Master thesis : The effects of transparent adaptive façades on energy and comfort performances in office buildings

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The effects of transparent adaptive façades on energy and comfort performances in office buildings

Electrochromic glazing, dynamic shading devices and double-skin façades

Master's thesis in order to obtain a master degree in

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Table of content

Acknowledgement 4
Abstract 5
Résumé 6
List of acronyms 7
1. Introduction 8
2. Literature review 11
2.1. Dynamic envelopes 11
2.1.1. Adaptive façades classification 11
2.1.2. Switchable windows 13
2.1.2.1. Thermochromic window 13
2.1.2.2. Photochromic window 14
2.1.2.3. Electrochromic window 15
2.1.2.4. Nanocrystal-in-glass electrochromic 15
2.1.2.5. Gasochromic window 16
2.1.2.6. Liquid crystals glazing 17
2.1.2.7. Suspended-particle devices 18
2.1.2.8. Electrokinetic pixel window 18
2.1.2.9. Elastomer-deformation tunable window 19
2.1.2.10. Liquid infill window 19
2.1.2.11. Phase change material 20
2.1.3. Movable shading devices 21
2.1.3.1. Fixed shading device 22
2.1.3.2. Adjustable shading device 22
2.1.3.3. Motorized shading device 22
2.1.3.4. Dynamic shading device 23
2.1.3.5. Hybrid shading device 24
2.1.3.6. Dynamic photovoltaic shading device 26
2.1.4. Solar active façades 26
2.1.4.1. Double-skin façade 26
2.1.4.2. Green roofs and green façades 28
2.1.4.3. Static photovoltaic shading device 29
2.1.4.4. Phase change material 29
2.1.5. Active ventilative façades 29
2.1.5.1. Closed cavity façade 30
2.1.5.2. Automated operable windows 30

2.1.5.3. Actively ventilated double-skin façade 30
2.2. Control strategies 31
2.3. Similar studies 33
3. Methodology 36
3.1. Selected software 37
3.2. Base case: 37
3.2.1. Shoe box design 37
3.2.2. HVAC specification 39
3.2.3. Internal gains 40
3.2.4. Base case Validation 41
3.3. Location and climate design 41
3.4. Electrochromic case 43
3.5. Dynamic shading case 45
3.6. Double skin façade with natural ventilation 46
3.7. Double skin façade with hybrid ventilation 47
3.8. Control strategies 48
3.9. Sensitivity analysis 49
3.10. Daylighting simulation 51
3.11. Comparative analysis 53
3.12. Boundary conditions 53
3.13. Resume of simulated cases and their analyzed outputs 55
4. Results 57
4.1. Base case 57
4.1.1. Model validation 57
4.1.2. Energy loads 57
4.1.3. Thermal comfort 59
4.1.4. Visual comfort 59
4.2. Electrochromic case 60
4.2.1. Energy loads 60
4.2.2. Thermal comfort 63
4.2.3. Visual comfort 63
4.3. Dynamic shading 64
4.3.1. Energy loads 64
4.3.2. Thermal comfort 66
4.3.3. Visual comfort 66
4.4. Double skin façade with natural ventilation 67

4.4.1. Energy loads ... 67
4.4.2. Thermal comfort ... 71
4.4.3. Visual comfort ... 71
4.5. Double skin façade with hybrid ventilation ... 73
4.5.1. Energy loads ... 73
4.5.2. Thermal comfort ... 76
4.5.3. Visual comfort ... 76
5. Sensitivity and comparative analysis ... 77
5.1. Sensitivity analysis ... 77
5.1.1. Electrochromic case ... 77
5.1.2. Dynamic shading case ... 79
5.1.3. Double-skin façade ... 84
5.1.4. Double-skin ventilated façade ... 85
5.2. Comparison analysis ... 88
5.2.1. Influential parameters ... 88
5.2.2. Comparative analysis results ... 89
6. Discussion ... 91
6.1. Summary of the main findings ... 91
6.2. Interpretation and recommendations ... 92
6.4. Implication on practice and future research ... 95
7. Conclusion ... 96
Bibliography ... 97
Table of Figures ... 102
Table of tables ... 104
Appendices ... 105
Appendix A: Dynamic building envelopes review ... 106
Appendix B: Screenshots of all steps made in DesignBuilder ... 108
Appendix C: Hourly weather data file of Uccle ... 124
Appendix D: Daylighting results ... 126
Appendix E: Summary of the annual results given by all simulations ... 130
Appendix E.1: Results of the base case ... 133
Appendix E.2: Results of electrochromic cases ... 134
Appendix E.3: Results of dynamic shading cases ... 135
Appendix E.4: Results of double-skin façade cases ... 136
Appendix E.5: Results of double-skin ventilated façade cases ... 137

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Abstract

The effects of transparent adaptive façades on energy and comfort performances in office buildings

Electrochromic glazing, dynamic shading devices and double-skin façades

For the last decades, international organizations have attached a huge importance to building's energy-efficiency. In fact, the construction sector is one of the most responsible for the greenhouse gas emissions and accounts for more than 40% of the total energy consumption. Furthermore, the occupant comfort became a decisive factor of the user's satisfaction. In addition, the European Union intends to recognize the smartness of building with a Smart Readiness Indicator (SRI). In this way, emerging dynamic building envelopes that are adaptive façades are high potential solutions for the building sector. Moreover, these can significantly reduce the energy demand and improve occupant comfort. Many studies analyzed the impact of such façades by investigating one or several of these technologies. However, a single adaptive façade family was mostly studied. Thereby, in this thesis, four smart envelopes from four different families have been simulated and investigated through EnergyPlus with the help of DesignBuilder. Additionally, three control strategies were chosen to study the dynamic aspect of such systems. These are based on solar, operative temperaturel and glare control. The study aims to perform the energy, thermal and visual comforts performances. Then, the building envelope technologies are compared with a base case based on BESTEST case 600 which consist of a single office room with two windows. The simulated location is Uccle, in the Brussels-capital region in Belgium. Finally, a sensitivity analysis is made to strengthen the results and to determine influential parameters.

By comparing the different dynamic building technologies, it is demonstrated that dynamic shading devices and electrochromic glazing have a remarkable influence on the energy savings with a decrease of the total annual loads that can reach 31,3% compared to a simple office room without smart technologies. They mostly influence the cooling energy loads. Double-skin façades have a smaller impact on the energy consumption. However, these can significantly improve thermal comfort by decreasing discomfort hours by 14,8% compared to the base case. In fact, electrochromic glazing and dynamic shading do not really influence thermal comfort. In addition, this study points out the importance of control strategy's choice and parameters. Due to DesignBuilder limitations, visual comfort has only been investigated for double-skin façade cases. Nevertheless, this adaptive façade is able to reduce drastically unwanted daylight by more than 35%.

In conclusion, this thesis helps to determine the impacts of transparent adaptive façades on energy and comfort performances in office buildings. By studying several adaptive façade families and control strategies and different impact criteria, an overview of their potential is possible and can help in decision making of such façades.

Résumé

Les effets des façades adaptives transparentes sur les performances énergétiques et le confort dans les bâtiments de bureaux

Vitrage électrochromique, pare-soleil dynamique et façade double peaux

Depuis quelques décennies, les organisations internationales accordent de plus en plus d'importance à l'efficacité énergétique des bâtiments. En réalité, le secteur de la construction est responsable de plus de 40% de la consommation d'énergie totale. En outre, le confort des occupants est un facteur primordial pour améliorer leur satisfaction. De plus, l'Union Européenne désire évaluer l'intelligence des bâtiments à l'aide d'un indicateur : le *Smart Readiness Indicator* (SRI). Ainsi, les nouvelles technologies dynamiques d'enveloppes, que sont les façades adaptatives, promettent d'offrir des solutions de qualité pour le secteur de la construction. Aussi, celles-ci peuvent considérablement diminuer la demande d'énergie et améliorer le confort des occupants. Plusieurs études portent sur l'analyse d'une ou plusieurs de ces technologies. Mais la plupart du temps, ces dernières font partie de la même famille de façade adaptive. C'est pourquoi, cette thèse de master simule et étudie quatre systèmes de quatre familles différentes de façades adaptatives à l'aide du logiciel EnergyPlus. D'autre part, trois stratégies de contrôle ont été choisies pour évaluer l'aspect dynamique de ce genre de système. Celles-ci sont basées sur le contrôle par les gains solaires, la température opérative et l'index d'éblouissement. L'étude porte sur l'évaluation des performances énergétiques et de conforts thermique et visuel. Outre cela, ces technologies sont comparées à un cas de base, fondé sur le cas 600 de BESTEST qui consiste en une simple pièce de bureau avec deux fenêtres. La localisation de la simulation est, quant à elle, fixée à Uccle, ville de la région de Bruxelles-capitale en Belgique. Finalement, une étude de sensibilité est effectuée afin de déterminer si des paramètres sont susceptibles de varier.

En comparant ces différentes technologies d'enveloppes intelligentes, il est démontré que les pare-soleils dynamiques et le vitrage électrochromique permettent d'économiser remarquablement la consommation d'énergie jusqu'à 31,3% comparé au cas de base. Ceux-ci agissent principalement sur la demande de refroidissement. Les façades double-peau ont, un impact plus modeste sur la demande d'énergie. Néanmoins, elles permettent d'améliorer le confort thermique en diminuant les heures d'inconfort thermique jusqu'à 14,8% par rapport au cas de base. En réalité, le vitrage électrochromique et le pare-soleil dynamique n'influencent que très peu le confort thermique. De plus, cette étude met en évidence l'importance du choix de la stratégie de contrôle et du paramétrage. Cependant, les limitations du logiciel utilisé ont réduit l'étude du confort visuel aux cas de façade double-peau. Toujours est-il que ce type de façade peut réduire le rayonnement solaire non-désiré de plus de 35%.

En conclusion, cette thèse de master permet de déterminer les impacts des façades adaptatives transparentes sur les performances énergétiques et de confort dans les bâtiments de bureaux. En étudiant différentes familles, diverses stratégies de contrôle ainsi que plusieurs domaines d'impact, une vue globale de leur potentiel est possible et peut aider dans le choix de façade intelligente.

List of acronyms

- AF: Adaptive façade
- BPS: Building Performance Simulation
- DB: DesignBuilder
- DS: Dynamic shading
- DS0: Dynamic shading with schedule control
- DS1: Dynamic shading with solar control
- DS2: Dynamic shading with operative temperature control
- DS3: Dynamic shading with glare control
- DSF: Double-skin façade
- DSF0: Double-skin façade not ventilated
- DSF1: Double-skin façade naturally ventilated with schedule control
- DSF2: Double-skin façade naturally ventilated with operative temperature control
- DSFV: Double-skin façade ventilated
- DSFV1: Double-skin façade mechanically ventilated with operative temperature control
- DSFV2: Double-skin façade naturally and mechanically (hybrid) ventilated with operative temperature control
- ECW: Electrochromic window
- ECW0: Electrochromic window with schedule control
- ECW1: Electrochromic window with solar control
- ECW2: Electrochromic window with operative temperature control
- ECW3: Electrochromic window with glare control
- GCW: Gasochromic window
- LC: Liquid crystal
- NC: Nanocrystal-in-glass
- PCM: Phase change materials
- PCW: Photochromic window
- PV: Photovoltaic
- SPD: Suspended particle device
- TCW: Thermochromic window

1. Introduction

For many years, international organizations have attached a huge importance to the building's energy-efficiency. For example, one of the objectives of the *EU Energy Efficiency Action Plans* for 2030 is to reduce, by 2050, the greenhouse gas by more than 95% below the level of 1990 (European Commission, 2014). Currently, the construction sector accounts for more than 35% of greenhouse gas emissions in Europe and for more than 40% of the total energy consumption (Raji, Tenpierik, & Van den Dobbelsteen, 2016). Furthermore, there is a need to take care of the indoor comfort of occupants in buildings (Luna-Navarro, et al., 2020). In addition, due to the present needs and all new and future innovations, the European Union intends to recognize the smartness of building with a *Smart Readiness Indicator* (SRI) (Vito NV, 2020). Building envelopes are the interface between the outdoor and the indoor environment and could have important impacts on the energy and comfort performances of buildings (Raji, et al., 2016). Moreover, innovative building envelopes could become one of the key solutions to reduce environmental impacts and increase the performances of buildings (Attia, Lioure, & Declaude, 2020).

For the last decades, dynamic building envelopes also called adaptive façades have been of great interest for researchers (Casini, 2018). In fact, adaptive façades are able to respond or to benefit from the changing outside boundary conditions (Attia, et al., 2020). Their main advantage is their possibility to control solar heat gain and daylight while preventing overheating and glare. In most cases, static blinds or roller shades are used but smart technologies exist for in this purpose (Tällberg, Petter Jelle, Loonen, Gao, & Hamdy, 2019). Attia, et al. (2020) reviewed the current trends and future potential of adaptive façades. From this study, it can be seen that there is a large choice in terms of adaptive and smart envelopes. Furthermore, several dynamic technologies are still in the experimentation phase and not on the market (Casini, 2018). Nevertheless, by simulating and studying these, the evaluation of their impacts on energy and comfort performances is possible (Favoino, et al., 2018).

Many studies investigated impacts of adaptive façades. Tällberg, et al. (2019) evaluate the influence of thermochromic, photochromic and electrochromic on energy consumption by simulating an office room in Trondheim, Madrid and Nairobi with IDA ICE tool. Furthermore they investigated the impact of three control strategies: solar control, operative temperature control and daylight control. It was demonstrated that electrochromic glazing would have a better energy performance than two other smart windows. It was also shown that operative temperature control is the most efficient strategy. In 2017, Dussault & Gosselin (2017) studied the impact of electrochromic glazing on the energy, thermal and visual comfort performances with the help of TRNSYS and DaySim softwares. By implementing different control strategies, they also evaluate the influence of the dynamic aspect. Many different locations in the USA and Canada were studied. On the first hand, their conclusion was that electrochromic windows are able to reduce energy consumption while the control strategies mostly improve the visual comfort. On the other hand, thermal comfort is not really sensible to this smart technology. In a previous study made by Mäkitalo (2013), the influence of electrochromic glazing with several control logics was simulated for an office building located in Stockholm by using IDA ICE. This study pointed out that electrochromic windows proposed a better energy performance than conventional windows with blinds. Mäkitalo also analyzed the influence of different parameters through sensitivity analyses. However, no parameters studied were influential regarding energy consumption. Moreover, Jensen Skarning, Anker Hviid, & Svendsen (2017) analyzed the impact of dynamic shading devices on energy consumption, thermal and visual comfort. This was performed by simulating dynamic shading systems of a loft room through EnergyPlus in Rome and Copenhagen. Globally, dynamic shading devices improved the room performances. Before that, Vraa Nielsen, Svendsen, & Bjerregaard Jensen (2011) also studied dynamic shading impact on the energy demand, thermal and visual comfort by simulating a single room in Denmark with the help of iDbuild and LightCalc. A comparison with windows with and without static shading devices was made and demonstrated a significant reduction of the cooling and heating energy loads as well as the amount of daylight. Finally, related to double-skin façades, Alberto, Ramos, & Almeida (2017) evaluated the implementation of this adaptive façade type on the energy performance by simulating an existing office building in Porto with EnergyPlus. A sensitivity analysis was performed to determine sensible parameters. Their conclusion was that a double-skin helps to reduce significantly the energy demand. Furthermore, cavity depth, ventilation mode and airflow path could strongly influence the results. This was also in accordance with experimental findings of Shi, Tablada, & Wanga (2020). They simulated an office room in Singapore through the EnergyPlus tool and analyzed the influence of double-skin façades on energy demand. At the same time, their study proved a better visual comfort with this smart technology. Further information about relevant studies is gathered in section 2.3.

However, none of the mentioned studies compared adaptive façades from different families. Most of the time, the scope was limited to a single family or technology such as switchable windows, dynamic shading devices or double-skin façade. Moreover, it is expected that dynamic building envelopes are able to reduce the energy demand. However, the occupant's environment as thermal and visual comforts could also be influenced by these technologies but is less studied. In addition, dynamic control strategies are important but few studies evaluate their impacts. In fact, a single control logic is mostly chosen. It appears that sometimes, some of them are investigated but only on one impact criteria which is usually the energy demand. Finally, sensitivity analysis is suitable to determine influential parameters that can improve or worsen adaptive façade performances.

Regarding the previous points, the objective of this study is to compare dynamic transparent building envelopes. Thus, electrochromic glazing, dynamic shading devices and double-skin façades with and without ventilation were chosen. The first technology is able to switch its color from a clear to a dark state by applying a voltage (Casini, 2018). In contrast to static shading devices, the second smart technology is able to move the shading devices in a dynamical way (Attia, et al., 2020, double-skin façades are the most popular smart technologies and are studied in this thesis. This façade type is composed of two glass skin layers separated by a gas cavity (Alberto, et al., 2017). In addition, it was interesting to add control strategies to analyze the influence of the dynamic part of the adaptive façade. Regarding previous studies related to adaptive façade, solar control, operative temperature control and glare control strategies impacts were investigated. At first, a base case, established on the BESTEST case 600, has been modeled with DesignBuilder software. Then the different smart technologies and their control strategies were implemented and simulated. Different impact criteria were analyzed: energy savings, thermal and visual comforts. All simulations were performed annually and for the location of Uccle, in the Brussels-capital region, in Belgium. In total, eighty-nine simulations were performed.

The results related to energy performance showed that electrochromic glazing and dynamic shading cases mostly impact the cooling energy loads and thereby can decrease the total energy loads. Double-skin façades are less efficient than these technologies. However, double-skin façades have a significant impact on thermal comfort while electrochromic glazing and dynamic shading cases poorly influence this domain. Due to the software's limitations, visual comfort has only been studied for this last dynamic building envelope and displays a remarkable improvement.

This master thesis study aims at helping decision-making of adaptive façades. This could become a reference in terms of dynamic transparent building envelope models and simulations since several adaptive façades, control strategies and impact criteria were investigated. The study is addressed to the construction sector as well as individuals who are interested in smart envelopes technologies. The corresponding research questions to the objectives are:

- What is the influence of the different dynamic technologies on energy consumption and comfort in smart office buildings?
- How to optimize, with strategic controls, thermal comfort and energy efficiency in smart offices buildings with the technologies studied?
- What are the factors that determine the smart readiness of a dynamic envelope?

The thesis is structured as follows. Chapter 2 introduces, reviews and presents adaptive façades currently existing which have a high potential for the future of the building sector. Then, the whole methodology of simulated cases is explained in Chapter 3. After, the results of these simulations are presented in Chapter 4 and the results of the sensitivity and comparative analysis are provided in Chapter 5. Next, Section 6 discusses the main findings, interpretations, recommendations, strengths and limitations of the study. Finally, Section 7 concludes the paper.

2. Literature review

This chapter gathers the theory related to the thesis. At first, a section is dedicated to dynamic envelopes with a classification of adaptive façades that could be used in smart office buildings, followed by the description of each of them. Then, the dynamic aspects of adaptive façade, that is to say the control strategies in occupant's interactions, are explained. Finally, a section that gathers the most relevant studies related to the topic is proposed.

2.1. Dynamic envelopes

2.1.1. Adaptive façades classification

For the last 30 years, new building envelope materials and façade components have been more and more numerous. As a mediator between the exterior and interior, there are many functions for a façade with an effect on the performances of a building (Böke, Knaack, & Hemmerling, 2019). These innovative building envelopes aim to improve the energy efficiency as well as the occupant comfort, their health and the environmental impacts (Casini, 2018). Also called adaptive façades, these are dynamic building envelopes that can adapt themselves to the changing boundary conditions. Actually, these innovative building façades are able to adapt themselves depending on the outside climatic conditions and dynamic occupant requirements and ensure step-change progress of the energy performance. The words "dynamic" or "adaptive" are used with reference to the capacity of a façade to benefit from, or to respond to the boundary conditions to improve the performances and the occupant's needs (Attia, et al., 2018).

In this thesis *dynamic envelope* or *adaptive façade system* is defined as the whole façade assembly which means that the material level or component level is considered with the control systems that might be used to control them. Thereby, these systems can be prefabricated and preassembled or built on site. This definition is in line with EU COST Action TU1403 "adaptive façades network" (Favoino, et al., 2018). The objectives of this Action is to define adaptive façade and to share technological knowledge at European level.

A lot of scientific publications and relevant projects about such façade systems indicate important performance benefits by comparison with conventional alternatives. The main improvements are related to the energy savings and thermal and visual performances with reduction of glare, reflections and discomfort besides the windows (Casini, 2018). Most of the time, comparison analyses were made. In fact, by assessing the performance of this type of façade, it is possible to optimize their design, operation and maintenance. In contrast, it abides a challenge to assess the dynamic aspect of such façades. (Attia, et al., 2018).

Numerous technologies are currently available on the market and others are still in the experimentation phase. In this context, it is important to overview these technologies. Based on several framework and review studies (Al-Masrani et al., 2018 ; Attia, et al., 2020 ; Favoino, et al., 2018 ; Casini, 2018 ; Sibilio, et al., 2018) the dynamic envelope's types or products existing are presented in the following sections.

The global classification is inspired by Attia, et al. (2020) who proposed a technical classification of adaptive façade based on façade experts' interviews and content analysis. Therefore to complete the framework proposed, a literature review on other frameworks has been made. The purpose of COST Action TU 1403 was to provide a general framework, standardized methods and tools to evaluate, in a quantitative way, the performance of adaptive façade. The book joins the research and knowledge of many scientists from Europe to define a standardized approach which can support the integration of adaptive façades in buildings. According to them, switchable glazing, movable solar shading, dynamic insulation and multifunctional façades are the most promising adaptive façade for buildings (Favoino F. , et al., 2018). Al-Masrani et al., (2018) mostly reviewed existing shading devices and Casini (2018) developed a review of so-called switchable glazing. The paper is focused on the dynamic glazing technologies which are on the market or on experimental phase and compared them regarding their operation, performances and building application potential (Casini, 2018). Finally, the 16th international forum of *La Vie dei Mercanti* pointed out some transparent adaptive materials with their optical properties and description (Sibilio, Iavarone, Mastantuano, Mantova, & D'Ausilio, 2018).

From these sources, it appears that there are four main families that can be considered as *dynamic building envelopes*:

- **Switchable windows**
- **Movable shading devices**
- **Solar active façades**
- **Active ventilative façades**

The two first and the last envelopes gather mostly transparent building envelopes while the third groups mainly opaque façades. However, this master thesis studies transparent building envelope systems. Figure 2.1 below is a summary of all adaptive façades currently existing and that have real future potential in the construction sector.

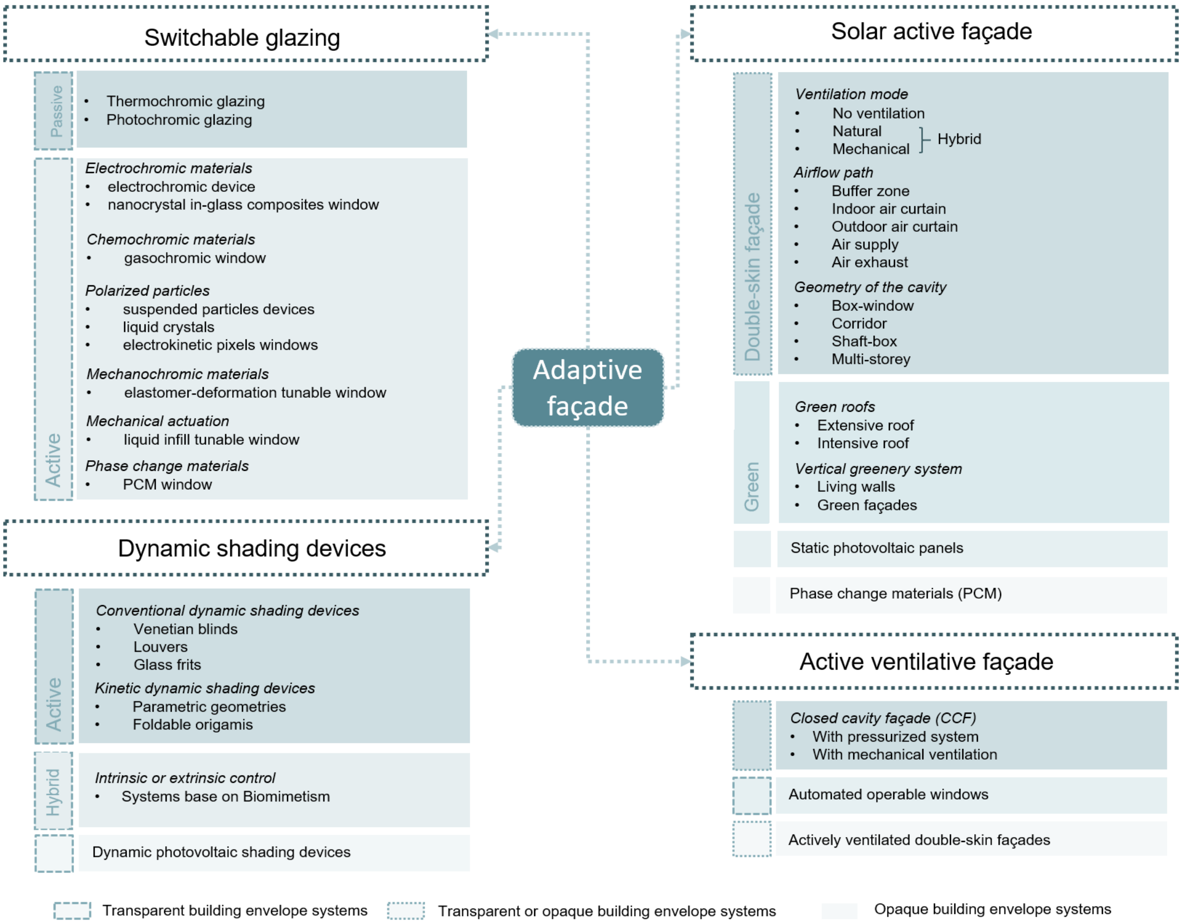


Figure 2.1 - Main existing dynamic transparent building envelopes

More detailed descriptions and specifications of these dynamic envelopes are presented in the following sections. However, the Appendix A gathers all the adaptive envelopes, their descriptions and specifications.

2.1.2. Switchable windows

These windows have the ability to change their optical properties and thus to modulate the solar gains or daylight of interior spaces by reflecting it or absorbing it (Sibilio, Iavarone, Mastantuano, Mantova, & D'Ausilio, 2018). The main purpose of these smart windows is their help in the improvement of visual and thermal comfort. By limiting the solar heat, the energy performance can be improved as well. Some of the switchable windows are already on the market, some others are still in a development phase (Casini, 2018). Also called chromogenic glazing, these are divided in (Sibilio, Iavarone, Mastantuano, Mantova, & D'Ausilio, 2018):

- **Passive dynamic control** also called *intrinsic* which means that the switching mechanism is activated autonomously by a natural stimulus such as temperature or solar radiation. This is the case of thermochromic and phase change material (heat stimuli) and photochromic (light stimuli) glazing.
- **Active dynamic control** also called *extrinsic*. This means that an external stimulus is needed to switch the mechanism. These switchable windows are more suitable in terms of energy savings and refer to:

    - *Electrochromic materials* as electrochromic device or nanocrystal in-glass composites window
    - *Chemochromic materials* as gasochromic window
    - *Polarized particles* as suspended particles devices, liquid crystals or electrokinetic pixels windows
    - *Mechanochromic materials* as elastomer-deformation tunable window
    - *Mechanical actuation* as liquid infill tunable window
    - *Phase change materials* that are also used in opaque walls.

The following paragraphs describe and explain how these dynamic switchable windows operated by firstly presenting passive dynamic controlled technologies, followed by active dynamic control.

2.1.2.1. Thermochromic window

Thermochromic windows (TCW) are able to change their color from a clear to dark state depending on the temperature. Actually, these types of windows have the capability to modulate the light and solar heat transmitted through the window as a function of its temperature (Tällberg, et al., 2019). A thermochromic layer material is placed between two glass panes. Above a certain temperature threshold, a metallic hue appears and makes the thermochromic material reflective of infra-red radiations. The consequence is that the solar gains in summer are controlled and allow lower cooling demand. In fact, by using this kind of technology, its performances depend totally on the outside climatic conditions. Thus, metal oxides are mostly used for building façades and especially VO_2 doped with tungsten ions or with fluorine to adjust the temperature transition of this metal oxide suitable for building applications. Usually, a low emissivity coating is placed near the inner glass pane (Costanzo, Evola, & Marletta, 2016). The following Figure 2.2 helps to understand the operation mode of thermochromic glazing and is inspired by the state-of-the-art of Costanzo.

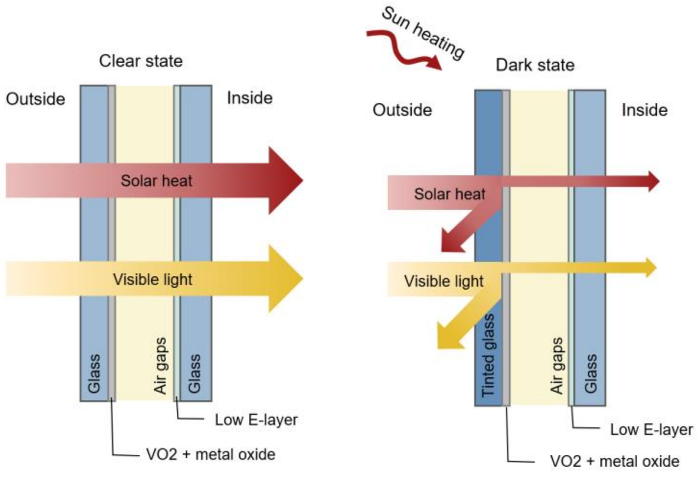


Figure 2.2 - Thermochromic glazing operation - inspired by (Costanzo, Evola, & Marletta, 2016)

2.1.2.2. Photochromic window

Photochromic windows (PCW) work the same way as thermochromic glazing. However, they can modulate the light transmission and the solar heat transmitted depending on the solar radiation instead of the temperature (Tällberg, et al., 2019). Most of the time, the photochromic layer is made of silver crystallites embedded into an $AlPO_4$ or a borosilicate matrix. The color of the tinted glass depends on the size of silver crystallites. Photochromic glasses exist for more than 50 years but have been poorly investigated for a utilization in the building sector. In fact, this technology is commonly used for sunglasses (Fries, Fink-Straube, Menning, & Schmidt, 2011).

Actually, very poor information could be found about photochromic windows. The Figure 2.3, illustrates the photochromic glass operation and is based on Fries's study. In fact, photochromic windows as well as thermochromic windows are unusually used in the building sector because of their uncontrollable aspect. In addition, few manufacturers are producing them (Tällberg, et al., 2019).

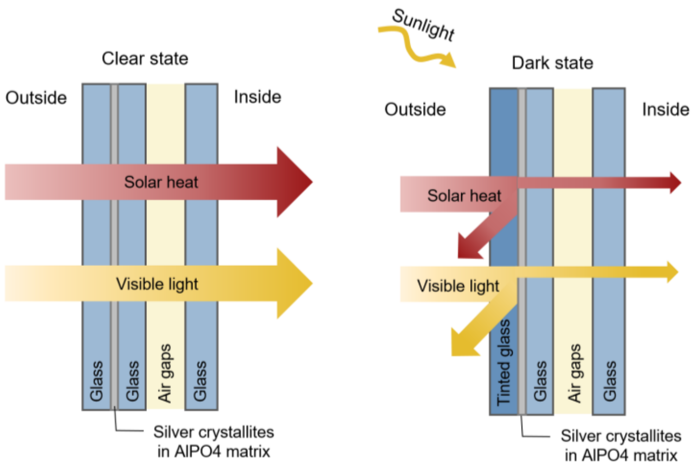


Figure 2.3 – photochromic glazing operation - inspired by (Fries, Fink-Straube, Menning, & Schmidt, 2011)

2.1.2.3. Electrochromic window

Electrochromic windows (ECW) are able to change their color from a clear to a dark state by reduction or oxidation reactions as a response to the external electrical stimuli. This will help to reduce the light and solar heat transmitted through the glazing. Electrochromic glazing is made of five layers. These are composed of (Casini, 2018):

- Outer layer made of transparent conductive oxide
- Electron accumulation layer which acts as a counter electrode ($Li_xV_2O_5$)
- Ion conductor layer or electrolyte (usually $LiAlF_4$)
- Electrode layer (usually WO_3 or Nb_2O_5)
- Outer layer made of transparent conductive oxide

By applying a voltage, the Li+ ions are transferred from the accumulation layer to the electrode and switch the color to a dark state (Iuliano, et al., 2016). This is made in the accumulation layer (anodic coloration because of the loss of ions) or in the electrode layer (cathodic coloration because of the ions' gain) depending on the electrochromic materials used. By applying again a voltage the ions return from the electrode to the accumulation layer and the device is made transparent again (Sibilio, et al., 2018). Figure 2.4 below represents the operating scheme of electrochromic glazing.

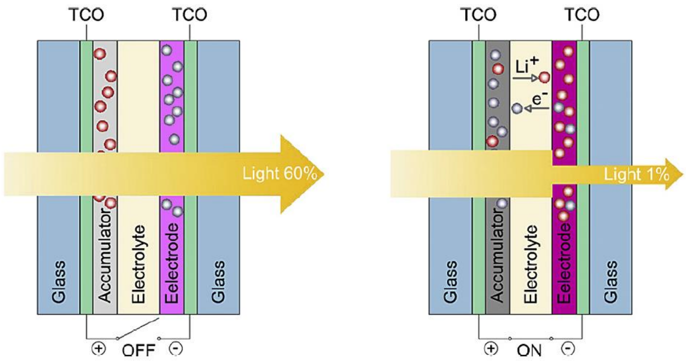


Figure 2.4 - Electrochromic glazing operating scheme (Casini, 2018)

One of the particularities of electrochromic devices is that they could reach different intermediate states from a clear one to a darker one. Today, electrochromic devices are the most suitable for building envelope and commercialized switchable windows. This technology appeared on the market at the beginning of the 2000's and has been improved since. For example, it has the best proven durability and can be self-powered by a photovoltaic battery located in the window edge to avoid power supply wires (Casini, 2018). A lot of studies has been made to investigate the performance improvement of electrochromic glazing, and these showed that electrochromic technology significantly influences the energy performance, thermal and visual comfort (Aldawoud, 2013 ; Cannavale, Ayra, & Martellotta, 2018 ; Dussault & Gosselin, 2017 ; Frattolillo, Loddo, Mastino, & Baccoli, 2019 ; Mäkitalo, 2013 ; Tällberg, at al., 2019).

2.1.2.4. Nanocrystal-in-glass electrochromic

The *nanocrystal-in-glass electrochromic (NC)* is not commercialized currently but represents a promising electrochromic emerging technology that could improve the overall performance of electrochromic glazing. NC is composed of Indium oxide nanocrystal embedded in a glass matrix made of niobium oxide (Sibilio, et al., 2018). Contrary to electrochromic glazing, nanocrystal-in-glass operates by both absorbing Li+ ions and losing electrons from a donor layer. A first reduction voltage increases the ions carriers in the thin-oxide nanocrystals and gives the Cool state represented on Figure 2.5. Solar heat is blocked but light is still transmitted through the glass. Then the reduction of niobium oxide of the glass matrix is generated by turning down the voltage and the dark state is reached. This state blocks the solar heat gains as well as the light transmission (Casini, 2018).

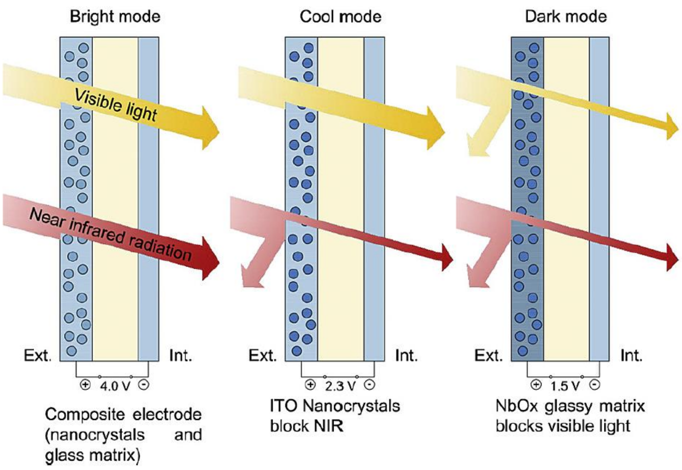
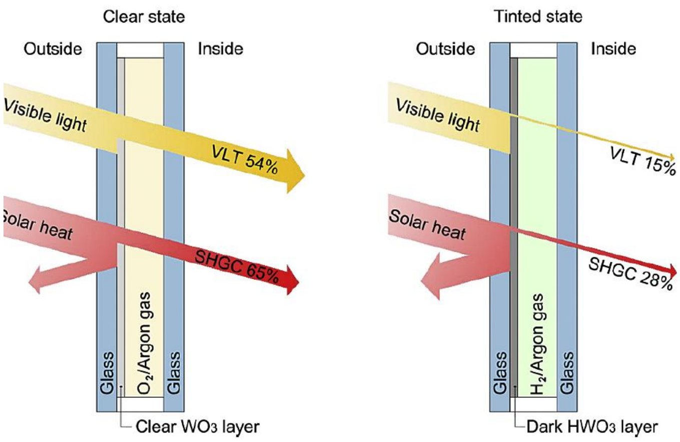


Figure 2.5 - Nanocrystal-in-glass composite (Casini, 2018)

2.1.2.5. Gasochromic window

After electrochromic glazing, *gasochromic glazing* (GC) is the second most suitable switchable glazing on the market. This technology is cheaper than ECW because it need only one thin layer of WO_3 covered by a platinum or palladium catalyst[1] (Casini, 2018). Another advantage is that GC can be coated on any transparent substrate which means that the substrate can differ from glass. This chemochromic material switches in a dark state by exposing a gas-sensible layer to a mixture of Ar and H_2. Contrarily, by introducing O_2, the clear state is reverted to H_2O (Feng, et al., 2016). To allow a quick transport of the H_2 molecules, structural water is needed in the tungsten film-layer. The higher is the concentration of H_2 the darker is the color (Sibilio, et al., 2018). This is represented on the following Figure 2.6.



[1] Palladium catalyst: It has been shown in 2010 that *palladium* acts as a *catalyst*. Thereby, it enables and encourages a reaction between individual carbon atoms (Casini, 2018).

Figure 2.6-Gasochromic glazing composition (Casini, 2018)

Gasochromic glazing is cheaper also due to the manufacturing process and a simpler assembly. The switching time is faster than for electrochromic windows. As electrochromic glazing, a small power consumption is needed to switch the states but due to its chemical operation, no power is needed to keep a constant tint (Casini, 2018). A study made by Feng shows that HVAC loads can decrease by 28,4% compared to a single clear glass. Despite that, gasochromic glazing consumes less energy than electrochromic glazing does (Feng, et al., 2016).

2.1.2.6. Liquid crystals glazing

Liquid crystals glazing are polarized particles contained in the cavity of a glass that are able to control the translucence of the window (Seung-Won, Sang-Hyeok, Jong-Min, & Tae-Hoon, 2018). Inside, small droplets of liquid crystal are suspended in a polymer matrix located between two glass pane substrates. The opaque and dark state is obtained in the "off" state of these particles which are in a random position, the *nematic phase*. By applying a voltage for some extrinsic LC device or by cooling it for an intrinsic LC device, the liquid crystals tend to align and reduce the refractive index between the liquid crystals and the polymer. This is the *smectic phase* shown on Figure 2.7. Thereby, the clear and translucent state is reached. Contrary to most of the switchable windows, extrinsic liquid crystals devices need a continuous voltage to keep the state clear. Several type of polymer dispersed liquid crystals are existing but the most known and used is based on *Smectic phase A*[2] (Gardiner, Morris, & Coles, 2009). Figure 2.7 below is inspired by Seung's study which proves better visual and thermal performances.

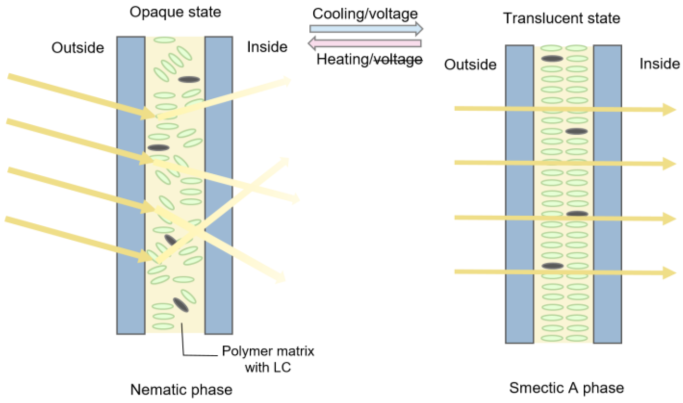


Figure 2.7-Liquid crystal window operation – Inspired by (Seung-Won, Sang-Hyeok, Jong-Min, & Tae-Hoon, 2018)

Due to the self-alignment of LC, the production process is simple and only requires the injection of the LC mixture in the window's cavity. Also liquid crystal devices can be improved by adding other components in the polymer matrix as for example azobenzene proposed by Seung-Won Oh. Liquid crystal devices have been experimented for more than 10 years now and their visual improvement has been proved (Seung-Won, et al., 2018). However, this technology is unusually used in building envelopes because it needs a continuous voltage to be correctly controlled (Casini, 2018).

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[2] Smectic A phase of a liquid crystal device has the particularity that the orientation is made along the normal layer while for some other smectic, these are oriented away from this layer. The smectic phases differ from each other by the types and degrees of orientation and position. Smectic A phase is preferred because the alignment tendency of liquid crystals is in correlation with the position order. Their combination induces the clear state of liquid crystal devices (Gardiner, Morris, & Coles, 2009).

2.1.2.7. Suspended-particle devices

Suspended-particle devices (SPD) work the same way as liquid crystal devices but with droplets of liquid suspension (Favoino, et al., 2018). By applying a voltage, the suspended particles are polarized and are forced to align with the field. Actually, when SPD contained in a conduction coating comes into contact with the electricity they align them and allow light to flow through the window. Without electricity, the suspended particles are positioned and oriented randomly (Oltean, 2006). This operation is represented on Figure 2.8.

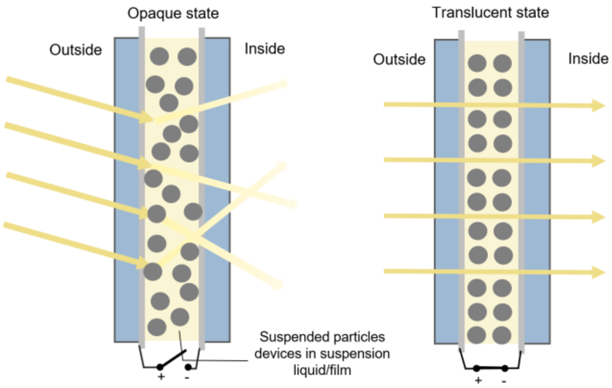


Figure 2.8-Suspended particle devices operation – Inspired by (Oltean, 2006)

2.1.2.8. Electrokinetic pixel window

Electrokinetic pixel windows have the capability to modulate the hue and the temperature that are coming from the visible light. The Figure 2.9 shows the electrokinetic pixel window composition.

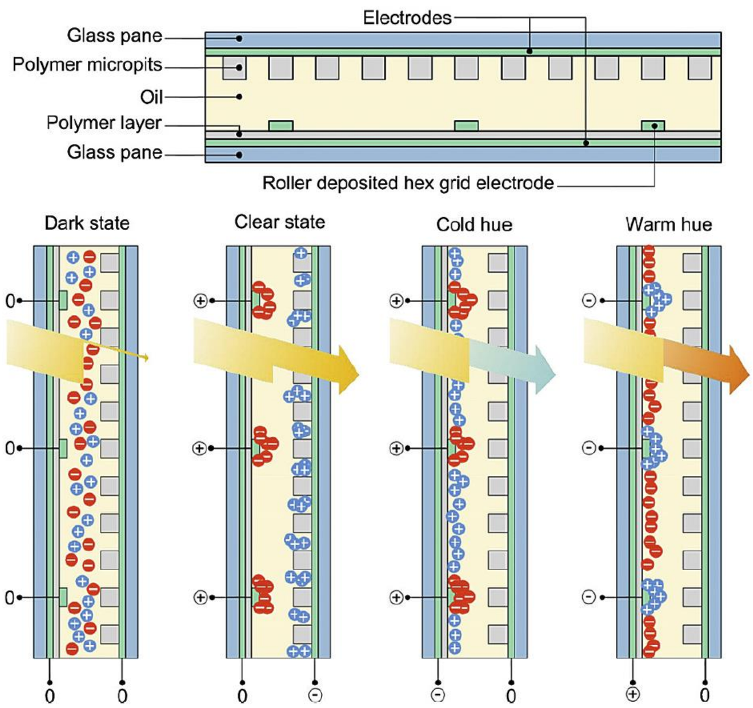


Figure 2.9 - Electrokinetic pixel window composition (Casini, 2018)

Two planar electrodes are used to control the electrophoretic dispersion of complementary colors (blue/yellow for example). These are characterized by opposite electrical charges and according to the negative or positive sign of the supplied charge, the color particles move to the inferior, upper or perimeter electrode. In addition, a third electrode creates a mesh and is placed in the interlayer cavity. Furthermore, the lower electrode presents polymer-replicated micro pits that are able to catch the color particles and inhibit their spread. The dark state is obtained when the electrodes are not charged and thus the color particles are dispersed uniformly. The clear state is achieved when the color particles are condensed towards the perimeter and inferior electrodes. One of the particularities of this technology is the control of the color which can be warmer if yellow particles are dispersed and blue particles compacted around the perimeter electrode or colder if the opposite operation appears (Sibilio, et al., 2018).

2.1.2.9. Elastomer-deformation tunable window

The *elastomer-deformation tunable window* is also an emerging technology not available on the market. This type of window is an alternative to electrochromic glazing which presents the ability to vary from a clear state to an opaque state by diffusing the light. This mechanochromic technology uses the geometric deformation of the glass surface to control the light diffusion by switching the hue to opaque or clear state. This is achieved by inserting a polymer pane between two elastomer layers that are transparent and dielectric. These are sprayed with electrically conducting silver nanowires that are invisible to the eye and still allow the light transmission. By applying a voltage, the nanowires turn to the electrodes which tend to deform the two elastomer layers below. Their surface becomes rough and irregular which decreases the light transmission while keeping a perfect neutral color. The curvature of the elastomer layers depends on the intensity of the voltage and thus the hue can be more or less opaque (Casini, 2018). Figure 2.10 below shows how elastomer deformation tunable windows operate.

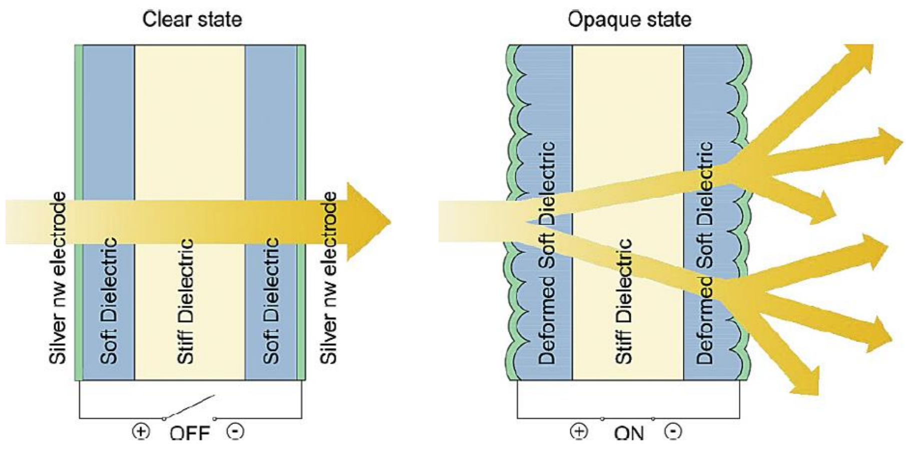


Figure 2.10 - Elastomer deformation tunable window operation (Casini, 2018)

2.1.2.10. Liquid infill window

Another prototypal device is *the liquid infill window.* This technology reduces the light transmission by pumping liquids in or out of a triple glazed insulated glass unit. Actually, a shading fluid is pumped from the bottom to up of the second cavity while the gas is extracted to a dedicated tank. The first cavity acts as thermal insulation. In the end, this technology is able to block unwanted light and solar heat (Casini, 2018). This is represented on Figure 2.11.

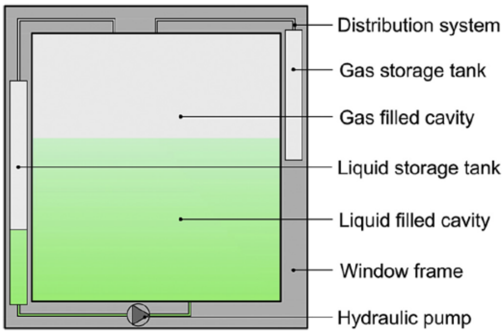


Figure 2.11 – Liquid infill tunable window operation (Casini, 2018)

2.1.2.11. Phase change material

Finally, the last switchable technology to review is *phase change material* (PCM). Usually implemented for opaque envelope components, this technology has also been developed in a transparent system. Its particularity is that the phase change material is able to change its phase (usually solid-to-liquid in building applications) over a certain temperature range (Vigna, Bianco, Goia, & Serra, 2018). On the first hand, PCM solidifies and releases the latent heat into the building when the external temperature decreases and reaches the melting point. On the other hand, the liquid phase of PCM is able to absorb energy (Sibilio, et al., 2018). In this way, the main purpose is to improve the thermal comfort and energy performances by increasing the thermal inertia of glazed components due to the buffer zone induced by this PCM layer. In fact, phase change materials used can absorb the infrared radiation while still allowing light transmission (Vigna, et al., 2018). However, even if the main PCM commercialized are sensible to the temperature, it can be noticed that the charging/discharging method can be active (or extrinsic), by forcing the convection heat transfer or mass transfer, as well as passive (or intrinsic) where solar radiation of temperature can switch autonomously the phase (Favoino, et al., 2018). This is why this technology is presented as active switchable glazing. There are different ways to integrate PCM in transparent building systems (Vigna, et al., 2018) and these are presented on the Figure 2.12:

- In the glazing which will mostly improve the thermal comfort and energy performances (Figure 2.12.a – b – c)
- In a shutter which will also improve the visual comfort by decreasing the glare (Figure 2.12.d)
- In the façade system into a glass container which is the most complex method (Figure 2.12.e – f – g)

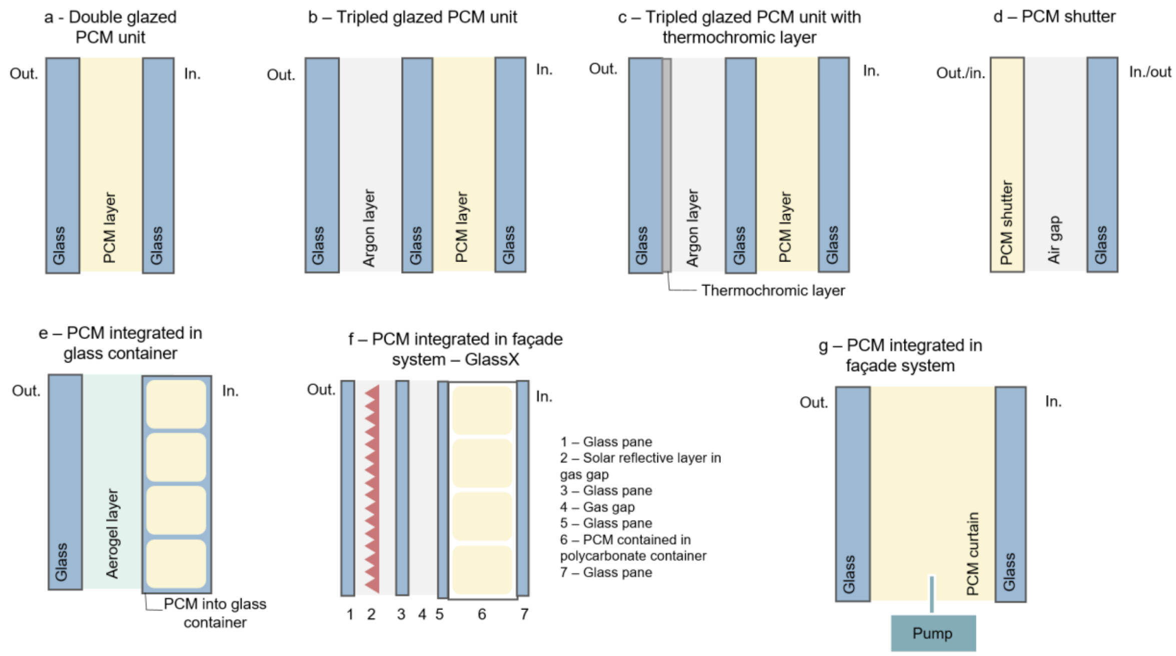


Figure 2.12 - Phase change material integrated in transparent envelopes - inspired by (Vigna, Bianco, Goia, & Serra, 2018)

The most known phase change materials are the paraffin wax, mostly used in PCM glazing units and salts hydrates also used in PCM shutter and façade systems. These technologies improve the energy, thermal and visual comforts performances. However, PCM systems are not stable and inconvenients are numerous (Vigna, et al., 2018).

2.1.3. Movable shading devices

Today's building façades are expected to be highly multifunctional, for example in terms of energy consumption, glare prevention and thermal comfort. Movable shading devices are technologies that are able to respond to these high-performance requirements. Examples include venetian blinds, prismatic film, glass frits, louvers and many others (Favoino, et al., 2018). These kinds of technologies can be static or dynamically controlled depending on the strategies chosen. Several studies showed that such shadings could significantly improve the energy consumption (De Luca, Voll, & Thalfeldt, 2018 ; Vraa Nielsenet al., 2011 ; Mostafa, et al., 2016) as well as the thermal comfort (Jensen Skarninget al., 2017) and visual comfort (Kyu Yi, Yin, & Tang, 2018 ; Jayathissa, et al., 2017 ; Mahmoud & Elghazi, 2016)

Considered as the most used adaptive technology, dynamic shading devices have been analyzed for several years. Many studies performed such shading with many different control strategies. However, shadings are categorized regarding their energy involvement (Al-Masrani, et al., 2018):

- **Passive** which is static shading devices and thus is fixed or manually adjustable. Their improvement is based on a parametric study.
- **Active** which gathers the motorized and automated/dynamic shading devices. This mostly means simple motion mode.
- **Hybrid** that remains systems based on *biomimetism* (shape morphing skin). For these, a control strategy has to be implemented and as for switchable glazing, could be intrinsic or extrinsic with the help of actuators.
- **Integrated photovoltaic panels** are another type analyzed in some studies (Kyu Yi, Yin, & Tang, 2018 ; Favoino F., et al., 2018).

Active, hybrid shading devices and integrated photovoltaic panels are considered as smart technologies since they involve a control strategy. Some of these shading devices can be internal, mid-pane or external (DesignBuilder, 2020) but a focus is made on the external shading devices.

2.1.3.1. Fixed shading device

Fixed shading devices are the usual shading systems as overhangs, perforated screens, egg-crates or side fins for example. Their main purpose is to break down the direct solar irradiation as well as the light transmission (Al-Masrani, et al., 2018). Examples are presented on Figure 2.13.

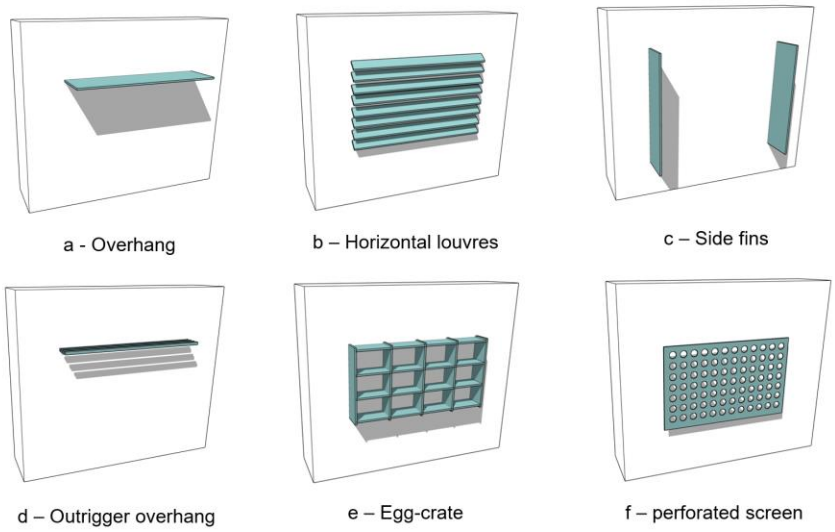


Figure 2.13 - Fixed shading examples – inspired by (Al-Masrani, Al-Obaidi, Zalin, & Aida Isma, 2018)

2.1.3.2. Adjustable shading device

The common *adjustable shading devices* available on the market are venetian blinds, roller shades, vertical blinds and louvers. Since these can be adjusted manually by the occupants, they are preferred over fixed devices. In addition to control the diffuse solar beams, adjustable devices allow occupants to control the view into the room and thus provide them privacy when needed (Al-Masrani, et al., 2018). Examples are shown on Figure 2.14 below.

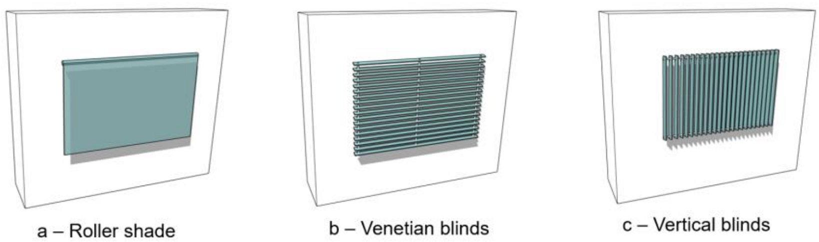


Figure 2.14 – Adjustable shading examples – inspired by (Al-Masrani, Al-Obaidi, Zalin, & Aida Isma, 2018)

2.1.3.3. Motorized shading device

Since they operated with electrical motors, *Motorized shading systems* are more advanced in terms of adjutancy than adjustable shading devices. In contrast to their more sophistical structure, their design abides limited compared to models with simple geometries. However, due to this motorized aspect, it has been shown that occupants adjust more often the shading devices to their needs and thus improve the thermal and visual comforts. Anyhow, this fully depends on the user's behavior. Usually, motorized shadings are roller shades and blinds (Al-Masrani, et al., 2018).

2.1.3.4. Dynamic shading device

On the contrary, *dynamic shading devices* constitute a suitable way to improve energy and comfort performances by responding to the outside boundary conditions with an automatic control strategy (De Luca, et al., 2018). This technology is considered as extrinsic because of the external stimuli needed such as light and solar heat. Exactly as for active switchable windows, dynamic shading devices need to operate sensor networks to obtain the data, a controller to determine suitable actions that should be performed and mechanical actuators (Al-Masrani, et al., 2018). This is explained in more detail in section 2.3. Dynamic operation of dynamic blinds is presented on Figure 2.15.

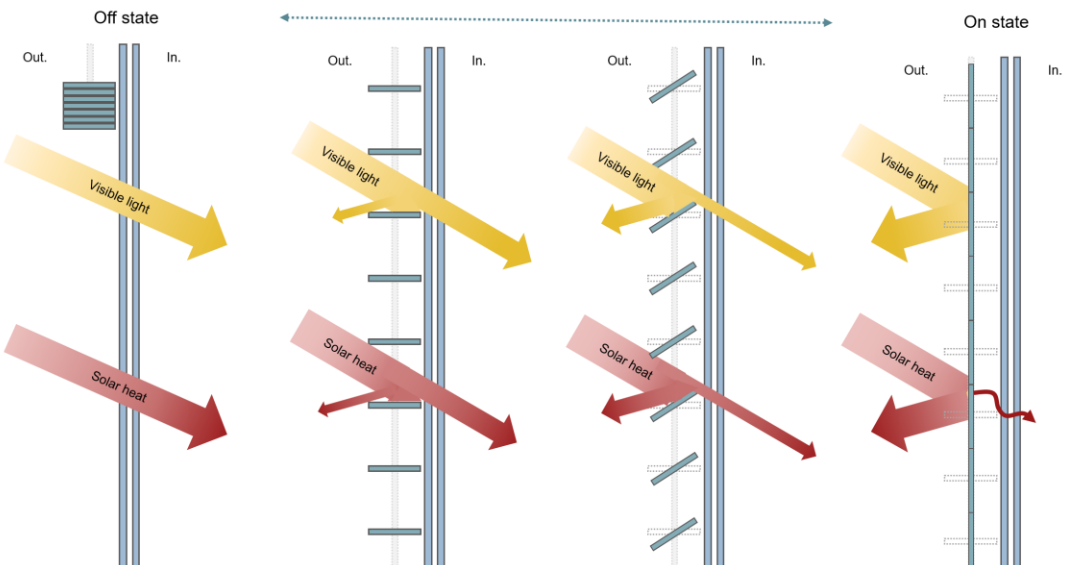


Figure 2.15 – Automated shading blinds operation - inspired by (Vraa Nielsen, Svendsen, & Bjerregaard Jensen, 2011)

Al-Masrani et al., (2018) pointed out two main groups related to dynamic shading devices:

- *Conventional dynamic shading device* with a simple motion design (such as venetian blinds, louvers and roller shades)
- *Kinetic dynamic shading device* with more complex motion design (such as foldable origamis, parametric geometries and other models)

Kinetic refers to the relationship between motions and their sources. These kinetics motions can be in one direction, a rotation, scaling motion (contraction or expansion) but also a deformation of the material. The combination of more than one of these motions results in a complex and more complicated motion such as twisting or rolling (Al-Masrani, et al., 2018). The Figure 2.16 below presents examples of kinetic dynamic shading devices.

