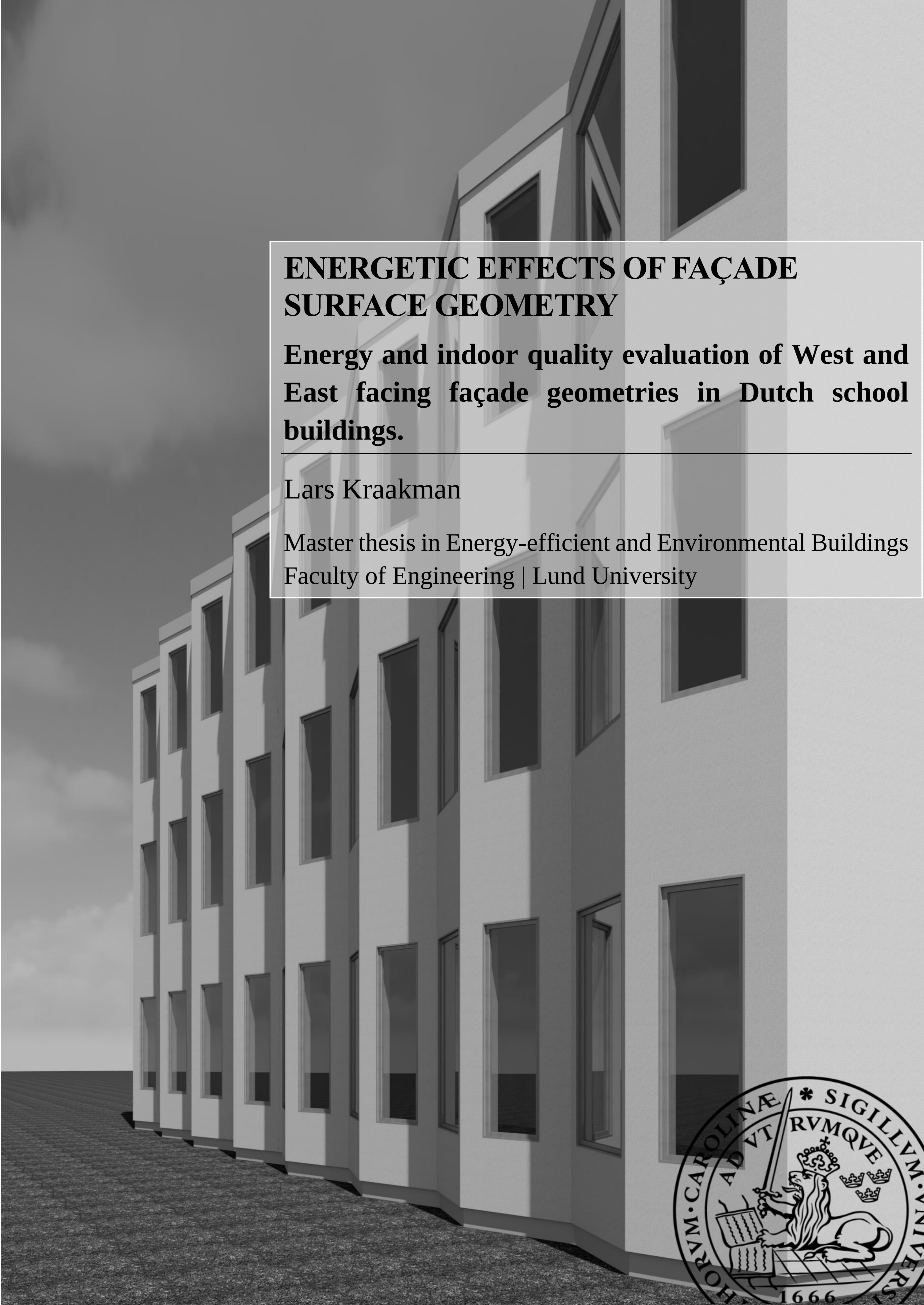

ENERGETIC EFFECTS OF FAÇADE SURFACE GEOMETRY

Energy and indoor quality evaluation of West and East facing façade geometries in Dutch school buildings.

Lars Kraakman

Master thesis in Energy-efficient and Environmental Buildings

Faculty of Engineering | Lund University

Lund University

Lund University, with eight faculties and a number of research centers and specialized institutes, is the largest establishment for research and higher education in Scandinavia. The main part of the University is situated in the small city of Lund which has about 112 000 inhabitants. A number of departments for research and education are, however, located in Malmö. Lund University was founded in 1666 and has today a total staff of 6 000 employees and 47 000 students attending 280 degree programmes and 2 300 subject courses offered by 63 departments.

Master Programme in Energy-efficient and Environmental Building Design

This international programme provides knowledge, skills and competencies within the area of energy-efficient and environmental building design in cold climates. The goal is to train highly skilled professionals, who will significantly contribute to and influence the design, building or renovation of energy-efficient buildings, taking into consideration the architecture and environment, the inhabitants' behaviour and needs, their health and comfort as well as the overall economy.

The degree project is the final part of the master programme leading to a Master of Science (120 credits) in Energy-efficient and Environmental Buildings.

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Abstract

Designing an energy-efficient building with the use of passive design measures is not always possible due to the location, surrounding buildings or site layout. This can result in larger façade areas facing East or West and causes issues with the low sun altitude. The sun can thereby not be blocked constantly, since daylight is needed for the well-being of students and improves their study performance. It was expected to improve the energy efficiency, indoor thermal- and visual comfort by applying a vertical folded façade geometry of the envelope surface. Additionally, a vertical type of façade geometry was rarely touched by literature. Therefore, this study of the effect of a vertical folded facade was carried out in order to find an improved façade design. Thereby included a sensitivity analysis taking into account the heating- and cooling demand, electric lighting, daylight factor and overheating period as indicators. The analysis was conducted on a hypothetical classroom, based on references and located in Amsterdam, with one exterior wall facing East or West. The results showed that a folded façade slightly increases the energy efficiency and mainly the cooling demand of the classroom while the change in window type has a greater impact on the energy efficiency. Also enlarging the distance related to base line (flat façade) lowers the energy efficiency. Furthermore, the daylight conditions mainly decreased and the overheating period always exceeded the maximum allowed time, although a slight decrease was observed by applying a folding façade geometry. The holistic approach used in this work did not generate one specific design.

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Table of content

Terminology

BREEAM-NL: Building Research Establishment Environmental Assessment Methodology for the Netherlands

FS: Frisse Scholen (Fresh Schools), is a requirement form at which designers and contractors can base their plans

PH: Passive House, is a standard in order to design energy efficient buildings and reduce the ecological footprint.

BB: BouwBesluit (Building regulations), is the Dutch building regulations regarding the construction, use and demolition of buildings.

DF [%]: Daylight factor, is the percentage wherein the measured indoor illuminance on a work plane is divided by the measured outdoor illuminance at the same time.

DA [%]: Daylight autonomy, is the percentage that a specific point or work plane receives light above a required threshold illumination within the annual daytime hours or occupied hours.

UDI [%]: Useful daylight illuminance, is the percentage of the annual illuminances on the work plane that are within a range considered “useful” by occupants.

WWR [%]: Window-to-wall ratio, is the ratio of the window area divided by the exterior envelope area.

U-value $[W/m^2 \cdot K]$: Thermal transmittance coefficient, the heat transfer (in watts) due to thermal radiation, thermal convection and thermal conduction, through one square meter of a structure, divided by the difference between the indoor and outdoor temperature.

g-value [%]: Solar heat gain coefficient, is the transmittance of solar heat by a material.

Vt [%]: Visual transmittance, is the quantity of daylight passing through a glazing material. It is the daylight in the perceptible part of the spectrum.

Annual operational energy $[kWh/m^2]$: The annual heating- and cooling demand plus electric energy for artificial lighting combined.

Overheating period [%]: The percentage of occupied time wherein the operative temperature exceeds the maximum temperature.

1 Introduction

1.1 Background

The European Union (EU) aims to reduce the greenhouse gas (GHG) emissions, energy savings and to increase the use of renewable energies by 20 % by 2020 compared to 1990. By 2030, a reduction of 40 % for GHG-emissions must be achieved (European Union, 2015). The EU uses the GHG, energy savings and the increase of renewable energies as metrics to assess whether Member States implement the European 2020 and 2030 strategies correctly. Each country sets thereby their own national targets for reducing GHG emissions, energy savings and renewable energies. For the Netherlands, the objective is to reduce GHG for 16 % by 2020 and 40 % by 2030, energy savings of 1.5 % each year (from year 2010) and to increase renewable energy use by 14 % by 2020 (Ministerie van Economische Zaken, 2014). Within the building sector, all newly constructed buildings must be net zero-energy or nearly zero-energy buildings, by 31 December 2020 (European Parliament & Directive Council, 2010).

The Intergovernmental Panel on Climate Change (IPCC) reported that the global mean surface temperature will rise within the 21th century, by approximately 1.1°C to 4.8 °C by the end of 2099 relative to 1986-2005 (IPCC, 2014). Due to future increased temperatures, the cooling load will increase. Therefore, it is important to avoid unnecessary solar gains (Wang, et al., 2010). The coherence between active and passive design strategies should be well considered to reduce the heating and cooling demand, and electrical energy for lighting as well. Implementing and optimizing passive design measures in the initial design stage are essential to reduce the thermal energy and electrical energy of active systems (Stevanović, 2013).

Nowadays pupils spend most time at school, aside from home. Therefore, including thermal- and visual comfort is important to improve the performances and well-being of students (Zomoradian, et al., 2016). Applying passive solar design strategies and utilize solar energy for new and refurbished buildings will allow architects to improve the thermal comfort and in addition, decrease the energy use. In order to make optimal use of solar energy, several design decisions, which do all have an effect on the building performance, such as building shape, orientation, envelope construction and geometry, window type, glazing area and shading should be carefully applied (Stevanović, 2013).

1.2 Problem statement

Besides energy, daylight has an important role in architecture in which the health and productivity of the user is highly important, especially in schools in connection with the performance of children (RVO, 2015). Sunlight is essential when designing schools, but due to site layouts, neighboring buildings and building function, it is not always possible to achieve the highest building performances. If a building cannot be optimally oriented it consequently can have larger facade sections facing East and West. Due to a low sun angle on East and West are solar gains and daylight conditions difficult to manage with traditional sun protection appliances which may cause glare and overheating. Normally the daylight conditions are reduced in the occupied space if sun protection is applied, thus increasing the energy for artificial lighting, (Piccolo & Simone, 2009).

The educational use of electrical devices as laptops and tablets in classrooms is increasing each year. Last year, laptops or tablets were available for every fourth child in the classroom and is further expected to increase to every third or second child (Kennisnet, 2015). Although more energy efficient equipment is used, people will interact more and more with the digital world around us and this may potentially increase internal heat gains, since more devices are used and eventually use more energy. In addition, internal heat sources are a dominant factor in energy-efficient buildings (Johnston, et al., 2011). Therefore it is wise as designer to avoid unnecessary solar radiation into the space by using passive measures. By adapting the façade geometry will change the solar heat gains that is absorbed or prevented, which in turn, affect the thermal comfort and daylight conditions.

1.3 Objectives

The aim of this work is to investigate the effect of applying folded geometry on the West and East envelope surface on the energy performance and indoor climate comfort. In order to reach this goal, a sensitivity analysis is conducted comparing various folded façade surface geometries with flat facades for East and West orientations. Since there are few studies conducted on façade geometry adaptations to schools, this work focus on façade foldings and their influence on the indoor climate conditions of classrooms.

1.3.1 Hypothesis

The hypothesis of this work is that the energy use decreases (more efficient) and the thermal and visual indoor comfort improves by applying a folded façade surface geometry, i.e. the building performance is assumed to be optimized. The work is confined to East and West façades and by adapting the façade geometry, it is assumed to minimize glare problems and reduce the overheating period.

1.3.2 Research question

The following research question is formulated: "Can the building's energy performance and indoor thermal and visual comfort be improved by applying a folded façade geometry of the envelope surface, facing East and West?"

The following sub questions, to define the energy performance and indoor comfort, are examined:

Energy performance:

- Can a folded façade surface geometry for East and West design reduce the energy use for artificial lighting, heating and cooling demand?

Indoor comfort:

- Can a folded façade surface geometry for East and West design improve the thermal and daylight comfort?

1.3.3 Scope and limitations

A study on Dutch schools reveals that thermal comfort quality for most schools does not satisfy the needs (Versteeg, 2007). Therefore, the scope of the work lies on a hypothetical classroom, based on average Dutch classrooms, and the improvement potential of the thermal indoor environment and energy efficiency. Additionally, the thesis is conducted at and for Ector Hoogstad architects (EHA). EHA design many school buildings, hence for the office this work could give information for upcoming projects.

The classroom has one wall connected to the outside air. The floor, ceiling and the remaining three walls are adiabatic. Heat losses through thermal bridges or other construction joints like wall junctions are not considered. Furthermore, limitations in terms of the analysis for ventilation comfort, clothing level and metabolic rate are not considered in the analysis. In addition no static, active or occupant controlled shading systems are applied and economics like construction or energy costs are not included.

1.4 Research Methodology

The methodology process applied in this study is divided in the following five parts:

- *State-of-the-art*: provides an overview from previous studies on surface façade geometries. Since passive strategies are rarely linked to surface facades geometries, other studies are dealing with parameters reviewed, such as envelope, orientations, window specification, window area and shading devices. The majority of the studies used a holistic approach and evaluated various indicators at once, such as energy and daylight conditions. In addition, existing buildings with applied folded facades have been examined and a research conducted on Dutch schools is reviewed.
- *Reference case*: is the description of the base case.
    - *Reference case*: is a hypothetical classroom based on the Dutch building code and average Dutch classrooms. Analyses are conducted on a flat façade, facing East, South and West, to investigate the change in energy performance and indoor thermal and visual comfort.
- *Analyses setup*: this chapter analyses the following scenario cases and their performance impact. The analyses are divided in the following steps:
    - *Folded surface geometry*: facade foldings and variables for the window-to-wall ratio (WWR).
    - *Window type*: a variety of window types (windows with different U-value, g-value and Vt) will be examined on the energy performance, indoor thermal and visual comfort.
    - *Improved case*: this is the final analysis step including the improved geometry, WWR and window type. Furthermore, a comparison study with the reference case is examined.
- *Results*: shows the results in the same order like the analyses chapter:
    - *Folded surface geometry*
    - *Window type*
    - *Improved case*
- *Discussion*: on the analysis results and comparison to the state of the art.
- *Conclusion*: answer to the research questions and the overall hypothesis.

1.4.1 **Structure of work**

The structure of work is addressed in Figure 1-1. Whereby, analysis one is the folding sensitivity analysis and analysis two the window type sensitivity analysis.

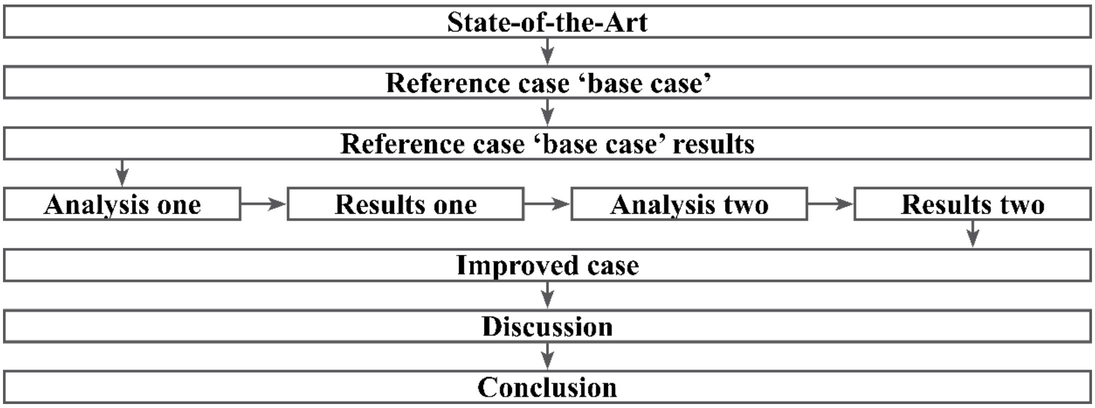

Figure 1-1. Structure of work for this thesis.

1.4.2 **Description of software**

The simulations are carried out using the Grasshopper (grasshopper3d, 2016) canvas plugin in Rhinoceros (Robert McNeel & Associates, 2016), shown in Figure 1-2. Grasshopper is an scripting tool for Rhino's 3D modeling tools. Rhinoceros is a free-form 3-D modeling tool. In addition, the Ladybug and Honeybee plugins within Grasshopper are used to simulate the energy performance, thermal indoor comfort and daylight conditions, (Sadeghipour Roudsari, 2016). Ladybug and Honeybee are two open-source plugins for Grasshopper to analyse environmentally-conscious designs. Ladybug imports standard EnergyPlus Weather files (.EPW) into Grasshopper, Honeybee connects Grasshopper to EnergyPlus, Radiance, Daysim and OpenStudio, which is used further for building energy and daylighting simulation (Sadeghipour Roudsari, 2016).

EnergyPlus is an extensively used building energy simulation tool to compute the energy performance, thermal comfort and water usage (NREL, 2015). Radiance is a software package for the analysis of light conditions (University of California, 2014), OpenStudio is an open source software application to support EnergyPlus and Radiance for a complete energy simulation (NREL, et al., 2016). Daysim is a Radiance-based verified program to analyse annual daylight conditions (Reinhart, 2016). The calibration, presented in of all these programs, ultimately helps to analyse the complete building energy performance.

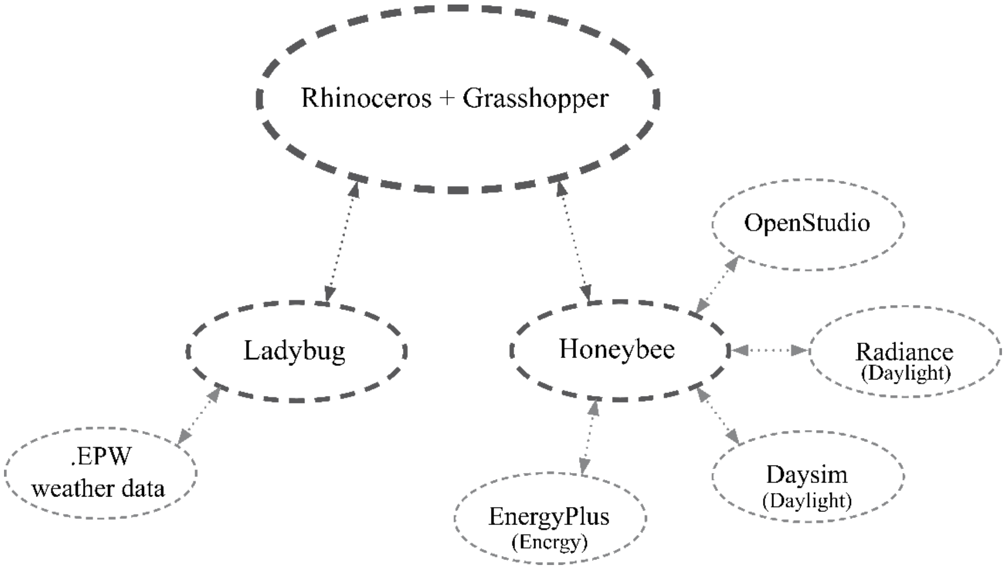

Figure 1-2. The program calibration for a complete energy building analysis.

2 State of the Art

This chapter describes the importance of indoor comfort conditions in regards to the well-being of students, followed by the presentation of studies on passive design methods for the building envelope, particularly the façade, to improve energy efficiency of buildings. Furthermore, some examples of existing buildings with a folded façade are presented. Finally, an investigation carried out on Dutch schools is reviewed and a frame work of the Dutch regulations is described.

2.1 Well-being in schools

As students spend their time to a large extent at schools, the thermal and visual indoor comfort plays an important role for the student's well-being (Zomoradian, et al., 2016). Concerning the Netherlands, there is still much to gain for the indoor climate in schools as it does not satisfy the required quality for the majority of built schools (Versteeg, 2007).

2.1.1 Thermal comfort

Nowadays the density in classes and the possibility of uncomfortable indoor climate can have an adverse effect on students' achievements, learning process and health. Studies reviewed by Zomorodian et al. concluded that students would rather stay in a colder temperature since they experience warmer temperatures as less pleasant. All reviewed studies by Zomorodian et al. confirm that buildings should be designed to improve the indoor climate, at first the comfort temperatures but also the air quality, so that students can perform better and the overall energy demand decreases, although this is not easy to accomplish. To determine the thermal comfort many studies utilize the operative temperature (explained in 2.1.2) as an assessment method (Zomoradian, et al., 2016).

2.1.2 Thermal comfort metric

Thermal comfort is "that condition of mind which expresses satisfaction with the thermal environment" (ASHRAE, 2013). The key factors that affect thermal comfort are those that determine heat gain and loss, such as metabolic rate, clothing insulation, air temperature, mean radiant temperature, air speed and relative humidity.

- *Metabolic rate*: The ASHRAE 55-2013 standard defines the metabolic rate as "the level of transformation of chemical energy into heat and mechanical work by metabolic activities within an organism, usually expressed in terms of unit area of the total body surface." Metabolic rate unit is stated in met, 1 met = 58.2 W/m^2, "which is equal to the energy produced per unit surface area of an average person seated at rest", (ASHRAE, 2013).
- *Clothing insulation*: is the insulation that a person wears. It effects the heat losses and expressed in clo. 1 clo is equal to 0.155 m^2 · K/W. This represents pants, a long-sleeved shirt and a jacket. (ASHRAE, 2013)
- *Air temperature*: The temperature of the air in the room, referred to as dry bulb temperature, since the air temperature is measured with a dry-bulb thermometer.

- *Mean radiant temperature*: is the uniform temperature of an imaginary enclosure in which the radiant heat transfer from the human body is equal to the radiant heat transfer in the actual non-uniform enclosure. (ASHRAE, 2013)
- *Air speed*: is the average speed of the air to which the body is exposed, with respect to location and time. (ASHRAE, 2013)
- *Relative humidity*: is the percentage of quantity of water vapor in the air to the quantity of water vapor that the air can hold at a particular temperature and air pressure.

Equal to the ASHRAE standard is EN 15251 (Indoor environmental input parameters for design and assessment of energy performance of buildings), which is applied in the Netherlands. It is incorporated into the building code and Frisse Scholen regulations, as presented in chapter 2.4.2 with set point data. In addition, a commonly used method, and also confirmed by Zomoradian (Zomoradian, et al., 2016) and implemented in the Dutch legislation, is the operative temperature:

- *Operative temperature*: "the uniform temperature of an imaginary black enclosure in which an occupant would exchange the same amount of heat by radiation plus convection as in the actual non-uniform environment." (CEN & Standardization, 2015). The operative temperature combines the effects of average air temperature and mean radiant temperature in a single metric.

The Predicted Mean vote (PMV) is a survey used to express the "human perception of thermal comfort" and conceived by P.O. Fanger, (Fanger, 1970). The index has been created from many statistical studies out of a big group of individuals. Each individual assessed their own impression on thermal comfort in a specific climate. The index makes use of the indicators listed above.

