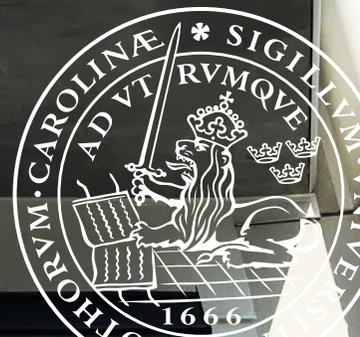




**SUNSPACE DESIGN SOLUTIONS BASED  
ON DAYLIGHT PERFORMANCE IN  
A MULTI-STOREY RESIDENTIAL  
BUILDING**

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Master Thesis in Energy-efficient and Environmental Buildings  
Faculty of Engineering | Lund University



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## Abstract

With the development of low energy buildings in Northern European countries, conflicts regarding balancing daylight and energy performances in buildings arise. Therefore, design solutions that balance daylight and energy performances in buildings are needed. MKB Greenhouse is a newly-built, Miljöbyggnad Gold and Feby-Passive House certified, multi-family housing in Malmö, Sweden. Greenhouse also encourages urban farming by adding sunspace and balcony as the cultivation area. On the contrary, the addition of sunspace and balcony can affect both daylight and energy performances in the adjacent living space. This thesis, as a part of daylight and energy research project at White Arkitekter AB, focused mainly on the impact and optimization of sunspace and balcony design on the daylight performance of MKB Greenhouse.

Four apartments with different floor heights and orientations were modelled using Rhino3D and simulated in Grasshopper using Radiance and Daysim as the daylight simulation engines. Studying the impact of the actual sunspace and balcony on the daylight performance in the adjacent living spaces (living room, kitchen and workshop), the results showed that the daylight received in the adjacent spaces was reduced by at least 50% compared to the apartments without sunspace and balcony.

Different sunspace and balcony design parameters, such as geometry, glazing-wall-ratio (GWR) and light reflectance value (LRV), were investigated to study the effect on the daylight conditions in the adjacent living spaces. Based on the parametric studies, it was found that geometry was the most important factor affecting the daylighting conditions in the adjacent spaces followed by the GWR and LRV of the sunspace and balcony. Orientation, floor heights and site's obstructions had larger impact on the daylight autonomy (DA) of the adjacent spaces.

This thesis revealed that the least depth and the shortest length of the sunspace and balcony gave the highest average daylight factor (DF) and average daylight autonomy (DA) in all living spaces of the four studied apartments. However, in designing a sunspace and balcony, one must not forget the functionality of the space itself. All determining aspects such as functionality, climate and geometry should always be taken into consideration to create a high-performing sunspace and balcony. The findings of this thesis are further analysed in the whole research project to develop sunspace and balcony design solutions that improves the daylight and energy performances of the building.

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## Terminology

*BREEAM, Building Research Establishment Environmental Assessment Method:* an established environmental certification system, developed by the Building Research Establishment, which consists of assessing, rating and certifying the sustainability of masterplanning projects, infrastructure and buildings (Building Research Establishment, 2016).

*CBDM, Climate-Based Daylight Modelling:* the prediction of various radiant or luminous quantities, such as irradiance, illuminance, radiance and luminance, using sun and sky conditions that are obtained from the standard meteorological datasets or climate files (Mardaljevic, 2006).

*CIE, Commission Internationale De L'Eclairage:* the ISO recognized international commission on illumination that operates in exchanging information on all matters relating to the science and art of lighting, colour and vision, photobiology and image technology (CIE, 2016).

*CIE Standard Overcast Sky:* the meteorological condition of clouds completely obscuring all of the sky, which is characterized by the luminance at the zenith is three times brighter than at the horizon (Brown & DeKay, 2001).

*Daylight:* the combination of all light received from the sky as direct light from the sun and indirect light from the diffused daylight scattered in the atmosphere and reflected light from the ground and surrounding objects.

*Daylighting:* the illumination of interior spaces in buildings by natural light (direct and indirect light) by using properly designed windows and skylights.

*DA, Daylight Autonomy:* the percentage of annual daytime hours, usually operational or occupancy hours, at a given point in a space above a specified illumination level.

*DF, Daylight Factor:* the ratio of the illuminance due to daylight at a point on the indoors working plane, to the simultaneous outdoor illuminance on a horizontal plane from an unobstructed CIE overcast sky.

*FEBY, Forum för Energieeffektiva Byggnader:* a forum for energy-efficient buildings in Sweden.

*GWR, Glazing to Wall Ratio:* is the ratio of the total glazed area to the exterior envelope wall area.

*Illuminance:* the total luminous flux incident on a surface, per unit area, which is measured in lux (lumen/m<sup>2</sup>).

*LRV, Light Reflectance Value:* is a measure of the total quantity of visible light reflected by a surface at all wavelengths and directions when illuminated by a light source. LRV is represented by a scale of 0% (absolute black) to 100% (perfectly reflective white) (Jeffries, 2013).

*LT, Light Transmittance value:* also known as visible light transmittance (VT or TVis), which is the amount of visible light that passes through a glazing material. A higher LT means there is more daylight coming through the windows (Efficient Windows Collaborative, 2016).

*Miljöbyggnad:* a building certification system for Swedish conditions developed by the Swedish Green Building Council (SGBC).

*Perez sky model:* a mathematical model used to describe the relative luminance distribution of the sky dome and it has become the standard model for daylighting calculations since it uses weather data gathered from weather stations around the world.

*Point DF, Point Daylight Factor:* a daylight factor measuring point that is taken 1,00 m away from the darkest wall, 0,80 m above the floor, halfway from the exterior envelope.

*Sunspace:* an additional glazed area or room in a building that is intended to collect and store solar energy.

*Urban farming:* a practice of cultivating, processing and distributing food in or around a village, town or city (Bailkey & Nasr, 2000).

*UR, Uniformity Ratio:* the ratio of minimum daylight factor and average daylight factor in a space.

# 1 Introduction

## 1.1 Background and problem motivation

Low energy housing developments are currently emerging in Northern European countries as one of the consequences of EU2020 Energy Strategy (European Commission, 2016). However, conflicts regarding balancing daylight and energy performances in buildings arise. In achieving low heating demand, building's envelope is required to be airtight and highly insulated with high-performance windows, which can reduce the light transmittance more compared to the ordinary clear-glass windows (Bülow-Hübe, 2001). In common early design phase, the building's energy performance is often prioritized over daylight utilization, resulting in negative consequences for the indoor visual comfort (Vanhoutteghem, et al., 2015). Hence, there is an urgent need to develop design solutions that balance both daylight and energy performances in buildings, especially in the residential building sector.

Addressing the conflicting topics, this thesis is a part of an ongoing research project at White Arkitekter AB which analyses the daylight and energy performances in the newly-built Greenhouse project in Malmö, Sweden. Being located in the eco-city of Augustenborg, Malmö. Greenhouse is Miljöbyggnad Gold and Feby-Passive House certified mixed-use development which consists of a kindergarten, student housings and apartments.

The multi-family housing, Greenhouse, implements a combination of 20 m<sup>2</sup> fully glazed (sunspace) and unglazed balcony with cultivation area in each apartment units. The sunspace and balcony in each apartment provide the possibility for the tenants to grow their own food, a practice commonly known as urban gardening. Urban farming or urban gardening is rapidly growing in cities around the world, since it provides not only food but also many other benefits, such as adding greenery to the cities, increasing shading to the adjacent spaces and improving the biodiversity into the local surrounding (Howard, 2016). For this reason, Greenhouse is considered as one of the unique sustainable project in Sweden.

Although the sunspace and balcony provides extra living space and the urban gardening possibilities, it can actually influence daylight and energy issues in the adjacent living spaces. Integrating sunspace into residential buildings can potentially lead to dramatic increase in energy consumption due to occupants' behavior and bad design. It was found in previous studies that improper design of the sunspaces increased the energy consumption by 200%, while using proper design can save energy up to 28% with heated balconies and up to 40% with unheated balconies (Jorgensen & Hendriksen, 2000).

On the other hand, the impact of having a sunspace on the daylighting performance in residential buildings has not been studied extensively (Wilson, et al., 2000). Design of a sunspace has a definite impact on daylight quality and quantity, along with heating and cooling loads in the adjacent living space. Therefore, a study that will provide impacts, as well as design solutions of the attached sunspace to balance daylight and energy performances in the adjacent space is needed. Furthermore, the scarcity of studies in

balancing both daylight and energy performance in the residential sector, motivated this research to be conducted.