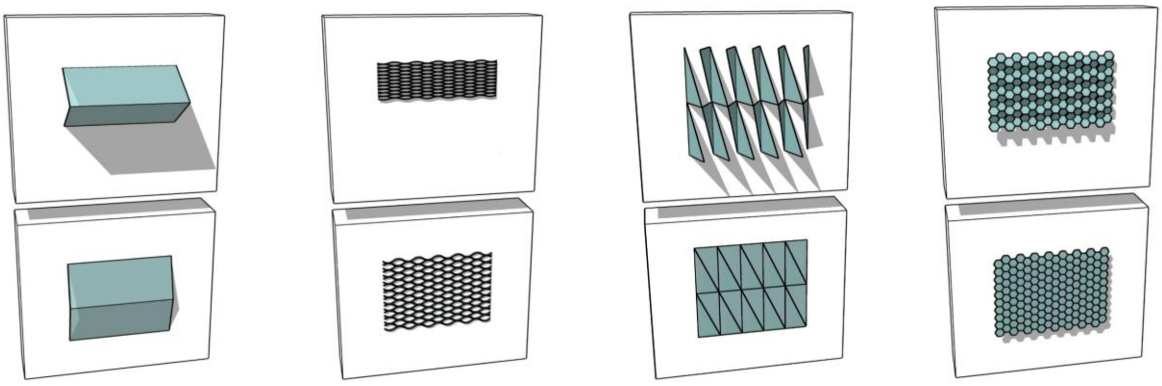
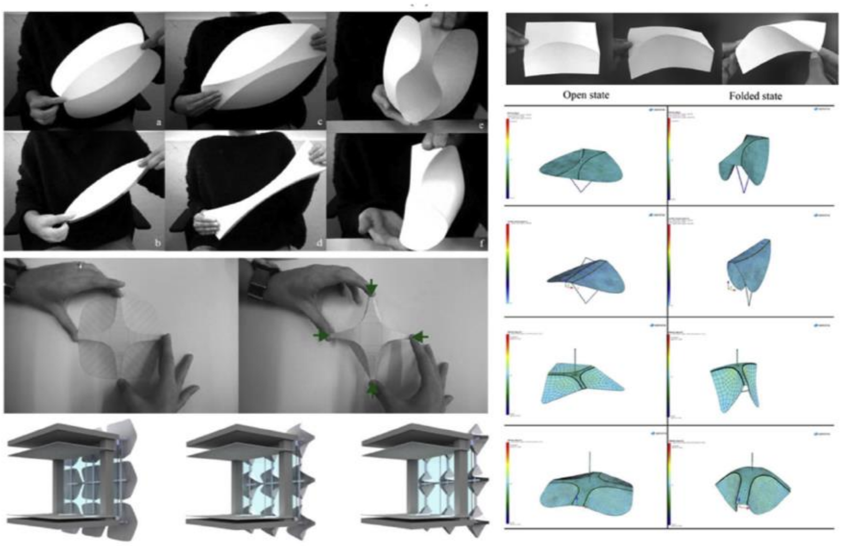


Figure 2.16 - Example of kinetic shading devices

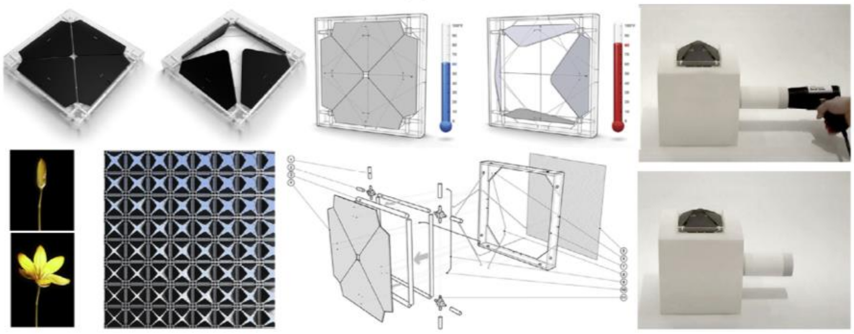
These examples were taken from different studies. Mostafa, et al. (2016) assessed the thermal and energy performances of a kinetic shading system as represented on Figure 2.16.a. The study was performed in Egypt and the panels could move up and down in translational motion and rotational up to 180°. The study showed an improvement of the cooling energy loads of 20% energy savings. Kyu Yi, et al. (2018) presented a new shading device type able to move up to down by an expansion and a contraction of the shading device. Its scheme is presented on Figure 2.16.b. Furthermore, Henning Larsen Architects (2020) built a part of Denmark Southern University and added perforated aluminum panels able to move by rotation as shown on Figure 2.16.c. Finally, Mahmoud & Elghazi (2016) tested kinetic shading devices based on a parametric study. These hexagonal patterns, represented on Figure 2.16.d, can move by rotation and translation. They pointed out an improvement of the visual comfort of more than 30%.

2.1.3.5. Hybrid shading device

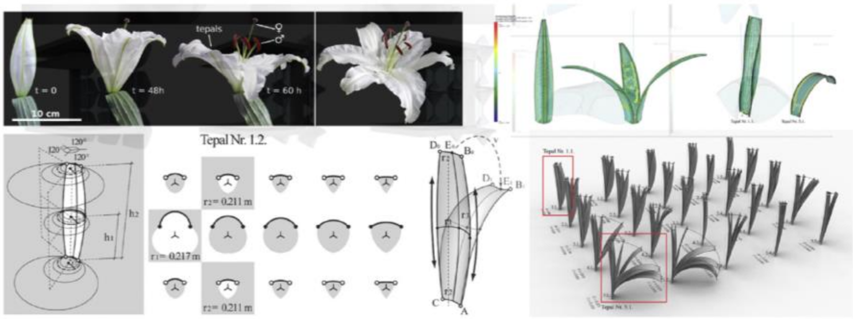
The most innovative category is finally the *hybrid shading systems*. These types of shading devices are able to use the deformation capacity of smart materials to move. A lot of these shading systems are based on *biomimetism* which means that they emulate models, elements, processes, textures or behaviors of nature to solve technical problems. Actually, shape-morphing solar shadings are one of the applications of adaptive and smart building skin that reproduces functions and structure of biological skin (Al-Masrani, et al., 2018). Their control can be either intrinsic or extrinsic (Attia, Favoino, Loonen, Petrovski, & Monge-Barrio, 2015). The Figure 2.17 gathers some examples of hybrid shading devices existing.



a – Shading system inspired by curved-line folding (Vergauwen, De Temmerman, & De Laet, 2014)



b – Four-leaf shading prototype (LIFT Architects, 2020)



c – Shading system inspired by lily flower blooming operation (Schleicher, Lienhard, Poppinga, Speck, & Knippers, 2015

Figure 2.17 - Example of hybrid shading devices

The first example shown on Figure 2.17.a has been investigated by Vergauwen, De Temmerman, & De Laet (2014). They tested the potential of curved-line folding shading devices for their implementation in kinetic shading devices. Thus they studied the behavior, thickness, model scale and other parameters. LIFT Architects (2020) proposed a four-leaf prototype shading system, shown on Figure 2.17.b with the purpose of regulating interior airflow and temperature. Their concept is inspired by the behavior of the yellow crocus flower. Furthermore Schleicher et al. (2015) emulated lily flower's blooming mechanism as it can be seen on Figure 2.17.c. Their parametric based study investigated the material used, scale, edge expansion and curvature level.

2.1.3.6. Dynamic photovoltaic shading device

Finally, another type of movable shading device should be considered: *integrated photovoltaic panels in shading devices.* The Figure 2.18 below presents an example from Jayathissa's study (Jayathissa, et al., 2017).

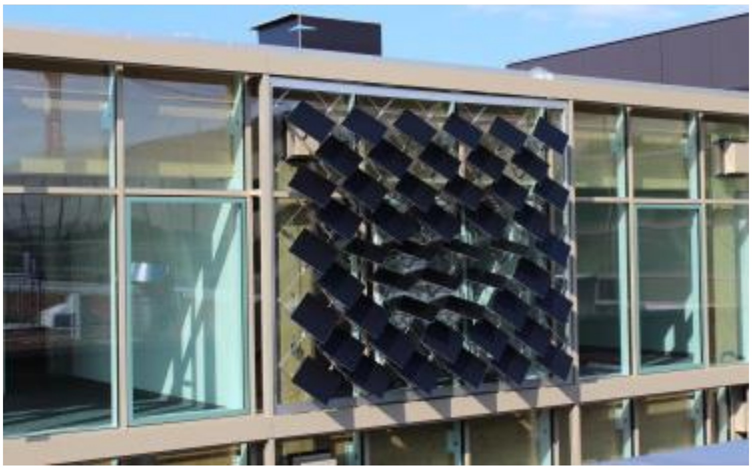


Figure 2.18 - Example of dynamic photovoltaic shading system (Jayathissa, et al., 2017)

Photovoltaic panels are composed of photovoltaic cells which are able to transform sunlight into electricity. In fact, the light is absorbed and electrons are loosed from the atoms in a semiconductor material. This loose electrons flow will create a current that will be transferred to wires (Energysage, 2018). In addition improving the building performances related to thermal and visual comfort, these technologies are able to generate electricity. In fact, fixed photovoltaic shading devices are already existing but the dynamic aspect can be added and is expected to improve the performances (Favoino F. , et al., 2018). For example, Jayathissa's study investigated an existing photovoltaic façade and reported savings between 20 and 80% of the net energy by adding dynamic control strategies instead of keeping a static movement (Jayathissa, et al., 2017).

2.1.4. Solar active façades

The third adaptive façade family represents *Solar active façades.* As indicated by this name, solar active technologies are activated by the help of the sun. In addition controlling the solar gain and sometimes the daylight, they also influence thermal comfort and energy savings. In fact, their performances fully depend on chemical, physical and/or biological reaction between materials and sun and temperature changes (Attia, et al., 2020). With the help of in depth experts' interviews, Attia, et al. (2020) categorize four technologies in this family type:

- Double-skin façades
- Green roofs and façades
- Building integrated photovoltaics
- Phase change materials

2.1.4.1. Double-skin façade

For several years, *double-skin façades* have been investigated and became a common innovative technology throughout the world. Due to their performances and characteristics, these technologies are performed more and more in high buildings. They mainly reduce the energy consumption and improve thermal comfort. In addition to that, materials used are durable and these building façades could be transparent as well as opaque (Yazdizad, Rezaei, & Faizi, 2014). However, transparent building façades are predominant to opaque (Favoino, et al., 2018). The term “Double-skin” refers to the fact that such façades are composed of two “skins”, usually two layers of glass or at least the outermost one, separated by a large air layer. In fact, these two layer skins act as insulation between outside and inside providing a reduction of the energy consumption (Yazdizad, Rezaei, & Faizi, 2014). In addition, by placing a shading device in the cavity space, further reduction could be achieved (Alberto, et al., 2017).

The ventilation type can have a significant effect on the provided performances. The action of the wind on the construction can create a positive pressure at the bottom inlet and a negative pressure at the top outlet, providing a *natural ventilation* of the cavity. However, *mechanical ventilation* can be added too. Mixing natural and mechanical ventilation is called hybrid ventilation (Yazdizad, Rezaei, & Faizi, 2014).

Besides their geometric composition and ventilation mode, there are different classifications related to double-skin façades. The most known is related to the ventilation mode. In fact, air inlet/outlet devices can be added to the skin layers and depending on their position, the airflow path could change (Alberto, et al., 2017). This is represented on Figure 2.19.

- Buffer zone, which means that there is no air inlet/outlet devices
- Outdoor air curtain mostly for natural ventilation
- Indoor air curtain
- Air supply
- Air exhaust

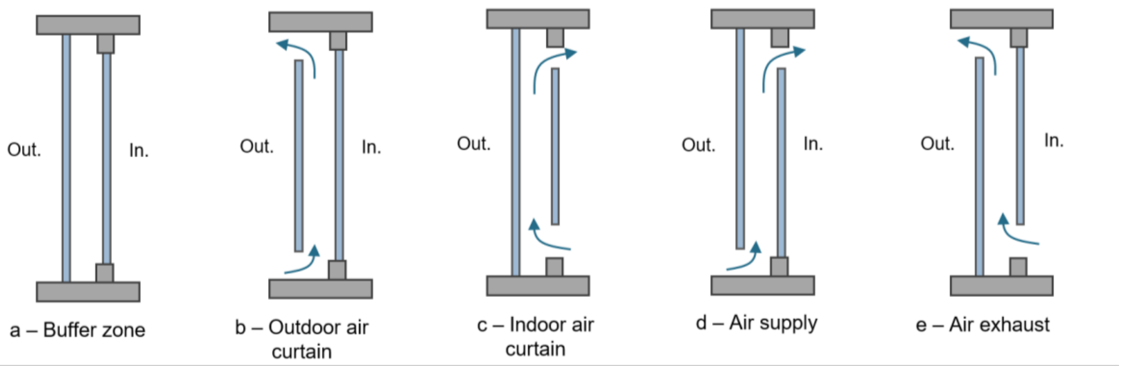


Figure 2.19 - Airflow path - inspired by (Yazdizad, Rezaei, & Faizi, 2014)

Moreover, the partitioning of the cavity is also important in the dynamic aspect of a DSF to improve the interior condition as well as the environmental performances (Yazdizad, et al., 2014). Double-skin façades can be divided into four groups related to their geometry represented on Figure 2.20 (Alberto, et al., 2017):

- **Box-window** partition into a single module, these will be juxtaposed.
- **Corridor** partition is made by storey and thus the cavity of each floor is separated.
- **Shaft-box** partition consists of juxtaposed façade modules with a vertical ventilation duct.
- **Multi-storey** partition which means that there is no partition either vertically or horizontally. This type provides a high acoustic performance (Yazdizad, et al., 2014).

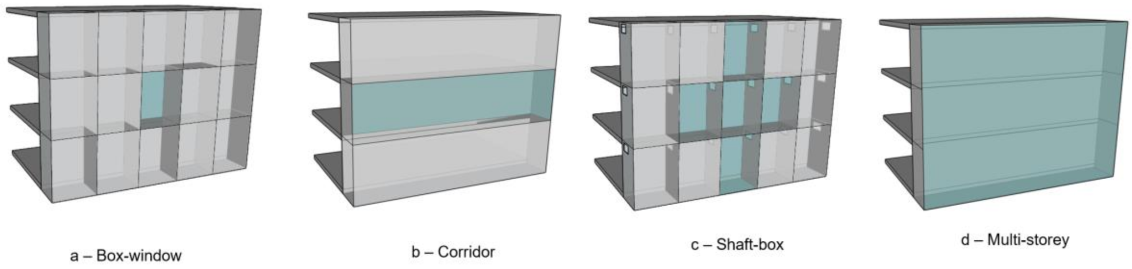


Figure 2.20 - Double-skin façades partition - inspired by (Alberto, Ramos, & Almeida, 2017)

Many studies conducted to improved energy performances of double-skin façades compared to conventional façades (Alberto, et al., 2017; Anđelković, Mujan, & Dakić, 2016 ; Pomponi, Piroozfar, Southall, Ashton, & Farr, 2016 ; Yang, Zhou, Jin, & Zhan, 2015 ; Zomorodian & Tahsildoost, 2018). In addition to saving energy, these technologies help to improve the acoustic insulation, the environmental impacts, the thermal comfort and badly reduce effects due to wind pressure. However, these induce overheating problems, a higher cost and additional maintenance (Yazdizad, et al., 2014).

2.1.4.2. Green roofs and green façades

On the first hand, the second solar active technologies are *green façades and green roofs*. Covered by a vegetative external coating, green roofs can be *intensive* or *extensive*. The first term is attributed to a heavy and thick (between 15cm and 70cm) vegetative cover. Different types of plants are supported as small trees and bushes. Intensive green roofs refer to thin vegetative cover (between 6cm and 25 cm) and allow small plants (Favoino, et al., 2018). These roofs are supposed to provide benefits in summer, by the thermal resistance of the soil layer, and in winter, by the thermal mass of the soil layer. In fact, this translates into a better thermal comfort and an improved energy performance (Zhang, He, Zhu, & Dewancker, 2019). Due to the absorbed radiation and to the evapotranspiration phenomenon of plants, this type of façade is able to release a great amount of latent heat (Kalani & Lun Chow, 2017). Figure 2.21 presents green roofs operation.

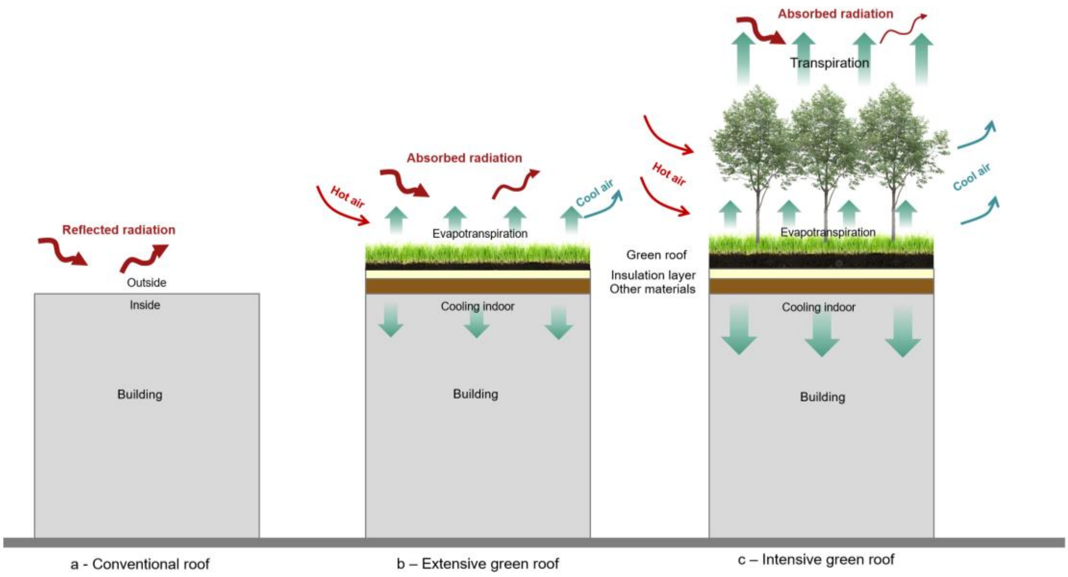


Figure 2.21 - Green roof types and their operation - inspired by (Zhang, He, Zhu, & Dewancker, 2019)

On the other hand, *green façades*, also called *vertical greenery systems*, are composed of specific species and are becoming popular in urban environments. However, two types are existing: *living walls* and *green façades*. For the first type, façades are composed of a growing media and a vertical irrigation system (Favoino, et al., 2018) while for green façades the growing system is placed on the ground (Safikhani, et al., 2014). Their main purpose is their shading effect on the building envelope and the reduction of heat flux with the exterior environment. In addition, due to the evapotranspiration phenomenon of plants, a great amount of latent heat is released (Kalani, et al., 2017). By adding an irrigation system, living walls can have a higher impact on heating and cooling energy loads (Favoino, et al., 2018). Figure 2.22 below represents the difference between living walls and green façades.

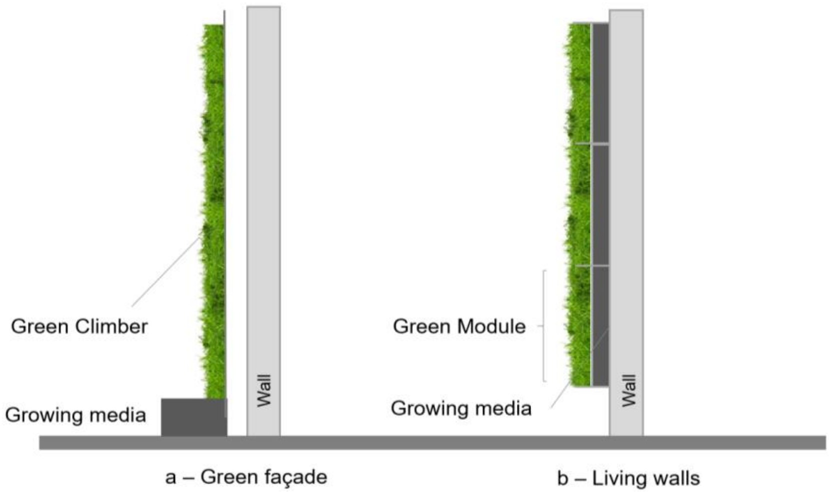


Figure 2.22 - Green façades and living walls operation - inspired by (Safikhani, Megat Abdullah, Remaz Ossen, & Baharvand, 2014)

2.1.4.3. Static photovoltaic shading device

Then, *buildings with integrated photovoltaics panels* used as shading devices have the ability to produce renewable energy. Their aim is to reduce the total energy consumption by balancing the energy demand with the energy production at the same time rather than providing a shading device. These devices are considered as static. However, by adding a dynamic operation, comfort and energy performances are improved as presented in the section 2.2.3.6. (Jayathissa, et al., 2017). Thereby, this technology will not be presented deeper.

2.1.4.4. Phase change material

Finally, *phase change materials* were presented in section 2.2.2.11. but for transparent building envelopes. In opaque PCM, the operation is the same as for transparent PCM. The only difference is the layers and materials used to contain the phase change material (Vigna, et al., 2018). Experts agree to categorize them as solar active façade (Attia, et al., 2020) but others classify them with switchable glazing since they are able to “switch” from a liquid to a solid phase and vice versa due to an external stimulus (heat) (Sibilio, et al., 2018). Also, others separated transparent from opaque phase change materials (Favoino, et al., 2018). Thereby, it is considered here that these can be in both categories.

2.1.5. Active ventilative façades

Active ventilative façade category gathers only three technologies:

- Actively ventilated closed cavity façade (CCF)
- Automated operable windows
- Actively ventilated double-skin façade

These adaptive technologies are based on ventilation where the aim is to control the airflow inside the cavity for the first and last cases, while automated operable windows aim to control the air that enters into the building. Besides controlling thermal comfort, these technologies include an active ventilative cooling as a major characteristic (Attia, et al., 2020).

2.1.5.1. Closed cavity façade

The first technology, which is *closed cavity facades* (CCF), has the same configuration as *double-skin façades* without air inlet or outlet devices (Buffer zone). However, a ventilation unit is installed but there is no direct air exchange with outdoor or indoor spaces that avoid wet and pollutant air from outside. Indeed, the dry air in the cavity space prevents accumulation and settlement of particles and dust. In addition, by supplying continuously new dry air, CCF prevents the formation of condensation (Zani, Galante, & Ramming, 2020). In fact, the dry air is controlled with its dew point temperature which guarantees the suppression of condensation risks. Closed cavity façade are attractive since the supplementary investment compared to double-skin façade is balanced by lower maintenance needs. Furthermore, thermal and acoustic properties of double-skin façades are conserved. There are two types of CCF (Balog, 2019):

- With a pressurized system
- With a mechanical ventilation system

In fact, closed cavity façades with pressurized systems could have a thinner cavity than conventional double-skin façade (Balog, 2019). The Figure 2.23.c below represents CCF operation.

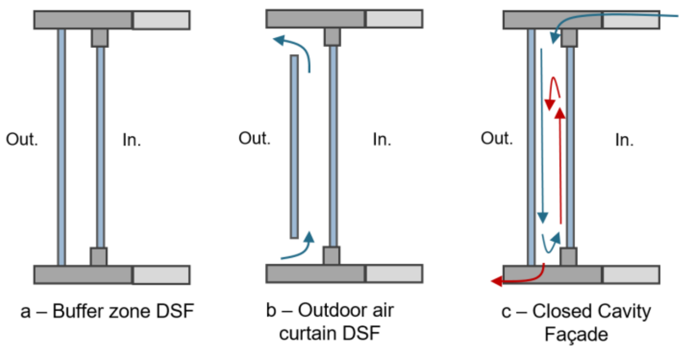


Figure 2.23 - DSF and CCF comparison operation - inspired by (Balog, 2019)

2.1.5.2. Automated operable windows

Finally, *automated operable windows* are the last adaptive façade technology to review. In fact, these windows are able to open or close dynamically with the help of a control strategy. This will mostly influence the ventilation rate entering the room which could reduce overheating and improve thermal comfort (Favoino, et al., 2018).

2.1.5.3. Actively ventilated double-skin façade

Double-skin façades have been presented in the section 2.2.4.1. However, by adding mechanical (thus also hybrid) ventilation to the cavity, this type of façades can be considered as *actively ventilated.*

2.2. Control strategies

The dynamic part of the adaptive façade is usually translated through a control strategy. For example, the dark state of electrochromic glazing will be switched on if the *inside air temperature* is below a certain threshold. This will conduct an automated On/Off system that controls the state of the smart glazing depending on the indoor conditions (Favoino, et al., 2018). By applying control options, it is possible to optimize the performances of a building (Tällberg, Petter Jelle, Loonen, Gao, & Hamdy, 2019). In Building Performance Software (BPS) models, the control strategies bring the link between sensed variables (inside air temperature) and actuator actions (shading state of electrochromic glazing). In the end, the (non-)availability of control strategies determines what can be modeled by the software used (Favoino, et al., 2018).

In the context of smart buildings, control strategies are very important since these are able to improve the overall performances of buildings. In fact, control logics can interact with different components and thus there are different physical elements that can be considered (Luna-Navarro, et al., 2020):

- **Occupant(s)** (O)
- **The physical façade** (F)
- The **control logic** or control strategy (L= rule-based logic, Lm= automated logic)
- **Building services** (B) which include, heating, cooling, artificial lighting and HVAC systems
- **Indoor or outdoor environment** (Ei or Eo)

Interactions between each component are possible and can be categorized into two main groups (Luna-Navarro, et al., 2020):

- **Direct interaction** (I) which means that a direct action (Ia), feedback (If) or information display (Id) is done.
- **Automatic sensing interaction** (S) which means that an indirect interaction is made through sensing devices. The sensing action can be through the occupants (So), through sensors in indoor environments (Si), or outdoor environments (Sext) or by monitoring the occupant's adaptive actions.

Figure 2.24 below, given by Luna-Navarro, et al. (2020) represents a classification scheme of occupant façade interactions and can thus inform about the control strategies operation in the context of dynamic envelopes. The arrows represent the interactions from/to an element.

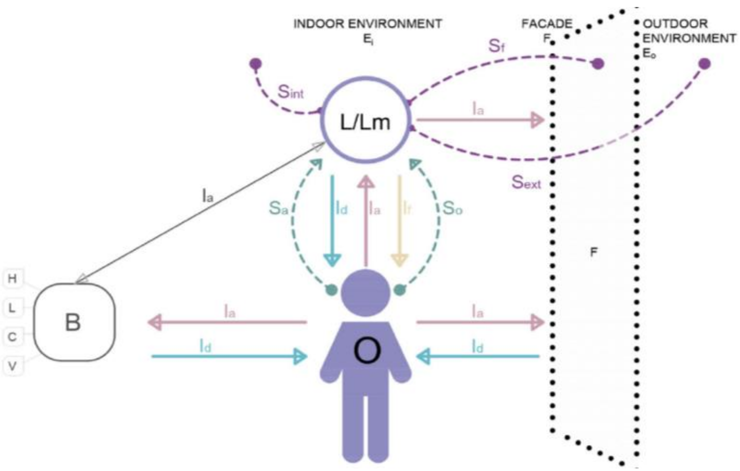


Figure 2.24 - Classification scheme and interaction diagram of occupant façade interaction (Luna-Navarro, et al., 2020)

In this thesis, it is considered that an adaptive façade is able to respond or benefit from the outside boundary conditions to improve the performances and the occupant's needs (Attia, et al., 2018). In many cases, sensors measure the indoor or outdoor environment but can also measure the occupant's presence or comfort index for example. Intrinsic materials as thermochromic glazing or phase change materials induce a direct action from the façade to respond to outside boundary conditions while extrinsic technologies need external stimuli, perceived by sensors, to perform. Actuators will then help to command dynamic envelopes systems (Favoino, et al., 2018).

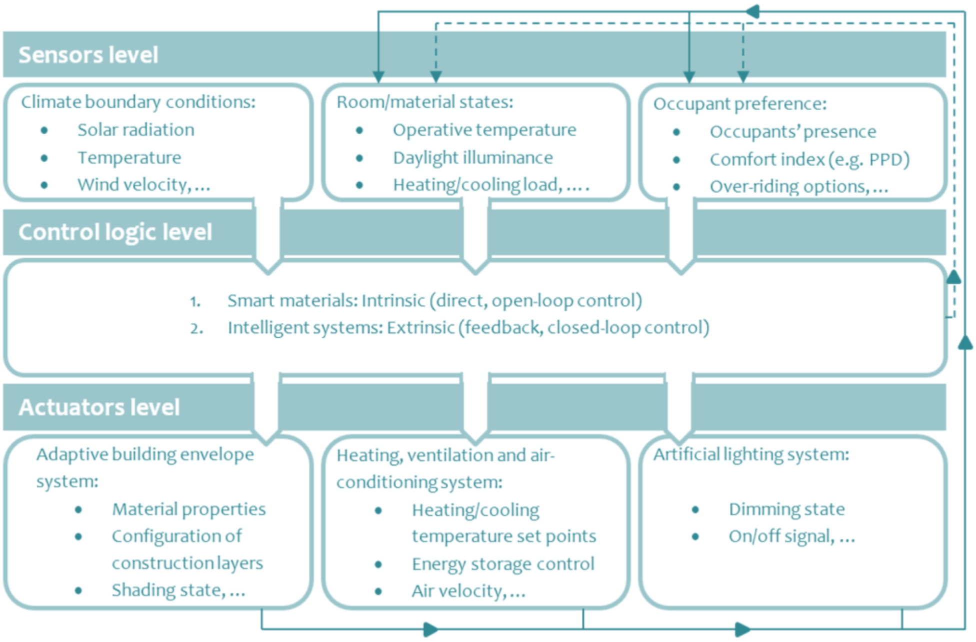


Figure 2.25 - Control architecture for buildings systems (Favoino, et al., 2018)

The Figure 2.25 above comes from the COST Action TU 1403 and illustrates the general architecture of control strategies of building systems available in BPS tools and thereby gives a clear overview of control strategies operation. This framework can be divided in:

- **Sensors level:** this is the climatic boundary conditions, occupants preferences or building internal boundary that will be perceived by sensing systems
- **Control logic level:** which is intrinsic or extrinsic as explained before
- **Actuators level:** this is the building components that can be controlled (HVAC, artificial light or adaptive building envelope systems for example)

The continuous line represents extrinsic logic while the dashed line shows the intrinsic logic (Favoino, et al., 2018).

Since the cases studied are performed in simulations, it is helpful to take into account the control strategies available for adaptive facades in BPS tools:

- **Hard-coded intrinsic:** are control options which are already performed into the software.
- **Hard-coded extrinsic** includes typically if-then-else statements where the modeler can select sensor types and control thresholds to precise a specific adaptive technology.
- **Time-scheduled control** is similar to the previous control option but the control actions are dependent on the time instead of boundary conditions or simulation state variables.
- **Script-based** can be one of these three types of control options but is directly coded by the user in the simulation tool. This helps to test a specific control approach.

2.3. Similar studies

This thesis is also based on different relevant studies that helped during the whole work elaboration. Tällberg, et al. (2019) helped in the modelling of electrochromic cases while Alberto, et al. (2017) supported the double-skin façade's modelling as well as sensitivity analysis. The methodology is strongly based on these two studies. Dynamic shading cases were modelled regarding DesignBuilder capability. However, many other studies were used in the writing, discussion, validation and modelling of this thesis. The Table 1 below gathers the review of the most relevant studies related to the investigated cases with their specification in the context of this thesis.

Table 1 - Review of the most relevant studies related to the study cases

List of existing studies related to the topic								
Reference	**Dynamic envelopes simulated**	**Control strategies**	**Performances studied**	**Sensitivity analysis**	**Software**	**Case studied**	**Location simulated**	**Year**
(Alberto, Ramos, & Almeida, 2017)	Double-skin façade	/	Energy	Cavity depth Opening area Type of glass Internal gains Airflow path Spatial configuration Facade orientation	EnergyPlus	Existing office building	Porto (PT)	2017
(Aldawoud, 201	Electrochromic glazing Static shading device	Solar control	Energy	/	EnergyPlus	Office building of ten storeys	Phoenix (US)	2013
(Cannavale, Ayra, & Martellotta, 2018)	Electrochromic glazing	Daylight control : 300-3000 lux Glare control : 22 Solar control : 200 - 250 - 300 W/m²	Energy Visual comfort	/	EnergyPlus	One room	Roma (IT)	2018
(Costanzo, Evola, & Marletta, 2016)	Thermochromic glazing	/	Energy Thermal comfort Visual comfort	/	EnergyPlus	Existing office buildings	Catania (IT) Milan (IT) Paris (FR)	2016
(De Luca, Voll,	Static shading device Dynamic shading device	Schedule control Occupant's preferences control	Energy	Size of shading devices Shading device orientation Quantity of window panes	IDA ICE	One storey of an office building	Tallinin (EE)	2018
(Dussault & Gosselin, 2017)	Electrochromic glazing	Solar control : 63 - 95 - 315 W/m² Heat flux control : 23°C Daylight control : 500 - 2000 lux	Energy Thermal comfort Visual comfort	Orientation Window-to-wall ratio Control strategy Thermal mass Internal gains Air tightness Loction	TRNSYS DaySim	One office room	Atlanta, Chicago, Miami, New-Orleans, San Francisco, Washington (US) Calgary, Montreal, Toronto, Vancouver (CA)	2017
(Feng, et al., 20	Gasochromic glazing	/	Energy	/	eQUEST	Office building of eight storeys	Shanghai (CN) Beijing (CN) Changchun (CN) Guangzhou (CN) Harbin (CN)	2016
(Frattolillo, Loddo, Mastino, & Baccoli, 2019)	Electrochromic glazing	Solar control	Energy Thermal comfort	/	?	On room with six window	Cagliari (IT)	2019
(Jensen Skarning, Anker Hviid, & Svendsen, 2017)	Dynamic shading device	Solar control : 300 W/m² Outdoor temperature control : 18°C	Energy Thermal comfort Visual comfort	/	EnergyPlus	One room	Roma (IT) Copenhagen (DK)	2016
(Kyu Yi, Yin, & Tang, 2018)	Dynamic shading device	Thermal control	Thermal comfort Visual comfort Indoor air quality	/	EnergyPlus Diva4Rhino	One room	?	2018
(Liang, et al., 20	Gasochromic glazing	Solar control : 100 W/m² Outdoor temperature control : 20°C Cooling loads control 500W	Energy Visual comfort	Solar trhreshold : 100 - 200 - 300 - 400 W/m² Out. Temp : 20 - 25 - 30 - 35°C Cooling loads : 500 - 1000 - 1500 - 2000 W	EnergyPlus	Office room with one window	Harbin (CN) Beijing (CN) Hangzou (CN) Kunming (CN) Guangzhou (CN)	2018

Table 1 (continued) - Review of the most relevant studies related to the study cases

(Mahmoud & Elghazi, 2016)	Dynamic shading device	./	Visual comfort	/'.	Diva	One office room	Cairo (EG)	2015
(Mäkitalo, 2013	Electrochromic glazing	Schedule control Solar control (light and schedule) : 50 W/m² Solar control (Schedule, façade and window) : 50 W/m² - 225W/m² - 450 W/m² Operative temperature control : 24,5°C Daylight control : 500 lux Light levels	Energy	Tinting speed : 5 - 60 min Solar threshold : 50 - 60 - 120 W/m²	IDA ICE	Office building of six storeys	Stockholm (SE)	2013
(Mostafa, et al.,	Dynamic shading device	/	Energy Thermal comfort	/	?	One apartment	Alexandria (EG)	2016
(Raji, Tenpierik, & Van den Dobbelsteen, 2016)	Electrochromic glazing Static shading device Green roof	/	Energy	Window-to-wall ratio Glazing type Infiltration rate	EnergyPlus	Existing office buildings	Delft (NL)	2016
(Sala & Romano, 2011)	Double-skin façade Double-skin façade with fixed shading devices Double-skin façade with dynamic shading	/	Energy	/	TRNSYS	Office room with two windows	Milan (IT) Palermo (IT) Florence (IT)	2011
(Shi, Tablada, & Wanga, 2020)	Double-skin façade Double-skin façade with dynamic shading device	/	Energy Visual comfort	Shading size Shading orientation	EnergyPlus	One office room	Singapore (SG)	2020
(Tällberg, Petter Jelle, Loonen, Gao, & Hamdy, 2019)	Thermochromic glazing Photochromic glazing Electrochromic glazing	Solar control : 450 W/m²-K Operative temperature control : 24°C Daylight control : 500 lux	Energy	/	IDA ICE	BESTEST case 600	Trondheim (NO) Madrid (ES) Nairobi (KE)	2019
(Vraa Nielsen, Svendsen, & Bjerregaard Jensen, 2011)	Dynamic shading device	/	Energy Thermal comfort Visual comfort	Window height Orientation	iDbuild LightCalc	One room with one window	Denmark	2011
(Yang, Zhou, Jin, & Zhan, 2015)	Double-skin façade Double-skin façade with photovoltaic shading device	Indoor air temperature Surface temperature	Energy	U- Value Cavity depth Discharge coefficient Airflow rate	TRNSYS	Single skin façade	Darwin (AU) Sydney (AU) Canberra (AU)	2020
(Zomorodian & Tahsildoost, 2018)	Double-skin façade Double-skin façade with shading device	Indoor air temperature : 18°C	Energy Thermal comfort Life cycle cost Life cycle assessment	Ventilation mode Spatial configurations Shading device type	EnergyPlus	Existing office buildings	Tehran (IR)	2018

Many other studies about dynamic envelopes exist. However, those presented in the table above are considered as being relevant for the thesis. Since the elaboration of the simulations is based on two specific studies, these are detailed in the following paragraphs.

Tällberg, et al. (2019) investigated thermochromic, photochromic and electrochromic glazings. They firstl made a review of these smart windows available on the market and then evaluated their energy performance compared to a base case. The software used was IDA ICE while the case studied was BESTEST case 600. Three different locations were studied: Trondheim in Norway with a cold climate, Madrid in Spain with a Mediterranean climate and finally Nairobi in Kenya with a warm and temperate climate. They chose to evaluate the influence of control strategies with solar radiation control, operative temperature control and daylight control. Their conclusion was that electrochromic glazing has the best performance related to energy and especially in southern locations. The control strategies have also a significant influence on the energy savings with the lowest energy consumption by using the operative temperature control strategy.

Second, Alberto, et al. (2017) made a parametric study of double-skin façades with the help of EnergyPlus for the location of Porto in Portugal. At first, they reviewed the different types of double-skin façades and studied different parameters which are the types of ventilation, the space configuration and the airflow path. Sensitivity analyses were performed to evaluate the influence of the cavity depth, the opening area, the type of glass, the internal gains and the façade orientation. In contrast to Tällberg's study, they used EnergyPlus with the help of DesignBuilder and studied a multi-storey building. In addition, results showed that large cavity depth, *Outdoor air curtain airflow path* and the type of glass significantly influence the energy performance of the double-skin façade studied.

3. Methodology

This chapter assembles all the steps of the methodology. As a reminder, the research questions are:

- What is the influence of the different dynamic technologies on the energy consumption and the comfort in smart office buildings?
- How to optimize, with strategic controls, the thermal comfort and the energy efficiency in smart offices buildings with the technologies studied?
- What are the factors that determine the smart readiness of dynamic envelopes?

The thesis is based on modeling cases and investigating simulations since an important part is to determine the influence of dynamic envelope and control strategies in office buildings. And in this thesis, these are simulated for the location of Uccle situated in the Brussels-capital region in Belgium. Furthermore, the meteorological station of Belgium is located there. This will be explained further later in the methodology. The final results are a comparative analysis between the cases chosen. The quantitative output data given by the software used, help to achieve it. Also, qualitative results will be given for the visual comfort.

Figure 3.1 represents the *study conceptual framework* of the thesis. This scheme helps to resume and to understand the main steps of the study.

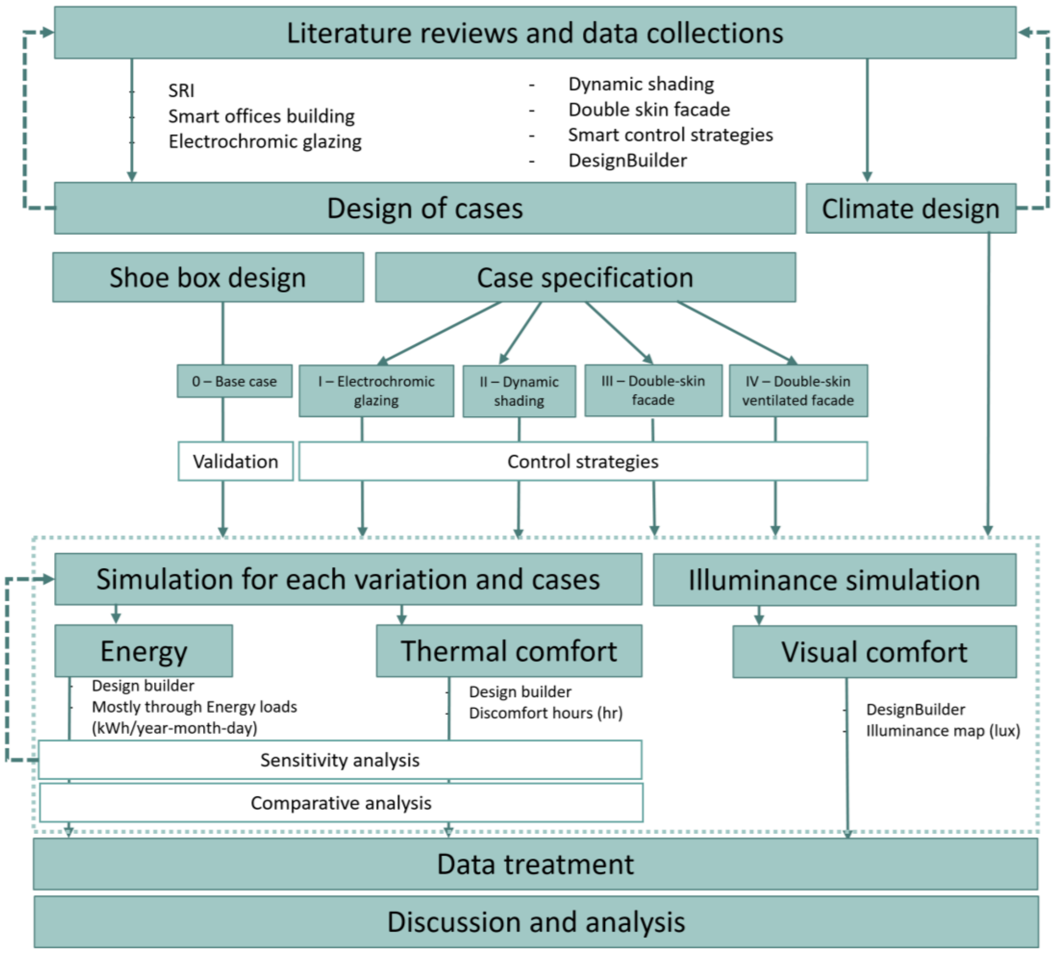


Figure 3.1 – Study conceptual framework

The dynamic technologies studied are chosen regarding the dynamic envelopes review in section 2.1. Actually, the scope has been limited to transparent building envelopes. The dynamic building envelopes available on the market or at least in the prototypal phase are given and explained in Section 2.

This chapter is divided into different sections. Firstly, the software used is described and its choice is explained. Then, the design of the different cases is presented from the base case, which corresponds to the shoe box design, to electrochromic, dynamic shading and double skin façade cases. The *Location and climate design* section follows the base case section since this step is made at the beginning of the design. Then, a part is dedicated to control strategies and another one to sensitivity analysis. Afterward, the methodology for the comparative analysis and daylighting analysis is shown and finally, a resume of the different simulated cases is presented. Appendix B gathers screenshots of all the steps made in DesignBuilder to model the cases.

3.1. Selected software

The energy simulation software tool used is essential. Several energy simulation tools are available on the market. The main advantages of these software are that they can predict the thermal behavior of buildings studied before their construction and can help to optimize the energy consumption. However, these can also simulate the costs of energy of existing buildings in their current conditions. Other fields can be calculated related to HVAC, lighting or occupant satisfaction. Actually, the use of energy simulation software tools will influence the decision-making of the designers (Sousa, 2012).

In this thesis, EnergyPlus has been chosen. This software has been developed in 1996 by the Department of Energy[3] (DOE) in the United States of America. Mostly used by engineers, architects and researchers, this software allows the energy analysis and thermal load of a building. *Daylighting* and *Computational Fluid Dynamic* (CFD) analysis can be made. EnergyPlus has the advantage of having several modules. Thus, these can be easily performed separately or together. However, it needs an external visual interface: DesignBuilder (Sousa, 2012). Moreover, with the introduction of EnergyPlus Language (ERL), users are able to implement Energy Management Systems (EMS) (Favoino, et al., 2018). EMS are custom simulation runtime control to avoid some aspects of standard EnergyPlus software behavior. EMS brings a robust way to extend the capability of EnergyPlus (EnergyPlus, 2020). In this thesis, only predefined functionalities of DesignBuilder are used. In fact, this software is used because all adaptive technologies can be modeled in an easy way. Furthermore, this building performance simulation tool was already known and is commonly used to model such systems.

3.2. Base case:

3.2.1. Shoe box design

First and foremost, it is important to take into account that there are different types of reference buildings that can be modelled (Corgnati, Fabrizio, Fillipi, & Monetti, 2013):

- **Theoretical Reference Building**: is an “ideal” and fictional building model and is defined by statistical data of features found within a category of buildings in the stock. The most commonly used materials and systems are taken.

[3] The mission of the Energy Department is to ensure America’s prosperity and security regarding its energy, environmental and nuclear challenges with the help of technology solutions (Favoino, et al., 2018).

- **Example Reference Building**: is also an “ideal” and fictional building model and is defined from experts’ assumptions and inquiries to provide a building that is the most suitable to be modeled. This model type is mostly used when statistical data are not available.
- **Real Reference Building**: corresponds to model an existing building, with its average characteristics based on statistical analysis. A large amount of information is needed to be as close as possible of the existing building.

Most of the existing studies made about smart envelopes simulated a theoretical or a real building because of the hypothetical aspect of the example reference building type. Since the purpose of the study is to make a relative comparison to inform the decision-making on adaptive facades, the theoretical model seems to be the most suitable. In this way, the base case 600 from BESTEST has been chosen. Tällberg’s study also used this base case (Tällberg, et al., 2019). BESTEST is a Building Energy Simulation Test project of which the objective is to develop a methodology to test building energy simulation software tools and thereby to diagnose the sources of predictive disagreement (Ashrae, 2017). By using this base case, it is possible to validate the model made with DesignBuilder and to compare its results with other studies.

The materials specification and geometry of BESTEST case 600 correspond to a low mass building with two windows positioned on the south wall. The window-to-wall ratio is about 55% (Ashrae, 2017). The Figure 3.2 shows the illustration of the building in DesignBuilder.

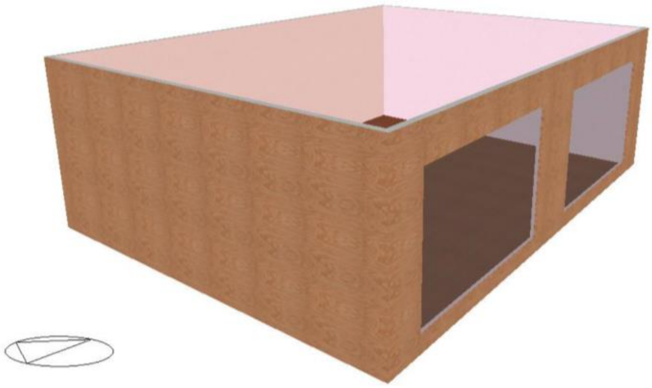


Figure 3.2-Geometric view of BESTEST Case 600 (rendering view) - ANSI/ASHRAE Standard, 1.-2. (2014)

In this case, the floor is directly connected to the ground and all surfaces are external. It is considered that the building will continuously be exposed to solar radiation. All of these parameters are the same for every simulation: location, geometry, materials specifications. The Table 2 resumes the detailed materials component for each layer and the Figure 3.3 displays geometry specifications.

Table 2 - Materials specifications Low mass building - BESTEST case 600

Composition	Layer	Thickness (m)	Conductivity (W/m-K)	U-Value (W/m²-K)	Resistance (m²K/W)	Specific Heat (J/kg-K)	Density (kg/m³)
External wall (outside to inside)	exterior surface coefficient	-	-	29,3	0,00	-	-
	Wood Siding	0,009	0,14	15,6	0,06	900	530,0
	Fiberglass quilt	0,066	0,04	0,6	1,65	840	12,0
	PlasterBoard	0,012	0,16	13,3	0,08	840	950,0
	interior surface coefficient	-	-	8,29	0,12	-	-
	Total air-air			**0,516***	**1,94**		
Roof (outside to inside)	exterior surface coefficient	-	-	29,3	0,03	-	-
	Roof deck	0,019	0,14	7,368	0,14	900	530,0
	Fiberglass quilt	0,1118	0,04	0,358	2,79	840	12,0
	PlasterBoard	0,01	0,16	16,0	0,06	840	950,0
	interior surface coefficient	-	-	8,29	0,12	-	-
	Total air-air			**0,321***	**3,15**		
Floor (outside to inside)	exterior surface coefficient	-	-	29,3	0,00	-	-
	Insulation	1,003	0,04	0,0	25,08	-	0,00001
	Timber flooring	0,025	0,14	5,6	0,18	1200	650,0
	interior surface coefficient	-	-	8,29	0,12	-	-
	Total air-air			**0,039**	**25,37**		

Building component	**Area (m²)**	**U-value (W/m²-K)**	**U*A (W/K)**
Walls	62	0,516*	31,99
Roof	48	0,321*	15,41
Floor	48	0,039	1,87
Window	12	N/A**	N/A**
Total	170	N/A**	N/A**
Volume (m³)	**Window-to-wall ratio**	**Window-to-env. ratio**	**Env.rea per volume**
128	55%	7%	1,33 m²/m³

* The total air-air U-value does not match with the one given by the input report of DesignBuilder. This is probably due to the fact that the software takes into account the ground properties in the calculations of the U-value.

** It is considered that the window properties will vary from each case, thus the values will change.

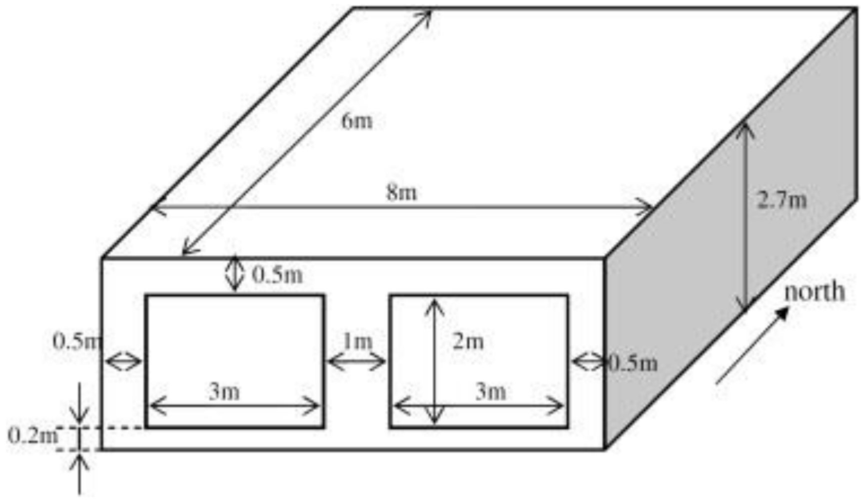


Figure 3.3 - BESTEST case 600 geometry - Ashrae. (2017). ASHRAE standard 140-2017 - standard method of test for evaluation of building energy analysis programs.

3.2.2. HVAC specification

The paragraph below gathers BESTEST case 600 data related to HVAC, heating and cooling systems (Ashrae, 2017).

DesignBuilder allows different HVAC sizing methods that can be set to *Simple* or *Detailed*. Case 600 uses *Simple* sizing and thus, heating and cooling systems are modelled using ideal loads (DesignBuilder, 2020). Furthermore, HVAC of case 600 is modeled to permit the heating and cooling systems to always meet the demand and to reach setpoint temperatures of the room. This BESTEST case assumes that the office is heated with natural gas like fuel and cooled with electricity and the Coefficient Of Performance (COP) is equal to 0,5 and 4,5 respectively for the heating and cooling systems. These values are the default value of DesignBuilder. Also, the heating and cooling work continuously throughout the day. Humidification/dehumidification is not implemented and heating for domestic hot water is not included in the model. Losses due to infiltration or thermal bridges or other system losses are not considered to ease the comparison of each case.

To standardize the model, HVAC inputs are kept for the base case study. Table 3 below resumes HVAC specification.

Table 3 - Differences between BESTEST case 600, Tällberg's study and the simulated cases regarding HVAC

Difference	Case 600	Tällberg	Thesis
Simulated case	BESTEST Case 600	TCW, PCW, ECW	ECW, DS, DSF, DSFV
Location	Denver, Colorado, USA	Madrid, Nairobi, Tromso	Brussels
Software	DesignBuilder	IDA ICE	DesignBuilder
Changing inputs of HVAC system from base case 600			
Natural ventilation	No	No	No
Mechanical ventilation	No	No	No
(De)humidification	No	No	No
Heating system			
Fuel	Natural gas	Natural gas	Natural gas
Schedule	Continiously	Continiously	Continiously
COP	0,5	1	0,5
Heating for domestic water	No	No	No
Cooling system			
Fuel	Electricity	Electricity	Electricity
Schedule	Continiously	Continiously	Continiously
COP	4,5	1	4,5

3.2.3. Internal gains

DesignBuilder is able to model the internal gains that consist of occupants, equipment and lighting. However, the case 600 does not include any internal gains (Ashrae, 2017).

Compared to the BESTEST case 600, Tällberg (2010) changed some parameters to humanize the model. This is also made in this master thesis. Thus, internal gains are varied. One occupant is considered inside the room which induces an occupation of 0,0207 person/m². It is presumed that people could be present from 7am to 6pm during weekdays. The *equipment* emits, as for Tällberg's study, 150W which means 3,13W/m² and is active only during the same schedule. *Process* is set on continuously with a power of 4,17 W/m². It is assumed that the *lighting* is turned on from 7am to 6pm with the default setting of 5 W/m²-100lux as power density. A lighting control is implemented and switches off the lighting when daylight is higher than 500 lux. This threshold is considered as the optimal threshold to improve the productivity of workers (Tabadkani, Roetzel, Xiang Li, & Tsangrassoulis, 2020). By choosing the *Continuously lighting control*, from 0 to 500 lux, the software linearly interpolates so that the lighting power is gradually increased like natural daylighting decreases. This is represented in Figure 3.4.

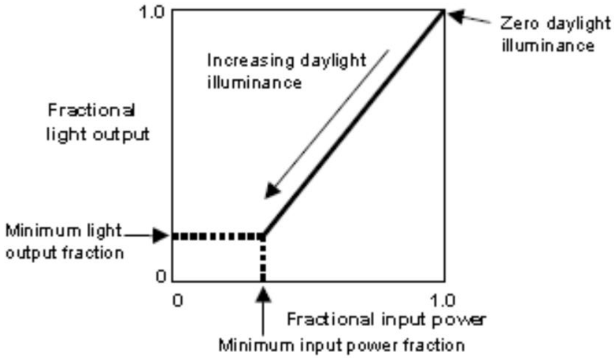


Figure 3.4 - Continuous lighting control as it is considered by DesignBuilder - (DesignBuilder, 2020)

Setpoint temperatures of BESTEST case 600 for the room are set to 20°C for heating and 27°C for cooling and are kept for the study cases.

Table 4 below points out the differences between BESTEST case 600, Tällberg's study and the simulated cases of this thesis regarding the internal gains.

Table 4 – Differences between BESTEST case 600, Tällberg's study and the simulated cases regarding internal gains

Difference	Case 600	Tällberg	Thesis
Simulated case	BESTEST Case 600	TCW, PCW, ECW	ECW, DS, DSF, DSFV
Location	Denver, Colorado, USA	Madrid, Nairobi, Tromso	Brussels
Software	DesignBuilder	IDA ICE	DesignBuilder
Changing inputs of internal gains from base case 600			
Occupancy	0 person	= 1person in the office	= 1person in the office
Schedule heat gain	On 24h/7	7-17:00	7-18:00
Equipement	0 W	emit 150W	emit 150W
Lighting	power density of 5W/m²-lux Max daylight is 300 Lux	emit 50W with lumen efficacity of 12lm/W Max daylight is 500Lux	power density of 5W/m²-lux Max daylight is 500Lux
Heating set point	20°C	21°C (defaults setting of IDA)	20°C (defaults setting of BESTEST case 600)
Cooling setpoint	27°C	25°C (defaults setting of IDA)	27°C (defaults setting of BESTEST case 600)
Catering	0 W	0 W	0 W
Miscellaneous	0 W	0 W	0 W
Computer	0 W	0 W	0 W
Process (industrial)	4,17 W/m² set continiously by electric fuel	4,17 W/m² set continiously by electric fuel	4,17 W/m² set continiously by electric fuel

3.2.4. Base case Validation

Since the base case of the study is based on the Case 600 of BESTEST with Denver, California, USA as location, this one is modelled and simulated first. If the results are acceptable regarding BESTEST, the model is validated and can be used for the study. Afterwards, the modifications specified in the previous subsection are made to obtain the base case of the thesis. Results of the validation will be shown in section 4.

3.3. Location and climate design

BESTEST base case 600 is simulated for the location of Denver in the USA. The cases studied in the thesis will be simulated for Uccle in the Brussels-Capital region, in Belgium. This section describes how the location has been changed for and from the case 600. Nevertheless, it is explained for Uccle, since the approach stays the same.

Uccle is located in the Brussels-Capital region, which means very close to the capital of Belgium. Located approximately in the middle of the country, the city enjoys a temperate climate influenced by the North Sea and the Atlantic Ocean and characterized by a mild winter and cool summer. Rainfall is abundant but well distributed throughout the year with summer and fall season rainier. Between November and March, the country is subject to high speed wind mostly in the south-west direction. (Bruxelles environnement.brussels, 2018)

Climate design has been configured in two ways. First, the *hourly weather data file* comes from EnSimS.com. This website gathers .epw[4] weather data files for many locations in the world. An EPW map helps to find the appropriate files needed. Figure 3.5 shows the different .epw files available for the different locations in and near Belgium. The marker colors correspond to the files' sources (EnergyPlus website[5] in blue, climate.onebuilding.org[6] in red or White Box Technologies[7] in green). Thereby, the chosen file is the most recent one located in the city of Uccle.

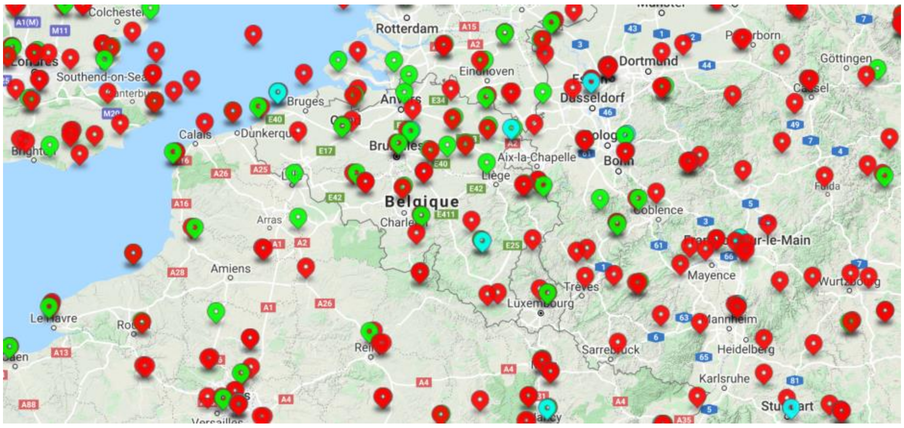


Figure 3.5 - Screenshot - Location of available Weather data files EnSimS (EnSimS, 2019)

The *hourly weather data file* is delivered by the Royal Meteorological Institute of Belgium[8], and is an .epw file which is mostly associated with EnergyPlus hourly weather data. Furthermore, the type of the file is a .tmy3 which means "typical meteorological year 3". TMY contains a set of meteorological data values for every hour in a year and for a given geographical location. These data are selected in a longer time period (normally 10 years or more). The word "Typical" actually means that the weather data has been selected for each month in an entire year from the year that was accepted as the most "typical" for that month. For instance, the year of typical months can differ (January can be from 2009, June from 2012 and November from 2007 for example) (EnergyPlus, 2020). Number *3* corresponds to the version of TMY type. TMY2 is older and less accurate than TMY3 for example. Here, the .epw file for Uccle gathers weather data from 2004 to 2018 and Table 5 reviews geographical information of the station. More detailed information about epw files are given in Appendix C.

