How adaptive facade systems can improve hotel energy consumption and comfort

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Abstract

High comfort requirements of hotel guests together with the climate and 24-hour operation schedules are the main reasons of the high energy performance in a hotel. Current studies show controlling the HVAC systems and the climate can provide energy-savings and thermal comfort. However, despite the many advantages of tackling energy performance with adaptive elements, such systems are not widely implemented in hotel buildings. Therefore, this study analyses if an adaptive facade can contribute to the energy performance in a hotel as well as the comfort requirements of hotel guests. The results show that the configurations, depending on the orientation and combinations of the adaptive systems, create a significant contribution in improving the energy performance and provide a sufficient starting point and guidelines for architects and engineers for designing a facade for a hotel in the Dutch environment.

Keywords: *Adaptive facade configurations, Energy performance, Hotel building, User comfort, Dutch climate*

1. Introduction

Hotel buildings are among the tallest types of commercial buildings that have the largest energy consumption. This is due to the variety of facilities and functions such as a restaurant, conference centers, swimming pool, in-house laundry, guest rooms, etc. These different facilities have a big influence on the operation schedules and also on the energy performance. The problem is that guests don't make optimal use of these facilities and as a result sudden peaks can occur during the day (Udawatta et al., 2010). This leads to high energy cost. Studies show that hotels in European countries have an energy use of 305-330 kwh/m2 (Hotel energy solutions, 2011). This number has decreased over time if you look at different studies which have investigated the energy performance. In 1996, 158 hotels in Greece, show that the annual average energy use was 612kwh/m2 (Bohdanowicz et al., 2007). In 1991, hotels in Ottawa had an average energy use of 688,7 kwh/m2 (Zmeureanu et al., 1994).

Studies conducted in Asia show that the main cause of energy consumption is not the capacity utilization, but is mainly due to the HVAC (Deng et al., 2000). In particular the air-conditioning, which provides 1/3 of the energy. These systems are related mainly to the climate and don't have a direct relation with the occupancy rate of hotels. This is also apparent from a previous research of hotels in Shanghai, where the air-conditioning is always on, regardless of the presence or absence of a guest, in an effort to prevent discomfort (Yoa et al., 2015). This does not apply to Hotels in Europe. These studies show that the presence of hotel guests has indeed a direct influence on a high-energy performance. Different guests have different preferences regarding comfort and needs depending on their satisfaction and expectations. It also appears that the guests can cause unnecessary loss and waste of energy. Hotels that have unoccupied hotel rooms for 60-65% a day while the HVAC-systems are still running. Also the guests have full control over the thermostat and air-conditioning and little to no concern for energy conservation (Hotel Energy Solutions, 2011)

The high energy consumption of hotels leads to the following issues, which will be addressed in this research paper. The energy performance is related strongly with the climate, the presence of the hotel guests and the 24-hour operation schedules. Studies have shown that the use of an adaptive facade can reduce these problems. These studies use different adaptive elements that take the climate into account, such as Facet research that provides energy-saving and thermal comfort in office buildings (Loonen et al., 2015). The research from Park (2003) also investigates a facade system where the user acts according to his of her comfort and needs. Looking at an adaptive facade there is still a lack of studies on how to reduce the energy performance and comfort needs of hotel guests. Therefore the aim of this study is to contribute to the improvement of energy performance of hotels in the Dutch climate as well as creating a comfortable indoor climate for hotel guests, using an adaptive facade. This study will verify the success of making use of varying insulations, sun shading and thermal mass. The facade configuration has to function based on the parameters of the Dutch climate. This leads to my research question:

How can varying insulation, sun shading and thermal mass contribute to the energy performance of a hotel as well as creating a desirable comfortable indoor climate?

It is important that guests can control the parameters to their satisfaction and needs, however this has impact on the facade. Ventilation, air quality and color are also elements which can influence the facade. However for this research, insulation, sun shading and thermal mass are chosen, because they have a strong relation with each other which can have a positive influence on the energy performance and comfort of the hotel guests.

2. Methodology

2.1. Case study

Previous studies have looked at the operation and the comfort needs in adaptive facades and highlighted/showed that facades have many parameters that are influenced by both internal and external factors. To understand which adaptive elements contribute to a facade, this study reviewed previous studies and existing buildings in which the findings were combined and processed in a facade system. This provides sufficient starting points and guidelines for other architects and engineers for designing a facade for a hotel in the Dutch environment. The outcome also gives enough knowledge to able to answer the main question of this research.

3. Parameters

Important for this research is to define and specify the scenarios and needs that a facade has to deal with. In other words to define the influences in which the facade is exposed too. These different scenarios and needs ensure the adaptively of the facade, because the configuration is influenced differently each time due to internal and external factors. The influences that apply to this research are subdivided into two categories, the climate and the presence and/or absence of hotel guests. These categories are further explained and elaborated in the paragraphs and matrix below (Table 3). These matrices will be used during the research and show the relevance of the facade system.

3.1. The Climate

To determine how the different scenarios react during the year, in relation with insulation and sun shading thermal mass, a reference year had to be chosen. In this study the Test Reference Year (TRY) was chosen, which is widely used by researchers over the world (Lund, 2001). The TRY is a method, where accurate data of three places in the Netherlands (Vlissingen, de Bilt, Eelde) are combined into an artificial reference year. The accurate data makes it a good standard for this research to create a facade configuration throughout the year. The extreme peaks of data in the TRY are not taken into account. Especially looking at the new standards which are focused on climate change. There will be a increase of 3,7 to 4,8 degrees if no counter measurements are applied (KNMI, 2015). Therefore this study looks at the TRY and climate change and is divided into two sub-sections: Summer and Winter. These periods in relation to the sun, gives it three options; Sunny, Cloudy and Night. Table 1 gives a global overview of the six options which take place throughout the year. This table will be used in the matrix (Table 3). It is important to note that this table gives an overview of the two extremes of the reference year. It is evident that there are many intermediate scenarios which can occur, particularly in the spring and autumn. The following paragraphs highlight the different scenarios using the six options mentioned above with the three adaptive elements, insulation, sun shading and thermal mass.

Table 1. Overview of the six options

Summer			**Winter**		
Sunny	Cloudy	Night	Sunny	Cloudy	Night

3.1.1. Insulation

According the Dutch Building code, a thermal resistance (Rc) of 4,5(m2.K/W) for the facade is required (NEN, 2014). However taking into account that the facade could deal with extremes due to climate change, it should be future proof. Therefore the thermal resistance for this study is 6(m2.K/W). The design task is that the insulation element should fulfill this criteria. The high thermal resistance is good option when there is a large difference in temperature inside and outside. Still there are moments throughout the year where this difference is small or absent. In this case a high thermal resistance is not recommended due to overheating caused by a build-up of warm air. By making insulation adaptive, and creating different thermal resistance, it overcomes these challenging moments throughout the year.

3.1.2. Sun shading

The sun had a positive effect on the heat demand where it functions as a perfect passive heat source, especially in the winter. In the summer the sun has a higher intensity and shines for more hours, compared to the winter (KNMI, 2017). This intensity and longer sun hours can lead to overheating with the internal heat production. The summer solar heat is something which is desired to be kept outside. Applying sun shading is the most effective way. This can be achieved with something as simple as creating a 1,5 meter overhang (de Boer, 2003). This ensures that the sun rays would not touch the glass. In the winter the sun angle is lower which allows the sun to pass the overhang and will be used to heat up the room.

3.1.3. Thermal Mass

Thermal mass is ideal for the temperature changes from outside. It can act as a buffer for the inside and outside where the warm and cold temperate can be delayed and flattened. The thermal mass can also be used to store the heat and coolness and emit it to the required area at a later moment.