## 1.2 Hypotheses and objectives

Integrating a sunspace in a multi-storey residential building can provide benefits to reduce heating loads during the winter period if designed properly. On the contrary, it can cause reductions in the amount of daylight in the adjacent living spaces and an increase in overheating issues during the summer period. For solving these issues and balancing the daylight and energy performances, a thorough sunspace design optimization is developed for each study cases based on various parametric studies throughout the research project. This thesis covers the daylighting part of the whole research project.

In order to study the daylighting impact of the sunspace design, as well as developing the sunspace design solutions, two main research questions are addressed in this thesis:

- What are the impacts of having sunspace and balcony on the daylighting performance in the adjacent living spaces?
- Which sunspace and balcony design solutions based on the parametric studies can improve the daylighting conditions in the adjacent living spaces?

In answering the second research question, this thesis studied different design parameters such as sunspace geometry, glazing areas (half and fully-glazed percentage areas) and glazing types of the sunspace. The hypotheses of the study are listed below:

- The larger the sunspace and balcony area, the larger the daylight reduction in the adjacent living space.
- The geometry of the sunspace and balcony is the most affecting parameter in developing the sunspace design solutions.

Overall, the main goal of this study is to develop sunspace design solutions to achieve good indoor natural lighting in an energy-efficient multi-family housing.

## 1.3 Limitations

This thesis only studied the daylighting performance, therefore there was no energy studies or energy simulations conducted during this thesis. For the daylight studies, design iterations were only investigated by computer simulations since it was not possible to build each apartment configuration. Simplifications of the studied apartments were made in the computer simulations by only selecting the main studied areas which consist of glazed-unglazed balcony and the adjacent living spaces. The users' behavior was not considered in this thesis and only one occupancy profile was used in the study. This thesis only analyzed the daylight quantity, so the visual comfort, such as glare, was not studied. Shading caused by plants in the sunspace and balcony was not taken into consideration in this study.

## 2 Sunspace

### 2.1 Sunspace as a passive solar strategy

Passive solar is a term used for a system that collects, stores and redistributes solar energy without the use of any mechanical system. The system works by relying on the integration of the building design and surrounding climate. Passive solar heating system consists of two essential features: a collector which usually consists of south-facing glazing and a thermal mass to store the solar energy. There are three main concepts of passive solar systems integrated into building design, which are direct gain, trombe wall and sunspace (Lechner, 2008).

Amongst the three passive solar systems, adding an adjacent sunspace is considered as one of the most popular passive solar systems, due to its potential as an energy collecting system which can also provide extra space to the building, as well as its aesthetics appearance towards the building (Mihalakakou, 2002). Adding a sunspace can provide not only an extra living space to the main building, but also extra green spaces for cultivation area or urban farming. Even though a sunspace is usually added to the living area, it must be designed as a separate thermal zone that can be isolated from the adjacent space, which is essential during cold winter days (Lechner, 2008). Improper sunspace design can lead into increasing heating demand in a cold climate area.

For the climate of the southern latitudes, passive solar systems should provide space heating during the winter. On the contrary, passive solar systems can lead to overheating problems during the summer, which can be solved by using effective solar control and passive cooling systems such as night ventilation and earth-to-air heat exchangers. For temperate climates, although the conditions are more favorable in implementing passive solar systems, it is still necessary to take into account the climatic conditions while also applying effective shading devices, effective ventilation and sufficient thermal insulation so that the thermal comfort in the adjacent space can be achieved. For northern climates, where the buildings are highly insulated, problems with overheating are more acute and the design of sunspaces should include shading devices and adequate ventilation (Mihalakakou, 2002).

Sunspace can be a suitable and efficient system to reduce energy demand in the building if designed according to the local climate and passive design measures. Apart from adding extra living space and urban farming possibility, the main purpose of a sunspace is to collect solar energy and reduce the need for other energy resources along with its energy demand (Aelenei, et al., 2014).

#### 2.1.1 Integration of sunspace with buildings

There are three ways to integrate a sunspace with a building: attached, semi enclosed and enclosed, as described in Figure 1.

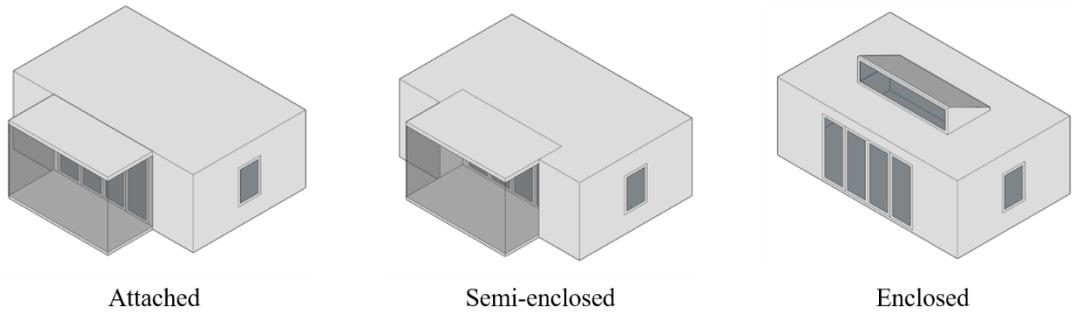


Figure 1: Sunspace integration with buildings

In building retrofitting projects, sunspaces are used extensively as a technique to store solar energy in the building. In this case, existing balconies are often glazed and turned into sunspaces or sunspaces are added additionally as new building extensions (Jaure, 1998). Sunspace which consists of attached glass house or glass-covered balconies, acts as a solar energy storage that can be applied in various ways to the building block. The adjacent space functions as a thermal buffer between the interior and exterior of the building and as a solar collector. This space could also be used as a ventilation pre-heating area using operable vents or windows to let the warm air flow into adjacent spaces. To solve overheating issues in the summer, operable vents placed at the top of the sunspace could be used in combination with a shading device (Aelenei, et al., 2014).

During the day, the sunspace collects heat, which is carried into the building through doors, windows or vents. The rest of the heat is then absorbed by the sunspace's thermal mass which is useful during the night when the door and windows are closed to keep the main building warm and avoid freezing in the sunspace, see Figure 2.

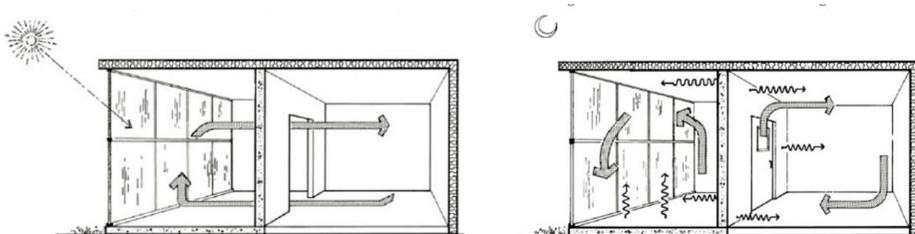


Figure 2: Sunspace behavior during day and night.  
(Source: Lechner, 2008)

A sunspace can provide a great potential of energy savings during the winter period through passive solar gain if it is not heated (IEA Task 20, 1999). If a sunspace is conditioned then it can be a potential energy waster, increasing the heating or cooling load of the building (Lechner, 2008).

## 2.2 Sunspace and daylight

Wilson, Jørgensen and Johannesen (2000) conducted a study to develop design solutions to establish good daylighting and low energy use for apartments connected with a sunspace. The study took place in two eight-storey refurbished social housing blocks in Engelsby, northern Germany. The study was a part of the EU DGXVII THERMIE Project SHINE. The buildings were originally built in 1966 and the refurbishment project in 1994 targeted to achieve energy savings of 60% compared to the original energy use. The design of the refurbished building blocks consisted of integrating sunspaces into the apartments, which raised questions about the daylighting and energy use in the apartment. The renovated buildings' constructions consisted of insulated external walls, double-glazed with low-E coating windows and single-glazed sunspaces. Two types of sunspaces, recessed (inside sunspace) and attached (outside sunspace), were investigated in terms of the effect of integration with the building and orientation of the sunspaces. Both daylight factor and heating demand were simulated and monitored in this study.