[4] The files epw contains data about:

- Time fields: Year, Month, Day, Hour, Minute
- Atmospheric fields: dry-bulb temperature, dew point temperature, relative humidity, atmospheric station pressure, wind direction, total sky cover, opaque sky cover, visibility, ceiling height, present weather observation, present weather codes, aerosol optical depth, precipitable water, snow depth, liquid precipitation depth, albedo, liquid precipitation quantity
- Radiation fields: extraterrestrial horizontal radiation and direct normal radiation, horizontal Infrared radiation Intensity, global horizontal radiation, direct normal radiation, diffuse horizontal radiation, global horizontal illuminance, direct normal illuminance, diffuse horizontal illuminance, zenith luminance,

[5] Official website of EnergyPlus where .epw are available for more than 1000 locations (EnergyPlus, 2020).

[6] Website that groups .epw weather data files from numerous public sources. In total, there is files for 13250 locations (EnSimS, 2019).

[7] White Box Technologies is the official distributor and original developer of the ASHRAE IWEC2 dataset. Files are available for more than 3000 locations (EnSimS, 2019).

[8] The Royal Meteorological Institute of Belgium is the federal scientific institute in Belgium that does research about weather and climate and provides meteorological services

Table 5 – Geographical information of the hourly weather data file

City	Latitude (°)	Longitude (°)	Elevation (m)	Time zone (h)
Uccle, Brussels, Belgium	50,79	4,36	101	+1

Secondly, the location *UCCLE* has been directly input into the model from the DesignBuilder database when choosing the location. Table 6 gathers geographical information that corresponds almost exactly to the geographical information of a station that made the hourly weather data file used in this thesis.

Table 6 – Geographical information of Bruxelles national

City	Latitude (°)	Longitude (°)	Elevation (m)	Time zone (h)
Uccle, Brussels, Belgium	50,8	4,35	104	+1

3.4. Electrochromic case

When simulating smart glazing, three aspects depending on the smart technologies are important (Tällberg, et al., 2019):

- Control mechanism: in this case, electrochromic glazing is extrinsic since this technology needs external stimuli to work.
- Wavelength range: the optical properties of smart windows can change as for electrochromic windows, the tint.
- Optical properties: the smart glazing can have a diffuse behavior when activated depending on the refractive index of the materials contained in the functional layer.

Tällberg (2019) modeled smart windows by implementing an integrated shading device. After applying *Window shading* into the *Opening tab* in DesignBuilder, the type can be chosen. Detailed methodology is gathered in Appendix B. Table 7 shows all window shading types in DesignBuilder.

Table 7 - Window shading type in DesignBuilder

Window shading category	Type	Pre-defined subtype
Diffusing shades	Drapes	Close - semi open - open weave
		Light - medium - dark
	Shades	Low - medium - high reflectance
		Low - medium - high transmittance
	Shade roll	Light - medium
		Opaque - translucent
	Venetian blinds	Light - medium
Electrochromic switchable	EC absorptive	EC absorptive 6mm
	EC reflective	EC reflective 6mm
SageGlass Electrochromic		Blue - green - grey - classic
Slatted blinds	Blinds	Low - medium - high reflectivity slats
	Microlouvre	
	Mid-pane blind	medium reflectivity slats
Transparent isulation		

To model the **dark state** of ECW, *Electrochromic switchable* or *SageGlass electrochromic* can be selected (DesignBuilder, 2020). DesignBuilder will simulate differently depending on the type chosen. The first option, more general, allows numerous control strategies. These are also available for the other *Window shading type*. Table 8 gathers all the strategies possible.

Table 8 - Control types proposed in DesignBuilder for electrochromic switchable and SageGlass Electrochromic

Window shading category		Control type	Definition
Electrochromic switchable	1	Always on	Always activated
	2	Daylight	Daylighting control adjust the transmittance of the glazing to allow the illumance to be as close as possible of the daylight setpoint.
	3	Schedule	Tinting operation only defined through a schedule.
	4	Solar	ON if solar setpoint is exceeded by beam and diffuse solar radiation incident on the window
	5	Glare	ON if the total daylight glare index exceeds the maximum glare index specified in the daylighting input for zone.
	6	Outside air temperature	ON if the outside air temperature setpoint is reached
	7	Inside air temperature	ON if the inside air temperature setpoint is reached
	8	Cooling	ON if the cooling rate is not equal to 0
	9	Day cooling and solar + night	ON at night, ON during the day regarding the solar setpoint and cooling rate (4 + 8 + Night)
	10	Day cooling and solar	ON during the day regarding the solar setpoint and cooling rate (4 + 8)
	11	Night outside low air temp	ON at night regarding the outside temperature setpoint and schedule, OFF during the day regarding specified schedule (6 - Night)
	12	Night inside low air temp	ON at night regarding the inside temperature setpoint and schedule, OFF during the day regarding specified schedule (7- Night)
	13	Night heating	ON at night if the heating rate is higher then 0, OFF during the day regarding specified schedule
	14	Night outside low air temp + day cooling	ON at night regarding the outside temperature setpoint and schedule, ON during the day regarding cooling rate (6-Night + 8)
	15	Night heating + day cooling	ON at night if the heating rate is higher then 0, ON during the day if cooling rate not equal to 0 (8 + 13)
	16	Horizontal solar	ON if horizontal solar setpoint is exceeded by beam and diffuse solar radiation incident on the window
	17	Outdoor air temp + Solar on window	ON if the outside air temperature setpoint is reached and if solar setpoint is exceeded (4 + 6)
	18	Outdoor air temp + horizontal solar	ON if the outside air temperature setpoint is reached and if horizontal solar setpoint is exceeded (6 + 16)
SageGlass Electrochromic	1	Daylight only	Tinting defined by the solar illuminance
	2	No tinting when heating	Tinting is activated when there is no heating. Otherwise, tinting is defined by the solar illuminance
	3	Full tinting when cooling	Tinting is activated when there is cooling. Otherwise, tinting is defined by the solar illuminance
	4	Full tinting when cooling + non tinting when heating	Tinting is activated when there is cooling and desactivated when there is

By choosing *SageGlass*, there are less control types, but the hue can have intermediate states. Not only a "clear" state when off and a "dark" state when switched on. Obviously this option will have more precise results with an optimized tinting control but the lack of choice in control type is clearly a disadvantage.

Since control strategies are part of this study and since comparison of the different cases will be made, the first option is more suitable. With *Electrochromic switchable* option which is an integrated shading device, DesignBuilder is able to model, in a reasonable way, the behavior of electrochromic glazing. When thresholds are reached, the software will switch the state of the glazing from clear to dark as represented on the Figure below. After a few seconds or minutes (which correspond to the tinting phase), the dark state is reached.

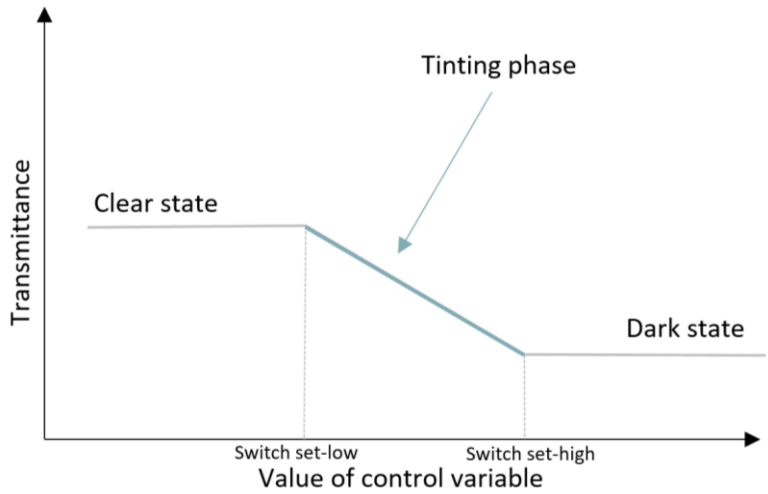


Figure 3.6 - Control action in DesignBuilder of switchable glazing

However, DesignBuilder needs optical properties of both states. To be as realistic as possible, those of real manufacturers were taken (Tällberg, et al., 2019). By changing the properties of predefined *Electrochromic switchable*'s subtype, it is possible to model the dark state of electrochromic glazing. Clear state can be modelled by modifying the optical properties of the Window's *glazing type*. Table 9 resumes optical input data.

Table 9 - Optical properties of Base case and ECW case

Envelope	State	g_value	T_sol	T_vis	U-value (W/m²-K)	Reference
Base case	-		0,747	0,898	2,87	Design Builder BESTEST case 600 default settings
ECW	Clearest state (Window glazing)	0,46	0,3	0,4	1,59	Tällberg, R., Petter Jelle, B., Loonen, R., Gao, T., & Hamdy, M. (2019, Septembre 15). Comparison of the energy saving potential of adaptive and controllable smart windows: A state-of-art review and simulation studies of thermochromic, photochromic and electrochromic technologies. *Solar Energy Materials and Solar Cells, (200)*, pp. 1-29
	Darkest state (EC pane)	0,09	0,01	0,023		

3.5. Dynamic shading case

Most known and studied adaptive technology (Favoino, et al., 2018), dynamic shading uses technology to control or automate external and/or internal solar shading devices, as for example, blinds, louvres, screens and shades with the help of a smart building control system. Current building simulation tools are able to model conventional dynamic shading devices but have difficulties in the modelling of new dynamically responsive shading devices (Kyu Yi, Yin, & Tang, 2018).

As said before, Table 8 gathers window shading types that can be selected into DesignBuilder. However, many sizes and shapes are existing and tailored shading devices can be created. To normalize the methodology, existing subtype *blinds low reflectivity* has been chosen as shading devices. The following Figure 3.7 shows how blinds are modelled in DesignBuilder.

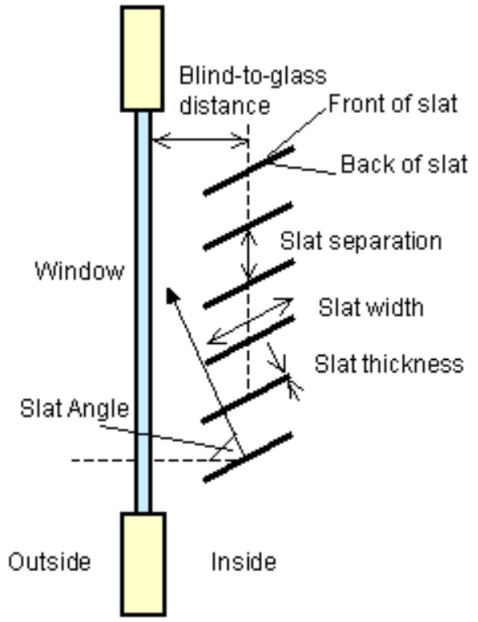


Figure 3.7 - Blinds as represented in DesignBuilder

Different parameters influence blinds as salt angle or slat thickness Table 10 resumes default input data of the dynamic shading chosen.

Table 10 – Blinds with low reflectivity default properties in DesignBuilder

Slat properties	
Blind-toglass distance (m)	0,05
Slat width (m)	0,025
Slat separation (m)	0,01875
Slat thickness (m)	0,001
Slat conductivity (W/m-K)	0,9
Slat angle (°)	45
Slat solar properties	
Slat solar transmittance	0
Slat visible properties	
Slat visible transmittance	0

3.6. Double skin façade with natural ventilation

Modelling a double skin façade is one of the capabilities of DesignBuilder (DesignBuilder, 2020). The principle is based on adding an internal partition into the base model. Firstly, the initial block is extruded with a length equal to the cavity thickness. Windows are deleted from the external wall and implemented in the partition wall. Then, a large window that covers almost the entire surface of the exterior wall is drawn. This is represented on Figure 3.8 named *Glass wall*. Because of DesignBuilder's drawing limitations, the window-to-wall ratio is 91%. In reality, this percentage would represent the proportion of the window compared to the proportion of the structure usually made in metal.

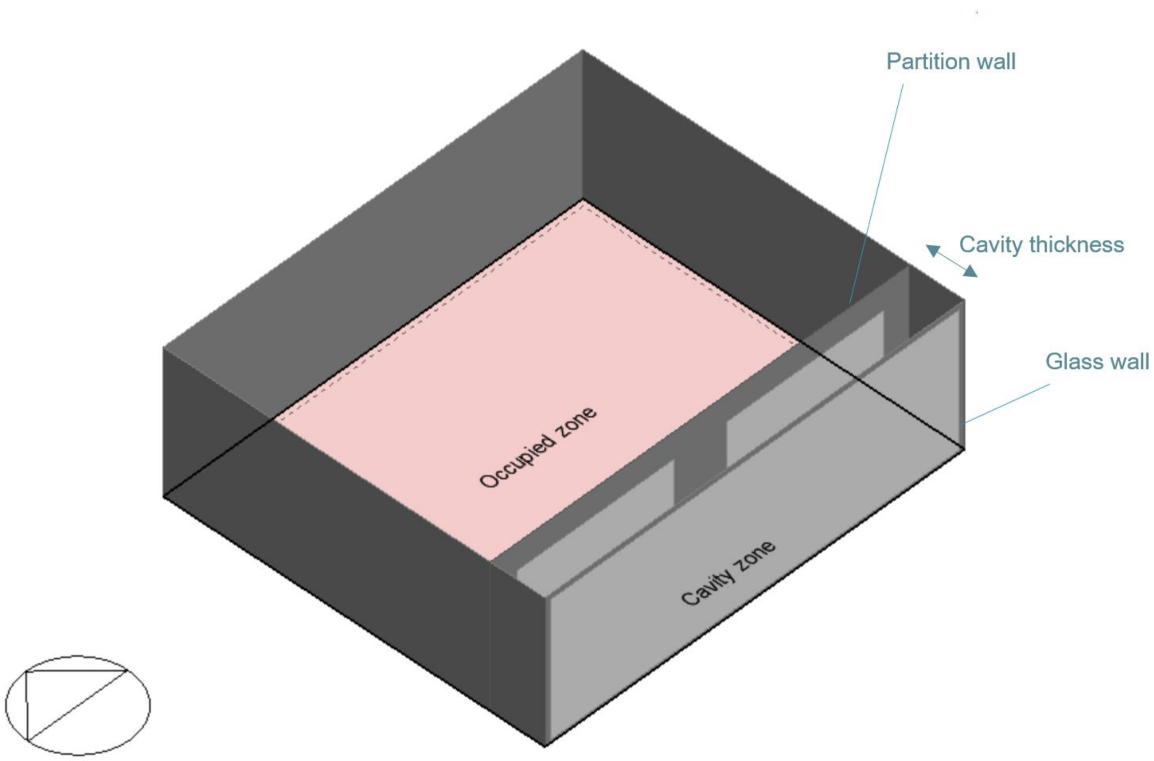


Figure 3.8 - Double skin facade model: Cavity et occupied zone

Some assumptions were made for the double skin façade model:

- The base model assumes no transfer of air between the cavity zone and the occupied space. Thus airflow path is considered as *Outdoor Air Curtain* (OAC). Furthermore, it has been shown that this airflow path is the most efficient in mild climates (Porto) in terms of energy saving (Alberto, et al., 2017).
- Cavity depth is set to 1 meter since the larger is the cavity the more energy is saved (Alberto, et al., 2017).
- Air flow in naturally ventilated double-skin façade is generally low but difficult to measure since it depends on the geometry specifications, climate type and wind speed. Given that the goal of this thesis is to measure the influence of each case, the default airflow rate of DesignBuilder, which is 5 ac/h, is kept.

3.7. Double skin façade with hybrid ventilation

In the end, there is a 4th family of dynamic envelopes: actively ventilated façades with *double skin ventilated façade* for this thesis. By adding mechanical ventilation, it is possible to model it in a reasonable way. One of the purposes of the study is to give information to architects and clients about dynamic envelopes. This way, the efficiency of the cases studied are very interesting. Thus two declinations are studied:

- Double skin façade with mechanical ventilation
- Double skin façade with hybrid ventilation (natural+mechanical)

Airflow rate of mechanical ventilation can be changed easily. As for naturally ventilated double-skin façade, the air change rate per hour is set to 5 ac/h.

3.8. Control strategies

Adaptive façades can have a significant effect on energy savings. Furthermore, these building envelopes can control the visual and/or thermal comfort of the occupants by applying appropriate control strategy. In fact, these control strategies can improve the occupant's productivity and their wellbeing (Tabadkani, et al., 2020).

DesignBuilder has the advantage to have numerous pre-defined control types available (cfr Table 9). Since the purpose of this thesis is to investigate energy savings, thermal and visual comfort, the control types chosen are:

- On during schedule. This means that the technologies is always on during the occupied hours.
- Solar radiance
- Operative temperature. This last option is modelled by applying the control type *inside air temperature* and then, when simulating, *temperature control* is set on *2- Operative temperature*
- Glare

According to COST Action TU 1403 (Favoino, et al., 2018), these control strategies are *time-scheduled control* for the first one and *hard-coded extrinsic control* for the others. Thresholds are determined regarding standards and other studies. Furthermore, a study made in Germany in 2003, investigates the moment when individuals tended to use electric lighting. Thereby, they all activated their blinds to avoid incoming solar gains when it reaches 450 W/m² (Reinhart & Voss, 2003). Finally, based on the standard NBN EN 15251, the optimal indoor temperature is appreciated between 21 and 25,5°C. (Bureau de Normalisation, 2007). But without a clear data for the operative temperature, the threshold, 24°C, chosen in Tällberg's study is used (Tällberg, Petter Jelle, Loonen, Gao, & Hamdy, 2019). No threshold needed for the glare control. Moreover, Designbuilder considers a glare index of 22 for office buildings. (DesignBuilder, 2020) Table 11 resumes the threshold for each control strategy.

Table 11 - Control types and thresholds in the study

N° in DB	Control type	Threshold
3	On during schedule	-
4	Solar	450 W/m²
7	Inside air temperature	24°C
5	Glare	22

When exceeding a certain threshold, dynamic envelopes will appear or will be activated to decrease heat gain and lighting under this threshold depending on the control strategy. In DesignBuilder, when the device is *On*, it is assumed that blinds and shades cover all of the window except its frame. On the contrary, when the device is *Off,* it is assumed that these cover none of the window. For switchable glazing, *On* means that the glazing is in the fully-switched dark or opaque state while *Off* means that it is in its clear state (DesignBuilder, 2020).

Unfortunately, due to DesignBuilder's limitations, control strategies couldn't be employed for all cases. Thus, electrochromic case and dynamic shading case were the only two that could use these three control strategies. It is possible to control the natural and/or mechanical ventilation of double skin façades only by adding a minimum and/or maximum indoor temperature set point. However, this option will help to use a common control strategy with the other study cases which is *Operative temperature*. The minimum indoor temperature is set to 24°C. It means that besides this value, the ventilation will be set off to avoid overcooling.

The Figure 3.9 below resume control strategies available and simulated for each case.

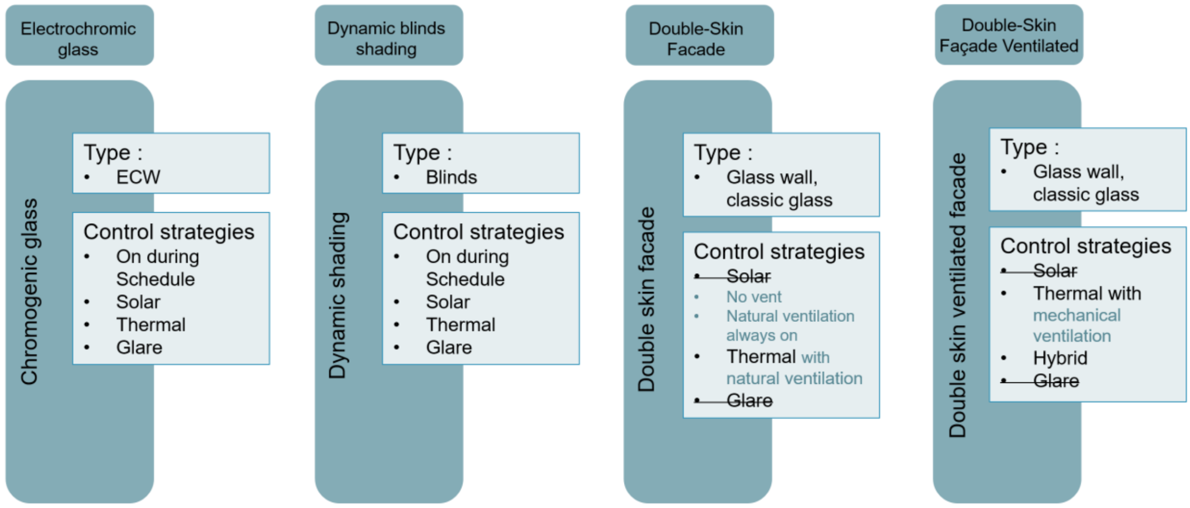


Figure 3.9 - Control strategies chosen for the different cases

Planning a schedule for the use of these smart envelopes would be a solution to optimize their use (Favoino, et al., 2018). Since the study concerns office buildings, the schedule is from 7:00 am to 6:00 pm from Monday to Friday. Therefore, dynamic envelopes could be switched on or activated during the schedule by taking into account control strategies as shown on Figure 3.10.

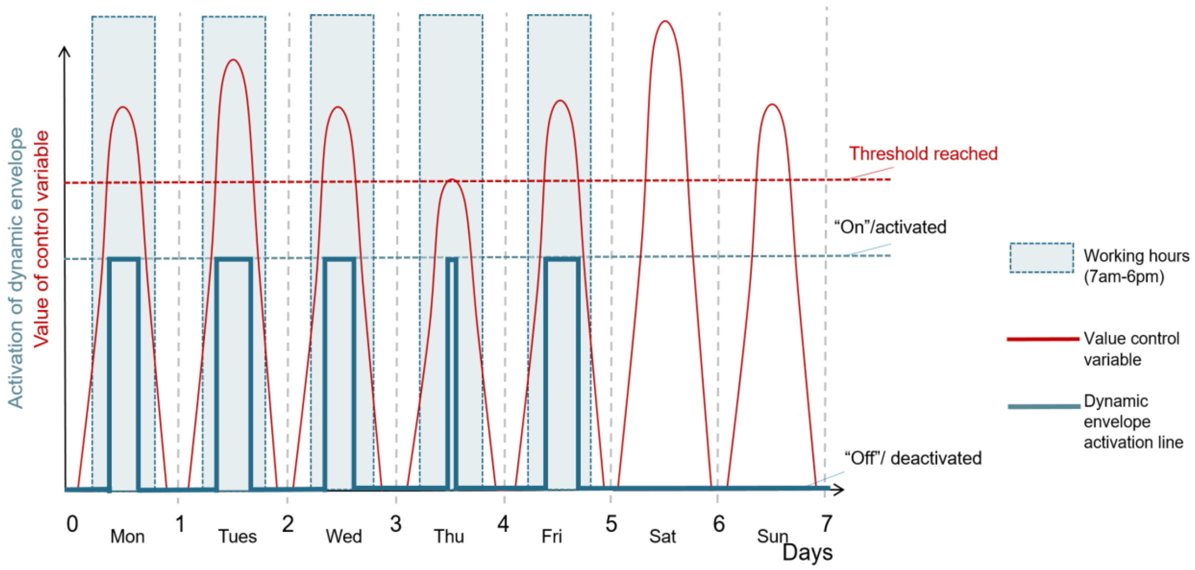


Figure 3.10 - Dynamic envelope operating schema according to the schedule and control strategy

3.9. Sensitivity analysis

Depending on the results, parametric studies were made to determine the sensitivity of different parameters and thereby to determine the reliability of each case. Several studies investigated the influence of settings (see Section 2.3). Alberto's study is interesting since they have pointed out a huge variation of results. For example, the air flow path could induce at least 30% less HVAC related energy consumption compared to the others airflow path and variation of cavity depth from 25 cm to 100cm save up 9,5% of energy demand (Alberto, et al., 2017).

Therefore, to strengthen the study, sensitivity analysis will be made for cases that can save more than 10% compared to the base case. These analyses will be considered only for energy saving and thermal comfort because simulations give quantitative results. Visual comfort is delivered as qualitative results.

By taking into account the Chapter 4. related to the results, it is possible to determine the technology that has the best performance related to energy consumption and thermal comfort. These analyses are divided into different cases.

Different parameters will be studied:

- **Electrochromic windows:** the optical properties of electrochromic glazing come from an existing study (Tällberg, et al., 2019) which took properties from real manufacturers. Thus these will be kept. Thereby, the parameters that vary are the thresholds chosen for *solar control* (ECW 1) and *operative temperature control* (ECW 2). The *schedule control* (ECW 0) is not changed since it is considered as the working hours. Glare control strategy is not varied.
- **Dynamic shading:** dynamic shading device of the study is a default device of DesignBuilder. Different physical properties can be studied as the slat angle, the slat separation, slat width and the blind-to-glass distance. As for ECW, control strategies' thresholds are varied and studied.
- **Double-skin façades**: the most influential parameters have already been studied but for an oceanic temperate climate (Alberto, et al., 2017). Because of the purpose of this study, the only parameters from Alberto's study analyzed are the ventilation type, which was analyzed through DSF 2, DSFV 1 and DSFV 2, and the cavity depth. A parametric study of the temperature control threshold is also investigated.
- **Double-skin ventilated façades:** it is assumed that the only difference between double-skin façades (DSF) and double-skin ventilated façades (DSFV) is the ventilation mode. Thus, the parameters that will be studied are the air flow and, again, the temperature threshold.

Figure 3.11 gathers the sensitivity analysis chosen for the different cases.

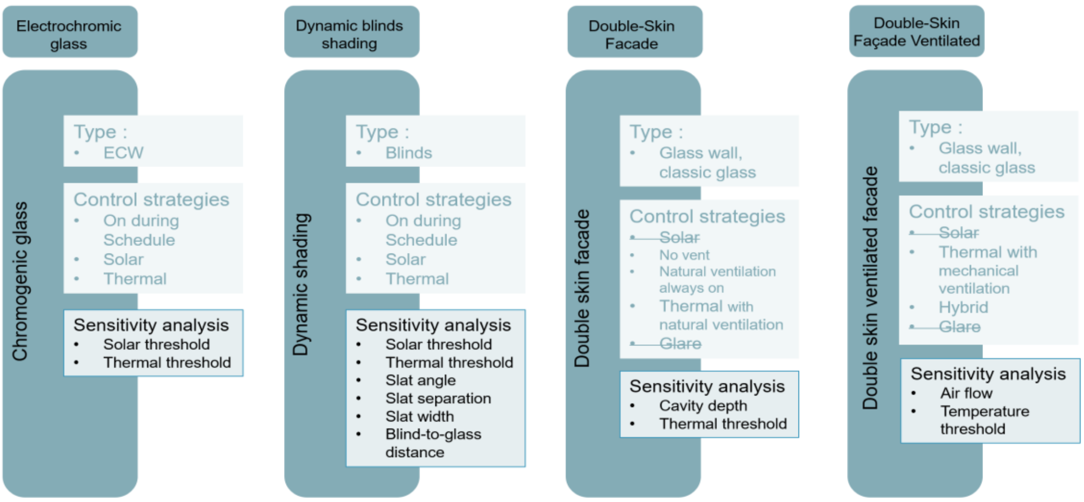


Figure 3.11 – Sensitivity analysis chosen for the different cases

Nevertheless, the measured protocol could be broken if the results are repetitive. For example, the air flow rate can increase until a huge number but the results of this sensitivity analysis can be unvaried or recurrent. A detailed explanation of how the results are analyzed and shown is gathered in section 5.1.

3.10. Daylighting simulation

One of the purposes of this thesis is to analyze the visual comfort of the cases. A dedicated option of daylighting model is existing in DesignBuilder and helps to simulate it in a fairly suitable way (DesignBuilder, 2020). At first, lighting control has to be put *On*, it will save internal gains due to lighting loads. The default settings are kept to standardize it.

Lighting control and daylighting simulation are based on the implementation of daylight sensors. By default one sensor is located in the middle of the room and is supposed to represent a desk. The height of this one is set to 0,8m (DesignBuilder, 2020). This sensor can be moved but by centering it, daylighting results will be more representative. Figure 3.12 represents the sensor's position.

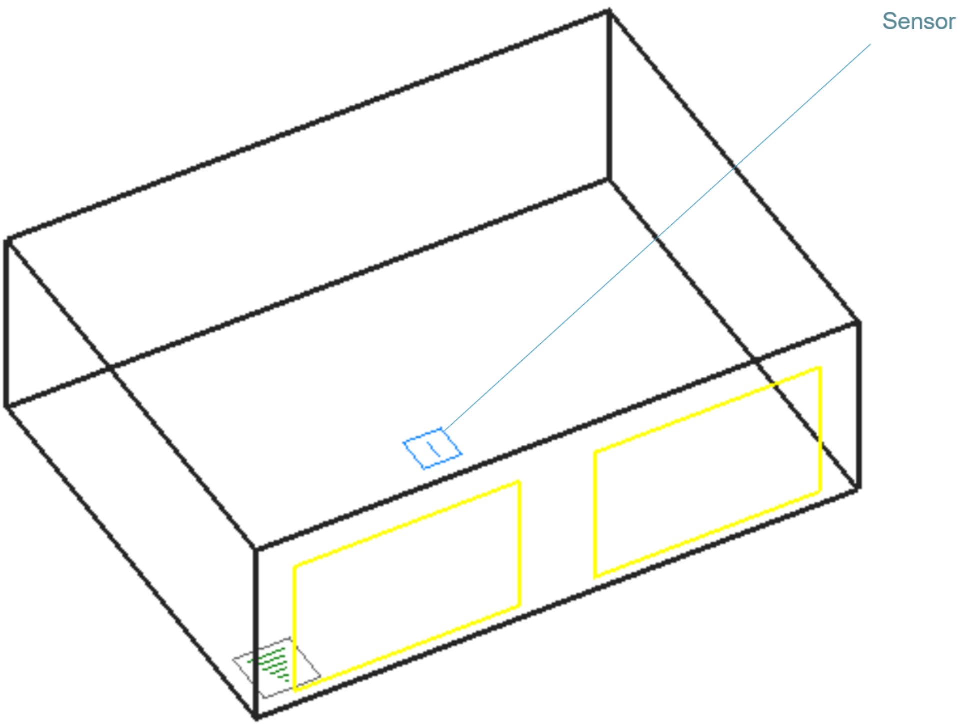


Figure 3.12 – Screenshot – position of the lighting sensor

The daylight illuminance depends on many factors, including sky condition, sun position, sensor(s) position and location (DesignBuilder, 2020). DesignBuilder proposes several sky models, from clear to cloudy with or without taking into account the direct illuminance. Table 12 gathers Sky models of DesignBuilder.

Table 12 – Sky's models in DesignBuilder and their specifications

N° in DB	Name	Clouds	Direct illuminance from sun	Specifications
1	CIE - Sunny clear day	-	Yes	The exact day and time can be selected.It is thus possible to compare results at different moment of the year.
2	CIE - Clear day	-	No	
3	CIE - Sunny intermediate day	+/-	Yes	
4	CIE - Intermediate day	+/-	No	
5	CIE - Overcast day	+	Yes	Adopted as a standard by the CIE in 1955, the sky brightness increases gradually in this model with altitude from the horizon to the zenith.
6	CIE - Overcast day (specify illuminance)	+	Yes	Similar to 5 but the direct illuminance can be varied
7	CIE - Uniform cloudy day	+	No	Totaly uniform illuminance.

By choosing the first sky model, results will be more significant. To show it, the Figure 3.13 shows the results of the base case, on 21st June at 12 am for sky models 1, 2, 3 and 4 and standard day for sky models 5, 6 and 7. The Useful Daylight Illuminance is defined as "the occurrence of illuminances across the work plane where all the illuminances are within the range 100-2000 lux". (Mardaljevic, 2005). The minimum and maximum threshold are based on occupant preferences and behavior in daylight offices with the possibility for the users to operate shading devices (Mardaljevic, 2005). Thus, this range is supposed to help the productivity of the workers.

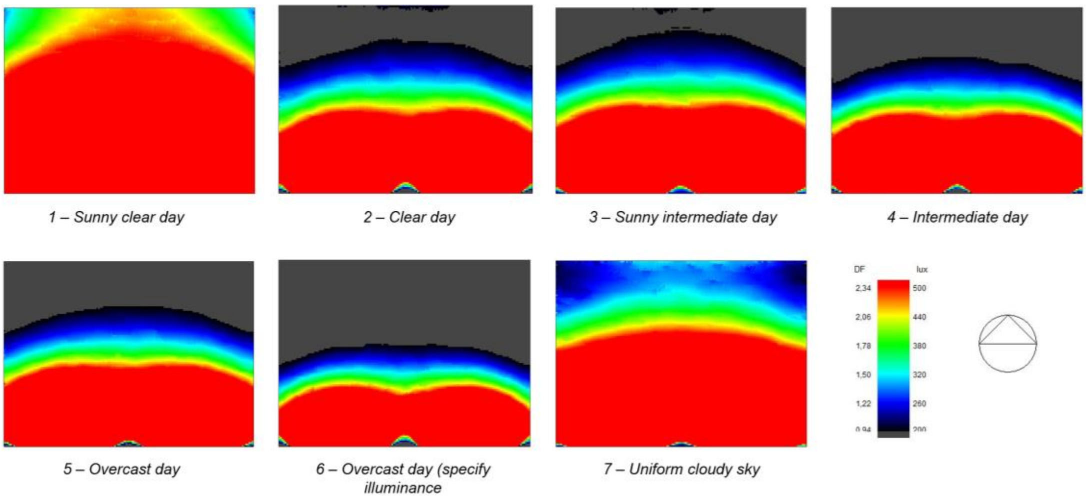


Figure 3.13 - Illuminance simulation - base case - sky models (21st June, 12 am)

On Figure 3.13-1, the first sky model, *Sunny clear day*, is more sensitive and can be considered as the least favorable sky in terms of visual comfort. Thereby, this sky model is chosen. On this one, the maximal level is set to 500 lux, to have more representative results and to better compare the different types of sky. Nevertheless, illuminance maps will have a scale from 100 to 2000 lux which is the Useful Daylight Illuminance (UDI).

The date and time can vary with this sky model. This is represented on Figure 3.14. Here, the grey color on maps is the only part where daylight illuminance is less than 100 lux and pink color is the part where illuminance exceeds 2000 lux. All the other colors correspond to the range between these thresholds.

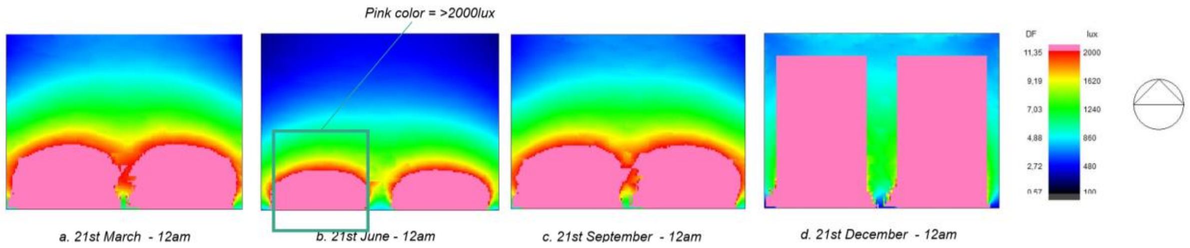


Figure 3.14 - Illuminance simulation - base case - date and time (12 am)

As expected, daylight goes deeper in the room in December because the sun is low and even more on the 21st December which is the winter solstice. On 21st march and September, daylight is supposed to be almost the same since it is the equinoxes, which means that the day has a duration equal to the night. Actually, the Sun is crossing the celestial equator during this day, from one polar circle to another.

Of course, daylight is changing during the day and the Figure 3.15 above shows how the software simulates it. The last map is almost completely grey. It means that the illuminance is lower than 100 lux.

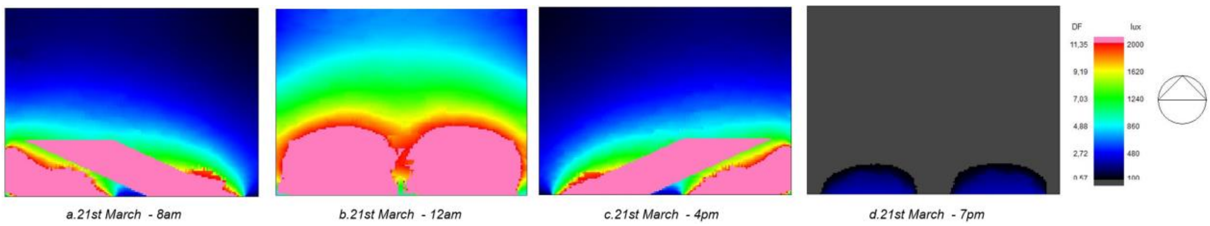


Figure 3.15 - Illuminance simulation - base case - Moment of the day (21st March)

However, due to the limits of the software, daylighting analysis cannot be performed for electrochromic case and dynamic case. Therefore, the visual comfort is only studied for base case and double-skin façade cases.

3.11. Comparative analysis

The last step of this thesis is a comparative analysis. Firstly, influential parameters are determined according to the sensitivity analysis results, which are gathered in section 5.1. These influential parameters will help to analyze in the most suitable way the comparative analysis' results. Thereby, this analysis is made between all studied cases and their optimal sensitivity variation. Since the comparative analysis is related to the sensitivity results, the influential parameters could not be fixed in this section. Thus a more detailed methodology that gathers the influential parameters and the final case studies results for this comparative analysis is explained and shown in Chapter 5.

3.12. Boundary conditions

This section introduces boundary conditions and the limitations of the study

- Firstly, the study is based on the Case 600 of BESTEST, the Tällberg's and Alberto's study.
- Secondly, the cases investigated have been chosen to take into account a large part of adaptive façades with a case for each adaptive façade family (cf. Figure 2.1)
- The purpose of the study is initially to analyze the energy consumption and the thermal comfort. Regarding the limitations of DesignBuilder and since the output data are more qualitative, the visual comfort is secondary but studied when possible.

- Because of the hourly weather file found, the location is Uccle in the Brussels Capital Region. Furthermore, it has been created by the Royal Meteorological Institute of Belgium which is Belgium's reference station.
- Each case is studied with several control strategies from a simple one to smarter control strategies. Most of the time the first control strategy studied is *Schedule during working hours*.
- Control strategies were chosen with reference to impact criteria and the Tällberg's study. The first assumption was to take exactly the same as Tällberg which seems to be more suitable. But, *2-Daylight* could not be selected for the dynamic shading case. Consequently, the closest control strategy possible was *5-Glare*.
- The other control strategies for dynamic shading and electrochromic cases are *4 – Solar control* and *7 – Inside air temperature* (which will be operative temperature, cf. Section 3.8). However, due to DesignBuilder's limits, only *Operative temperature control* could be investigated for the double-skin façade cases.
- Input data of electrochromic case is based on Tällberg's study (Tällberg, et al., 2019) while input data of double-skin façade is based on Alberto's study (Alberto, Ramos, & Almeida, 2017). Input data of dynamic shading are default settings of DesignBuilder
- Sensitivity analyses are made to strengthen the thesis and will be performed only on relevant technologies regarding the results.
- The sensitivity analysis of the double-skin façade could not be performed for the same parameters as Alberto's study. In fact, the geometry of the case impedes the study of the geometry of the cavity and the height of the façade. Automated open windows are not the purpose of this thesis. Then, since the natural air flow rate in the cavity depends on the configuration of the path and meteorological data, it will vary with the airflow path and the weather. Thus this parameter is too complex to model and is neglected in this thesis.
- Daylighting analysis is modeled for the "worst day" with a *clear sunny sky.* The study days are the equinoxes and solstices and are not randomly chosen. Default settings of the daylight sensor position are kept.
- In this study, technology is considered as *significant* when the impact criteria are improved with more than 10% and *remarkable* when the impact criteria are improved with more than 30%.

3.13. Resume of simulated cases and their analyzed outputs

Table 13 describes the simulated cases performed for the different adaptive façades families. Sensitivity simulations are not included in this table. The results of these cases are given in the Chapter 4.

Table 13 – Resume of simulations

Family	Type	Control strategy	Ventilation mode	Setpoint	Diminutive
Chromogenic glass	Electrochromic glass	Schedule control	-	7am-6pm	ECW 0
		Solar control	-	24°C	ECW 1
		Thermal control	-	22	ECW 2
		Glare control	-	450 W/m^2-K	ECW 3
Dynamic shading	Automated blinds	Schedule control	-	7am-6pm	DS 0
		Solar control	-	24°C	DS 1
		Thermal control	-	22	DS 2
		Glare control	-	450 W/m^2-K	DS 3
Double-skin façade	Double-skin transparent façade controlled with	No ventilation	-	-	DSF 0
		Schedule control	Natural	0°C*	DSF 1
		Thermal control	Natural	24°C	DSF 2
Double-skin ventilated façade	Double-skin transparent façade	Thermal control	Mechanical	24°C	DSFV 1
		Thermal control (Hybrid ventilation)	Hybrid	24°C	DSFV 2

* To avoid temperature control of natural ventilation, a very low cooling setpoint temperature can be set

Depending on the impact criteria studied, the output data and units retained are different. Energy saving is mainly treated through both *heating and cooling loads*, while thermal comfort is processed through *hours of discomfort* with *winter and/or summer clothes.* Both of these output data are quantitative whereas visual comfort is more qualitative with an *illuminance map* as result. Figure 3.16 represents this.

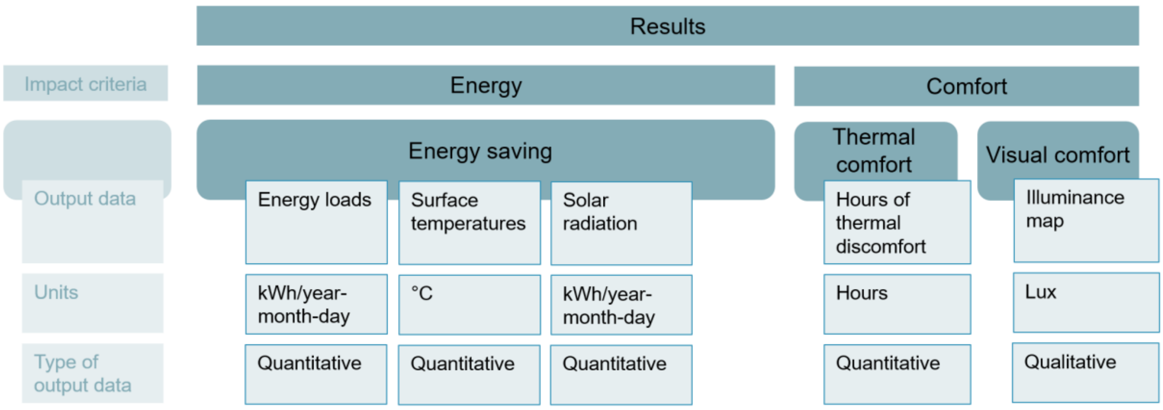


Figure 3.16 - Representation of results chosen given by DesignBuilder

In addition, the time dependent energy consumption is an important variable that could not be neglected. This way, the other following results to thoroughly understand the impact on the energy consumption of dynamic envelope have been analyzed:

- Zones sensible heating and cooling which means the heating and cooling effect of the HVAC system in the zone. These outputs are the main data studied related to energy, subdivided into heating and cooling energy loads monthly and annually (kWh/month or kWh/year).
- Monthly energy balances from window level for surface temperature of the glass pane and the solar radiation on the window.

Hours of discomfort given by DesignBuilder are based on ASHRAE Standard 55-2004[9]. These hours are considered as out of the thermal comfort zone when the combination of humidity ratio and the operative temperature is out of the region shown in Figure 3.17.a for summer and b for winter. 0.5 Clo level is used for summer and 1.0 Clo level is used for winter (DesignBuilder, 2020).

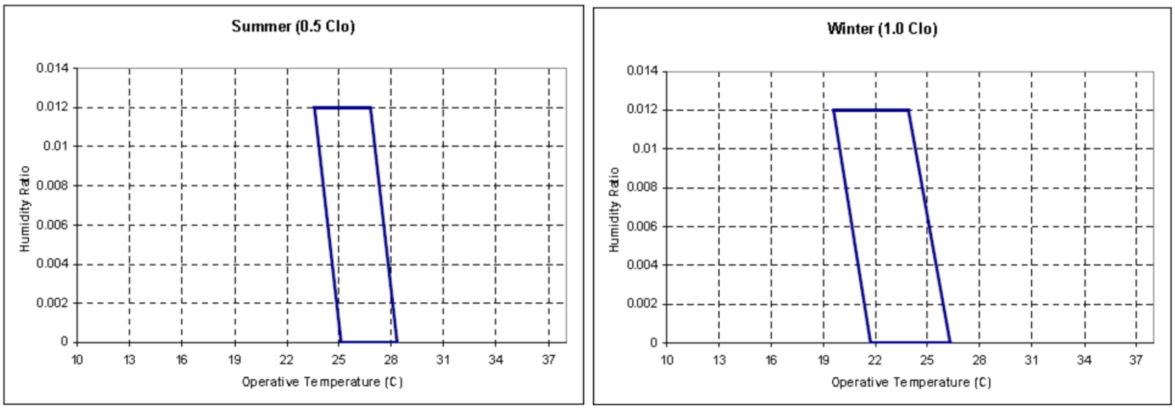


Figure 3.17 - Comfort region ASHRAE Standard 55-2004 for summer (a) - winter (b) - (DesignBuilder, 2020)

[9] ASHRAE Standard 55-2004 is a standard which specifies the combinations of personal factors and indoor thermal environmental factors that will produce acceptable thermal conditions of the environment to most of the occupants within the space (DesignBuilder, 2020).

4. Results

This chapter gathers all the results provided by annual simulations with DesignBuilder and is subdivided into four sections which correspond to each case. Then, energy, thermal comfort and visual comfort have been studied for each case. To determine the energy loads, each case is firstly presented by the energy loads, followed by a more detailed analysis of the energy by surface temperatures and solar radiations on the window and glazing heat flow. Secondly, thermal comfort is presented for each case. Finally, a dedicated subsection shows the results of the daylighting analysis.

Comparisons are always made with the base case which is set to 100% and the different control strategies used. At the end of the section, comparisons are made for all significant cases.

4.1. Base case

4.1.1. Model validation

Since the model is based on BESTEST case 600, its validation is essential. This way, BESTEST case 600 has been modeled. Table 14 presents the annual energy heating and energy cooling energy loads for modeled BESTEST case 600 and the values obtained by the official BESTEST case 600 with DesignBuilder.

Table 14 - Annual energy loads of BESTEST case 600 - official and modeled case.

	BESTEST case 600 output	DesignBuilder Case 600 output	Divergence (%)
Annual heating loads (kWh)	4516,5	4477,4	0,866
Annual cooling loads (kWh)	6710,4	6719,8	0,140

On this table, the difference between official and modeled cases is less than 1% and thus, it can be concluded that the model is validated (Ashrae, 2014). From this BESTEST case 600, modifications done to obtain the study base case are gathered in Section 3.2. These changes concern mainly location, climate data and internal gains.

The next sections will not take into account BESTEST case 600 and will only be about case studies.

4.1.2. Energy loads

The following results come from entire year simulations and all the analysis will be based on the comparison with the base case. Thus, the base case is explained in detail.

Figure 4.1 shows the monthly heating and cooling energy loads for the base case. Heating energy loads are quite high in winter while cooling energy loads are more important in spring and summer. Actually, 58% of the energy loads are due to the cooling in Uccle, Belgium. The most heating demand month is December whereas the most cooling demand month is August. However, the cooling energy demand points out a peak in April with a higher demand than the previous and following months. This Figure is the reference for energy loads analysis and is supposed to represent 100% of the energy performance where good performance implies low energy loads and bad performance implies high energy loads.

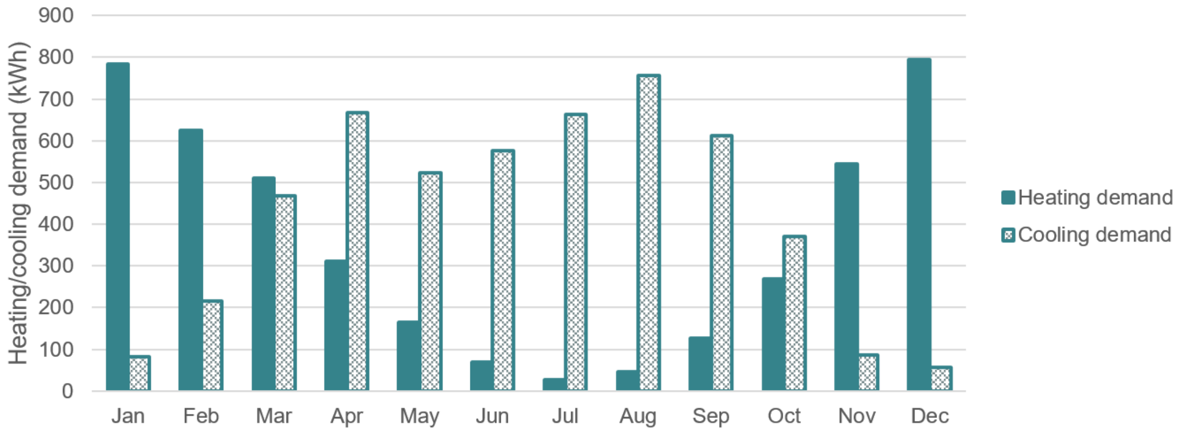


Figure 4.1 - Monthly energy loads - Base case – Building level

Figure 4.2 shows month by month the inside and exterior surface temperatures of the window for the base case. This data will help to understand in a deeper way how the variation of the surface temperatures of the window influences the annual loads. It is shown that the surface temperature difference between interior and exterior is higher in winter than in summer.

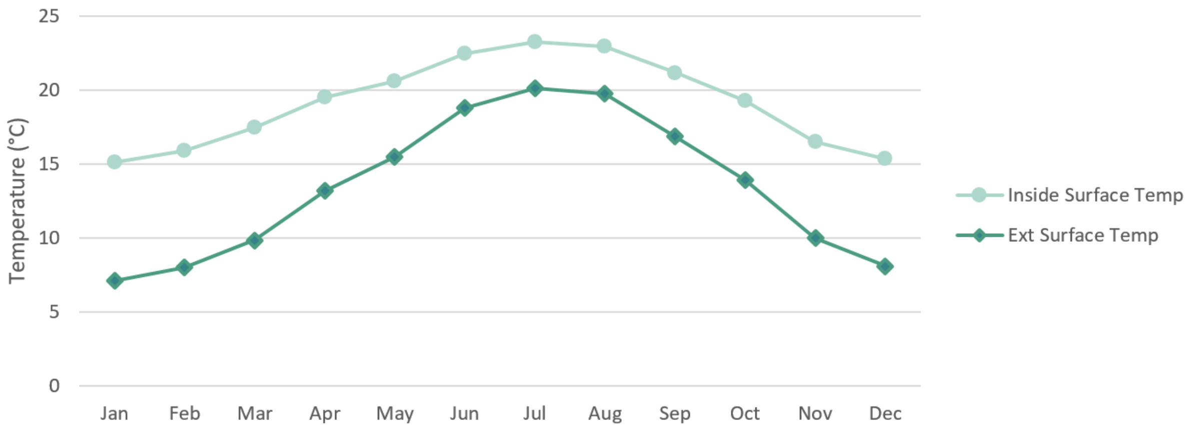


Figure 4.2 - Monthly surface temperature of glass pane - Base case - Window level

Figure 4.3 shows monthly solar radiation incidents and transmitted through the window. This data will help to see how many technologies can block the solar radiation or absorb it. It is shown that a smaller part of the solar radiation is transferred through the window in summer than in winter. Furthermore, solar radiation is higher in spring and fall while the lower season is winter. Surprisingly, solar transmitted radiation is higher than the solar incident radiation from September to April.

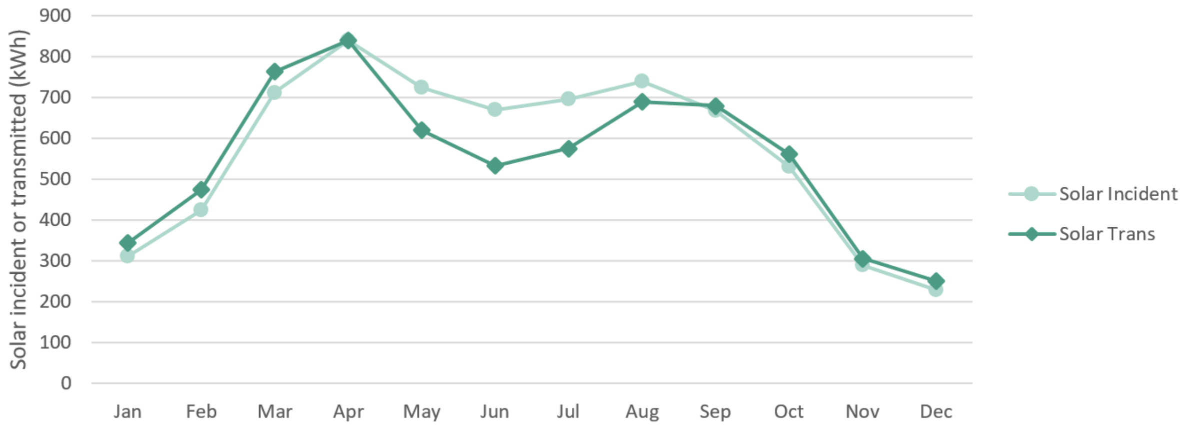


Figure 4.3 - Monthly solar radiation on the window - Base case - Window level

Table 15 resumes the energy simulation results for the base case. Relative results are set to 100% for the base case.

Table 15 – Resume of energy results – Base case

Energy	Heating demand (kWh/year)	3804
	Heating loads saving (%)	100,0
	Cooling demand (kWh/year)	5287
	Cooling loads saving (%)	100,0
	Annual loads (kWh)	9091
	Energy saving (%)	100,0

4.1.3. Thermal comfort

Thermal comfort is studied through hours of discomfort. DesignBuilder gives this data only for the entire duration of the simulation, which in this case is, one year. These hours of discomfort take into account the way the occupants are dressed, if they wear summer clothes or winter clothes and are shown on Table 16.

Table 16 – Hours of discomfort – Base case

Hours of discomforts with winter clothes (h)	Hours of discomforts with summer clothes (h)	Hours of discomforts with winter or summer clothes (h)	Total hours of discomfort (h)	Thermal comfort reduction (%)
2221	1282	704	4207	100,0

As for energy loads, this value is the reference which represents 100% of the thermal comfort performance where good performance implies small hours of discomfort and bad performance implies numerous hours of discomfort.

4.1.4. Visual comfort

Visual comfort or discomfort is represented by the daylighting simulation. However, the results of the daylighting simulation are more qualitative than quantitative. Thus the conclusions made could be less objective.

Figure 4.4 presents the results of the daylighting simulation on solstices and equinoxes since these days represent extreme and specific days of the climate related to daylighting. As explained in section 3.10, the pink color corresponds to an illuminance higher than 2000 lux which means bad performance for the visual comfort (Mardaljevic, 2005). A geometric form of the pink color as on Figure 4.4.d - 21st December represents the direct solar irradiation that comes from the window while the rest of the room receives diffuse irradiation. There are less warm colors as yellow or red for this day which means that the solar diffuse radiation is less intense than for summer solstice and equinoxes. Therefore, winter solstice seems to have the worst results related to visual comfort because the pink rectangles come almost to the bottom of the room. In fact, it is deeper because the sun is at its lowest position of that day. Without shading devices, this could cause a glare problem for the occupants.

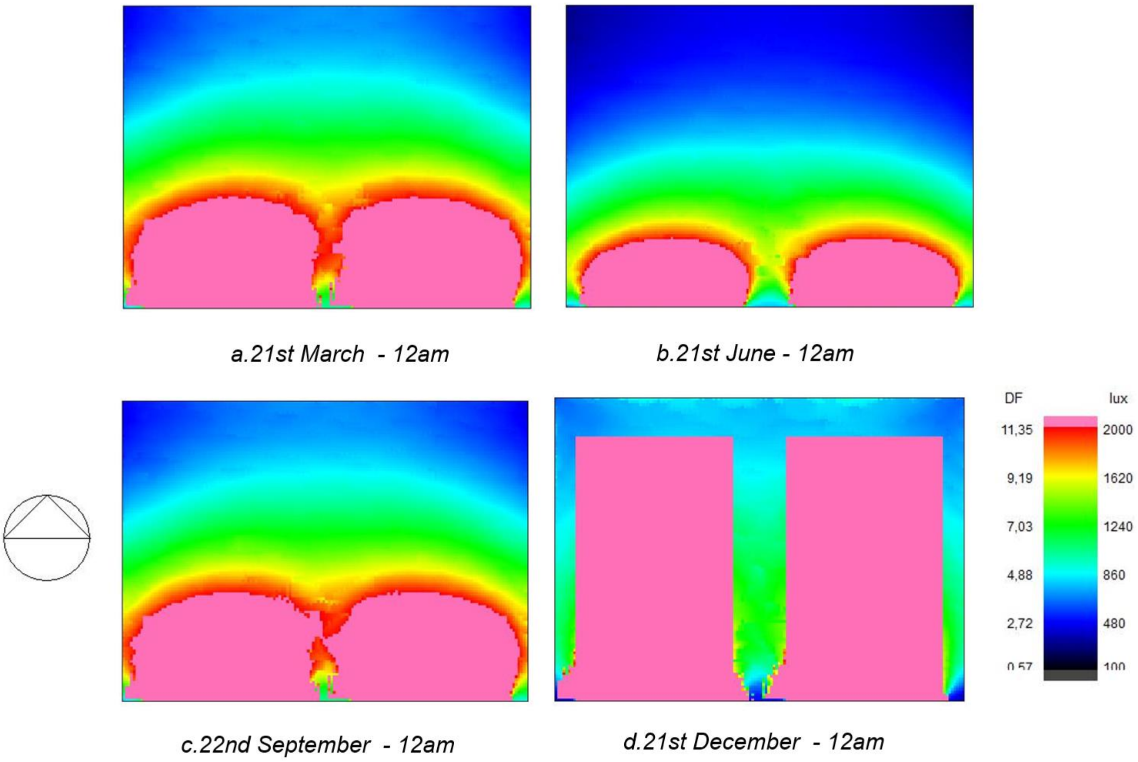


Figure 4.4 - Illuminance map - Base case

4.2. Electrochromic case

4.2.1. Energy loads

Figure 4.5 shows the heating energy loads for electrochromic cases and their control strategies studied. Legend corresponds to:

- Base case
- ECW 0 – Electrochromic case On during schedule
- ECW 1 – solar = Electrochromic case with solar control
- ECW 2 – OT = Electrochromic case with operative temperature control
- ECW 3 – Glare = Electrochromic case with glare control

The simulations give almost the same heating energy loads results. The *ECW with solar control* (ECW 1) is a little higher while *electrochromic glazing with operative temperature control* (ECW 2) is almost the same as *electrochromic glazing with schedule control* (ECW 0). *Electrochromic glazing with glare control* (ECW 3) seems to have similar heating energy loads than the base case. This is confirmed by the annual results. Thus this control strategy will not be studied further. The most heating consuming month is December while the least is July.