In the summer it is desirable to have a heavy mass, where it absorbs the heat for a long time before it emits the heat to the room inside. During the night it is the opposite, where a light mass is desired. The mass will want to release the heat to the outside, which is stored in the mass during the day. Just as in the summer its desirable to have different thickness in every seasonal period, winter, spring and autumn. For example, in the winter its desirable to have a light mass, whereby exposure to the heat of the sun is given faster to the inside area. However this can also cause heat to emit fast to the open air.

3.2. Hotel guests

The presence and absence of the hotel guest has a big influence on the energy demand of a hotel, because of their varying individual expectations and comfort needs (Hotel energy solutions, 2011). The users of a hotel are mainly tourists, expatriates and business travelers (Horwath HTL, 2017). These guests are mostly active in the morning and the evening for a few hours. Any other time the guests are asleep or absent. Studies show that people sleep on average eight hours (Iglowstein et al., 2003), and the rooms are unoccupied 60-65% of the time in Europe. Table 2 gives a global overview of the three options which are important for hotel guests. This table will be used in the matrix (Table 3).

When hotel guests are present in the room, comfort plays a big role, which can be divided into four elements; thermal, visual, air and acoustical comfort. The following paragraphs highlight the different comfort criteria using the three options mentioned above.

Table 2. Hotel guests options

Present		**Absent**
Awake	Asleep	

3.2.1. Thermal comfort

Thermal comfort is seen as an ideal temperature which can be calculated accurately. In practice, this not the case, aside the culture influence, the temperature depends on personal expectation and satisfaction. Previous studies concluded that insufficient adaptive possibilities lead to discomfort of the user (Kurvers and Leijten, 2013b).

The outside temperature is also an important factor to create an optimal thermal comfort. The outside temperatures are not fixed and sudden changes lead to discomfort in comparison with gradual changes. There are multiple studies performed which result in standards and guidelines. These studies looked at buildings around the world, where they included all the different comfortable temperatures of different cultures, which gives it a good starting point of an average user. These studies show that there is a strong relation between the outside temperature and comfort of the user (Dear and Brager, 2002). If the outside temperature is higher, the acceptance of the user changes, therefore the comfort temperature becomes higher.

In the literature it can be concluded that the comfort temperature can change in a specific bandwidth. By absence of the hotel guests the facade keeps the comfort temperature between this bandwidth. The facade ensures for a thermal comfort, by making optimal use of the influence from outside.

3.2.2. Visual comfort

Visual comfort is an important aspect to the comfort of the guest. The ‘praktijkboek gezonde gebouwen’ (Cauberg, 1996) show different options to create a pleasant visual comfort. For example, the relation with the outdoor environment, which has an important psychological impact on well-being c an include recognition of statues, observation of the outdoor climate, orientation in the building, green and so forth. These aspects are different for every location and orientation of the facade. In this study, primarily the daylight is important when the guests are present and awake. Looking at the de data from Cauburg, the Light Transmittance (LT) value is between 60-80%. However after contacting the market leader, Luxaflex (2007), their table showed an LT of 60%. Therefore the minimal value of this study for LT is 60 %. When the user is present but asleep the minimal requirement of 0 % is used.

3.2.3. Acoustical and air comfort

Besides thermal and visual comfort, air and acoustical comfort plays a role for the comfort of the guests. Most important for the guests is to guarantee little disturbance from the system or influences from outside. According the Dutch Building Code, there are no requirements for minimum sound insulation, but an average demand of 45dB is desirable (Hasselaar et al., 2013). For the air comfort it is important the user can open a window any time he/she desires. They only have to consider that the possible temperature change can affect the thermal comfort.

Table 3. Matricesj Dutch climate and Hotel guests

	Insulation	**Sun shading**	**Thermal Mass**
Summer			
Sunny	move in place	block the sun	absorb and delay the heat
Cloudy	move away	prevent warm air flow and create insulation buffer	absorb and delay the heat
Night	move away	move away	emit the collected heat to the outside
Winter			
Sunny	move away	let sun heat inside	absorb and emit the heat to the inside
Cloudy	move in place	prevent cold air flow and create insulation buffer	delay the heat flow to the outside
Night	move in place	prevent cold air flow and create insulation buffer	emit the collected heat to the inside

	Thermal comfort	**Visual comfort**	**Air comfort**	**Acoustical comfort**
Present				
Awake	quick response	opening with enough view and daylight	open a window	no sudden and continuous sound
Asleep	slow response	create dark room	enough fresh air	Not enough noise
Absent	slow response and keeps between bandwidth	-	-	-

4. Results

4.1. Operations of adaptive systems

An adaptive facade system integrated in a building structure, can play an important role for the internal climate of the building by using outside temperature fluctuations. Despite the many advantages, such systems are not widely implemented yet. Examples of these systems are either built for high end structures or for experiments on a smaller scale. Due to new innovation and techniques, the high end buildings require expensive investments. The aesthetics of the building still plays an important role, as e.g. the Milwaukee Art Museum shows (Nichols, 2004). Until now, the focus of the studies of adaptive facade systems were mainly based on creative and conceptual developments and less on data. Therefore this study is focused more on real projects and subsystems as well on conceptual systems. A short description of these projects are given in Appendix 1.

4.1.1. Projects

The projects used for this study show clearly the dominant impact of the sun on the systems. Movable panels and louvres, controlling the position, allow them in the winter to use the warmth of the sun and in the summer to block the heat of the sun. To control the temperature inside even more, adaptive insulation is a good addition. This combination of adaptivity allows, in the absence of the user, to slow down the heat and coolness penetration inside the room. The QO Hotel in Amsterdam is a good example of this system and reduces the energy performance (Wopereis, 2017). Air can function as a good thermal buffer, which is done in a second skin facade. As an example, a second skin facade is used both in the East as the West facade, of the Sydney Law School, in combination with vertical louvres. This combination keeps the excessive heat and coolness outside, using an efficient ventilation structure. When no ventilation system is in place, an adaptive second skin facade can be the solution which is for example done in an office of Solarlux in Bissendorf (Imagine envelope, 2017). Here the outer glass is removed in the summer and be used in the winter.

4.1.2. Subsystems

The subsystems are primary focusing on the quality of the climate, comfort of living, and the operation of the system. The practical implementation of these systems, in combination of the aesthetics and the program of the building, is often a challenge. This is seen in the example of Baer (2009), who designed a wall of water barrels. Using thermal mass in a passive way makes it an interesting way to design and can also be seen in another example, the Trombe wall and Roof Pond. To implement adaptive systems, like movable and sliding elements and sun shading, makes it even more interesting (Baer, 2009). The Hammond House controls this by using the heat or blocking the sun-rays and slows down the coolness by its mass. The effect of absorbing and emitting heat and coldness can also be replicated in a thinner and liquid form, using Phase Change Materials (PCM). This creates the opportunity to influence the effect of thermal mass between glass which is for example done by Tenpierik (2017) in his translucent trombe wall 'Double Face 2.0'.

4.1.3. Conceptual systems

Studies from universities and students delivered multiple conceptual facade systems. These systems use the climate factors through adaptivity, to design energy-efficient buildings. Varying insulation, thermal-mass and sun-shading are applied to these conceptual systems. Interesting are the different approaches of collecting heat and coolness, for example with collectors on the facade, and using fluid PCM. These elements are combined with movable and slidable panels insulation, used as a buffer to block the sun. Because of the use and combination of these elements, at least in theory, the concepts of Godfroij (2013) can deal perfectly with the climate all year round. In practice, many factors like operation, draughts and ventilation, are difficult to implement. These conceptual systems show a different approach and support a designer or architect in his/her design process.