In the research, the authors estimated the impact of glazing on daylighting in a room. If no other structures except glazing structure is included, allowing 85% transmission for single glazing and 70% for double (less for low-e), with 15% loss caused by the glazing frame, then the reduction of daylight received in the room was around 30% to 45% respectively. Daylighting in buildings is already reduced through unshaded windows, adding additional sunspaces to the glazed areas in buildings is a great concern to the greater daylight reduction in the adjacent space. The reduction can be much higher if the sunspaces added into the building creates a block of tower attached to the main building.

The authors studied a 4,5 m deep living room with an adjacent 1,5 m deep sunspace. The results showed that the average daylight factor (DF) in the living room and added sunspace was reduced by around 20%. When the sunspace was treated as an overhang with a height of 2,5 m, the average DF in the adjacent room behind the sunspace was reduced by 30% to 35%, excluding the glazing and glazing structure loss. It was estimated that 60% of the daylight in the adjacent space was lost when glazing and glazing frame were added.

As a case study of the Engelsby apartment, the authors performed daylight simulations for the east facing apartment with a balcony which was then glazed into a sunspace. The amount of daylight reaching the adjacent space was decreased by 50%. A solution of adding an additional west-facing window to the space was introduced to the project and it increased the amount of daylight incident in the adjacent space, as well as increasing the uniformity of light.

In another study related to the Engelsby project, Jørgensen and Hendriksen (2000) also recommended to make a design that will increase the daylight level in the adjacent space to the sunspace. Adding a window where it is possible in the project can be the best solution to solve low daylight level issue caused by the additional sunspace.

Wilson, Jørgensen and Johannesen (2000) also performed another study for a refurbished apartment project in Lyon, France. The interesting fact was that the tenants were pleased with the daylight improvement in the living spaces even though the sunspace was added into the apartment units. This could be explained by the fact that in this project, the windows

adjacent to the sunspace were extended up to the floor allowing the ground-reflected light to penetrate into the room. For buildings in sunnier climates such as Lyon, the ground reflectance becomes one of the determinant factors. In addition, human's perception of daylight is greatly connected with the view out. Although the tenants were pleased with the quality of light in the living spaces, the amount of daylight received in the adjacent space to the sunspace was in fact reduced, especially for the spaces which had East-facing sunspaces. As suggested previously, from daylighting point of view, one solution that can be used is to open more windows on the external wall which is not attached to the sunspace.

## 2.3 Sunspace and energy

Regarding the impact of sunspaces on energy use, previous studies have been conducted in order to evaluate different types of sunspaces on the thermal performance and optimum sunspace design solutions have been developed.

Jørgensen and Hendriksen (2000) investigated different designs of glazed balconies (sunspace) on three different buildings in Europe to determine whether sunspace can provide energy savings or actually increase the energy demand of the adjacent space. There is a tendency that sunspace is treated as an extra space in the apartment which might be heated by the tenants. If the sunspaces are not designed for the extra heating, the energy consumption might increase significantly. For this reason, the study was carried out for various glazing types, orientations and patterns of occupancy. The research was also a part of IEA SHCP Task 20, Subtask B "Development of Improved/Advanced Renovation Concepts" and Subtask F "Improvement of Solar Renovation Concepts".

The three studied buildings were a part of refurbishment building projects that were firstly built during the 1900s until 1960s and all of them had high energy demands. The first building, The Yellow House, was a four-storey high apartment building located in Aalborg, Denmark, which is oriented South-North. The building was expected to have 60% reduction in the energy demand. The second building is an apartment building with existing unglazed balconies, which is located in Østerbo, Denmark. In this building, energy savings of 50% were expected. The third building located in Engelsby, Germany, was also studied to find the impact of sunspace on daylight conditions as mentioned in the previous section. The energy savings of the Engelsby apartments were expected to be up to 60%, although the apartments were in a very poor condition in terms of the thermal performance and indoor climate.

In studying these three buildings, the authors carried out a series of parametric studies to reach energy savings. Different design parameters, such as glazing types, glazing areas, insulation and airtightness of the sunspace were studied and simulated with different patterns of occupancy. The authors simulated heat flows and thermal conditions annually using the thermal simulation program called "tsbi3", which was developed for analysis and design of building elements and system components as well as dynamic simulation of building performance under realistic use and operation. The authors also utilized full scale mock-ups for critical elements and intensively monitored the energy consumption and thermal comfort of the three studied buildings.

From the simulation results, the authors concluded that there were three most influential parameters for finding the optimum design solution for the sunspace, which were: the glazing types and sizes, orientation and the sunspace occupancy profiles. Four glazing types, consisting of single glazing with no framing and sealing, single glazing with standard framing, double glazing with standard framing and low-E glazing with standard framing, were modelled. Three orientations and different sunspace types, which were east oriented enclosed sunspaces, south oriented enclosed and attached sunspaces and west attached sunspaces, were modelled for this research. Eleven occupancy scenarios with heating and no heating of the sunspace were also studied. Other parameters such as the insulation level and airtightness of the sunspace were investigated, but the impact of these parameters were not resulting in significant effect on energy savings compared to the three main aspects mentioned before.

By firstly studying the influence of the sunspace glazing area on the energy savings, the results showed that the glazing areas had a slight influence on the energy savings because with a good glazing U-value (around 1,1 W/m<sup>2</sup> K), the energy savings were almost independent of the glazing area. From all the parameters combined, the overall results showed that the highest energy savings for unheated sunspace in all cases were obtained by using low-E gas filled double glazing for the sunspace glazing which provided up to 40% of energy savings. The next best cases were followed by conventional double glazed sunspace with insulated walls between sunspace and adjacent space, then all glazed sunspace with insulated walls, single glazed sunspace with insulated walls and finally conventional double glazed sunspace with uninsulated walls. If the sunspace was heated to 20°C in the heating season, only enclosed sunspaces with insulated walls and either low-E glazing or conventional double glazing provided any kind of energy savings up to 28%. All other sunspace types increased the heating demand by more than 200%. The relatively large glazing areas in sunspaces can lead to overheating in the sunspace and adjacent rooms during summer, which can be prevented by naturally ventilating the sunspace and using shading devices.

In conclusion, the authors recommended two principal design solutions regarding implementing sunspace in buildings:

- For enclosed sunspaces, the design with energy-efficient glazing and insulation between the sunspace and the adjacent space is highly recommended to increase the sunspace robustness against unintended use, such as heating. In this way, heating the sunspace can still provide energy savings for the space heating due to the high level of insulation.
- For attached sunspaces, the design with very “open” glazing is recommended as this design will also be robust against unintended use as heating of the sunspace. It will be difficult to heat the space to a comfortable level due to the very open design. These types of sunspaces can also benefit from the highly-insulated solution, but it will be costly due to the large glazing area.

From the Jørgensen and Hendriksen (2000) study, it was proved that it was possible to design cost-effective and architecturally attractive glazed balconies which provide energy savings, increased thermal and visual comfort, improved air quality and building protection against degradation when designed according to all aspects.

Few years after, another study of sunspace thermal performance in buildings was conducted by Mihalakakou (2002). The author investigated the energy potential of a sunspace connected with a building for four European cities: Milan, Dublin, Athens and Florence, during the cold period (December to March) and warm period (June to September) of the year 1996. The studies were carried out by performing a series of simulations using TRNSYS, a transient simulation environment with modular structure. The study model was a heavily constructed single zone with 6,0 m wide, 10,0 m long and 4,5 m floor to ceiling height building which was connected to a south-facing with 3,0 m wide, 10,0 m long and 2,6 m high sunspace. Simulations were performed hourly taking into account that all measurements were taken on an hourly basis. To solve the overheating problems, strategies such as shading devices, night ventilation, earth-to-air heat exchangers and combined case scenarios were also simulated to find the optimum solutions for each climate.

To study the influence of sunspace during the cold period, simulations were performed for January 12<sup>th</sup>, 1996. In the four cities, it was found that the sunspace had a potential in increasing the indoor temperature inside the building by up to 5°C depending on the building's location and outdoor ambient air temperature in each location. In Milan, the maximum indoor temperature difference between the building connected with a sunspace and without sunspace was 4°C, while in Athens, the difference was 3°C and in Florence, it was only 2°C. It was more beneficial for a colder city like Dublin, because having a sunspace could raise the indoor temperature in the building by up to 5°C.