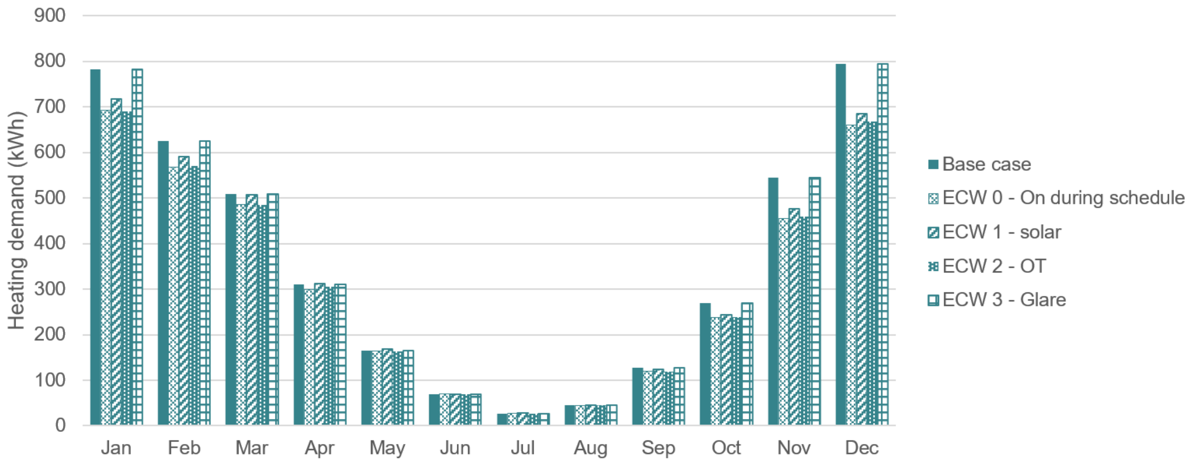


Figure 4.5 - Monthly heating loads - Electrochromic case - Building level

Cooling loads showed monthly speak for themselves. On Figure 4.6, cooling energy loads are significantly lower for the three first cases of electrochromic glazing with an annual decrease of 45,5%, 50,2 % and 44,7 % for *schedule control, solar control* and *operative temperature control* respectively. As for heating energy loads, the *glare control strategy* does not change the cooling energy loads from the base case. Thus, by using electrochromic glazing it is possible to decrease the cooling energy loads by more than 44%.

With a more detailed analysis of Figure 4.6, the most cooling consumer month is August for all electrochromic cases. It also appears that the most economical month is April and not August which is the hottest one. Finally, from November to February, ECW *with schedule control* (ECW 0), *solar control* (ECW 1) and *operative temperature control* (ECW 2) have a similar impact on the cooling energy loads until March when it begins to diverge.

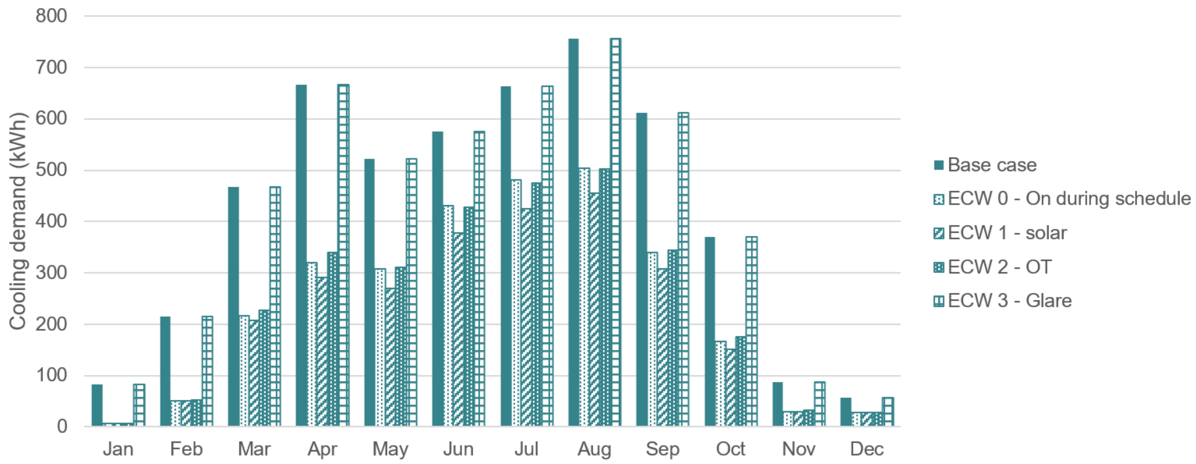


Figure 4.6 - Monthly cooling loads - Electrochromic case - Building level

Figure 4.7 displays surface temperatures of the glazing for base and electrochromic cases. Here, the gaps between interior and exterior surface temperatures of electrochromic cases are smaller than for the base case. Furthermore, it appears that the *Electrochromic case with schedule control* (ECW 0) closely followed by *operative temperature control* (ECW 2) induce higher surface temperature and smaller gaps than *Electrochromic case with solar control* (ECW 1) or base case. However, the most economical strategy is the second one with solar control regarding the results given by DesignBuilder. The hottest month regarding inside surface temperatures is July, which is also the least month with heating energy loads. Nevertheless, the month with the higher cooling energy loads is August. Finally, it seems that electrochromic cases are more sensitive to the climate regarding the small peak that can be observed in April.

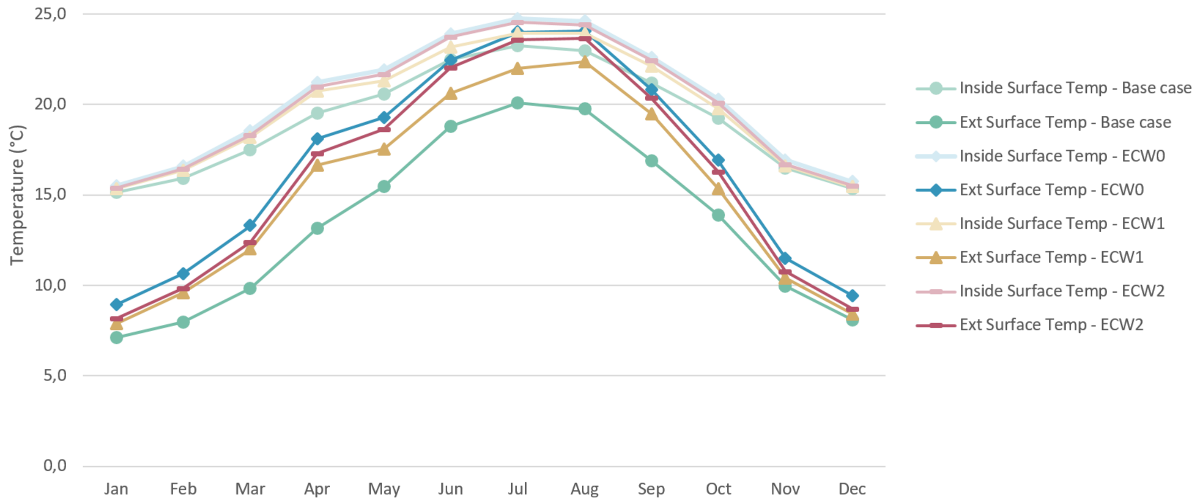


Figure 4.7 - Monthly surface temperature of glass pane - Base case and Electrochromic cases - Window level

By comparing the solar radiation absorbed by the glazing, it can be seen that the implementation of electrochromic glazing decreases significantly the solar radiation transmitted to the room. Moreover, Figure 4.8 shows a more linear behavior for electrochromic cases and even more when cooling energy loads are smaller. *Electrochromic case with schedule control* (ECW 0) closely followed by *operative temperature control* (ECW 2) has the best performance regarding energy and thus has smaller transferred solar radiation. Then, *solar control* (ECW 1) has a higher transmitted solar radiation from March to October but displays a lower transmitted one after. In addition, April points out a peak, however, for electrochromic cases, March is the month that has higher solar radiation transmitted to the room. For July and August, ECW 2 is closer to ECW 0 than for the other months.

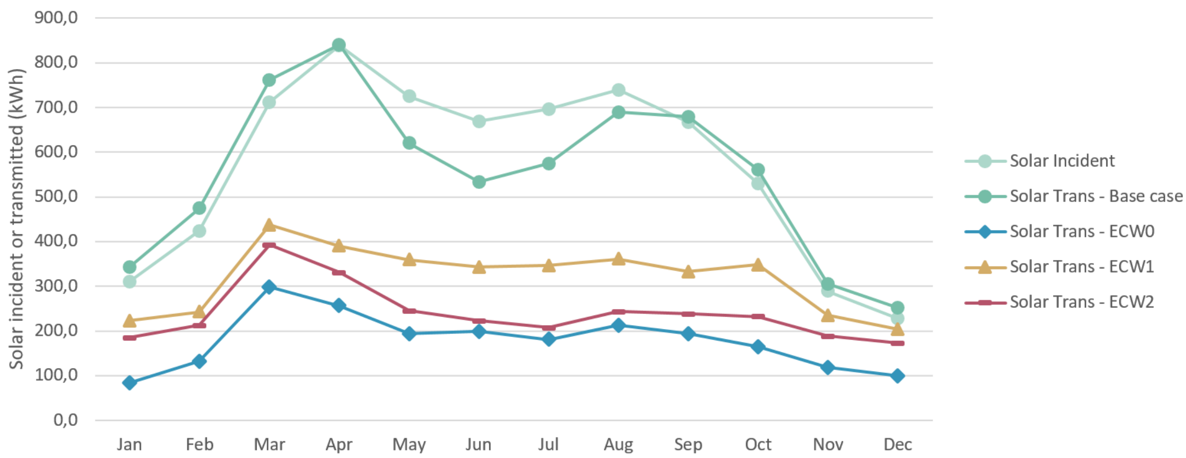


Figure 4.8 - Monthly solar radiation on the window - Base case and electrochromic cases - Window level

Table 17 resumes the energy simulation results for the base case and Electrochromic cases. The percentage of energy compared to the base case is calculated. This percentage is always calculated as the following equation:

$$\frac{\{Value\ of\ the\ case\}}{\{Value\ of\ base\ case\}} * 100 = improvement\ compared\ to\ base\ case\ in\ \%$$

Electrochromic glazing with solar control (ECW 1) and *with schedule control* (ECW 0) save the most energy with respectively 72,3% and 73,7% compared to the base case. ECW 2 also has good performance with 74,4% while ECW 3 does not change the energy consumption. In general, heating energy loads do not really change. This table shows that Electrochromic glazing remarkably reduces the annual and especially cooling energy loads by avoiding overheating.

Table 17 – Resume of energy results – Base case and Electrochromic cases

	Case	Base	Electrochromic glazing			
	Name		ECW 0	ECW 1	ECW 2	ECW 3
	Control strategy	-	Schedule	Solar	Operative temp.	Glare
	Threshold	-		450 W/m²-K	24°C	22
Energy	Heating demand (kWh/year)	3804	3824	3969	3845	3804
	Heating loads reduction (%)	100,0	100,5	104,3	101,1	100,0
	Cooling demand (kWh/year)	5287	2880	2601	2922	5287
	Cooling loads reduction (%)	100,0	54,5	49,2	55,3	100,0
	Annual loads (kWh)	9091	6704	6570	6767	9091
	Total energy reduction (%)	100,0	73,7	72,3	74,4	100,0

4.2.2. Thermal comfort

Table 18 displays thermal comfort performance for electrochromic cases. By comparing the results with the base case, the first control strategy (ECW 0) brings a better thermal comfort. Nevertheless, the difference is very small and does not exceed 4%. *Electrochromic glazing with solar control* (ECW 1) brings the worst thermal comfort with a percentage of 107% compared to the base case. Furthermore, as for the energy loads, *electrochromic glazing with glare control* (ECW 3) does not change the results. With a more precise analysis, the discomfort hours with summer clothing increase a little bit for ECW 2 while it strongly increases for ECW 1 and ECW 0. Discomfort hours with winter clothing decrease more for ECW 0 than for the other cases and Discomfort hours with winter and summer clothes increase by more than 20% for ECW 1.

Table 18 – Hours of discomfort – Base case and Electrochromic cases

Case	**Control strategy**	**Threshold**	**Hours of discomforts with winter clothes (h)**	**Hours of discomforts with summer clothes (h)**	**Hours of discomforts with winter or summer clothes (h)**	**Total hours of discomfort (h)**	**Thermal comfort reduction (%)**
Base	-	-	2221	1282	704	4207	100,0
Electrochromic	On during schedule	-	1864	1555	655	4074	96,8
	Solar	450 W/m²-K	1974	1664	862	4500	107,0
	Operative temp.	24°C	2078	1360	702	4140	98,4
	Glare	22	2221	1282	704	4207	100,0

4.2.3. Visual comfort

The visual comfort for electrochromic cases cannot be investigated due to the software's limitations.

4.3. Dynamic shading
4.3.1. Energy loads

The Figure 4.9 shows the results of heating energy loads for the different dynamic shading cases. Legend corresponds to:

- Base case
- DS 0 – Dynamic shading case On during schedule
- DS 1 – solar = Dynamic shading case with solar control
- DS 2 – OT = Dynamic shading case with operative temperature control
- DS 3 – Glare = Dynamic shading case with glare control

As for the electrochromic case, the three first control strategies have almost the same heating demand throughout the year while the fourth *case with glare control* (DS 3), seems to have exactly the same energy loads than the base case. This is also confirmed in Table 19. The most consumer month is December while the least is July.

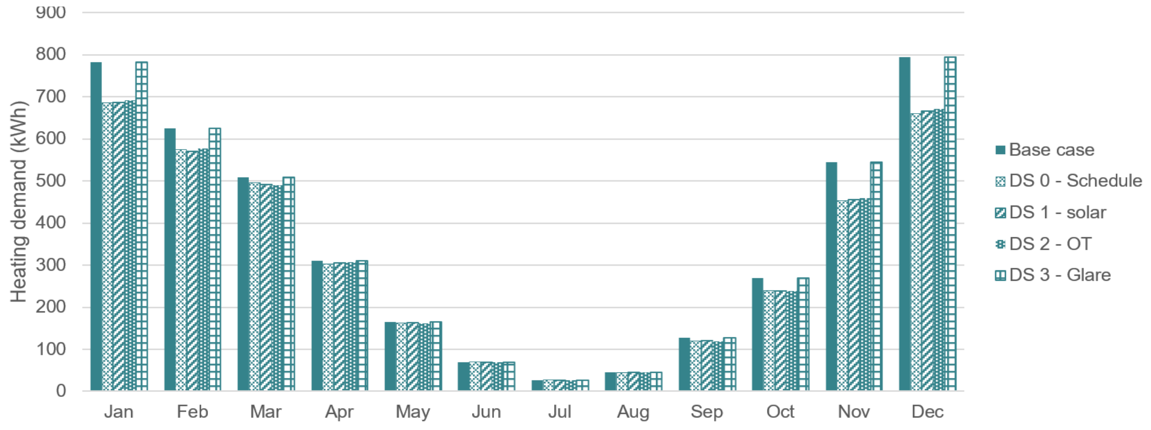


Figure 4.9 - Monthly heating loads – Dynamic shading cases - Building level

The behavior of the dynamic cases for cooling energy loads is similar to the electrochromic cases' behavior with the best results for *schedule* control (DS 0) closely followed by the *Operative temperature control* (DS 2). Then, as shown on Figure 4.10, *the solar control* (DS 1) also decreases cooling demand but with a smaller impact. Once again, dynamic shading with *glare control* (DS 3) consumes the same amount of cooling energy than the base case. Thus, this control strategy will not be studied deeper with the surface temperatures and solar radiation. Peaks in August and April are visible as for electrochromic cases.

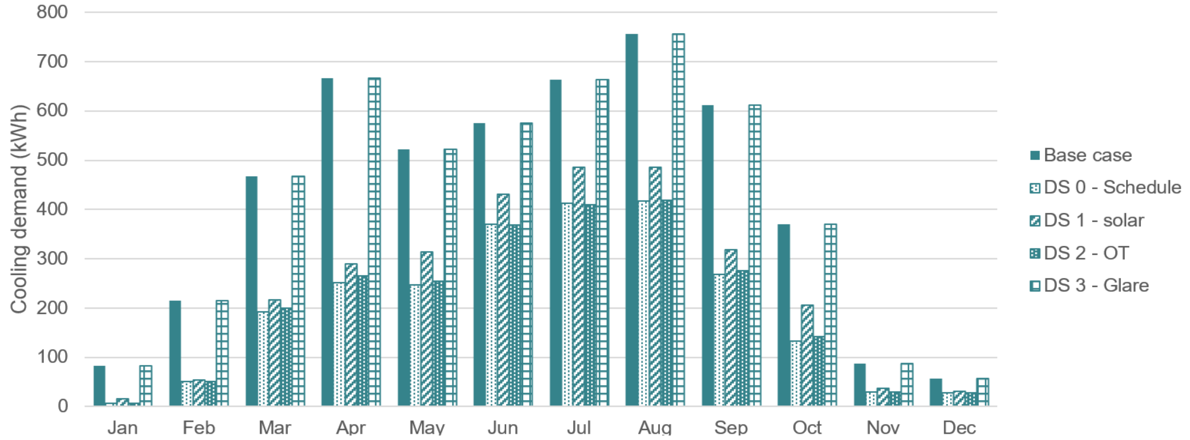


Figure 4.10 - Monthly cooling loads – Dynamic shading cases - Building level

Figure 4.11 above reveals smaller gaps of surface temperatures when using dynamic shading devices. In fact, gaps are even smaller for *dynamic shading set on during schedule* (DS 0) and the case *with operative temperature control* (DS 2). As for electrochromic glazing, the more a technology can save cooling energy loads, the higher are the surface temperatures and smaller are the gaps. By making a more detailed analysis, the curves of exterior surface temperatures are close to each other during winter before diverging during summer. Inside surface temperatures are almost the same for all cases except for the *dynamic shading with operative temperature control* (DS 2). It seems that dynamic shading is more sensitive to the climate variability regarding the peak in April.

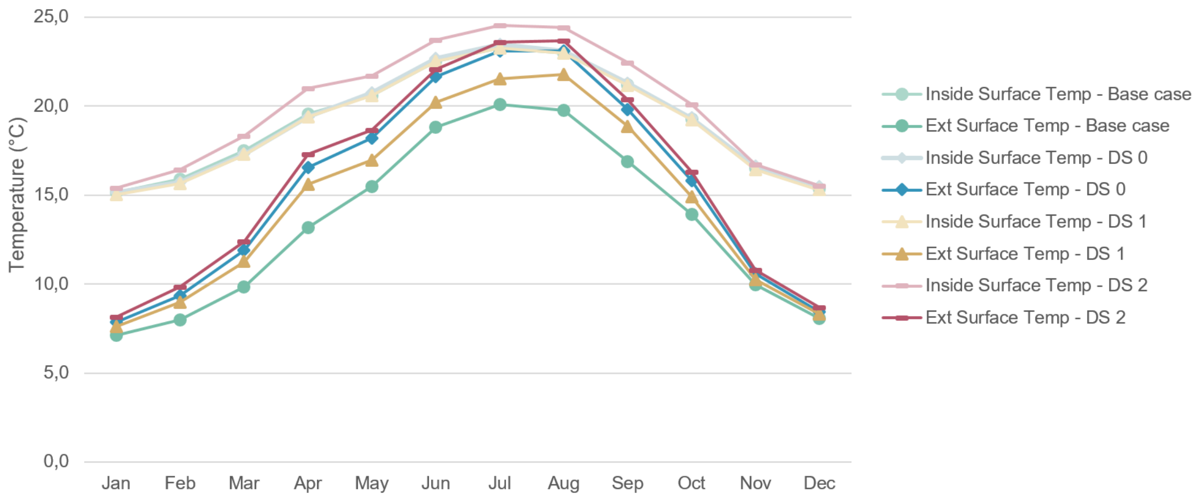


Figure 4.11 - Monthly surface temperature of glass pane - Base case and dynamic shading cases - Window level

Figure 4.12 compares the solar radiation absorbed by the glazing for dynamic shading cases. Dynamic shading devices drastically reduce the transmitted solar radiation. Their behavior is similar to a peak in March which was also the case for electrochromic glazing. For the months of July and August, the transmitted solar radiations are practically equal for *dynamic shading with schedule* control (DS 0) and *with operative temperature control* (DS 2). *Dynamic shading with solar control* (DS 1) has higher solar radiation transferred to the room but has also a worse performance in terms of energy consumption. Furthermore, during these summer months, the curve does not converge to DS 0 as it is the case for DS 2.

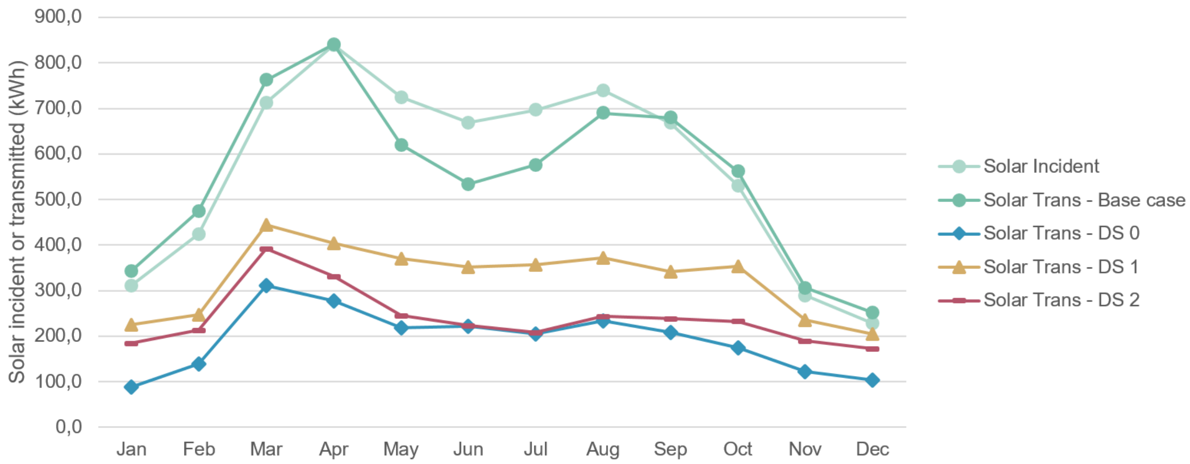


Figure 4.12 - Monthly solar radiation on the window - Base case and dynamic shading cases - Window level

Finally, Table 19 resumes results related to the energy loads. It appears that *dynamic shading with schedule control* (DS 0) and *with operative temperature control* (DS 2) have the best performance with a small difference and can be considered as remarkable technologies. These mostly improve the cooling energy loads with 45,6%, 54,6% and 46,3% of the cooling demand of the base case respectively for DS 0, DS 1 and DS 2. As for electrochromic glazing, *glare control* does not change the energy consumption. This table shows that dynamic shading helps to avoid the overheating of the room.

Table 19 – Resume of energy results – Base case and dynamic shading cases

	Case	Base	Dynamic shading			
	Name		DS 0	DS 1	DS 2	DS 3
	Control strategy	-	Schedule	Solar	Operative temp.	Glare
	Threshold	-	-	450 W/m²-K	24°C	22
Energy	Heating demand (kWh/year)	3804	3834	3840	3858	3804
	Heating loads reduction (%)	100,0	100,8	100,9	101,4	100,0
	Cooling demand (kWh/year)	5287	2409	2886	2450	5287
	Cooling loads reduction (%)	100,0	**45,6**	54,6	**46,3**	100,0
	Annual loads (kWh)	9091	6243	6726	6308	9091
	Total energy reduction (%)	100,0	**68,7**	74,0	**69,4**	100,0

4.3.2. Thermal comfort

Table 20 presents the discomfort hours for dynamic shading cases. It occurs that these technologies do not have an important or significant impact on thermal comfort. And as for the energy loads analysis, DS 0 and DS 2 have the best performance related to thermal comfort with a really small difference. Discomfort hours with summer clothing slightly increase for all control strategies but even more for *schedule control* (DS 0). Discomfort hours with winter clothing decreases slightly.

Table 20 – Hours of discomfort – Base case and dynamic shading cases

Case	Control strategy	Threshold	Hours of discomforts with winter clothes (h)	Hours of discomforts with summer clothes (h)	Hours of discomforts with winter or summer clothes (h)	Total hours of discomfort (h)	Thermal comfort reduction (%)
Base	-	-	2221	1282	704	4207	100,0
Dynamic shading	On during schedule	-	1780	1667	692	4139	98,4
	Solar	450 W/m²-K	2029	1461	722	4212	100,1
	Operative temp.	24°C	1944	1477	706	4127	**98,1**
	Glare	22	2221	1282	704	4207	100,0

4.3.3. Visual comfort

The visual comfort for dynamic shading cases cannot be investigated.

4.4. Double skin façade with natural ventilation

4.4.1. Energy loads

The Figure 4.13 shows the results of heating energy loads for the different double skin facade cases. Legend corresponds to:

- Base case
- DSF 0 – No vent = Double skin façade without ventilation. This case corresponds to a buffer zone (no airflow path)
- DSF 1 – Schedule = Naturally ventilated double skin façade On during schedule
- DSF 2 – OT = Naturally ventilated double skin façade with operative temperature control

Double-skin facades decrease the heating energy demand of the room. The control strategies seem to have poor influence on this demand. However, *Double skin façade with schedule control* (DSF 1) requires more heating demand. The most consuming month is December while the least is July.

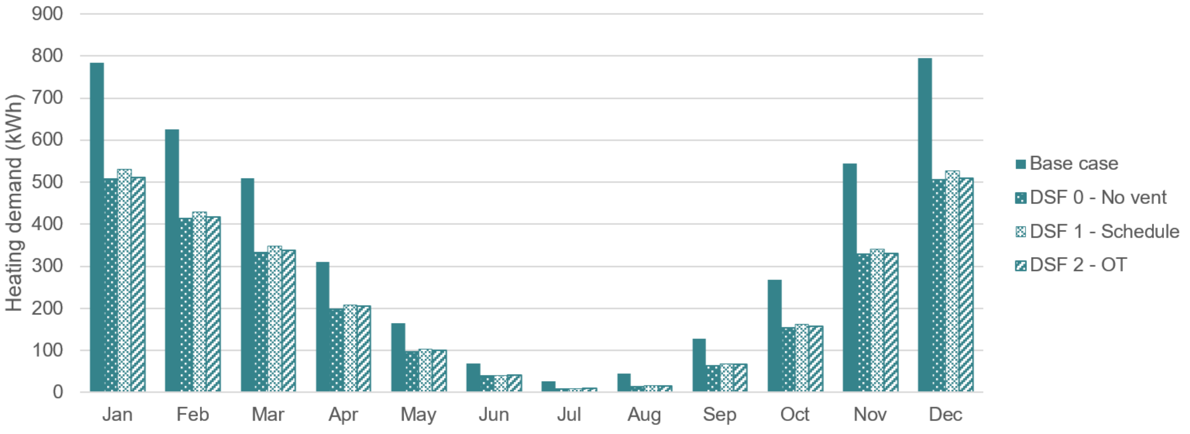


Figure 4.13 - Monthly heating loads – Double skin facade cases - Building level

Contrary to electrochromic and dynamic shading cases, a simple or naturally ventilated double-skin façade has really small influence on the cooling energy loads. Figure 4.14 points out that a control strategy improves the energy performance related to cooling energy loads. Thus, *Double skin façade without ventilation* (DSF 0) consumes more cooling energy loads followed by *naturally ventilated double skin façade with operative temperature control* (DSF 2) and then *naturally ventilated double skin façade with schedule control* (DSF 1). The most consumer month is August whereas the least is December.

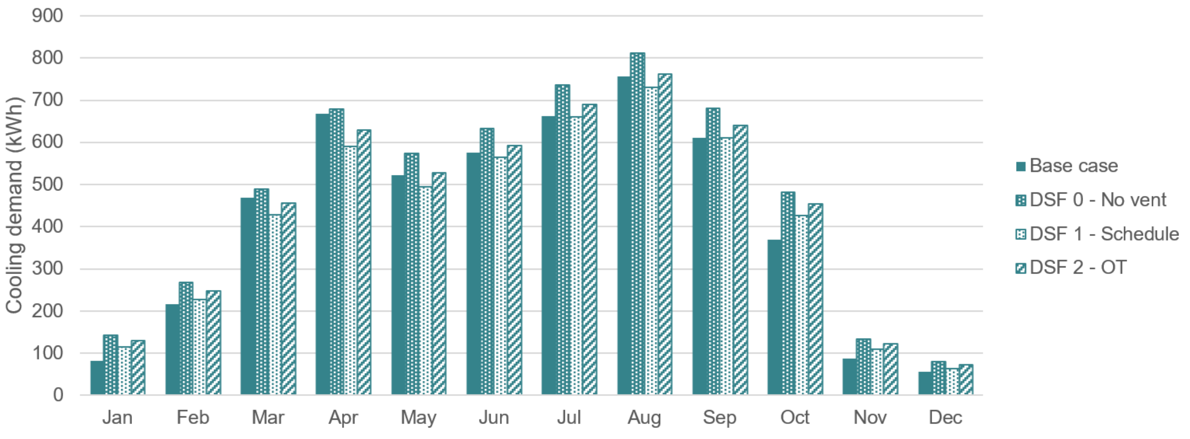


Figure 4.14 Monthly cooling loads – Double skin facade cases - Building level

Since there is a cavity, four surface temperatures are considered. To be the most understandable possible, surface temperatures are analyzed for each case. Then a figure gathers these outputs in one simplified graphic. Figure 4.15 represents the different surface temperatures with:

- **E.C**. temperature which is the exterior surface temperature on the window of the cavity. This temperature corresponds to the **exterior surface temperature** of the glass pane of the base case.
- **I.C.** temperature which is the inside surface temperature on the window of the cavity. The heat flux will come by conduction through the glass pane.
- **E.R** temperature which is the exterior surface temperature on the glass pane of the room. The heat will be transmitted by convection inside the cavity
- **I.R.** temperature which is the inside surface temperature on the glass pane of the room. The heat will be transmitted by conduction through the glass pane. This temperature corresponds to the **inside surface temperature** of the glass pane of the base case.

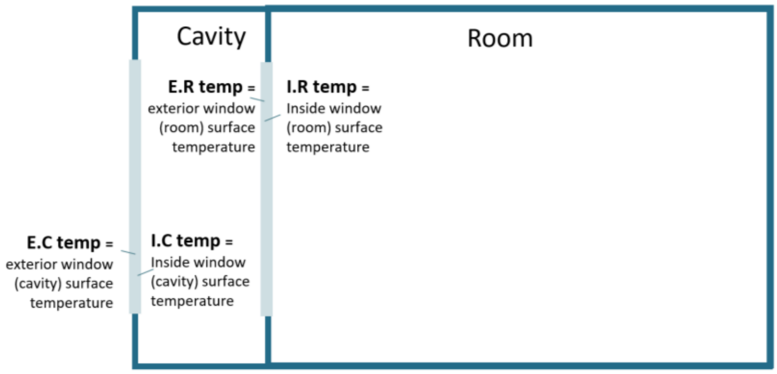


Figure 4.15 – Window surface temperatures of double skin facade cases

Figure 4.16 shows the surface temperatures for the DSF 0 case. It shows that I.R. temperature is significantly higher than the inside surface temperature of the base case throughout the year. Secondly, the E.C. temperature is higher than the exterior surface temperature of the base case during summer but lower during winter. However, compared to I.R. and the inside surface temperature of the base case, the difference between the E.C. temperature and the exterior surface temperature of the base case is smaller.

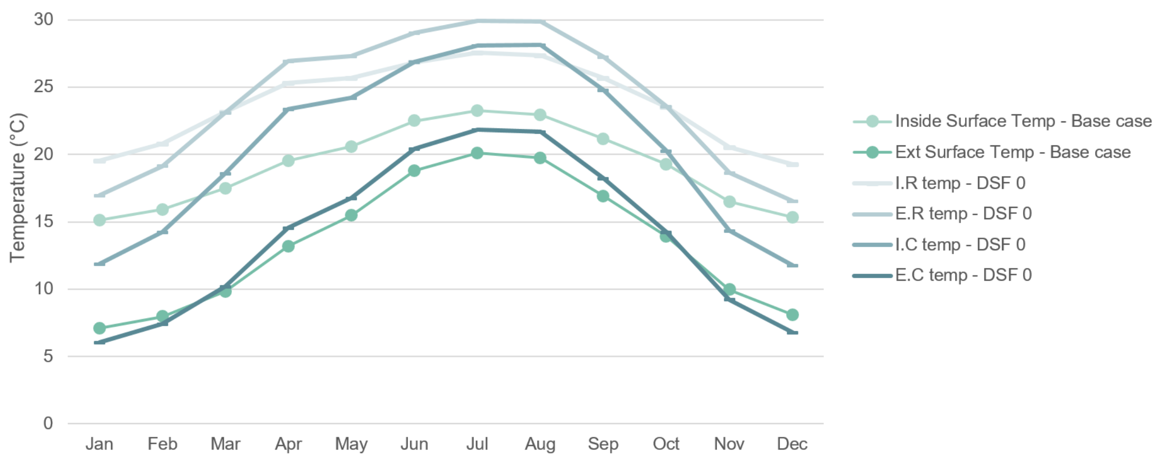


Figure 4.16 - Monthly surface temperature of glass pane - Base case and DSF 0 - Window level

Temperatures inside the cavity (E.R. and I.C. temperatures) have similar behavior. Furthermore, these temperatures are higher than the inside surface temperature of the room for DSF 0 (I.R. temp) which means that the temperature of the cavity is higher than outside or in the room. Finally, the surface temperatures inside the cavity seem to be more sensitive to the climate in April.

Figure 4.17 and 4.18 present the surface temperatures respectively for the DSF 1 and DS2 cases. Their behavior is similar and almost equal to the surface temperatures of DSF 0.

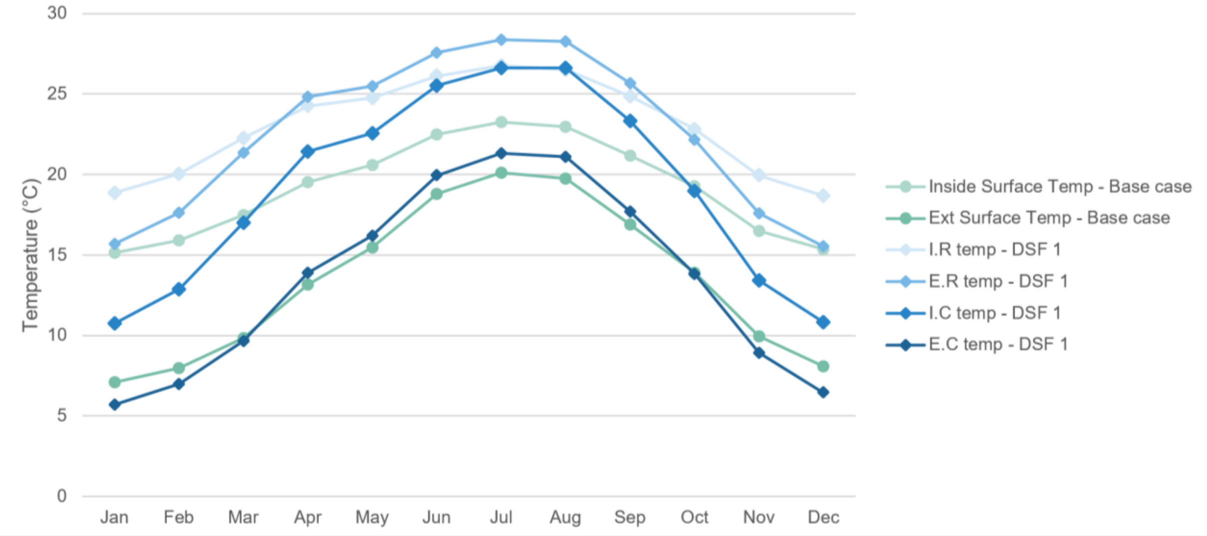


Figure 4.17 - Monthly surface temperature of glass pane - Base case and DSF 1 - Window level

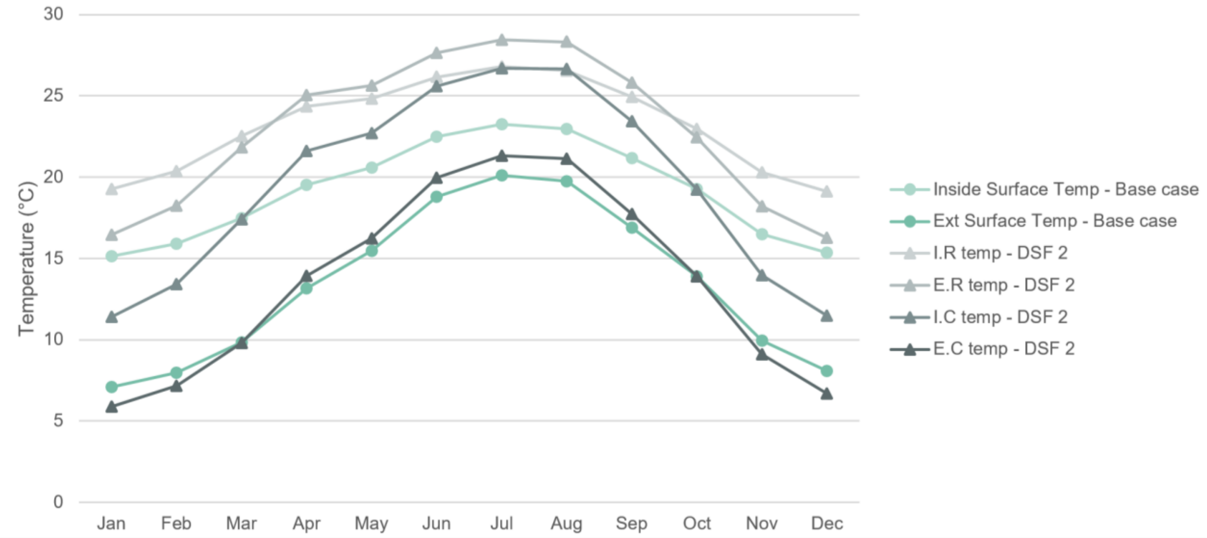


Figure 4.18- Monthly surface temperature of glass pane - Base case and DSF 2 - Window level

Figure 4.19 displays the extreme inside and outside surface temperatures of the base case and all double-skin façade cases. The inside surface temperatures for double skin façade cases are higher than for the base case. Actually, these cases could have an inside surface temperature range that varies between 19 and 28°C for double-skin while it varies between 15 and 23°C for the base case. The gap between inside and outside surface temperatures is significantly smaller for double-skin façades than for the base case. However, the difference is less significant than seen previously for electrochromic and dynamic shading cases.

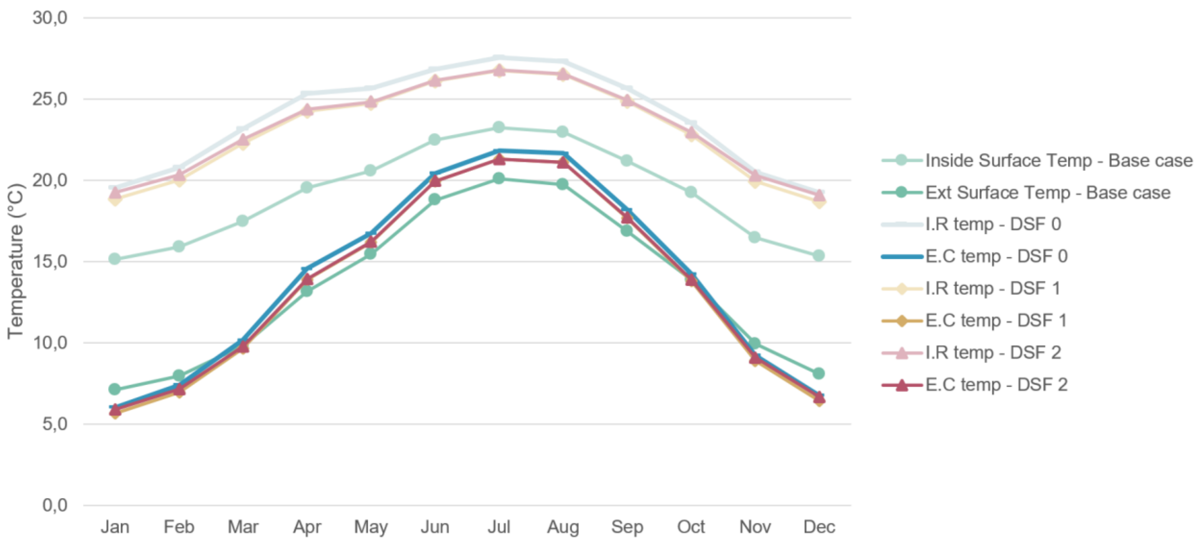


Figure 4.19 - Monthly surface temperature of glass pane - Base case and double-skin facade cases - Window level

Since there is no shading device, the solar radiation transmitted to the room is the same. This is shown on Figure 4.20 below. However, this value is the solar radiation transmitted through the external window, between the exterior and the cavity.

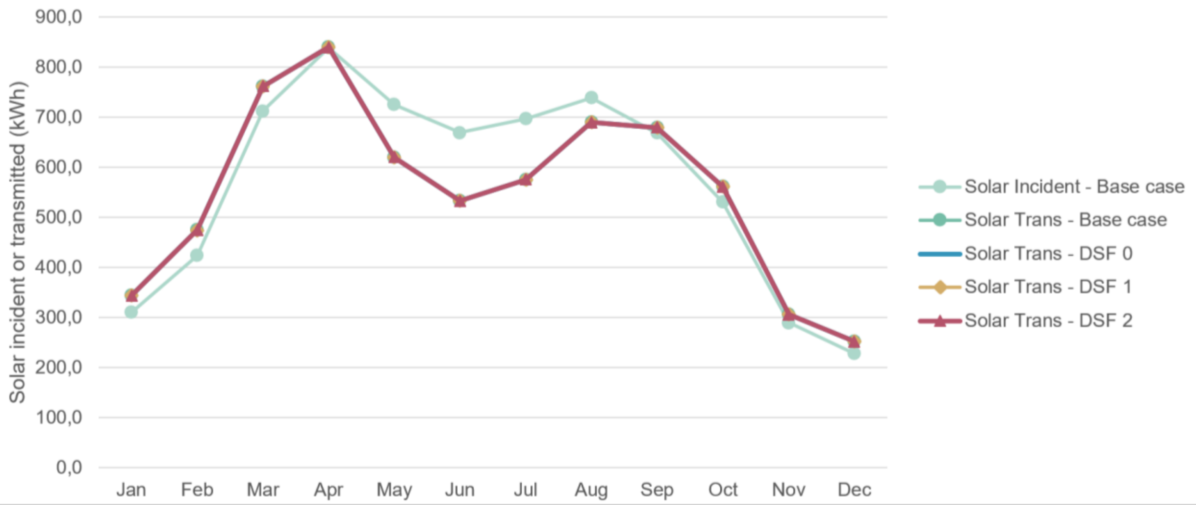


Figure 4.20 - Monthly solar radiation on the window - Base case and double-skin facade cases - Window level

Finally, Table 21 resumes the results related to the energy loads. It appears that a double-skin façade helps to improve in a significant way the energy performance and it is even more the case with control strategies. *Double-skin façade with schedule control* (DSF 1) seems to have the best results related to energy consumption. A *double-skin façade without any ventilation* (DSF 0) helps to decrease the heating energy loads but the cooling energy loads are higher with 108% compared to the base case.

Table 21 – Resume of energy results – Base case and double skin façade cases

	Case	Base	Double skin facade		
	Name		DSF 0	DSF 1	DSF 2
	Control strategy	-	-	Schedule	Operative temp.
	Threshold	-	-	-	24°C
Energy	Heating demand (kWh/year)	3804	2663	2788	2704
	Heating loads reduction (%)	100,0	70,0	73,3	71,1
	Cooling demand (kWh/year)	5287	5710	5026	5329
	Cooling loads reduction (%)	100,0	**108,0**	95,1	100,8
	Annual loads (kWh)	9091	8373	7814	8033
	Total energy reduction (%)	100,0	92,1	86,0	88,4

4.4.2. Thermal comfort

The Table 22 below gathers the discomfort hours for the double-skin façade cases. A double-skin façade improves significantly the thermal comfort with percentages of hours of discomfort compared to the base case of 86,7%, 88,4 and 86,6% respectively for DSF 0, DSF 1 and DSF 2. Thus *Naturally ventilated double-skin façade with operative control* (DSF 2) has the best performance regarding thermal comfort. Actually, double-skin façades mostly reduce the discomfort hours with summer clothes and with summer and winter clothes which means that they mostly improve the thermal comfort in summer.

Table 22 – Hours of discomfort – Base case and double skin façade cases

Case	Control strategy	Threshold	Hours of discomforts with winter clothes (h)	Hours of discomforts with summer clothes (h)	Hours of discomforts with winter or summer clothes (h)	Total hours of discomfort (h)	Thermal comfort reduction (%)
Base	-	-	2221	1282	704	4207	100,0
Double skin facade	-	-	2202	1014	432	3648	86,7
	On during schedule	(10ac/h)	2188	1071	458	3717	88,4
	Operative temp.	24°C ; 10ac/h	2197	1015	432	3644	86,6

4.4.3. Visual comfort

To compare the visual comfort from the base case, each day studied for the double-skin façade case has been placed next to the corresponding base case illuminance map. This is represented on Figure 4.21 (Illuminance maps from DesignBuilder are gathered in Appendix D).

A double skin façade helps to decrease the amount of daylight. The pink part represents the daylight above 2000 lux. The geometric pink rectangles correspond to the direct solar radiation. These are long on Figure 4.21.d since the sun is low in the sky on that day. The other colors correspond thus to the diffuse solar radiation. For all days studied, the colors are colder, which means that there is less diffuse solar radiation transmitted to the room.

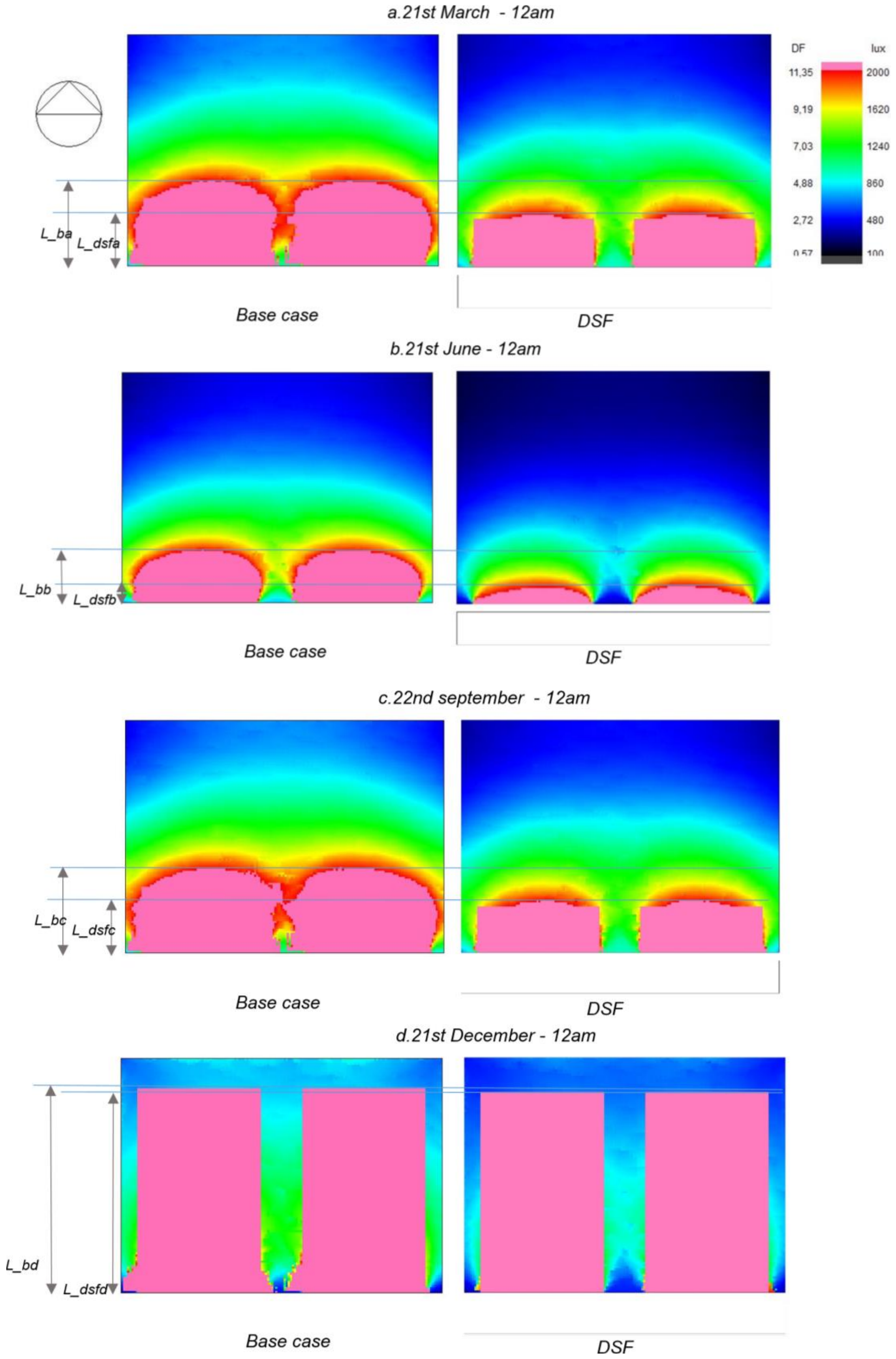


Figure 4.21 – Illuminance map for double skin façade cases

Then to quantify the visual discomfort, lengths from the window to the limit of the pink part have been measured since it represents how deep the daylight goes. The following calculations have been made:

$$\frac{L_{dsfx}}{L_{bx}} = \%\ of visual\ discomfort\ compared\ to\ base\ case$$

Figure 4.22 shows the percentage of visual discomfort for the double-skin façade cases compared to the base case. Real improvement is shown especially in June with 34,9% of visual discomfort compared to the base case. In December, the improvement is low with 96,9%. Daylight simulations have are for a clear sunny sky and thus represent the “worst” case.

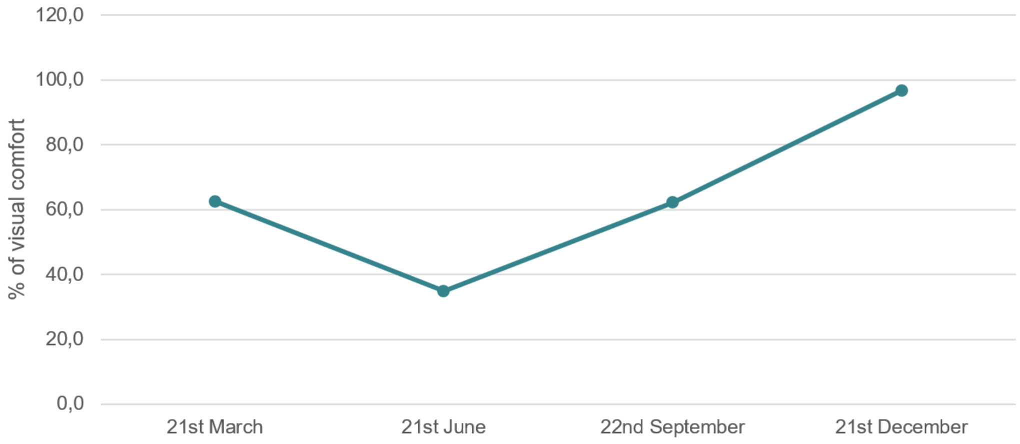


Figure 4.22 – Percentage of visual discomfort for double-skin façade compared to the base case

Thus, it is assumed the double-skin façade cases improve the visual discomfort and have a percentage of 64,2% compared to the base case.

4.5. Double skin façade with hybrid ventilation

4.5.1. Energy loads

The Figure 4.23 shows the results of heating energy loads for the different double-skin facade cases. Legend corresponds to:

- Base case
- DSFV 1 – Only mech. = Mechanically ventilated double-skin façade with operative temperature control
- DSFV 2 – hybrid = Naturally and mechanically (=hybrid) ventilated double-skin façade with operative temperature control

Heating energy loads are lower for both cases and almost equal. Thus, hybrid ventilation does not really influence the heating energy loads. The most consumer month is December while the least is July as for all other cases.

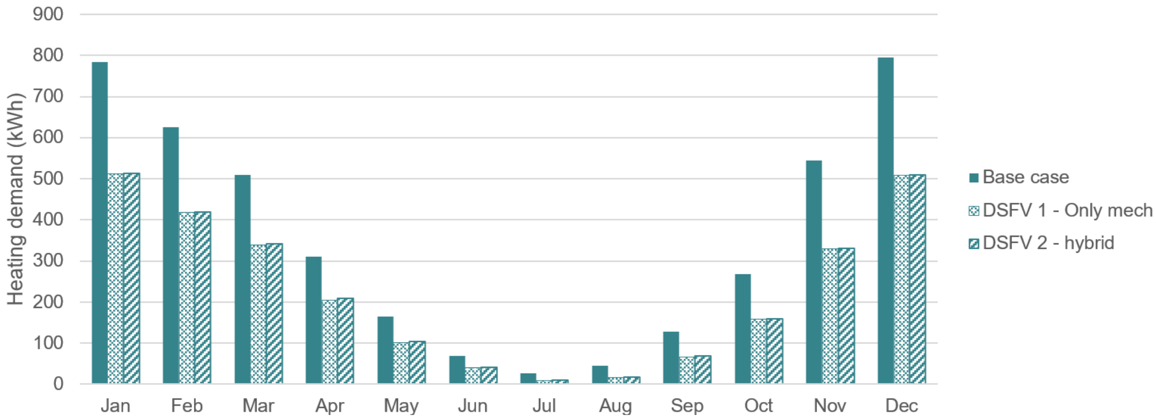


Figure 4.23 - Monthly heating loads – Double skin ventilated façade cases - Building level

Figure 4.24 represents the cooling energy demand for double-skin ventilated façade cases. It appears that mechanical ventilation does not really impact the cooling energy loads since the cooling energy demand is higher than the base case for some months but lower for others. Furthermore, hybrid ventilation impacts the cooling energy demand but with a small impact. The most consumer month is August while the least is December.

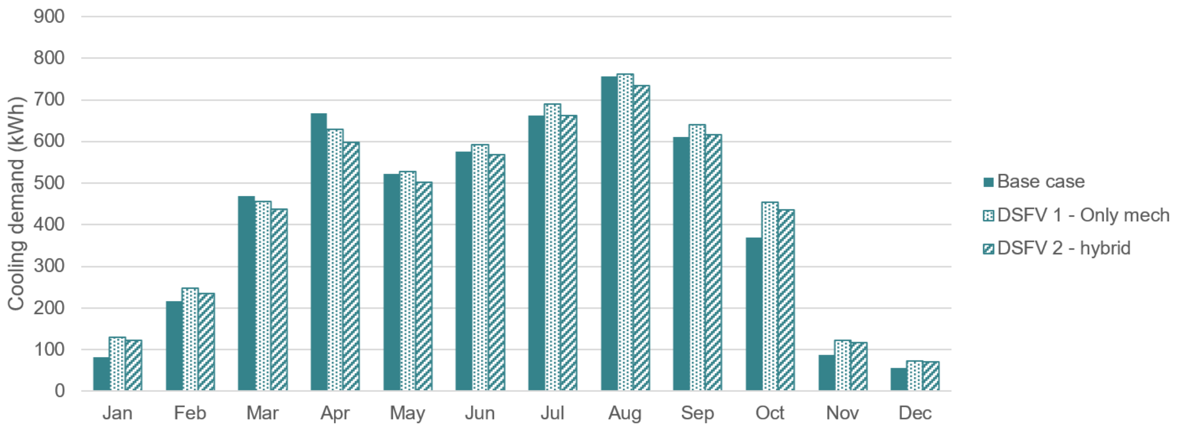


Figure 4.24 - Monthly cooling loads – Double skin ventilated façade cases - Building level

Figure 4.25 and 4.26 represent the surface temperatures of glass pane for *double-skin façade with mechanical ventilation* (DSFV 1) and *hybrid ventilation* (DSFV 2) respectively.

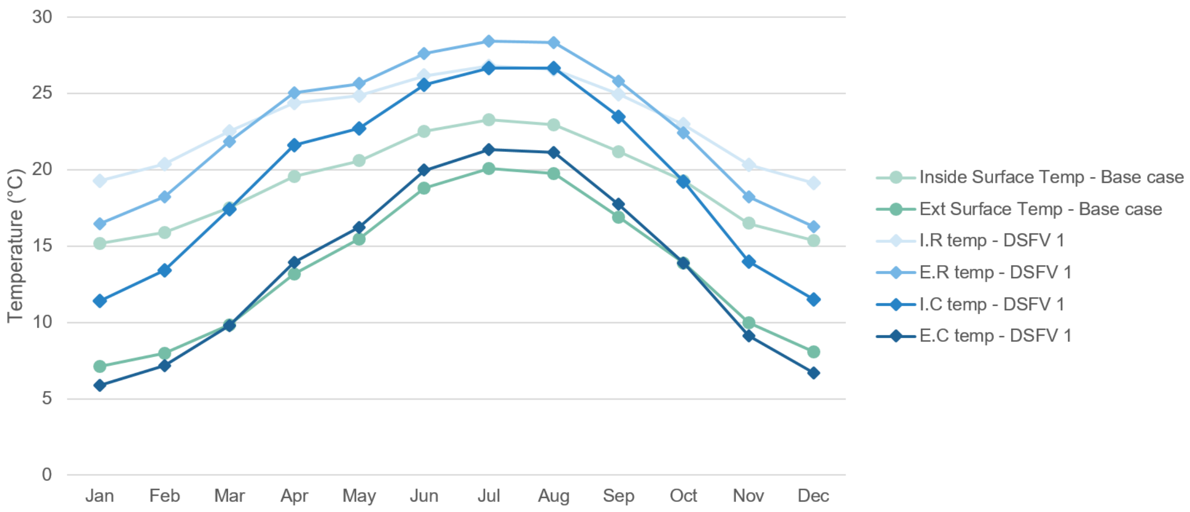


Figure 4.25 - Monthly surface temperature of glass pane - Base case and DSFV 1 - Window level

As for naturally ventilated façade, the I.R. temperature is higher than the base case throughout the year and E.C. temperature is higher than the base case in summer but lower in winter. Temperatures inside the cavity (E.R. and I.C. temperatures) have, again, a similar behavior. Furthermore, E.R. temperature of DSFV 1 is higher than I.R. of DSFV 1. Finally, the surfaces temperatures inside the cavity seem to be more sensitive to the climate regarding the peak in April.

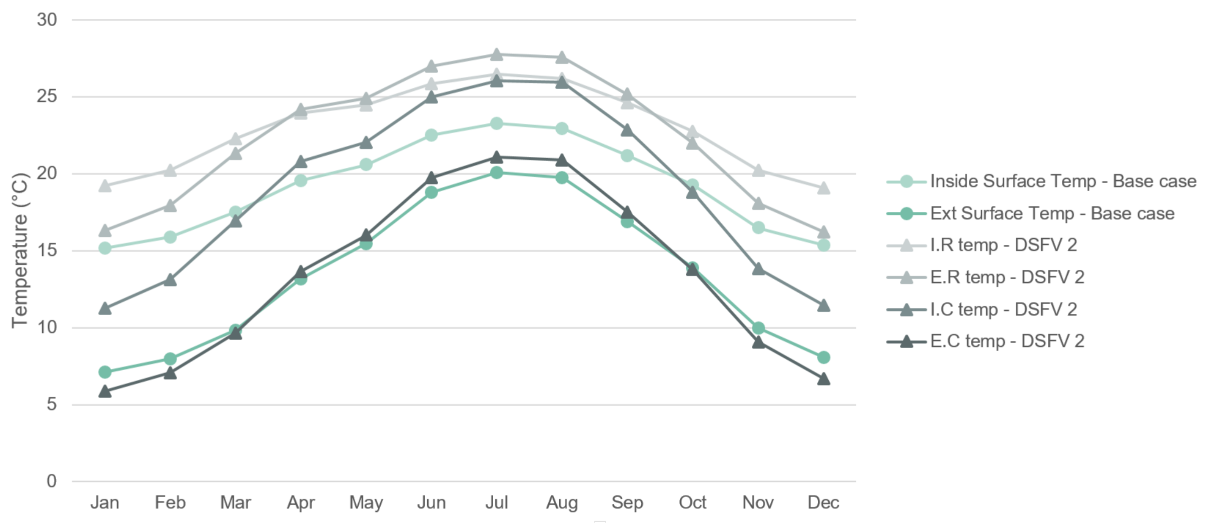


Figure 4.26 – Monthly surface temperature of glass pane – Base case and DSFV 2 - Window level

Figure 4.27 shows the extreme surface temperatures for base case and all double-skin ventilated façade cases. Their behavior is identical and the inside surface temperatures for double-skin ventilated façade are significantly higher than for the base case. In fact, these cases could have an inside surface temperature range that varies between 19 and 27°C for double skin with mechanical ventilation and between 19 and 26°C with hybrid ventilation while it varies between 15 and 23°C for the base case. The difference between inside and exterior surface temperatures is smaller for double skin façade in comparison to the base case. But this difference is less significant than seen previously for electrochromic and dynamic shading cases.

