or a passive design would be adequate?

A1: Adaptive facades regulate a lot of things and they incorporate automated aspects. There are already traditional forms of adaptive elements, like windows. Moreover, the use of sensors is involved in the adaptive facades. In general, I believe it is a good thing.

Q2: Have you already applied adaptive solutions in your designs and in what extent? If so, do you calculate and monitor the performance of adaptive facades and how does this influence your decisions? What do you calculate and how do you monitor it if you do so?

A2: I have used sunshading, screens, adaptive louvers, CO2 sensors, operable windows and register, which operates manually. I haven't monitored their performance.

Q3: Are you aware of the adaptive facade systems that are already available in the market and do you think they would be prone to restrict your design freedom or contribute to the design quality of the project?

A3: I am aware of the systems that I have already

used like automatic louvers and screening. I also know about electric glass, however, it is very costly. I believe that these systems are very adaptable, easy to apply and can fit to any size so they provide freedom.

Q4: Would you sacrifice performance in virtue of design purposes and how do you think they should be combined?

A4: No, I wouldn't. I believe that a good design comes from the performance and that it is technically driven so they are strongly combined.

Q5: Put the following aspects that an adaptive façade should regulate in order of importance (1 being the most important and 5 being the least)

2 thermal performance

5 energy production

1 visual and lighting

3 acoustic

4 indoor air quality

Q6: Which of the above parameters would you like to be combined in a product?

A6: Thermal performance & IAQ

Acoustics & visual (if you open a window...)

Q7: Where do you think the market should orient itself from a product production point of view?

Do you think there are aspects that are being neglected?

A7: I think that the market should orient itself to user friendliness and user control and adaptability. The user should be able to regulate easily the light, the fresh air and the noise. So, visual quality, IAQ, and acoustics.

Q8: Adaptive façades are strongly connected with customization but there are also already studies about Multi-functional Façade Modules (MFM). MFM is a category of Advanced Integrated Facades (AIF) and it is a development of integrated and modular multifunctional systems which incorporate different technologies with the aim of energy efficiency. They consist of prefabricated units with several functionalized layers which can be assembled with several combinations depending on the architectural design. Would you consider that a unitized system is adaptive?

A8: With a unitized system everything is fixed and it is not easy to be changed later. So, it should be perfect from the beginning and thus adaptability should be incorporated in the system from the start.

Q9: What is in your opinion the future of adaptive facades?

A9: The future should be simple and not complex. A lot of systems have failed in the past because of their complexity. In relation to the previous question, I would say yes to an integrated system only if it is done simple and in an effective way. Complex systems are also maintenance sensitive.

On the other hand, curtain walls offer many options. They are a successful basic system that fits many solutions.

3rd interview

Name: Arie Bergsma

Architect partner at GAAGA & TU Delft Teacher/Researcher

Q1: What is your opinion about adaptive facades? Do you believe that adaptive façades really improve the performance of a building or a passive design would be adequate?

A1: *Yes, I do, but it is not a goal in itself. It depends on the strategy that are mainly two. If there is more opaque surface, the level of adaptivity is lower and it is easier to control the building physics. On the contrary, with big transparent surfaces the intervention is more extreme and complex. In this case the risk of damage is more.*

Q2: Have you already applied adaptive solutions in your designs and in what extent? If so, do you calculate and monitor the performance of adaptive facades and how does this influence your decisions? What do you calculate and how do you monitor it if you do so?

A2: *Yes, I have applied adaptive solutions mainly for daylight and solar control. But I do not monitor the performance of the design applied.*

Q3: Are you aware of the adaptive facade systems that are already available in the market and do you think they would be prone to restrict your design freedom or contribute to the design quality of the project?

A3: *Yes, mainly for daylight and solar control*

purposes. I don't think it restricts the design freedom.

Q4: Would you sacrifice performance in virtue of design purposes and how do you think they should be combined?

A4: *Sometimes, it depends on priorities and on limitation of the systems.*

Q5: Put the following aspects that an adaptive façade should regulate in order of importance (1 being the most important and 5 being the least)

3 thermal performance

4 energy production

1 visual and lighting

5 acoustic

2 indoor air quality

Q6: Which of the above parameters would you like to be combined in a product?

A6: *I think that a mass variation between summer and winter would be interesting. In the past, for example, the shading systems were used also as thermal mass in winter.*

The triple glazing works good in winter but not in summer.

Both these cases are examples about how a change of thermal mass would increase the performance.

Q7: Where do you think the market should orient itself from a product production point of view? Do you think there are aspects that are being neglected?