During the summer period, the simulation date was limited to July 4<sup>th</sup>, 1996. The results was as expected, that the sunspace created serious overheating problems in the building adjacent to the sunspace, except in Dublin. For warmer cities, such as Milan which had maximum ambient air temperature of 35,6°C in the simulated date, the maximum indoor temperature for the building adjacent to a sunspace reached 36,2°C which was higher than the outdoor air temperature. The same trend was observed in Athens, where the maximum indoor temperature for the building adjacent to the sunspace reached up to 38,1°C which was 2°C above the maximum outdoor air temperature. It was also the same for Florence, where the sunspace increased the indoor air temperature by 2°C compared to the building without a sunspace. In Dublin, where the summer outdoor air temperature is not as high as the other three cities, the overheating problems were not observed.

To overcome the overheating issues, few techniques were applied to be integrated with the sunspace. First, buried pipes as earth-to-air heat exchanger were integrated into the existing building. It was observed that the use of buried pipes in combination with the sunspace in Dublin during the winter time was effective. It increased the temperature in the building by 2°C. Even in Athens, the system was also useful to increase the indoor temperature. Looking at the cities with major overheating problems, the simulations revealed that the addition of buried pipes as a cooling method can reduce the indoor temperature by up to 6°C in Milan and 7°C in Athens.

Another improvement was to implement night cooling into the building in combination with the sunspace. It was found that night ventilation gave slightly better result in providing cooling into the building compared to the buried pipes. The effectiveness of the night ventilation is related to the relative difference between indoor and outdoor air temperatures.

In general, a reduction of the outdoor night temperatures represents an increase of the night-ventilation system potential (Santamouris, et al., 1994).

The third approach explored by Mihalakakou (2002) consisted of introducing shading to the building. It was proven in the study that the additional shading device reduced the indoor temperature of the adjacent building, although it did not solve the overheating problem completely.

In the end, all three passive techniques, buried pipes, night ventilation and shading devices, were combined together to solve the overheating problem during the summer period. The author observed that by combining these three methods into one scenario, the overheating problem in Milan and Athens was avoided. The maximum temperature difference between the indoor air temperature inside the building connected only with the sunspace and the building connected with the sunspace combined with three passive methods was 10°C for Milan and 11°C for Athens respectively. The combined passive techniques proven to be the most effective way for the warm period to prevent overheating and provide adequate space cooling, especially in the warmer European climates.

In a more recent study, Bataineh and Fayez (2011) evaluated the thermal performance of sunspace technology for a typical Mediterranean climate in Amman, Jordan (Mediterranean Climate) with cold winters and hot-dry summers. The thermal simulations were carried out using Derob-LTH, a dynamic thermal simulation tool originally developed at Austin School of Architecture, University of Texas and further developed at Lund Institute of Technology (LTH). Derob-LTH has accurate models which can manage irregular geometries, buildings with several zones and calculate peak loads, energy demand, temperatures and thermal comfort for a building (Lund Institute of Technology, 2016). Different sunspace configurations of various opaque and glazing ratios, as well as passive measures to optimize the thermal performance of the sunspace were investigated taking into account the diffuse and direct solar radiation. With conventional Jordanian construction, the simulations were performed by analyzing the effect of sunspace itself, number of glazed surfaces of sunspace, construction absorptivity, and the orientation of the sunspace. As an addition, passive measures were implemented and simulated to overcome the overheating issues during the summer and high thermal losses during the winter night. The effect of having an inclined front glazed surface, both with single and double glazed windows, was studied as well.

For the single glazed sunspace, increasing the glazed area decreased the annual heating load. However, this also resulted in an increase in the annual cooling load due to the overheating problem in the summer. The amount of solar gains received in the summer is higher than in the winter. This excessive amount of solar gains in the summer needed to be removed which resulted in a higher cooling load. During winter time, a single glazed unheated sunspace increased the thermal losses during night time. Increasing the glazed area increased the amount of thermal transfer to the colder outdoor air during the night. Furthermore, using double glazed windows for the sunspace decreased the annual energy demand. The impact on the cooling load was not significant during the summer months. As for the vertical wall and floor absorptivity, increasing the value reduced the heating load in the winter. Nevertheless, it increased the cooling load in the summer. This was due to the high amount of solar energy being absorbed during the summer.

While simulating for three different orientations (south, north and east), Bataineh and Fayez (2011) found that the heating load was the lowest when the sunspace was facing south and the highest when facing north. Whereas for the cooling load, the results showed that north had the minimum value for all sunspace configurations. For annual heating and cooling load in all configurations, the best orientation for the sunspace was towards the south and the worst was the north orientation.

Having a sunspace connected to a building can cause serious overheating problems during the summer months when not designed wisely. The authors tried to avoid the overheating issue by also implementing passive techniques. Night ventilation and additional shading devices during daytime were applied in the sunspace to overcome the overheating issues during the summer period. These two measures combined with increasing ratio of glazed surface to the opaque surface of the sunspace reduced the heating and cooling load. The larger the glazed area, the larger the reduction.

Another passive measure was to reduce thermal losses during winter night. Bataineh and Fayez applied internal shading device during the night which increased the thermal resistance of the sunspace and reduced the amount of heat transfer to the colder outdoor air. The internal shading device can also block the radiation exchange between sunspace walls and deep sky. A study was carried out for January 1<sup>st</sup> with heating set point temperature 24°C and it was found that the internal shading device reduced the night thermal losses, as well as improving the thermal performance of the adjacent building. For all configurations, the heating load reduction was 25% on average for this day.

They also conducted a study to compare single and double-glazed sunspace by applying three passive techniques. The results showed that single glazed sunspace performed better than double glazed sunspace. Another research of inclined front glazed surface was also performed and it was found that the sloped front glazed surface increased the viewing factor during winter time. Utilizing a low-angled sloped front glazed sunspace with 2,0 m high double glazed vertical sunspace walls outperformed the other configurations with single glazed sloped sunspaces.

More recently, Aelenei and Leal (2014) performed a sensitivity study about sunspaces applied to an existing residential building in six different cities in Portugal with five key parameters: natural ventilation, shading devices, number of glazed surface layers, orientation and opaque wall ratio. In order to study the thermal performance of the attached sunspace in each case, the authors performed dynamic thermal simulation using EnergyPlus, a building energy simulation program which can be used to model energy consumption and water use in buildings (EnergyPlus, 2016). The simulations were performed for a single zone with the sunspace implemented as a different thermal zone. Four different sunspace configurations were studied, two were attached and one was integrated while the other one was partially integrated to the existing building. The thermal performance of the studied building model with each of the sunspace integration was simulated for a whole year, assuming the heating and cooling set point temperatures of 20°C and 25°C respectively. Besides the configurations, six cities, which were Faro, Lisboa, Evora, Coimbra, Porto and Braganca, had different heating degree days and mean daily temperatures.

The authors evaluated the thermal performance of the sunspace by estimating the energy demand of the building for all sunspace configurations. The comparison was made based on the reference case which was the building without the sunspace. The authors found that the most effective sunspace configuration in reducing the annual energy demand across six cities was the south oriented, fully integrated, naturally ventilated sunspace with a highly reflective inner shading device. For the rest of the sunspace configurations, the most effective design was based on the climatic characteristics of each studied cities. For Porto and Braganca which experience colder and longer winters, fully adjacent or fully integrated double-glazed sunspaces were more effective compared to other combinations. For warmer cities, such as Faro, a fully integrated sunspace with less opaque wall in the sunspace was found to be more suitable in reducing the amount of solar gains received and stored in the wall to avoid the risk of overheating in the summer.

Also in the same study, it was found that having sunspace can really be beneficial for the winter period since it was proven to reduce the heating demand in Faro by 100% when using the fully integrated sunspace. On the contrary, the sunspace introduced overheating issues in four cities: Evora, Coimbra, Porto and Braganca, during the summer months. The authors suggested that passive measures for decreasing the overheating risk was crucial and needed to be applied to obtain a high performance sunspace design. Another important measure which can strongly affect the energy savings was the user behavior which is dependent on the user availability and knowledge to control the amount of heat to be delivered to the house or extracted from the sunspace depending on the comfort and climatic conditions. Sunspace can be seen as an extension of a building and this will lead to an extra heated space in the winter which can actually increase the heating demand rather than reducing it. This can either be more or less energy efficient, depending on the user behavior, which needs to be considered.

## **2.4 Successful projects integrating sunspace**

Several projects integrating sunspaces into the buildings are discussed in this section.