Out of the PMV, P.O. Fanger created the Predicted Percentage of Dissatisfied (PPD), which is an equation describing the percentage of occupants that are dissatisfied with the given thermal conditions. Since an optimal thermal climate is not feasible for each individual, a PPD of 5 % is the lowest percentage possible.

2.1.3 Visual comfort

Bright light or daylight is very valuable in an educational environment because it can improve "alertness" and "performance" (Vandewalle, et al., 2006). Moreover, a brief light exposure can have a substantial impact on the circadian system regulation (Aries, et al., 2013) (Chang, et al., 2012). The reverse may occur when excessive light, including direct sun, for example, a low sun level on East or West, is experienced and glare causes a negative influence on the performance (Energy Commission, 2003). Besides the psychological and physiological effect, the absence of daylight due to e.g. smaller window size causes a reduction of vitamin D, which is likely to affect myopia, although no concrete evidence has been found (Hobday, 2016).

2.1.4 Annual daylight metrics

The daylight conditions can be measured in several ways and the indicators serve as criteria for regulations like 'BREEAM-NL' and Frisse scholen, as described in 2.4.1.

Daylight factor

The daylight factor (DF) is a relatively simple calculation for daylight access applied under a CIE[1] overcast sky and therefore direction independent and suitable for early design decisions, eq. (1). However, the DF is less realistic in an environment with lots of sun, since direct sun light or non-overcast skies are not applicable. In addition, the DF measure is dependent on the sky luminance distribution making the DF percentages highly variable. The DF is the percentage wherein the measured indoor illuminance on a work plane is divided by the measured outdoor illuminance at the same time. (New Buildings Institute, 2016)

$$DF = \frac{Ei}{Eo} \times 100\ \%\ [\%] \qquad \text{eq. (1)}$$

Where:
DF: the daylight factor measured at a specific point. [%]
Ei: available lux indoors at a specific point on a working plane. [lux]
Eo: simultaneous available lux outdoors under a CIE overcast sky. [lux]

In addition, 'BREEAM-NL' (chapter 2.4.1) applies the uniformity ratio, which is the lowest DF divided by the mean DF, eq. (2). The higher the ratio the better the uniformity of light distribution in the room. (DGBC, 2014)

$$Uniformity\ ratio = \frac{DFmin}{DFmean} \qquad \text{eq. (2)}$$

Daylight autonomy

Daylight Autonomy (DA) was developed by the Association Suisse des Electricians and enhanced by Christoph Reinhart, 2006, (Reinhart, et al., 2006). It is an annual daylight metric and calculates the percentage that a specific point receives light above a required threshold illumination within the annual daytime hours or occupied hours. It has many advantages over the daylight factor, since DA uses the geographic location and annual weather data containing the global, diffuse and direct irradiance measurements. Furthermore, it also works for artificial light savings, which calculates this for each hour when sufficient daylight is obtained based on the amount of received lux above a defined threshold. (Reinhart, et al., 2006)

Useful daylight illuminance

Useful Daylight Illumination (UDI) is an adjustment of DA devised by Nabil and Mardaljevic (2005) (Nabil & Mardaljevic, 2005). The UDI is divided into three categories: insufficient illuminance, sufficient illuminance and exceeded illuminance. The illuminance range can be adjusted to preferred settings, like an annual illumination range of 100-2000 lux on a work

[1] Commission Internationale de l'Éclairage: the International Commission on Illuminance

plane is preferred by occupants as a sufficient daylight space. If the annual illumination exceeds the preferred range of 2000 lux, risk of glare and discomfort occurs (Nabil & Mardaljevic, 2005).

2.2 Passive energy saving measures

An energy efficient design of a building can be conducted in a number of ways for which the energy efficiency, thermal- and visual comfort is improved. One way is by making adjustments of the building shell such as thermal quality of the construction, air tightness and thermal bridges. Another way is addressing building characteristics, such as the thermal mass use, natural ventilation and thermal zoning, namely buffer zones or double skin facades.

Particularly, and examined for this work, are passive building envelope and façade measures with the goal to reduce the need of active systems (like movable shading devices) for a good operation. For this work, passive design measures are divided in following measures; (a) the building shape in which the whole building is formed or oriented in order to improve the overall energy and thermal comfort, (b) the façade envelope with geometrical optimization to make the best use of the sun, and (c) detailed façade measures, such as the window size and type or solar protective appliances for sufficient daylight conditions.

2.2.1 Building shape

A few studies have conducted research on the effect of building shape on the energy performance. Capeluto, studied the self-shading building envelope, located in Jerusalem, to reduce the solar heat gains and improve the building energy performance. East and West façades are inclined by 34 degrees, to exclude direct radiation in summer from ten to two o’clock. Capeluto’s findings shows that the self-shading envelope lowered the energy loads for all orientations. It is even higher in the case for East and West compared to South oriented offices. Although the self-shading building envelope improved the building performance it can be noted that relatively the same improvements were found with low-E coated glass on flat facades for buildings in Jerusalem. (Capeluto, 2003)

To reach an ideal geometric shape which reduces the yearly solar irradiation on the facade surface for the locations Basel and Dubai, Caruso and Kämpf (2015) used an evolutionary simulation algorithm. The results showed that the design must be compact and directed to the sky whereby the building is self-shading. Thereby, the building must be prevented from surface directions, gaining too much solar irradiation, in order to diminish the use of shading devices. The most gained irradiance was found to be facing South-West and not towards South, therefore, the building should avoid surfaces facing South-West. South-West was also found to be more critical since it had more impact caused by the outside temperature that is higher in the afternoon. This implies a positive effect in the early hours and a disadvantageous in the afternoon. (Caruso & Kämpf, 2015)

Another geometry study in Philadelphia, conducted by Yi and Malkawi (2009), investigated a way to change the geometric shape by consistence of geometric points, in order to achieve different shapes than only a simplified box. They added five additional points per vertical surface that allowed the geometry to take other forms, as presented in Figure 2-1. A “genetic algorithm” in combination with EnergyPlus calculated the building heating energy performance. The final generated building shape had a self-shading concept in the summer on the East, South and West façades. However, the inclined angle of the surface was inadequate to create shadows on the facade in winter. The improved building shape lowered the heating capacity roughly by 12 % per total volume and the entire annual energy usage by 8.42 %, both with respect to the reference case. (Yi & Malkawi, 2009)

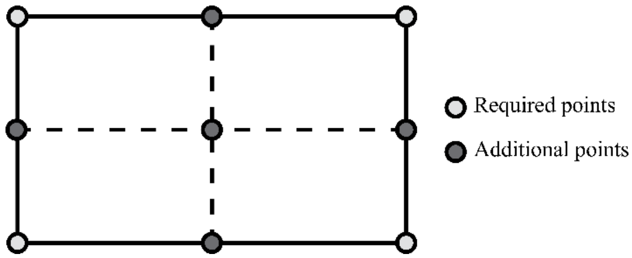

Figure 2-1. The geometry research conducted by Yi and Malkawi (Yi & Malkawi, 2009). Showing the additional points for each vertical surface of a box where over the geometry could change form.

2.2.2 Façade geometry

Rodrigues et al. (2015) simulated various designs within eight different climates (Las Palmas de Gran Canaria (Spain), Murcia (Spain), Rome (Italy), Porto (Portugal), Bucharest (Romania), Paris (France), Helsinki (Finland), and Kiruna (Sweden)) to understand whether geometry could be used as a trustful method to improve the thermal comfort. However, the study found that this was not the case, due to demanding building legislations, for these countries, to improve the thermal resistance of opaque walls and windows. For architects this creates a way to examine new façade designs, since the impact from the outdoor climate on the thermal comfort becomes less, since higher thermal resistance improves the energy efficiency. (Rodrigues, et al., 2015)

Lavafpour and Sharples (2015) also studied the shelf-shading concept on the South façade of a passive house in Islington, London. They studied various geometries in order to reach a possible improved energy efficient design under various future climate predictions. The investigated angles of the facade ranges, in steps of 5°, from 0° to 50° from the vertical to the horizontal plane. It was observed that as the angle becomes greater towards the horizontal plane the heating energy demand increases, as opposed to cooling wherein the opposite occured. Furthermore, the cooling demand increased and the heating demand decreased over a period of 65 years, in which the climate changes. They concluded that the geometry of the façade had an impact on the energy efficiency of the building and thereby lowered the overheating probability for, todays and prospective, London conditions. (Lavafpour & Sharples, 2015)

2.2.3 Façade measures

This chapter covers some facade quality measures that are applied in the examined studies, such as window-to-wall ratio (WWR), window types and shading. The window-to-wall ratio is a measure of the percentage of area calculated by dividing the glass surface area by the wall area.

Window to wall ratio and orientation

Tzempelikos and Athienitis (2007) studied an office room on energy and lighting demand for the four cardinal directions, located in Montreal. The authors found, for a window to wall ratio (WWR) of 40 % on West facing facades a daylight availability (DA) of 70 %, as presented in Table 2-1. This merely increased with an enlarged WWR of 50 % to 74 % DA. On East it flattened out after 50 % WWR and the same was applied for North-faced windows. However, this had a disadvantage on the energy demand for North-faced windows. To meet the energy requirements for East- West-facing windows, it was acceptable to have a WWR between 30 - 50 %. (Tzempelikos & Athienitis, 2007)

Table 2-1. Annual daylight availability ratio for orientations in Montreal as a function of window-to-wall ratio.

WWR [%]	Annual DA North [%]	Annual DA East [%]	Annual DA South [%]	Annual DA West [%]
5	0	1	2	2
10	0	16	26	24
15	0	24	54	36
20	2	35	68	50
30	16	47	76	63
40	40	58	80	70
50	60	67	81	74
80	72	78	84	84

Echenagucia et al. (2015) used a holistic approach for the initial design phase to receive specific data for energy efficient design configurations, for the climates of Palermo, Torino, Frankfurt and Oslo. The study was conducted for an open plan office building and change the amount, size, position and properties of glazed and opaque wall elements. The benefit of obtaining solar heat in cold months on East and West oriented windows was not efficient enough, due to higher heat losses through windows with lower U-values compared to the higher thermal quality of the opaque walls. In addition, the lack of fenestration on the East and West was beneficial to reduce solar gains in the summer months. (Echenagucia, et al., 2015)

Two conducted studies in Sweden and Denmark on low energy houses concluded on North facing windows to meet the daylight conditions. Persson et al. (2006) proclaims, there was no need to design small windows for North façades, because of heat losses, when using high thermal resistance glazing (Persson, et al., 2006). For nearly zero-energy houses in Denmark, the North facing window area can be sized to meet the daylight requirements (Vanhoutteghem, et al., 2015). Hence, increasing the window area facing North had minimal impact on the energy performance. To diminish overheating for South facing spaces, the window should be sized based on daylight performance but with solar-coated glazing with as good as possible daylight efficiency.

Another daylight and energy performance study, conducted by Shen and Tzempelikos (2012), examined cell closed offices with interior blinds in Chicago and Los Angeles, considering glazing area, window characteristics, orientation, blind characteristics and controls. Shen and Tzempelikos used three types of double glazing: one clear glazing (type 1) and two low-e glazing's with selective coating (type 2) whereby one has high reflectivity (type 3), as presented in Table 2-2. For this study the useful daylight illuminances was set between 500 and 1000 lux (UDI500-1000), although this indicator did not reflect the full potential of the reduced electricity for artificial lighting. It provided sufficient daylight for the indoor space and minimized the chance of glare. The maximum UDI500-1000 values without shading on South and West was achieved with 15 % WWR (30 % of the annual time) for glazing types 1 and 2. For type 3 the WWR could increase to 30 % while still maintaining an UDI500-1000 of 30 % of the annual time. On North and East orientations the highest UDI 500-1000 percentage (34 % and 40 %) was achieved having a WWR near 30 %, for glazing type 1 and 2. For type 3, the WWR must be 50 %. (Shen & Tzempelikos, 2012)

Table 2-2. Used window types by (Shen & Tzempelikos, 2012).

Window	τ_V (visual transmittance)	τ_S (solar transmittance)
Type 1	0.79	0.61
Type 2	0.70	0.33
Type 3	0.37	0.19

Shading and window orientation

Although this work focused on passive measures, the following studies provide a good inside into the daylight quality when using active sun protection on various facades.

A retrofit study, conducted by Secchi et al. (2015), analyzed external shading and spectral selective glazing for East facing classrooms in Tuscany in Italy with a WWR of 43 %. Applying horizontal or vertical shades provided a decrease on artificial lighting demand and enhances the overall daylight conditions, and consequently, reduced the use of shutters. Shades reached a greater efficiencies in clear skies, whereby spectral selective glazing (passive measure) achieved a better performance at a cloudy sky. Exterior shades were the most effective option within this Italian research. It provided better daylight condition while keeping solar heat gains within the cold months and prevented from overheating in the summer period. Thereby the difference between horizontal and vertical shading on the daylight conditions and solar gains was minimal. (Secchi, et al., 2015)

Goia et. al. (2013) studied the WWR for an office building with triple glazed low-E coated windows and external venetian blinds in relation to daylight conditions, lighting energy, heating and cooling demand. The ideal WWR was found between 35 % and 45 % despite the orientations, while keeping the energy efficiency and tolerable light around 50 % of the time. The North facing windows obtain the highest tolerable light of over 55 % of the working time, while no excessive light occurred for WWR above 30 %. Excessive light may cause glare problems and happened for 20 % and 12 % of the time for South and East/West facing windows. (Goia, et al., 2013).

Shen and Tzempelikos (chapter 0, "*Window to wall ratio and orientation"*), they described further in their research, the use of sun protection. They simulated that the mechanical blinds (solar transmittance of 3 %, 5 % and 7 %) were closed, from nine to twelve on the East side and from twelve to five on the West side, when more irradiation than 20 W/m² occurred on the façade surface. The North oriented glazing areas received, for both locations, Chicago and Los Angeles, sufficient daylight when WWR was larger than 30 %, since almost no blinds were closed. Given that the blinds were down for less occupied hours, East outperforms South and West oriented windows. "A significant observation" was found for cases with automated blinds, whereby a good reduction of energy for WWR of 30-50 % compared to higher or lower window areas was found. (Shen & Tzempelikos, 2012).

2.3 Existing folding facades examples

Generally there are a few buildings applied with a folded façades or saw-tooth façades. However, the majority of buildings are intended architectural aesthetic elements instead of making use of or avoid the sun. Some examples are listed in the following:

- KFW bank by Sauerbruch Hutton, Frankfurt, Germany.
- Al Bahar Towers by Aedas, Abu Dhabi, United Arab Emirates.
- Sheffield Car Park by Allies and Morrison Architects, Yorkshire, England.
- Dizengoff Tower by Yitzhak Yashar, Tel Aviv, Israel.
- IAAC's Solar-Powered Endesa Pavilion, Barcelona, Spain.

There are also a few buildings with folded façade either in a horizontal or vertical folding. Although these geometrical strategies are not schools they do indicate the opportunity, for schools. Two types are exemplarily shown in this work. The ENERGYbase in Vienna, Austria (Haus der Zukunft, 2005) and DIFFER in Eindhoven, Netherlands (Ector Hoogstad architects, 2015). For these two buildings the idea was to improve the overall energy performance and daylight quality while making use of the solar energy.

The ENERGYbase is an office building built in passive house standard in 2008 in Vienna, and designed by pos architects. It is designed with a horizontal folding façade orientated to the South and utilizes innovative technologies, such as heat pumps, building intergrated photovoltaic (BIPV), solar cooling and concrete core activation (Haus der Zukunft, 2005). The façade is folded to utilize the solar gains in winter and self-shaded in summer, as shown in Figure 2-2. The glazed part of the façade faces downwards (63.4° from horizontal) and the BIPV faces upwards towards the sun (31.5° from horizontal).

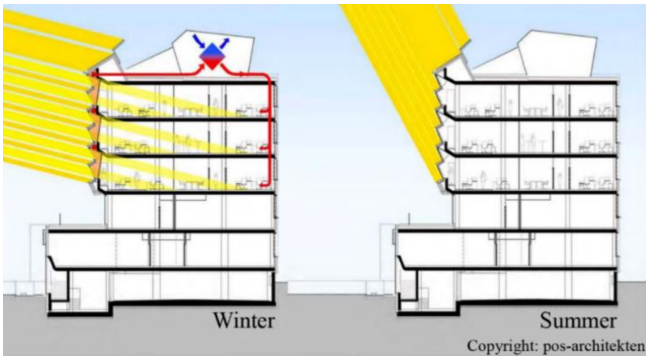

Figure 2-2. The passive house ENERGYbase folded facade function for winter and summer (Haus der Zukunft, 2005)

An later energy analysis on the real performance of the ENERGYbase, conducted by Goschenhofer (2011), revealed that the actual energy use is lower than the by forehand simulated energy demand. Goschenhofer observed that the cooling demand is 33 % lower than anticipated. Meanwhile, the heating demand is 12 % larger. This was mainly due to storage losses and auxiliary energies. Furthermore, various offices are scarcely taken into use, thus, resulting in an overal energy difference between actual use and expected energy use. (Goschenhofer, 2011)

Another example in Europe is Differ (Figure 2-3), Dutch Institute for Fundamental Energy Research, designed by Ector Hoogstad architects. It achieved the BREEAM Excellent certificate as first laboratory building in the Netherlands. To achieve this, the building is built with triple glazing and solar panels on the roof. Another important design principle was the East-West façade design. They made use of the "saw-tooth" principle, whereby the windows are turned towards North and South. Their vision is that the glazing towards North can remain transparent, to keep the visual view and occupied controlled screens can prevent overheating, on the South. Furthermore, the facades are fully glazed to lower the artificial lighting energy. (Ector Hoogstad architects, 2015)

Figure 2-3. DIFFER, with a saw-tooth design on East and West facades (Ector Hoogstad architects, 2015).

2.4 Dutch research and regulations for schools

Since this work aims at Dutch schools, the following chapter describes a comprehensive research carried out for schools in the Netherlands, and therefore provides a good overview of the indoor quality conditions for Dutch schools. New and refurbished schools must comply with the Dutch regulations and additionally some extra criteria can be applied to improve the indoor climate conditions, as described in chapter 2.4.2.

2.4.1 Research on Dutch schools

In 2007 a research commissioned by the Dutch ministries VROM[2], OCW[3], SZW[4] and VWS[5] was conducted regarding the indoor environment (air quality, acoustic quality and thermal comfort) of primary schools. The research concluded that the quality in primary schools, especially in the classrooms, was not desirable. This report induced to set up "Frisse Scholen" (FS) requirements for future school buildings to create healthy indoor climates and energy efficient buildings (RVO, 2015).

The research on thermal comfort consisted of a small field research of five weeks and a questionnaire, filled by the teachers, about relative humidity and operative temperatures. The field research, conducted in the winter months, shows that 77 % of the investigated classrooms did not met the temperature criteria for a temporary period, whereby 57 % of the investigated classrooms were below the lower limit of 19 °C for 21 % of the lecture time. Furthermore, 20 % of the classrooms exceeded the upper limit of 23 °C for 8 % of the lecture time. Exceeding the upper limit of 23 °C occurred rarely in mechanical ventilated classrooms.

The survey showed that 18 % to 36 % of the teachers experienced unpleasant warm temperatures in winter months and 45 % in summer months. On average the thermal comfort was not well manageable for 62 % of the classrooms with natural ventilation. This percentage dropped to 39 % when mechanical ventilation was applied. Schools with natural ventilation were generally older in comparison to schools with installed mechanical ventilation. In most cases, the older buildings had larger glass areas and made less use of shading devices. (Versteeg, 2007)

2.4.2 Dutch frame work conditions

The Dutch regulations regarding safety, health, usability, energy efficiency and the environment is defined in the "Bouwbesluit" (Building Regulations) (BB). The bb describes the Dutch building legislations for which buildings and structures must comply, as presented in Table 2-3. (Binnenlandse Zaken, 2016)

The BB does not implicate all criteria and the question to improve indoor comfort in schools became more critical by the municipality and school boards. Therefore the National Service

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[2] The Ministry of Housing (Volkshuisvesting), Spatial planning (Ruimtelijke Ordening) and Environmental managment (Milieubeheer).

[3] The ministry of Education (Onderwijs), Culture (Cultuur) en Science (Wetenschap).

[4] The Ministry of Social Affairs (Sociale Zaken) and Employment (Werkgelegenheid).

[5] The Ministry of Health (Volksgezondheid), Welfare (Welzijn) and Sport (Sport).

of Entrepreneurial Netherlands developed a program of requirements. This list of requirements, the “Frisse Scholen” FS, is intended to assist in design development between designers, engineers and contractors. FS requirements are divided into three ambition levels: Quality C, B and A. Quality C is meant for existing buildings (not shown in Table 2-3), Quality B and C are ambition levels for new buildings. (RVO, 2015) (Agentschap NL, 2012)

Building requirements

Besides the BB and FS, the “Passive House” (PH) criteria (Passive House Institute, 2015) and PH criteria for schools (Passivhaus Institut, 2014) may be applied, but is not mandatory in the Netherlands. PH will overlap certain criteria with BB and FS, since not all criteria set points in the BB and FS requirements are described. As an example, lower construction U-values and infiltration rate are imposed by PH. Infiltration or air leakage can occur through cracks, joints or seals at windows and doors, plus a pressure differences between outside and inside. Besides the annual energy demand and infiltration Table 2-3 presents the U-value, which is the heat loss factor for various parts of the building envelope.

Table 2-3. Building requirements according to “Bouwbesluit” (Binnenlandse Zaken, 2016), “Frisse scholen” (RVO, 2015) and “Passive house” standard (Passive House Institute, 2015).

	Bouwbesluit	Frisse scholen Quality B	Frisse scholen Quality C	Passive house
Annual heating demand [kWh/m²]	-	-	-	15
Annual cooling demand [kWh/m²]	-	-	-	15
Infiltration				
Infiltration [l/(s • m²)]	0.15 at 10 Pa	-	-	0.583 at 50 Pa (Or 0.6 (1/h))
Construction in U-value [W/m² • K]				
Wall	0.167	0.28	0.2	0.15
Window + frame	1.65	1.2	1.2	0.85
Geometry				
Floor to ceiling height [m]	2.6	3.2	3.5	-

Thermal comfort requirements

The thermal comfort can be separated into several requirements, as presented in Table 2-4. The operative temperature is only assessed in FS and split into a cooling and heating period. For example, if the outside temperature is below 10 °C, the operative temperature can be set lower and the opposite is applied to the outside temperatures above 10 °C. The overheating period based on indoor temperature is only assessed in the PH standard. There is a matter of overheating if 10 % of the occupied time is above 25 °C. Each standard describes a ventilation rate for both standard ventilation per square meter and per person in the room.

Table 2-4. Thermal comfort requirements according to the "Bouwbesluit" (Binnenlandse Zaken, 2016), "Frisse scholen" (RVO, 2015) and "Passive house" standard (Passive House Institute, 2015).