4.1.4. Conclusion

First of all, the case studies showed clearly that managing the heat of the sun, the main driver is to design a sun shading tool. This is often linked with the combination of an efficient insulation and ventilation system. Aesthetic elements are an important factor, especially the buildings who are realized, giving the users a good impression of an innovative building controlling its climate. Secondly, thermal mass is mostly used in the sub- and conceptual systems only, and not very often in the project examples. This is probably because the effect of thermal mass goes slowly and creates no visibility for the users satisfaction. However, by positioning it just the right way it can have a significant influence on the heat and coolness inside, without having to much active elements. Last but not least, not only the climate outside, but also other factors are important to manage, like comfort requirements as described below.

4.2. Contributions of the comfort requirements

Comfort requirements are different for every user, and it is important that the facade has enough adaptive tools to deal with the users needs and their satisfaction. In most case-studies, the systems deals with the comfort needs, but hardly with the four parameters described in chapter 3.2. Movable and slidable panels, using different functions, can already lead to manage these parameters (Godfroij, 2013). Also the example of Colt (2016) shows that louvres are a perfect tool to guarantee most comfort requirements. Only the thermal comfort, which is an important comfort requirement, is not tackled by this system. A combination of insulation inside the louvres can deal with this, shown in the Coulissen facade ensuring both temperature changes as well as visibility and daylight.

Studies like Hilbra (2017), give preferences to horizontal folding shutters, especially for the South facade. This ensures optimal solar gain as well as enough daylight in closed and open positions. In addition, the system also has to deal with the direct sunlight in wintertime, regardless from the heat advantages, causing discomfort to the user. For the East and West facade vertical louvres are most common, where for optimal comfort individually working louvres are the best, like in the Sydney Law School. In this school a buffer of air is used instead of closed insulation, which creates, regardless the outside temperature, optimal visual comfort. The disadvantage of the second skin facade is, when opening a window, it does not create air comfort for the user. In case of comfort, this is an important factor to consider. In most of the studies, the air comfort for the user is not taken into account.

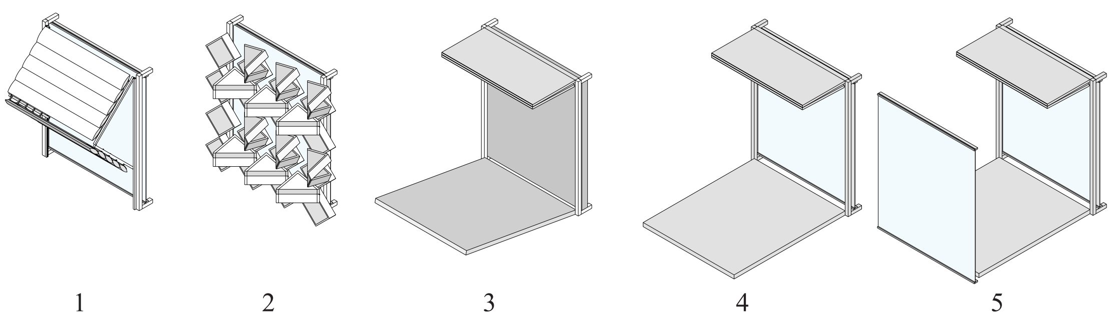
Both (closed) thermal mass and insulation, reduces the visual comfort. Glassx uses translucent PCM between the layers of glass. Despite the good climate quality, the prismatic and translucent PCM only create daylight and no visibility. A combination of glass and the system Glassx good solve this.

In appendix 2, a table shows the results the different case-studies dealing with both the climate as well as the comfort requirements.

4.3. Configurations

The case-studies provided different concepts of configurations as shown in Figure 1. The configurations will be discussed and elaborated in more details e.g. their position in relation to the temperature changes during the year in Appendix 3.

Figure 1. Five concepts of a facade configuration



Configurations one and two are made due to the result of the good combination of adaptive sun shading and insulation. For these two systems it is important to meet the comfort requirements of the users and the possibility to move the panels individually. During wintertime direct sunlight is beneficial for getting heat inside in a passive way, but can also lead to discomfort for the user. Therefore each panel can, regardless if the person is sitting or standing, be closed or opened. Due to climate changes it is important that the system is designed for the future, in order to deal with extreme temperatures. The separate movable louvres of the system can overcome these temperature changes, and keep sufficient visibility and daylight, e.g. by partially closing the window. These louvres also gives the opportunity to meet the requirement of a LT of 60%. Configuration one can be fully opened, giving a better view for the user. However system two has only one mechanism to make it work probably. So, taking the low presence of the hotel quests into account, system two seems to be a more logical choice. Also a simplified version of configuration two, that only needs enough insulation when the user is absent, can be used for the North facade.

Where the first and second system takes the user into account, the third system is based on the climate parameters only, requiring a thermal resistance of 6(m2.K/W). Therefore thermal mass and insulation are playing an important role to make the facade ready for the future. To meet the thickness requirements of the wall in the winter as well as in the summer, the wall is made out of two layers PCM and one layer of insulation. The layers have a different thermal resistance, that allows it not only to absorb the extreme temperatures but also to manage the different seasons of the year. The outside layer, that consists of insulation, can be folded and act as a sun shading as well. The second layer consist of PCM, and when flipped open, the sunlight can be absorbed and reflected to the third layer. By opening the two layers the third layer has a lower thermal resistance and, as a consequence, the heat can be emitted faster into the room. When the temperature reaches a low level, the second layer will be closed. This allows the heat to be absorbed and, at the same time, it will delay the cold entering through the wall.

The fourth system is a combination of functionality of the third system and possible influence of the user. In configuration four a double glass window is placed instead of a static PCM layer. As an advantage, the window emits the heat quicker and keeps it inside when the middle layer of PCM is put in front of the glass. Also at the same time it can emit the collected heat quickly during the night. However, as an disadvantage, the outer and middle layer have to get a higher thermal resistance. And the system cannot partially block the winter sun, which can cause discomfort to the users. The PCM is a good element in this system when the hotel guests are absent. It allows to collect the heat and emits it slowly inside when the users are away. Additionally, the layer, flipped down, provides a perfect balcony for the users in the summer. Some examples of the case-studies are using in their design a second skin facade, which can be a great addition for configuration four. The second skin facade can create an insulation buffer that ensures a perfect thermal comfort throughout the day. This addition is defined as configuration five.

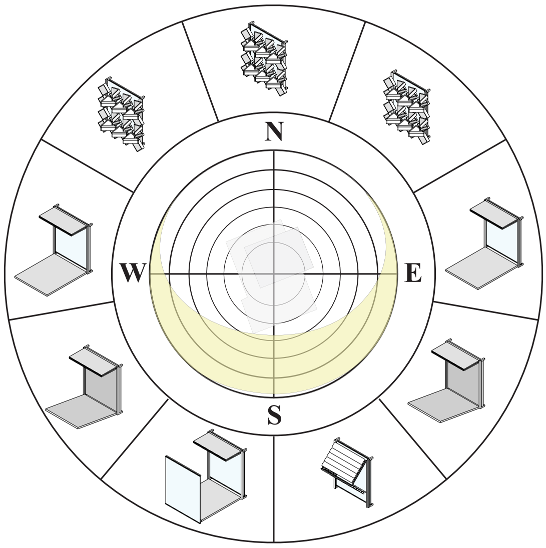
4.4. Orientation of the configurations

Besides the comfort requirements and climate parameters, each configuration has his own orientation preferences. For example, the first system using a folding panel and horizontal louvres prefers the South facade. The impact of the sun is stronger in the South and is easier to block the sun using system one. In case of a lower positioned and slightly angled sun from the East and West, system two is preferable. A combination of these two systems can be used to cope with the climate temperatures as well as to guarantee the comfort of the user.