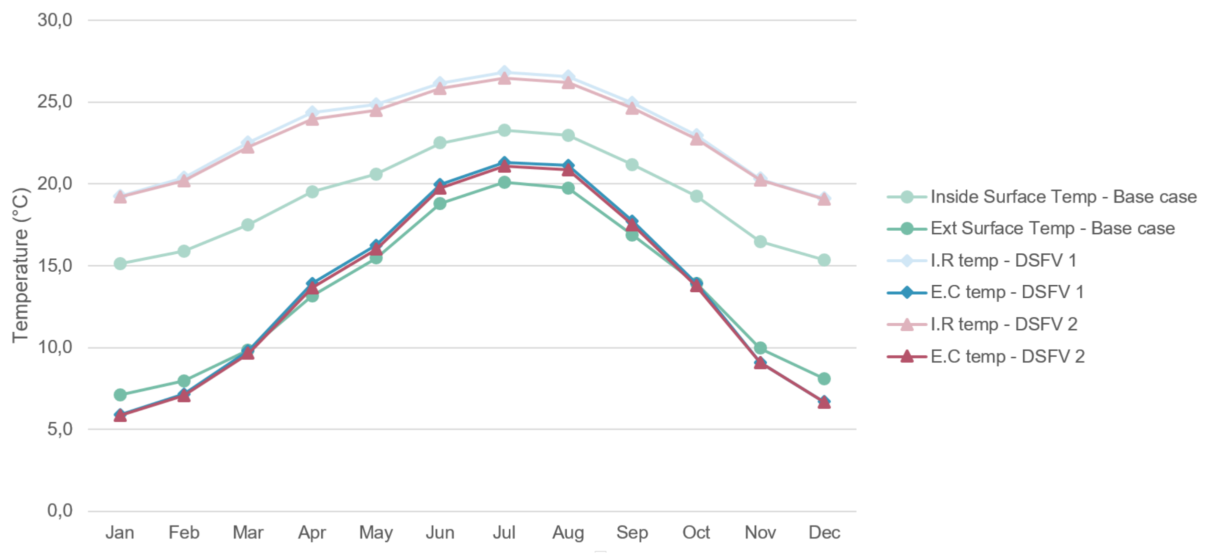


Figure 4.27 – Monthly surface temperature of glass pane – Base case and double skin ventilated facade cases – Window level

Solar radiation transmitted to the room is not changed from the previous section since there is still no shading device. This is shown on Figure 4.28.

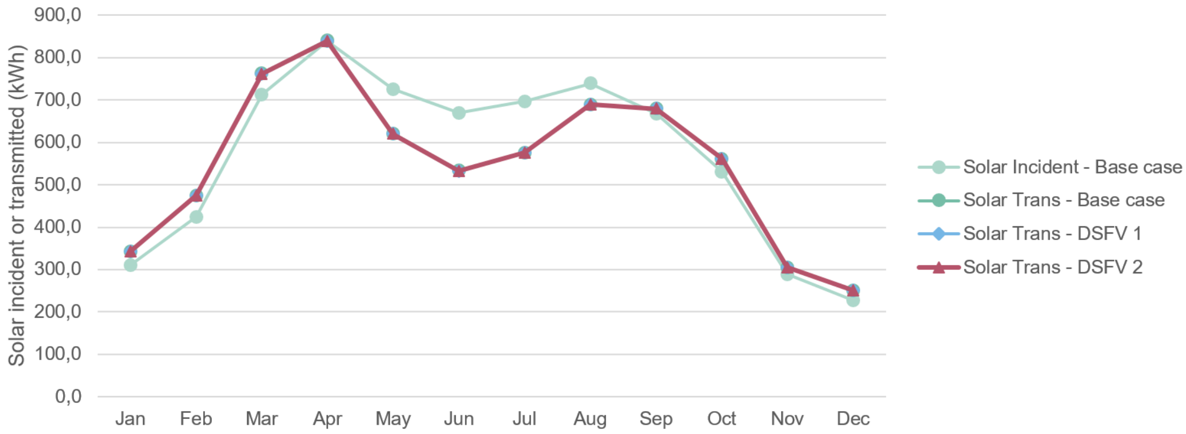


Figure 4.28 - Monthly solar radiation on the window - Base case and double skin ventilated facade cases - Window level

Finally, the Table 23 gathers the total energy loads. As seen on Table 22, a double-skin façade helps to improve the energy performance and natural ventilation increases even more the performances. There is no difference between naturally or mechanically ventilated double-skin façade. However, hybrid ventilation shows a better performance in terms of energy saving with 86,1% of the energy loads compared to the base case.

Table 23 – Resume of energy results – Base case and double skin ventilated façade cases

	Case	Base	Double skin ventilated facade	
	Name		DSFV 1	DSFV 2
	Control strategy	-	Mech. - OT	Hybrid - OT
Energy	**Threshold**	-	24°C	24°C
	Heating demand (kWh/year)	3804	2705	2723
	Heating loads reduction (%)	100,0	71,1	71,6
	Cooling demand (kWh/year)	5287	5329	5100
	Cooling loads reduction (%)	100,0	100,8	96,5
	Annual loads (kWh)	9091	8034	7823
	Total energy reduction (%)	100,0	88,4	86,1

4.5.2. Thermal comfort

Double-skin façade helps to improve thermal comfort performance (see Section 4.4.2). Table 24 gathers the discomfort hours of double skin façade with mechanical and hybrid ventilation. It shows that the difference between these two ventilation modes does not really affect the results. In fact, a double-skin façade helps to decrease discomfort hours with summer clothes and with summer and winter clothes.

Table 24 – Hours of discomfort – Base case and double skin ventilated façade cases

Case	Control strategy	Threshold	Hours of discomforts with winter clothes (h)	Hours of discomforts with summer clothes (h)	Hours of discomforts with winter or summer clothes (h)	Total hours of discomfort (h)	Thermal comfort reduction (%)
Base	-	-	2221	1282	704	4207	100,0
Double skin ventilated facade	Operative temp.	24°C	2196	1014	431	3641	86,5
	Operative temp.	24°C	2196	1014	432	3642	86,6

4.5.3. Visual comfort

Since the HVAC is the only system changed, the solar radiation transmitted to the room is same as the double-skin façade cases. The results for all double-skin façade, without and with ventilation, related to visual comfort are gathered in section 4.4.3.

5. Sensitivity and comparative analysis

This chapter gathers the results given by the sensitivity and comparative analysis.

5.1. Sensitivity analysis

Contrary to Chapter 4, the sensitivity results related to energy loads will only be shown for the entire year. This will help to point out to the correlation between parameters and energy loads and thermal comfort. Furthermore, visual comfort is not taken into account since the results are more qualitative. This is represented on Figure 5.1.

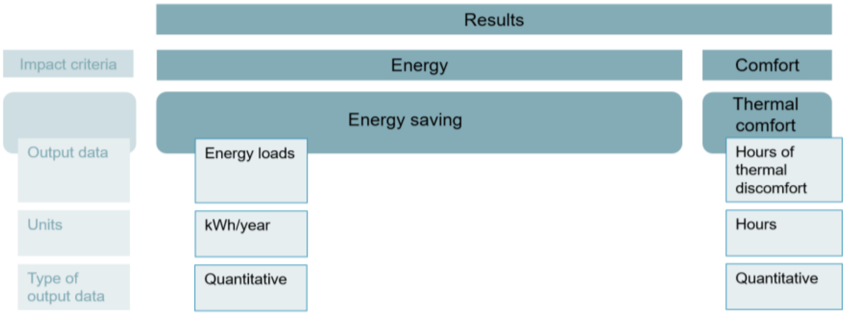


Figure 5.1 – Representation of results chosen given by DesignBuilder for sensitivity analysis

Additionally, the reference cases will be highlighted with clear color on each graph and table. First, these results are compared with the base case and then within the case studied, the variation is compared. It is assumed that *reference cases* are the cases studied in chapter 4. Then, tables are shown and will help to finally understand the value that should be chosen. On these tables, annual energy loads and total discomfort hours will be shown in a reduction percentage compared to the base case which is set to 100%. A more detailed methodology of the sensitivity analysis is made in Section 3.11.

5.1.1. Electrochromic case

Regarding the results concerning the electrochromic glazing cases in chapter 4, it can be concluded that ECW with *schedule control* (ECW 0) has the best performance related to energy loads and thermal comfort. However, the threshold of the control strategies could be varied.

ECW 1 – Solar threshold variation

Figure 5.2 below shows the correlation between energy loads and discomfort hours and the solar threshold of the solar control strategy case. As shown, the solar threshold has an important impact on the cooling demand and small impact on the thermal comfort. The reference case studied displays some good performance.

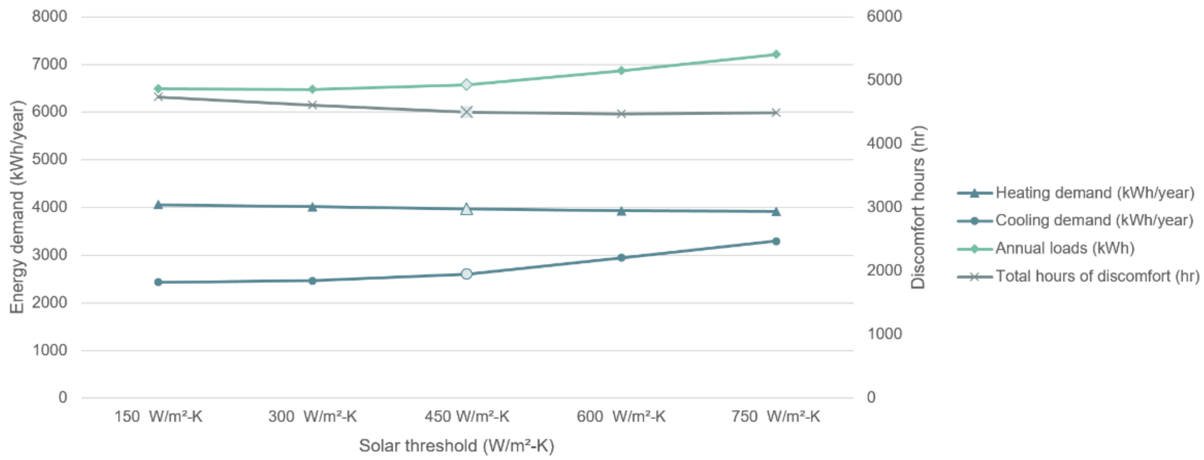


Figure 5.2 – Sensitivity analysis – ECW 1 – Solar threshold

Table 25 gathers the main output data of this sensitivity analysis. By applying a solar threshold of 150 W/m²-K, the energy loads decrease and by comparing it with the results obtained in chapter 4 (see Table 17). ECW 1 could have better results than ECW 0. The discomfort hours increase by more than 10%. According to this table, the reference case seems to stay the best compromise.

Table 25 – Sensitivity analysis – ECW 1 – solar threshold variation improvement

Diminutive	Case	Fixed paramet	Parameter varied	Annual loads (kWh)	Total loads reduction %	Total hours of discomfort (hr)	Thermal comfort reduction %
Sensitivity analysis : electrochromic - Solar threshold							
Base case	Base	-	-	9091	100,0	4207	100,0
ECW1-s150	Electrochromic	Optical properties	150 W/m²-K	6489	71,4	4740	112,7
ECW1-s300			300 W/m²-K	6480	71,3	4611	109,6
ECW1			450 W/m²-K	6570	72,3	4500	107,0
ECW1-s600			600 W/m²-K	6872	75,6	4475	106,4
ECW1-s750			750 W/m²-K	7213	79,3	4493	106,8

ECW 2 – Operative temperature threshold variation

Figure 5.3 displays the results of the sensitivity analysis of the operative temperature control strategy for electrochromic glazing when varying the operative temperature threshold. It reflects that the thermal threshold does not have a serious impact on the energy consumption except for the thermal threshold of 26°C. However, it is assumed that the indoor temperature is appreciated between 21 and 25,5°C (Bureau de Normalisation, 2007). Thus, 26°C seems to be a too high threshold even if it is in relation to the operative temperature and not to the indoor temperature. The thermal comfort is also relatively the same for the different thermal thresholds.

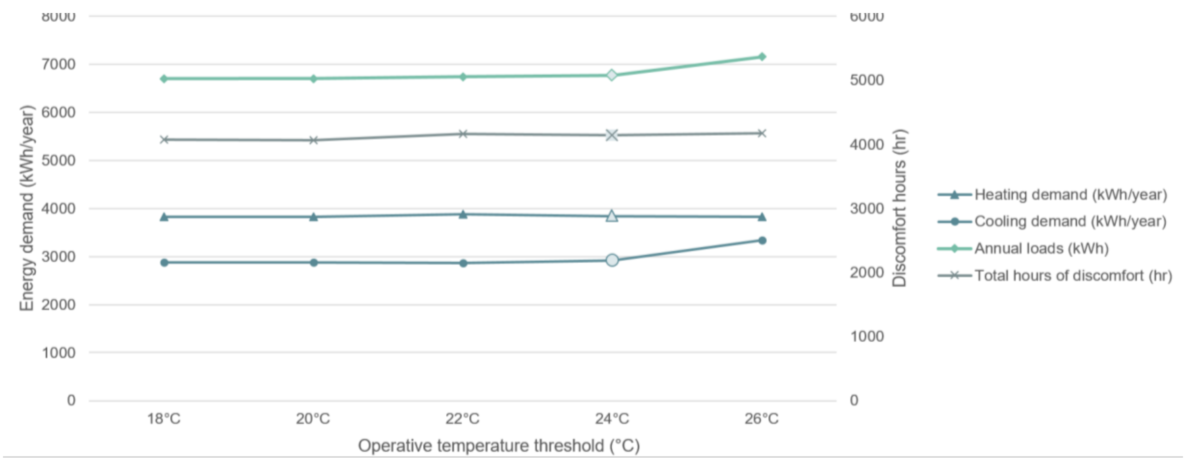


Figure 5.3 – Sensitivity analysis – ECW 2 – Operative temperature threshold

Table 26 below resumes the main results of this sensitivity analysis. Applying a thermal threshold of 20°C is the best option regarding the energy consumption and thermal comfort. Nevertheless, it can be observed that the thermal comfort variation is less than 3% and the energy consumption difference is less than 1% between 18 and 24°C compared to the reference case.

Table 26 – Sensitivity analysis – ECW 2 – thermal threshold variation improvement

Diminutive	**Case**	**Fixed paramet**	**Parameter varied**	**Annual loads (kWh)**	**Total loads reduction %**	**Total hours of discomfort (hr)**	**Thermal comfort reduction %**
Sensitivity analysis : electrochromic - Operative temperature threshold							
Base case	Base	-	-	9091	100,0	4207	100,0
ECW2-t18	Electrochromic	Optical properties	18°C	6705	73,8	4074	96,8
ECW2-t20			20°C	6704	73,7	4070	96,7
ECW2-t22			22°C	6741	74,2	4164	99,0
ECW2			24°C	6767	74,4	4140	98,4
ECW2-t26			26°C	7157	78,7	4177	99,3

5.1.2. Dynamic shading case

As for the electrochromic case in chapter 4, the *dynamic shading with schedule control* (DS 0) has the best performance regarding energy loads but *dynamic shading with operative temperature control* (DS 2) has the best performance related to thermal comfort. However, the thresholds and slats properties can vary and change the results.

DS 1 – Solar threshold variation

The sensitivity of control strategies' thresholds have also been investigated. The solar threshold has a significant impact on the energy loads and especially on the cooling demand. Actually, the lower the solar threshold is the lower the energy loads are and the higher are the discomfort hours. The correlation is not linear as it can be seen on Figure 5.4. Higher values of solar threshold were not investigated since the performance is worse for higher values.

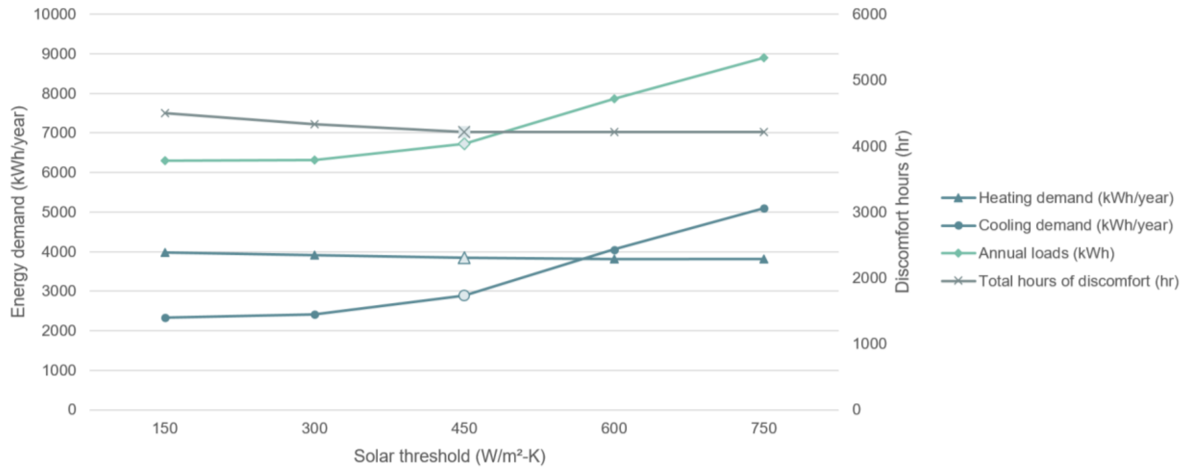


Figure 5.4 – Sensitivity analysis – DS 1 – Solar threshold

Table 27 helps to determine the most efficient solar threshold which is 300W/m²-K. Actually, this value seems to be the best compromise between energy consumption and thermal comfort. The annual energy loads can vary from 28,7% between 150W/m²-K and 750W/m²-K as solar threshold.

Table 27 – Sensitivity analysis – DS 1 – solar threshold variation improvement

Diminutive	Case	Fixed paramet	Parameter varied	Annual loads (kWh)	Total loads reduction %	Total hours of discomfort (hr)	Thermal comfort reduction %
Sensitivity analysis : dynamic shading - solar threshold							
Base case	Base	-	-	9091	100,0	4207	100,0
DS2-s150	Dynamic shading	Slat properties	150 W/m²-K	6294	69,2	4502	107,0
DS2-s300			300 W/m²-K	6322	69,5	4337	103,1
DS2			450 W/m²-K	6726	74,0	4212	100,1
DS2-s600			600 W/m²-K	7858	86,4	4214	100,2
DS2-s750			750 W/m²-K	8901	97,9	4210	100,1

DS 2 – Operative temperature threshold variation

Figure 5.5 presents the sensitivity analysis results of the operative temperature threshold variation of the dynamic shading case. The differences are really small and almost continuous for thermal comfort and energy consumption. Thus it is assumed that the dynamic shading case is not sensitive to this variation.

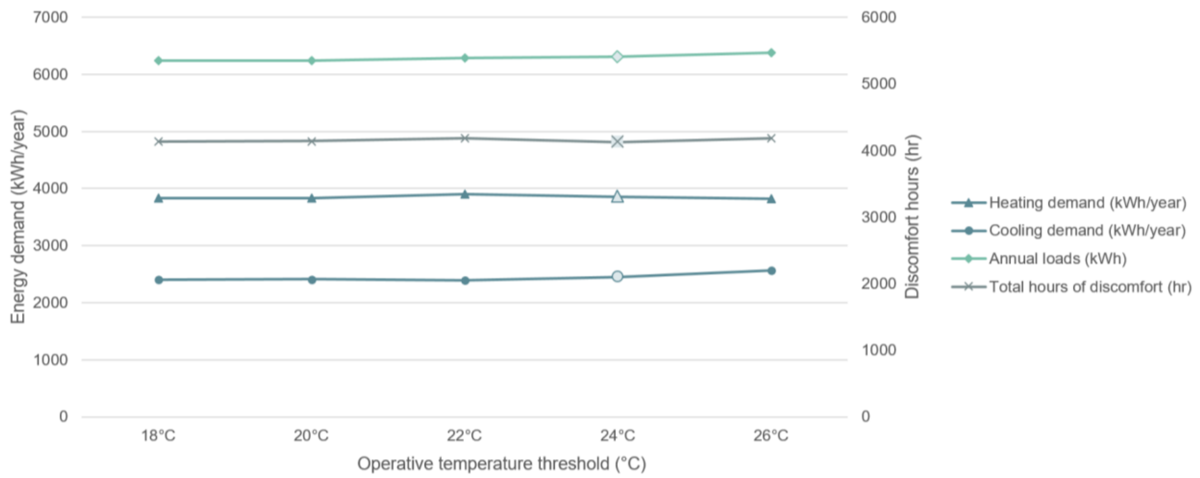


Figure 5.5 – Sensitivity analysis – DS 2 – Operative temperature threshold

This is confirmed with the Table 28 below which gathers the main output data of this sensitivity analysis. The difference between the thermal thresholds chosen is less than 2% for both energy demand and thermal comfort.

Table 28 – Sensitivity analysis – DS 2 – thermal threshold variation improvement

Diminutive	Case	Fixed paramet	Parameter varied	Annual loads (kWh)	Total loads reduction %	Total hours of discomfort (hr)	Thermal comfort reduction %
Sensitivity analysis : Dynamic shading - Operative temperature threshold							
Base case	Base	-	-	9091	100,0	4207	100,0
DS2-t18	Dynamic shading	Slat properties	18°C	6242	68,7	4139	98,4
DS2-t20			20°C	6243	68,7	4140	98,4
DS2-t22			22°C	6291	69,2	4187	99,5
DS2			24°C	6308	69,4	4127	98,1
DS2-t26			26°C	6386	70,2	4185	99,5

DS 2 – Slat angle variation

Geometrical properties and the position of the slats are analyzed.

On Figure 5.6, it appears that the slat angle does not have an important impact on the energy consumption and thermal comfort. The line seems to be totally straight which agrees with the Table 29 below.

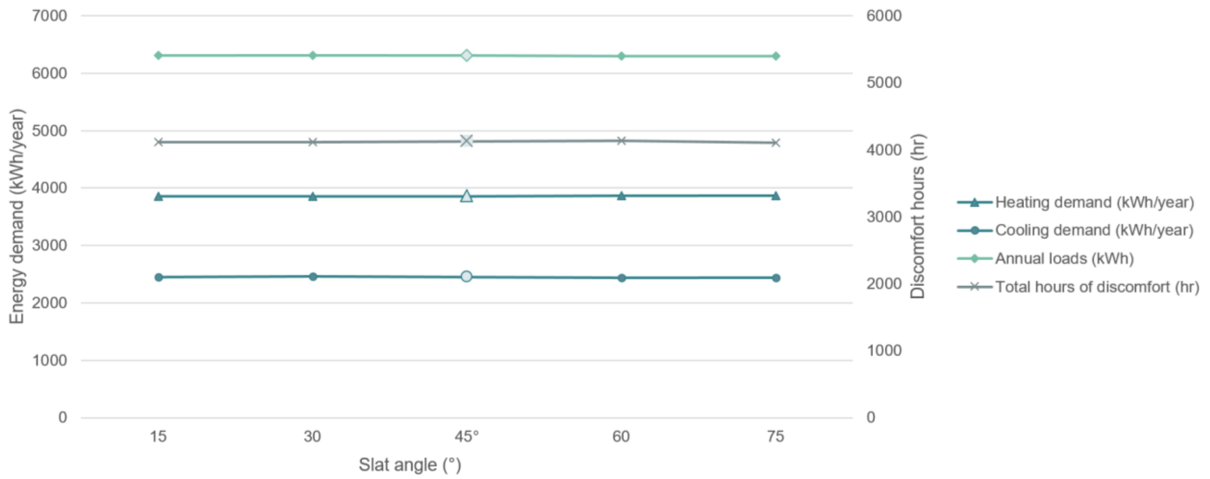


Figure 5.6 – Sensitivity analysis – DS 2 – Slat angle

Table 29 – Sensitivity analysis – DS 2 – Slat angle variation improvement

Diminutive	Case	Fixed paramet	Parameter varied	Annual loads (kWh)	Total loads reduction %	Total hours of discomfort (hr)	Thermal comfort reduction %
Sensitivity analysis : dynamic shading - slat angle							
Base case	Base	-	-	9091	100,0	4207	100,0
DS2-a15	Dynamic shading	OT - Threshold = 24°C, BtG, slat width, slat separation	15°	6309	69,4	4112	97,7
DS2-a30			30°	6317	69,5	4116	97,8
DS2			45°	6308	69,4	4127	98,1
DS2-a60			60°	6301	69,3	4140	98,4
DS2-a75			75°	6298	69,3	4104	97,6

DS 2 – Slat separation variation

Figure 5.7 displays the correlation between the slat separation variation of the dynamic shading device and the energy loads and thermal comfort. In this way, the slat separation does not have a significant influence on the impact criteria. However, it appears that the cooling loads increase when the salt separation is really high.

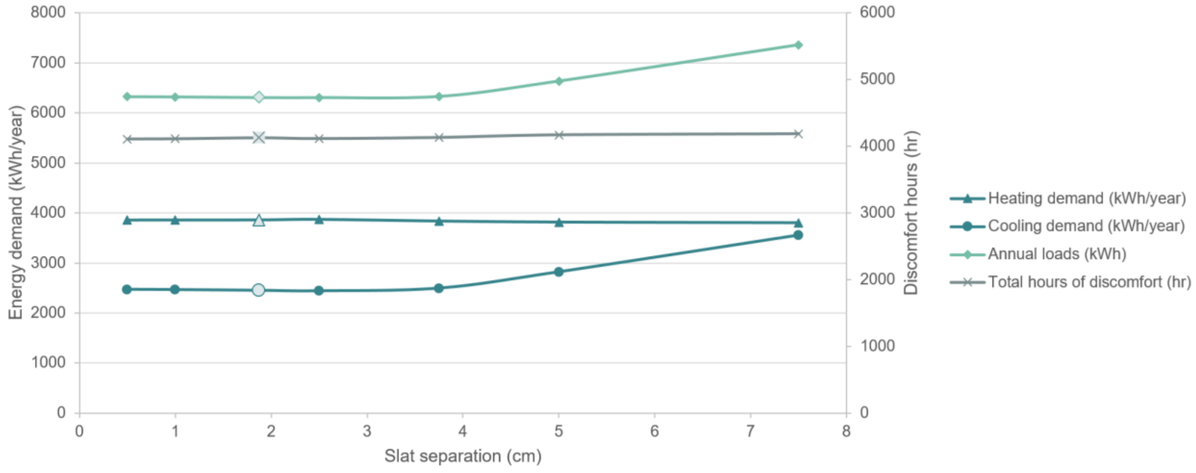


Figure 5.7 – Sensitivity analysis – DS 2 – Slat separation

Table 30 gathers the results of this sensitivity analysis. It indicates that the variation influences thermal comfort and energy consumption with less than 1% until a slat separation of 5 cm. Thus, the settings of the reference case are kept.

Table 30 – Sensitivity analysis – DS 2 – Slat separation variation improvement

Diminutive	Case	Fixed paramet	Parameter varied	Annual loads (kWh)	Total loads reduction %	Total hours of discomfort (hr)	Thermal comfort reduction %
Sensitivity analysis : dynamic shading - slat separation							
Base case	Base	-	-	9091	100,0	4207	100,0
DS2-p005	Dynamic shading	OT - Threshold = 24°C, S_a , BtG, slat width	0,5 cm	6325	69,6	4110	97,7
DS2-p010			1 cm	6321	69,5	4113	97,8
DS2			1,875 cm	6308	69,4	4127	98,1
DS2-p025			2,5 cm	6308	69,4	4116	97,8
DS2-p0375			3,75 cm	6331	69,6	4133	98,2
DS2-p050			5 cm	6638	73,0	4171	99,1
DS2-p075			7,5 cm	7361	81,0	4187	99,5

DS 2 – Slat width variation

The width of the slat can vary. This variation influences the energy loads and especially the cooling loads. If the slats are too thin the cooling energy loads increase significantly. This is shown on Figure 5.8. However, the width does not have an important impact on thermal comfort.

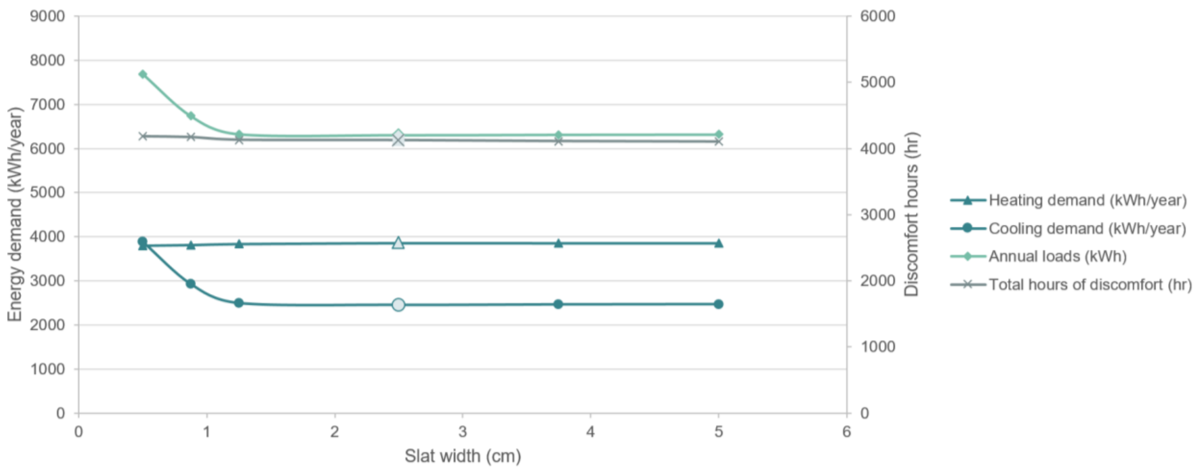


Figure 5.8 – Sensitivity analysis – DS 2 – Slat width

The Table 31 below gathers the main output data of the slat variation of DS 2 and its influence on the energy loads and the thermal comfort. Thus, by changing the slat width from 0,5 cm to 5 cm, the annual loads decrease by more than 15% but the thermal comfort varies with less than 2%.

Table 31 – Sensitivity analysis – DS 2 – Slat width variation improvement

Diminutive	Case	Fixed paramet	Parameter varied	Annual loads (kWh)	Total loads reduction %	Total hours of discomfort (hr)	Thermal comfort reduction %
Sensitivity analysis : dynamic shading - slat width							
Base case	Base	-	-	9091	100,0	4207	100,0
DS2-w0,5	Dynamic shading	OT - Threshold = 24°C, S_a, BtG, slat separation	0,5	7689	84,6	4185	99,5
DS2-w0,875			0,875	6740	74,1	4173	99,2
DS2-w1,25			1,25	6329	69,6	4132	98,2
DS2			2,5	6308	69,4	4127	98,1
DS2-w3,75			3,75	6317	69,5	4112	97,7
DS2-w5,00			5	6322	69,5	4104	97,6

DS 2 – Slat Blind-to-glass distance variation

Finally, the last sensitivity analysis is made for the dynamic shading case concerning with Blind-to-glass distance of the slat. The Figure 5.9 presents the energy loads and discomfort hours related to this sensitivity analysis. There are no significant influences of this parameter. However, it seems that too small distance induces a little higher cooling demand and thus higher annual energy loads.

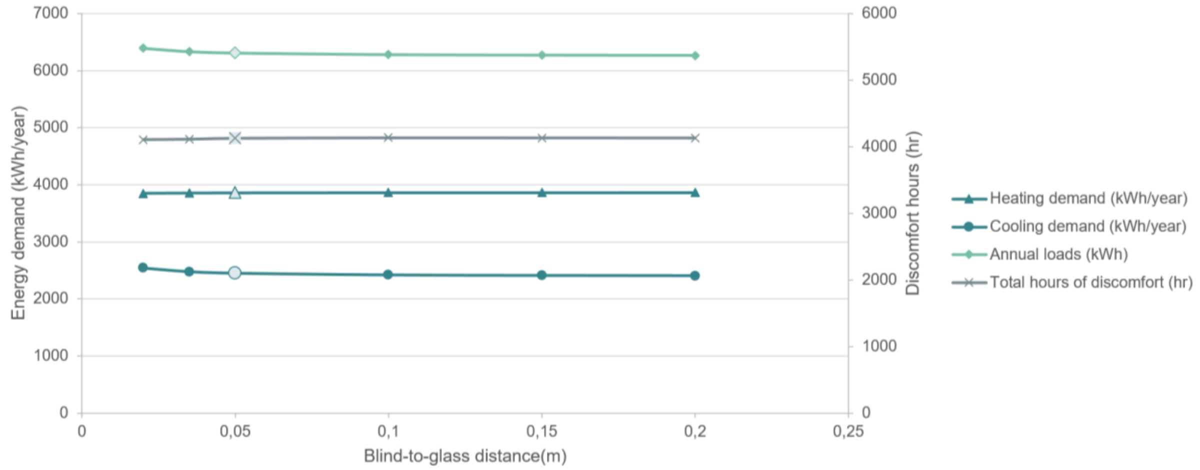


Figure 5.9 – Sensitivity analysis – DS 2 – Blind-to-glass distance of the slat

Table 32 below resumes the output data of the variation of this parameter. The difference in energy demand is less than 2% and less than 1% on discomfort hours.

Table 32 – Sensitivity analysis – DS 2 – Slat width variation improvement

Diminutive	Case	Fixed paramet	Parameter varied	Annual loads (kWh)	Total loads reduction %	Total hours of discomfort (hr)	Thermal comfort reduction %
Sensitivity analysis : dynamic shading - Blind-to-glass distance							
Base case	Base	-	-	9091	100,0	4207	100,0
DS2-b02	Dynamic shading	OT - Threshold = 24°C, S_a, slat width, slat separation	0,02	6392	70,3	4106	97,6
DS2-b035			0,035	6332	69,7	4112	97,7
DS2			0,05	6308	69,4	4127	98,1
DS2-b10			0,1	6280	69,1	4135	98,3
DS2-b15			0,15	6271	69,0	4134	98,3
DS2-b20			0,2	6267	68,9	4133	98,2

5.1.3. Double-skin façade

According to the results given for the double-skin façade in chapter 4, it appears that *double-skin façade with schedule control* (DSF 1) has the best performance related to energy loads and *double skin façade with operative temperature control* (DSF 2) has the best performance related to thermal comfort. However, it is assumed that the schedule could not be varied in this study since the analysis is made for office buildings. But the threshold of the other control strategies and properties of the double-skin façade could vary.

DSF 2 – Cavity depth variation

In Figure 5.10, the correlation between energy demand and thermal comfort and the cavity depth is represented. It can be seen that the cavity depth is a really important parameter. As shown, the larger the cavity is, the smaller are the energy loads and especially the cooling loads. Cavity depth influences very poorly the heating demand and the thermal comfort.

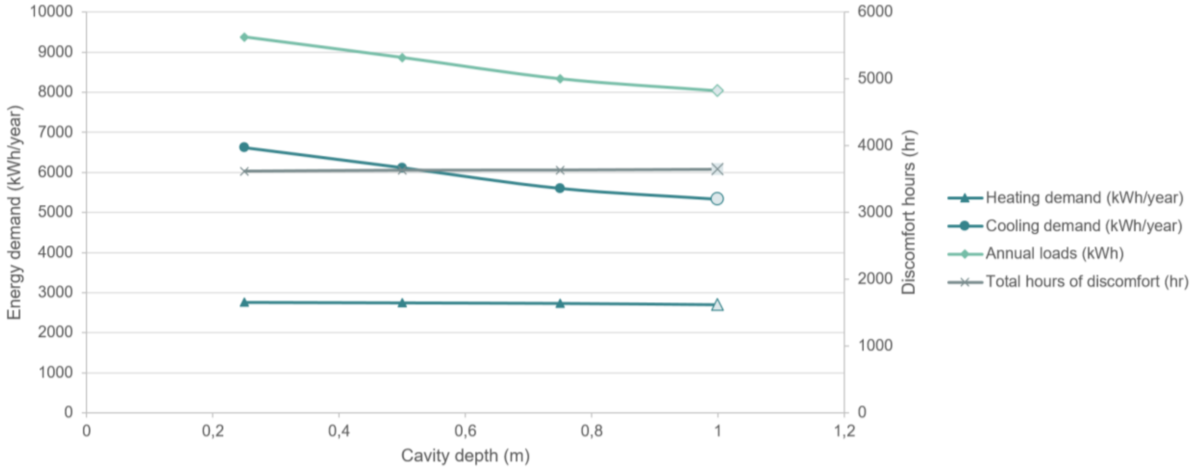


Figure 5.10 – Sensitivity analysis – DSF 2 – Cavity depth

Table 33 below gathers the output data and relative data of the sensitivity analysis. Thermal comfort is poorly influenced and energy consumption can decrease by 14,8% from a variation of 1m to 0,25m of the cavity depth. If the cavity is larger, the annual loads will decrease more. However, a cavity of 1m is often used in construction and Alberto investigates these values in his study (Alberto, Ramos, & Almeida, 2017). Thus, the cavity depth of the reference case is kept (1m).

Table 33 – Sensitivity analysis – DSF 2 – Cavity depth variation improvement

Diminutive	Case	Ventilation mode	Fixed parameters	Parameter varied	Annual loads (kWh)	Total loads %	Total hours of discomfort (hr)	Thermal comfort reduction %
Sensitivity analysis : Double skin facade - natural ventilation - cavity depth								
Base case	Base	-	-	-	9091	100,0	4207	100,0
DSF2-c1	Double skin facade	Natural	T_n=24°C; 5ac/h	1	8033	88,4	3644	86,6
DSF2-c0,75		Natural		0,75	8334	91,7	3635	86,4
DSF2-c0,5		Natural		0,5	8865	97,5	3632	86,3
DSF2-c0,25		Natural		0,25	9378	103,2	3618	86,0

DSF 2 – Operative temperature threshold

According to Figure 5.11, the thermal threshold of natural ventilation does not impact the thermal comfort or the energy demand. The Table 34 below resumes the output data of the variation of this parameter and confirms an increase of less than 0,5% for energy demand and thermal comfort from 18 to 26°C.

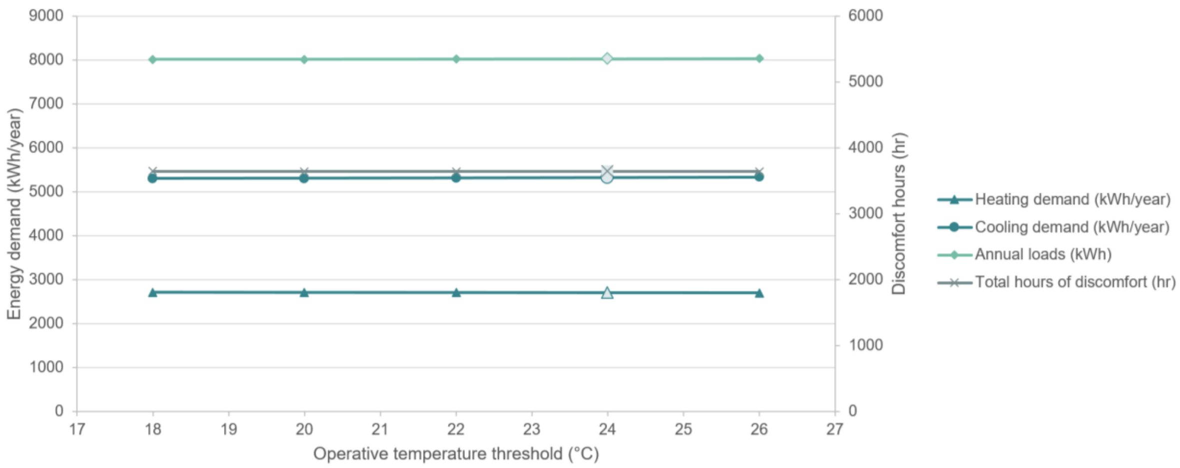


Figure 5.11 – Sensitivity analysis – DSF 2 –thermal threshold

Table 34 – Sensitivity analysis – DSF 2 – thermal threshold

Diminutive	Case	Ventilation mode	Fixed parameters	Parameter varied	Annual loads (kWh)	Total loads %	Total hours of discomfort (hr)	Thermal comfort reduction %
Sensitivity analysis : Double-skin facade - temperature threshold								
Base case	Base	-	-	-	9091	100,0	4207	100,0
DSF2-t18	Double skin ventilated facade	Natural	Cavity depth 1m,	18	8022	88,2	3649	86,7
DSF2-t20		Natural		20	8023	88,3	3646	86,7
DSF2-t22		Natural		22	8028	88,3	3644	86,6
DSF2		Natural		24	8033	88,4	3644	86,6
DSF2-t26		Natural		26	8042	88,5	3645	86,6

5.1.4. Double-skin ventilated façade

As seen in the previous chapter, *double-skin façade with hybrid ventilation* (DSFV 2) gives the best performance related to energy. The thermal comfort is improved when applying *mechanical* (DSFV 1) or *hybrid ventilation* but the difference between the two cases can be neglected. However, these results can be linked to some parameters. Thus, the parameters studied are the mechanical airflow and the thermal threshold.

DSFV 1 – Mechanical airflow

The following Figure 5.12 helps to understand the influence of the mechanical airflow on the energy demand and the thermal comfort. As represented, the energy demand and especially cooling loads, decrease by applying higher airflow rate inside the cavity. Thermal comfort seems to be unaffected.

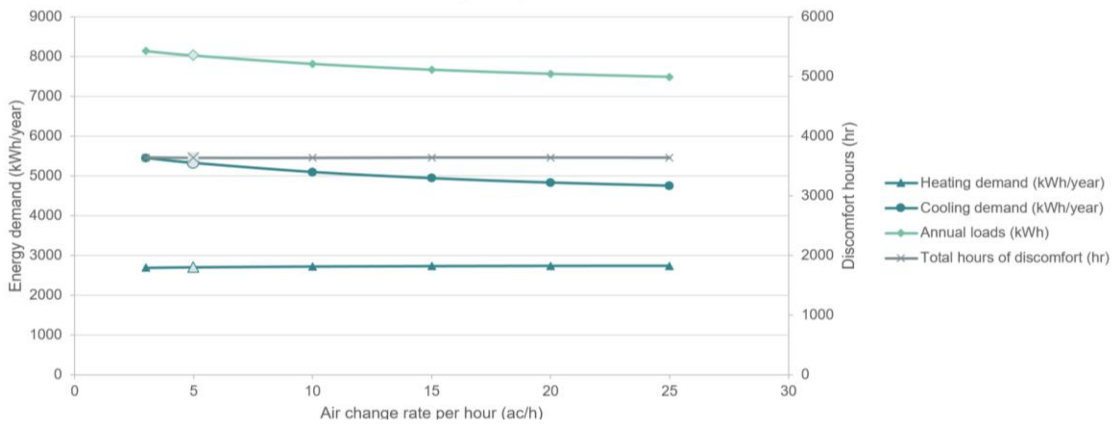


Figure 5.12 – Sensitivity analysis – DSFV 1 – mechanical airflow

Table 35 below gathers the results of the annual energy demand and thermal comfort. The higher the airflow rate is, the lower are the annual loads. Actually, this energy demand can vary from 7,2% for an airflow rate between 3 and 25 ac/h. The thermal comfort is not influenced by airflow rate since the difference is less than 0,2% between 3 and 25 ac/h.

Table 35 – Sensitivity analysis – DSFV 1 – mechanical airflow

Diminutive	Case	Ventilation mode	Fixed parameters	Parameter varied	Annual loads (kWh)	Total loads %	Total hours of discomfort (hr)	Thermal comfort reduction %
Sensitivity analysis : DSF mechanical ventilation - mechanical flow ventilation								
Base case	Base	-	-	-	9091	100,0	4207	100,0
DSFV1-f3	Double skin ventilated facade	Mechanical	Cavity depth 1m, T_m=24°C	3	8147	89,6	3646	86,7
DSFV1		Mechanical		5	8034	88,4	3641	86,5
DSFV1-10		Mechanical		10	7823	86,1	3641	86,5
DSFV1-f15		Mechanical		15	7676	84,4	3645	86,6
DSFV1-f20		Mechanical		20	7571	83,3	3645	86,6
DSFV1-f25		Mechanical		25	7495	82,4	3644	86,6

DSFV 1 – Operative temperature threshold

Figure 5.13 presents the sensitivity analysis results of thermal threshold variation for the mechanically ventilated double-skin façade. The influence is really small and almost continuous for thermal comfort and energy consumption. Thus, it is assumed that this case is not sensitive to the variation of the operative temperature control thresholds.

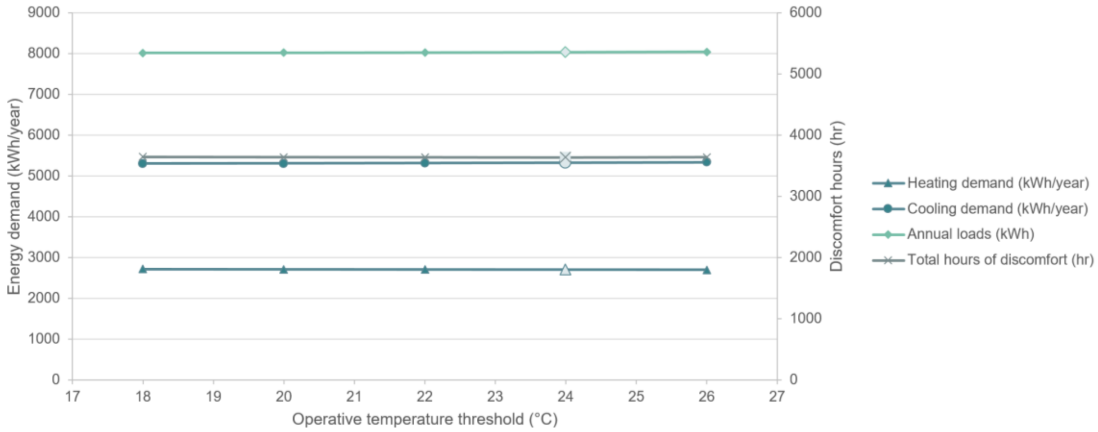


Figure 5.13 – Sensitivity analysis – DSFV 1 – Thermal threshold

The Table 36 confirms it since the percentage of the energy consumption and thermal comfort presents a poor reduction.

Table 36 – Sensitivity analysis – DSFV 1 – thermal threshold

Diminutive	Case	Ventilation mode	Fixed parameters	Parameter varied	Annual loads (kWh)	Total loads %	Total hours of discomfort (hr)	Thermal comfort reduction %
Sensitivity analysis : mechanical ventilation - temperature threshold								
Base case	Base	-	-	-	9091	100,0	4207	100,0
DSFV1-t18	Double skin ventilated facade	Mechanical	Cavity depth 1m, 5ac/h	18	8023	88,3	3649	86,7
DSFV1-t20		Mechanical		20	8024	88,3	3646	86,7
DSFV1-t22		Mechanical		22	8028	88,3	3644	86,6
DSFV1		Mechanical		24	8034	88,4	3641	86,5
DSFV1-t26		Mechanical		26	8043	88,5	3646	86,7

DSFV 2 – Mechanical air flow of hybrid ventilation

As for the mechanical ventilation, the airflow rate has been investigated. Figure 5.14 shows the results of this sensitivity analysis and displays the correlation between the mechanical airflow rate of the hybrid ventilation and the impact criteria.

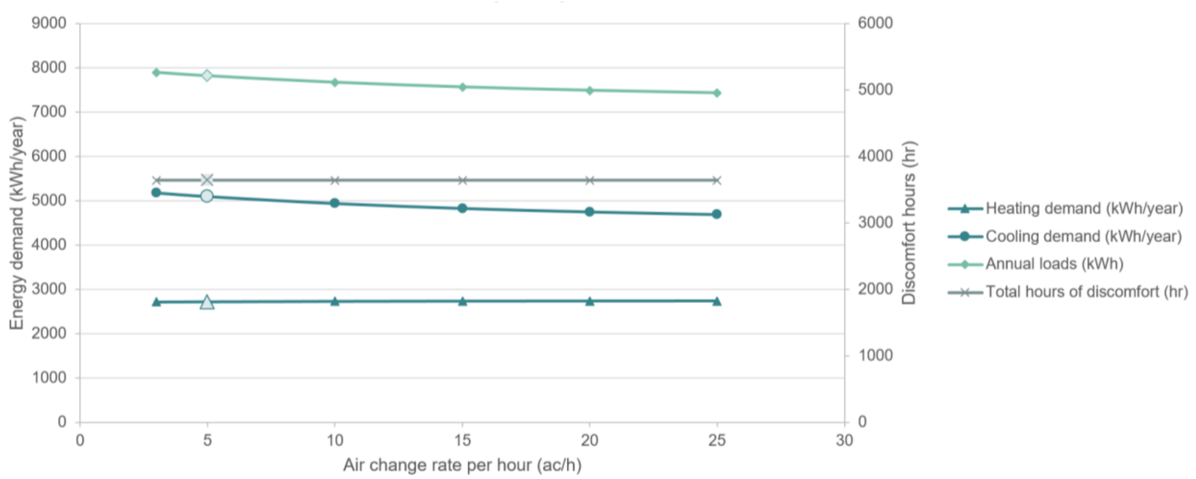


Figure 5.14 – Sensitivity analysis – DSFV 2 – Airflow rate

Contrary to the mechanical ventilation case, the influence is smaller with an energy demand that varies from 5,1% between 3 and 25 ac/h against 7,2% for the mechanical ventilation. Changing the airflow rate does not induce a difference related to the discomfort hours. The relative data of this sensitivity analysis are given in Table 37. The performance is improved for high airflow rate.

Table 37 – Sensitivity analysis – DSFV 2 – Airflow rate

Diminutive	Case	Ventilation mode	Fixed parameters	Parameter varied	Annual loads (kWh)	Total loads %	Total hours of discomfort (hr)	Thermal comfort reduction %
Sensitivity analysis : hybrid ventilation - temperature threshold								
Base case	Base	-	-	-	9091	100,0	4207	100,0
DSFV2-t18	Double skin ventilated facade	Hybrid	Cavity depth 1m, 5ac/h	18	7799	85,8	3644	86,6
DSFV2-t20		Hybrid		20	7802	85,8	3642	86,6
DSFV2-t22		Hybrid		22	7811	85,9	3644	86,6
DSFV2		Hybrid		24	7823	86,1	3642	86,6
DSFV2-t26		Hybrid		26	7838	86,2	3645	86,6

DSFV 2 – Operative temperature threshold

Finally, the last sensitivity analysis is made on the operative temperaturel threshold variation but for the double-skin façade with hybrid ventilation. As seen before, the thermal threshold for *naturally ventilated* (DSF 2) and *mechanically ventilated double-skin façade* (DSFV 1) does not impact the energy consumption or the thermal comfort. Thus, it is assumed that the results will follow the same behavior for the hybrid ventilation case. Thereby, the thermal threshold will be changed together which means 18°C for both natural and mechanical thermal threshold, then 20°C for both natural and mechanical thermal threshold, etc.

The Figure 5.15 above shows the results of this variation for energy consumption and thermal comfort. The operative temperature threshold has a poor influence on these results. Furthermore, the Table 38 gathers the numerical results of this sensitivity analysis. The relative energy consumption varies from 5,1% between 3 and 25 ac/h while thermal comfort does not change.

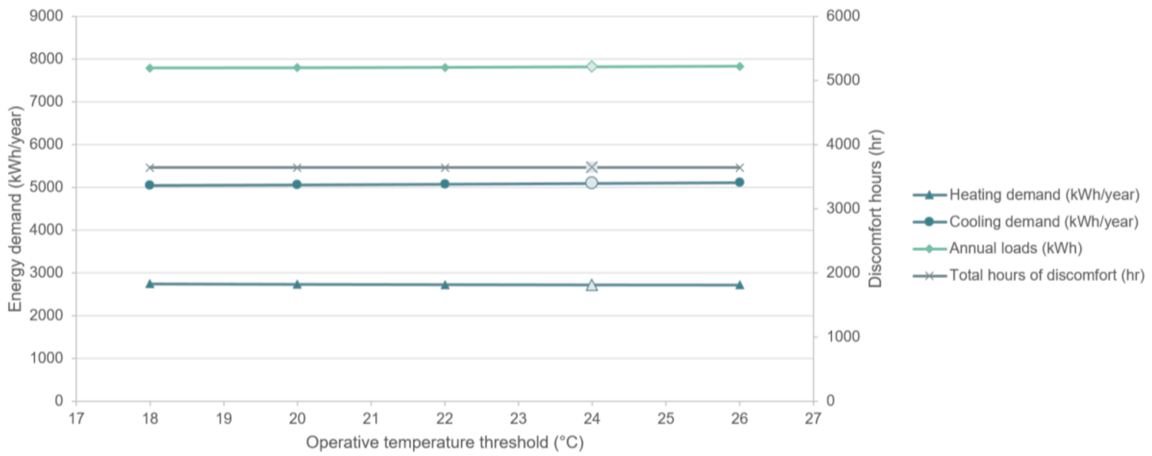


Figure 5.15 – Sensitivity analysis – DSFV 2 – Thermal threshold

Table 38 – Sensitivity analysis – DSFV 2 – thermal threshold

Diminutive	Case	Ventilation mode	Fixed parameters	Parameter varied	Annual loads (kWh)	Total loads %	Total hours of discomfort (hr)	Thermal comfort reduction %
Sensitivity analysis : mechanical ventilation - mechanical flow ventilation								
Base case	Base	-	-	-	9091	100,0	4207	100,0
DSFV2-f3	Double skin ventilated facade	Hybrid	Cavity depth 1m, T_m=24°C	3	7899	86,9	3644	86,6
DSFV2		Hybrid		5	7823	86,1	3642	86,6
DSFV2-f10		Hybrid		10	7676	84,4	3644	86,6
DSFV2-f15		Hybrid		15	7571	83,3	3645	86,6
DSFV2-f20		Hybrid		20	7495	82,4	3643	86,6
DSFV2-f25		Hybrid		25	7438	81,8	3644	86,6

5.2. Comparison analysis

This section gathers the comparative analysis results. First, the influential parameters pointed out by the sensitivity analysis are shown and explained. Then the comparative analysis is presented.

5.2.1. Influential parameters

After the investigation of the influence of parameters, it is possible to compare the different cases to each other. In this thesis, some parameters are influential but not taken into consideration: either because the reference cases are better or because the difference with the best variation value is less than 1%.

The Figure 5.16 below presents the parameters that are taken into account. As seen, there are only three influential parameters.

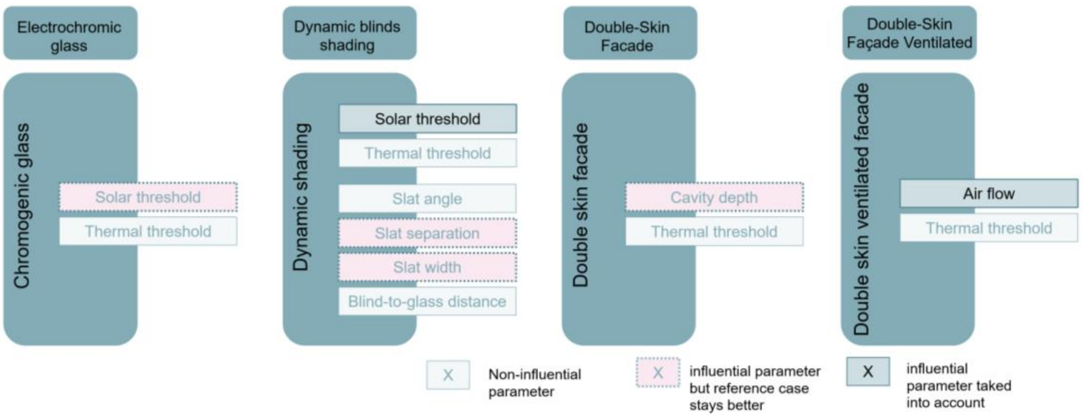


Figure 5.16 – Influential parameters taken into account in the comparative analysis

According to sensitivity analysis, some parameters are influential but in the extremes value of the variation. Most of the time, these extreme values display worse performances except for the cavity depth and the air flow variation which showed better performances for larger depth and higher air flow rate respectively. However, a cavity or the mechanical air flow could not be infinite. Thus the extremes values are fixed to the one chosen in the sensitivity analysis.

Changed values are given by Table 39. Thereby, there are three study cases that were changed.

Table 39 – Sensitivity analysis – DSFV 2 – thermal threshold

Family case	Parameter	Reference case	Reference value	Sensitivity analysis case	Value
Dynamic shading	Solar thresold	DS1	450 W/m²	DS1-s300	300 W/m²
Double-skin façade	Air flow rate	DSFV1	5 ac/h	DSFV1-f25	25 ac/h
Double-skin façade	Air flow rate	DSFV2	5 ac/h	DSFV2-f25	25 ac/h

5.2.2. Comparative analysis results

The comparative analysis is made for all the subcases of each family. The Figures below gather the relative results compared to the base case after taking into account the influential parameters. The percentage corresponding to 100% is highlighted to differentiate when a subcase has worse performance than the base case.

The Figure 5.17 shows the relative energy performance of each case and their control strategies by taking into account the sensitivity analysis. As seen, dynamic shading followed by electrochromic glazing cases help to improve the energy consumption. *Dynamic shading with schedule control* (DS 0) indicates the best energy performance with 68,7% compared to the base case. For the electrochromic cases, the *solar control strategy* (ECW 1) reveals the greatest energy performance with 72,3% compared to the base case. Finally, the double-skin façade helps to decrease the energy demand but with a smaller impact than electrochromic and dynamic shading cases. However, the leading cases are *double-skin façade with schedule control* (DSF 1) and *double-skin façade with hybrid ventilation* (DSFV 2) with respectively 87,2% and 84,2% of the energy consumption compared to the base case. This comes from the fact that double-skin façades mostly influence the heating loads which are lower than the cooling loads. Thus the impact is smaller too since the cooling loads take a larger part of the total loads. On the contrary, the dynamic shading and electrochromic glazing technologies influence mostly the cooling loads. In general adaptive façade studies will always improve the energy performance if the control strategy is smartly chosen.

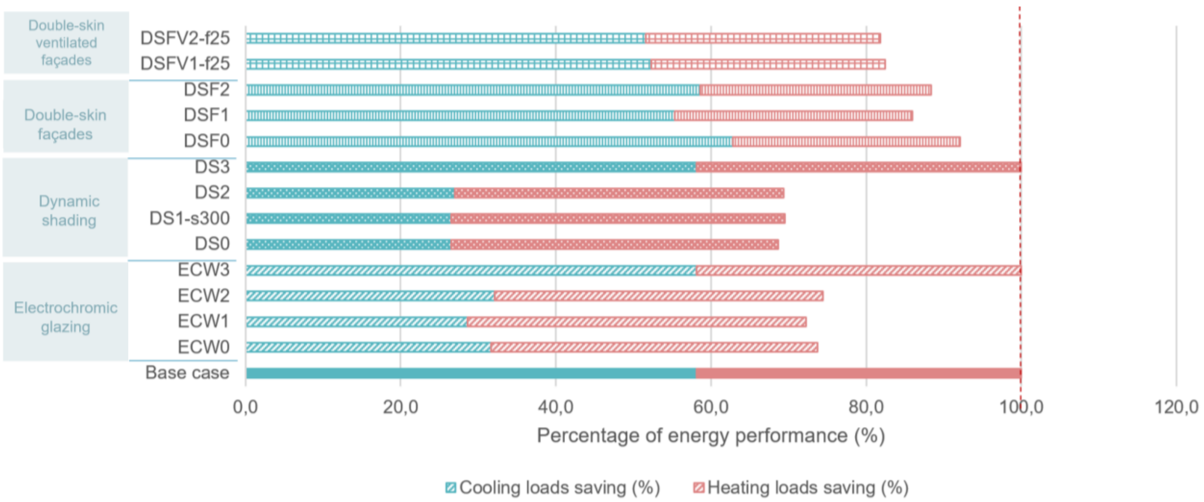


Figure 5.17 – Energy performance – percentage for energy consumption of all cases

Then the thermal comfort is shown for all cases and their control strategies on Figure 5.18. Contrary to the energy performance, it is the double-skin façade cases that improve the most the thermal comfort performance with a thermal comfort between 88,6 and 88,4% compared to the base case. In fact, the electrochromic case and dynamic cases have poor impacts on the thermal comfort with an improvement of less than 4%. But the solar control strategy damages this thermal comfort for both dynamic shading and electrochromic glazing with a percentage of respectively 107,0% and 103,1% compared to the base case. With a more detailed analysis, the *discomfort hours with winter clothes* decrease for electrochromic glazing and dynamic shading cases while the *discomfort hours with summer clothes* and *with winter and summer clothes* increase for these cases and decrease for double-skin façade cases.