	Bouwbesluit	Frisse scholen Quality B	Frisse scholen Quality C	Passive house
Operative temperatures [°C]				
Annual operative temperature	-	-	-	< 25
Operative temperature winter (<10 °C)	-	19 > X < 25	20 > X < 24	-
Operative temperature summer	-	22 > X < 27	23 > X < 26	-
Overheating				
Overheating hours	-	-	-	10 % of occupied time > 25 °C
Ventilation				
Standard ventilation rate [l/(s • m²)]	0.9	0.9	0.9	0.55
Ventilation rate per person [l/s]	8.5	8.5	12	> 5.55

Daylight requirements

The daylight requirements are well described in FS and BREEAM-NL, (DGBC, 2014). The BREEAM-NL sustainability certification for Dutch buildings and infrastructure is developed by the Dutch Green Building Council an independent foundation. The BREEAM-NL family of labels is entirely based on, and follows to very large extent, the international BREEAM[6] developed by the BRE[7] in the UK. The educational daylight criteria are divided into two classes to evaluate the daylight conditions, as shown in Table 2-5, whereby the horizontal plane is located at a height of 0.7 m for daylight measurements. The FS daylight requirements is divided into three ambition levels and contains the DF and the required artificial lighting in lux on the work plane, as mentioned in chapter 2.4.2.

Table 2-5. Daylight requirements by BREEAM-NL (DGBC, 2014) and "Frisse Scholen" (RVO, 2015).

	BREEAM-NL		Frisse Scholen		
	Credit criteria	Exemplary performance	Quality C: acceptable	Quality B: good	Quality A: very good
Daylight factor at desk level [%]	2	3	3	5	7
DF uniformity ratio	0.4	0.4	-	-	-
Artificial light at desk level [lux]	-	-	300	500	500

[6] Building Research Establishment Environmental Assessment Method (BREEAM)

[7] Building Research Establishment is a private research, consultancy and testing organization in the United Kingdom

2.5 Summary

Although it seems that not much is published in regards to the idea of folding façade geometry optimization for energy and daylight optimization, it can be assumed that geometry adaptations of façades do affect energy or daylight conditions. The in various studies described self-shading concept proved to affect the energy efficiency of the building. However, it is also found that the effect is minimized as the thermal resistance increases. Furthermore, most studies clearly show that sufficient daylight conditions are achieved by WWR ranging from 30 to 50 %, whereby North can have a larger window area than South. Thus, when the thermal resistance of building components, like windows and opaque walls, is high, windows can be freely sized to meet the daylight conditions. Additionally it can be noted that the wellbeing of students is important to improve the performance and learning process.

3 Reference case

For this work, one exemplary classroom was studied to investigate the effects that take place in a single room facing East and West, when façade geometry adaptations are applied. The studied classroom is not a real case, but a hypothetical classroom based on average Dutch classrooms and according to, the BB, FS and PH requirements. The classroom is located in Amsterdam, the Netherlands. The choice is based on the availability of climate files (.epw) for the simulation program EnergyPlus, which is free of costs and can be obtained from the U.S. Department of Energy website (NREL, 2016). The hypothetical classroom geometry based on the BB, FS and PH consisting the various regulations and certificates, wherein higher demands are chosen in order to meet expected future requirements.

3.1 Classroom geometry

The classroom measures 7.2 x 7.2 m in width and depth, and follows a common Dutch building grid. The room floor-to-ceiling height is 3.5 m (FS quality C). Regular education should be based on 30 students and one teacher per classroom (RVO, 2015). Using the grid and number of people per classroom accounts to 1.67 m² per person, although this seems a worst case scenario. It falls in a range between 1.3 - 3.3 m² which correspondents to 87 % of all classrooms within the Netherlands (Versteeg, 2007).

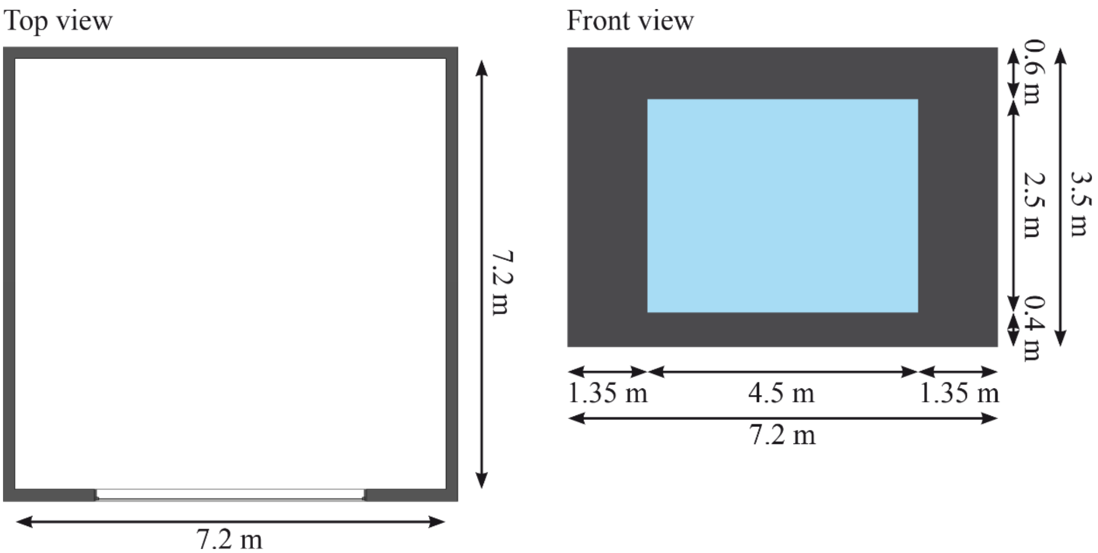


Figure 3-1. Reference case geometry.

There is not a typical Dutch window for schools. To find an average window size, a small study has been conducted on nine projects from Ector Hoogstad architects. By means of this small research, it can be concluded that the average window area is larger than 50 % of the façade, as shown in Table A-1. Furthermore, the window sill height varies from 0 to 0.8 m. However, previous studies found that window sill heights lower than the work plane have no extra effect on the daylight conditions (Naeem & Wilson, 2007). For this work the reference case (RC) gets a WWR of 45 %, which is less than the average found by the research. Because the geometry of the classroom does not have wall thicknesses, which may reduce the daylight, the WWR is slightly corrected to 45 %. The window sill height will be set on 0.4 m like the average found in the window research.

3.1.1 Construction

The construction is based on BB and PH requirements. The U-value characterizes the heat transmission through a building element. The window g-value expresses the coefficient of the solar heat transmission and Vt the visual transmittance of glass. The glazing plus frame U_w-value is, according to Velfac, measured for a window size of 1230 x 1480 (W x H) mm (Velfac, 2016). A change of the U-value by the alteration in window and frame size is not included in this study, the same accounts for thermal bridges. Although an U_w-value of 1.55 seems to be high, it still meets the BB requirements.

Table 3-1. The reference case construction framework obtained from "Bouwbesluit" (Binnenlandse Zaken, 2016), "Frisse scholen" (RVO, 2015) and "Passive house" standard.

Construction type	U-value [W/m² • K]			
Floor	Adiabatic			
Wall	0.15			
Ceiling	Adiabatic			
Air leakage				
Infiltration [l/(s • m²)]	0.583 at 50 Pa (0.6 ach)			
Window				
	U-value [W/m² • K]	G-value [%]	Vt [%]	U_w-value [W/m² • K]
Window clear argon	0.8	62	80	1.55

3.1.2 Material reflectance

Typical surface material reflectances, as given by the NEN-EN 12464-1 (obtained from the Philips guide (Philips, 2011)) are applied as a guideline for minimum lighting requirements for indoor workplaces and presented in Table 3-2. Average reflectance values are applied, since the user can be unpredictable when it comes to wall and ceiling decorations. Furthermore, furniture could also lower the reflectance.

Table 3-2. Material reflectance (Philips, 2011).

Surface	NEN reflectance [%]	Applied reflectance [%]
Floor	20 – 40	30
Wall	50 – 80	65
Ceiling	70 – 90	80

3.1.3 Occupancy schedule

An occupancy schedule with an occupancy rate for schools is used for the simulations. The schedule is necessary to determine the heating and ventilation time. Furthermore, the artificial lighting schedule is adapted to the occupancy and daylight conditions. A standard and widely used Dutch high school timetable consists of six to eight teaching slots of 50 minutes (Wikipedia, 2015). The starting time varies by school, but most classes begin around 8:15 or 8:45 and do have a break after two classes ((Segbroek College, 2016) and (KGC, 2016)). Assumptions are made for the occupancy rate, whereby it is expected that teachers arrive around 30-60 minutes earlier than students and during the break, one or two persons will occupy the room. The activity level was set to 1 met, which corresponds to approximately 60 W of heat loss from the occupant. The occupancy schedule is simplified to an hourly rate as shown in Table 3-3.

Table 3-3. Occupancy schedule used for this study obtained from typical high school timetable with occupancy rates for 30 students and one teacher (Segbroek College, 2016) and (KGC, 2016).

	Timetable	Occupancy rate [%]
Night	0:00 - 7:30	0
Teacher preparation	7:30 - 8:30	0.05
4 Lectures	8:30 - 12:30	1
Break	12:30 - 13:30	0.05
4 Lectures	13:30 - 17:30	1
Extra lessons	17:30 - 18:30	0.05
Evening	18:30 - 24:00	0

The school holidays were obtained from the national government for school year 2016-2017 presented in Table 3-4. (Rijksoverheid, 2016)

Table 3-4. School holidays for school year 2016-2017.

Holidays	Date
Summer	9 Jul – 20 Aug
Autumn break	14 Oct – 22 Oct
Christmas	23 Dec – 8 Jan
Spring break	25 Feb – 5 Mar
May break	22 Apr – 30 Apr

3.1.4 Internal loads

Currently, one laptop or tablet per four students is common. However the trend of using more devices is increasing and it is expected to have one device per three or two students (Kennisnet, 2015). It depends on the school what type of device is used, but to take an average for this work a laptop is assumed with 18 W (Consumentenbond, 2016). The laptop usage per class is approximately 60 % of the teaching time according to Kennisnet (Kennisnet, 2015). Nowadays, each class uses a smartboard instead of only a whiteboard, which provides additional internal loads of approximately 300 W. The equipment loads are calculated per classroom and not per square meter, because in the sensitivity study adaptations on the facade do alter the floor area but not the quantity of people, meaning that the equipment load remains constant, as presented in Table 3-5.

Table 3-5. Equipment loads per classroom.

Device	Power consumption [W/device]	Amount per classroom	Operation time per hour [%]	Total load [W / classroom]
Laptop	18	14	60	151.2
Smartboard	300	1	70	210

3.1.5 Daylight settings

The daylight simulations for DF, DA and UDI are conducted with the support of an analysis grid. The grid is divided in half a meters at a height of 0.7 m, resulting in 72 points receiving the quantity of light. The grid will not adapt when performing the analysis in this work, and therefore the results are always relative to the reference case. This may result that a point receiving less light due to the fact that the façade position is further away with respect to the reference model. The daylight condition must meet the BREEAM-NL and FS criteria, as mentioned in chapter 2.4.2, criteria which are based on the DF and uniformity ratio, as shown in Table 3-6. The DA and UDI are not criteria but give an impression of the light conditions in the room and will therefore be considered in this analysis.

Table 3-6. Daylight criteria to meet according to BREEAM-NL (DGBC, 2014) and "Frisse Scholen" (RVO, 2015).

Frisse Scholen	
Artificial light at desk level [lux]	500
Daylight factor at desk level [%]	5
BREEAM-NL	
Uniformity ratio [min DF/ avg. DF]	0.4

As explained earlier in chapter 1.4.2, the simulation plugin 'Honeybee' makes use of the daylight simulations software 'Radiance' in which five parameters are adjustable to keep it comprehensible for the general user, as summarized in Table 3-7. Changing these parameters defines the quality of detail and hence also the duration of the simulation time. Due to limited simulation time the settings are average.

Table 3-7. Set parameters for daylight simulations

Parameter	abbreviation	Value
Ambient bounces	AB	5
Ambient accuracy	AA	0.2
Ambient resolution	AR	64
Ambient division	AD	2048
Ambient super-samples	AS	2048

FS requires a minimum illumination of 500 lux on the working level for both quality requirements B and C. To fulfill this criteria at least eight LED luminaires of 39 W are needed to distribute sufficient light on the work surface for areas around 50-55 square meters, according to Philips (Philips, 2016). The lights are managed by two photo sensors (1 W standby power each) to dim the lights with respect to the daylight conditions. The artificial lighting is split into two rows, as presented in Figure 3-2. The second row will switch on if insufficient daylight is experienced in the back of the room, while the light can be off at the first row. In order to control this lighting system, one photo sensor is placed 1.8 meters from the window and the second one 5.4 m from the window at work plane level.

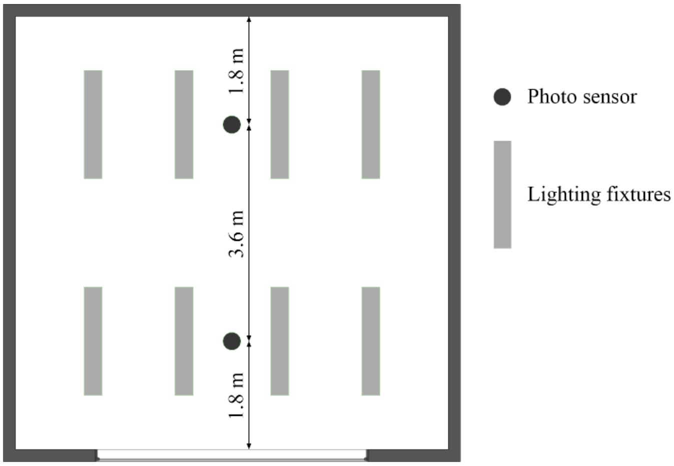


Figure 3-2. Lighting grid and lighting photo sensor positions.

3.1.6 HVAC

The HVAC has to be set to guarantee a certain air quality inside the classroom. The standard ventilation rate for occupied zones is 0.9 l/(s • m²) according to NEN-EN 13779. The FS heating and cooling set points for temperatures above or below 10 °C, as presented in Table 2-4cannot be applied in the energy script. Therefore, the annual heating set point is chosen from FS quality A (20 °C) and the cooling set point is applied according to PH requirements (25 °C) to analyse the overheating period, as shown in Table 3-8.

Table 3-8. HVAC settings.

Ventilation	
Standard ventilation rate [l/(s • m²)]	0.9
Ventilation rate per person [l/s]	8.5
Heat recovery [%]	80
Schedule	Always on
Operative temperatures [°C]	
Heating set point	20
Heating setback temperature (unoccupied)	17
Cooling set point	25
Cooling setback temperature (unoccupied)	28

4 Analyses setup

The analyses is divided into steps in order to provide an overview on the working method, as shown in Figure 4-1. First, after the obtained results of the 'reference case', the sensitivity 'analysis one' is conducted for the 'single fold' giving results. Secondly, cases from the 'single fold' results, which meet the established criteria, are proceeded as input for sensitivity 'analysis two' containing 'window case one', which generates further results. The steps from 'single fold' to 'window case one' are also repeated for the 'double fold' and 'triple fold'. Finally, from all these results an 'improved case' is obtained.

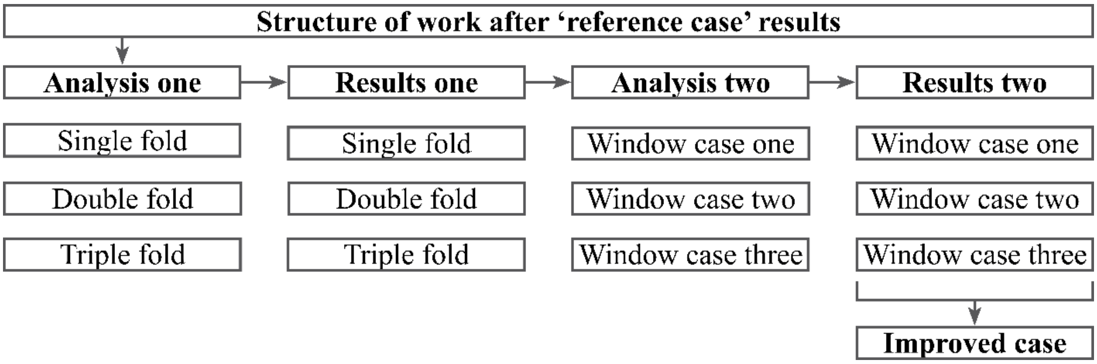


Figure 4-1. Structure of work and steps it takes to reach the "improved case".

The energy and daylight simulations are performed in Grasshopper following the process presented in Figure 4-2. First it begins with stage one, setting the parameters and define the model. Secondly, stage two, a daylight simulation is performed according to the daylight settings. The daylight simulation leads to a generated lighting schedule and subsequently imported into the energy calculations. This is an interaction between the Ladybug and Honeybee components. As last, stage three, an energy simulation will be conducted to obtain annual energy demands, operative temperatures and overheating hours.

From this point in the analysis the sum of the heating- and cooling demand and the electrical energy needed for artificial lighting is defined as the annual operational energy, eq. (3).

$$Q = H + C + E_l \text{ [kWh/m}^2\text{]} \qquad \text{eq.(3)}$$

Where:
H = Annual heating demand per m² [kWh/m²]
C = Annual cooling demand per m² [kWh/m²]
E_l = Annual electricity lighting per m² [kWh/m²]
Q = Annual operational energy per m² [kWh/m²]

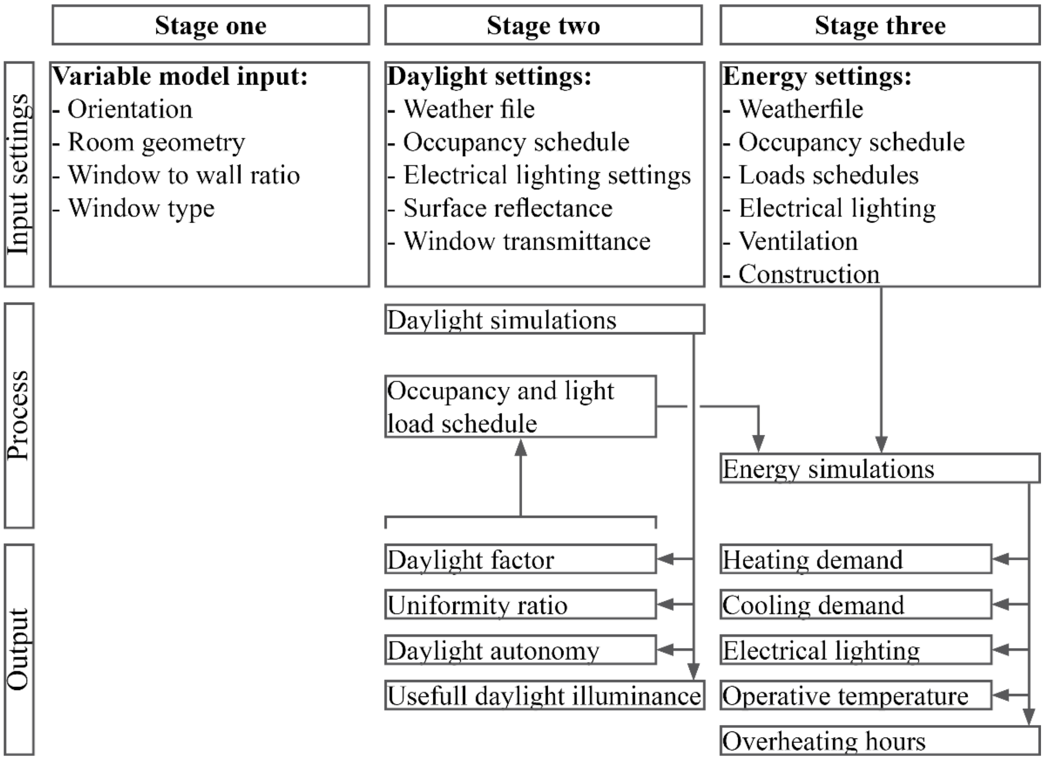


Figure 4-2. The process carried out in grasshopper for daylight and energy simulations.

4.1 Analysis of reference case

First, an analysis is conducted on the reference case in order to identify the daylight conditions, energy demand and when overheating appears. The energy performance and daylight results of the reference case serve as reference data relative to the parametric simulations that follow later.

4.1.1 Variables

The analysis focuses on East and West facades, but will also consider South to make a comparison, since several studies have been carried out for South (Figure 4-3). After the sensitivity analysis, a selection will be made between East and West for the further research, considering the most inefficient case and/or higher percentage of overheating.

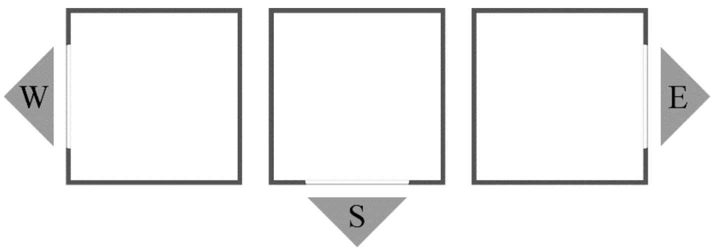


Figure 4-3. Orientation parameters for the reference case analysis.

4.2 Sensitivity analysis "folded surface geometry"

After the reference case analysis, a sensitivity analysis for the identification of improvement potentials of the façade geometry is conducted.

4.2.1 Case 1 'single fold'

Within this study, a folded façade means that the facade is separated into two wall sections shifting along the grid, as shown in Figure 4-4. The wall sections are referred in this report to one wall facing towards 'South-West' (SW) and the other facing towards 'North-West' (NW). The point where the two walls join is called the 'folding point'. The folding point is situated in the middle of the flat facade as base location. From there the folding point is able to move over a grid.

In order not to create too many iterations, which would make the simulation extensively time-consuming, some simplifications are made. The folding point can vary along the X-axis (A, B and C) and Y-axis (-5 to 5) as shown in Figure 4-4. The incremental variables over the X and Y-axis for the folding point are presented in Table 4-1.

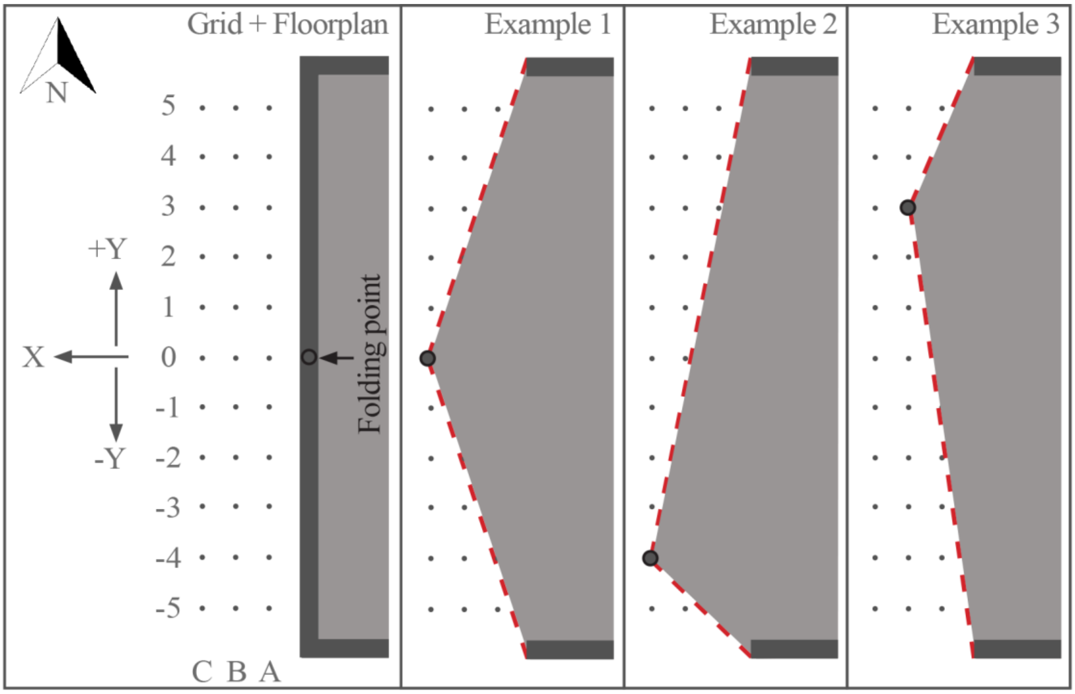


Figure 4-4. The single fold adapting geometry parameter for the sensitivity analysis. On the left, floorplan with grid. On the right, some examples to visualize the idea of the folding façade geometry.