A7: *The market should orient to the thermal performance and to the integration of different solutions.*

Q8: Adaptive façades are strongly connected with customization but there are also already studies about Multi-functional Façade Modules (MFM). MFM is a category of Advanced Integrated Facades (AIF) and it is a development of integrated and modular multifunctional systems which incorporate different technologies with the aim of energy efficiency. They consist of prefabricated units with several functionalized layers which can be assembled with several combinations depending on the architectural design. Would you consider that a unitized system is adaptive?

A8: *There are many unitized solutions that are already adaptive. Yes, depends on the system.*

Q9: What is in your opinion the future of adaptive facades?

A9: *They should focus on the variation of performance of the façade. An interesting simulation would be about day and night cycle. The calculations and the performances should be given according to different parameters and situations and not just by winter and summer. An important future development would be to reduce the cooling demand in summer situation.*

APPENDIX D

DESIGN BUILDER RESULTS

The simulations were run for the cases of each module separately, of a WWR (Window-Wall-Ratio) of 40% and 50%, while each case was simulated twice, once for the heating season (Oct-Apr) and once for the cooling season (May-Sep). After the simulations were conducted, the energy performance of each case was calculated as well for the heating and cooling season but also for the whole year. The detailed results of the simulated cases and the corresponding energy performance can be found in the following three pages in Tables D1 - D9.

heating season	blinds	EC	BIPV	BIPV/T	PCM	Unit
zone sensible heating	2,99	2,12	4,61	0,74	0,63	kWh/m ²
zone sensible cooling	17,96	10,78	7,67	9,83	10,25	kWh/m ²
general lighting	7,54	6,72	7,07	16,86	16,79	kWh/m ²
solar gains windows	26,21	29,06	22,80	-	-	kWh/m ²
electricity generation	-	-	24,31	37,22	-	kWh/m ²
BIPV/T: heat provided by the ventilated cavity	-	-	-	21,65	-	kWh/m ²
PCM: heat provided by the ventilated cavity	-	-	-	-	9,42	kWh/m ²
operative temperature (08:00-18:00)	22,8	22,4	22	21,8	21,9	°C
comfort (08:00-18:00)	99	97	98	98	98	%
discomfort (08:00-18:00)	14,4	26,45	21,8	17,8	17,15	hours
annual comfort	97	95	95	94	94	%
energy performance	12,63	9,83	-14,40	-39,41	10,05	kWh/m ²

Table D1: Simulation results for the heating season for each module separately

cooling season	blinds	EC	BIPV	BIPV/T	PCM	Unit
zone sensible heating	-	-	-	-	-	kWh/m ²
zone sensible cooling	38,47	23,43	17,10	7,36	7,32	kWh/m ²
general lighting	3,35	2,45	2,51	12,50	12,45	kWh/m ²
solar gains windows	26,99	29,68	22,84	-	-	kWh/m ²
electricity generation	-	-	27,23	44,78	-	kWh/m ²
operative temperature (08:00-18:00)	24,5	24,5	24,4	24,2	24,2	°C
comfort (08:00-18:00)	93	91	91	88	89	%
discomfort (08:00-18:00)	68,7	81,8	85,6	108,85	108,55	hours
annual comfort	97	95	95	94	94	%
energy performance	12,97	8,31	-20,44	-30,44	14,28	kWh/m ²

Table D2?: Simulation results for the cooling season for each module separately

annual energy performance	25,60	18,14	-34,84	-69,85	24,33	kWh/m ²
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Table D3: Annual Energy Performance of each case of the modules simulated separately

heating season	reference project	PCM+blinds	PCM+EC	PCM+BIPV	BIPV/T +blinds	PCM+blinds +BIPV/T	PCM+EC +BIPV/T	Unit
zone sensible heating	1,49	1,75	2,23	2,72	1,75	1,73	2,19	kWh/m ²
zone sensible cooling	13,40	9,23	6,04	8,58	9,28	9,25	6,15	kWh/m ²
general lighting	7,86	10,99	9,60	8,05	11,53	11,38	10,16	kWh/m ²
solar gains windows	30,08	9,50	10,10	22,29	9,49	9,54	10,09	kWh/m ²
electricity generation	-	-	-	8,44	21,40	9,16	9,16	kWh/m ²
BIPV/T: heat provided by the ventilated cavity	-	-	-	-	12,99	5,41	5,41	kWh/m ²
PCM: heat provided by the ventilated cavity	-	5,65	5,65	5,65	-	3,30	3,30	kWh/m ²
operative temperature (08:00-18:00)	22,7	22,2	21,6	22,2	22,2	22,2	21,6	°C
comfort (08:00-18:00)	99	98	98	98	98	99	98	%
discomfort (08:00-18:00)	14	16,9	20,45	19,15	16,85	16,55	20,5	hours
annual comfort	96	95	95	95	95	96	95	%
energy performance	11,50	7,99	5,90	-3,35	-20,19	-3,83	-5,74	kWh/m ²