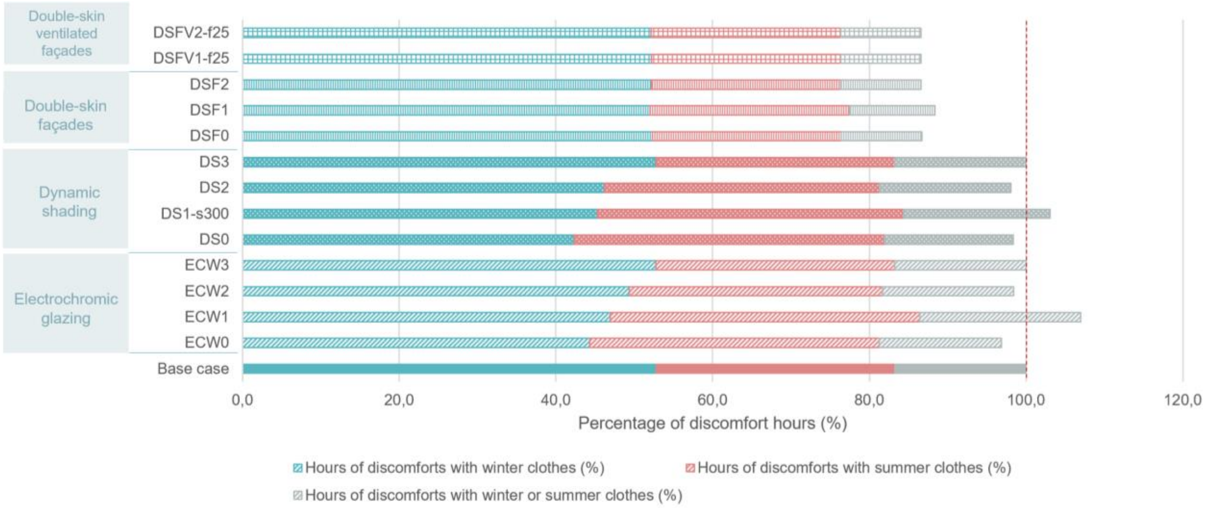


Figure 5.18 – Thermal comfort performance – percentage for thermal comfort of all cases

6. Discussion

This chapter gathers the discussion of the thesis with firstly the main findings and recommendations that are brought out. Then the interpretations, strengths, limitations and difficulties of the study are pointed out. Finally, the implication of practice and future research are presented.

6.1. Summary of the main findings

The main findings highlighted by the study made for the location of Brussels are:

- The **most efficient cases** for the location of are the *dynamic shading case with schedule control* (DS 0) closely followed by *dynamic shading case with thermal control* (DS 2) and *Double-skin façade with hybrid ventilation* (DSFV 2).

- In general, the cases with dynamic shading and electrochromic glazing have the best energy performance with a reduction of the total annual loads between 26,3% and 31,3%.
  These technologies mostly influence the cooling demand with a decrease between 44,7% and 54,4%. However, these loads take a larger part of the annual energy loads.
- The control strategies have a significant impact on energy and thermal comfort performances since the *glare control strategy* (ECW 3, DS 3) does not affect them. Furthermore, *solar control* increases the discomfort hours by 7% and 3,1% for electrochromic glazing (ECW 1) and dynamic shading (DS1) respectively. For *schedule control* and *thermal control* strategies (ECW0, ECW2, DS0, DS2), thermal comfort is poorly impacted.
- The sensitivity analysis for electrochromic glazing pointed out that the most influential parameter of electrochromic cases is the solar threshold of the solar control strategy which mainly acts on the cooling loads with a decrease that can reach 7,9%.
- Some slat properties such as the *slat separation* and the *slat width* are considered as influential parameters on the energy performances of the dynamic shading cases. On the first hand, it appears that a slat separation larger than 3,75cm increases significantly the cooling loads with an augmentation of more than 20% from 3,75 to 7,5cm. On the other hand, a slat width below 1,25cm increases the cooling demand by more than 26% from 0,5 to 1,25cm.

- Unlike electrochromic glazing and dynamic shading cases, double-skin façade cases have significant impacts on both energy consumption and thermal comfort with a reduction that can reach 18,8% and 13,4% respectively. This technology mostly affects the heating loads with a decrease of 28% in a year.
- The visual comfort is only studied for double-skin façade cases. However, the discomfort can be decreased by 35,8% compared to the base case.
- From the sensitivity analysis, it appears that the most influential parameters are the cavity depth and the air flow rate. These affect the energy demand and especially the cooling loads. Thus from 0,25 to 1m for the cavity depth and from 3 to 25 ac/h the cooling demand decreases by 14,8% and 5,1% respectively. In fact, these parameters can vary more but the values studied were enough to conclude this.

6.2. Interpretation and recommendations

Generally, it would be suggested that dynamic façades would improve energy and thermal comfort performances. In this study, the *dynamic shading device with schedule control* (DS 0) displays the best energy performance with a decrease of 31,3% compared to the base case. However, except for the glare control which gives exactly the same results as the base case, control strategies have a poor impact on the energy performance. This is also valid for electrochromic glazing cases which have a reduction between 25,6% and 27,7% of the total energy demand. Furthermore, these technologies mostly help to decrease the cooling loads and especially in spring and summer. Also during these times of the year, the solar radiation transmitted to the room and the gaps between surface temperatures are smaller than for the base case. If the solar radiation transmitted is lower, it means that there is less solar heat gain and thus smaller cooling needs. However, higher outdoor temperatures should induce higher heat gain through the window. But smaller gaps observed between surface temperatures could mean lower heat transmitted through this same window. Since the cooling demand is due to both the temperature difference between indoor and outdoor (thus also inside surface and outside surface) and the solar heat gain, it can be assumed that these smart windows are able to block solar heat gains when unwanted. This would be made for dynamic shading devices by their slats and electrochromic glazing by switching to the dark state. This is also confirmed by Tällberg's study (Tällberg, et al., 2019). The *electrochromic glazing with schedule control* (ECW 0) and with *operative temperature control* (ECW 2) have an almost equal solar radiation transmitted in July and August (see Figure 4.8) and this is valid for dynamic shading too (see Figure 4.12). In this way, it is reasonable to think that the operative temperature would almost always exceed the thermal threshold for these months. Thus, the dark state and the devices are switched on for a longer period. Because most of the energy demands are due to the cooling loads, better performance would be expected in warmer and sunnier climates for these technologies.

The sensitivity analysis proved that the thresholds and some slats properties have to be correctly chosen concerning the energy performance. For example, a high solar threshold induces low cooling energy loads (see Figure 5.7). This means that the dynamic technology is rarely activated. But a too small threshold causes too low cooling demand at the expense of higher heating demand. Furthermore, a too large separation between slats or a too thin width would let more sun pass through the window because the slat cover would be too poor.

By using these smart windows, the thermal comfort is not really improved. In fact, *the solar control strategy* induces a worse performance for both electrochromic glazing (ECW 1) and dynamic shading (DS 1) with an increase of 7% and 3,1% compared to the base case. Actually, for the electrochromic glazing case, the *discomfort hours with winter and summer clothes* are increased by 22% and *discomfort hours with summer clothes* increase by 29,7% compared to the base case. This means that the thermal comfort is mostly badly impacted during the cooling period. Regarding the global warming context, it is expected that summers would be warmer. Thus, this control strategy could have worse thermal performance in the future or in hotter climates. Nevertheless, the other control strategies that are *schedule control* and *operative temperature control* are not really impacted. Although the schedule control strategy induces higher *discomfort hours with summer clothes* with an augmentation of 21,3%. The operative temperature strategy has a similar behavior as the base case regarding the thermal comfort. This is also valid for the dynamic shading cases with a smaller impact. Thus *Operative temperature control* could be the best control strategy solution for thermal comfort in the current context.

Visual comfort has only been studied for double-skin façades but it is expected that electrochromic glazing and dynamic shading devices would improve it too. This is mainly due to the fact that these technologies are able to block the solar radiation transmitted to the room. Thus the direct solar radiation is reduced too. However, the *On state* of dynamic blinds cases considers an entire covering of the window's surface in DesignBuilder. Thereby, the light transmission could be totally blocked which could induce very low daylighting for the occupants. In this way, electrochromic glazing should be preferable.

Globally, double-skin façades would improve the energy performance but with a lower impact than the electrochromic glazing and dynamic shading devices. The reduction is between 7,9% and 18,2% compared to the base case. However, this technology mostly impacts the heating energy loads with the decrease between 30% and 26,7% compared to the base case. Since these take a smaller part of the total loads, the impact of double-skin façades on energy performance is lower. Nevertheless, by using mechanical ventilation, the cooling loads also decrease by more than 10% and improve the energy performance. As seen before, the surface temperatures inside the cavity exhibit higher values than the inside surface temperature of the room (cf. Figures 4.16, 4.17, 4.18, 4.25 and 4.26). Thus, the heating loads reduction could be due to the fact that the cavity is able to act as a buffer zone which will store heat. Because double-skin façades mainly impact the heating loads better energy performances would be expected in colder climates. However, the ventilation mode has an important effect on the energy demand especially on the cooling demand by adding mechanical ventilation. Thus, better performance would also be expected in mild climates.

Contrary to the electrochromic and dynamic shading cases, double-skin façades improve significantly the thermal comfort with a reduction of the discomfort hours between 11,6% and 13,4%. Actually, the inside surface temperature of the room (I.R. temperature) generally varies from 19 to 28°C while the inside surface temperature of the room varies between 15 and 23°C for the base case (see Figure 4.19 and 4.27). Furthermore, a higher inside surface temperature would induce higher indoor air temperature and smaller gaps between indoor air temperature and this inside surface temperature. In addition, based on the standard NBN EN 15251, the optimal indoor temperature is appreciated between 21 and 25,5°C. (Bureau de Normalisation, 2007). Besides that, this technology helps to decrease the *discomfort hours with summer clothes* by 20,6 % and the *discomfort hours with winter and summer clothes* by 38,8% compared to the base case. Therefore, it could be the reason why thermal comfort is improved.

The sensitivity analyses demonstrate that some parameters could significantly influence the energy performance as the cavity depth and the mechanical airflow rate which reduce respectively the energy demand by 14,8% and 5,1%. The main effect of the first parameter is on the cooling loads. A 25 cm depth causes an increase of cooling needs of more than 25% compared to the base case. This is probably due to the fact that the double-skin offers a heat storage through the cavity but too thin to limit the solar heat gain. Consequently, the room is probably overheated and needs a higher cooling.

Double-skin façades have remarkable effects on the visual comfort since it reduces the unwanted illuminance of 35,8%. However, the visual comfort is mostly improved in spring and summer seasons. This is maybe because the sun is higher in the sky during these seasons than in autumn or winter.

Overall, electrochromic glazing and dynamic shading devices could be more efficient and interesting in warmer and sunnier climates while double-skin façades are more profitable to colder climates. Furthermore, the control strategy has to be adequately chosen and some parameters could have a significant influence.

6.3. Strengths and limitations of the study

In my opinion, this study has a real potential in the decision-making of adaptive façades. Since there are four dynamic façades families that are studied, a large part of these smart envelopes is taken into account. Furthermore, this study could become a reference since the geometrical base case studied is internationally known from BESTEST and has also been validated. In addition, the technologies studied are already available on the market and are not in an experimentation phase. In this point of view, architects, engineers, builders and private individuals have direct access to them. However, these technologies are for some of them, really new and a little bit unknown by the population. Besides, this evaluation is made for office buildings where comfort is really important for the workers. Thus, by analyzing the thermal comfort as well, the study brings betterment in the professional living of these people. The visual comfort is an important factor too. However, due to the software's limitations, it could not be completely investigated. In fact, by analyzing three impact criteria that are the energy performance, the thermal comfort and the visual comfort, this study gives an overall view of the possible improvement brought by these transparent dynamic envelopes. Thereby, depending on their priority, builders could choose which technology to use. This joins the point of view of COST Action TU 1403 for which effective performance predictions have to be made considering multiple levels simultaneously in term of time resolution (monthly, seasonal and annually made in this thesis) and physical domains (energy, thermal and visual comforts) (Favoino, et al., 2018).

On the contrary, the software limitations led to some choices made during the modeling. With the use of another building performance tool, maybe the study would have been totally different. As a reminder, the control strategies were chosen regarding the one available for each technology on DesignBuilder. Most of the time, the (non-)availability of these control logics determines what can be modeled in the simulation tool (Favoino, et al., 2018). Then, the visual comfort could have been modeled with an exterior software but was not the primary purpose of the thesis. Also, the output data given by DesignBuilder were more qualitative and consequently their analysis more subjective. Additionally, some sensitivity parameters were not investigated regarding the energy and thermal comfort performances. This is mostly due to the complex modification that should be made and these sensitivity analyses were not the main purpose of the thesis. They were supposed to strengthen the study. Nevertheless, due to these three impact criteria, defining the best technologies with the best control strategy is not easy. Sometimes the energy performance is largely better but at the expense of the thermal comfort. In contrast, it appears that energy and thermal comfort could be improved at the same time. Thereby, defining the best dynamic building envelopes related to energy and thermal comfort is difficult.

In this way, the purpose of this thesis has been reached since the impacts of the dynamic envelopes studied and their control strategies have been analyzed and discussed. In the context of a master thesis, it could not be possible to analyze all impact criteria, such as greenside and durability that could be decisive in the decision-making. Lastly, the technologies studied are really new. Thereby, there are only few studies about them and the data collection was difficult.

Finally, smart technologies are solutions that comprise a cost-effective measure to create healthier and more comfortable buildings, in an energy-efficient way. *The European Energy Performance of Buildings Directive* (EPBD) intends to recognize the smartness of buildings by introducing an indicator called *Smart Readiness Indicator* (SRI). The methodology and calculations methods are still in discussion, however, all buildings should, in the near future, be labeled with this SRI (Vito NV, 2020). Thereby, smart technologies as adaptive façades are identified as high potential solutions for future buildings and tend to become more and more popular (Attia, Lioure, & Declaude, 2020). Thus, these smart technologies are expected to become the “new standard” in terms of façade. And by analyzing them, the smartness through the different domains studied could be performed.

6.4. Implication on practice and future research

The first thing that could improve this study should certainly be to evaluate the entire visual comfort of these technologies, since this one has not been investigated for electrochromic glazing and dynamic shading devices. Nevertheless, it is expected that these smart windows would reduce the unwanted illuminance by blocking out a part of the solar incident radiation. Thereby, analyzing the visual comfort with the help of another software should be the first future research to complete this study.

Secondly, the construction costs and maintenance are a crucial criteria in the selection of materials, systems and “smartness” of the constructed building. Furthermore, adaptive façades are mostly commissioned for protective performance as structural, air permeability, radiation properties, etc) and for energy performance (Attia, et al., 2018). However, there is a lack of information and accuracy about environmental and user satisfaction performances. Moreover, the green side could have a significant influence on investors. Thereby, analyzing the life cycle assessment or the life cycle cost could be a good way to deepen this thesis.

Then, the location chosen, Uccle, located in the region of Brussels-Capital in Belgium. This location has been chosen because and Uccle remains the reference meteorological station of Belgium. Since the study pointed out that some technologies could be more efficient in a warmer climate and others in a colder climate, studying different locations for these technologies could be interesting.

Thereafter, a post-occupancy evaluation is a suitable way to perform adaptive façades in relation to the users. In fact, this kind of evaluation could help to determine the most suitable control strategy regarding the user’s needs or optimize the technology and the user’s satisfaction (Attia, et al., 2018). Luna-Navarro, et al. (2020) showed the importance of occupant interactions related to dynamic façades and showed that occupant interactions are most of the time ignored, which can lead to lower building performances more than expected (Luna-Navarro, et al., 2020). In this way, by measuring the local environment or with the help of surveys to users in real cases, user’s satisfaction can be improved.

The role of dynamic façades is to provide the users an anticipated control of their personal environment, view to outside and/or privacy to fulfill comfort needs but models stay a simulation that could differ from reality (Attia, et al., 2018). Furthermore, the user’s behavior and satisfaction could vary depending on the dynamic technology. For this reason, such studies on real cases could be interesting to evaluate and to validate the simulated cases.

7. Conclusion

The current context of global warming questioned our way of living. With more than 30% of the greenhouse gas emissions and more than 40% of the total energy consumption, the building sector has its share of responsibility in climate change. Furthermore, the occupant's comfort becomes a decisive factor for users. Also, due to the present needs and all new and future innovations, the European Union intends to recognize the smartness of building with a Smart Readiness Indicator (SRI). In this way, many smart technologies are existing in numerous fields. Their aim is to improve the performances of buildings, as for example, reducing the energy consumption, the environmental impacts, the maintenance needs, and the costs. But also preventing the glaring risk, unwanted solar heat, producing renewable energy or also taking into account occupant interactions to improve the user's satisfaction.

Thereby, this master thesis focuses on dynamic building envelopes such as adaptive façades that are high potential solutions for the construction sector. In fact, this study has been made to help in the decision-making of adaptive façade. Accordingly, by simulating and analyzing the energy and comfort performances of four dynamic building envelopes, a large part of the adaptive façade is taken into account. Furthermore, by quantifying and comparing these dynamic envelopes, their impacts are determined. On the first hand, electrochromic glazing and dynamic shading devices seem to be more promising technologies for warm and sunny climates regarding the energy performance. In fact, the study cases showed a decrease of the total loads between 26,3% and 31,3% and especially cooling loads between 44,7% and 54,4% compared to the base case. On the other hand, double-skin façades could be more appropriate for cold climates by decreasing the total loads between 7,9% and 18,2% and especially the heating loads between 27,9 and 30%.

Regarding thermal comfort, double-skin façade cases have the best performance by decreasing significantly the discomfort hours between 11,6% and 13,4%. Moreover, the control strategies influence the thermal comfort and have to be correctly chosen. Thereby, this study demonstrates that operative temperature control seems to be the most encouraging control strategy regarding the current context for electrochromic glazing and dynamic shading cases and hybrid ventilation mode for double-skin façades cases.

Then, the visual comfort is expected to be improved as seen for the double-skin façade cases which decrease the unwanted illuminance by more than 35% compared to the base case.

Several studies investigated such façades but none of them compared different building envelope technologies from different adaptive façade families. In this way, by studying several adaptive façade families, an overview of their potential is possible. Furthermore, by analyzing three domains and different control strategies, this study helps in the decision making of these types of façades. To help future research on the topic, the base case chosen is internationally known and can be easily simulated through different building performance simulation tools.

This study could be useful and interesting for architects, engineers, and people from the construction sector but also private individuals who are interested in such systems. In fact, it could raise awareness and popularize smart façade technologies.

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Table of Figures

Figure 2.1 - Main existing dynamic transparent building envelopes 12
Figure 2.2 - Thermochromic glazing operation - inspired by (Costanzo, Evola, & Marletta, 2016).................. 14
Figure 2.3 – photochromic glazing operation - inspired by (Fries, Fink-Straube, Menning, & Schmidt, 2011) .. 14
Figure 2.4 - Electrochromic glazing operating scheme (Casini, 2018)... 15
Figure 2.5 - Nanocrystal-in-glass composite (Casini, 2018) 16
Figure 2.6-Gasochromic glazing composition (Casini, 2018) 17
Figure 2.7-Liquid crystal window operation – Inspired by (Seung-Won, Sang-Hyeok, Jong-Min, & Tae-Hoon, 2018).. 17
Figure 2.8-Suspended particle devices operation – Inspired by (Oltean, 2006) 18
Figure 2.9 - Electrokinetic pixel window composition (Casini, 2018)... 19
Figure 2.10 - Elastomer deformation tunable window operation (Casini, 2018)... 19
Figure 2.11 – Liquid infill tunable window operation (Casini, 2018) 20
Figure 2.12 - Phase change material integrated in transparent envelopes - inspired by (Vigna, Bianco, Goia, & Serra, 2018).. 21
Figure 2.13 - Fixed shading examples – inspired by (Al-Masrani, Al-Obaidi, Zalin, & Aida Isma, 2018)................ 22
Figure 2.14 – Adjustable shading examples – inspired by (Al-Masrani, Al-Obaidi, Zalin, & Aida Isma, 2018) 22
Figure 2.15 – Automated shading blinds operation - inspired by (Vraa Nielsen, Svendsen, & Bjerregaard Jensen, 2011) 23
Figure 2.16 - Example of kinetic shading devices a - (Mostafa, et al., 2016) b - (Kyu Yi, Yin, & Tang, 2018) c - (Henning Larsen Architects, 2020) d - (Mahmoud & Elghazi, 2016)... 24
Figure 2.17 - Example of hybrid shading devices a - (Vergauwen, De Temmerman, & De Laet, 2014), b - (LIFT Architects, 2020), c - (Schleicher, Lienhard, Poppinga, Speck, & Knippers, 2015) 25
Figure 2.18 - Example of dynamic photovoltaic shading system (Jayathissa, et al., 2017) 26
Figure 2.19 - Airflow path - inspired by (Yazdizad, Rezaei, & Faizi, 2014)... 27
Figure 2.20 - Double-skin façades partition - inspired by (Alberto, Ramos, & Almeida, 2017) 28
Figure 2.21 - Green roof types and their operation - inspired by (Zhang, He, Zhu, & Dewancker, 2019).......... 28
Figure 2.22 - Green façades and living walls operation - inspired by (Safikhani, Megat Abdullah, Remaz Ossen, & Baharvand, 2014)... 29
Figure 2.23 - DSF and CCF comparison operation - inspired by (Balog, 2019) 30
Figure 2.24 - Classification scheme and interaction diagram of occupant façade interaction (Luna-Navarro, et al., 2020) 31
Figure 2.25 - Control architecture for buildings systems (Favoino, et al., 2018).. 32
Figure 3.1 – Study conceptual framework 36
Figure 3.2-Geometric view of BESTEST Case 600 (rendering view) - ANSI/ASHRAE Standard, 1.-2. (2014)... 38
Figure 3.3 - BESTEST case 600 geometry - Ashrae. (2017). ASHRAE standard 140-2017 - standard method of test for evaluation of building energy analysis programs. 39
Figure 3.4 - Continious lighting control as it is considered by DesignBuilder - (DesignBuilder, 2020)........... 41
Figure 3.5 - Screenshot - Location of available Weather data files EnSimS (EnSimS, 2019) 42
Figure 3.6 - Control action in DesignBuilder of switchable glazing 45
Figure 3.7 - Screenshot - Blinds as represented in DesignBuilder.. 46
Figure 3.8 - Screenshot - Double skin facade model : Cavity et occupied zone 47
Figure 3.9 - Control strategies chosen for the different cases 49
Figure 3.10 - Dynamic envelope operating schema according to the schedule and control strategy............. 49
Figure 3.11 – Sensitivity analysis chosen for the different cases 50
Figure 3.12 – Screenshot – position of the lighting sensor 51
Figure 3.13 - Illuminance simulation - base case - sky models (21st June, 12 am) 52
Figure 3.14 - Illuminance simulation - base case - date and time (12 am)... 53
Figure 3.15 - Illuminance simulation - base case - Moment of the day (21st March) 53
Figure 3.16 - Representation of results chosen given by DesignBuilder... 55
Figure 3.17 - Comfort region ASHRAE Standard 55-2004 for summer (a) - winter (b) - (DesignBuilder, 2020)56
Figure 4.1 - Monthly energy loads - Base case – Building level 58
Figure 4.2 - Monthly surface temperature of glass pane - Base case - Window level..................................... 58
Figure 4.3 - Monthly solar radiation on the window - Base case - Window level 59
Figure 4.4 - Illuminance map - Base case 60
Figure 4.5 - Monthly heating loads - Electrochromic case - Building level... 61
Figure 4.6 - Monthly cooling loads - Electrochromic case - Building level 61
Figure 4.7 - Monthly surface temperature of glass pane - Base case and Electrochromic cases - Window level 62
Figure 4.8 - Monthly solar radiation on the window - Base case and electrochromic cases - Window level .. 62

Figure 4.9 - Monthly heating loads – Dynamic shading cases - Building level 64
Figure 4.10 - Monthly cooling loads – Dynamic shading cases - Building level 64
Figure 4.11 - Monthly surface temperature of glass pane - Base case and dynamic shading cases - Window level 65
Figure 4.12 - Monthly solar radiation on the window - Base case and dynamic shading cases - Window level 65
Figure 4.13 - Monthly heating loads – Double skin facade cases - Building level 67
Figure 4.14 Monthly cooling loads – Double skin facade cases - Building level 67
Figure 4.15 – Window surface temperatures of double skin facade cases 68
Figure 4.16 - Monthly surface temperature of glass pane - Base case and DSF 0 - Window level 68
Figure 4.17 - Monthly surface temperature of glass pane - Base case and DSF 1 - Window level 69
Figure 4.18- Monthly surface temperature of glass pane - Base case and DSF 2 - Window level 69
Figure 4.19 - Monthly surface temperature of glass pane - Base case and double skin facade cases - Window level 70
Figure 4.20 - Monthly solar radiation on the window - Base case and double skin facade cases - Window level 70
Figure 4.21 – Illuminance map for double skin façade cases 72
Figure 4.22 – Percentage of visual discomfort for double-skin façade compared to base case 73
Figure 4.23 - Monthly heating loads – Double skin ventilated façade cases - Building level 73
Figure 4.24 - Monthly cooling loads – Double skin ventilated façade cases - Building level 74
Figure 4.25 - Monthly surface temperature of glass pane - Base case and DSFV 1 - Window level 74
Figure 4.26 – Monthly surface temperature of glass pane – Base case and DSFV 2 - Window level 75
Figure 4.27 – Monthly surface temperature of glass pane – Base case and double skin ventilated facade cases – Window level 75
Figure 4.28 - Monthly solar radiation on the window - Base case and double skin ventilated facade cases - Window level 76
Figure 5.1 – Representation of results chosen given by DesignBuilder for sensitivity analysis 77
Figure 5.2 – Sensitivity analysis – ECW 1 – Solar threshold 78
Figure 5.3 – Sensitivity analysis – ECW 2 – Operative temperature threshold 79
Figure 5.4 – Sensitivity analysis – DS 1 – Solar threshold 80
Figure 5.5 – Sensitivity analysis – DS 2 – Operative temperature threshold 80
Figure 5.6 – Sensitivity analysis – DS 2 – Slat angle 81
Figure 5.7 – Sensitivity analysis – DS 2 – Slat separation 82
Figure 5.8 – Sensitivity analysis – DS 2 – Slat width 82
Figure 5.9 – Sensitivity analysis – DS 2 – Blind-to-glass distance of the slat 83
Figure 5.10 – Sensitivity analysis – DSF 2 – Cavity depth 84
Figure 5.11 – Sensitivity analysis – DSF 2 –thermal threshold 85
Figure 5.12 – Sensitivity analysis – DSFV 1 – mechanical airflow 85
Figure 5.13 – Sensitivity analysis – DSFV 1 – Thermal threshold 86
Figure 5.14 – Sensitivity analysis – DSFV 2 – Airflow rate 87
Figure 5.15 – Sensitivity analysis – DSFV 2 – Thermal threshold 88
Figure 5.16 – Influential parameters taken into account in the comparative analysis 88
Figure 5.17 – Energy performance – percentage for energy consumption of all cases 89
Figure 5.18 – Thermal comfort performance – percentage for thermal comfort of all cases 90

Table of tables

Table 1 - Review of the most relevant studies related to the study cases 33
Table 2 - Materials specifications Low mass building - BESTEST case 600 39
Table 3 - Differences between BESTEST case 600, Tällberg's study and the simulated cases regarding HVAC 40
Table 4 – Differences between BESTEST case 600, Tällberg's study and the simulated cases regarding internal gains 41
Table 5 – Geographical information of the hourly weather data file 43
Table 6 – Geographical information of Bruxelles national 43
Table 7 - Window shading type in DesignBuilder 43
Table 8 - Control types proposed in DesignBuilder for electrochromic switchable and SageGlass Electrochromic . 44
Table 9 - Optical properties of Base case and ECW case 45
Table 10 – Blinds with low reflectivity default properties in DesignBuilder 46
Table 11 - Control types and thresholds in the study 48
Table 12 – Sky's models in DesignBuilder and their specifications 52
Table 13 – Resume of simulations 55
Table 14 - Annual energy loads of BESTEST case 600 - official and modelled case. 57
Table 15 – Resume of energy results – Base case 59
Table 16 – Hours of discomfort – Base case 59
Table 17 – Resume of energy results – Base case and Electrochromic cases 63
Table 18 – Hours of discomfort – Base case and Electrochromic cases 63
Table 19 – Resume of energy results – Base case and dynamic shading cases 66
Table 20 – Hours of discomfort – Base case and dynamic shading cases 66
Table 21 – Resume of energy results – Base case and double skin façade cases 71
Table 22 – Hours of discomfort – Base case and double skin façade cases 71
Table 23 – Resume of energy results – Base case and double skin ventilated façade cases 76
Table 24 – Hours of discomfort – Base case and double skin ventilated façade cases 76
Table 25 – Sensitivity analysis – ECW 1 – solar threshold variation improvement 78
Table 26 – Sensitivity analysis – ECW 2 – thermal threshold variation improvement 79
Table 27 – Sensitivity analysis – DS 1 – solar threshold variation improvement 80
Table 28 – Sensitivity analysis – DS 2 – thermal threshold variation improvement 81
Table 29 – Sensitivity analysis – DS 2 – Slat angle variation improvement 81
Table 30 – Sensitivity analysis – DS 2 – Slat separation variation improvement 82
Table 31 – Sensitivity analysis – DS 2 – Slat width variation improvement 83
Table 32 – Sensitivity analysis – DS 2 – Slat width variation improvement 83
Table 33 – Sensitivity analysis – DSF 2 – Cavity depth variation improvement 84
Table 34 – Sensitivity analysis – DSF 2 – thermal threshold 85
Table 35 – Sensitivity analysis – DSFV 1 – mechanical airflow 86
Table 36 – Sensitivity analysis – DSFV 1 – thermal threshold 86
Table 37 – Sensitivity analysis – DSFV 2 – Airflow rate 87
Table 38 – Sensitivity analysis – DSFV 2 – thermal threshold 88
Table 39 – Sensitivity analysis – DSFV 2 – thermal threshold 89

Appendices

Appendix A: Dynamic building envelopes review ……………………………106

Appendix B: Screenshots of all steps made in DesignBuilder ………………108

Appendix C: Hourly weather data file of Uccle ………………………………..124

Appendix D: Daylighting results …………………………………………………126

Appendix E: Summary of the annual results given by all simulations ………130

Appendix E.1: Results of the base case ………………………………………133

Appendix E.2: Results of electrochromic cases ……………………………....134

Appendix E.3: Results of dynamic shading cases …………………………….135

Appendix E.4: Results of double-skin façade cases …………………………136

Appendix E.5: Results of double-skin ventilated façade cases ……………...137

Appendix A: Dynamic building envelopes review

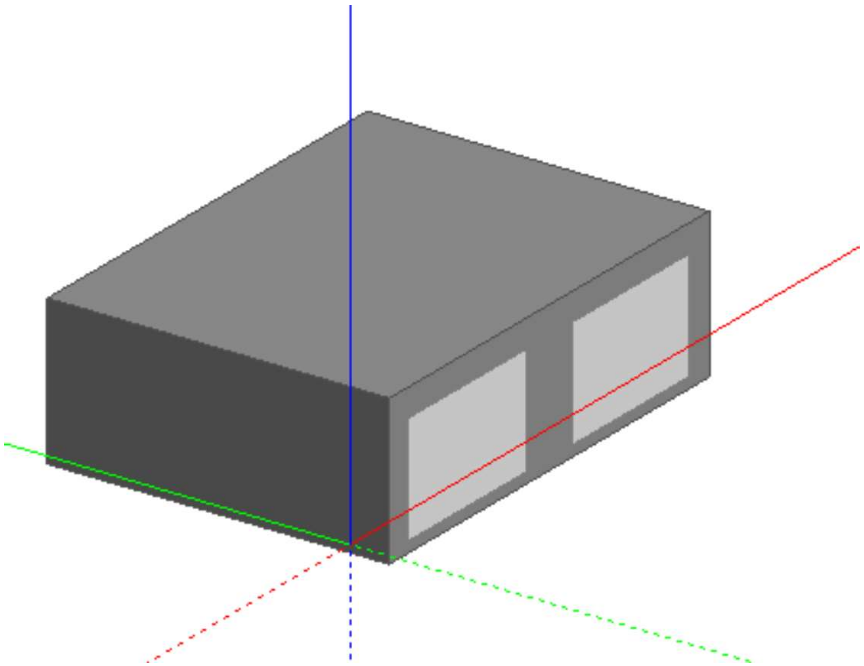
Dynamic envelopes

			What ?	Description	Controllable ?	Parameters: Energy consumption	Thermal comfort	Visual comfort	Energy generation	Acoustic perf.	Advantages	Inconvenients	References or study
Transparent	Switchable glazing	Intrinsic	Photochromic glazing	Tinting of the glazing when there is sun (solar radiation (UV)). There is a photochemical reaction between argent molecule contained into the glass and UV of the sun. Molecules come off and take their metallic form	No	X	X	X	/	/	- Improve visual and thermal comforts	- Less efficient than ECW - poor information from manufacturers - Autonomous	(Casini, 2018 ; Costanzo, Evola, & Marletta, 2016 ; Favoino F. , et al., 2018 ; Sibilio, Iavarone, Mastantuano, Mantova, & D'Ausilio, 2018 ;Tällberg, Petter Jelle, Loonen, Gao, & Hamdy, 2019)
Transparent	Switchable glazing	Intrinsic	Thermochromic glazing	Tinting of the glazing depending of the temperature. A suntuitive interlayer is placed between glass layers which will react with a variation of temperature.	No	X	X	X	/	/	- Improve visual and thermal comforts	- Less efficient than ECW - Autonomous	(Casini, 2018 ; Favoino F. , et al., 2018 ; Sibilio, Iavarone, Mastantuano, Mantova, & D'Ausilio, 2018 ; Fries, Fink-Straube, Menning, & Schmidt, 2011 ; Tällberg, Petter Jelle, Loonen, Gao, & Hamdy, 2019)
Transparent	Switchable glazing	Extrinsic	Electrochromic glazing	Tinting of the glazing by changing voltage. Need a low voltage to operate. Most known electrochromic glazing is based on WO3 film. This chromogenic glazing is the most known and used on the market.	Yes	X	X	X	/	/	- The most suitable switchable glazing for building envelopes - Most used on the market - Since it is an extrinsic dynamic window, control strategies are allowed. - Improve energy performance, visual and thermal comfort.		(Aldawoud, 2013 ; Casini, 2018 ; Favoino F. , et al., 2018 ; Frattolillo, Loddo, Mastino, & Baccoli, 2019 ; Mäkitalo, 2013 ; Sibilio, Iavarone, Mastantuano, Mantova, & D'Ausilio, 2018 ; Tällberg, Petter Jelle, Loonen, Gao, & Hamdy, 2019)
Transparent	Switchable glazing	Extrinsic	Nanocrystal-in-glass composite	NC is composed by Indium oxide nanocrystal embedded in a matrix of niobium oxide. Need a low voltage to tint the glazing. NC operates by absorbing Li+ ions and losing electrons from a donor layer. It exists the clear state where lighting and solar heat pass through the windows, then the cool state where solar heat is blocked and finally the dark state where solar heat and lighting are blocked.	Yes	X	X	X	/	/	- Supposed to provides better performances than ECW	- Quiet new technology that is still in an experimental phase	(Casini, 2018 ; Favoino F. , et al., 2018 ; Sibilio, Iavarone, Mastantuano, Mantova, & D'Ausilio, 2018)
Transparent	Switchable glazing	Extrinsic	Gasochromic glazing	Tinting of the glazing to mirror or bronze-color by changing voltage. The glass is tinting when hydrogen interacts with the active layer (usually a film of WO3). The clear state is reverted by introducing O2 in the cavity with the help of electrolyse reaction.	Yes	X	X	X	/	/	- GCW is less expensive than ECW due to its manufacturing process and to a simpler assembly. - GCW needs only one WO3 layer compared to ECW which needs 5-layer configuration. - Improve energy performance, visual and thermal comfort. - Faster switching phase than ECW		(Casini, 2018 ; Favoino F. , et al., 2018 ; Sibilio, Iavarone, Mastantuano, Mantova, & D'Ausilio, 2018 ; Feng, et al., 2016)
Transparent	Switchable glazing	Extrinsic	Liquid Crystal Device Windows	Liquid crystals modulate the optical properties of the window by applying an electromagnetic field that align the liquid crystals allowing the sunlight to pass through it.	Yes	X	X	X	/	/		- This technology appears almost 15 years ago. However, its used is unfrequent in window device. - Poor investigations on it	(Casini, 2018 ; Favoino F. , et al., 2018 ; Gardiner, Morris, & Coles, 2009 ; Sibilio, Iavarone, Mastantuano, Mantova, & D'Ausilio, 2018 ; Seung-Won, Sang-Hyeok, Jong-Min, & Tae-Hoon, 2018)
Transparent	Switchable glazing	Extrinsic	Suspended Particle Device (SPD) Windows	Same than for le liquid crystals device but where microscopic particles are suspended. Need 100 volts to operate,	Yes	X	X	X	/	/		- This technology appears almost 15 years ago. However, its used is unfrequent in window device. - Poor investigations on it - Need higher voltage than LC	(Casini, 2018 ; Favoino F. , et al., 2018 ; Oltean, 2006 ; Sibilio, Iavarone, Mastantuano, Mantova, & D'Ausilio, 2018)
Transparent	Switchable glazing	Extrinsic	electrokinetics pixels	Electrokinetic pixel window can modulate the hue and the temperature that are coming from visible light. Two planar electrodes are controlling the electrophoretic dispersion of complementary colors are used (blue/yellow fexample).	Yes	X	X	X	/	/	- Can change and control the hue of the glazing which can be warmer or colder if blue yellow chosen, but also black and white opaque hue is black/white chosen. - due to its operation mode the production process should be easy and could be made for large are window	- Quiet new technology, very poor references about it - still in experimentation phase	(Casini, 2018 ; Sibilio, Iavarone, Mastantuano, Mantova, & D'Ausilio, 2018)
Transparent	Switchable glazing	Extrinsic	elastomer-deformation tunable window,	Can vary from a clear state to an opaque state by diffusing the light. It uses the geometric deformation of the glass surface to control the light diffusion. This is achieved by inserting a polymer pane between two elastomer layers that are transparent and dielectric. These are sprayed with electrically conducting silver nanowires. By applying a voltage, the nanowires turn to the electrodes which tend to deform the two elastomer layers. Their surfaces become rough and which decrease the light transmission while keeping a perfect neutral color.	Yes	X	X	X	/	/	- The production process should be cheaper because elastomer sheets are available in large format on the market - The main purpose is supposed to be the glare reduction while keeping a sufficient light transmission. - This technology can vary its transparency and thus control the view through the window	- Prototypal technology. Quiet new and thus very poor references about it. - The performances are still uncertain	(Casini, 2018 ; Sibilio, Iavarone, Mastantuano, Mantova, & D'Ausilio, 2018)
Transparent	Switchable glazing	Extrinsic	Liquid infill tunable window	This technology reduces the light transmission by pumping liquids in or out of a triple glazed insulated glass unit. Actually, a shading fluid is pumped from the bottom to up of the second cavity while the gas is extracted to a dedicated tank.	Yes	X	X	X	/	/	- Liquid height can vary and be controlled.	- Quiet new technology, very poor references about it - still in experimentation phase	(Casini, 2018 ; Sibilio, Iavarone, Mastantuano, Mantova, & D'Ausilio, 2018)
Transparent	Switchable glazing	Extrinsic	Phase change materials	Phase change materials increase the thermal storage capacity of the window. The aim of PCM is to absorb solar radiation. PCMs are able to change their phase (usually liquid-solid transition) and can use the latent heat of this transition for thermal energy storage purposes. typology: paraffin wax, salt hydrates, bio PCM,.. PCM can be used for opaque facade, shutters and glazing.	Yes	X	X	?	/	/	- Help to improve the energy, thermal and visual comfort performances but need a large PCM layer to show significant results - peak temperatures reduced	- Sometimes difficult to predict the effect (can be negative), can bu used in opaque surfaces - Very dependent of the climatic conditions and locations. - few manufacturers - Weak optical properties - Expensive	(Casini, 2018 ; Favoino F. , et al., 2018 ; Sibilio, Iavarone, Mastantuano, Mantova, & D'Ausilio, 2018 ; Vigna, Bianco, Goia, & Serra, 2018)
Transparent	Shadings	Active	Motorized shading device	These shading systems are the addition of shading device and motors that help to adjust these.	Yes	X	X	X	/	/	- Better than adjustable or fixed shading device. However, the dynamic part is poor.	- Costly while performances depend on the occupant's behavior	(Al-Masrani, Al-Obaidi, Zalin, & Aida Isma, 2018 ; Favoino F., et al., 2018).
Transparent	Shadings	Active	Dynamic/automated shading device	Shading devices dynamically controlled by algorithm. Most of the time depending of occupancy schedules and/or occupants preferences. Considered as the most usual smart façade technology. Thus many shapes and sizes are existing. The motion design can be simple (louvers, blinds, roller shades) or more complex (foldable origamis, parametric geometries,...)	Yes	X	X	X	/	/	- Many studies proved the advantages to add dynamic or automated aspect to shading devices	- Should be correctly studied before to be implemented (control strategies,..)	(Al-Masrani, Al-Obaidi, Zalin, & Aida Isma, 2018 ; De Luca, Voll, & Thalfeldt, 2018 ; Favoino F., et al., 2018 ; Henning Larsen Architects, 2020 ; Kyu Yi, Yin, & Tang, 2018 ; Mahmoud & Elghazi, 2016 ; Mostafa, et al., 2016)
Transparent	Shadings	Hybrid	Hybrid shading device	Dynamic shading devices that are more advanced in term of operation and shapes. These are based on biomimetism and are ablo to use the deformation of materials and systems to operate.	Yes	X	X	X	/	/	- Architectural - Better energy and comfort performances	- Many prototypal are studied because require a deep study to optimize their creation and implementation as shading device	(Al-Masrani, Al-Obaidi, Zalin, & Aida Isma, 2018 ; Attia, Favoino, Loonen, Petrovski, & Monge-Barrio, 2015 ; De Luca, Voll, & Thalfeldt, 2018 ; Favoino F., et al., 2018 ; LIFT Architects, 2020 ; Schleicher, Lienhard, Poppinga, Speck, & Knippers, 2015 ; Vergauwen, De Temmerman, & De Laet, 2014)
Transparent	Shadings	PV	Dynamic photovoltaic shading	Shading devices made of small photovoltaic panels which are dynamically controlled. In addition to save energy and to improve the visual comfort, such shading devices generate electricity on site due to the sun	Yes	X	X	X	X	/	- This type of dynamic shaidng device help to generate electricty in addition to save energy. - Dynamic side of photovoltaic shading help to decrease between 20 and 80% the energy consumption	- Difficult to simulate - Each case are supposed to be tailored (no standard)	(Energysage, 2018 ; Favoino F. , et al., 2018 ; Jayathissa, et al., 2017)

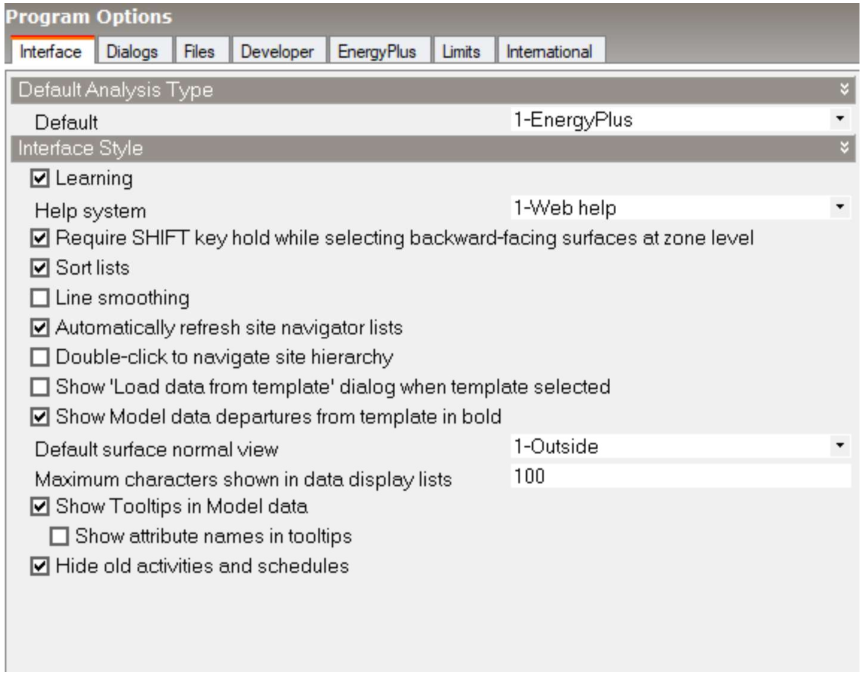
Opaque	Solar active facades	Double skin	**Double skin ventilated façade**	Typically a double curtain wall. Made of two glass wall layers separated by a gas cavity. This kind of facade can be (or not) ventilated, by natural, mechanical or mixed ventilation	**Yes**	**X**	**X**	**/**	**/**	**X**	- Higher window-to-wall ratio possible - Act as heat storage, so more efficient in cold climates - View to exterior kept - Good energy and thermal comfort performances - Acoustic and thermal insulation	- Less efficient in warm climate and unadvised in humid climate (condensation risk) - Costly in renovation - High maintenance if ventilated - Increased construciton weight	(Alberto, Ramos, & Almeida, 2017 ; Attia, Lioure, & Declaude, 2020 ; Favoino F. , et al., 2018 ; Pomponi, Piroozfar, Southall, Ashton, & Farr, 2016 ; Yazdizad, Rezaei, & Faizi, 2014 ; Zomorodian & Tahsildoost, 2018)
			Double skin opaque ventilated facade	Facade made with two layer separated by a gas cavity that can be from 2cm to more than 1m thick. One is a typical wall construction layer (opaque) and the other one can an opaque wall. This kind of facade can be (or not) ventilated, by natural, mechanical or mixed ventilation. An example is Trombe wall	**Yes**	**X**	**X**	**/**	**/**	**X**	- Less usual than transparent double-skin façade - Act as heat storage, so more efficient in cold climates - View to exterior kept - Acoustic and thermal insulation	- Less efficient in warm climate and unadvised in humid climate (condensation risk) - Costly in renovation - High maintenance if ventilated - Increased construction weight	(Alberto, Ramos, & Almeida, 2017 ; Attia, Lioure, & Declaude, 2020 ; Favoino F. , et al., 2018 ; Pomponi, Piroozfar, Southall, Ashton, & Farr, 2016 ; Yazdizad, Rezaei, & Faizi, 2014 ; Zomorodian & Tahsildoost, 2018)
		Green	**Green façades**	Façades with growing plants	**No**	**X**	**X**	**/**	**/**	**X**	- Influence the thermal comfort and the energy performance - Regulation of heat transmitted to the building (radiation absorbed, evapotranspiration, transpiration) - Absoption of CO2 - High potential in urban environment - Part of the architectural aspect of the building	- Production of humidity	(Favoino F. , et al., 2018 ; Kalani & Lun Chow, 2017 ; Safikhani, Megat Abdullah, Remaz Ossen, & Baharvand, 2014)
			Green roofs	Roof with a vegetative layer	**No**	**X**	**X**	**/**	**/**	**/**	- Influence the thermal comfort and the energy performance - Regulation of heat transmitted to the building (radiation absorbed, evapotranspiration, transpiration) - Absoption of CO2 - High potential in urban environment - Part of the architectural aspect of the building	- Production of humidity	(Favoino F. , et al., 2018 ; Kalani & Lun Chow, 2017 ; Zhang, He, Zhu, & Dewancker, 2019)
		PV	**Static photovoltaic panels**	Photovoltaic panels can be used as shading devices and thus electricity is produced due to the solar radiation	**No**	**X**	**X**	**/**	**X**	**/**	- Production of renewable electricity		(Attia, Lioure, & Declaude, 2020 ; Favoino F. , et al., 2018)
		PCM	**Phase change materials**	PCMs are able to change their phase (usually liquid-solid transition) and can use the latent heat of this transition for thermal energy storage purposes. typology: paraffin wax, salt hydrates, bio PCM, etc. PCM can be used for opaque facade, shutters and glazing. But only opaque façade are considered in this family	**Yes**	**X**	**X**	**/**	**/**	**/**	- Help to improve the energy, thermal and visual comfort performances but need a large PCM layer to show significant results - peak temperatures reduced	- Sometimes difficult to predict the effect (can be negative), can bu used in opaque surfaces - Very dependent of the climatic conditions and locations. - few manufacturers - Weak optical properties - Expensive	(Attia, Lioure, & Declaude, 2020 ; Favoino F. , et al., 2018 ; Sibilio, Iavarone, Mastantuano, Mantova, & D'Ausilio, 2018)
	Active ventilative façades	**Closed cavity façade**		Advanced double-skin façade with a actively ventilated closed cavity. The air pulsed is dried before to enter in the cavity. Thereby, is allows less pollutant and particles to enter in.	**Yes**	**X**	**X**	**X**	**/**	**X**	- Less pollutant and particles in the cavity space - Less condensation's risks - Less maintenance needed - Longer durability - Smaller cavity needed compared to double-skin façade	- Very new technology, so very poor informaiton or studies made about it	(Attia, Lioure, & Declaude, 2020 ; Balog, 2019 ; Favoino F. , et al., 2018 ; Zani, Galante, & Ramming, 2020)
		Automated operable window		Operable window controlled by a dynamic control strategy which controls the ventilation rate entering in the indoor space	**Yes**	**X**	**X**	**X**	**/**	**/**	- Better thermal performance and energy performance	- High investement for small impacts	(Attia, Lioure, & Declaude, 2020 ; Favoino F. , et al., 2018)
		Actively ventilated double-skin façade		Considered as double-skin façade with mechanical or hybrid ventilation	**Yes**	**X**	**X**	**X**	**/**	**X**	- Shows better performance than naturally ventilated double-skin façade - Ventilation rate can be controlled - View kept - Act as a heat storage	- Less efficient in warm climate and unadvised in humid climate (condensation risk) - Costly in renovation - High maintenance if ventilated - Increased construction weight	(+E16:O27Alberto, Ramos, & Almeida, 2017 ; Attia, Lioure, & Declaude, 2020 ; Favoino F. , et al., 2018 ; Pomponi, Piroozfar, Southall, Ashton, & Farr, 2016 ; Yazdizad, Rezaei, & Faizi, 2014 ; Zomorodian & Tahsildoost, 2018)

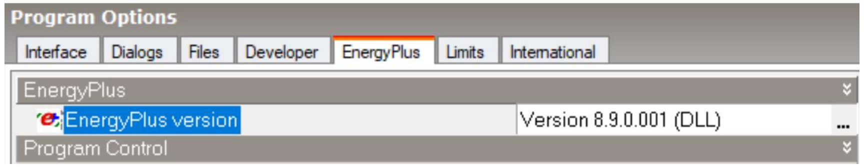
Appendix B: Screenshots of all steps made in DesignBuilder

Base case 600 Design Builder

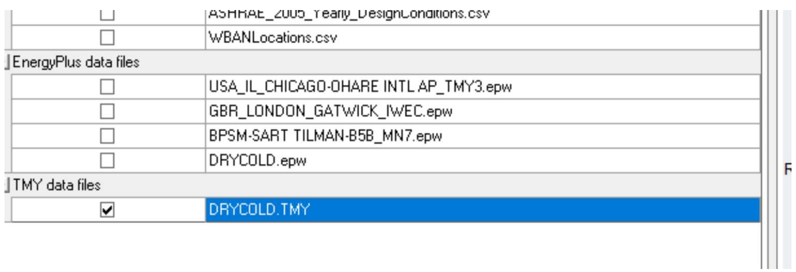


Site data

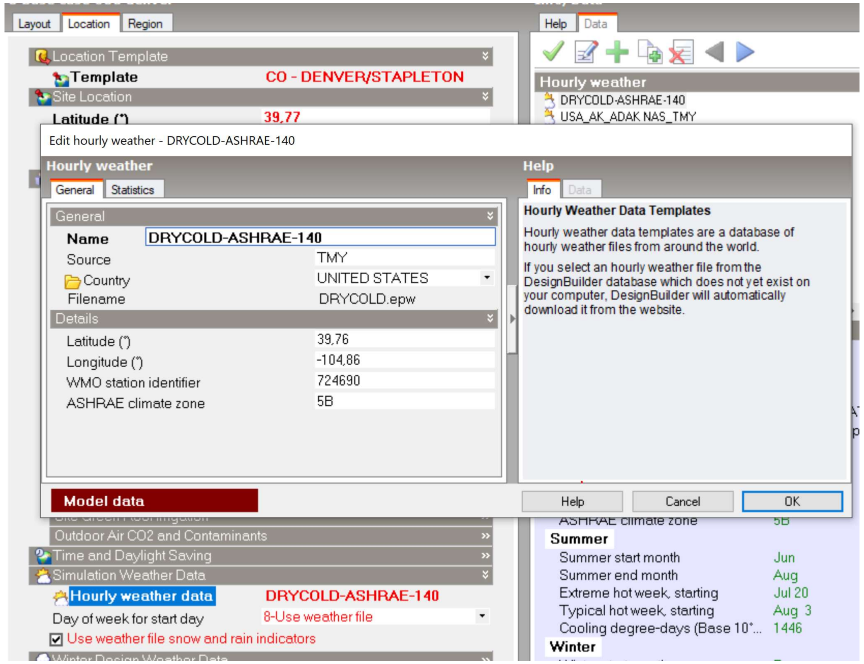




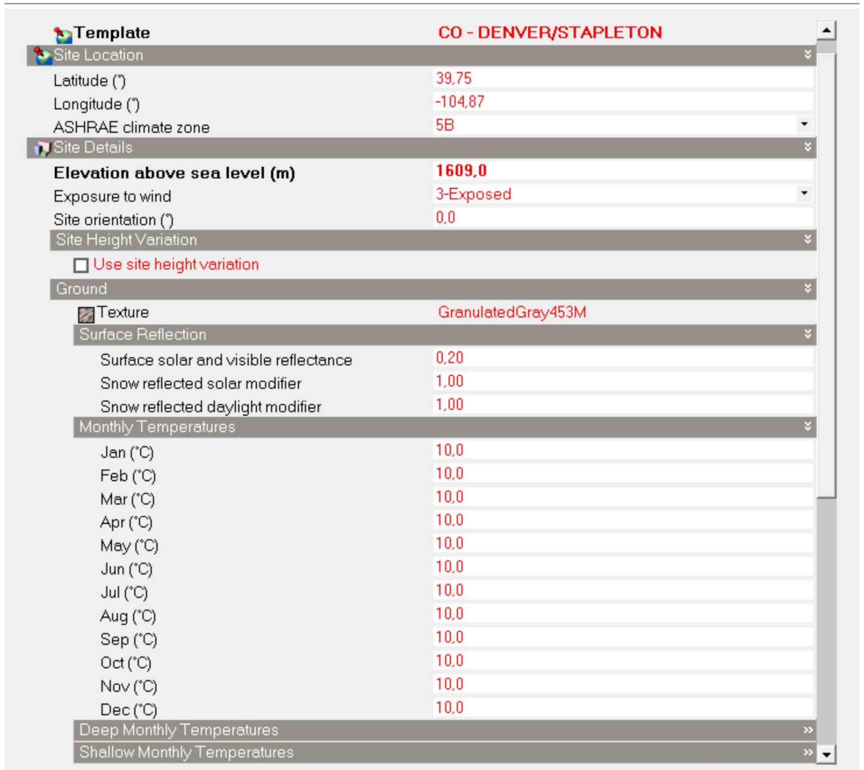
Different version than the one in the tutorial

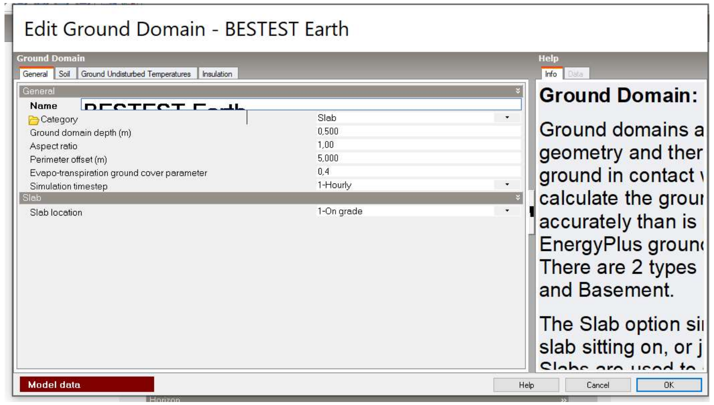


In **LOCATION tab it is possible to add the weather data file**



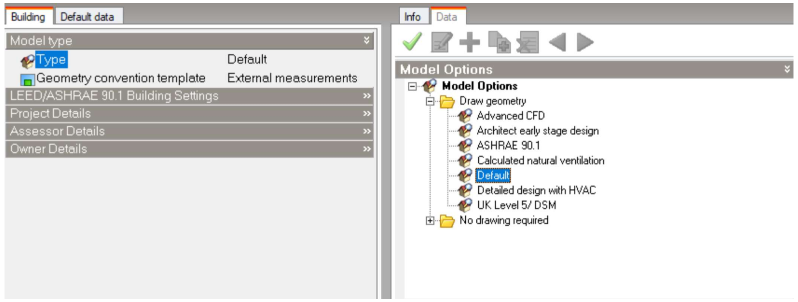
The Ground was changed into the location tab





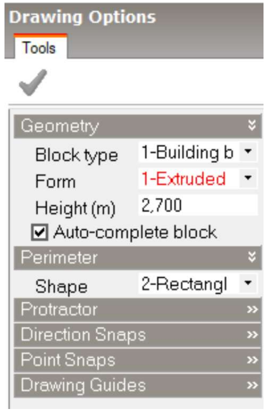
Selection of the hourly weather data files

Building

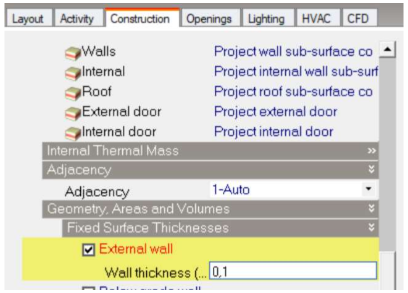


in layout tab, add building

we do not have “draw building+standard data”, parametric

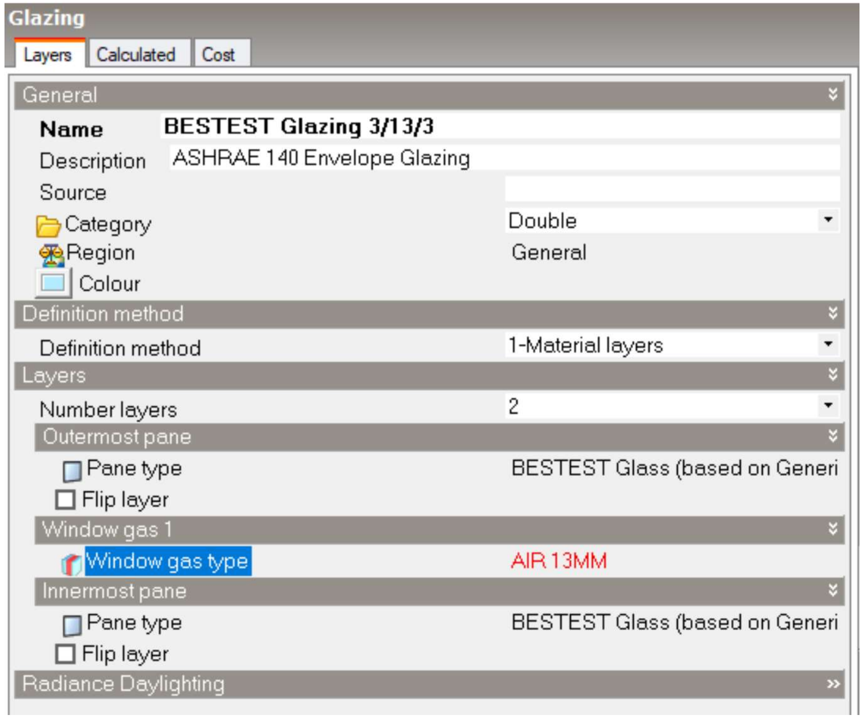


We cannot choose the wall thickness before to model.

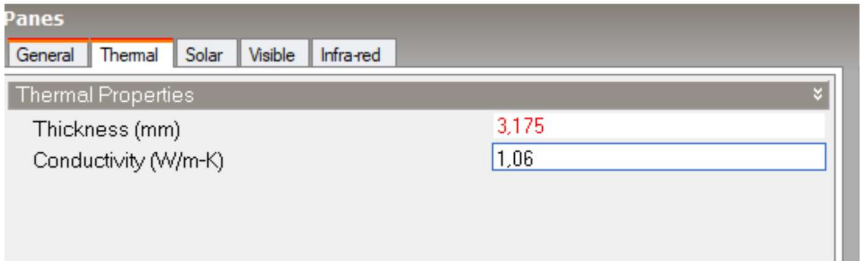


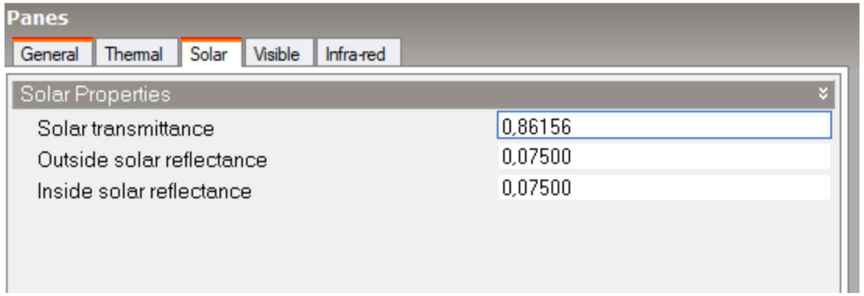
The building is modelled following the geometric data given.