Table 4-1. The grid size for X and Y-axis for a single fold.

X-axis	A				B				C		
Meters	0.4				0.8				1.2		
Y-axis	-5	-4	-3	-2	-1	0	1	2	3	4	5
Meters	-3	-2.4	-1.8	-1.2	-0.6	0	0.6	1.2	1.8	2.4	3

In addition to the adapting geometry, the window-to-wall ratio (WWR) ranges in four various steps (0.3, 0.4, 0.5 and 0.6), as shown in Figure 4-5. The WWR of 0.3 and 0.4 are proven to be effective by numerous studies for the energy performance and daylight conditions. Furthermore, WWR 0.5 and 0.6 are taken into account to increase the WWR on one façade whereby the second façade may have a lower WWR (Tzempelikos & Athienitis, 2007), (Goia, et al., 2013), (Shen & Tzempelikos, 2012). It must be noted that if a facade changes in size the same WWR adapts in correlation to the façade. For example, two walls with different widths but the same WWR gives two different answers:

$$Window\ area = Width\ [m] x\ Height\ [m]\ x\ WWR = 2\ x\ 3.5\ x\ 0.4 = 2.4\ m^2$$

$$Window\ area = Width\ [m] x\ Height\ [m]\ x\ WWR = 5\ x\ 3.5\ x\ 0.4 = 7\ m^2$$

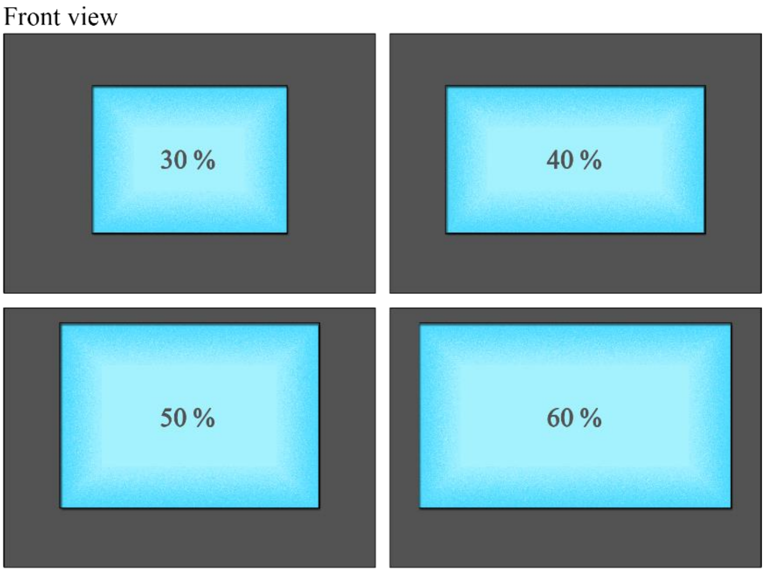


Figure 4-5. WWR parameter: Window to wall ratios for each wall section for the sensitivity analysis on the folding geometry.

Despite the simplification, 528 iterations will be calculated for a single fold, based on following formula (eq. (4)):

$$Iterations = X \bullet Y \bullet W \bullet R \qquad \text{eq. (4)}$$

Where:
X: Amount of variables over the X-axis.
Y: Amount of variables over the Y-axis.
W: Amount of wall sections per direction, which is always two. Meaning, if two walls are facing South-West they will always be counted as one and the two walls facing North-West will be counted as one.
R: Amount of window-to-wall ratios

4.2.2 Case 2 'double fold'

The description above for a single fold is also used for a 'double fold'. More foldings change the façade geometry and may influence the energy performance or daylight conditions. Figure 4-6 represents an adjusted grid for two folding points, maintaining a room width of 7.2 m. The folding points can no longer move three meters up and down over the Y-axis. Instead of three meters it is 1.8 meters as shown in Table 4-2. The double fold geometry generates 336 iterations in conjunction with the WWR parameters, as explained in chapter 4.2.1.

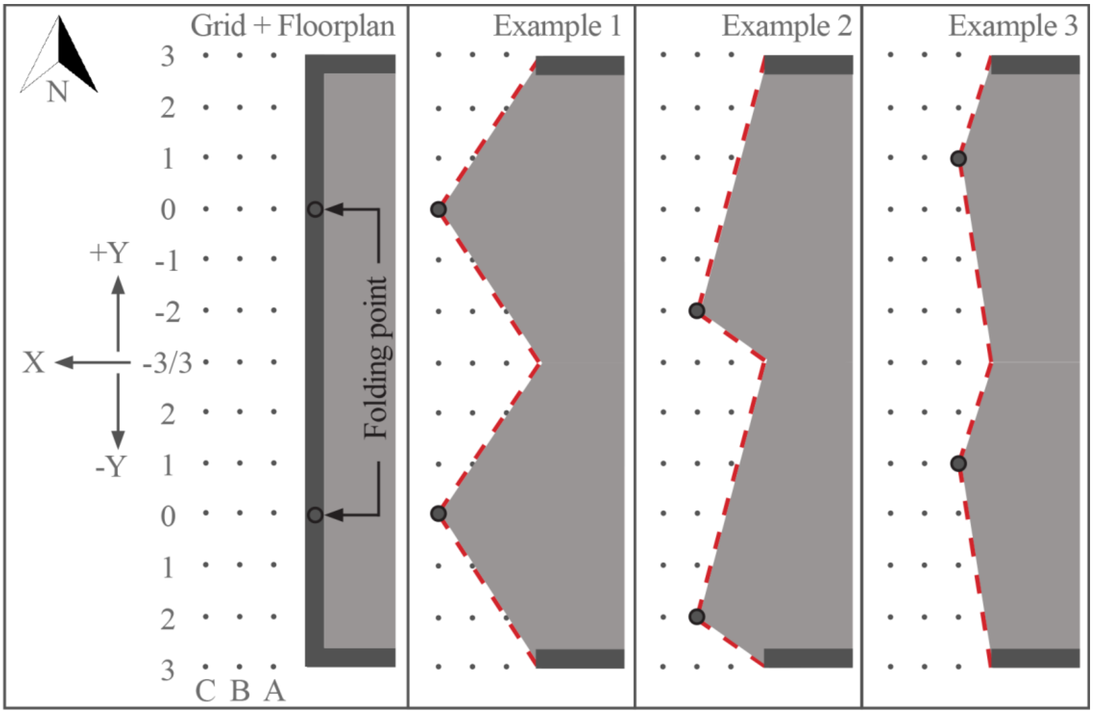


Figure 4-6. The double fold adapting geometry parameter for the sensitivity analysis. On the left, floorplan with grid. On the right, some examples to visualize the idea of the folding façade geometry.

Table 4-2. The grid size for X and Y-axis for a double fold.

X-axis	A		B		C		
Meters	0.4		0.8		1.2		
Y-axis	-3	-2	-1	0	1	2	3
Meters	-1.8	-1.2	-0.6	0	0.6	1.2	1.8

4.2.3 Case 3 'triple fold'

The last folding geometry analysis is conducted on three foldings as presented in Figure 4-7. Again, the grid space becomes smaller when more foldings are applied and thereby result in less iterations up to 240. The maximum up and downward displacement over the Y-axis is adjusted to 1.2 meter, as shown in Table 4-3. The WWR parameters are also included besides the geometry adaptations for the triple fold as described in chapter 4.2.1.

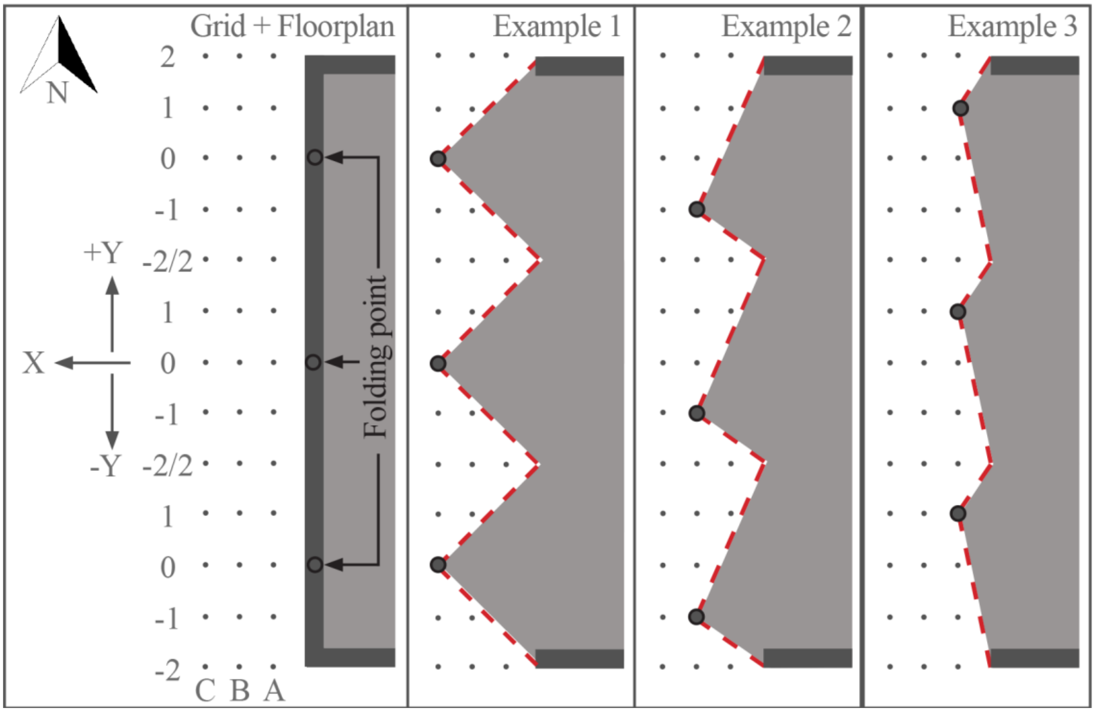


Figure 4-7. The triple fold adapting geometry parameter for the sensitivity analysis. On the left, floorplan with grid. On the right, some examples to visualize the idea of the folding façade geometry.

Table 4-3. The grid size for X and Y-axis for a triple fold.

X-axis	A	B	C		
Meters	0.4	0.8	1.2		
Y-axis	-2	-1	0	-1	-2
Meters	-1.2	-0.6	0	0.6	1.2

4.3 Sensitivity analysis "window type"

After the reference case and folded surface geometry analysis, the best cases based on energy performance and daylight conditions are used for further research for the window cases. The facade measure for this second sensitivity analysis consists of adjustments in the window properties, which may provide more or less solar radiation (solar heat gain) and daylight availability.

4.3.1 Parameters

For the next sensitivity analysis, three types of windows were chosen from Velfac, (Velfac, 2016). As mentioned in chapter 4.2.1, the folded façade is divided into two sections 'SW' and

'NW'. For each wall section three types of windows can be simulated resulting in three times three (nine) variants by each facade, as shown in Figure 4-8, and presented in Table 4-4.

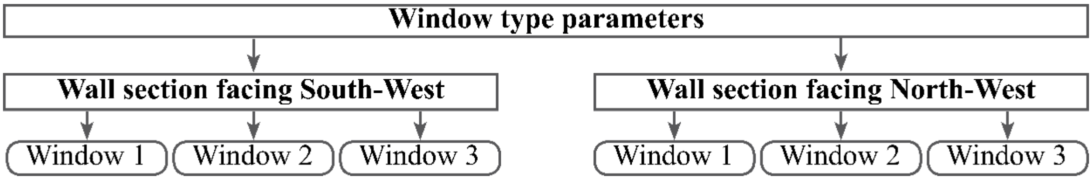


Figure 4-8. Window type parameters for each wall section in 'single fold', 'double fold' and 'triple fold'.

Table 4-4. Window type explained for each variant. The first number is the window type for 'SW' direction and the second number for window type on the 'NW' side.

Variant	1	2	3	4	5	6	7	8	9
Window type	1-1	1-2	1-3	2-1	2-2	2-3	3-1	3-2	3-3

The window types are presented in Table 4-5, whereby window type one is the basic window used for the reference case and folded surface geometry cases. Window type two has a lower u-value, allows less solar radiation and less visual transmittance. Window type three also has a lower u-value but partly preserves the properties for solar gains and visual transmittance like window type one. For this second sensitivity analysis the window Uw-value plus frame was set, but excluded the extra heat losses by changing the window size (Velfac, 2016).

Table 4-5. Window properties for each window type.

Window type	Construction	Type by Velfac	U-value [W/m² • K]	g-value [%]	VT [%]	U_w-value [W/m² • K]
1	4-16-4	Clear argon	1.11	62	80	1.55
2	4-18-4-18-4	Energy clear argon	0.5	43	65	0.82
3	4-18-4-18-4	Energy South clear argon	0.62	62	73	0.79

4.3.2 Single fold 'window case 1'

The models out of 'single fold' analysis that are subject to further investigation should meet the DF requirement of 5 %, and in addition, have an annual operational energy use of less than 20 kWh/m². The annual operational energy limit of 20 kWh/m² is not based on a criteria, but chosen to limit the number of window case simulations.

The following is based on the results of the 'single fold'. Within the above mentioned criteria are 24 cases. These 24 cases are further examined for the window types and each case will generate eight additional options ending up to 192 iterations, excluding the already simulated base windows (type 1), as presented in Table 4-6 (including the base windows type 1).

Table 4-6. The amount of cases obtained from the 'single fold' results towards the total cases for the 'window case 1' including the base window type 1.

	Single fold cases meeting the boundaries	New iterations	Total cases for 'window case 1'
X-axis A	14	112	126
X-axis B	9	72	81
X-axis C	1	8	9

4.3.3 Double fold 'window case 2'

For the double fold 'window case 2' the annual operational energy boundary of 20.0 kWh/m² was not met. So, the boundary was raised to 20.2 kWh/m², although not set higher to minimize the amount of cases. Furthermore the DF remains 5 %. Within these criteria, 18 options were further examined for the window types and thus each case will generate eight additional options ending up to 144 iterations, excluding the already simulated base windows (type 1).

It should be noted that since the energy boundary can be adjusted (in order to reduce the number of simulations) might exclude potential cases. Because none of the folding point X-axis at C cases met the criteria. Therefore one C case, meeting the DF but with the lowest possible operational energy, is included in the simulations, shown in Table 4-7.

Table 4-7. The amount of cases obtained from the 'double fold' results towards the total cases for the 'window case 2' including the base window type 1.

	Folding cases meeting the boundaries	New iterations	Total cases for 'window case 1'
X-axis A	16	128	144
X-axis B	2	16	18
X-axis C	1	8	9

4.3.4 Triple fold 'window case 3'

For triple fold the same operational energy criteria could not be used as the previous single and double fold, so therefore the boundary was adjusted to 20.5 kWh/m², and can be seen in Figure 5-11. The DF criteria is retained at 5 %. Resulting in 16 cases within the defined criteria, however, these are all cases with an X-axis A, besides one B.

In order not to immediately exclude potential X-axis B and C cases, are case adopted with minimal annual operational energy and sufficient daylight to find out if B and C could improve. Therefore, one extra case for X-axis B (20.7 kWh/m²) and one case for X-axis C (21.3 kWh/m²) are included. This brings the total number of cases at 18, resulting in 144 iterations excluding the already simulated base windows (type 1), as presented in Table 4-8.

Table 4-8. The amount of cases obtained from the 'triple fold' results towards the total cases for the 'window case 3' including the base window type 1.

	Folding cases meeting the boundaries	New iterations	Total cases for 'window case 1'
X-axis A	15	120	135
X-axis B	2	16	18
X-axis C	1	8	9

4.4 Sensitivity analysis 'improved case'

To be eligible for the improved case, the "window type" results must comply the DF requirement of 5 % and the annual operational energy to be lower than the reference case, thus below 20 kWh/m². In order not to end up with too many cases only three cases for each single, double and triple fold are selected and thereby having a different geometry. By using this method the architect or client can still have an architectural freedom of choice.

5 Results

5.1 Reference case

The reference case is simulated for three cardinal directions, as mentioned before in chapter 4.1.1. The worst case, on the operational energy, is chosen in this simulation for further analysis. Figure 5-1 shows that there is only a marginal difference between East and West facing directions. It can be observed, despite the slight variations, that West requires a higher annual heating and cooling demand compared to East. South, however, requires more cooling and less heating, due to higher solar gains and without shading (4318 kWh for South compared to 2912 kWh and 3077 kWh for the whole room on East and West). In addition, the lighting energy is slightly higher on West than East, primarily because West demands more lighting in the morning. Overall, West requires annually 0.4 kWh/m² more compared to East, which is only a difference of 2 %.

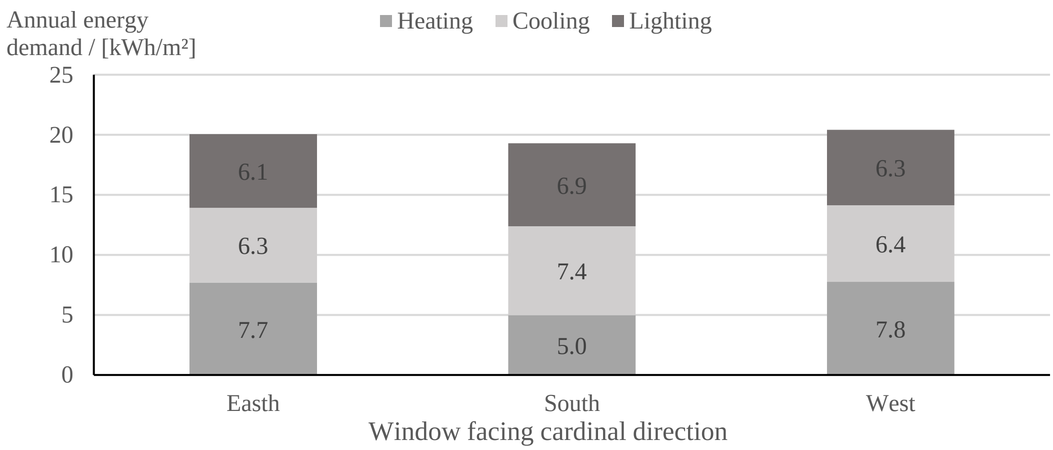


Figure 5-1. Reference case energy demand for different cardinal directions.

The overheating percentage of occupied time for East and West is approximately 15.9 % and 16.2 %, as presented in Table 5-1. South clearly has the most hours of overheating with 22.3 percent.

Table 5-1. Overheating percentage of occupied hours for different cardinal directions.

	East	South	West
Overheating hours / % of occupied hours	15.9	22.3	16.2

The moment of overheating is partly different between the two cardinal directions, although the percentage of overheating is approximately the same. At West (Figure 5-2) it is quite clear to see that more moments of overheating will take place in the afternoon, in contrast to the East (Figure 5-3) where it is evenly distributed throughout the day.

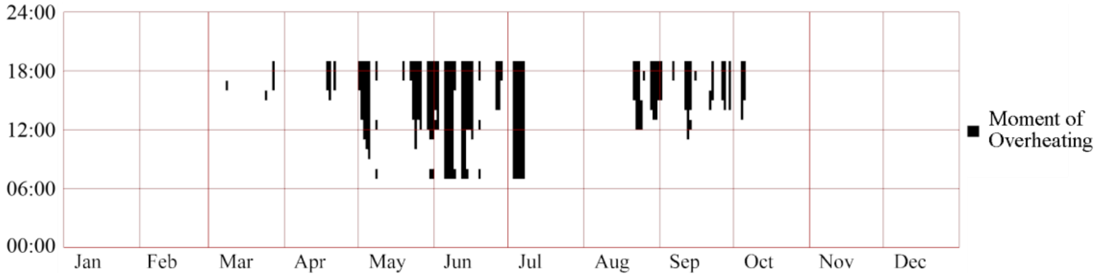


Figure 5-2. Overheating periods, cardinal direction: West.

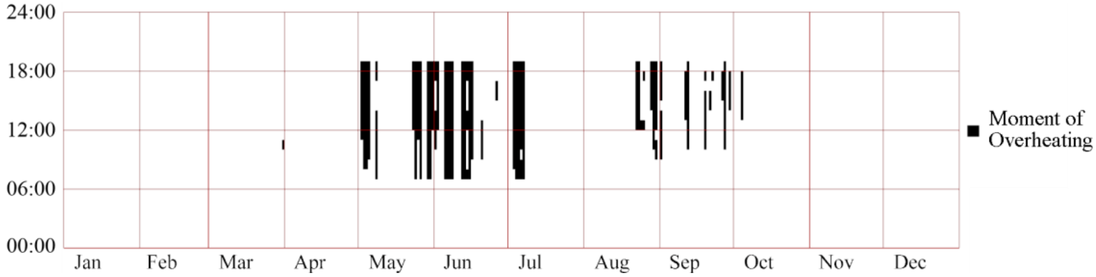


Figure 5-3. Overheating periods, cardinal direction: East.

In Figure 5-4, it can be observed that more glare, UDI above 2000 lux, can be experienced on the East and West cardinal directions, whereby the glare probability is reduced by half on the South. Assuming that the glare probability can be reduced for East and West. The useful daylight is in all cases more than 65 % of the time. As a side note it should be mentioned that this does not imply that it meets the daylight requirements. The DF, however, is an inspected factor by BREEM-NL (DF > 3 %) and FS (DF > 5 %) requirements and for all the cardinal directions it complies the requirements of 6.3 %. Only the uniformity ratio of 0.24 does not meet the BREEAM requirement of 0.4.