### **2.4.1 BedZED, London**

One successful example and award-winning project is the BedZED mixed-use development in the suburb of London, England. BedZED, designed by Bill Dunster in partnership with the BioRegional Development Group, The Peabody Trust, Bill Dunster Architects, Arup and Gardiner and Theobald, is UK's first large-scale, mixed use sustainable community with 100 homes, office space, a college and community facilities (Bioregional, 2016). The housing and office development in London is a carbon-neutral community with green spaces, recycling facilities, water saving features, and a green transport plan.

BedZED's houses and flats are heated using passive solar techniques, where highly insulated houses were placed towards south using multi-storey glazed sunspaces to maximize heat gain from the sun. Offices are facing north, where minimal solar gain reduces the tendency to overheat and the need for cooling (Inhabitat, 2008). Figure 3 explains the concept in section.

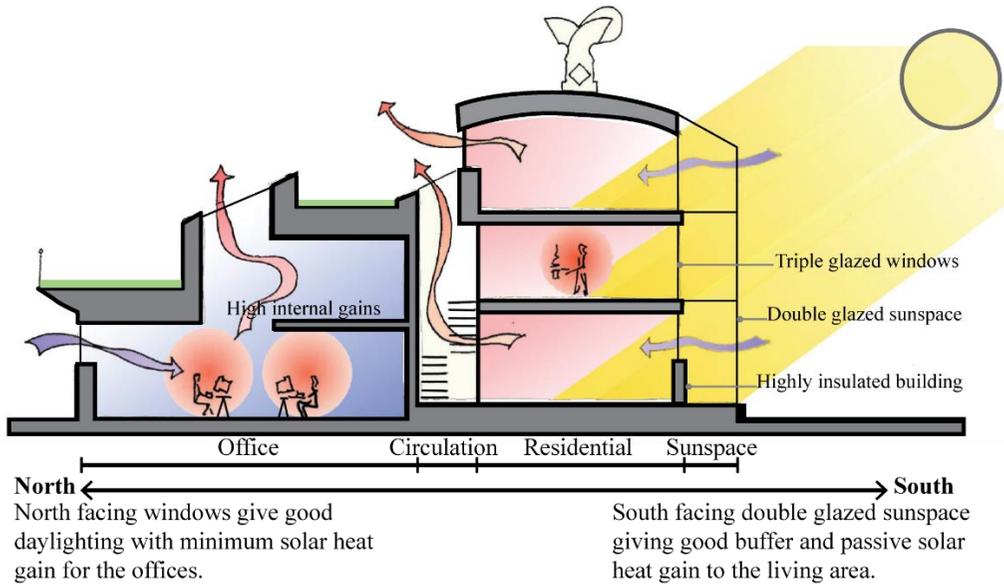


Figure 3: BedZED section describing passive solar heating techniques.

### 2.4.2 St. Matthews Keyworker Block

St. Matthews Keyworker Block is ZEDFactory’s residential project in England which implemented sunspace as a passive solar collector. In this project, the large south facing sunspaces were integrated with high performance windows which act as passive solar collectors on the building. St. Matthews project can be seen in Figure 4.



Figure 4: St. Matthews and the south-facing sunspace.  
Source: ZEDFactory, 2016.

According to ZEDFactory (2016), the south-facing sunspace provided up to 30% of the space-heating requirement. The savings of the space heating provided by the sunspace was also because of the highly insulated building envelope with high thermal mass and the high thermal performance windows. Another benefit from implementing the south-facing sunspace was to allow daylight into the living spaces.

## 2.5 Sunspace design guidelines

In all types of climates, designing a sunspace should always take into account the existing climatic conditions, either for providing space heating or cooling. It is essential to include an adequate amount of thermal insulation, effective shading devices and ventilation strategy into the sunspace design (Mihalakakou, 2002).

A study about various configurations of sunspaces was performed in Portugal and resulted that a fully integrated (enclosed) sunspace had the most advantage in reducing the annual energy demand due to its smaller glazing surface areas in contact with the outdoor (Aeleneia, Lealb & Aeleneic, 2014). Sunspace can benefit a building in many ways if designed appropriately according to the use and local climatic conditions. There are some suggestions based on recent studies and literature in determining the glazing, thermal mass and ventilation methods used in a sunspace.

- **Glazing**

According to Lechner (2008), in order to maximize solar gains during cold winter months, the slope of the sunspace’s glazing should be perpendicular to the sun. However, due to safety, shading and durability of the glazing, vertical glazing is considered the best to be applied in a sunspace. For an unheated sunspace, it was proven beneficial to use single-glazed sunspace in the warmer climates whereas for the colder climates, the double-glazed sunspace was more effective in keeping heat during the heating season (Aeleneia, Lealb & Aeleneic, 2014). According to Architecture 2030 (2016) recommendations, for the sunspaces that are facing equator, the glazing area can be sized as a percentage of the floor area of the adjacent space to be heated. The sunspace glazing area differs according to the climate and the latitude of the area, as seen in Table 1.

Table 1: Unheated sunspace glazing area recommendations

Source: [http://2030palette.org/swatches/view/indirect-gain-sunspace/institute\\_for\\_forestry\\_1.jpg](http://2030palette.org/swatches/view/indirect-gain-sunspace/institute_for_forestry_1.jpg)

Cold climate*	Sunspace glazing area	Temperate climate**	Sunspace glazing area
28° - 40° latitude	30%	28° - 40° latitude	20%
44° - 56° latitude	40%	44° - 56° latitude	30%

\*Cold climate: Climate with winter temperature varying from -6,7 °C up to -1,1 °C.

\*\*Temperate climate: Climate with winter temperature varying from 2,2 °C up to 7,2 °C.

Large glazing area for the sunspace can be aesthetically beneficial, but it can cause overheating during the cooling period. This issue can be avoided by ventilating the sunspace through opening the windows and adding solar shading devices (Jorgensen & Hendriksen, 2000).

- **Thermal mass**

The thickness of the thermal mass is dependent on the sunspace's function. If it functions as a heat collector, then less thermal mass is needed to let the heat to be distributed more into the adjacent space. More thermal mass is needed if the sunspace is allowed to have a more modest temperature swing. For a temperate climate, it is recommended to use thermal-storage wall (Lechner, 2008). For warmer summer area, a sunspace with a lower portion of opaque wall is more effective to reduce the overheating caused by the solar heat gain (Aeleneia, Lealb & Aeleneic, 2014).

In extremely hot or cold climates, it is better to isolate the house from the sunspace using an insulated less massive masonry wall. When heat is needed, the doors, windows or vents in the common wall are opened. But, when the sunspace needs to be isolated from the adjacent building, the openings are closed and then the insulated walls act as a thermal barrier (Lechner, 2008).

Thickness between various types of common wall connecting sunspace and the adjacent building can be determined using Table 2 as a general guidance.

Table 2: Wall thickness recommendation

Source: [http://2030palette.org/swatches/view/indirect-gain-sunspace/institute\\_for\\_forestry\\_1.jpg](http://2030palette.org/swatches/view/indirect-gain-sunspace/institute_for_forestry_1.jpg)

Type of wall construction	Thickness / cm
Adobe	20-30
Brick	25-36
Concrete	30-46

There are specific guidelines for estimating the required thermal mass in sunspace if masonry wall is used as the thermal mass materials, see Table 3.

Table 3: Masonry wall as thermal mass construction

Source: Lechner, 2008

Thermal Mass	Thickness/cm	Surface area/Glazing area
Uninsulated masonry common wall	20 to 30	1
Insulated masonry common wall	10 to 15	2

- **Vent sizing**

According to Lechner (2008), to prevent extreme summer overheating, especially for south-facing glazed sunspaces, operable shading and outdoor ventilation system is recommended to be integrated with the sunspace itself. The best way to add venting is to have both high and low openings to maximize the stack effect. The inlet and outlet should correspond to at least 8% of the glazing area in size. A smaller size inlet can be used if a fan is provided to exhaust the hot air.

In order to heat the house during the winter season, the indoor openings such as doors, windows, vents or fans are needed in the shared wall between the adjacent space and the sunspace to let the heat collected in the sunspace go through to the adjacent room. The total area of any combinations should be at least 16% of the glazing area.

## 2.6 Advantages and disadvantages of sunspace integration

According to Mihalakakou's study (2002), sunspaces can be an effective system during winter time in Europe, but they represent a risk for overheating in the summer.