The diamond-shaped panels of system two gets into conflict with each other when fully opened. Possible solutions are installing the possibility to shift the panels horizontally or combine open and closed panels. A combination with the three-layered wall can achieve this. For example making stripes of configuration three in combination with the diamond shaped panels of configuration two.

Besides the technical solutions, the absence of the hotel guests also has influence on the ratio between the closed and open panels. The facade configuration will be influenced mainly by the climate temperature during the absence of the guest and closed panels will dominate. What the ratio of open and closed panels in a facade will be depends on many factors. In such cases, the designer has to take into account more factors, like visibility, hotel program, room size etc. during the design process. These different preferences lead to a cycle of different configurations in relation with the orientation of the facades and are mapped in Figure 2.

Figure 2. Cycle of configurations in different orientations



5. Conclusion & Discussion

This study analyzed different case-studies about the relation of varying insulation, sun shading and thermal mass, and how they contribute to the climate factors and comfort requirements in hotels. The results, suggest an improvement of the energy performance by creating different configurations of an adaptive facade. The multiple configurations of this adaptive facade have different advantages depending on the choice of the orientation and parameters of the adaptive facades e.g. keeping sufficient visibility and daylight at the same time. The climate parameters are more important than the comfort requirements and therefore the main driver for the configuration due to the high level of absence of the hotel guests. By making more use of the climate parameters, a higher ratio of closed PCM or insulation is more realistic than an open window for a facade in a hotel. This study revealed that creating combinations of configurations are promising for the thermal and visual comfort of the hotel guest.

To summarize, the configurations, depending on the orientation and combinations of the adaptive systems, create a significant contribution in improving the energy performance and provide a sufficient starting points and guidelines for architects and engineers for designing a facade, for a hotel in the Dutch environment.

In this research, no attention is given to the implementation of the configurations into a functional and workable facade system which will be the next challenge. In addition, it would be worth testing the configurations to several other factors into a simulation program e.g. humidity, air infiltration, radiation heat of devices and light, reflective and diffuse sunlight. It would also be interesting to analyze the comfort requirements in shared areas and find out how an adaptive facade can cope with different comfort requirements of the user at the same time?'.

References

1. Baer S. 2009. Some Passive Solar Buildings with a Focus on Projects in New Mexico. [ONLINE] Available at: http://www.zomeworks.com/wp-content/uploads/2012/04/Passive-Solar-Design-Slideshow.pdf. [Accessed 6 December 2017].

2. de Boer , B.J ., Kaan, H.F., Jong, M.J.M., Koene, F.G.H., & Strooman, K.J. 2003. De optimale PZE-woning. Literatuurstudie, conceptontwikkeling & voorlopig ontwerp. ECN.

3. Bohdanowicz, P, Martinac, I. 2007. Determinants and benchmarking of resource consumption in hotels–case study of Hilton international and Scandic in Europe, Energy and Buildings.

4. Cauberg, J. J. M. 1996. Praktijkboek gezonde gebouwen. Rotterdam: Stichting Bouwresearch.

5. Colt. 2016. Colt Buitenzonwering Systemen voor de gevel, Zon- en warmtewering, daglichttoetreding en het gebruik van actieve en passieve zonne-energie. [ONLINE] Available at: https://www.coltinfo.nl/files/pdf/buitenzonwering/Brochure%20Colt%20buitenzonwering.pdf. [Accessed 6 December 2017].

6. de Dear, R., Brager, G. 2002. Thermal comfort in naturally ventilated buildings: revisions to ASHRAE Standard 55, Energy and Buildings 34 p. 549-561.

7. Deng Shiming, John Burnett. 2002. Energy use and management in hotels in Hong Kong, In International Journal of Hospitality Management, Volume 21, Issue 4, Pages 371-380 ISSN 0278-4319, https://doi.org/10.1016/S0278-4319(02)00016-6.

8. Facet. 2013. FACET Facade als Adaptief Comfort verhogend en Energiebesparend Toekomstconcept. [ONLINE] Available at: http://docplayer.nl/11560173-Facet-facade-als-adaptief-comfort-verhogend-en-energiebesparend-toekomstconcept.html. [Accessed 6 December 2017].

9. FJMTStudio. 2017a. Law School, University of Sydney, A law school as an open door and an urban window. [ONLINE] Available at: https://fjmtstudio.com/projects/sydney-law-school/. [Accessed 6 December 2017].

10. FJMTStudio. 2017b. Surry Hills Neighborhood Centre, A community centre as a doll's and tree house. [ONLINE] Available at: https://fjmtstudio.com/projects/surry-hills-library/. [Accessed 6 December 2017].

11. Glassx. 2017. Close UP GLASSX. [ONLINE] Available at: http://glassx.ch/index.php?id=707. [Accessed 6 December 2017].

12. Godfroij, H, 2013. Variety is the spice of life, Adaptieve gevel voor energie neutraal wonen. Master. Eindhoven: Eindhoven University of Technology.

13. Hasselaar, B. 2013. The comfort unit : developed as part of a climate adaptive skin. 's-Hertogenbosch: Uitgeverij BOXpress.

14. Hilbra. 2017. Vortrag der Passivhaustagung in Kassel. [ONLINE] Available at: http://hilbra.de/entwicklungsbuero/vortraege/40-vortrag-der-passivhaustagung-in-kassel.html. [Accessed 6 December 2017].

15. Horwath HTL. 2017. The Netherlands Hotel Market Sentiment Survey June 2017. [ONLINE] Available at: http://holland2.htl-web.com/files/2017/09/HorwathHTL-Sentiment-Survey-Netherlands-2017-I.pdf. [Accessed 6 December 2017].

16. Hotel Energy Solutions 2011, Analysis on Energy Use by European Hotels: Online Survey and Desk Research, Hotel Energy Solutions project publications

17. Iglowstein I, Jenni OG, Molinari L, Largo, RH. 2003. Sleep duration from infancy to adolescence: reference values and generational trends. Pediatrics;111:302-7.

18. Imagine envelope. 2017. Solarlux. [ONLINE] Available at: http://www.imagine-envelope.com/#/solarlux-plain/. [Accessed 4 December 2017].

19. Knaack, U, Klein, T, Bilow, M, & Auer, T. 2014. Façades : Principles of Construction, Birkhäuser, Basel/Berlin/Boston. Available at: ProQuest Ebook Central.

20. Kurvers SR, Leijten JL, 2013. TVVL magazine, Thermisch comfort: huidige en toekomstige normen, TU Delft, Faculteit

21. Loonen, R. C. G. M., de Boer, B. J., Kornaat, W., Bakker, L. G., & Hensen, J. L. M. 2015. Zoektocht naar de ideale adaptieve gevel. TVVL Magazine, 44(7-8), 36-38.

22. Lund, H. 2001. Design Reference Years and Test Reference Years in Europe, Turkey and Israel. [ONLINE] Available at http://site.cibworld.nl/dl/publications/Pub262.pdf

23. Luxaflex, 2007. Gegevens op basis van Belgium Building Research Institute (BBRI), Standard EN13363-1-2007, version 7

24. KNMI, 2015: KNMI'14-klimaatscenario's voor Nederland; Leidraad voor professionals in klimaatadaptatie, KNMI, De Bilt, 34 pp

25. KNMI. 2017. Klimatologie Daggegevens van het weer in Nederland. [ONLINE] Available at: http://projects.knmi.nl/klimatologie/daggegevens/selectie.cgi. [Accessed 5 October 2017].