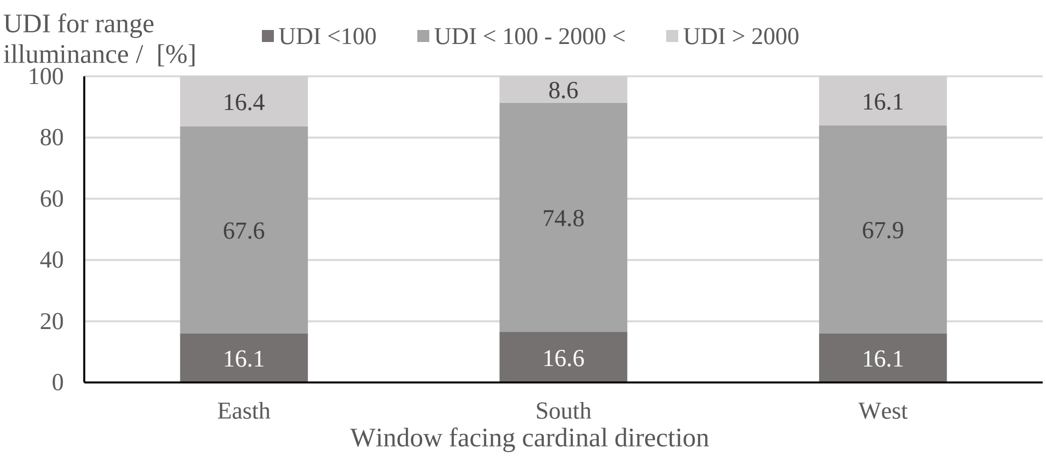


Figure 5-4. Reference case, useful daylight illumination for different cardinal directions.

5.1.1 Summary

West is considered more critical concerning energy demand, although this is minimal when compared to East. On the basis of this analysis, there might be potential improvements possible if compared with South, whereby less annual operational energy is needed, and the risk of glare is less present. So, it can be said that both cardinal directions are worth to be explored to decrease the energy demand and improve the daylight conditions. For this study West is chosen since it is slightly more critical than East.

5.2 Folded case results

The folded facades contain adaptations on the facade geometry and variations in window size, according to chapter 4.2.1. In this chapter, the results are shown in order to determine which design works out best for further research on the second sensitivity analysis 'window case'. The adaptation is analyzed with multiple façade foldings, explained in chapter 4.3 and mentioned for each subchapter.

5.2.1 Single fold

Figure 5-5 presents the DF relative to the annual operational energy. It can be observed that when the DF increases the annual operational energy also increases. From all 528 iterations, daylight factors are within 3.7 and 8.2 % and the annual operational energy does not exceed 22 kWh/m². The case with the lowest DF is also the one with the lowest annual operational energy use of 19.6 kWh/m². The average annual operational energy use of all 528 'single fold' iterations is 20.5 kWh/m², and has a DF of 5.9 %. The cases are also divided into the three various distances defined for the folding point over the X-axis grid. If the folding point moves further away from the base location (from A to C) the DF becomes less. The cases left of the reference case do all have a lower operational energy but lower DF. The cases on the right side do have a higher operational energy and also a higher DF.

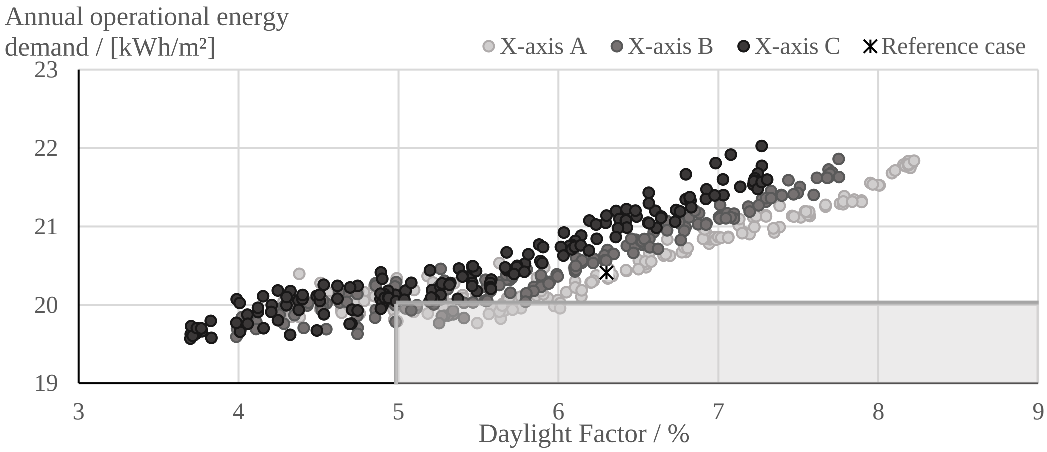


Figure 5-5. The daylight factor relative to the annual operational energy demand. Cases are presented for the different X-axis distances. The light gray box presents the criteria for which the cases must meet for further research on 'window case 1' as mentioned in chapter 4.3.2.

The overheating period, as presented in Figure 5-6, never meets the PH criteria of less than 10 % of the occupied time. Cases on the left from the reference case have a lower DF and also a decreased overheating period. The cases on the right side do mainly have a higher overheating period and also a higher DF. A same type of pattern as for Figure 5-5 can be observed whereby X-axis A has a higher DF but lower overheating period relative to B and C. In general, the cases have an overheating period of around 15 % of the occupied time and never exceeds the 20 %. The lowest overheating period is close to 10 % for X-axis C, however, it is not close to the required DF of 5 %.

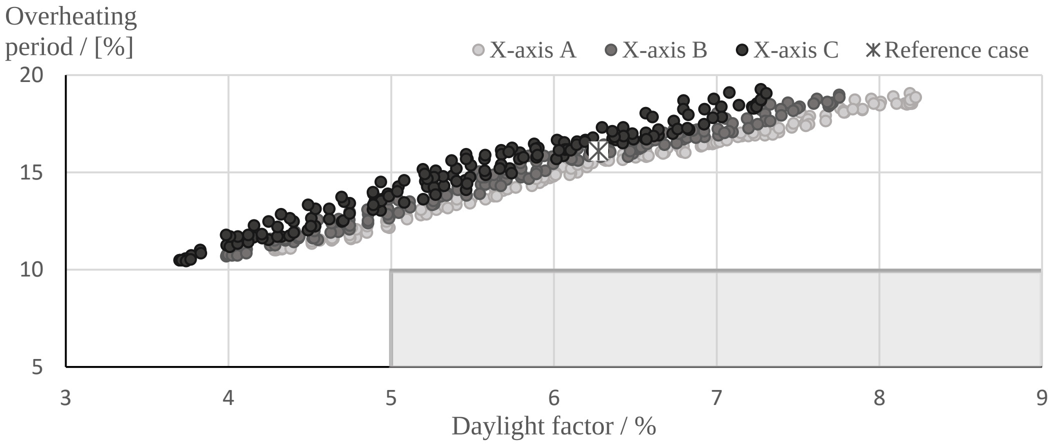


Figure 5-6. The daylight factor relative to overheating period and is divided into the different X-axis distances. The light gray box presents the criteria for FS (DF) and PH (overheating period).

Figure 5-7 shows the heating- and cooling demand and electric lighting separately and also per X-axis distance to observe the change in energy in relation to the DF. With the enhanced daylight factor a slight increase on heating demand is observed and how greater the X-axis distance the more heating is needed. The heating demand is mostly higher if compared to the reference model. Furthermore, the cooling demand rises much faster as a result of enlarged window areas gaining more solar heat, however the rise is less steep for a smaller X-axis distance, such as for cases A. The cooling cases have a lower demand on the left side of the reference case, and an increased cooling demand on the right side. On the other hand the electric lighting decreases at a higher daylight factor. It can be observed that the electric energy stays approximately the same regarding X-axis A, B and C, which is due to the two located photo sensors receiving the same percentage of annual lux (500 lux) within the simulated period.

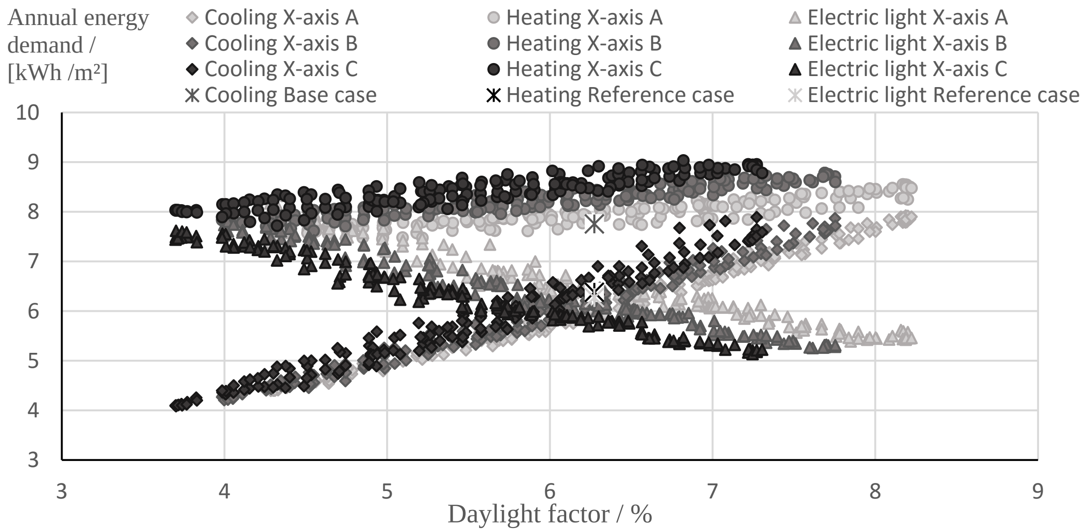


Figure 5-7. Daylight factor separated for the heating-, cooling demand and electric lighting over the X-axis categories.

5.2.2 Double fold

By applying two foldings fewer cases are located within the set boundaries as drawn up by one folding, shown in Figure 5-8. Again the higher the DF the more operational energy is used, as also observed by one folding. The lowest DF of 3.7 % has an annual operational energy of 19.9 kWh/m² for X-axis C. At X-axis A the least annual kWh/m² are required (19.8) and achieves a daylight factor of 4.2 %. Furthermore, the highest DF (8.3 %) requires annually 22 kWh/m² and the maximum energy is achieved for a case with a X-axis C. On average a double folding (21.0 kWh/m²) requires a higher annual operational energy compared to a single fold (20.5 kWh/m²) i.e. single fold performs better than double fold. Moreover, the average DF remains the same at 5.9 %. The cases left of the reference case do have a lower DF but not always a lower operational energy. The cases on the right side do have a higher operational energy and also a higher DF.

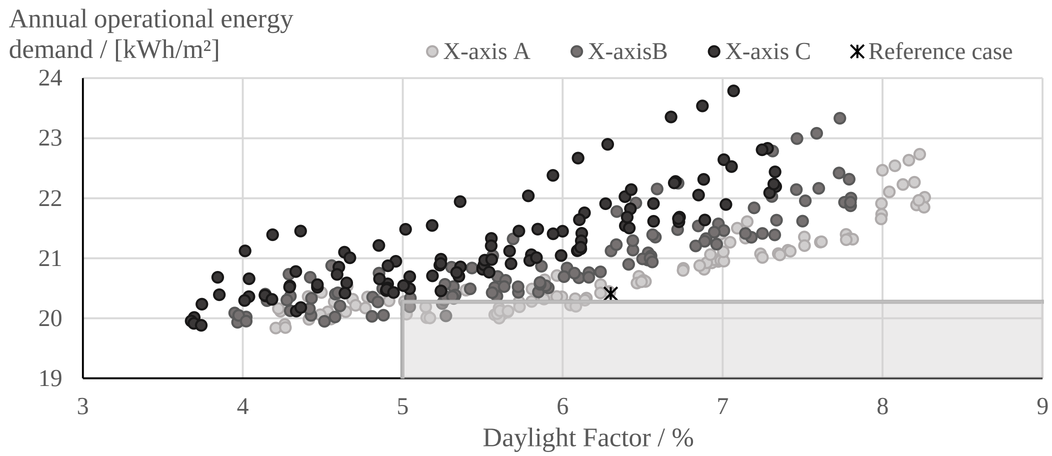


Figure 5-8. The daylight factor for two foldings relative to the annual operational energy demand. Cases are presented for the different X-axis distances. The light gray box presents the criteria for which the cases must meet for further research on 'window case 2' as mentioned in chapter 4.3.3.

The overheating period never meets the PH criteria of less than 10 % of the occupied time, as presented in Figure 5-9. It can be observed that lower overheating periods and better DF are achieved for X-axis A, compared to X-axis B and C, also found left from the reference case. In general, X-axis A (15.5 %) has a lower overheating period relative to B (15.7 %) and C (16.2 %), furthermore, 10 cases do exceed an overheating period of 20 %. Even though some cases have an overheating period of 11 % of the occupied time, they never meet the DF criteria of 5 %.

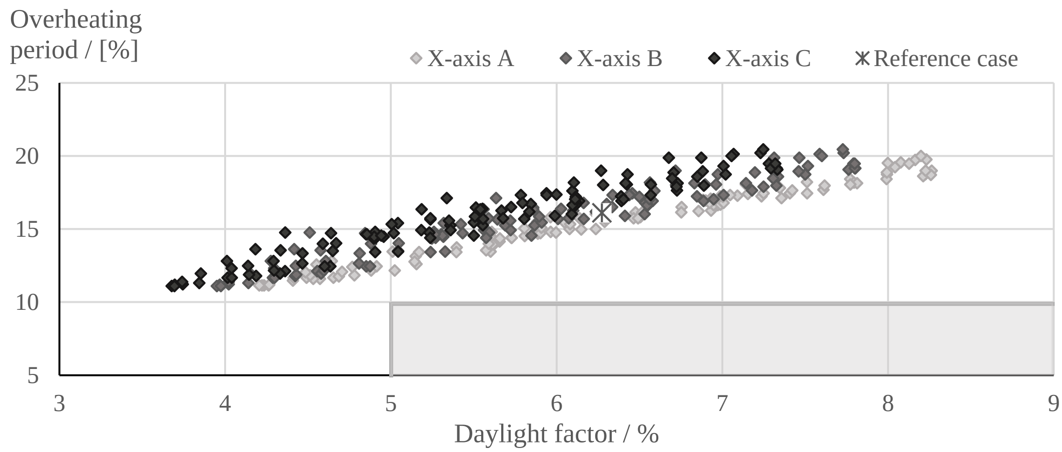


Figure 5-9. The daylight factor relative to overheating period and is divided into the different X-axis distances. The light gray box presents the criteria for FS (DF) and PH (overheating period).

For the double folding models it can be seen in Figure 5-10 that a quantity of cases for the annual heating demand rises above 9 kWh/m², which did not occur by the single fold models. Further, the X-axis distances are more scattered and do overlap more, although on average the X-axis A cases do still have a lower heating demand compared to X-axis B and C. The rise in the heating demand also appears for the cooling demand (Figure 5-10) whereby 30 cases exceed 8 kWh/m², which did not occur for a single fold. In addition, the cooling raises as the X-axis distance become larger.

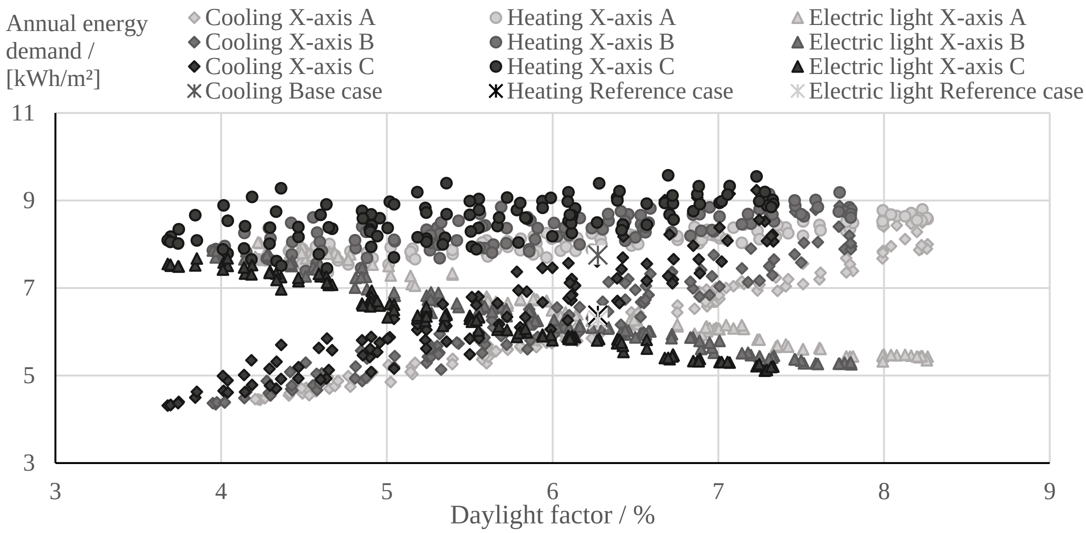


Figure 5-10. Daylight factor separated for the heating-, cooling demand and electric lighting over the X-axis categories.

5.2.3 **Triple fold**

Once again, in the application of an extra folding, the average annual operational energy is rising to 21.64 kWh/m² and the average DF remains the same at 5.9 %. The pattern repeats itself in which the X-axis C fall into the highest regions as it revolves around the operational energy demand and having the highest annual operational energy case of 25.5 kWh/m², as shown in Figure 5-11. The folding point closest to the base line (X-axis A) requires the least operational energy while the majority keeps sufficient daylight conditions above the defined DF of 5 %. The X-axis B is the one overlapping both X-axis A and C. The lowest annual operational energy case has an usage of 20 kWh/m² and the biggest DF is 8.3 %, both cases having X-axis A. The grey box represents the boundary condition for further research as described in chapter 4.3.4. Again the cases on the left hand side of the reference case do all have a lower DF but mainly not a lower operational energy. The cases on the right side do have a higher operational energy and also a higher DF.

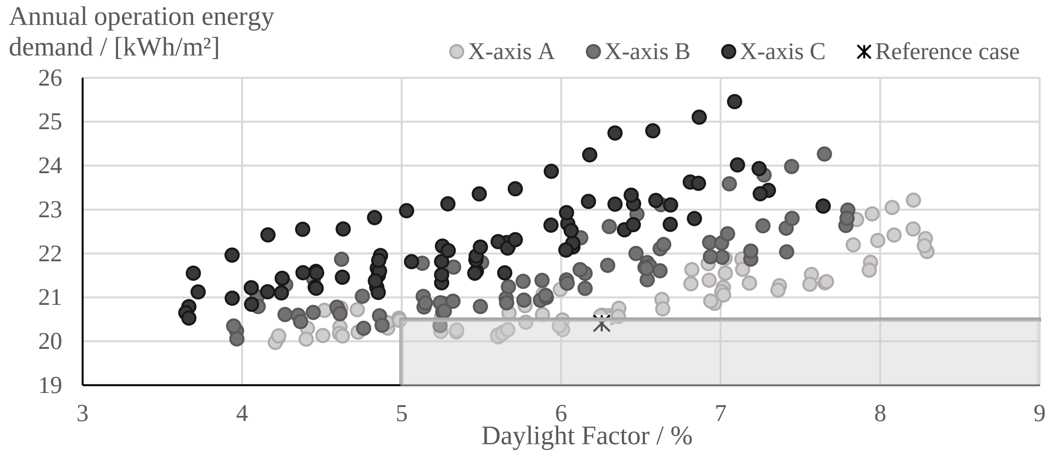


Figure 5-11. The daylight factor for a triple folding relative to the annual operational energy demand. Cases are presented for the different X-axis distances. The light gray box presents the criteria for which the cases must meet for further research on 'window case 3' as mentioned in chapter 4.3.4.

The PH overheating requirement is never achieved for a 'triple fold', as presented in Figure 5-12. It can be observed that X-axis A has a higher DF but a lower overheating period relative to B and C. In addition, X-axis B and C are more spread out compared to the 'single fold' and 'double fold' overheating cases. In general, X-axis A (15.8 %) has a lower overheating period relative to B (16.7 %) and C (17.4 %). Furthermore, 27 cases do exceed an overheating period of 20 %. Again, the cases on the left have a lower DF but certainly not always a lower overheating period compared to the reference case. On the other hand having a higher DF results mainly in a higher overheating period.

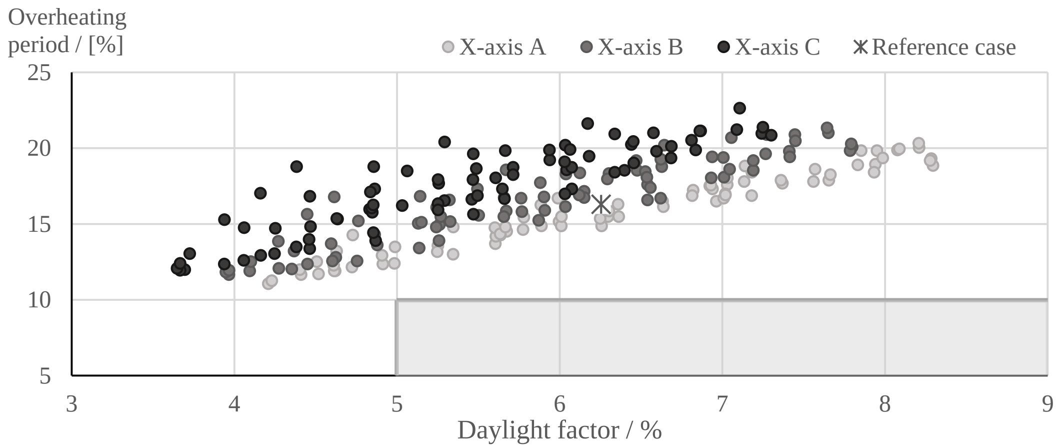


Figure 5-12. The daylight factor relative to overheating period and is divided into the different X-axis distances. The light gray box presents the criteria for FS (DF) and PH (overheating period).

Figure 5-13 presents the energy against the DF for the cooling, heating and electric lighting. All triple fold cases have a much wider distribution for both cooling and heating compared with single and double folds. Only the electric lighting has more or less the same linear results.

For the annual heating demand, one case exceeds 10 kWh/m² (X-axis C) and the least required energy is observed for X-axis A of 7.3 kWh/m². The annual cooling demand requires more energy compared with a single or double fold and also as the X-axis distance becomes larger. The lowest and highest annual cooling demand are 4.5 and 10.1 kWh/m². Moreover 46 cases do exceed the 8 kWh/m² annual cooling demand, as presented in Figure 5-13.

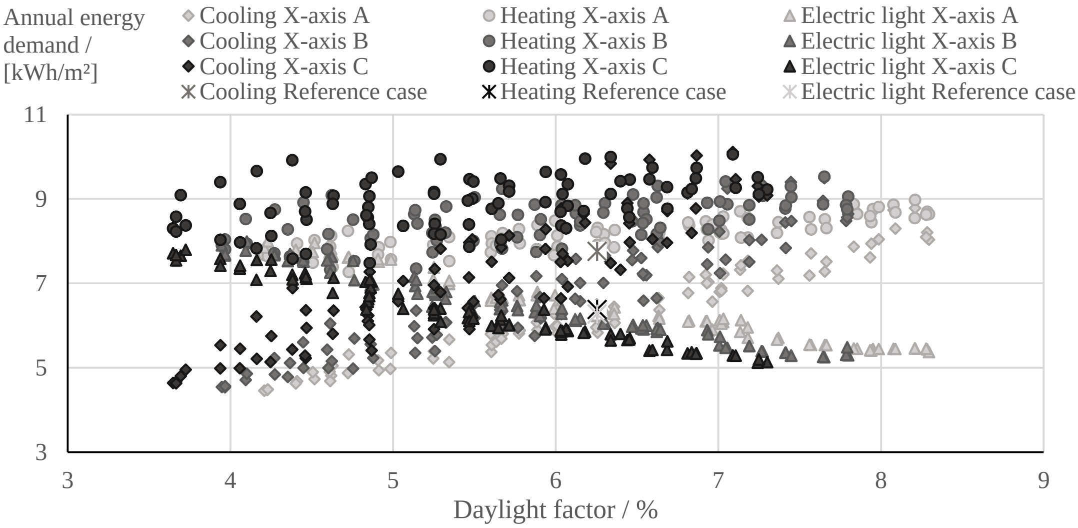


Figure 5-13. Daylight factor separated for the heating-, cooling demand and electric lighting over the X-axis categories.