Window

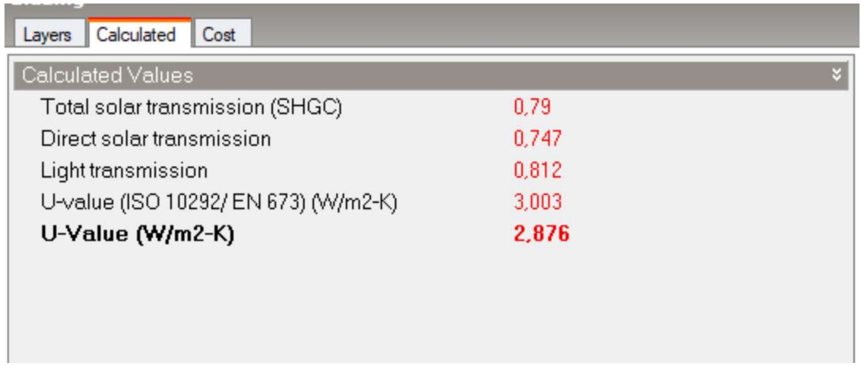


By clicking on the pane type, we created a new glass pane based on a Generic on : BESTEST Glass

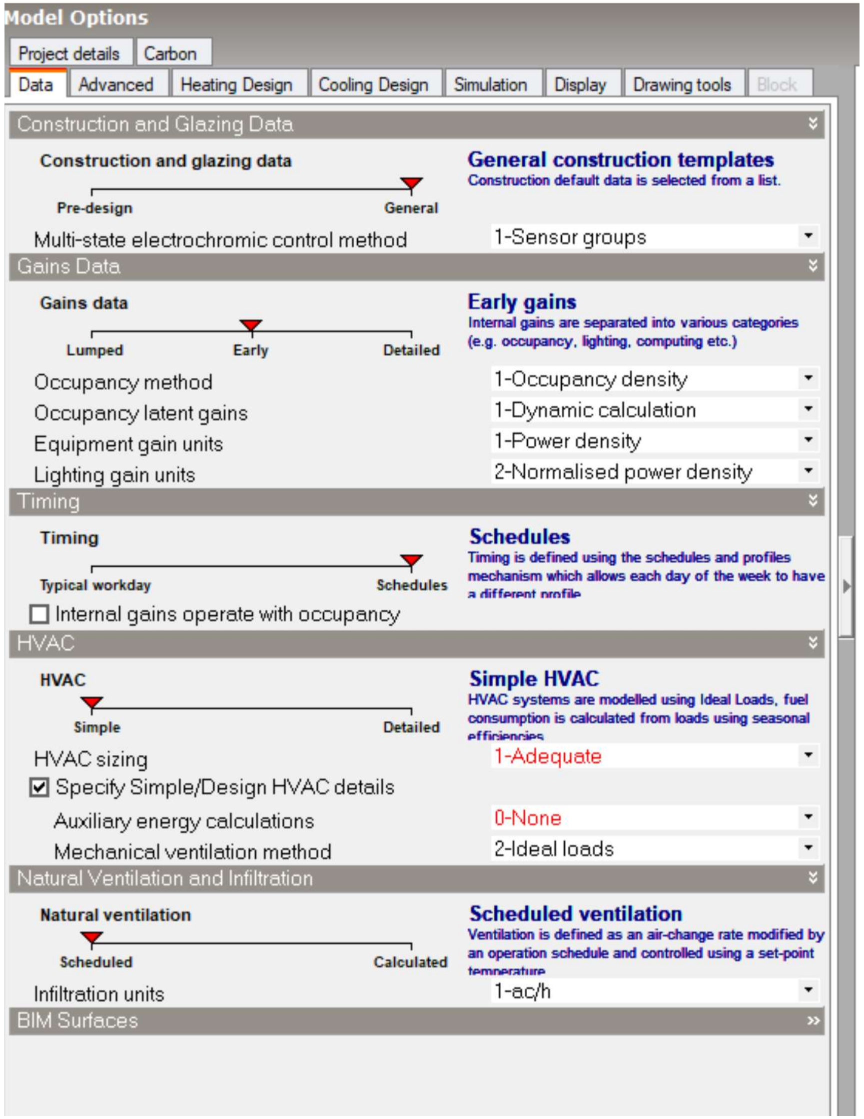


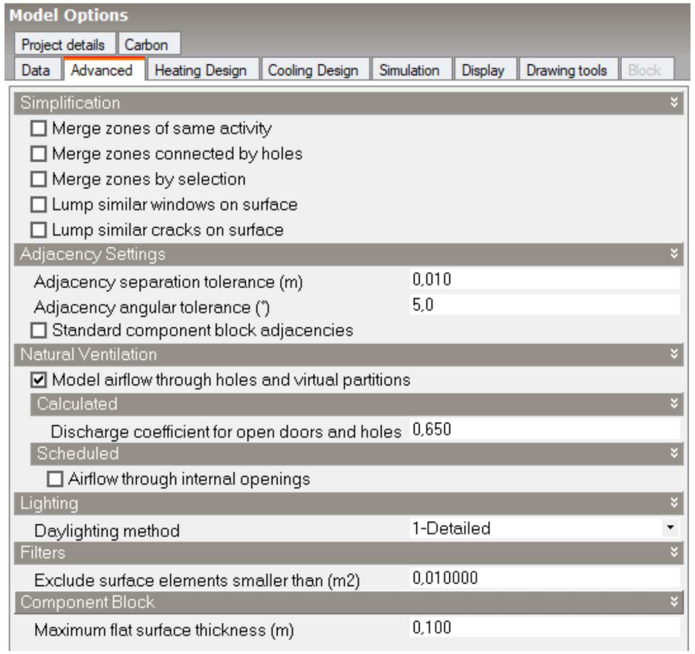


RESULTS TO have



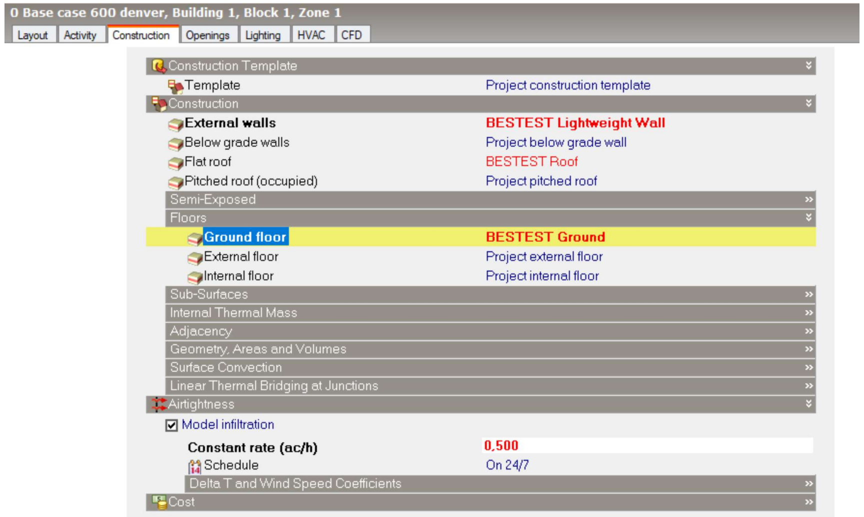
Model Option



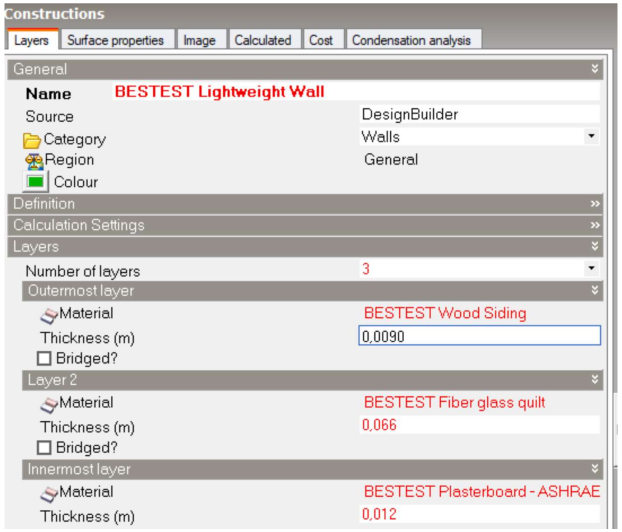


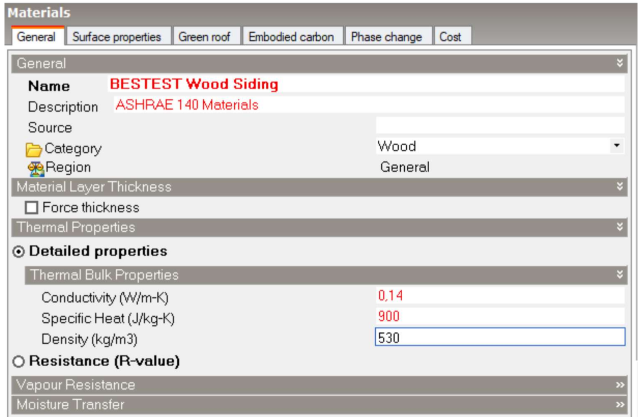
Construction tab

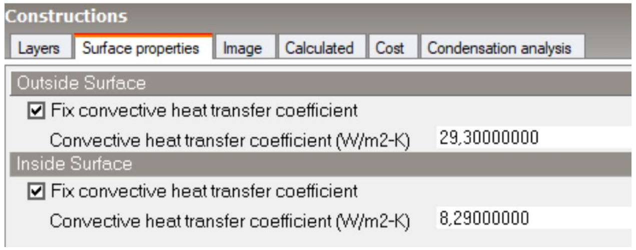
For each wall/floor/roof



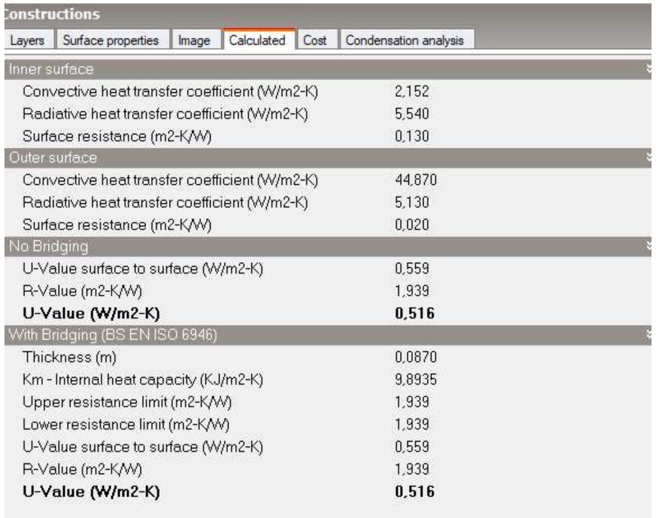
WALL







Edit construction - BESTEST Lightweight Wa



Now, do the same for the **ROOF**

Constructions

Layers | Surface properties | Image | Calculated | Cost | Condensation analysis

General	
Name	BESTEST Roof
Source	
Category	Roofs
Region	Colorado
Colour	
Definition	
Definition method	1-Layers
Calculation Settings	
Layers	
Number of layers	3
Outermost layer	
Material	BESTEST Roof deck
Thickness (m)	0,0190
☐ Bridged?	
Layer 2	
Material	BESTEST Fiber glass quilt
Thickness (m)	0,1118
☐ Bridged?	
Innermost layer	
Material	BESTEST Plasterboard
Thickness (m)	0,0100
☐ Bridged?	

Edit construction - BESTEST Roof

Constructions

Layers | Surface properties | Image | Calculated | Cost | Condensation analysis

Inner surface	
Convective heat transfer coefficient (W/m2-K)	4,460
Radiative heat transfer coefficient (W/m2-K)	5,540
Surface resistance (m2-K/W)	0,100
Outer surface	
Convective heat transfer coefficient (W/m2-K)	44,870
Radiative heat transfer coefficient (W/m2-K)	5,130
Surface resistance (m2-K/W)	0,020
No Bridging	
U-Value surface to surface (W/m2-K)	0,334
R-Value (m2-K/W)	3,113
U-Value (W/m2-K)	**0,321**
With Bridging (BS EN ISO 6946)	
Thickness (m)	0,1408
Km - Internal heat capacity (KJ/m2-K)	8,8872
Upper resistance limit (m2-K/W)	3,113
Lower resistance limit (m2-K/W)	3,113
U-Value surface to surface (W/m2-K)	0,334
R-Value (m2-K/W)	3,113
U-Value (W/m2-K)	**0,321**

And for the **FLOOR**

General	
Name	BESTEST Ground
Source	
Category	Floors (ground)
Region	Colorado
Colour	
Definition	
Definition method	1-Layers
Calculation Settings	
Layers	
Number of layers	2
Outermost layer	
Material	BESTEST Insulation
Thickness (not used in thermal calcs) (m)	1,0030
Innermost layer	
Material	BESTEST Timber flooring
Thickness (m)	0,0250
☐ Bridged?	

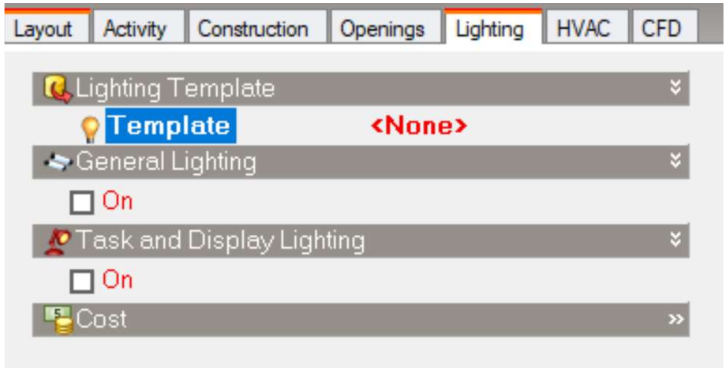
Edit construction - BESTEST Ground

Constructions

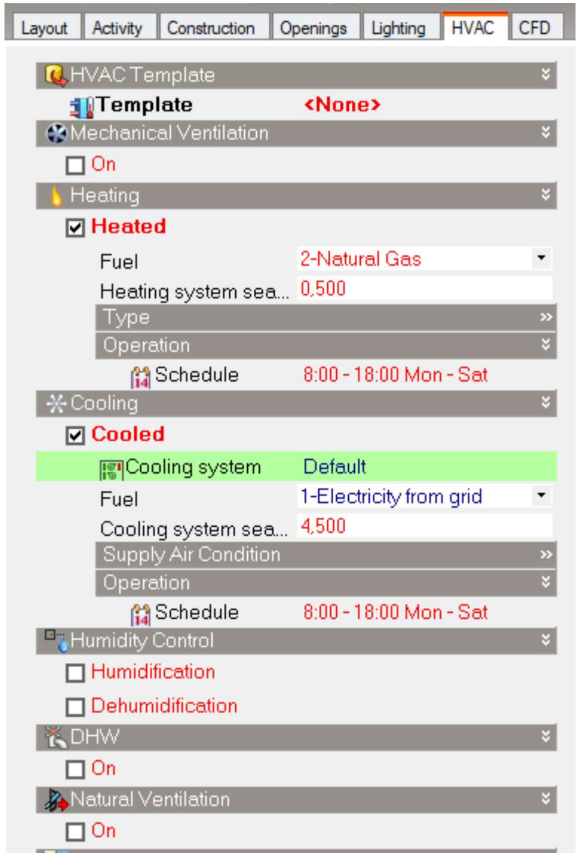
Layers | Surface properties | Image | Calculated | Cost | Condensation analysis

Inner surface	
Convective heat transfer coefficient (W/m2-K)	0,342
Radiative heat transfer coefficient (W/m2-K)	5,540
Surface resistance (m2-K/W)	0,170
Outer surface	
Convective heat transfer coefficient (W/m2-K)	44,870
Radiative heat transfer coefficient (W/m2-K)	5,130
Surface resistance (m2-K/W)	0,020
No Bridging	
U-Value surface to surface (W/m2-K)	0,040
R-Value (m2-K/W)	25,444
U-Value (W/m2-K)	**0,039**
With Bridging (BS EN ISO 6946)	
Thickness (m)	1,0280
Km - Internal heat capacity (KJ/m2-K)	19,5000
Upper resistance limit (m2-K/W)	25,444
Lower resistance limit (m2-K/W)	25,444
U-Value surface to surface (W/m2-K)	0,040
R-Value (m2-K/W)	25,444
U-Value (W/m2-K)	**0,039**

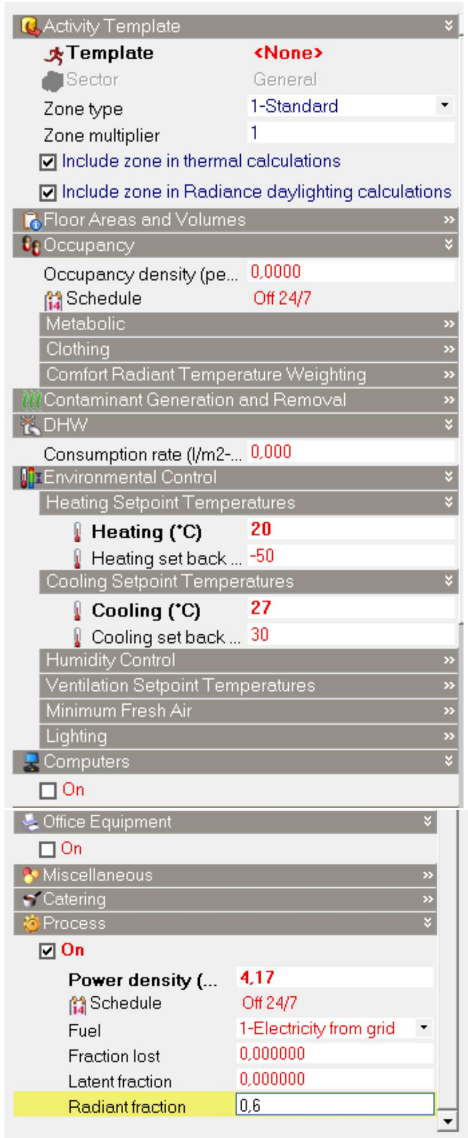
Lighting



HVAC Tab



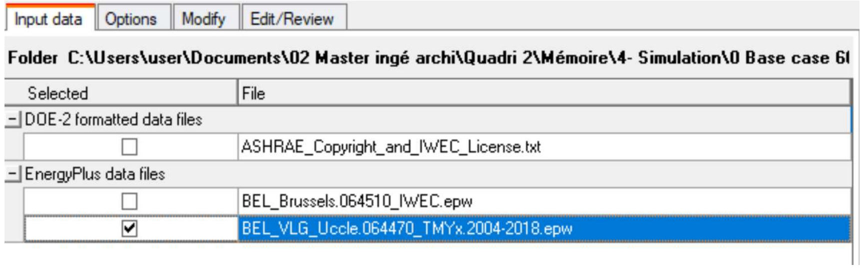
Activity

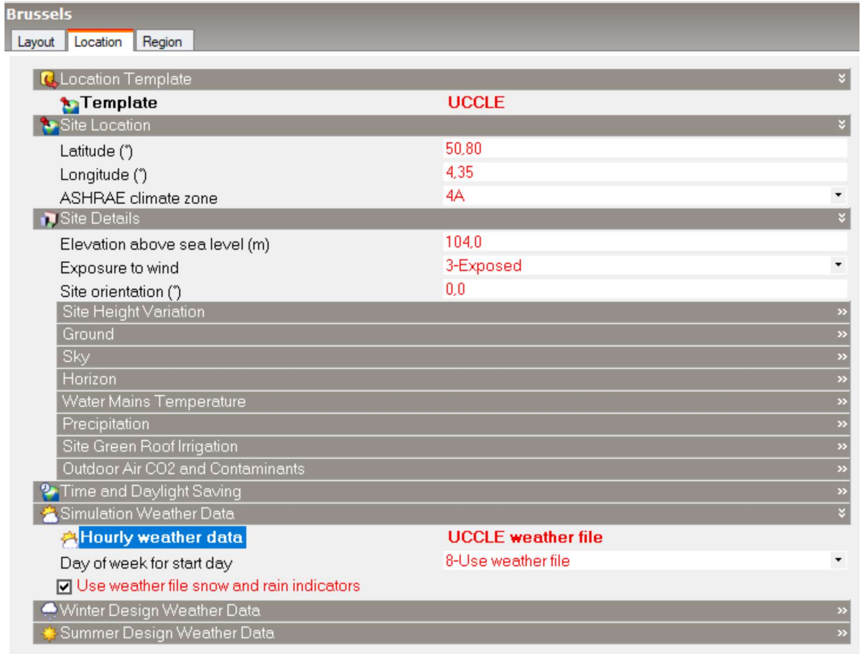


BRUSSELS BASE CASE 600

Changing location

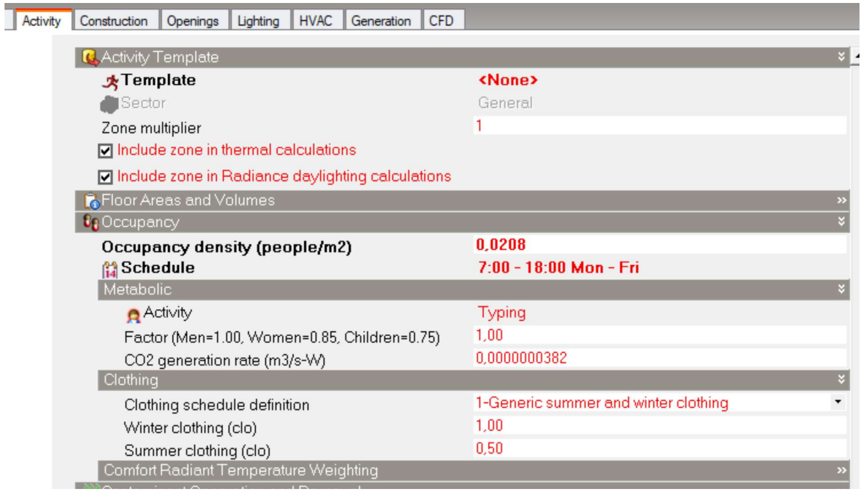
First we changed the location by BRUXELLES NATIONAL since it is the capital of the country.
Then, on download the weather data file from Energyplus





Location is set to Uccle since the most recent files are from this station.

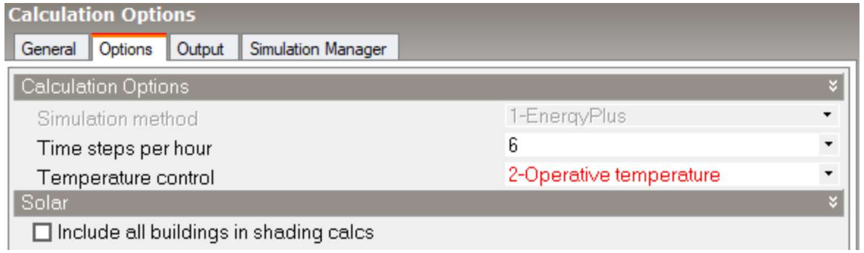
Activity tab



Occupancy has been change : 1person in the office during offices hours

Lighting put to 500lux

Equipment put to 150W (as Tällberg's study) = 3,125 W/m²

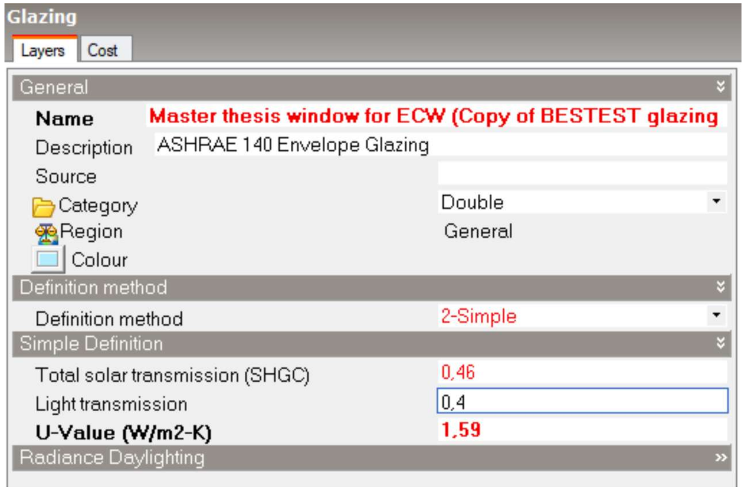


/!\ When simulating : **Operative temperature** have to be chosen

Chromogenic Glazing

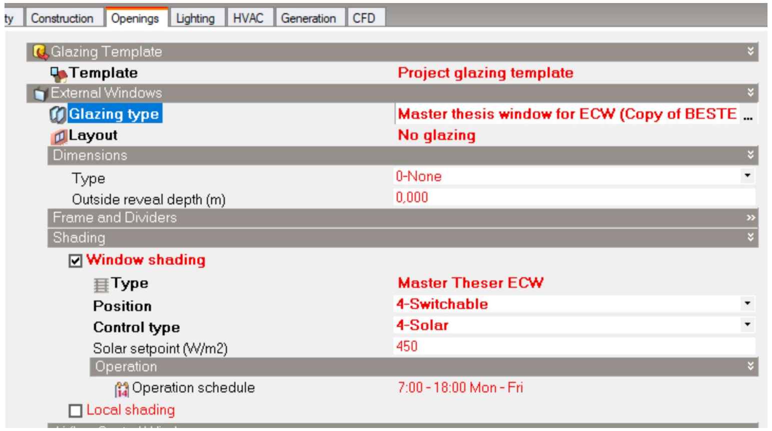
ECW

First we change the glazing type into the **clear state** of ECW

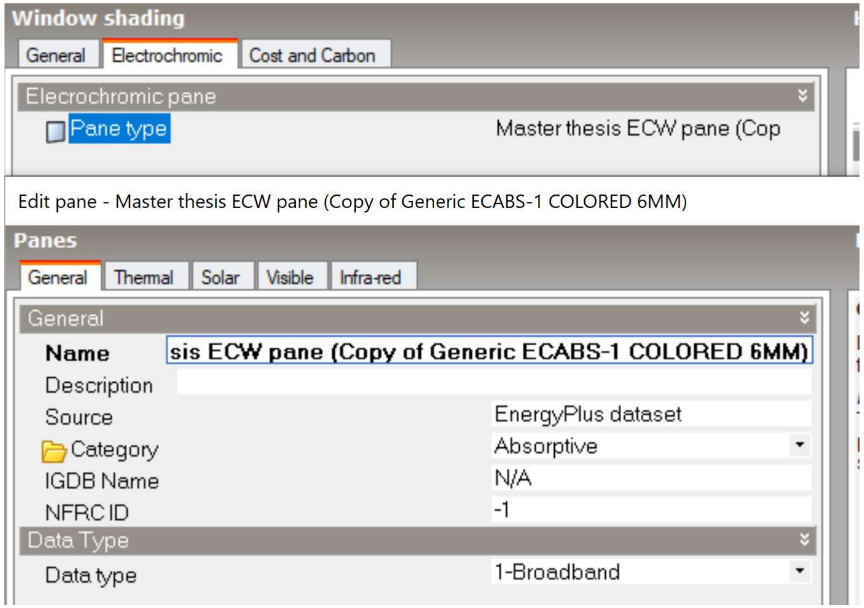


We choose definition method = 2-simple instead of 1- Material layers, to directly implement data given by Tällberg's study (NB : Light transmission = Visible transmittance)

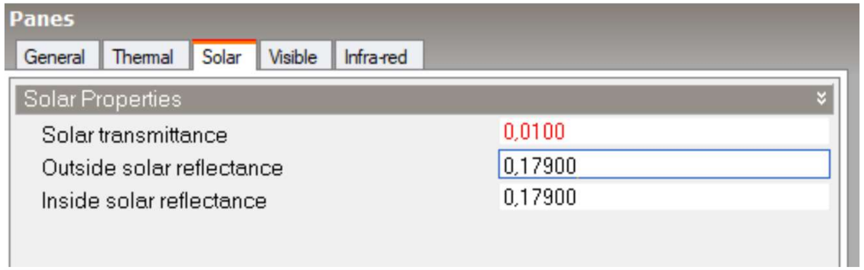
Window shading box checked = **dark state**

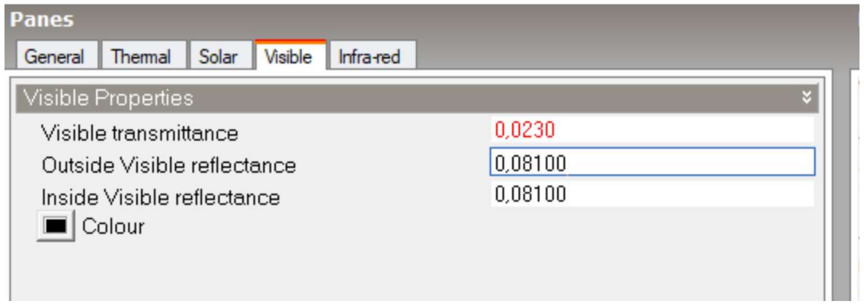


We change the Type of electrochromic glazing by clicking on the type and then the pane type :



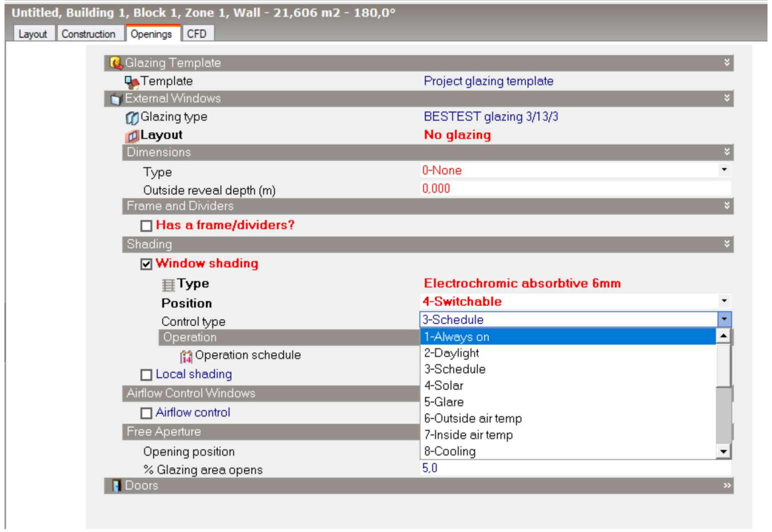
From Tällberg's study, we have T_vis, T_sol and g_value. Thus we will change solar and visible transmittance.

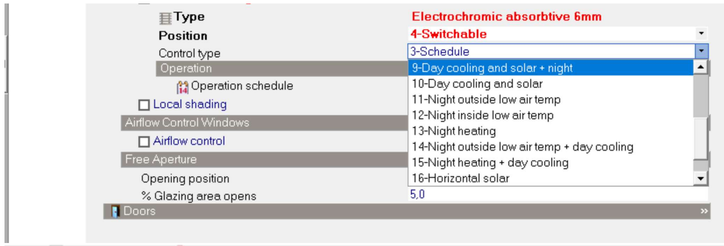


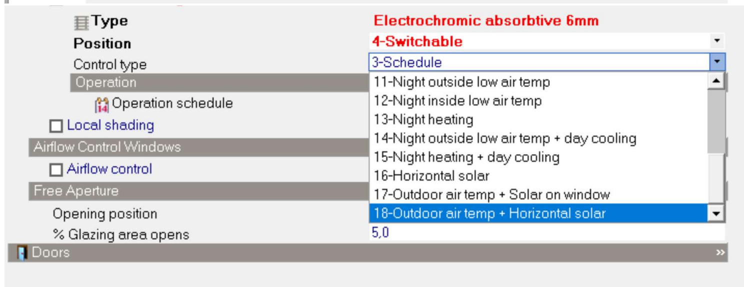


Control strategies

Then there is a lot of control type : Solar=Sun, daylight and operative temperature were made in the Tallberg study.

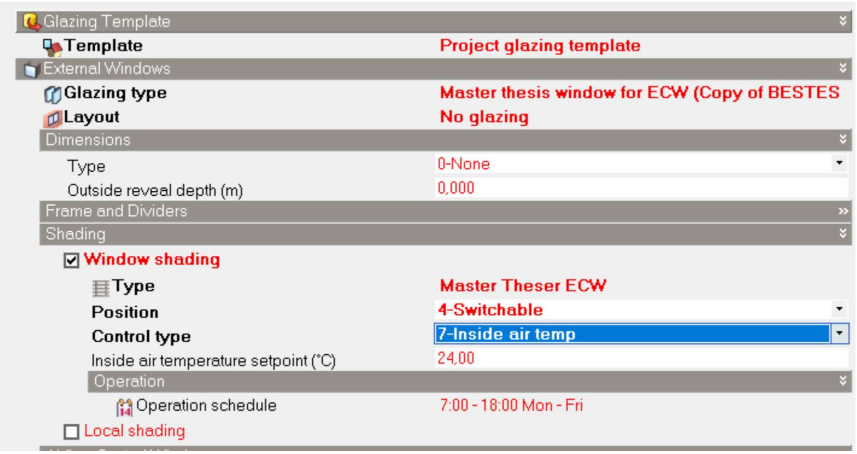




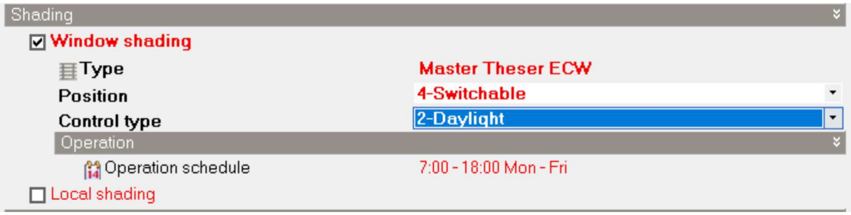


First choose : <4=solar : 450 W/m²

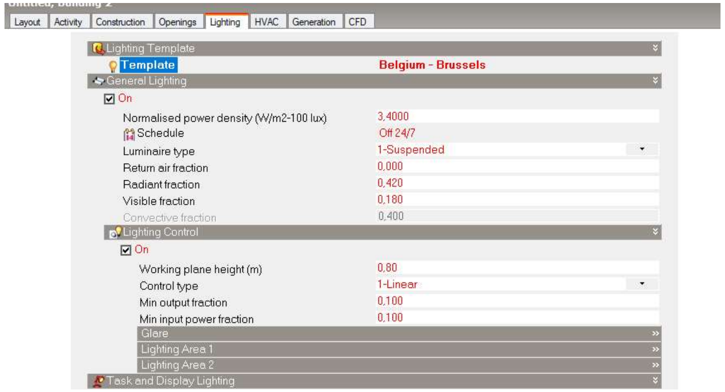
Second : 7=inside air temp : 24°C



3th, 2 daylight, target put on 500 lux

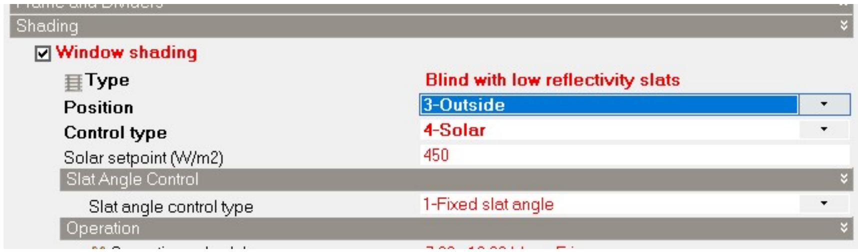


To operate, the lighting control have to be on

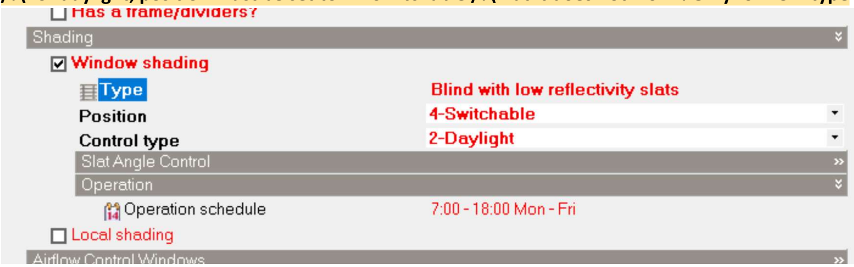


Dynamic shading

Control type are exactly **the same than for ECW** . We choose Blind low reflectivitity. To "normalize" results



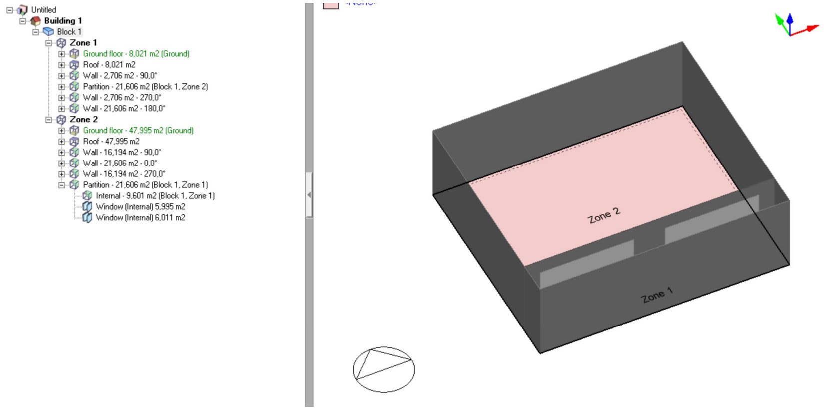
/!\ for daylight, position must be set to 4 – Switchable /!\ But it does not work ! Only for ECW type



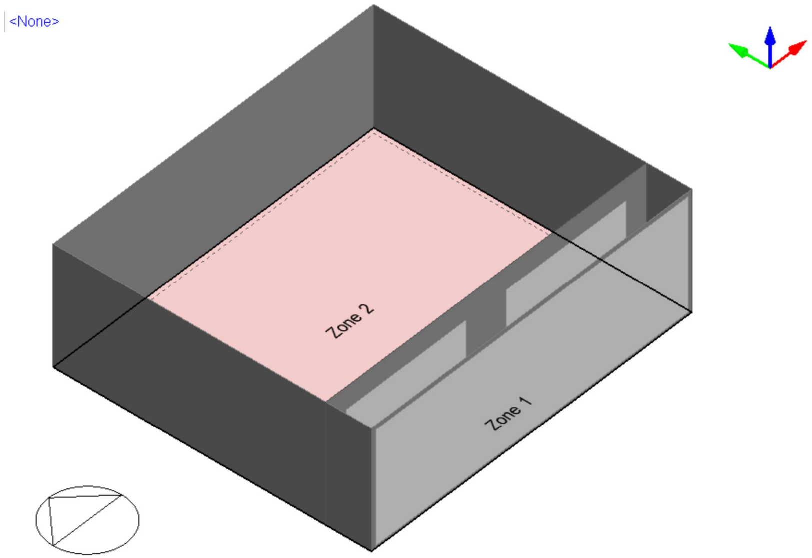
We try 5-Glare and it works. Thus this control strategy will be also studied.

Double skin façade natural ventilated

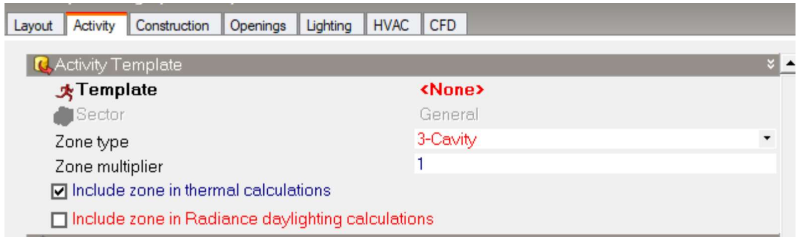
A double layer has been modelled into the same block. We first extruded the south wall and deleted the initial windows. Then we made a partition of 1m layer.
These windows (still from BESTEST) were redefined at surface level on the partition.



A big window was designed to represent a “curtain wall” with a Window-to-Wall ration of 91% (maximum allowed)

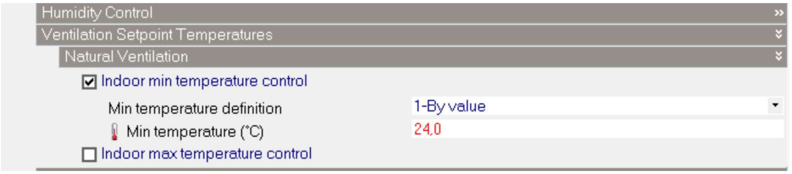


Activity where put to 3-Cavity

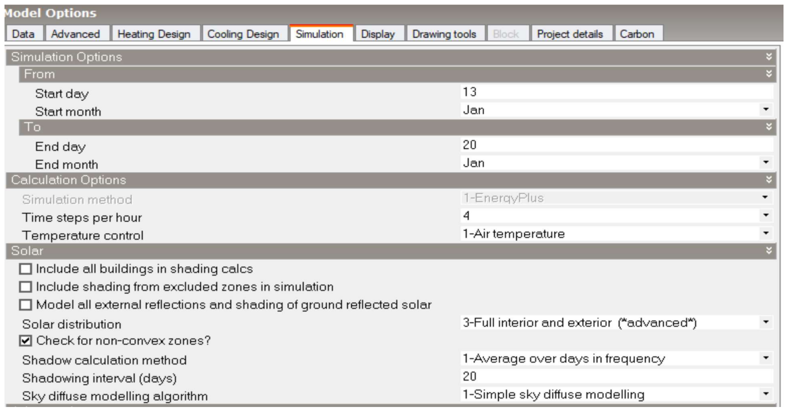


Firstly we assume no natural ventilation. Then we added it. At HVAC tab : default setting of DB but schedule only during offices hours

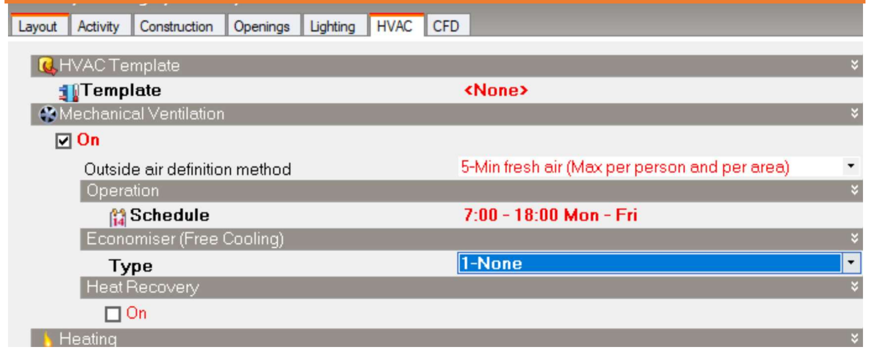
At activity tab



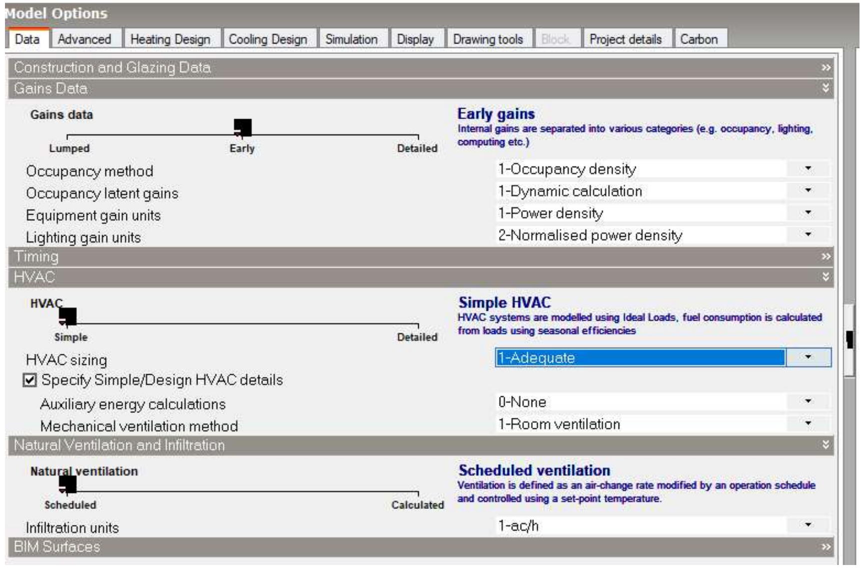
Because of the cavity, in model option, the solar distribution have to be 3-full exterior and interior



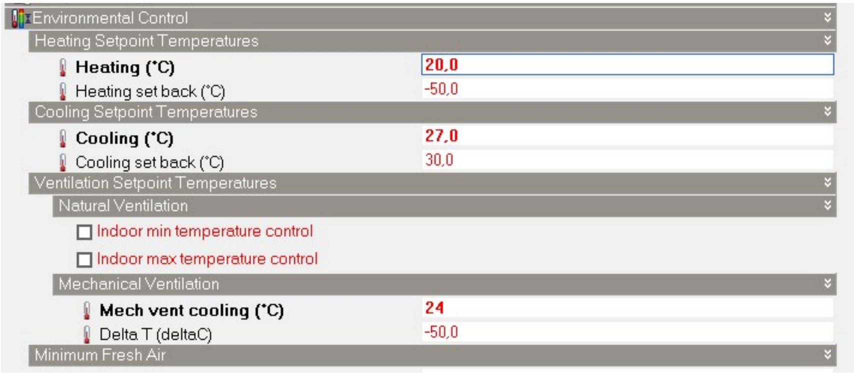
Double skin façade mechanically ventilated

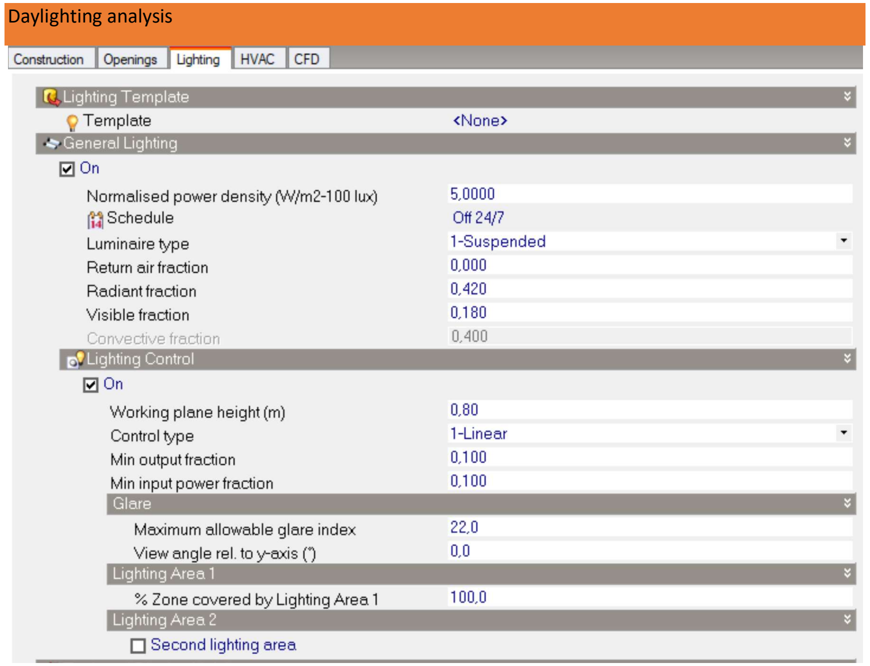


In model option, we have to put the mechanical ventilation method on 1-Room ventilation. By this way it is possible to control the mechanical ventilation with a temperature setpoint.

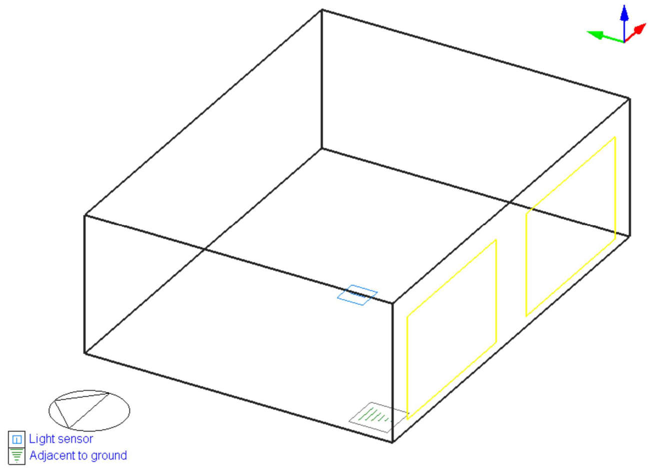


Mechanical ventilation cooling setpoint is the same than for natural ventilation

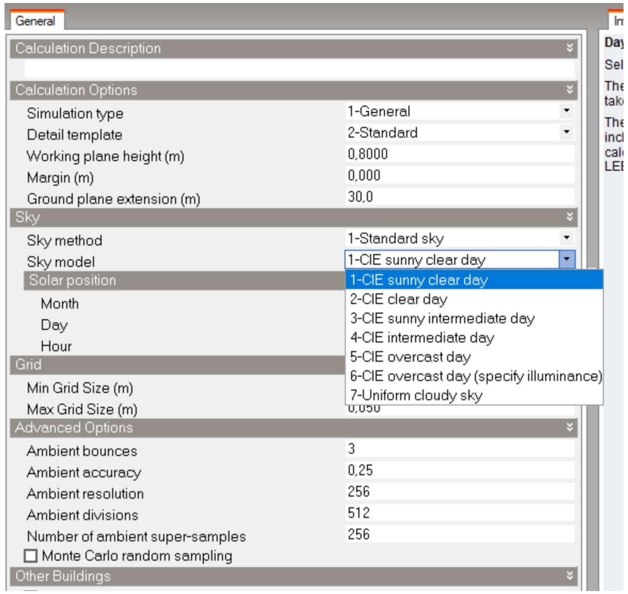




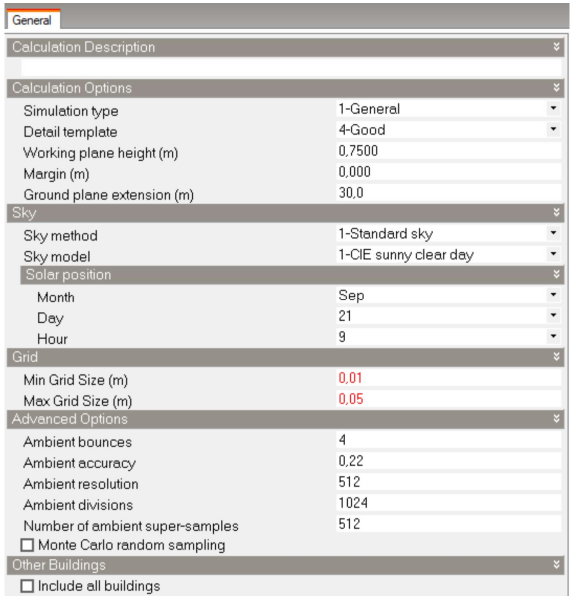
Control lighting on



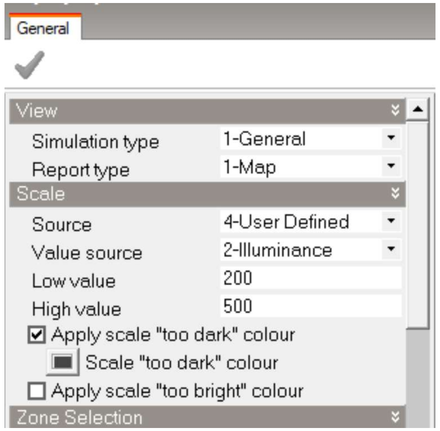
Light sensor is by default in the middle of the room

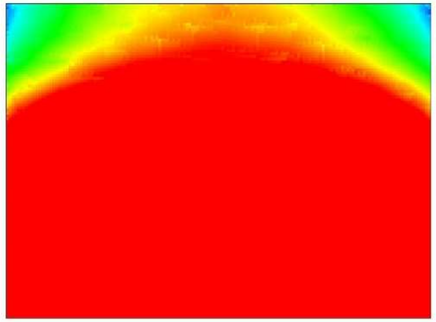


Sky model can be set for different type of day (cloudy, sunny,…)

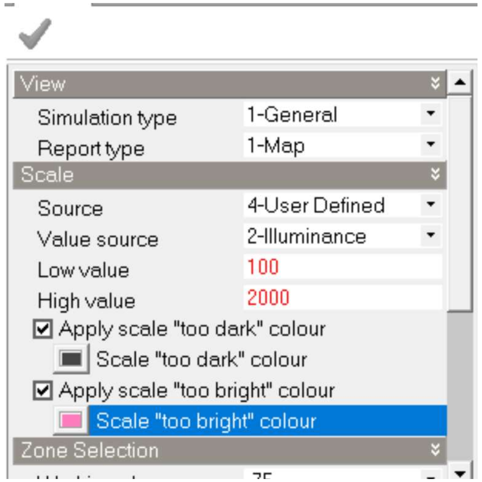


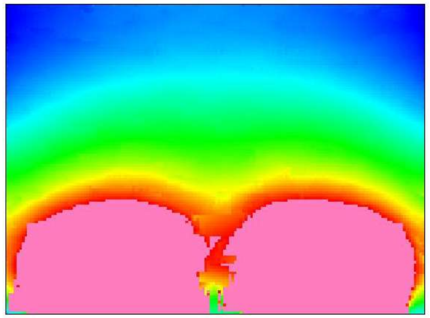
Grid is changed to have more relevant results.





High value is changed to see illuminance below 500lux





Or Between 100 and 2000 lux for example

Appendix C: Hourly weather data file of Uccle.

Figures 1, 2 and 3 below show some of the climate data of epw file. Figure 1 presents the daily maximum and minimum temperature profile. It can be seen on the Figure 2 that solar radiation is higher in summer than in winter. Furthermore a second peak is visible in April. Regarding the Figure 3, the wind is mostly oriented South West which confirms what was said before. The windiest month is February which is shown on Figure 4.