26. NEN. 2014. 1 januari 2015: aanscherping EPC en hogere Rc-waarden. Available at https://www.nen.nl/NEN-Shop/Bouwnieuwsberichten/1-januari-2015-aanscherping-EPC-en-hogere-Rcwaarden.htm

27. Nichols A. 2004. Example Case Study: Milwaukee Art Museum. [ONLINE] Available at: http://www.solaripedia.com/files/979.pdf. [Accessed 6 December 2017]

28. Park, Cheol-Soo. 2003. Occupant responsive optimal control of smart facade systems.

29. Paulderuiter. 2017. QO Hotel "Meaningful and sustainable". [ONLINE] Available at: https://www.paulderuiter.nl/nl/projects/qo-hotel. [Accessed 6 December 2017].

30. Tenpierik M. 2017. Renewed Trombe wall passively reduces energy consumption. [ONLINE] Available at: http://pure.tudelft.nl/ws/files/21496918/Wattez_et_al_2017_Renewed_Trombe_wall_passively_reduces_energy_consumption.pdf. [Accessed 15 December 2017].

31. Udawatta, L, Perera, A and Witharana, S (2010), Analysis of sensory information for efficient operation of energy management systems in commercial hotels. Electronic Journal of Structural Engineering, EJSE S. 113 - 120 . ISSN 1443-9255

32. Wopereis W. 2017. Slimme gevel voor Hollands klimaat QO door Mulderblauw architecten en Paul de Uitei Architects. [ONLINE] Available at: http://de-architect.instantmagazine.com/de-architect-digimagazine/editie-1-2017#!/slimme-gevel-reageert-op-klimaat. [Accessed 6 December 2017].

33. Zhuxian Yao, Zhi Zhuang, Wen Gu, Study on Energy Use Characteristics of Hotel Buildings in Shanghai, In Procedia Engineering, Volume 121, 2015, Pages 1977-1982, ISSN 1877-7058, https://doi.org/10.1016/j.proeng.2015.09.195.

34. Zmeureanu, R & , Hanna & , Fazio & , Silverio. 1994. Energy Performance of Hotels in Ottawa. ASHRAE Transactions. 100.

Appendix 1: Case-studies

QO Hotel, Amsterdam

The new hotel of Paul de Ruiter is designed in an innovative way, considering energy-efficiency as an important design factor. He uses an adaptive facade that takes the Dutch climate as well as the unoccupied rooms into account. The facade consist of slidable panels, that can block the sun in the summer and allow the sun-rays in the winter. The panels are filled with insulation keeping the rooms in a comfortable indoor temperature. This creates a saving of 90% on cooling and 65% on heating elements (Wopereis, 2017).

(paulderuiter, 2017)

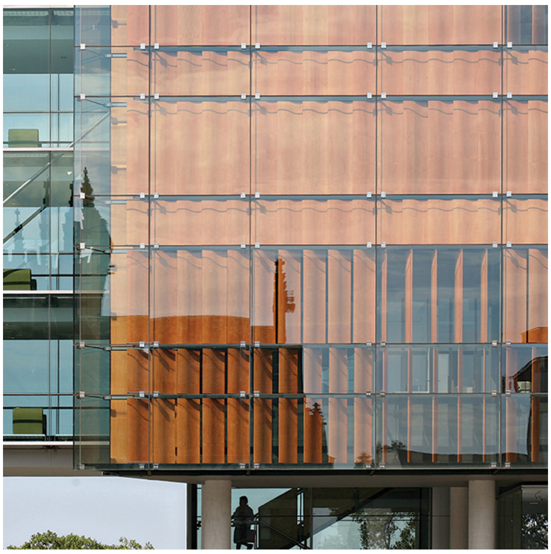
(Nichols, 2004)

Milwaukee Art Museum, Milwaukee

The museum consists two big wings blocking the direct sunlight when fully opened or closed. The atrium is blocked during summer from direct sunlight. The mechanism consists of multiple rotating spins with connected fins. This makes it possible to achieve the challenging positions, creating an aesthetic picture. However, if the wind becomes too strong, the system will shut down and reduces visual comfort for the visitors.

Sydney Law School, Sydney

FJMT architects show the design opportunities of a glass box in the Australian landscape. Designing the Sydney Law School, a second skin facade within vertical louvres has been used and can be positioned individually. This allows the system to react on the climate and comfort requirements. The direct sunlight will be blocked during summer and an air space will be used as a buffer in the winter. To avoid the air getting a high temperature, an efficient ventilation flow between the glass panels is installed. So the three layered system allows a degree of comfort by individual movements, sun shading, visibility and ventilation, and this creates a dynamic facade.



(FJMTStudio, 2017a)

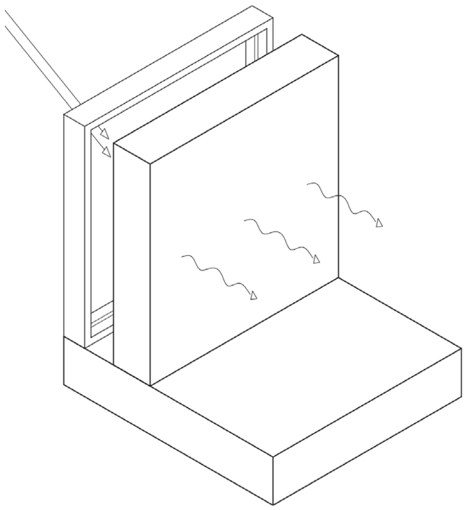
(FJMTStudio, 2017b)

Surry Hill Library, Sydney

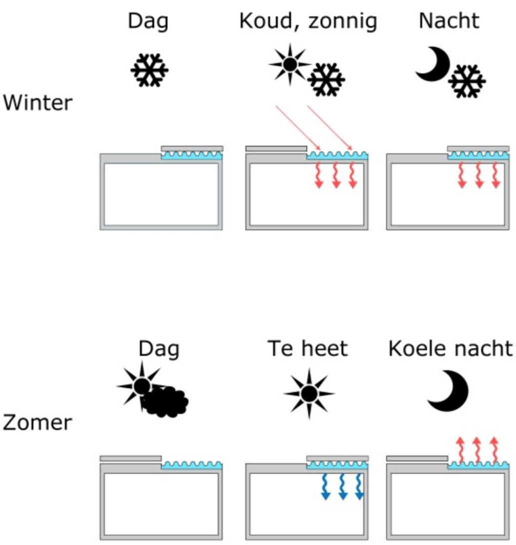
Surry Hills Library is also designed by FJMT, and is created both as an expressive building as well as a building who reacts efficiently on climate influences. The east and west adaptive facades are designed with vertical louvres and can block or allow the sun to enter the offices behind it. The south static facade is designed with a angled second skin with triangulated internal cavities in between. This creates, in combination with ventilation coming from above and below, a thermal-buffer with enough fresh air and visibility.

Trombe wall

The trombe wall uses solar heating in a passive way. The facade is built up by a glass layer and a thermal mass with mostly a black finish layer. During wintertime, the heat from the sunlight and the outside temperature is absorbed in the mass which is enhanced by the glass and the black finish layer. The mass emits it gradually into the room. During summertime, the thick mass creates a thermal-buffer and absorbs and delays the heat, until it emits it to the outside air during the night. Important during summertime is to avoid the direct sunlight, which can create overheating, by using for instance adaptive sun shading or insulation (Baer, 2009).