Table D4: Simulation results for the heating season for Window-Wall-Ratio, WWR = 40%

cooling season	reference project	PCM+blinds	PCM+EC	PCM+BIPV	BIPV/T +blinds	PCM+blinds +BIPV/T	PCM+EC +BIPV/T	Unit
zone sensible heating	-	-	-	-	-	-	-	kWh/m ²
zone sensible cooling	23,00	14,40	6,21	17,18	9,77	14,47	6,55	kWh/m ²
general lighting	2,79	7,04	5,71	2,96	7,41	7,34	6,28	kWh/m ²
solar gains windows	30,47	9,78	10,31	22,51	9,77	9,81	10,31	kWh/m ²
electricity generation	-	-	-	9,46	23,87	10,26	10,26	kWh/m ²
operative temperature (08:00-18:00)	24,5	24,4	24,2	24,4	24,4	24,4	24,3	°C
comfort (08:00-18:00)	91	90	90	91	90	91	90	%
discomfort (08:00-18:00)	83	88,8	92,55	82,65	88,1	87,15	90,75	hours
annual comfort	96	95	95	95	95	96	95	%
energy performance	8,54	10,64	7,26	-2,20	-14,01	0,70	-2,34	kWh/m ²

Table D5: Simulation results for the cooling season Window-Wall-Ratio, WWR = 40%

annual energy performance	20,04	18,64	13,17	-5,56	-34,20	-3,13	-8,07	kWh/m ²
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Table D6?: Annual Energy Performance of each simulated case of WWR = 40%

heating season	reference project	PCM+blinds	PCM+EC	PCM+BIPV	BIPV/T +blinds	PCM+blinds +BIPV/T	PCM+EC +BIPV/T	Unit
zone sensible heating	1,65	2,17	2,70	3,42	2,15	2,16	2,68	kWh/m ²
zone sensible cooling	16,64	9,62	5,95	9,64	9,65	9,59	5,96	kWh/m ²
general lighting	7,58	10,35	9,09	7,80	10,85	10,70	9,56	kWh/m ²
solar gains windows	38,51	11,87	12,62	27,86	11,87	11,92	12,62	kWh/m ²
electricity generation	-	-	-	10,56	17,79	9,16	9,16	kWh/m ²
BIPV/T: heat provided by the ventilated cavity	-	-	-	-	10,82	5,41	5,41	kWh/m ²
PCM: heat provided by the ventilated cavity	-	4,71	4,71	4,71	-	2,36	2,36	kWh/m ²
operative temperature (08:00-18:00)	22,9	22,3	21,6	22,4	22,3	22,3	21,6	°C
comfort (08:00-18:00)	99	98	98	98	98	98	98	%
discomfort (08:00-18:00)	12,5	16,4	20,85	18	16,35	16,45	20,65	hours
annual comfort	96	95	95	96	95	95	95	%
energy performance	12,07	8,47	6,41	-4,37	-14,92	-3,40	-5,34	kWh/m ²

Table D7: Simulation results for the heating season Window-Wall-Ratio, WWR = 50%

cooling season	reference project	PCM+blinds	PCM+EC	PCM+BIPV	BIPV/T +blinds	PCM+blinds +BIPV/T	PCM+EC +BIPV/T	Unit
zone sensible heating	-	-	-	-	-	-	-	kWh/m ²
zone sensible cooling	30,14	17,97	7,65	23,13	17,89	17,94	8,28	kWh/m ²
general lighting	2,65	6,38	5,05	2,83	6,73	6,65	5,57	kWh/m ²
solar gains windows	39,02	12,22	12,89	28,14	12,22	12,26	12,89	kWh/m ²
electricity generation	-	-	-	11,82	19,84	10,26	10,26	kWh/m ²
operative temperature (08:00-18:00)	24,5	24,4	24,3	24,5	24,4	24,4	24,3	°C
comfort (08:00-18:00)	92	91	91	92	91	91	91	%
discomfort (08:00-18:00)	75,75	81,65	88,8	76,95	79,85	80,05	88,7	hours
annual comfort	96	95	95	96	95	95	95	%
energy performance	10,19	10,88	6,96	-3,21	-8,64	0,88	-2,62	kWh/m ²

Table D8: Simulation results for the cooling season Window-Wall-Ratio, WWR = 50%

annual energy performance	22,25	19,35	13,37	-7,58	-23,56	-2,52	-7,97	kWh/m ²
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Table D9: Annual Energy Performance of each simulated case of WWR = 50%

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