5.2.4 Folding case: average occurrence

Figure 5-14 presents the average energy demand for each fold and X-axis distance. It can be observed that the cooling demand for a single fold decreases as the folding point expands from A to C, but increases for the double and triple fold. The heating demand always rises by having more folds and by enlarging the X-axis distance. Further, the electric lighting has a slight decrease but stays approximately the same compared with the reference case. As more foldings are applied and the further the X-axis distance the higher the annual operational energy demand, although minimal for a single fold.

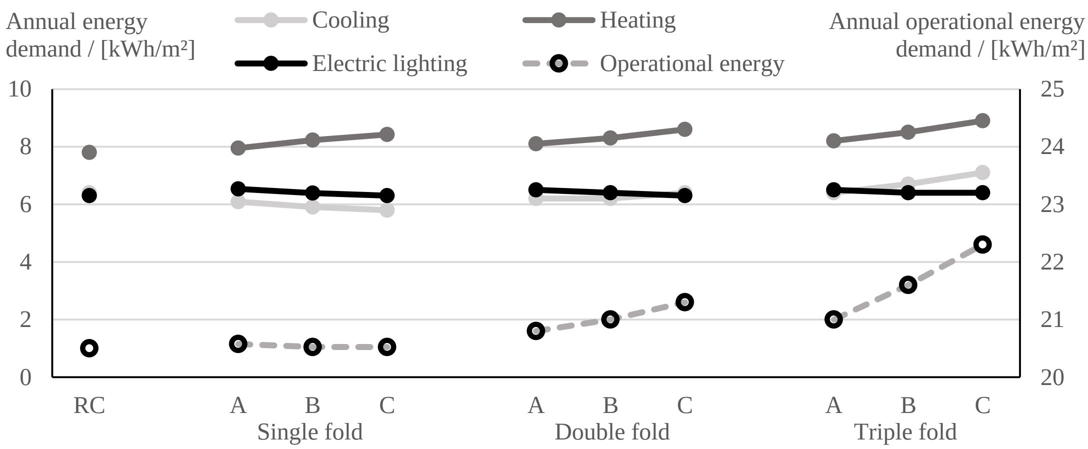


Figure 5-14. The average energy demand for cooling, heating, electric lighting and annual operational energy for each fold and X-axis distance.

The minimum difference for the electricity lighting demand can be explained by the daylight autonomy (DA), as presented in Figure 5-15, which is connected with the photo sensors. It can be seen that the annual DA barely decreases, meaning that the photo sensors receive the same amount of annual daylight regardless of the case and has little impact on the electric lighting demand. Meanwhile the DF decrease much more and caused primarily by the limitations of daylight factor metric.

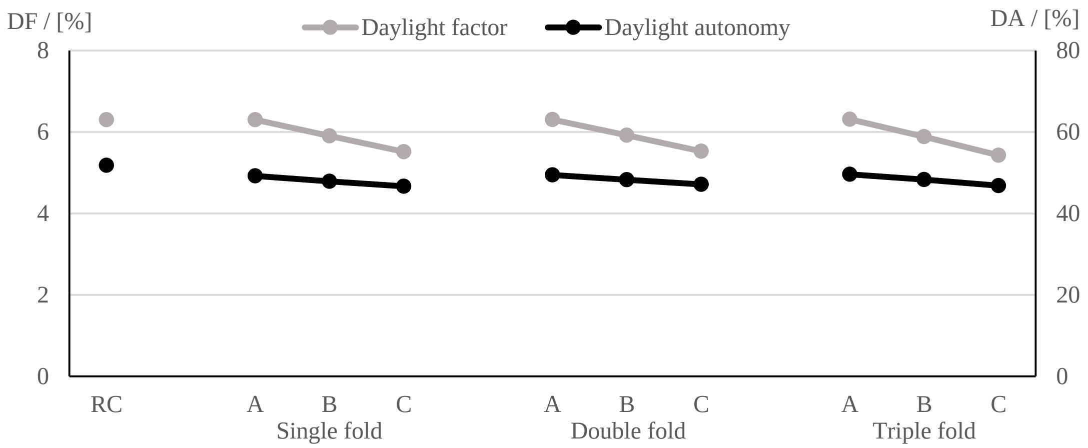


Figure 5-15. The average daylight factor and daylight autonomy for each fold and X-axis distance.

Figure 5-16 presents the obtained solar gains and overheating period. It can be observed that the solar gains increase as more foldings are applied and the X-axis distance becomes larger. Having more folds and greater X-axis distance does enlarge the wall and window areas i.e. bigger absorption surfaces (Figure A-6). This also results in increased overheating periods, although this is not directly the case for a single fold.

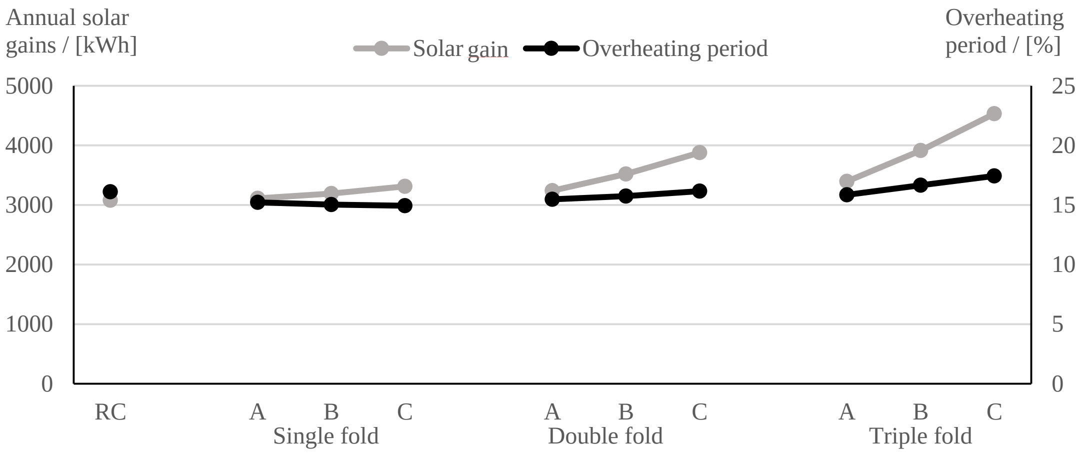


Figure 5-16. The average solar irradiation and overheating period for each fold and X-axis distance.

5.3 Window case results

The various cases covered in this chapter, who met the drafted boundaries as described in 4.3, were further studied and analyzed on multiple window types. The subchapters are subdivided by the number of foldings.

5.3.1 Window case 1

By observing the 24 cases obtained from the 'single fold' analysis it can be seen in

Table 5-2 that the Y-axis distances is widely spread without a pattern. Meaning that there is not one Y-axis turning out the best. From Table 4-6 it was already noted that the majority of cases meeting the boundary conditions are found in the X-axis A category. The WWR at South-West is largely 0.4, where it is split on North-West across 0.3 and 0.4. Naturally, the number of cases for each parameter can be calculated times nine, to have the amount of new window cases.

Table 5-2. Amount of cases per X-axis, Y-axis and WWR for both wall facing directions which do meet the chosen boundaries obtained after the single fold geometry analysis.

	Y-axis distance											Total for X-axis
	-3	-2.4	-1.8	-1.2	-0.6	0	0.6	1.2	1.8	2.4	3	
X-axis A	2	1	0	2	2	1	0	2	1	1	2	14
X-axis B	0	2	1	1	0	1	1	1	0	1	1	9
X-axis C	0	0	0	0	1	0	0	0	0	0	0	1

WWR on South-West				
WWR	0.3	0.4	0.5	0.6
Amount of cases	2	14	4	4
WWR on North-West				
WWR	0.3	0.4	0.5	0.6
Amount of cases	11	12	0	1

The 24 cases, as described in chapter 4.3.2, are further investigated ending up to 216 cases. From the 216 cases, 83 cases do meet the boundary conditions (annual operational energy demand of 20 kWh/m² and DF 5 %) and include 24 cases from the previous 'single fold' analysis, as shown in Figure 5-17 (the grey box). It can be observed that for most cases after a window change the annual operational energy is reduced, wherein one part achieves the DF requirement and a major part does not comply.

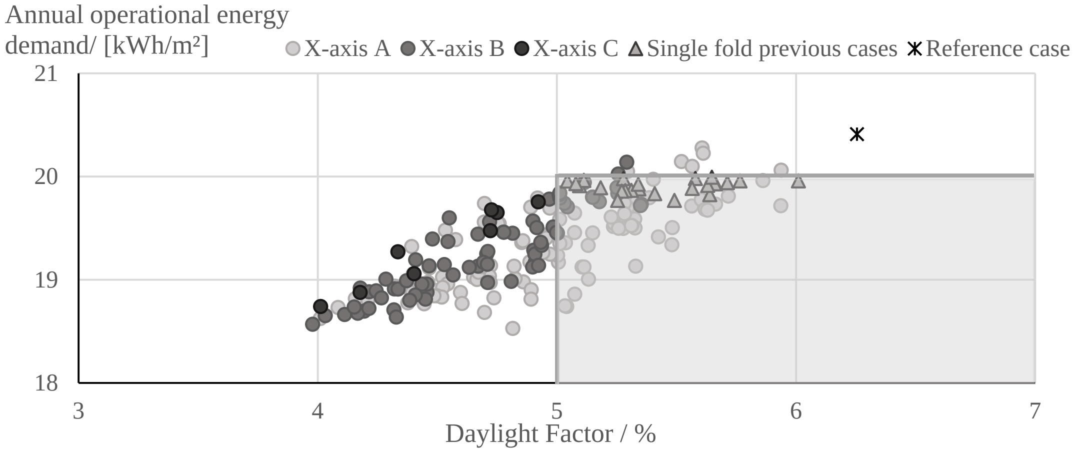


Figure 5-17. The daylight factor relative to the annual operational energy demand for one folding and various window types, but also shows the previous single fold cases. The satisfying cases are within the light gray box.

The window variants are investigated in order to find out which overall window variants are well applicable and meet the defined criteria, barring exceptions. Each case consists of nine window variants, resulting in nine variants having 24 cases each. Variant one is the appropriate base model, which is used to compute the alternative variant models. Figure 5-18 presents the percentage of the total window variants which do meet the criteria. It can be observed in Figure 5-18 that on average variant three (window type 1 NW and 3 SW) and seven (window type 3 NW and 1 SW) perform well, whereby 62.5 % out of 24 cases per variant are adequate. Furthermore, variants four (2 NW and 1 SW) and nine (3 NW and 3 SW) are options to take into account. If window type two is applied for any direction the annual operational energy is low, however, the DF is rarely never achieved. It is beneficial on the energy and daylight conditions to change one of the two windows to window type three.

Figure 5-18. Percentage of cases (maximum is 24) which do meet or not meet the set boundaries for each window variant. Boundaries; annual operational energy of 20 kWh/m² and DF of 5 %.

5.3.2 Window case 2

From the previous 'double fold' analysis, 19 cases were appropriate for further window type analysis, as shown in Table 5-3. Whereby the annual operational energy limit was set at 20.2 kWh/m², while the DF remained 5 %, as described in chapter 4.3.3. The most frequent Y-axis distances are -0.6 and 0.6, further the distances 1.2 and 0.0 occur three times. On South-West a WWR of 0.3 or 0.4 is an adequate size, which also applies for a WWR of 0.4 towards North-West.

Table 5-3. Amount of cases per X-axis, Y-axis and WWR for both wall facing directions which do meet the chosen boundaries obtained after the double fold geometry analysis.

	Y-axis distance							Total for X-axis
	-1.8	-1.2	-0.6	0	0.6	1.2	1.8	
X-axis A	0	2	4	3	5	1	1	16
X-axis B	0	0	1	0	0	1	0	2
X-axis C	0	0	0	0	0	1	0	1

WWR on South-West				
WWR	0.3	0.4	0.5	0.6
Amount of cases	7	7	4	1
WWR on North-West				
WWR	0.3	0.4	0.5	0.6
Amount of cases	4	11	2	2

The 19 cases do result in 152 new possibilities presented in Figure 5-19. Figure 5-19 presents the annual operational energy in correlation to the DF. The represented annual operational energy line is placed at 20 kWh/m² to select improved cases related to the reference case. thereby it can be noted that adjustments of the windows will reduce the annual operational energy and DF. However, the majority no longer meets the DF criteria.

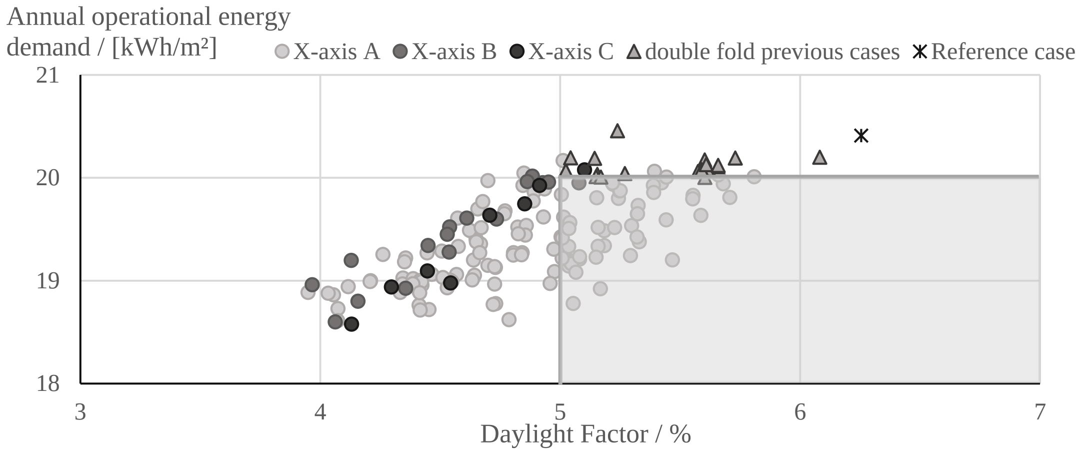


Figure 5-19. The daylight factor relative to the annual operational energy demand for one folding and various window types, but also shows the previous double fold cases. The satisfying cases are within the light gray box.

Just like the single fold, the double fold is also examined on the window variants whether it meets the criteria. This way, it is possible to determine which variant is suitable and which is inadequate. The annual operational energy criteria for Figure 5-20 is set at 20 kWh/m², since this work is searching for improvements in relation to the reference case and that is why variant one no longer meets the criteria. Two variants, seven and nine, satisfy for more than 50 % of the cases and have been carried out with window type three. Variants two, three and four satisfy for 25 % of the cases. It can be observed that window type three achieves better results compared to window type one or two. Moreover, window type two can only be used in combination with window type one in order to compensate for the low transmittance for window type two to achieve sufficient daylight, even though it achieves the energy criteria in many cases.

Figure 5-20. Percentage of cases (maximum is 19) which do meet or not meet the set boundaries for each window variant. Boundaries; annual operational energy of 20 kWh/m² and DF of 5 %.

5.3.3 Window case 3

As described in section 4.3.4, 17 cases comply with the defined criteria for further investigation in various window types. Whereby the annual operational energy limit was placed at 20.5 kWh/m², while the DF remained 5 %. The cases obtained from the 'triple fold' analysis are mainly X-axis A and the most frequent well performing Y-axis distance is found for 0.0 and 0.6, presented in Table 5-4. In addition, the WWR 0.3 and 0.4 are well performing dimensions for South-West and WWR of 0.4 and 0.5 for North-West facing facades.

Table 5-4. Amount of cases per X-axis, Y-axis and WWR for both wall facing directions which do meet the chosen boundaries obtained after the triple fold geometry analysis.

X-axis distance					
X-axis [m]	0.4 (A)	0.8 (B)	1.2 (C)		
Amount of cases	14	2	1		
Y-axis distance					
Y-axis [m]	-1.2	-0.6	0.0	0.6	1.2
Amount of cases	0	3	6	5	3
WWR on South-West					
WWR	0.3	0.4	0.5	0.6	
Amount of cases	7	6	2	2	
WWR on North-West					
WWR	0.3	0.4	0.5	0.6	
Amount of cases	2	9	4	2	

The 17 cases do result in 136 new possibilities presented in Figure 5-21. Figure 5-21 presents the annual operational energy in correlation to the DF. Thereby it can be noted by adjusting the windows will reduce the annual operational energy and DF. The line on the annual operational energy axis (<20 kWh/m²) represents the impassible value to at least outperform the reference case. The line on the DF axis (>5 %) represents the DF to be achieved in accordance to legislation. Within these boundaries 51 cases satisfy.

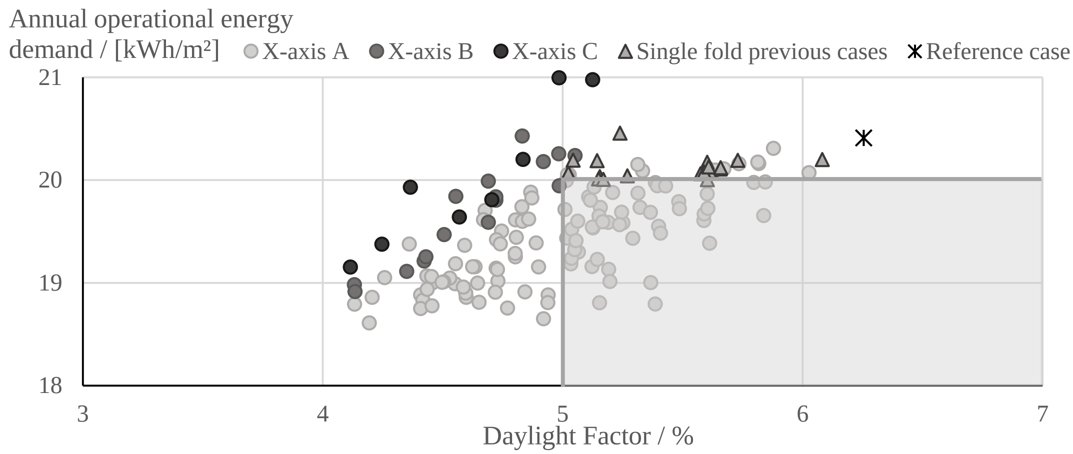


Figure 5-21. The daylight factor relative to the annual operational energy demand for one folding and various window types, but also shows the previous triple fold cases and reference case. The satisfying cases are within the light gray box.

Figure 5-22 presents the percentage of cases per variant which do meet the boundaries. The annual operational energy criteria for Figure 5-22 is set to 20 kWh/m², since this work is searching for improvements in relation to the reference case, that is why variant one no longer meets the criteria. Further, two variants, seven and nine, satisfy for 60 % of the cases and are carried out with window type three. Variants two, three and four satisfy for 30 % of the cases. Again it can be observed that window type three achieves better results compared to window type one or two. Moreover, window type two can only be used in combination with window type one in order to compensate for the low transmittance for window type two to achieve sufficient daylight, even though it achieves the energy criteria in many cases.

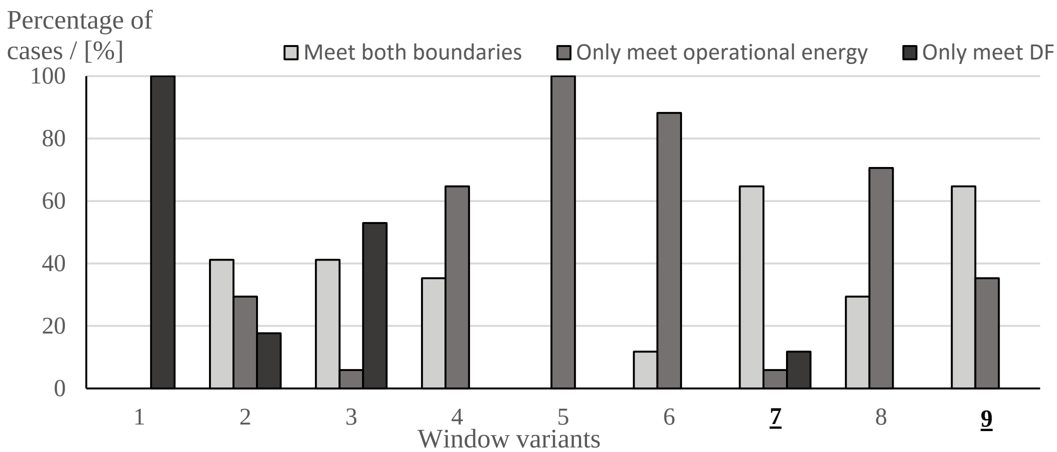


Figure 5-22. Amount of cases (maximum is 18) which do meet or not meet the set boundaries for each window variant. Boundaries; annual operational energy of 20 kWh/m² and DF of 5 %.

5.4 Summary of sensitivity analyses

Within this chapter, a short summary is given on the average output consisting of the 'reference case', 'folded cases', selected cases for further research and the 'window cases (type)'.

Concerning the 'folded cases', the average annual operational energy demand and overheating period will increase as more foldings are applied, while the DF remains constant. The selected cases have a lower operational energy, compared to the reference case, and this has mainly to do with the substantially lower cooling demand. Additionally, the DF and overheating period decreased and thereby should be noted that the average WWR is lower than in previous cases.

The 'window type cases' have a lower annual operational energy demand compared with the selected cases. Which is mainly attributable to the lower cooling- and heating demand compared to the selected cases, although the heating demand is still higher than the 'reference case'. However, fewer 'window type cases' satisfy the required daylight factor.

The percentage regarding the overheating period decreases slightly over the cases and is mainly case depended. Generally a façade fold or window type change do have a minimal influence on the overheating period.

Table 5-5. The average output for the reference case and each sensitivity analyses.

	Wall area	Window-to-wall ratio	operational energy	Heating demand	Cooling demand	Electric lighting	Annual solar radiation	Daylight factor	Overheating period
Unit	[m²]	[%]	Annual [kWh/m²]				[kWh]	[%]	
RC	25.2	45.0	20.4	6.4	7.8	6.3	3078	6.3	16.3
'Folded cases'									
Single	26.2	45.0	20.5	5.9	8.2	6.4	3205	5.9	15.1
Double	29.3	45.0	21.0	6.3	8.3	6.4	3546	5.9	15.8
Triple	32.9	45.0	22.3	7.2	8.8	6.2	4480	5.8	16.6
Picked iterations for further research on 'window type'									
Single	25.8	40.9	19.9	7.9	5.4	6.7	2780	5.4	13.9
Double	26.6	41.2	20.1	7.9	5.4	6.8	2833	5.4	13.9
Triple	28.6	41.9	20.4	8.0	5.7	6.6	3088	5.6	14.7
'Window type'									
Case 1	25.8	40.9	19.3	7.1	5.0	7.2	2429	4.8	13.4
Case 2	26.6	41.2	19.4	7.0	5.1	7.3	2475	4.8	13.8
Case 3	28.6	41.9	19.6	7.0	5.4	7.2	2683	5.0	14.4

5.5 Improved case

This chapter compares the reference case with three improved case variants per folding to determine whether there are improvements or not. As explained in 4.4 the improved cases are only compared with each other and the reference case. Then it would be a decision made by the architect to determine the final case. The three variant cases for each folding have been selected on the lowest possible operational energy usage, while still satisfying the DF criteria and are presented in Table 5-6 and Table 5-7.