(Knaack et al., 2014)



(Godfroij, 2013)

Roof pond

The Roof pond works identical like the trombe wall. The roof consists only of a mass of water and insulation panels, which slide aside. The principle is to use the water and the insulation as an extra buffer during summertime. When it becomes cool outside, it emits the heat. During the winter the sun heats up the water and, when the insulation is placed above the water, emits it the heat to the inside. The water in the systems ensure for an advantage due to the fast cool down, which allows it even faster to absorb heat again.

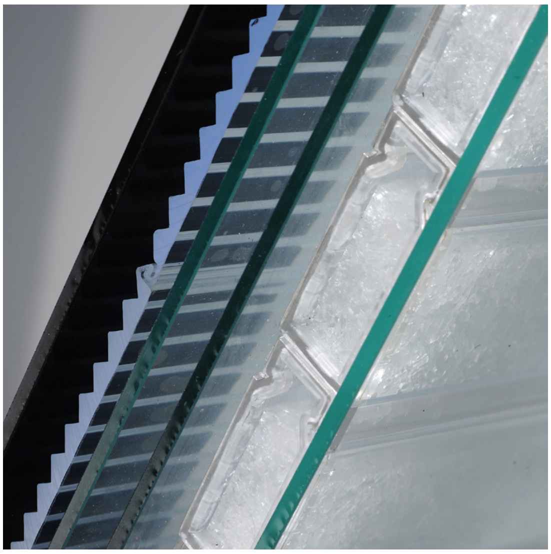
Colt Elisse

Colt Elisse is a slidable and folding system which especially allows daylight shining in and blocks the sun. The system has a big variety and flexibility of movable panels. On top if the functionalities, it shows that it can also create a good comfort for the user. The panels are placed in front of the glass allowing to open a window if needed. The system shows that, with a small intervention and clear operation, user-comfort can be achieved.

(Colt, 2016)

Glassx Crystall

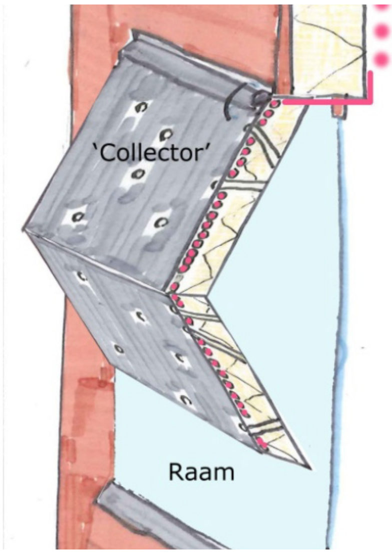
This system combines sun shading, insulation and thermal mass in one static panel. It consists of four layers of glass with prismatic glass between the first layers. This ensures sun-rays are blocked in the summer and getting through to the PCM during the winter. The PCM layer is placed between the last two layers and emits the heat slowly inside the room. Additionally, the many layers and PCM create enough mass to insulate efficiently and creates a comfortable inside temperature. The prismatic glass and PCM allows for enough daylight but reduces the visibility.



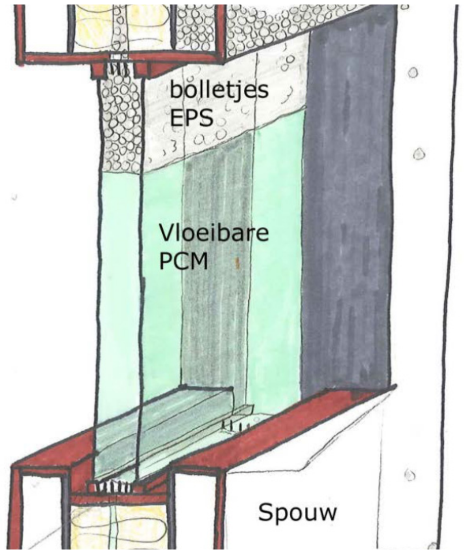
(Glassx, 2017)

Vouwluik

The 'vouwluik' concept consist of a folding insulation panel with water collectors. The different positions allow the panel, especially in the south facade, to block the sun-rays and let daylight inside. A combination of the water collectors with the PCM, which is located inside the wall, can, if needed, absorb and emit the warmth and the coolness inside. The use of fully folding panels, insulation and thermal mass, create a good thermal and visual comfort. The downside of this system is firstly the complicated operation and secondly the use of energy for the collectors to work.



(Godfroij, 2013)



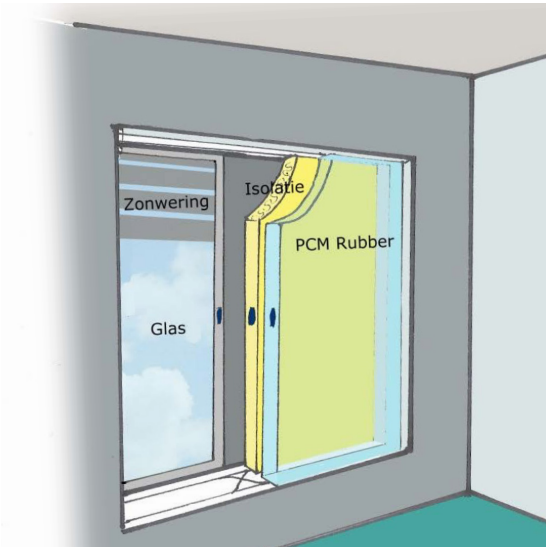
(Godfroij, 2013)

Bolletjes en vloeistof

This concept is based on the Beadwall of Baer (2017) who uses insulation inside the glass. The system consists of small pellets EPS insulation, which can be moved around. For instance, the pellets can be used for insulation inside the glass or inside the wall. Sun shading is created by using the pellets partly, so the user still gets enough daylight. In theory this system, which deals with the climate as well as the comfort, function well, but practically, It falls short at the tightness of the air gaps and the unpredictable PCM.

Schuivend luik

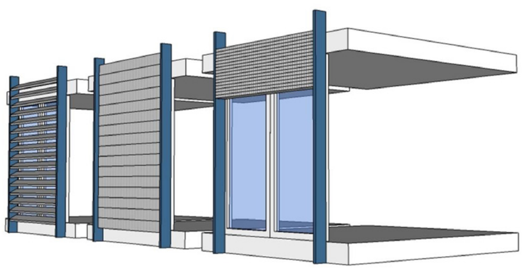
This is a box-window principle, that controls the comfort individually for every box (Knaack et al., 2014). The two elements, insulation and PCM, are located at the inside of the glass and can slide back and forth at the right time. This system needs extra sun shading to function probably, especially during summer, when it could become very warm between the glass and the slidable panels. In the winter, the adaptive of the elements are enough to encounter the climate circumstances and create thermal comfort. This concept is therefore designed to control climate and thermal comfort and does not create visual comfort.