The advantages of sunspaces as passive solar heating system are described below:

- Attractive addition to the building, providing extra living space.
- Can be used as a greenhouse for urban gardening or urban farming.
- Sunspace can provide insulation effect for the adjacent space, the supply of pre-heated ventilation air and the supply of sun-heated air to the building when the sun is shining.
- Sunspace can reduce heating loads during winter time in the adjacent space due to the solar heat gains.

The disadvantages of sunspace are listed below:

- Expensive system, especially if the glazing area is large and double glazing is needed.
- Least efficient as a passive solar heating.
- Overheating in the summer can occur, when solar shading devices and operable ventilation system are not integrated in the sunspace.
- Reduction of daylight level for the adjacent spaces.

## 2.7 Summary

As shown in previous studies, by integrating sunspace into buildings, daylight received in the adjacent room can be reduced. One benefit of adding a sunspace into a building is the energy saving potential during winter period, especially in the cold climate areas. A sunspace acts as an additional thermal buffer to the adjacent space. This can be achieved by careful design of the sunspace, regarding the glazing, thermal mass, ventilation sizing and placement, as well as the orientation.

In one of the studies, the maximum reduction of heating load was obtained when the sunspace was south-oriented. In general, increasing the absorption coefficient reduces the heating load. A double-glazed sunspace is recommended, especially in colder climates, to achieve a better thermal performance. In most cases, sunspaces will be beneficial if oriented towards south. North-facing sunspace should be avoided.

Although sunspace can be beneficial during the heating period when properly designed, it can cause overheating problems in the summer. A sunspace can easily increase the indoor temperature, which can rise above the indoor thermal comfort threshold in some cases. It is recommended to design sunspace that overcomes any issues both during winter and summer periods.

Some passive methods can be used to solve the overheating problems, such as night ventilation techniques and application of efficient solar shading devices. The application of these methods are site and climate specific. Overall, previous studies show that sunspaces

can be an appropriate and effective system all year round if designed properly according to the local climate and overheating is avoided by passive means.

There is a scarcity of studies about sunspace and daylight, especially in Nordic climates. Therefore, these thesis objectives, which focus on the sunspace's daylighting impact and sunspace design optimization based on the daylight performance, are crucial. Nevertheless, the impact of sunspace on the energy performance is also important and it is studied in the MKB Greenhouse research project at White Arkitekter AB.

### 3 Methodology

This chapter presents the current conditions of the studied case, methods and tools that were used during the study process. Four apartments in MKB Greenhouse, which is a newly built and environmentally certified multi-storey residential building in Malmö, were taken as a case study in this thesis. The specific location and actual building design on Greenhouse was modelled to provide a 3D representative of the actual building. Simplifications were made and the study was focused on the impact of sunspace and balcony to the adjacent living spaces, such as the living room, kitchen and workshop.

The impact of adding sunspace and balcony on the daylighting performance of the living spaces were simulated using advanced daylight simulation tool, Radiance, through Rhino3D and Grasshopper (using Ladybug and Honeybee) as simulation platform. Based on the impact of the actual sunspace and balcony design, parametric studies regarding the sunspace and balcony geometry, glazing to wall ratio (GWR) and material light reflectance value (LRV), were performed to develop sunspace and balcony design solutions to improve the daylight performance in the living spaces. The following sections explain the methodology thoroughly.

#### 3.1 Greenhouse as a study case

Greenhouse (see Figure 5) is a newly built, mixed use multi-family residential building that is recognized as one of Sweden's most sustainable building projects with Miljöbyggnad Gold and Feby's Passive House Standard certifications (MKB Fastighets AB, 2016). The construction started in 2014 and the building is occupied from June 2016.



Greenhouse architectural rendering  
Courtesy of Jaenecke Arkitekter



Greenhouse current development  
(Taken June, 2016)

Figure 5: Greenhouse development in Augustenborg, Malmö.

##### 3.1.1 Location

Greenhouse is located in the eco-city of Augustenborg, Malmö, Sweden (latitude: 55° N and longitude: 13° E). Augustenborg is one of Sweden's largest urban sustainability project

which was launched in 1998 and the neighborhood is socially, economically and environmentally sustainable (Malmö Stad, 2016).

In order to have a site specific study, Greenhouse apartment tower was modelled as similar as possible to the architectural design provided by the architects and the existing site conditions. Greenhouse is situated in a residential area with four or five storey high apartment buildings. The current condition of Greenhouse’s building site is shown in Figure 6. The existing apartment buildings surrounding Greenhouse were also included in the model as shown in Figure 7. Based on the location, the climate file of Copenhagen, Denmark, was used throughout the study.

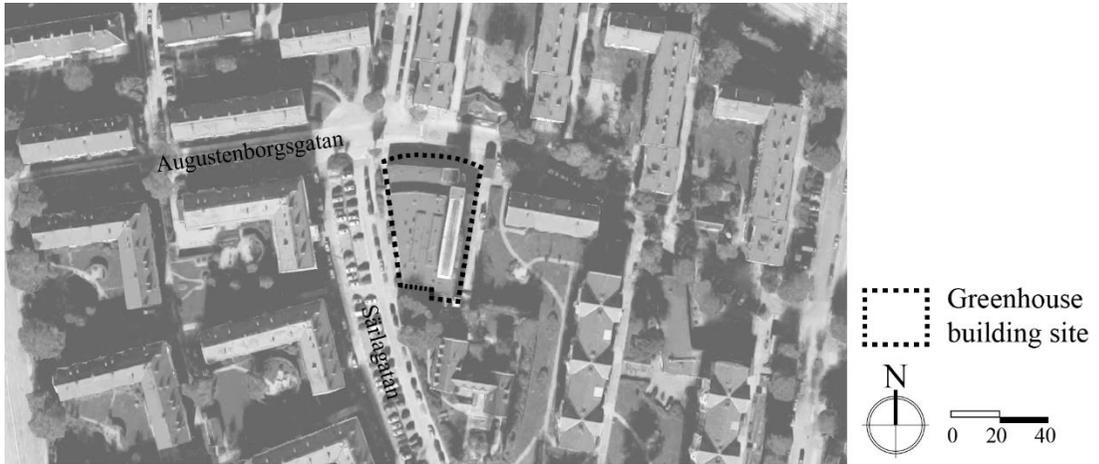


Figure 6: Site conditions shown from Google Earth.  
Source: Google Map Data (2016)

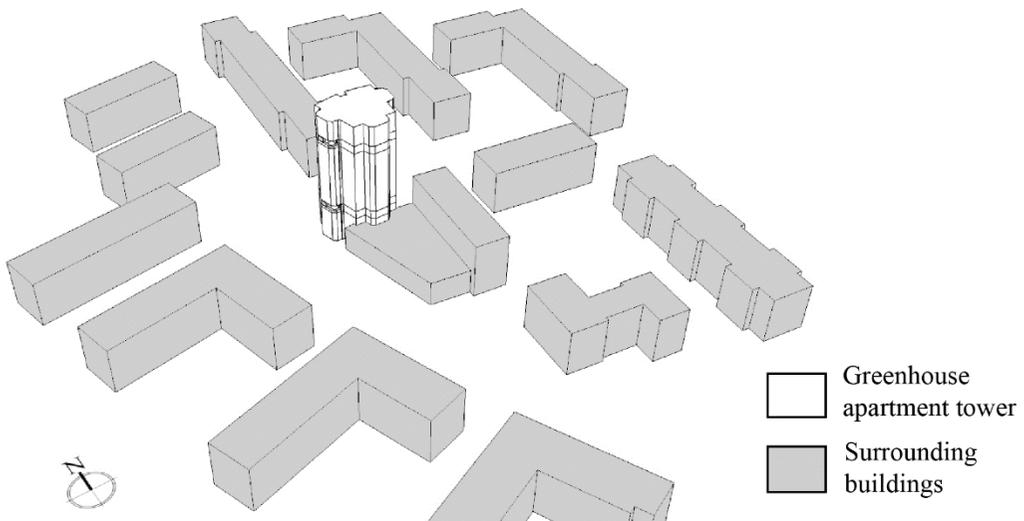


Figure 7: Modelled apartment tower and its context.

### 3.1.2 Geometry

The study was focused on the east and west facing apartments on the fourth and twelfth floor of the Greenhouse apartment tower in order to investigate the effects of orientation and floor level on the daylight performance of the living spaces adjacent to the sunspaces. The studied apartments are further shown in Figure 8, where the position of each apartment is marked clearly based on the elevation and orientation.