Table 5-6. The three chosen cases per single, double and triple fold which do meet the DF and have to lowest operational energy uses.

Case	X-axis [m]	Y-axis [m]	WWR SW	WWR NW	Window type SW	Window type NW	Total WWR
Single fold							
A	0.4	2.4	0.4	0.4	2	3	0.40
B	0.4	3	0.3	0.4	2	3	0.31
C	0.4	-3	0.4	0.3	3	3	0.31
Double fold							
A	0.4	0.6	0.5	0.4	3	2	0.47
B	0.4	1.2	0.4	0.4	2	3	0.40
C	0.4	1.8	0.3	0.4	2	3	0.31
Triple fold							
A	0.4	0	0.3	0.6	2	3	0.45
B	0.4	0.6	0.5	0.4	2	3	0.47
C	0.4	-0.6	0.4	0.5	3	2	0.47

Table 5-7. The nine geometry cases analyzed for improved case, view point from South-West. *Window type 2,* *Window type 3.*

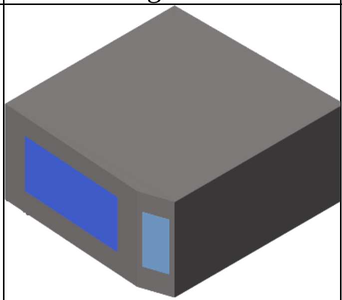
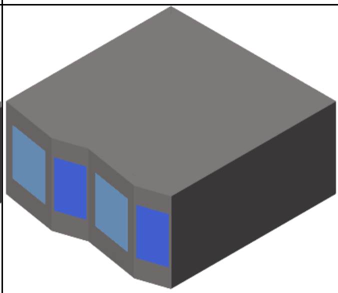
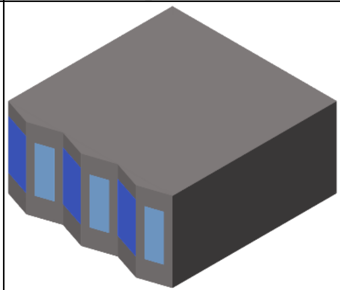
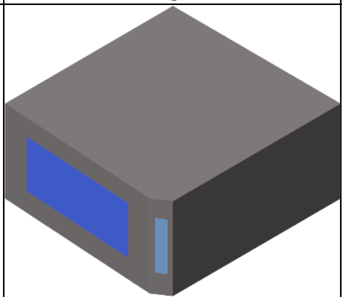
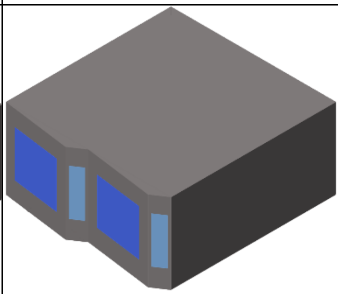
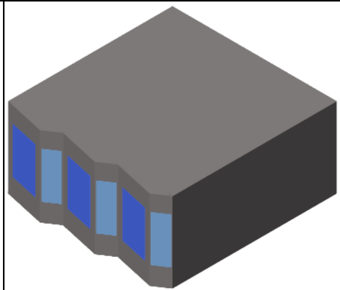
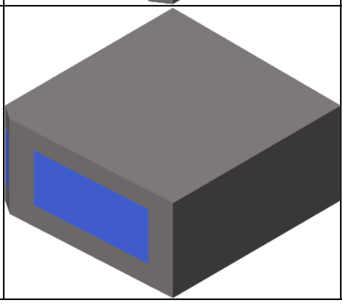
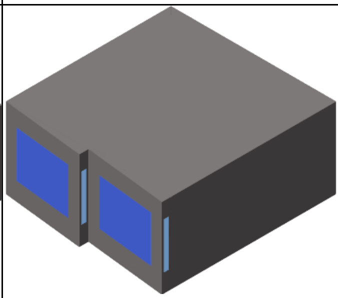
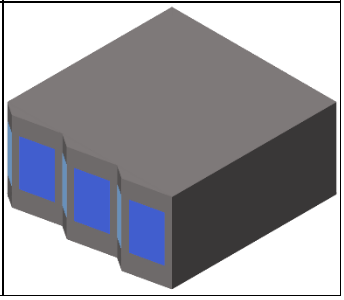
Case	Single fold	Double fold	Triple fold
A			
B			
C			

Table 5-8 presents the energy and daylight plus the percentage difference between the reference case and improved cases. It can be observed that the highest operational energy reductions are achieved for all single fold, double fold A and triple fold A cases. Out of these five cases triple fold A retrieves the highest DF.

Table 5-8. The annual operational energy and DF for the reference case and the improved cases, in addition the percentage difference for the improved cases compared to the reference case

Case	Annual operational energy [kWh/m²]	Operational energy reduction with regard to RC [%]	Daylight factor [%]	DF reduction with regard to RC [%]
RC	20.4	-	6.3	-
Single fold				
A	18.7	8.2	5.0	24
B	18.7	8.2	5.0	24.2
C	18.9	7.6	5.1	23.2
Double fold				
A	18.8	8.0	5.1	23.7
B	19.0	7.0	5.0	26.1
C	19.1	6.5	5.1	23.5
Triple fold				
A	**18.8**	**7.9**	**5.4**	**16.1**
B	19.0	6.8	5.2	20.3
C	19.1	6.3	5.2	20.5

Figure 5-23 presents the annual operational energy divided over the heating- and cooling demand and electric lighting energy for each improved case. In Figure 5-23 it can be seen that on average the heating demand more or less stays the same. However, there is a large reduction, between 23 % to 33 %, concerning the cooling demand. Furthermore, the lighting energy demand increased by about 6 % to 15 %.

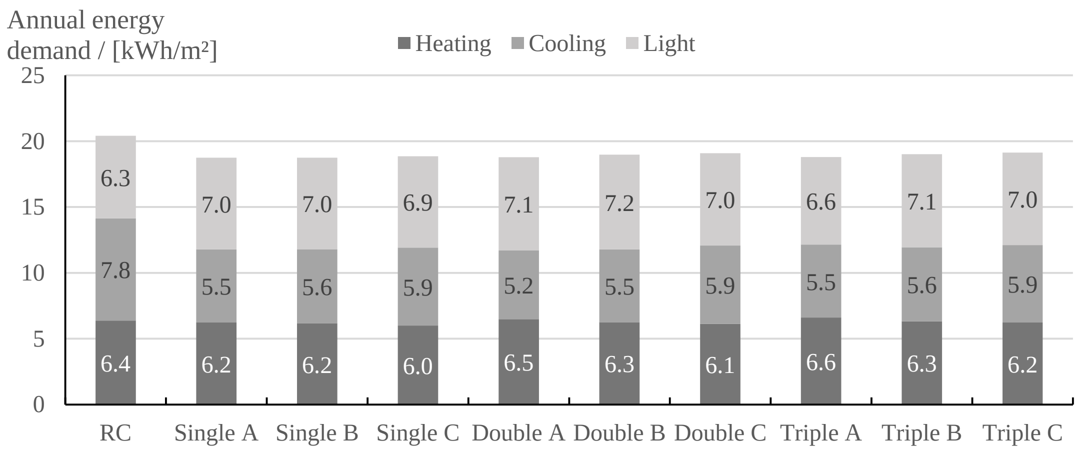


Figure 5-23. The annual energy demand for the various cases presented for heating- and cooling demand and electric lighting energy.

Figure 5-24 presents the UDI ranges for the reference case and improved cases. Adaptation of the façade reduces the received percentage above 2000 lux, and thus also the risk of glare, but on the other hand it also increases the percentage that receives insufficient daylight. Hence, there is a correlation between insufficient daylight and the changes of glare.

Figure 5-24. Useful daylight illumination, insufficient daylight and excessive daylight for the various cases.

As last the overheating percentage together with the annual solar radiation is shown in Figure 5-25. It can be observed that only two cases (Single C and Double C) have a higher percentage of overheating compared to the reference case, while they receive less radiation. In general, the percentage of overheating reduces for most cases relative to the reference case. Therein 'Double A' (14.5 %) out-performs the rest, although it does not satisfy the PH criteria to be lower than 10 %.

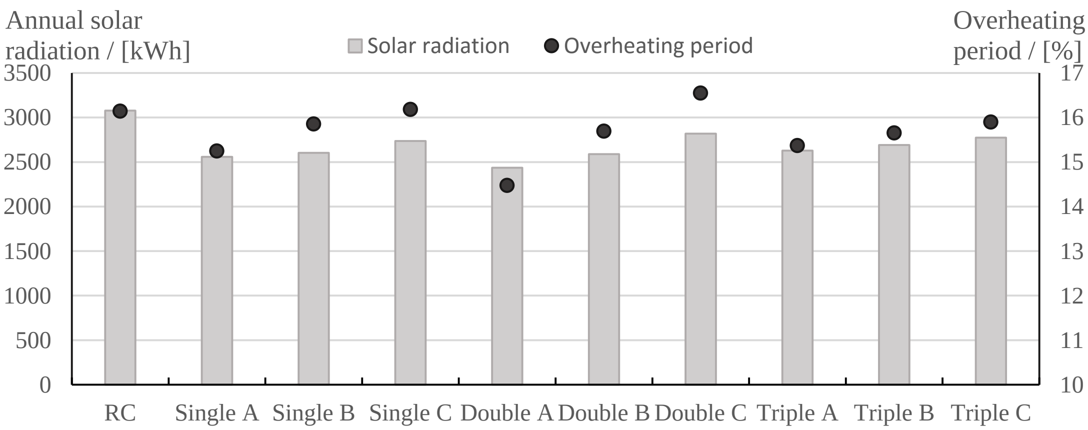


Figure 5-25. The annual solar radiation and overheating period within the occupied time for the various cases.

6 Discussion

This part of the work analyses and discusses the results. In the following subchapters, the energy performance, thermal comfort and daylight conditions are discussed. Each subchapter considers the results of the 'folding case' sensitivity analysis, selected cases, 'window case' sensitivity analysis and the improved cases related to the reference case.

6.1 Energy performance

Energy is mainly analyzed by the annual operational energy which is composed of the heating- and cooling demand plus the energy needed for artificial light. First it can be concluded that the West oriented classroom is more critical, as described in the work, and therefore used as a reference model for the sensitivity analyses. Applying a facade folding and WWR change has a certain effect on the energy and daylight conditions. It was observed, from the folding sensitivity analysis, by enlarging the X-axis distance (from A to C) or adding more foldings increased in general the annual operational energy, which is not beneficial. An important aspect in the application of one or more façade foldings is the increase in façade and window surface areas. The larger surface areas causes more heat losses by opaque walls and windows in the winter, while in summer more solar heat is absorbed through the larger windows. This is confirmed by the raising annual heating- and cooling demand, if more foldings are applied.

The increasing annual heating- and cooling demand should however be seen with caution, since no additional thermal bridges are included in the calculation. Each additional fold provides more heat losses due to more possible thermal bridges, which could result in a higher heating demand and might lower the cooling demand.

The selected cases, from the 'single', 'double' and 'triple fold' sensitivity analyses that have been used for further research, do have an energy efficiency reduction, which is a benefit compared to the reference case. The annual cooling demand drastically decreased, which is also related to the somewhat smaller window area and, hence, less solar heat gains. Meanwhile, the annual heating demand increased and the same applies to the electric lighting energy, which is a result of lower daylight conditions. Despite the fact that these cases improve on the average annual operating energy, it remains minimal and partly balanced between the cooling- and heating demand and drops scarcely at the same time for West oriented spaces (as the analysis is conducted on West oriented space). However, it seems that if the solar heat gains are partly prevented the cooling sufficiently reduces in order to have a positive effect on the annual operational energy demand, even though this involves a raise in the annual heating demand.

A greater improvement was achieved by changing the window types. Thereby it reduced the average cooling demand compared to the selected cases. Additionally, the average heating demand was reduced by about 11 % related to the selected cases. Window type two showed better annual operational energy performances, which had mainly to do with the low g-value preventing too much solar heat. In addition, window type three also resulted in acceptable energy performances. This improvement in the energy performance was largely attributable to the improved thermal insulation of the glass and not directly the result of a lower g-value, although it has an impact on the solar gains and energy performance.

Concerning the nine improved cases, the cooling demand decreased but the heating demand is barely reduced in relation to the reference case. This indicates that when the heating- and cooling demand is more balanced, the annual operational energy will decrease. Furthermore, the energy required for the artificial lighting increases compared to the reference case, caused by the reduced daylight conditions. In general, there is a slight improvement by about 6 % to 8.5 % compared to the reference case. However, this has mainly to do with the window size and window types instead of a direct impact by the façade design.

6.2 Thermal comfort

Thermal comfort is mainly analyzed by the overheating period of the occupied hours according to the PH criteria, which is supposed to be lower than 10 %. The reference case did not meet the maximum overheating percentage, which gave the possibility to achieve an improvement. The average overheating period went down after the first sensitivity analysis (‘folding cases’), except for the ‘triple folding’. However, a reasonable improvement is achieved by the selected cases for further research. Despite the various windows in this follow-up study (‘window cases’) showing a minimal improvement, it still does not achieve the desired result. Furthermore, for the nine improved variants, two cases (Single C and Double C) have an even higher overheating percentage compared to the reference case. Eventually only one design, Double A, that meets the daylight requirement and achieved a low energy usage, has a minimum improvement of approximately one percent.

The maximum requirement for the overheating period is always exceeded. This can be a result of the high internal loads and can be partly criticized on the occupancy rate, since FS assumes 30 students plus one teacher occupying the classroom. It raises the question on how often the classroom will be fully occupied. This does not only increase the internal loads, but also the energy needed for ventilation, even though the latter is not included in this study. Moreover, natural ventilation to take out surplus heat, is not applied in this work and could have a positive effect on the overheating time, since the overheating period not only occurs in mid-summer. However, the worst scenario is calculated and could in real situations, with a lower occupancy rate, lead to a decrease in the cooling demand. On the other hand, it could also lead to an increase of the heating demand, which might ask for a different design. Furthermore, a better or larger cooling system might solve the overheating issue.

6.3 Daylight conditions

The Daylight factor (DF) is mostly examined for daylight conditions in this work, because of the requirements of BREEAM-NL and “Frisse Scholen” (FS) whereby different light requirements are not included. The DF decreased by the use of a fold. In addition, the risk of glare (above 2000 lux) also lowers, but on the contrary the UDI of less than 100 lux (insufficient daylight) increases. So, the risk of glare and insufficient daylight is mainly affected and allowing sufficient daylight (between 100 and 2000 lux) to remain the same. This result cannot be directly attributed to the application of the fold but also to the used daylight grid, since the daylight grid remained untouched and the new areas that emerged from the fold were not included in the daylight calculations. The grid is created in this manner for the assumption that the immediate area behind a fold will not be used. Thus, in the application of a fold, it means that the windows are located further away from the receiving daylight points, and hence the daylight points will automatically receive less daylight.

The DF for the selected cases continued to decline. The main reason for the lower DF are the smaller window-to-wall ratios (WWR), barring the window distance to the grid. The smaller WWR causes a positive effect for the risk of glare. It is noticeable from the selected iterations that by having more foldings, like the ‘triple folding’, the daylight factor is improving, which can be explained by a slightly higher WWR (41.9 %) compared to the ‘single’ (40.9 %) and ‘double fold’ (41.2 %). Another explanation for a better DF is the better window distribution over the façade.

Window type one was the base window and window type two and three improved on the thermal resistance. Further, window type two had lower visual transmittance and solar heat gain. Changing the window types shows that the visual transmittance should not be too low, like window type two, since this rarely satisfies the daylight conditions. Therefore window type three is the better option wherein it conforms the DF at about 50 % of the cases, also taking into account the energy performance.

The DF for the improved cases is above the required 5 %. However, it is a substantial reduction compared to the reference case, knowing that the increased percentage of insufficient daylight does not improved the daylight conditions, although the risk of glare reduces. Out of the nine cases triple A comes out on top in terms of daylight conditions and in correlation with the energy. Triple A has the same WWR as the reference case whereby two thirds of the window area is facing North-West and one third South-West, resulting in less solar gains. The same kind of design also occurs in single C and triple C. But for the other cases, the opposite is true, with larger window surfaces pointing toward the South-West, which means that the design does not always need to be faced away from the sun to perform well.

It has to be mentioned that the thickness of exterior walls are not included in the daylight study, but this will in most cases give a worse light condition as a result. Optional, other designs with higher DF should be selected if the wall thickness is taken into account, which would also result in a higher energy demand. The results showed that higher daylight factors also have a raise in the energy demand.

This work is conducted to evaluate the effect of facade adaptation by comparison to a reference model. It is found that there is a correlation between the energy and daylight indicators and in relative terms there is no optimal design.

7 Conclusion

This work studies the effect of façade folding adaptation of a classroom in Amsterdam on the energy use, daylight conditions and thermal comfort. It can be concluded that the building's energy performance, indoor thermal and visual comfort cannot be completely improved by applying folded façade geometry of the envelope surface, facing West. Furthermore, a folded façade surface geometry for East and West design cannot decrease both the artificial lighting energy, heating- and cooling demand. However, having a fold can slightly improve the annual energy usage by around 6 % to 8.5 %, although it is minimal and mainly decreases the cooling demand, but the heating demand and electric lighting energy increases.

In addition, a folded façade surface geometry for East and West design slightly improves the thermal comfort but not the daylight conditions. It is found that:

- The overheating time can be lowered by the use of a folded façade, although by a minimal percentage. Thereby it mainly has to do with a smaller window-to-wall ratio (WWR) and thus less solar heat gains.
- The daylight conditions do not benefit from a fold in the façade, although the daylight factor still satisfied the required criteria.
- The fold point distance, the point that moves across the grid, should not be located too far from the base line, since the energy and daylight performance decreased by the increase of the distance.

From the analyses and results it can be concluded that not the facade fold, but the window quality and/or WWR have a greater impact on the energy usage, thermal comfort and daylight conditions. More after, the correct WWR is case dependent, since not all the improved cases have the same WWR.

This holistic approach clearly shows that it does not generate one specific design. Although there is one case, Triple A, performing on average better than the rest, it is still not a big difference compared to the other improved cases. In addition, improving the thermal insulation of windows improves energy performance and gives the architect more architectural freedom, which was also found by Rodrigues, et al. (2015).

It is recommended to first study the effect of the windows, before adjusting the façade on West oriented rooms.

7.1 Further research

This work with a holistic approach clearly shows that it does not generate one specific design. Therefore, one architectural design should be picked by the architect or client for further studies. Further research can be done for active or passive shading devices, natural ventilation or cost effectiveness. In addition, opaque walls facing South could be used, instead of walls partly glazed as studied in this work.

8 Summary

Designing an energy-efficient building and using solar energy in a proper way can sometimes be a challenging task for architects. They have to deal with requested needs, plot layout and surrounding buildings. This sometimes results in designs where large façade sections are facing towards East and or West. For South facades, the solar heat and daylight conditions are mainly controlled by overhangs or other passive or active shading devices. On East and West facades this can be difficult, due to a low sun height, causing glare problems. The solar radiation cannot be kept out instantly with shading devices since the whole window need to be covered due to the low sun angle, which reduces the daylight conditions. A space with insufficient daylight is not allowed for school buildings, because pupils need daylight for their well-being and school performances.

This work studied a vertical façade folding concept to improve the energy efficiency, indoor climate and visual aspects on East and West facing facades. It was questioned if a folded façade surface geometry for East and West design can reduce the energy use for artificial lighting, heating and cooling demand. Regarding comfort it was questioned if a folded façade surface geometry for East and West design can improve the thermal and daylight comfort. For the simulations, the facade is divided into different wall sections, dependent on one, two or three applied foldings.

The research and analysis was performed on a hypothetical classroom located in Amsterdam, Netherlands, and based on Dutch regulations. The study used the following conventional indicators; annual heating- and cooling demand, electric lighting (together the annual operational energy demand), daylight factor and overheating period. First, for the reference case the worst cardinal direction had to be found. Second, a first sensitivity analysis was conducted on the foldings and window-to-wall ratio (WWR). Third, cases from the first sensitivity study were selected and used for the second sensitivity analysis on window type properties. Finally, three variants for each single, double or triple fold were selected. These results can then be used by the architect to decide on one of the nine designs.

The results showed that by enlarging the X-axis distance or adding more foldings, the annual operational energy in general increased, and the daylight conditions lowered, which is not beneficial. An important aspect in the application of one or more façade foldings is the increase in façade and window surface areas. The larger surface areas cause more heat losses in the winter, while in summer more solar heat is absorbed through the larger windows. Thence, the maximum requirement for the overheating period is always exceeded.

It can be concluded that the building's energy performance, indoor thermal and visual comfort cannot be completely improved by applying folded façade geometry of the envelope surface, facing West. Furthermore, a folded façade surface geometry for East and West design cannot decrease both the artificial lighting energy, heating- and cooling demand. However, having a fold can slightly improve the annual operational energy usage by around 6 % to 8.5 %.

In addition, a folded façade surface geometry for East and West design slightly improves the thermal comfort but not the daylight conditions. The overheating time can be lowered with a minimal percentage. The daylight conditions do not benefit from the folded façade, although the daylight factor still satisfied the required criteria. Furthermore, the fold point distance (over the X-axis) should not be located too far from the base line, since the energy performance and daylight conditions decreased.

It can be further concluded that the window quality and/or WWR have a greater impact on the energy usage, thermal comfort and daylight conditions than a facade fold has. Furthermore, it is found that even though there is a correlation between the energy and daylight indicators it does not give one single optimal design.

References

Passive House Institute, 2015. *Criteria for the Passive House, EnerPHit and PHI Low Energy Building Standard*, Darmstad: Passive House Institute; Version 9d.

Agentschap NL, 2012. *Frisse Scholen Toets Handleiding*, Utrecht: Agentschap NL, Ministerie van Binnenlandse Zaken en Koninkrijkrelaties.

Aries, M., Aarts, M. & van Hoof, J., 2013. Daylight and health: A review of the evidence and consequences for the built environment. *Lighting Research and Technology,* Volume 0, pp. 1-22.

ASHRAE, 2013. *ASHRAE Terminology.* [Online]
Available at: https://www.ashrae.org/resources--publications/free-resources/ashrae-terminology
[Accessed 8 4 2016].

Binnenlandse Zaken, H. M. v. B. Z. e. K., 2016. *BRIS bouwbesluit online.* [Online]
Available at: http://www.bouwbesluitonline.nl/Inhoud/docs/wet/bb2012
[Accessed 22 2 2016].