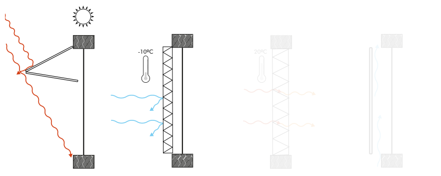
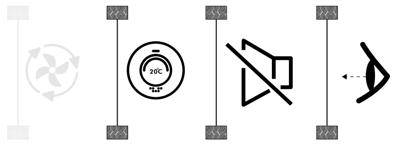
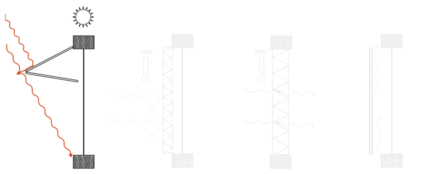
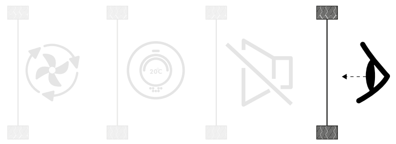
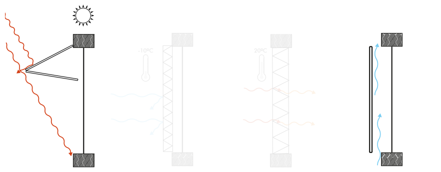
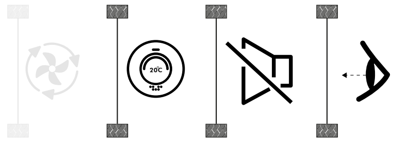
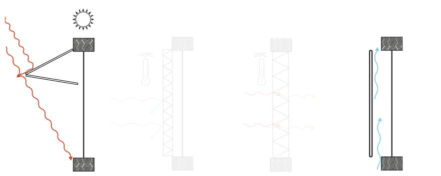
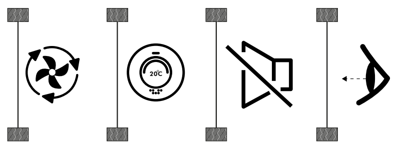
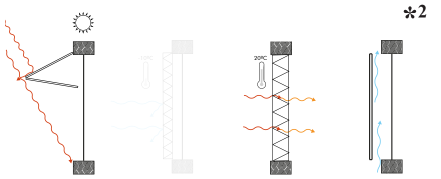
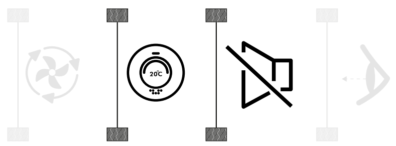
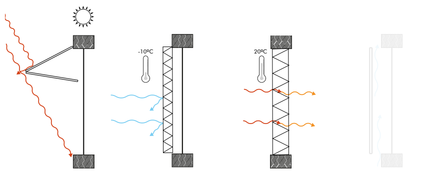
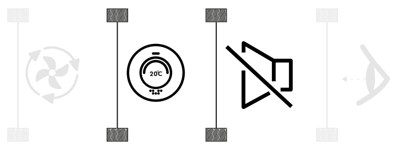
(Godfroij, 2013)

Coulissen facade

The Coulissen facade is a result from the FACET (2013) project. The concept is a combination of sun shading and insulation, like the QO hotel. Horizontal louvres can open and close individually and control how much of the window will be covered. This creates many possibilities to block the sun rays while still keeping enough daylight inside for the user. As the inside of the louvres consists of insulation material, it also gives comfort to the inside temperature of the user.

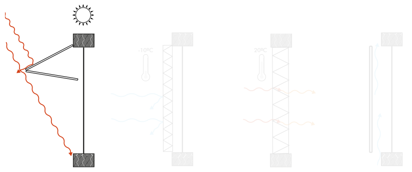
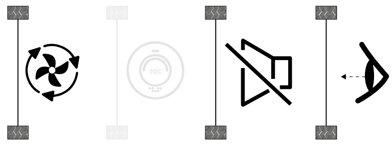
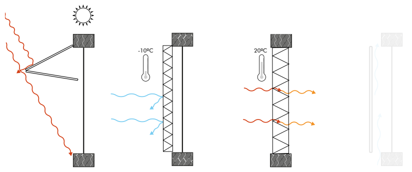
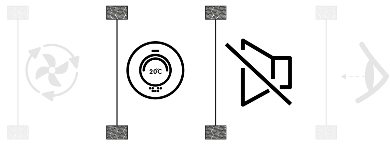
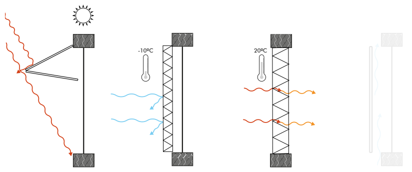
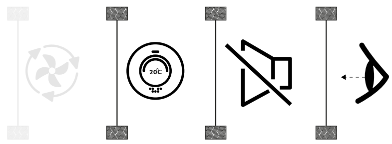
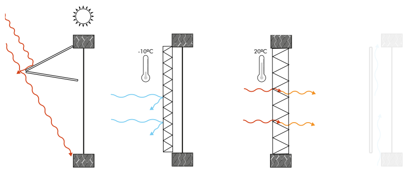
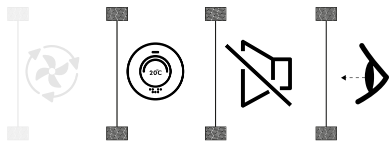
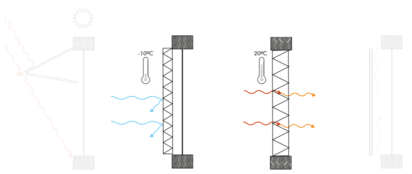
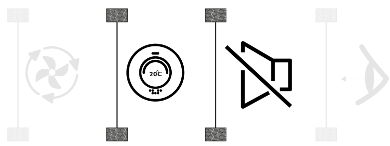
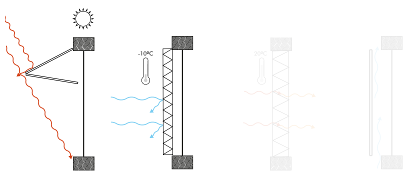
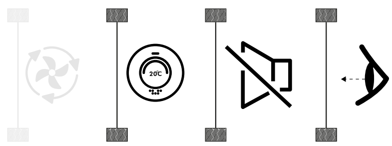

(FACET, 2013)

Appendix 2: Results of the case-studies.

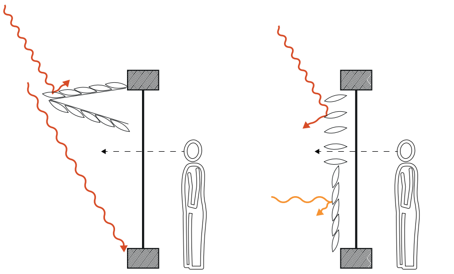
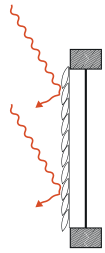
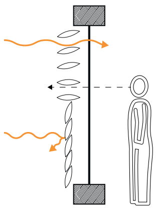
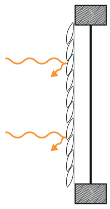
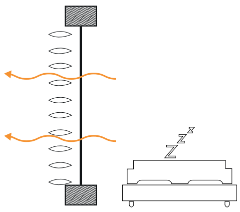
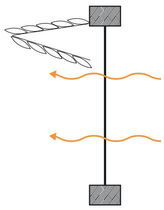
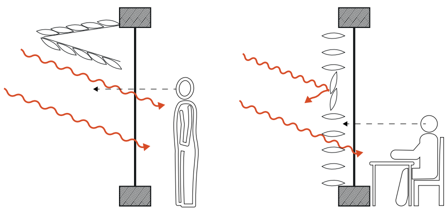
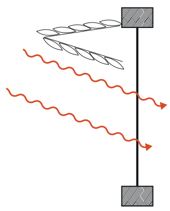
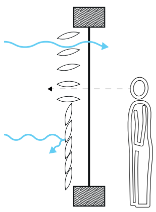
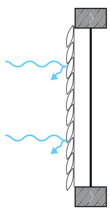
	Environmental impacts Sun shading · Insulation · Thermal mass · Ventilation	Comfortable indoor climate Air- · Thermal- · Acoustic- · Visual comfort
QO Hotel, Amsterdam		
Milwaukee Art Museum, Milwaukee		
Sydney Law School, Sydney		
Surry Hill *1 Library, Sydney		
Trombe Wall	*2 	
Roof Pond		