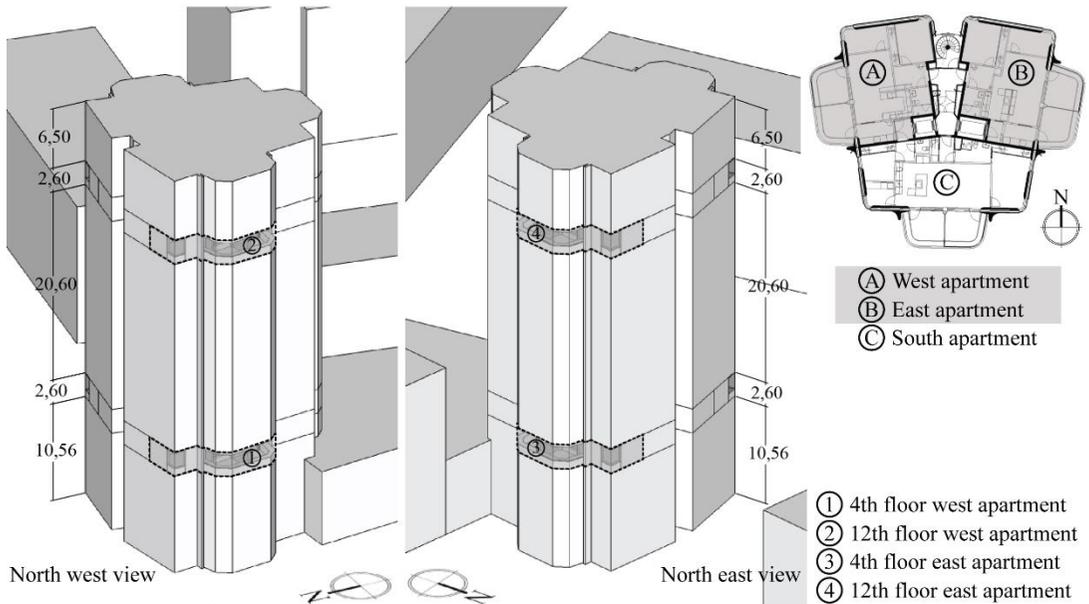


Figure 8: The studied apartments.

As it can be seen from the top right side of Figure 8, only the east and west orientations were investigated since they both have similar geometries and are thus comparable. Besides the orientation, the main concern of this study was only the living space of each apartment which consists of a living room, kitchen and an adjacent workshop. It is possible to add an extra bedroom in the living room, but this room is neglected in this study and transformed into one living room area. Other rooms such as bedrooms, bathrooms, hallways are not included in the study. In both orientations, a 20 m<sup>2</sup> balcony with 11 m<sup>2</sup> cultivation area is attached to the living space. The balcony is divided into two climate zones, half of the balcony is glazed and the rest is left open. The sunspace in this study thus refers to the glazed balcony area, whereas the unglazed area is referred as balcony throughout this study.

The studied apartments' geometry was simplified and shown in Figure 9.

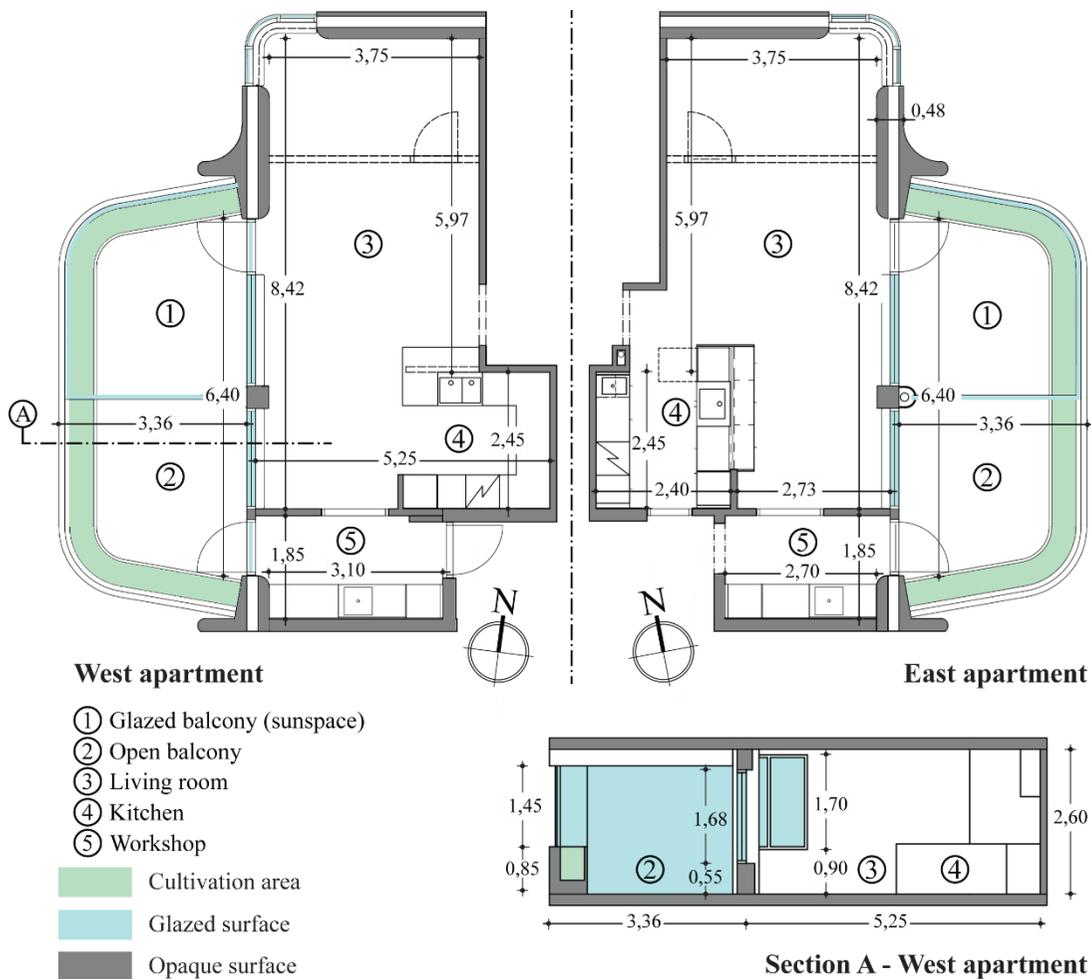


Figure 9: Geometry of the studied apartments.

The east and west apartments internal floor area of all the studied living spaces are described in Table 4, along with the sunspace glazing to wall ratio (GWR).

Table 4: Studied apartment's area and sunspace GWR.

Rooms	Area (m <sup>2</sup> )	
	West Apartment	East Apartment
Living room	31,5	31,5
Kitchen	3,7	3,7
Workshop	5,7	5,0
<b>Sunspace glazing to wall ratio</b>		
All sunspace walls	56%	56%
Sunspace-balcony divider wall	88%	88%

In the first phase of the study, the studied apartment was modelled as similar as the built apartment to obtain the most realistic results, especially for the daylight conditions in the adjacent living space. Simplifications of the sunspace and balcony were made for the final simplified models and kept as close as the real model as possible to avoid large differences between the models. Model simplifications are presented in the daylight model section that is described further below.

### 3.1.3 Building Occupancy

The building's occupancy schedules were based on a study of "Measured Occupancy Levels in 18 Swedish Apartment Buildings", where airflow rates in the ventilation systems and carbon dioxide concentrations in 18 Swedish apartment buildings were measured to determine the occupancy levels for the purpose of input data for building simulations (Johansson, et al., 2011). These occupancy levels were then further analyzed and developed by Bournas and Haav (2016) in order to define the daily occupancy schedule in the Greenhouse project. Each apartment was assumed to be occupied by two people who works during weekdays. The daily occupancy of the whole rooms in the apartment is presented as a fraction from 0 to 1 in Table 5, where 0 indicates an unoccupied space and 1 indicates that the space is fully occupied. The apartment's daily occupancy schedule is presented in Table 5.