Capeluto, I. G., 2003. Energy performance of the self-shading building envelope. *Energy and Buildings,* Volume 35, pp. 327-336.

Caruso, G. & Kämpf, J. H., 2015. Building shape optimisation to reduce air-conditioning needs using constrained evolutionary algorithms. *Solar Energy,* Volume 118, pp. 186-196.

CEN & Standardization, E. C. f., 2015. *NEN.* [Online]
Available at: https://www.nen.nl/pdfpreview/preview_207600.pdf
[Accessed 8 5 2016].

Chang, A.-M.et al., 2012. Human responses to bright light of different durations. *The Journal of Physiology,* 13(590), pp. 3103-3112.

Consumentenbond, 2016. *Consumentenbond; Consumers Association.* [Online]
Available at: http://www.consumentenbond.nl/laptop/extra/laptop-of-desktop/
[Accessed 24 2 2016].

DGBC, T. D. G. B. C., 2014. *BREEAM-NL Nieuwbouw en Renovatie: Keurmerk voor duurzame vastgoedobjecten; version 1.01,* Rotterdam: Dutch Green Building Council.

Echenagucia, T. M., Capozzoli, A., Cascone, Y. & Sassone, M., 2015. The early design stage of a building envelope: Multi-objective search through heating, cooling and lighting energy performance analysis. *Applied Energy,* Volume 154, pp. 577-591.

Ector Hoogstad architects, 2015. *DIFFER Eindhoven - Ector Hoogstad Architecten.* [Online]
Available at: http://www.ectorhoogstad.com/nl/projecten/differ-eindhoven
[Accessed 4 4 2016].

Energy Commission, C., 2003. *Windows and Classrooms: A Study of Student Performance and the Indoor Environment,* California: New Buildings Institute.

European Parliament & Directive Council, 2010. *On the energy performance of buildings.* [Online]
Available at: http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32010L0031&from=EN
[Accessed 21 1 2016].

European Union, L. P. o. t. C. o. t., 2015. *Intended Nationally Determined Contribution of the EU and its,* Riga: EU.

Fanger, P., 1970. *Thermal comfort : analysis and applications in environmental engineering.* Copenhagen: Danish Technical Press.

Frank, T., 2005. Climate change impact on building heating and cooling energy demand in Switzerland. *Energy and Buildings,* Volume 37, pp. 1175-1185.

Goia, F., Haase, M. & Perino, M., 2013. Optimizing the configuration of a façade module for office buildings by means of integrated thermal and lighting simulations in a total energy perspective. *Applied Energy,* Volume 108, pp. 515-527.

Goschenhofer, T., 2011. *Energy performance of the office building ENERGYbase (heating, cooling, air conditioning, lighting) 09/09 to 09/10,* Vienna: FH Technikum Wien.

grasshopper3d, 2016. *Grasshopper 3D.* [Online]
Available at: http://www.grasshopper3d.com/
[Accessed 25 2 2016].

Haus der Zukunft, 2005. *Sunny Research! Nachhaltiges Gebäude- und Energiekonzept für ein,* Vienna: On behalf of the Federal Ministry for Transport, Innovation and Technology.

Hobday, R., 2016. Myopia and daylight in schools: a neglected aspect of public health?. *Perspectives in Public Health,* 136(1).

IPCC, I. P. o. C. C., 2014. *Climate Change 2014 Synthesis Report,* Geneva, Switzerland: IPCC.

Jenkins, D., Liu, Y. & Peacock, A., 2008. Climatic and internal factors affecting future UK office heating and cooling energy consumptions. *Energy and Buildings,* 40(5), pp. 874-881.

Johnston, J., Counsell, J. & Strachan, P., 2011. *Trends in office internal gains and the impact on space heating and cooling demands. :CIBSE Technical Symposium.* Leicester, University of Strathclyde, Glasgow.

Kennisnet, 2015. *Vier in balans monitor,* Zoetermeer: Kennisnet.

KGC, 2016. *Karel de Grote College.* [Online]
Available at: http://www.kgcnijmegen.nl/Organisatie/Roosters.aspx
[Accessed 24 2 2016].

Lavafpour, Y. & Sharples, S., 2015. Using Tilted Facade to Reduce Thermal Discomfort in a UK Passivhaus Dwelling for a Warming Climate. *Energy Procedia,* Volume 78, pp. 2232-2237.

Ministerie van Economische Zaken, 2014. *Nederlands nationaal hervormingsprogramma,* Netherlands: Ministerie van Economische Zaken.

Nabil, A. & Mardaljevic, J., 2005. Useful daylight illuminance: a new paradigm for assessing daylight in buildings.. *Lighting Research & Technology,* 37(1), pp. 41-59.

Naeem, M. & Wilson, M., 2007. *A study of the application of the BRE Average Daylight Factor formula to rooms with window areas below the working plane.* Crete, Greece, London Metropolitan University, UK.

New Buildings Institute, 2016. *Daylight Pattern Guide.* [Online]
Available at: http://patternguide.advancedbuildings.net/using-this-guide/analysis-methods
[Accessed 8 4 2016].

Nik, V. M., Kalagasidis, A. S. & Kjellström, E., 2012. Statistical methods for assessing and analysing the building performance in respect to the future climate. *Building and Environment,* Volume 53, pp. 107-118.

NREL, 2016. *EnergyPlus.* [Online]
Available at: https://energyplus.net/
[Accessed 21 2 2016].

NREL, et al., 2016. *OpenStudio.* [Online]
Available at: https://www.openstudio.net/
[Accessed 25 2 2016].

NREL, U. D. o. E. B. T. O., 2015. *EnergyPlus Energy Simulation Software.* [Online]
Available at: http://apps1.eere.energy.gov/buildings/energyplus/
[Accessed 25 2 2016].

Paraskeva, P. & Vakouli, V., 2015. *Skylights in classrooms: optimal design for a cold climate through dynamic daylighting and energy simulations,* Sweden: Lund University.

Passivhaus Institut, 2014. *Passipedia; Passive House schools – Requirements.* [Online]
Available at: http://www.passipedia.org/planning/non-residential_passive_house_buildings/passive_house_schools/passive_house_schools_requirements.#passive_house_schools_requirements
[Accessed 23 2 2016].

Persson, M.-L., Roos, A. & Wall, M., 2006. Influence of window size on the energy balance of low energy houses. *Energy and Buildings,* 38(3), pp. 181-188.

Philips, 2011. *Technische Unie.* [Online]
Available at: https://www.technischeunie.nl/images/content/NEN-EN12464-1.pdf
[Accessed 26 2 2016].

Philips, 2016. *Philips.* [Online]
Available at: http://www.lighting.philips.nl/prof/armaturen-binnenverlichting/pendelarmaturen-/smartform-led-bps460/910504078103_EU/product
[Accessed 25 2 2016].

Piccolo, A. & Simone, F., 2009. Effect of switchable glazing on discomfort glare from windows. *Building and Environment,* 44(6), pp. 1171-1180.

Reinhart, C., 2016. *DaySim.* [Online]
Available at: http://daysim.ning.com/
[Accessed 25 2 2016].

Reinhart, C. F., Mardaljevic, J. & Rogers, Z., 2006. Dynamic Daylight Performance Metrics for Sustainable Building Design.. *Illuminating Engineering Society of North America,* 3(1), pp. 7-31.

Rijksoverheid, N. G., 2016. *Schoolvakanties; School holidays.* [Online]
Available at:
https://www.rijksoverheid.nl/onderwerpen/schoolvakanties/inhoud/schoolvakanties-2016-2017
[Accessed 23 2 2016].

Robert McNeel & Associates, 2016. *Rhinoceros.* [Online]
Available at: http://www.rhino3d.com/features
[Accessed 25 2 2016].

Rodrigues, E., Amaral, A. R., Gaspar, A. R. & Gomes, Á., 2015. How reliable are geometry-based building indices as thermal performance indicators?. *Energy Conversion and Management,* Volume 101, pp. 561-578.

RVO, 2015. *Programma van Eisen Frisse Scholen 2015 / Program of Requirements Fresh Schools 2015.* Utrecht: Rijksdienst voor Ondernemend Nederland; National service of Entreprenaurial Netherlands.

Sadeghipour Roudsari, M., 2016. *GitHub.* [Online]
Available at:
https://github.com/mostaphaRoudsari/ladybug/blob/master/resources/How_to_Reference_Ladybug_and_Honeybee.md
[Accessed 25 2 2016].

Secchi, S., Sciurpi, F., Pierangioli, L. & Randazzo, M., 2015. Retrofit strategies for the improvement of visual comfort and energy performance of classrooms with large windows exposed to East. *Energy Procedia,* Volume 78, pp. 3144-3149.

Segbroek College, 2016. *Segbroek College.* [Online]
Available at: https://www.segbroek.nl/onderwijs/segbroek-het-kort/
[Accessed 24 2 2016].

Shen, H. & Tzempelikos, A., 2012. Daylighting and energy analysis of private offices with automated interior roller shades. *Solar Energy,* Volume 86, pp. 681-704.

Stevanović, S., 2013. Optimization of passive solar design strategies: A review. *RenewableandSustainableEnergyReviews,* Volume 25, pp. 177-196.

Tzempelikos, A. & Athienitis, A. K., 2007. The impact of shading design and control on building cooling and lighting demand. *Solar Energy,* Volume 81, pp. 369-382.

University of California, t. L. B. N. L., 2014. *Radiance.* [Online]
Available at: http://radsite.lbl.gov/radiance/framew.html
[Accessed 25 2 2016].

Vandewalle, G. et al., 2006. Daytime light exposure: Dynamically Enhances Brain Responses. *Current Biology,* Volume 16, pp. 1616-1621.

Vanhoutteghem, L., Skarning, G. C. J., Hviid, C. A. & Svendsen, S., 2015. Impact of fac¸ade window design on energy, daylighting and thermal comfort in nearly zero-energy houses. *Energy and Buildings,* Volume 102, pp. 149-156.

Velfac, 2016. *Velfac standard glazing.* [Online]
Available at: http://velfac.co.uk/domestic/technical/velfac-200/10380,5865/velfac-standard-v200i
[Accessed 3 9 2016].

Versteeg, i. H., 2007. *Onderzoek naar de kwaliteit van het binnenmilieu in basisscholen,* Netherlands: VROM.

Wang, X., Chen, D. & Ren, Z., 2010. Assessment of climate change impact on residential building heating and cooling energy requirement in Australia. *Building and Environment,* Volume 42, pp. 1663-1682.

Wikipedia, 2015. *Wikipedia.* [Online]
Available at: https://nl.wikipedia.org/wiki/Lestijd
[Accessed 24 2 2016].

Yi, Y. K. & Malkawi, A. M., 2009. Optimizing building form for energy performance based on hierarchical geometry relation. *Automation in construction,* Volume 18, pp. 825-833.

Zomoradian, Z. S., Tahsildoost, M. & Hafezi, M., 2016. Thermal comfort in educational buildings: a review article. *Renewable and Sustainable Energy Reviews,* Volume 59, pp. 895-906.

A. Appendix

Table A-1. WWR for nine projects designed by Ector Hoogstad architects

	Wall			Window				
School	Width	Height	m²	Sill height	Width	Height	m²	WWR
Avans Hogeschool	7.2	2.8	20.2	0.0	4.3	2.6	11.2	0.55
Davinci Back	7.2	2.9	20.9	0.3	5.0	2.5	12.7	0.61
Davinci side	7.2	2.9	20.9	0.1	3.9	3.0	11.6	0.56
Melanchton	4.1	3.0	12.3	0.0	3.7	2.5	9.2	0.74
Merlet college	7.2	3.0	21.6	0.8	6.3	1.9	12.0	0.55
Minkema College Woerden	7.2	3.2	23.0	1.0	5.4	1.6	8.4	0.37
Montessori College Nijmegen 1	7.2	3.3	23.4	0.2	4.5	2.5	11.0	0.47
Montessori College Nijmegen 2	7.2	3.3	23.4	0.2	5.4	2.5	13.2	0.57
ROC Amsterdam	5.4	3.0	16.2	0.8	4.7	1.8	8.2	0.51
Average WWR								0.55

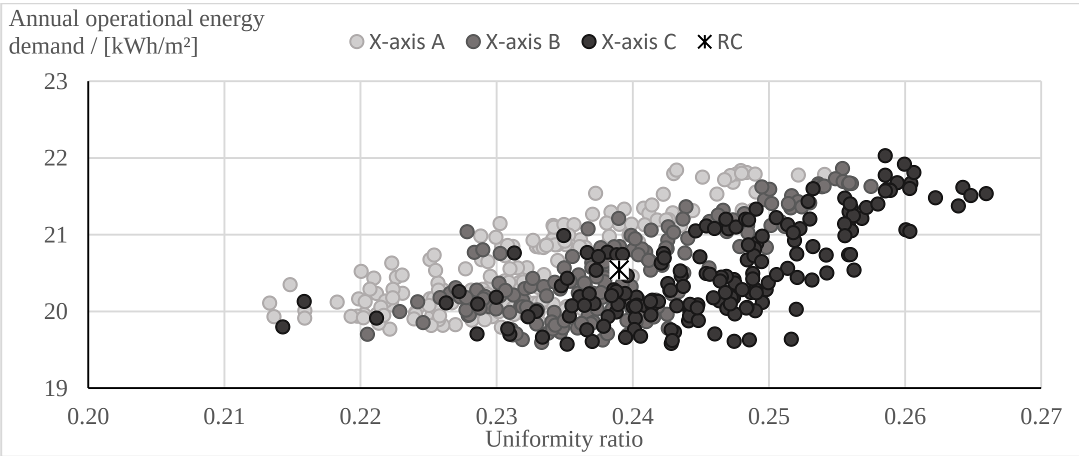


Figure A-1. The annual operational energy demand in relation with the uniformity ratio for single fold.

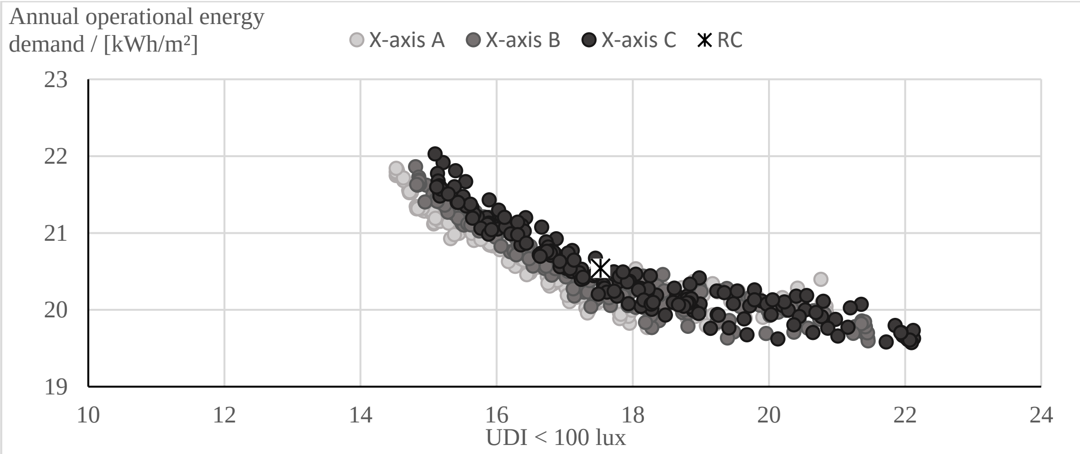


Figure A-2. The annual operational energy demand in relation with the UDI below 100 lux for a single fold.

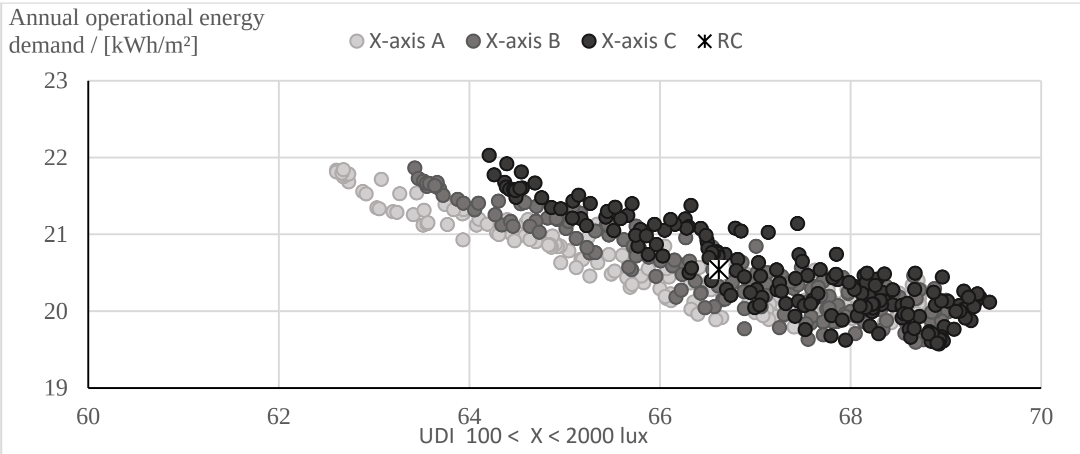


Figure A-3. The annual operational energy demand in relation with the UDI between 100 and 2000 lux for a single fold.

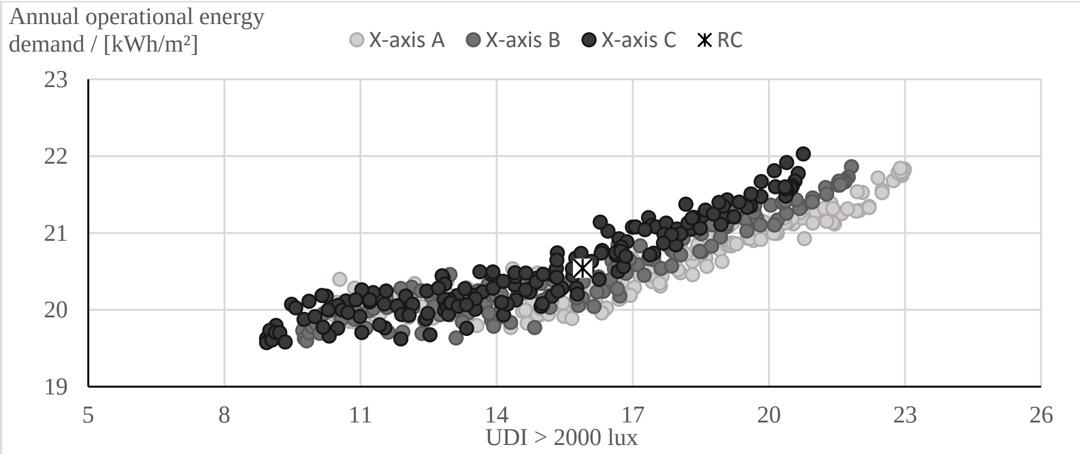


Figure A-4. The annual operational energy demand in relation with the UDI above 2000 lux for a single fold.

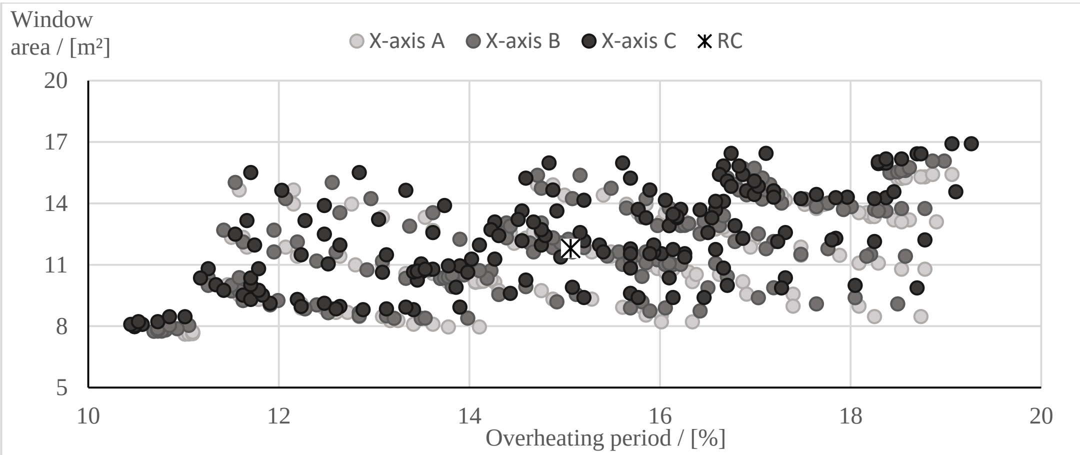


Figure A-5. The window area in relation with the overheating period for a single fold.

More or less the same patterns and results are found for double and triple fold. Because of the repetition, it is not presented in this work.

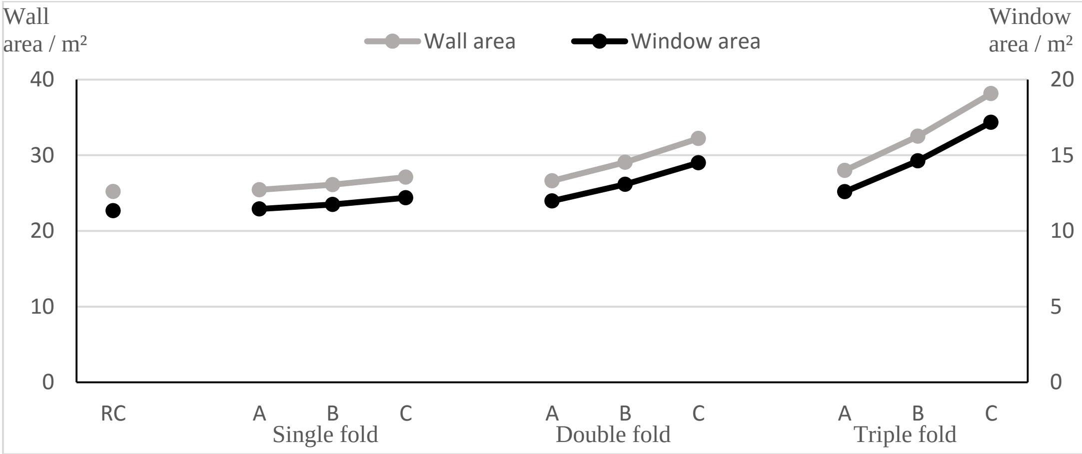


Figure A-6. The average wall area in relation with the average window area for the reference case, single fold, double fold and triple fold cases.

Table A-2. Analyzed cases 'window case 1' and the amount of new cases which meet the criteria.

	Total cases for 'window case 1'	Results 'Window case 1' meeting the boundaries
X-axis A	126	59
X-axis B	81	23
X-axis C	9	1

Table A-3. Analyzed cases 'window case 2' and the amount of new cases which meet the criteria.

	Total cases for 'window case 1'	Results 'Window case 1' meeting the boundaries
X-axis A	144	58
X-axis B	18	2
X-axis C	9	1

Table A-4. Analyzed cases 'window case 3' and the amount of new cases which meet the criteria.

	Total cases for 'window case 1'	Results 'Window case 1' meeting the boundaries
X-axis A	126	48
X-axis B	18	1
X-axis C	9	0

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