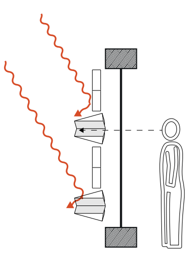
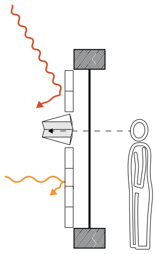
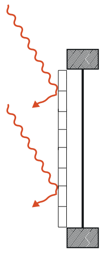
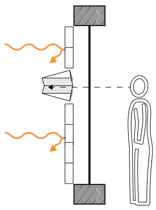
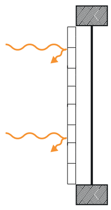
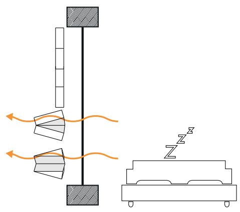
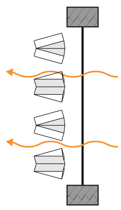
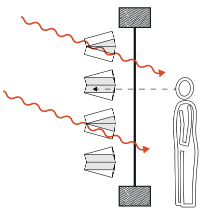
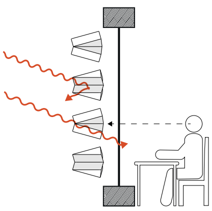
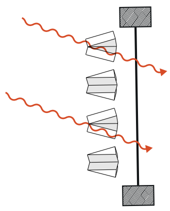
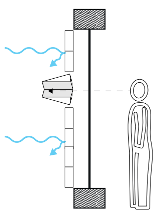
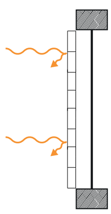
*1 based on two facades

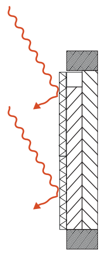
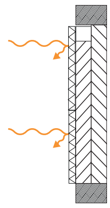
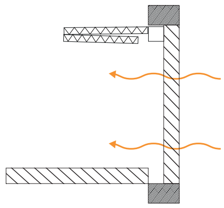
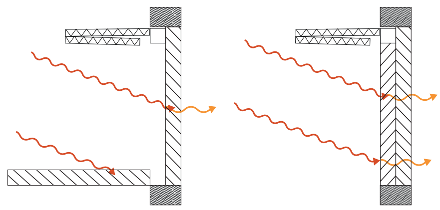
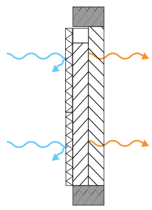
*2 ventilated trombe wall

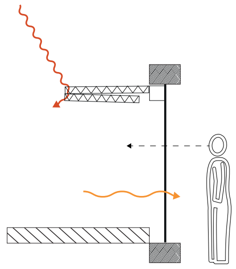
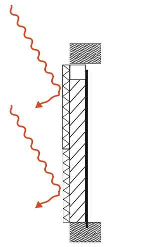
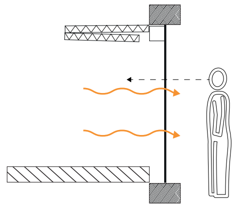
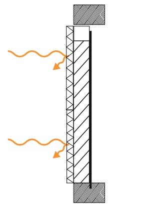
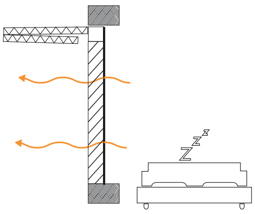
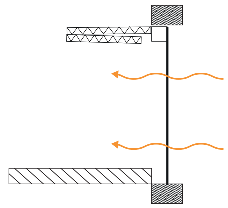
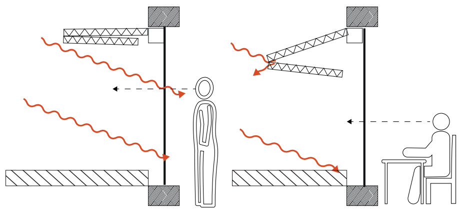
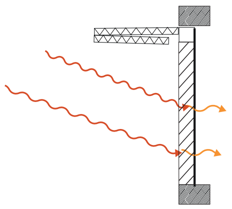
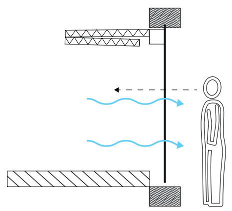
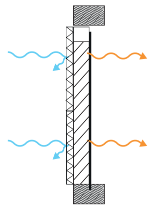
	Environmental impacts	Comfortable indoor climate
	Sun shading Insulation Thermal mass Ventilation	Air- Thermal- Acoustic- Visual comfort
Colt Elisse		
Glassx Crystall		
Vouwluik		
Bolletjes en vloeistof		
Schuivend luik		
Coulissen facade		

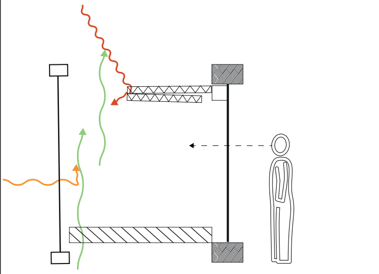
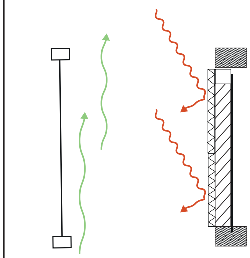
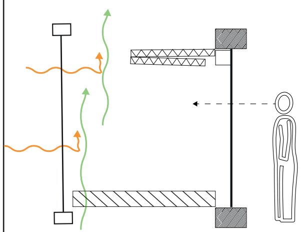
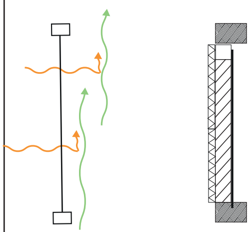
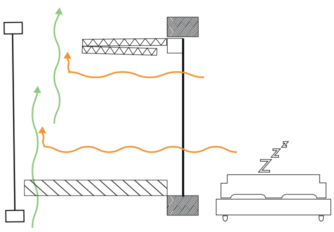
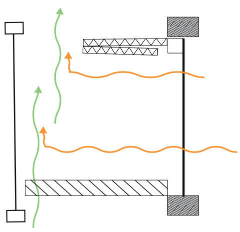
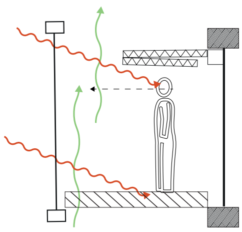
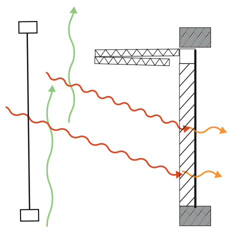
Appendix 3: Configurations

Configuration 1	Present	Absent
Summer		
Sunny		
Cloudy		
Night		
Winter		
Sunny		
Cloudy / Night		

Configuration 2	Present	Absent
Summer		
Sunny	 	
Cloudy		
Night		
Winter		
Sunny	 	
Cloudy / Night		

Configuration 3	Present	Absent
Summer		
Sunny		
Cloudy		
Night		
Winter		
Sunny		
Cloudy / Night		

Configuration 4	Present	Absent
Summer		
Sunny		
Cloudy		
Night		
Winter		
Sunny		
Cloudy / Night		

Configuration 5	Present	Absent
Summer		
Sunny		
Cloudy		
Night		
Winter		
Sunny		
Cloudy / Night