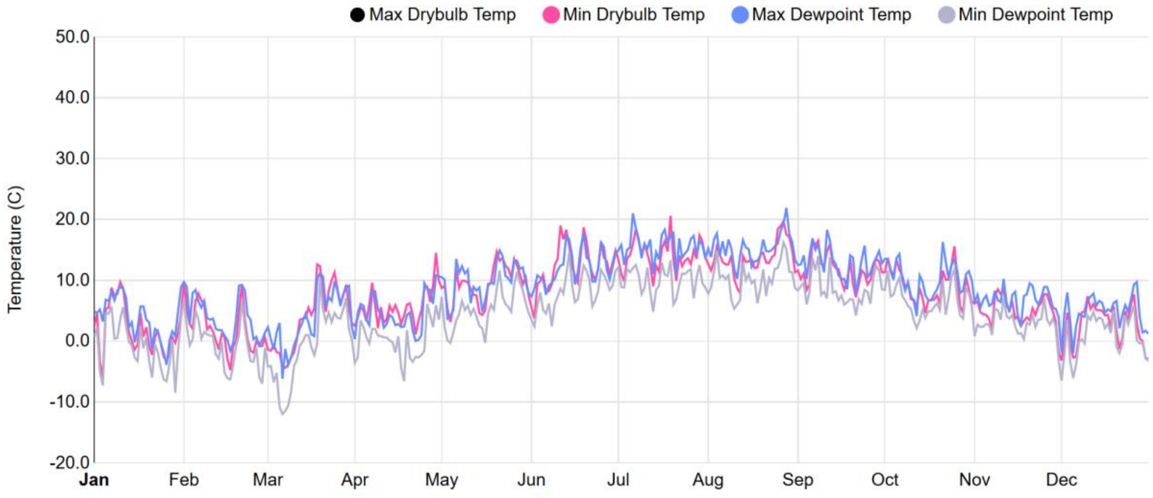


Figure 1 - Daily maximum and minimum temperature profile of the climate file (EnSimS, 2019)

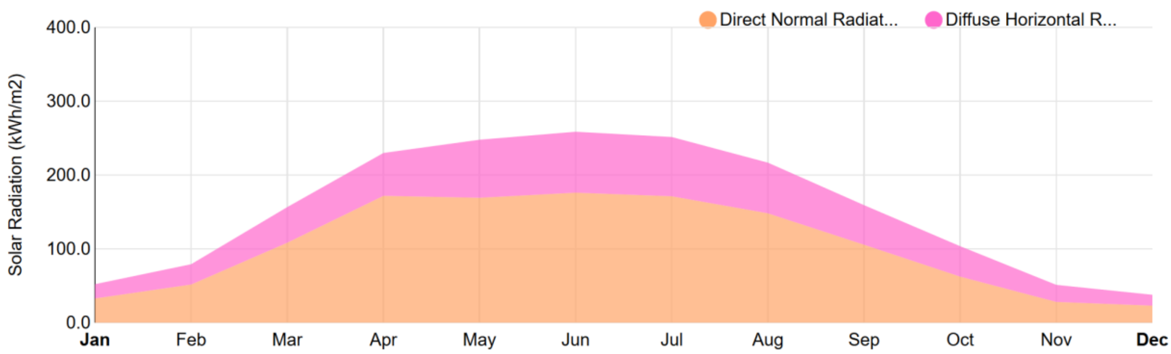


Figure 2 – Monthly total solar radiation profile of the climate file (EnSimS, 2019)

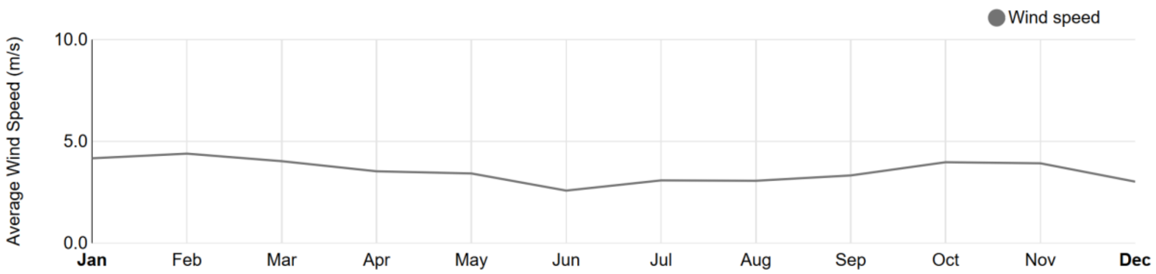


Figure 3 – Monthly total solar radiation profile of the climate file (EnSimS, 2019)

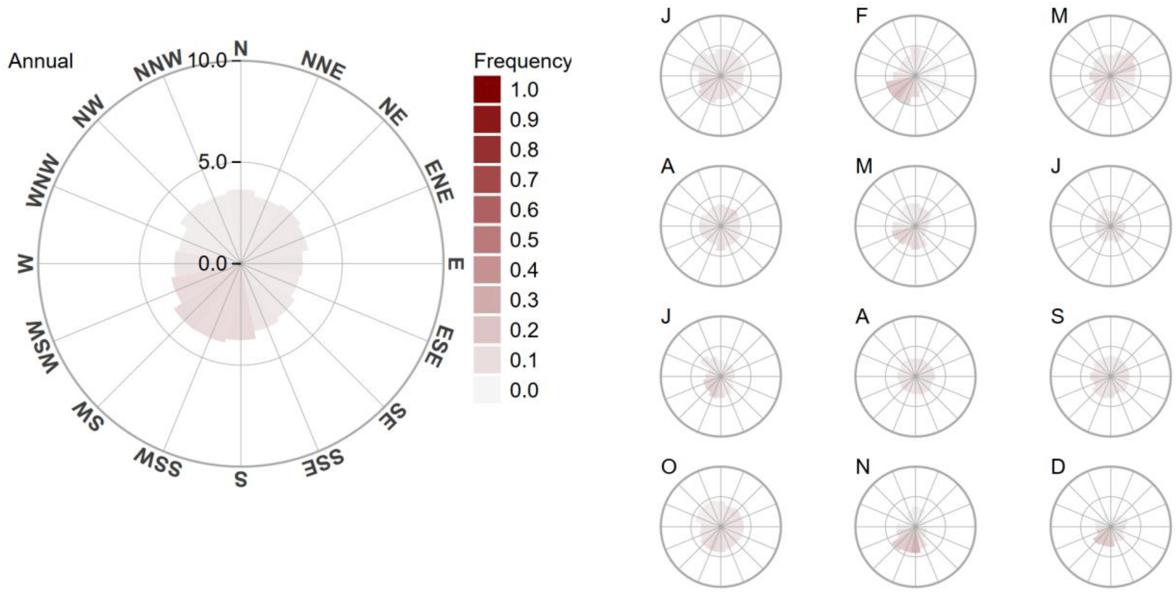
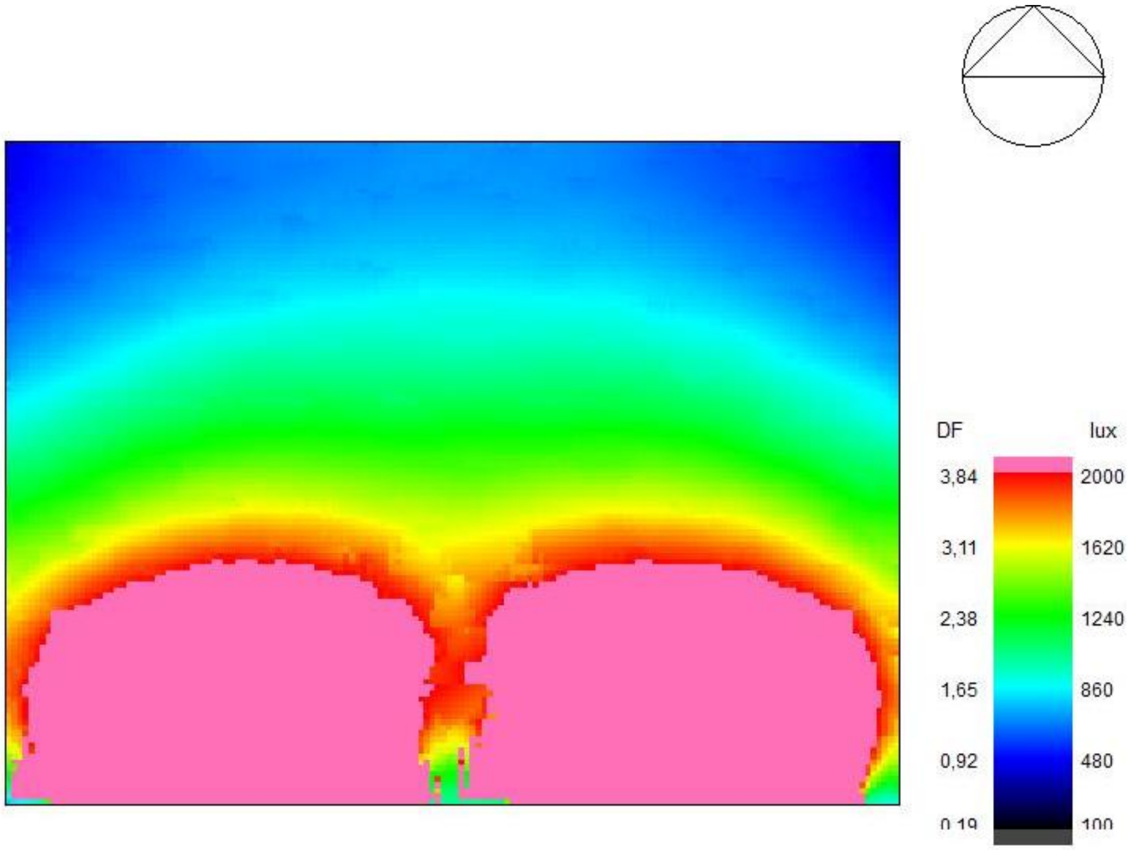
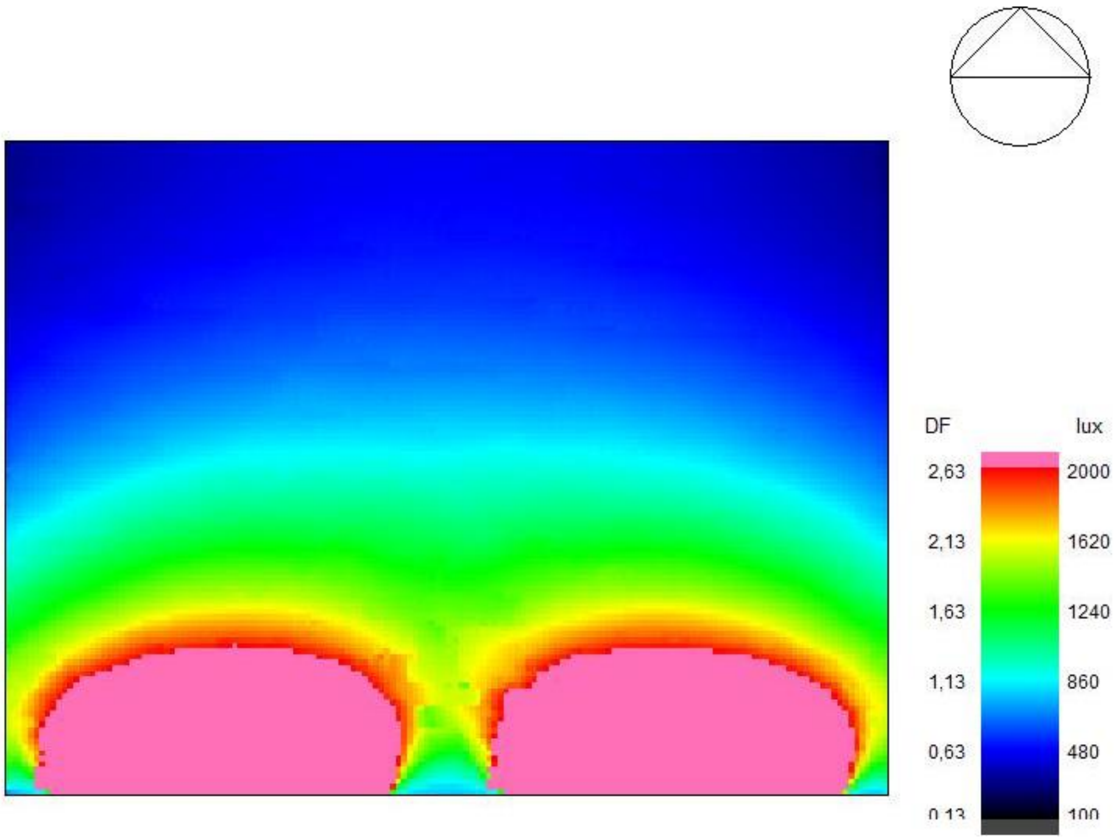


Figure 4 – Monthly wind direction of the climate file (EnSimS, 2019)

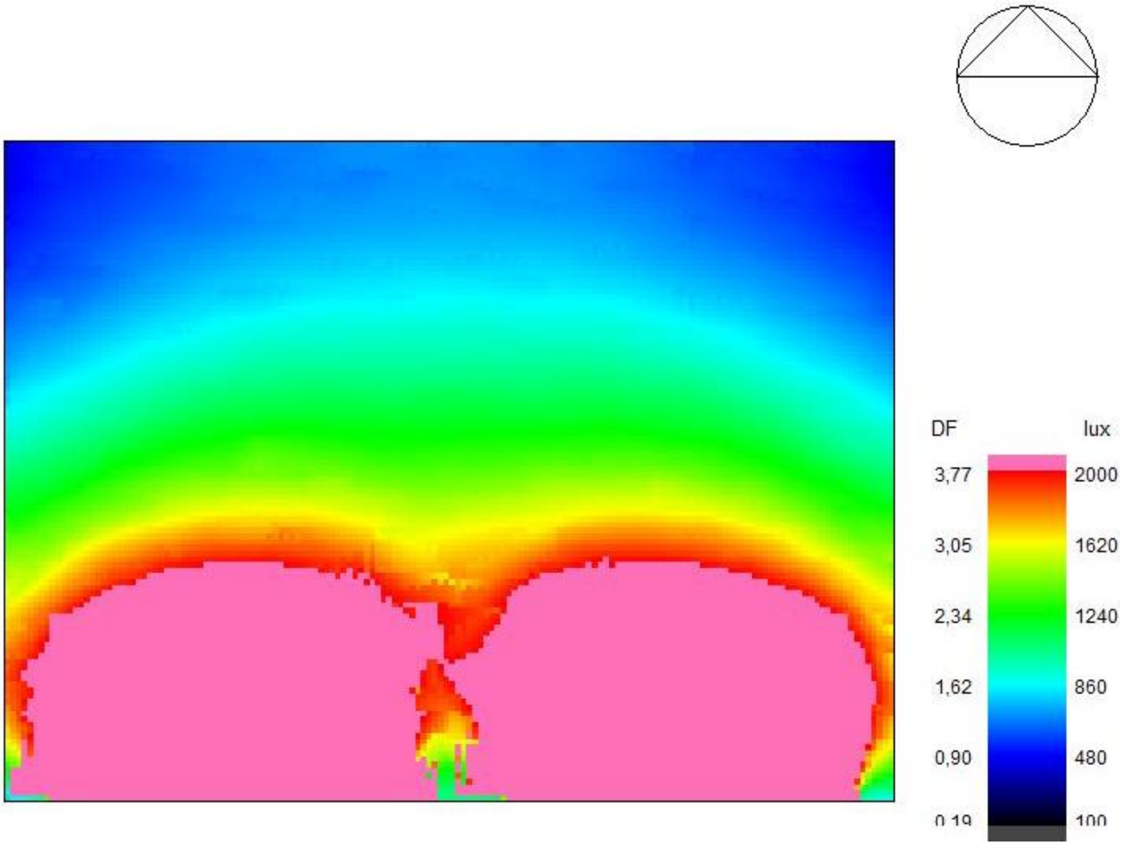
Appendix D: Daylighting results



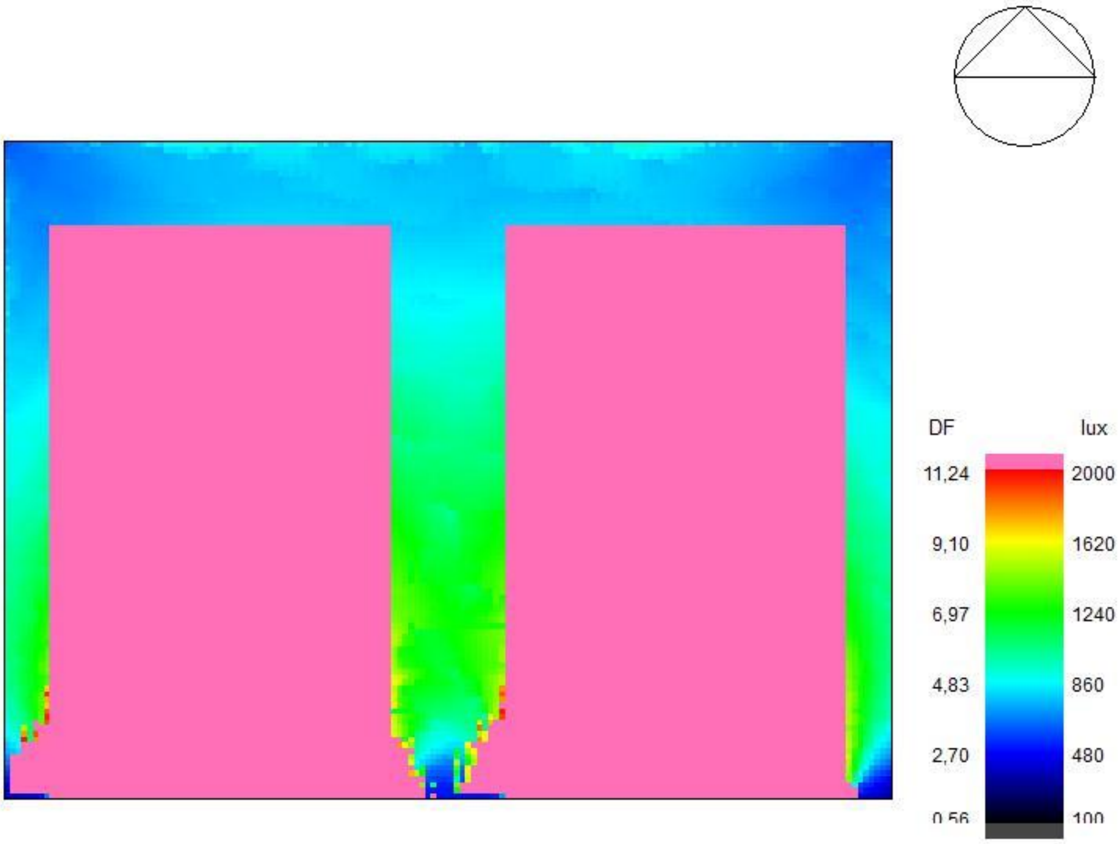
Base case, 21st March, 12 am



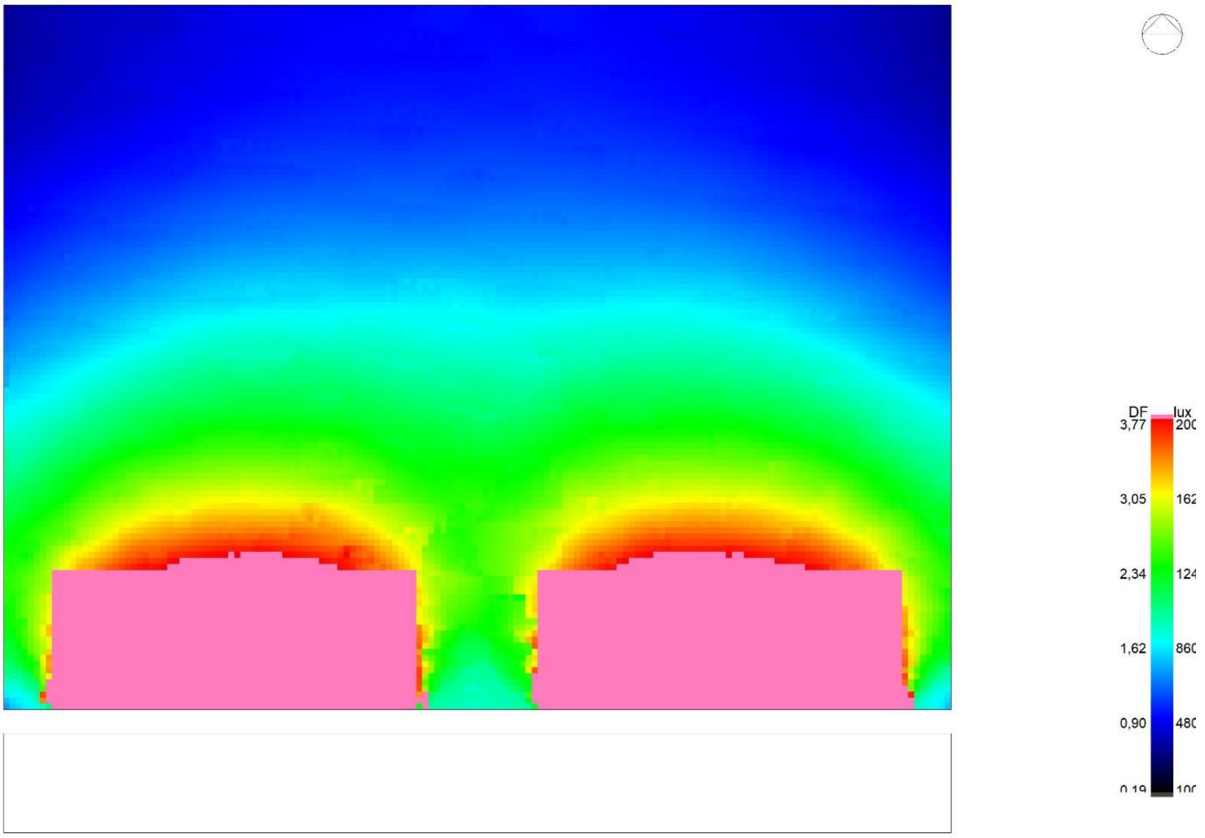
Base case, 21st June, 12 am



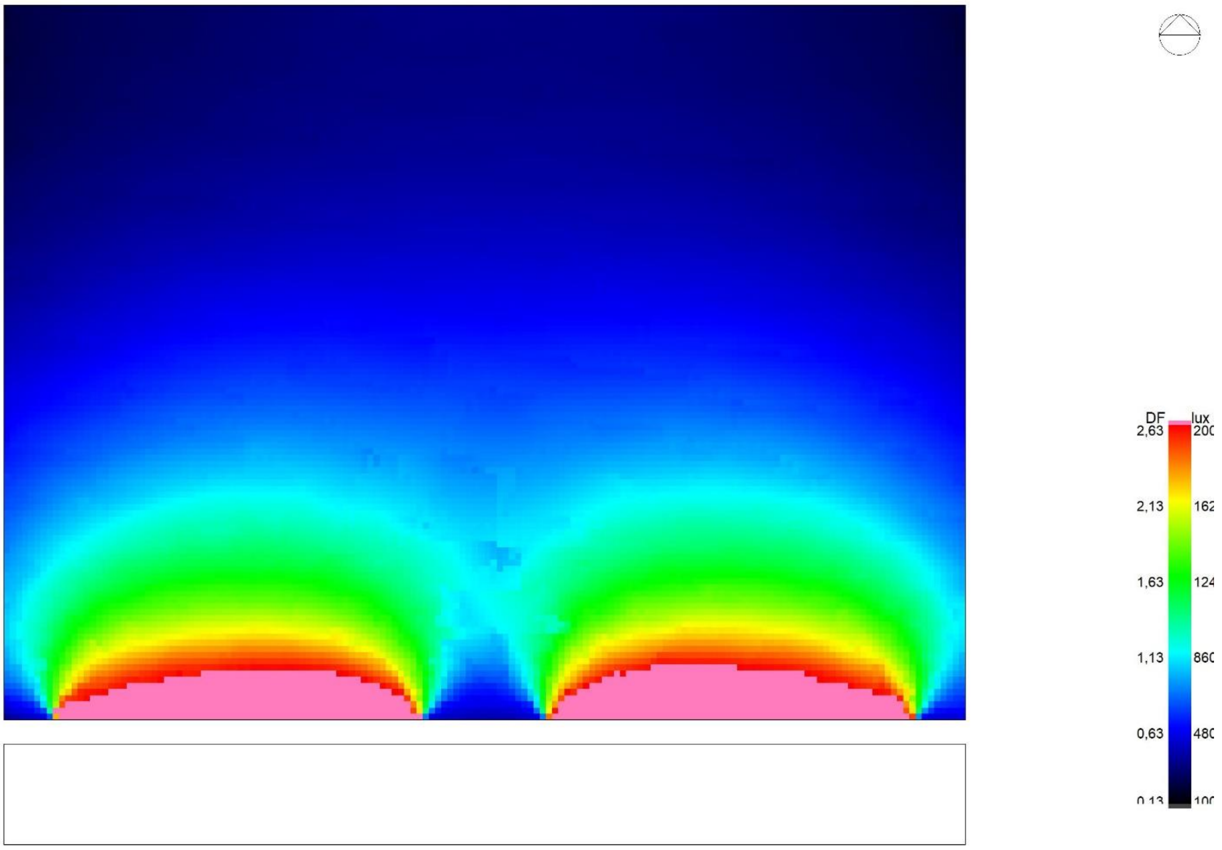
Base case, 21st September, 12 am



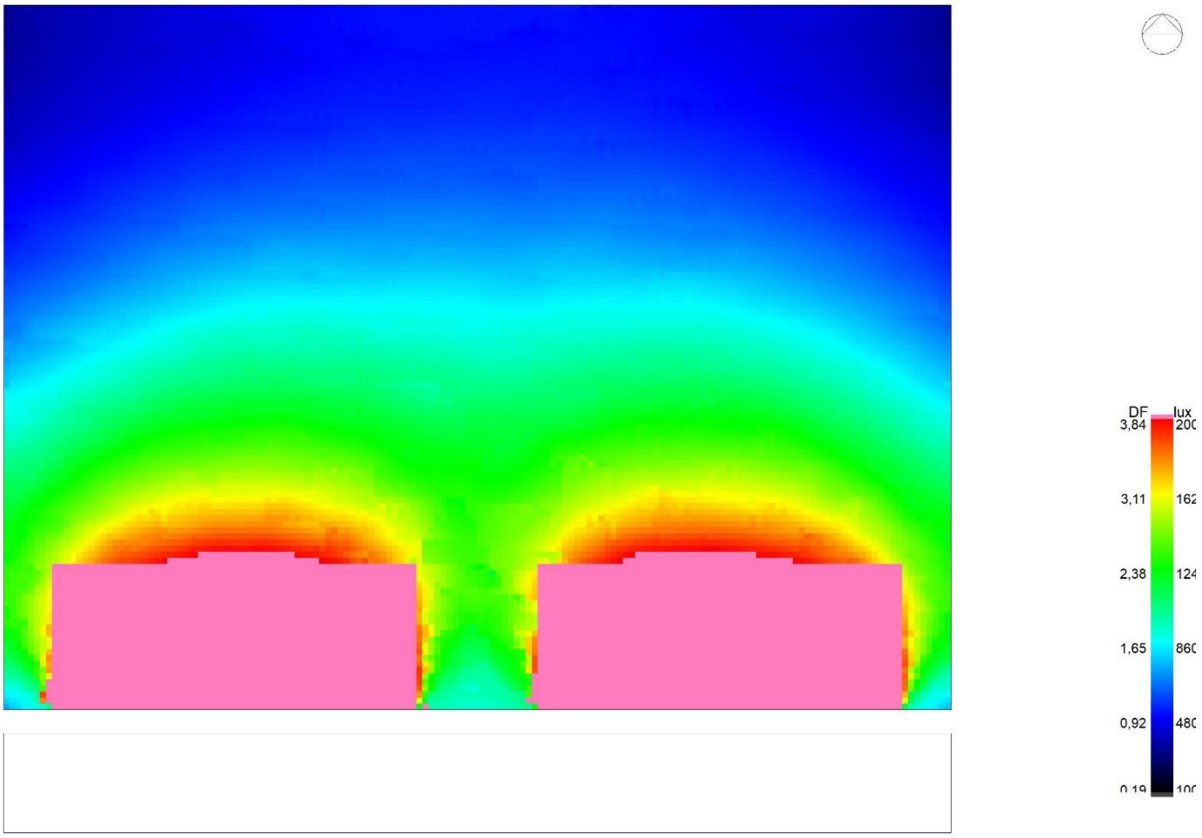
Base case, 21st December, 12 am



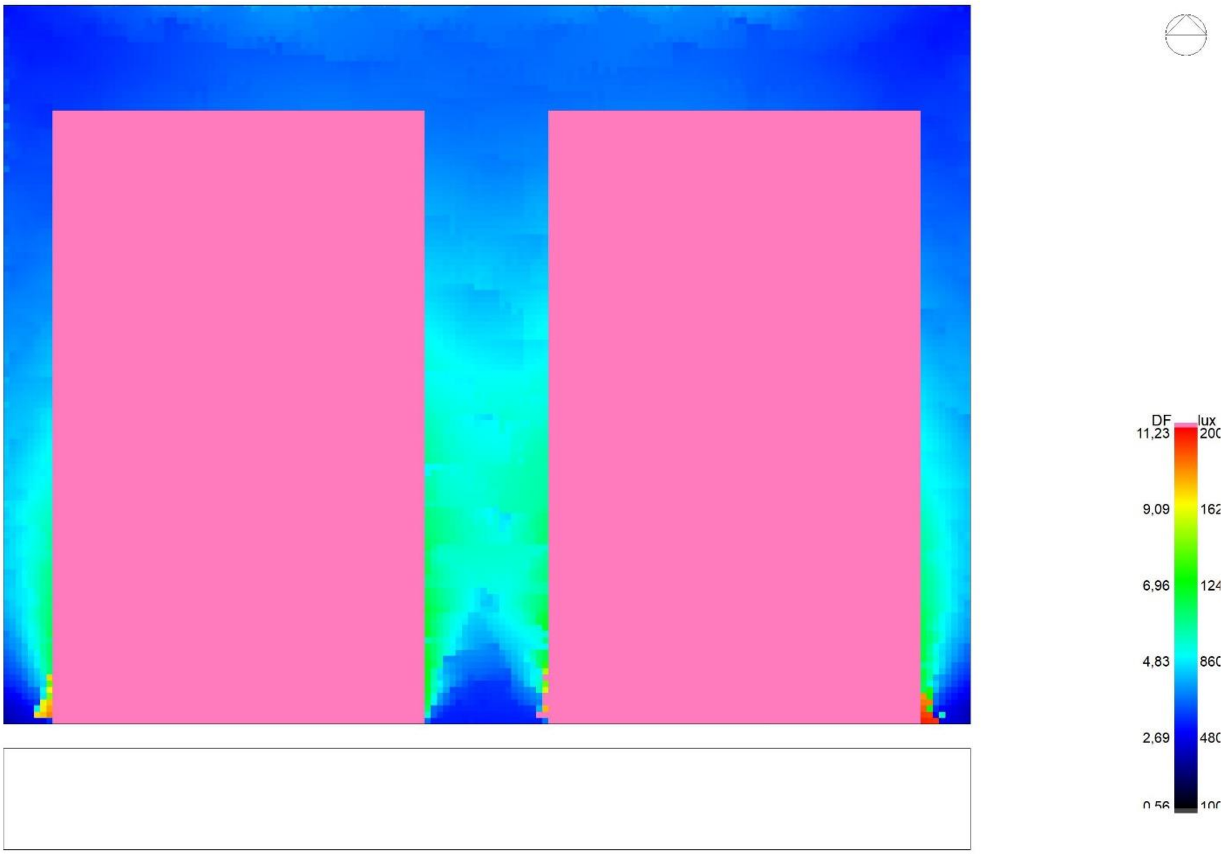
Double-skin façade case, 21st March, 12 am



Double-skin façade case, 21st June, 12 am



Double-skin façade case, 21st September, 12 am



Double-skin façade case, 21st December, 12 am

Appendix E: Summary of the annual results given by all simulations

						Energy						Thermal comfort				
	Diminutive	**Case**	**Ventilation mode**	**Control strategy**	**Threshold**	**Heating demand (kWh/year)**	**Heating loads saving (%)**	**Cooling demand (kWh/year)**	**Cooling loads saving (%)**	**Annual loads (kWh)**	**Energy saving (%)**	**Hours of discomforts with winter clothes (hours)**	**Hours of discomforts with summer clothes (hr)**	**Hours of discomforts with winter or summer clothes (hr)**	**Total hours of discomfort (hr)**	**Improving of thermal comfort (%)**
	Base case	Base	-	-	-	3804	100,0	5287	100,0	9091	100,0	2221	1282	704	4207	100,0
	ECW0	Electrochromic	-	On during schedule	-	3824	100,5	2880	54,5	6704	73,7	1864	1555	655	4074	96,8
	ECW1	Electrochromic	-	Solar	450 W/m²-K	3969	104,3	2601	49,2	6570	72,3	1974	1664	862	4500	107,0
	ECW2	Electrochromic	-	Operative temp.	24°C	3845	101,1	2922	55,3	6767	74,4	2078	1360	702	4140	98,4
	ECW3	Electrochromic	-	Glare	22	3804	100,0	5287	100,0	9091	100,0	2221	1282	704	4207	100,0
	ECW4	Electrochromic	-	Daylight	500 lux	3969	104,3	2600	49,2	6569	72,3	1974	1664	862	4500	107,0
	DS0	Dynamic shading	-	On during schedule		3834	100,8	2409	45,6	6243	68,7	1780	1667	692	4139	98,4
	DS1	Dynamic shading	-	Solar	450 W/m²-K	3840	100,9	2886	54,6	6726	74,0	2029	1461	722	4212	100,1
	DS2	Dynamic shading	-	Operative temp.	24°C	3858	101,4	2450	46,3	6308	69,4	1944	1477	706	4127	98,1
	DS3	Dynamic shading	-	Glare	22	3804	100,0	5287	100,0	9091	100,0	2221	1282	704	4207	100,0
	DSF0	Double skin facade	No vent.	-	-	2663	70,0	5710	108,0	8373	92,1	2202	1014	432	3648	86,7
	DSF1	Double skin facade	Natural	On during schedule	(5ac/h)	2788	73,3	5026	95,1	7814	86,0	2188	1071	458	3717	88,4
	DSF2	Double skin facade	Natural	Operative temp.	24°C ; 5ac/h	2704	71,1	5329	100,8	8033	88,4	2197	1015	432	3644	86,6
	DSFV1	Double skin ventilated facade	Mechanical	Operative temp.	24°C ; 5ac/h	2705	71,1	5329	100,8	8034	88,4	2196	1014	431	3641	86,5
	DSFV2	Double skin ventilated facade	Hybrid	Operative temp.	24°C ; 5ac/h	2723	71,6	5100	96,5	7823	86,1	2196	1014	432	3642	86,6
	Sensitivity analysis															
	Diminutive	**Case**	**Ventilation mode**	**Fixed parameters**	**Parameter varied**	**Heating demand (kWh/year)**	**Heating loads saving (%)**	**Cooling demand (kWh/year)**	**Cooling loads saving (%)**	**Annual loads (kWh)**	**Energy saving (%)**	**Hours of discomforts with winter clothes (hours)**	**Hours of discomforts with summer clothes (hr)**	**Hours of discomforts with winter or summer clothes (hr)**	**Total hours of discomfort (hr)**	**Improving of thermal comfort (%)**
Electrochromic case – Control strategythresholds	Sensitivity analysis : electrochromic - Solar threshold															
	ECW1-s150	Electrochromic	-	Optical properties	150 W/m²-K	4057	106,7	2432	46,0	6489	71,4	1979	1783	978	4740	112,7
	ECW1-s300	Electrochromic	-	Optical properties	300 W/m²-K	4015	105,5	2465,0	46,6	6480	71,3	1937	1765	909	4611	109,6
	ECW1	Electrochromic	-	Optical properties	450 W/m²-K	3840	100,9	2886	54,6	6726	74,0	2029	1461	722	4212	100,1
	ECW1-s600	Electrochromic	-	Optical properties	600 W/m²-K	3928	103,3	2944	55,7	6872	75,6	2080	1548	847	4475	106,4
	ECW1-s750	Electrochromic	-	Optical properties	750 W/m²-K	3918	103,0	3295	62,3	7213	79,3	2139	1506	848	4493	106,8
	Sensitivity analysis : electrochromic - Operative temperature threshold															
	ECW2-t18	Electrochromic	-	Optical properties	18°C	3825	100,6	2880	54,5	6705	73,8	1864	1555	655	4074	96,8
	ECW2-t20	Electrochromic	-	Optical properties	20°C	3824	100,5	2880	54,5	6704	73,7	1862	1555	653	4070	96,7
	ECW2-t22	Electrochromic	-	Optical properties	22°C	3877	101,9	2864	54,2	6741	74,2	1932	1521	711	4164	99,0
	ECW2	Electrochromic	-	Optical properties	24°C	3845	101,1	2922	55,3	6767	74,4	2078	1360	702	4140	98,4
	ECW2-t26	Electrochromic	-	Optical properties	26°C	3823	100,5	3334	63,1	7157	78,7	2186	1289	702	4177	99,3
c shading – Control strategythresholds	Sensitivity analysis : dynamic shading - solar threshold															
	DS1-s150	Dynamic shading	-	Slat properties	150 W/m²-K	3970	104,4	2324	44,0	6294	69,2	1885	1751	866	4502	107,0
	DS1-s300	Dynamic shading	-	Slat properties	300 W/m²-K	3910	102,8	2412	45,6	6322	69,5	1906	1644	787	4337	103,1
	DS1	Dynamic shading	-	Slat properties	450 W/m²-K	3840	100,9	2886	54,6	6726	74,0	2029	1461	722	4212	100,1
	DS1-s600	Dynamic shading	-	Slat properties	600 W/m²-K	3807	100,1	4051	76,6	7858	86,4	2175	1324	715	4214	100,2
	DS1-s750	Dynamic shading	-	Slat properties	750 W/m²-K	3805	100,0	5096	96,4	8901	97,9	2221	1284	705	4210	100,1
	Sensitivity analysis : electrochromic - Operative temperature threshold															
	DS2-t18	Dynamic shading	-	Slat properties	18°C	3834	100,8	2408	45,5	6242	68,7	1780	1667	692	4139	98,4
	DS2-t20	Dynamic shading	-	Slat properties	20°C	3834	100,8	2409	45,6	6243	68,7	1780	1667	693	4140	98,4
	DS2-t22	Dynamic shading	-	Slat properties	22°C	3898	102,5	2393	45,3	6291	69,2	1799	1672	716	4187	99,5
	DS2	Dynamic shading	-	Slat properties	24°C	3858	101,4	2450	46,3	6308	69,4	1944	1477	706	4127	98,1
	DS2-t26	Dynamic shading	-	Slat properties	26°C	3823	100,5	2563	48,5	6386	70,2	2190	1293	702	4185	99,5
	Sensitivity analysis : dynamic shading - slat angle															
	DS2-a15	Dynamic shading	-	OT - Threshold = 24°C, BtG = 0,05 m, slat width = 0,025 m, slat separation = 0,01875 m	15	3857	101,4	2452	46,4	6309	69,4	1946	1461	705	4112	97,7
	DS2-a30	Dynamic shading	-	OT - Threshold = 24°C, BtG = 0,05 m, slat width = 0,025 m, slat separation = 0,01875 m	30	3857	101,4	2460	46,5	6317	69,5	1946	1464	706	4116	97,8
	DS2	Dynamic shading	-	OT - Threshold = 24°C, BtG = 0,05 m, slat width = 0,025 m, slat separation = 0,01875 m	45°	3858	101,4	2450	46,3	6308	69,4	1944	1477	706	4127	98,1
	DS2-a60	Dynamic shading	-	OT - Threshold = 24°C, BtG = 0,05 m, slat width = 0,025 m, slat separation = 0,01875 m	60	3862	101,5	2439	46,1	6301	69,3	1935	1499	706	4140	98,4
	DS2-a75	Dynamic shading	-	OT - Threshold = 24°C, BtG = 0,05 m, slat width = 0,025 m, slat separation = 0,01875 m	75	3864	101,6	2434	46,0	6298	69,3	1920	1479	705	4104	97,6
	Sensitivity analysis : dynamic shading - slat separation															
	DS2-p005		-		0,005 m	3855	101,3	2470	46,7	6325	69,6	1954	1451	705	4110	97,7

Dynam	Slat properties	DS2-p010	Dynamic shading	-	OT - Threshold = 24°C, S_a = 45°, BtG = 0,05 m, slat width = 0,025 m,	0,01 m	3856	101,4	2465	46,6	6321	69,5	1950	1457	706	4113	97,8
		DS2		-		0,01875 m	3858	101,4	2450	46,3	6308	69,4	1944	1477	706	4127	98,1
		DS2-p025		-		0,025 m	3868	101,7	2440	46,2	6308	69,4	1894	1516	706	4116	97,8
		DS2-p0375		-		0,0375 m	3836	100,8	2495	47,2	6331	69,6	2040	1390	703	4133	98,2
		DS2-p050		-		0,05 m	3816	100,3	2822	53,4	6638	73,0	2118	1350	703	4171	99,1
		Sensitivity analysis : dynamic shading - slat width															
		DS2-w0,5	Dynamic shading	-	OT - Threshold = 24°C, S_a = 45°, BtG = 0,05 m, slat separation = 0,01875 m	0,5 cm	3799	99,9	3890	73,6	7689	84,6	2183	1302	700	4185	99,5
		DS2-w0,875				0,875 cm	3814	100,3	2926	55,3	6740	74,1	2128	1343	702	4173	99,2
		DS2-w1,25		-		1,25 cm	3837	100,9	2492	47,1	6329	69,6	2038	1391	703	4132	98,2
		DS2		-		2,50 cm	3858	101,4	2450	46,3	6308	69,4	1944	1477	706	4127	98,1
		DS2-w3,75		-		3,75 cm	3856	101,4	2461	46,5	6317	69,5	1948	1458	706	4112	97,7
		DS2-w5,00		-		5,00 cm	3855	101,3	2467	46,7	6322	69,5	1920	1479	705	4104	97,6
		Sensitivity analysis : dynamic shading - Blind-to-glass distance															
		DS2-b02	Dynamic shading	-	OT - Threshold = 24°C, S_a = 45°, slat width = 0,025 m, slat separation = 0,01875 m	0,02 m	3850	101,2	2542	48,1	6392	70,3	1970	1432	704	4106	97,6
		DS2-b035				0,035 m	3855	101,3	2477	46,9	6332	69,7	1950	1457	705	4112	97,7
		DS2		-		0,05 m	3858	101,4	2450	46,3	6308	69,4	1944	1477	706	4127	98,1
		DS2-b10		-		0,10 m	3861	101,5	2419	45,8	6280	69,1	1935	1494	706	4135	98,3
		DS2-b15				0,15 m	3861	101,5	2410	45,6	6271	69,0	1933	1494	707	4134	98,3
		DS2-b20		-		0,20 m	3862	101,5	2405	45,5	6267	68,9	1931	1495	707	4133	98,2
Double-skin facade		Sensitivity analysis : Double skin facade - natural ventilation - cavity depth															
	DB properties	DSF2	Double skin facade	Natural	T_n=24°C; 5ac/h	1	2704	71,1	5329	100,8	8033	88,4	2197	1015	432	3644	86,6
		DSF2-c0,75		Natural		0,75	2734	71,9	5600	105,9	8334	91,7	2217	995	423	3635	86,4
		DSF2-c0,5		Natural		0,5	2747	72,2	6118	115,7	8865	97,5	2236	977	419	3632	86,3
		DSF2-c0,25		Natural		0,25	2758	72,5	6620	125,2	9378	103,2	2248	961	409	3618	86,0
		Sensitivity analysis : Double-skin facade - temperature threshold															
	Threshold	DSF2-t18	Double skin facade	Natural	Cavity depth 1m,	18	2717	71,4	5305	100,3	8022	88,2	2187	1029	433	3649	86,7
		DSF2-t20		Natural		20	2712	71,3	5311	100,5	8023	88,3	2191	1022	433	3646	86,7
		DSF2-t22		Natural		22	2709	71,2	5319	100,6	8028	88,3	2194	1018	432	3644	86,6
		DSF2		Natural		24	2704	71,1	5329	100,8	8033	88,4	2197	1015	432	3644	86,6
		DSF2-t26		Natural		26	2701	71,0	5341	101,0	8042	88,5	2198	1015	432	3645	86,6
Double-skin ventilated façade		Sensitivity analysis : mechanical ventilation - mechanical flow ventilation															
	Mechanical ventilation	DSFV1-f3	Double skin ventilated facade	Mechanical	Cavity depth 1m, T_m=24°C	3	2693	70,8	5454	103,2	8147	89,6	2198	1016	432	3646	86,7
		DSFV1		Mechanical		5	2705	71,1	5329	100,8	8034	88,4	2196	1014	431	3641	86,5
		DSFV1-f10		Mechanical		10	2723	71,6	5100	96,5	7823	86,1	2196	1014	431	3641	86,5
		DSFV1-f15		Mechanical		15	2733	71,8	4943	93,5	7676	84,4	2196	1017	432	3645	86,6
		DSFV1-f20		Mechanical		20	2739	72,0	4832	91,4	7571	83,3	2196	1017	432	3645	86,6
		DSFV1-f25		Mechanical		25	2742	72,1	4753	89,9	7495	82,4	2196	1017	431	3644	86,6
		Sensitivity analysis : mechanical ventilation - temperature threshold															
		DSFV1-t18	Double skin ventilated facade	Mechanical	Cavity depth 1m, 5ac/h	18	2718	71,5	5305	100,3	8023	88,3	2187	1029	433	3649	86,7
		DSFV1-t20		Mechanical		20	2713	71,3	5311	100,5	8024	88,3	2191	1022	433	3646	86,7
		DSFV1-t22		Mechanical		22	2709	71,2	5319	100,6	8028	88,3	2195	1017	432	3644	86,6
		DSFV1		Mechanical		24	2705	71,1	5329	100,8	8034	88,4	2196	1014	431	3641	86,5
		DSFV1-t26		Mechanical		26	2702	71,0	5341	101,0	8043	88,5	2199	1015	432	3646	86,7
		Sensitivity analysis : hybrid ventilation - temperature threshold															
	Hybrid ventilation	DSFV2-t18	Double skin ventilated facade	Hybrid	Cavity depth 1m, 5ac/h	18	2745	72,2	5054	95,6	7799	85,8	2180	1032	432	3644	86,6
		DSFV2-t20		Hybrid		20	2736	71,9	5066	95,8	7802	85,8	2187	1023	432	3642	86,6
		DSFV2-t22		Hybrid		22	2729	71,7	5082	96,1	7811	85,9	2194	1018	432	3644	86,6
		DSFV2		Hybrid		24	2723	71,6	5100	96,5	7823	86,1	2196	1014	432	3642	86,6
		DSFV2-t26		Hybrid		26	2719	71,5	5119	96,8	7838	86,2	2198	1015	432	3645	86,6
		Sensitivity analysis : mechanical ventilation - mechanical flow ventilation															
		DSFV2-f3	Double skin ventilated facade	Hybrid	Cavity depth 1m, T_m=24°C	3	2718	71,5	5181	98,0	7899	86,9	2197	1015	432	3644	86,6
		DSFV2		Hybrid		5	2723	71,6	5100	96,5	7823	86,1	2196	1014	432	3642	86,6
		DSFV2-f10		Hybrid		10	2733	71,8	4943	93,5	7676	84,4	2196	1017	431	3644	86,6
		DSFV2-f15		Hybrid		15	2739	72,0	4832	91,4	7571	83,3	2196	1017	432	3645	86,6
		DSFV2-f20		Hybrid		20	2742	72,1	4753	89,9	7495	82,4	2195	1017	431	3643	86,6
		DSFV2-f25		Hybrid		25	2744	72,1	4694	88,8	7438	81,8	2194	1018	432	3644	86,6

Final comparative analysis															
Diminutive	**Case**	**Ventilation mode**	**Control strategy**	**Threshold**	**Heating demand (kWh/year)**	**Heating loads saving (%)**	**Cooling demand (kWh/year)**	**Cooling loads saving (%)**	**Annual loads (kWh)**	**Energy saving (%)**	**Hours of discomforts with winter clothes (%)**	**Hours of discomforts with summer clothes (%)**	**Hours of discomforts with winter or summer clothes (%)**	**Total hours of discomfort (%)**	**Improving of thermal comfort (%)**
Base case	Base	-	-	-	3804	100,0	5287	100,0	9091	100,0	2221	1282	704	4207	100,0
ECW0	Electrochromic	-	Schedule	-	3824	100,5	2880	54,5	6704	73,7	1864	1555	655	4074	96,8
ECW1		-	Solar	450 W/m²-K	3969	104,3	2601	49,2	6570	72,3	1974	1664	862	4500	107,0
ECW2		-	Operative temp.	24°C	3845	101,1	2922	55,3	6767	74,4	2078	1360	702	4140	98,4
ECW3		-	Glare	22	3804	100,0	5287	100,0	9091	100,0	2221	1282	704	4207	100,0
DS0	Dynamic shading	-	Schedule		3834	100,8	2409	45,6	6243	68,7	1780	1667	692	4139	98,4
DS1-s300		-	Solar	300 W/m²-K	3910	102,8	2412	45,6	6322	69,5	1906	1644	787	4337	103,1
DS2		-	Operative temp.	24°C	3858	101,4	2450	46,3	6308	69,4	1944	1477	706	4127	98,1
DS3		-	Glare	22	3804	100,0	5287	100,0	9091	100,0	2221	1282	704	4207	100,0
DSF0	Double skin facade	No vent.	-	-	2663	70,0	5710	108,0	8373	92,1	2202	1014	432	3648	86,7
DSF1		Natural	Schedule		2788	73,3	5027	95,1	7815	86,0	2188	1071	458	3717	88,4
DSF2		Natural	Operative temp.	24°C ; 5ac/h	2704	71,1	5329	100,8	8033	88,4	2197	1015	432	3644	86,6
DSFV1-f25	Double skin ventilated facade	Mechanical	Operative temp.	24°C ; 25ac/h	2742	72,1	4753	89,9	7495	82,4	2196	1017	431	3644	86,6
DSFV2-f25		Hybrid	Operative temp.	24°C ; 25ac/h	2744	72,1	4694	88,8	7438	81,8	2194	1018	432	3644	86,6

Appendix E.1: Results of the base case

Base case results								
	Heating demand (kWh)	Cooling demand (kWh)		Inside Surface Temp (°C)	Ext Surface Temp (°C)		Solar Incident (kWh)	Solar Trans (kWh)
Jan	783,5	82,8	Jan	15,2	7,1	Jan	310,6	343,8
Feb	625,1	215,8	Feb	15,9	8,0	Feb	424,0	474,7
Mar	509,8	468,3	Mar	17,5	9,8	Mar	712,4	762,4
Apr	311,1	667,4	Apr	19,5	13,2	Apr	838,6	840,3
May	164,7	522,9	May	20,6	15,5	May	725,0	620,3
Jun	69,6	576,2	Jun	22,5	18,8	Jun	669,1	533,5
Jul	27,1	663,2	Jul	23,3	20,1	Jul	696,8	575,5
Aug	45,1	756,3	Aug	23,0	19,8	Aug	739,2	690,1
Sep	127,4	611,3	Sep	21,2	16,9	Sep	667,9	679,7
Oct	269,0	370,1	Oct	19,3	13,9	Oct	530,1	561,7
Nov	544,3	86,9	Nov	16,5	10,0	Nov	289,1	305,9
Dec	795,3	56,5	Dec	15,4	8,1	Dec	227,9	251,6

Appendix E.2: Results of electrochromic cases

ECW results

	Heating demand (kWh)				
	Base case	ECW 0 - On during schedule	ECW 1 - solar	ECW 2 - OT	ECW 3 - Glare
Jan	783,5	692,2	684,3	689,9	783,5
Feb	625,1	567,7	563,8	571,0	625,1
Mar	509,8	485,2	485,9	485,7	509,8
Apr	311,1	299,0	305,4	305,7	311,1
May	164,7	164,4	163,1	164,3	164,7
Jun	69,6	69,8	69,6	69,8	69,6
Jul	27,1	27,2	27,0	27,2	27,1
Aug	45,1	45,0	44,9	45,0	45,1
Sep	127,4	120,3	120,4	119,7	127,4
Oct	269,0	238,5	238,6	238,2	269,0
Nov	544,3	454,8	455,1	460,2	544,3
Dec	795,3	660,5	665,0	668,8	795,3

	Cooling demand (kWh)				
	Base case	ECW 0 - On during schedule	ECW 1 - solar	ECW 2 - OT	ECW 3 - Glare
Jan	82,8	6,3	16,2	6,6	82,8
Feb	215,8	50,3	55,4	52,8	215,8
Mar	468,3	217,2	245,2	227,2	468,3
Apr	667,4	320,3	357,2	339,4	667,4
May	522,9	307,3	357,1	311,5	522,9
Jun	576,2	430,4	471,3	427,7	576,2
Jul	663,2	480,9	528,7	475,0	663,2
Aug	756,3	504,5	548,9	501,9	756,3
Sep	611,3	339,3	379,2	344,0	611,3
Oct	370,1	165,9	233,6	176,4	370,1
Nov	86,9	30,4	38,9	32,1	86,9
Dec	56,5	28,1	32,6	28,1	56,5

	Surface temperatures (°C)							
	Temp - Base case	Temp - Base case	Inside Surface Temp - ECW0	Ext Surface Temp - ECW0	Inside Surface Temp - ECW1	Ext Surface Temp - ECW1	Inside Surface Temp - ECW2	Ext Surface Temp - ECW2
Jan	15,2	7,1	15,5	8,9	15,3	7,9	15,4	8,2
Feb	15,9	8,0	16,6	10,7	16,4	9,6	16,4	9,9
Mar	17,5	9,8	18,5	13,3	18,2	12,0	18,3	12,4
Apr	19,5	13,2	21,2	18,1	20,7	16,7	21,0	17,3
May	20,6	15,5	21,9	19,3	21,3	17,5	21,7	18,6
Jun	22,5	18,8	23,9	22,4	23,2	20,6	23,7	22,1
Jul	23,3	20,1	24,8	24,0	23,9	22,0	24,6	23,6
Aug	23,0	19,8	24,6	24,1	23,9	22,4	24,4	23,7
Sep	21,2	16,9	22,6	20,8	22,1	19,5	22,4	20,4
Oct	19,3	13,9	20,3	16,9	19,8	15,3	20,1	16,3
Nov	16,5	10,0	16,9	11,5	16,6	10,4	16,7	10,8
Dec	15,4	8,1	15,7	9,4	15,5	8,4	15,5	8,7

	Solar radiation (kWh)				
	Solar Incident	Solar Trans - Base case	Solar Trans - ECW0	Solar Trans - ECW1	Solar Trans - ECW2
Jan	310,6	343,8	83,8	223,6	185,1
Feb	424,0	474,7	132,3	243,0	213,1
Mar	712,4	762,4	298,4	437,4	392,6
Apr	838,6	840,3	256,8	390,6	330,8
May	725,0	620,3	194,5	359,6	245,4
Jun	669,1	533,5	199,2	342,8	223,0
Jul	696,8	575,5	181,1	346,9	208,5
Aug	739,2	690,1	213,3	361,2	243,3
Sep	667,9	679,7	193,4	332,6	238,7
Oct	530,1	561,7	165,0	348,6	232,6
Nov	289,1	305,9	118,5	234,8	189,3
Dec	227,9	251,6	100,4	204,3	173,4

Appendix E.3: Results of dynamic shading cases

DS results

	Heating demand (kWh)				
	Base case	DS 0 - Schedule	DS 1 - solar	DS 2 - OT	DS 3 - Glare
Jan	783,5	686,7	686,6	691,6	783,5
Feb	625,1	574,2	571,3	577,2	625,1
Mar	509,8	495,4	491,2	491,0	509,8
Apr	311,1	302,0	305,5	306,3	311,1
May	164,7	162,4	163,1	162,5	164,7
Jun	69,6	69,8	69,6	69,8	69,6
Jul	27,1	27,1	27,0	27,1	27,1
Aug	45,1	44,9	44,9	44,9	45,1
Sep	127,4	120,1	120,4	119,4	127,4
Oct	269,0	239,0	238,6	237,9	269,0
Nov	544,3	453,2	455,4	459,8	544,3
Dec	795,3	659,6	666,9	671,0	795,3

	Cooling demand (kWh)				
	Base case	DS 0 - Schedule	DS 1 - solar	DS 2 - OT	DS 3 - Glare
Jan	82,8	6,3	15,3	6,3	82,8
Feb	215,8	50,3	54,1	50,3	215,8
Mar	468,3	192,6	217,0	199,6	468,3
Apr	667,4	252,2	290,1	266,0	667,4
May	522,9	246,7	314,0	254,2	522,9
Jun	576,2	369,6	431,3	368,9	576,2
Jul	663,2	412,5	486,4	409,5	663,2
Aug	756,3	418,0	485,2	418,8	756,3
Sep	611,3	268,4	318,5	275,6	611,3
Oct	370,1	133,7	205,6	142,6	370,1
Nov	86,9	30,4	36,7	30,4	86,9
Dec	56,5	28,1	32,0	28,1	56,5

	Surface temperatures (°C)							
	Inside Surface Temp - Base case	Ext Surface Temp - Base case	Inside Surface Temp - DS 0	Ext Surface Temp - DS 0	Inside Surface Temp - DS 1	Ext Surface Temp - DS 1	Inside Surface Temp - DS 2	Ext Surface Temp - DS 2
Jan	15,2	7,1	15,1	7,9	15,0	7,6	15,4	8,2
Feb	15,9	8,0	15,7	9,3	15,6	9,0	16,4	9,9
Mar	17,5	9,8	17,3	11,9	17,3	11,3	18,3	12,4
Apr	19,5	13,2	19,4	16,5	19,4	15,6	21,0	17,3
May	20,6	15,5	20,7	18,2	20,6	17,0	21,7	18,6
Jun	22,5	18,8	22,7	21,7	22,5	20,2	23,7	22,1
Jul	23,3	20,1	23,5	23,1	23,3	21,5	24,6	23,6
Aug	23,0	19,8	23,1	23,1	23,0	21,8	24,4	23,7
Sep	21,2	16,9	21,3	19,8	21,1	18,8	22,4	20,4
Oct	19,3	13,9	19,3	15,8	19,2	14,9	20,1	16,3
Nov	16,5	10,0	16,6	10,6	16,4	10,3	16,7	10,8
Dec	15,4	8,1	15,5	8,4	15,3	8,3	15,5	8,7

	Solar radiation (kWh)				
	Solar Incident	Solar Trans - Base case	Solar Trans - DS 0	Solar Trans - DS 1	Solar Trans - DS 2
Jan	310,6	343,8	88,5	225,1	185,1
Feb	424,0	474,7	139,3	246,6	213,1
Mar	712,4	762,4	310,8	444,4	392,6
Apr	838,6	840,3	277,4	403,9	330,8
May	725,0	620,3	218,2	370,5	245,4
Jun	669,1	533,5	221,6	352,3	223,0
Jul	696,8	575,5	205,2	357,3	208,5
Aug	739,2	690,1	234,1	372,5	243,3
Sep	667,9	679,7	208,3	341,3	238,7
Oct	530,1	561,7	174,8	352,7	232,6
Nov	289,1	305,9	122,8	235,8	189,3
Dec	227,9	251,6	103,5	204,9	173,4

Appendix E.4: Results of the double-skin façades

	Heating demand (kWh)			
	Base case	DSF 1 - Schedule	DSF 2 - OT	DSF 0 - No vent
Jan	783,5	530,2	511,5	508,0
Feb	625,1	430,1	418,2	413,3
Mar	509,8	348,3	338,7	332,0
Apr	311,1	209,1	205,1	197,9
May	164,7	103,9	101,2	96,6
Jun	69,6	41,5	40,7	39,1
Jul	27,1	10,0	9,5	8,8
Aug	45,1	16,8	15,9	14,6
Sep	127,4	68,9	67,0	64,4
Oct	269,0	161,7	157,9	153,6
Nov	544,3	341,3	330,2	328,2
Dec	795,3	527,0	508,9	506,7

	Cooling demand (kWh)			
	Base case	DSF 1 - Schedule	DSF 2 - OT	DSF 0 - No vent
Jan	82,8	114,8	130,1	142,7
Feb	215,8	227,4	247,9	268,4
Mar	468,3	427,9	456,3	488,4
Apr	667,4	591,2	629,9	680,0
May	522,9	495,2	528,7	574,1
Jun	576,2	564,9	592,2	632,6
Jul	663,2	660,3	690,9	737,1
Aug	756,3	731,1	762,8	811,3
Sep	611,3	611,7	641,0	681,2
Oct	370,1	427,5	453,6	482,0
Nov	86,9	109,4	122,5	132,9
Dec	56,5	64,3	73,5	79,8

	Surface temperatures (°C)													
	Inside Surface Temp -	Ext Surface Temp -	I.R temp - DSF 1	E.R temp - DSF 1	I.C temp - DSF 1	E.C temp - DSF 1	I.R temp - DSF 2	E.R temp - DSF 2	I.C temp - DSF 2	E.C temp - DSF 2	I.R temp - DSF 0	E.R temp - DSF 0	I.C temp - DSF 0	E.C temp - DSF 0
Jan	15,2	7,1	18,9	15,7	10,7	5,7	19,3	16,5	11,4	5,9	19,5	17,0	11,9	6,1
Feb	15,9	8,0	20,0	17,6	12,9	7,0	20,4	18,2	13,4	7,2	20,8	19,1	14,3	7,4
Mar	17,5	9,8	22,3	21,4	17,0	9,7	22,5	21,8	17,4	9,8	23,2	23,1	18,6	10,2
Apr	19,5	13,2	24,3	24,8	21,4	13,9	24,4	25,0	21,6	13,9	25,3	27,0	23,4	14,6
May	20,6	15,5	24,8	25,5	22,6	16,2	24,8	25,6	22,7	16,2	25,7	27,3	24,2	16,8
Jun	22,5	18,8	26,1	27,6	25,5	19,9	26,2	27,6	25,6	20,0	26,9	29,0	26,9	20,4
Jul	23,3	20,1	26,8	28,4	26,6	21,3	26,8	28,4	26,7	21,3	27,5	29,9	28,1	21,8
Aug	23,0	19,8	26,5	28,3	26,6	21,1	26,6	28,3	26,7	21,1	27,3	29,9	28,1	21,7
Sep	21,2	16,9	24,9	25,7	23,3	17,7	25,0	25,8	23,5	17,7	25,7	27,3	24,8	18,2
Oct	19,3	13,9	22,8	22,2	19,0	13,8	23,0	22,4	19,2	13,9	23,6	23,6	20,3	14,3
Nov	16,5	10,0	20,0	17,6	13,4	8,9	20,3	18,2	14,0	9,1	20,5	18,6	14,3	9,2
Dec	15,4	8,1	18,7	15,5	10,8	6,5	19,1	16,3	11,5	6,7	19,3	16,6	11,8	6,8

	Solar radiation (kWh)					
	Solar Incident - Base case	Solar Trans - Base case	Solar Incident - DSF	Solar Trans - DSF 1	Solar Trans - DSF 2	Solar Trans - DSF 0
Jan	310,6	343,8	310,5	343,6	343,6	343,6
Feb	424,0	474,7	423,8	474,5	474,5	474,5
Mar	712,4	762,4	712,1	762,2	762,2	762,2
Apr	838,6	840,3	838,2	840,0	840,0	840,0
May	725,0	620,3	724,7	620,1	620,1	620,1
Jun	669,1	533,5	668,8	533,3	533,3	533,3
Jul	696,8	575,5	696,5	575,3	575,3	575,3
Aug	739,2	690,1	738,9	689,8	689,8	689,8
Sep	667,9	679,7	667,7	679,4	679,4	679,4
Oct	530,1	561,7	529,9	561,5	561,5	561,5
Nov	289,1	305,9	289,0	305,8	305,8	305,8
Dec	227,9	251,6	227,9	251,5	251,5	251,5

Appendix E.5: Results of the double-skin ventilated cases

	Heating demand (kWh)		
	Base case	DSFV 1 - Only mech	DSFV 2 - hybrid
Jan	783,5	511,6	512,7
Feb	625,1	418,3	420,2
Mar	509,8	338,8	341,5
Apr	311,1	205,2	208,8
May	164,7	101,2	103,7
Jun	69,6	40,7	41,5
Jul	27,1	9,5	10,0
Aug	45,1	15,9	16,7
Sep	127,4	67,1	68,4
Oct	269,0	158,0	159,7
Nov	544,3	330,3	330,9
Dec	795,3	509,1	509,7

	Cooling demand (kWh)		
	Base case	DSFV 1 - Only mech	DSFV 2 - hybrid
Jan	82,8	130,1	123,4
Feb	215,8	247,9	235,6
Mar	468,3	456,3	437,0
Apr	667,4	629,9	598,6
May	522,9	528,7	501,4
Jun	576,2	592,2	567,8
Jul	663,2	690,9	663,3
Aug	756,3	762,8	734,0
Sep	611,3	641,0	616,3
Oct	370,1	453,6	435,4
Nov	86,9	122,5	117,3
Dec	56,5	73,5	70,5

	Surface temperatures (°C)									
	Inside Surface Temp - Base case	Ext Surface Temp - Base case	I.R temp - DSFV 1	E.R temp - DSFV 1	I.C temp - DSFV 1	E.C temp - DSFV 1	I.R temp - DSFV 2	E.R temp - DSFV 2	I.C temp - DSFV 2	E.C temp - DSFV 2
Jan	15,2	7,1	19,3	16,5	11,4	5,9	19,2	16,3	11,3	5,9
Feb	15,9	8,0	20,4	18,2	13,4	7,2	20,2	17,9	13,1	7,1
Mar	17,5	9,8	22,5	21,8	17,4	9,8	22,3	21,3	16,9	9,7
Apr	19,5	13,2	24,4	25,0	21,6	13,9	23,9	24,2	20,8	13,7
May	20,6	15,5	24,8	25,6	22,7	16,2	24,5	24,9	22,0	16,0
Jun	22,5	18,8	26,2	27,6	25,6	20,0	25,9	27,0	25,0	19,8
Jul	23,3	20,1	26,8	28,4	26,7	21,3	26,5	27,8	26,0	21,1
Aug	23,0	19,8	26,6	28,3	26,7	21,1	26,2	27,6	26,0	20,9
Sep	21,2	16,9	25,0	25,8	23,5	17,7	24,6	25,2	22,8	17,5
Oct	19,3	13,9	23,0	22,4	19,2	13,9	22,8	22,0	18,8	13,8
Nov	16,5	10,0	20,3	18,2	14,0	9,1	20,3	18,1	13,9	9,1
Dec	15,4	8,1	19,1	16,3	11,5	6,7	19,1	16,2	11,4	6,7

	Solar radiation (kWh)				
	Solar Incident - Base case	Solar Trans - Base case	Solar Incident - DSF	Solar Trans - DSFV 1	Solar Trans - DSFV 2
Jan	310,6	343,8	310,5	343,6	343,6
Feb	424,0	474,7	423,8	474,5	474,5
Mar	712,4	762,4	712,1	762,2	762,2
Apr	838,6	840,3	838,2	840,0	840,0
May	725,0	620,3	724,7	620,1	620,1
Jun	669,1	533,5	668,8	533,3	533,3
Jul	696,8	575,5	696,5	575,3	575,3
Aug	739,2	690,1	738,9	689,8	689,8
Sep	667,9	679,7	667,7	679,4	679,4
Oct	530,1	561,7	529,9	561,5	561,5
Nov	289,1	305,9	289,0	305,8	305,8
Dec	227,9	251,6	227,9	251,5	251,5