Table 5: Apartment's occupancy schedule  
Source: Bournas and Haav, 2016

	Weekday occupancy / fraction					Weekend occupancy / fraction				
	L*	K*	B*	W*	Ba*	L*	K*	B*	W*	Ba*
00:00 - 07:00	0	0	1	0	0	0	0	1	0	0
07:00 - 08:00	0	<b>0,7</b>	0	0	<b>0,3</b>	0	0	1	0	0
08:00 - 09:00	0	0	0	0	0	0	0	1	0	0
09:00 - 10:00	0	0	0	0	0	0	<b>0,5</b>	0	0	<b>0,5</b>
10:00 - 11:00	0	0	0	0	0	<b>0,8</b>	0	0	<b>0,1</b>	<b>0,1</b>
11:00 - 18:00	0	0	0	0	0	0	0	0	0	0
18:00 - 19:00	<b>0,1</b>	<b>0,8</b>	0	0	<b>0,1</b>	<b>0,1</b>	<b>0,8</b>	0	0	<b>0,1</b>
19:00 - 20:00	<b>0,8</b>	0	0	<b>0,1</b>	<b>0,1</b>	<b>0,8</b>	0	0	<b>0,1</b>	<b>0,1</b>
20:00 - 21:00	<b>0,8</b>	0	0	<b>0,1</b>	<b>0,1</b>	<b>0,8</b>	0	0	<b>0,1</b>	<b>0,1</b>
21:00 - 22:00	<b>0,5</b>	0	0	0	<b>0,5</b>	<b>0,9</b>	0	0	0	<b>0,1</b>
22:00 - 23:00	0	0	1	0	0	0	0	<b>0,5</b>	0	<b>0,5</b>
23:00 - 24:00	0	0	1	0	0	0	0	1	0	0

\* L: Living room, K: Kitchen, B: Bedroom, W: Workshop, Ba: Bathroom

Since the study only focused on the living room, kitchen and workshop, the occupancy schedules that were used as input data were the ones highlighted in grey in Table 5. This schedule was then used for the annual daylight simulations and electrical lighting calculations.

### 3.2 Work process and simulation tools

This section explains the whole work process and the tools used throughout this study. This study was based on two main research questions. First, the aim is to investigate the impact of having sunspace in a multi-storey residential building on the daylight performance in the adjacent living space. Second, from understanding the impact of the sunspace and balcony, a parametric study was then developed to yield sunspace design solutions to improve the daylight conditions in the apartments. Advanced daylight simulation tools were utilized to perform the base case and parametric studies. A whole work flow diagram and the simulation tools used are shown in Figure 9.

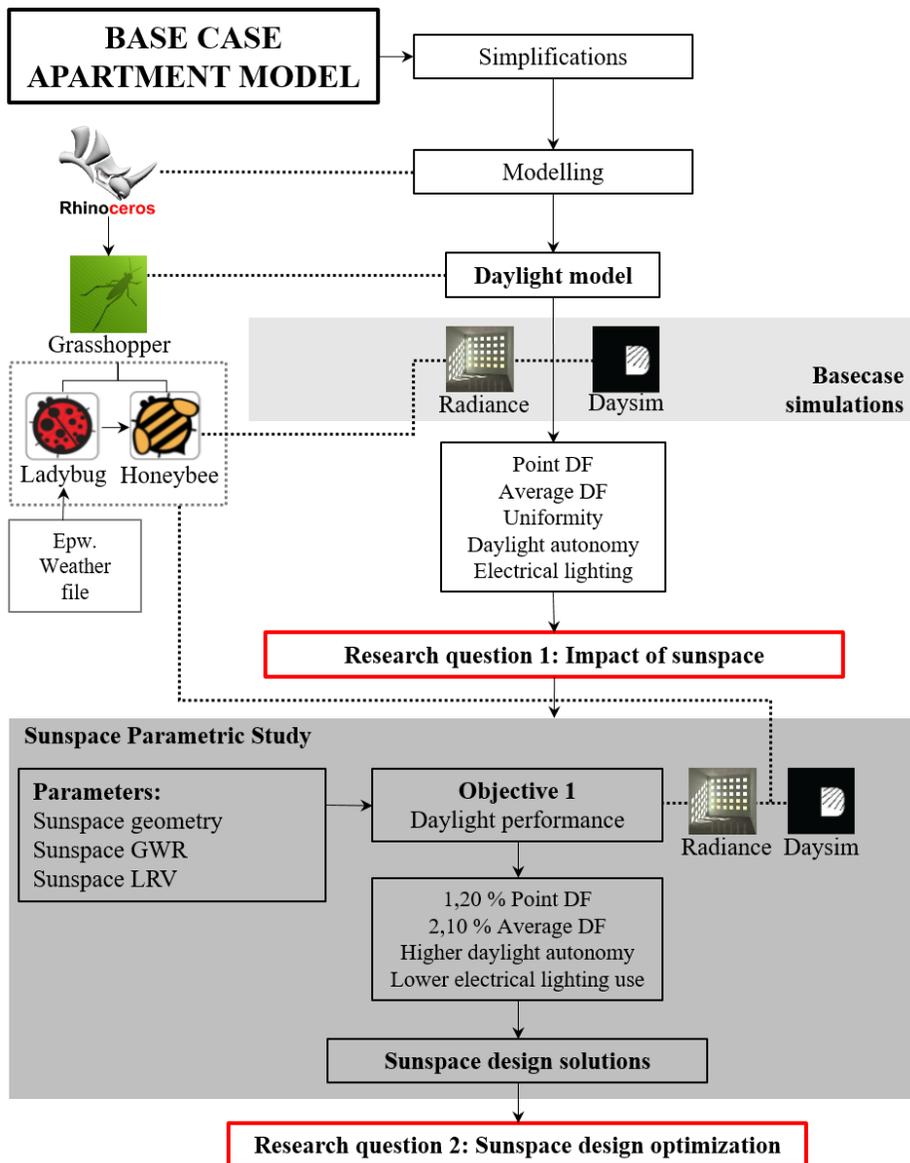


Figure 10: Work process diagram.

### **3.2.1 Rhinoceros**

Rhinoceros, which is often abbreviated as Rhino, is a 3D modelling tool capable of creating, editing, analyzing, documenting and animating complex geometries. Rhino provides unlimited free-form modelling tool which can translate NURBS<sup>1</sup> curves, surfaces, solids, point clouds and polygon meshes (Robert McNeel & Associates, 2016). Rhino can be coupled to an algorithmic modelling tool named Grasshopper. With this integration, Grasshopper can be used for modelling, analyzing and simulating within the Rhino environment (Davidson, 2016). Rhino was used for both modelling and simulating together with Grasshopper in this study.

### **3.2.2 Grasshopper**

Grasshopper is a graphical algorithm editor developed by David Rutten which runs within the Rhino-3D modeling tool (Davidson, 2016). The model in Rhino is generated firstly by dragging components into Grasshopper canvas and connecting them with other components or some input data. Grasshopper is an open-source tool which can be used for various kinds of modeling, analyzing and simulating if connected to various plugins. Grasshopper provides the flexibility of changing the model inputs into a multi-parametric study. Grasshopper was used mostly for the second phase and optimization phase of this study. Plugins for Grasshopper used in this study were Ladybug and Honeybee.

### **3.2.3 Ladybug and Honeybee**

Ladybug and Honeybee are two open source plugins for Grasshopper and Rhino that can be used to explore and evaluate the environmental performance of a model. Ladybug imports standard EnergyPlus weather files (.EPW) into Grasshopper and provides a variety of 3D graphics to support the environmental analysis during the initial stages of design. Honeybee connects the visual programming environment of Grasshopper to four validated simulation engines (EnergyPlus, Radiance, DAYSIM and OpenStudio). With these simulation engines, Honeybee is capable of evaluating building energy consumption, comfort and daylighting simultaneously and synergetically (Sadeghipour Roudsari & Pak, 2013). These two plugins, make parametric modeling possible based on validated environmental data sets and simulation engines. The results can be obtained to support the early stage of high performance building design. In this study, both Ladybug and Honeybee were used to perform the daylight simulations for the base case as well as parametric studies.

### **3.2.4 Radiance**

Radiance is a backward ray tracing program that calculates light levels in a simulated daylight space at specific points taking into consideration space geometry, glazing properties, luminaire specifications, and time, date and sky conditions. The program simulates lights based on physical laws of illumination. The calculated output includes 3-channel (RGB) radiance, irradiance and glare indices that may be displayed as color images, numerical values and contour plots (Fritz & McNeil, 2016).

Radiance uses backward ray-tracing method to solve the rendering equation under most conditions, which includes specular, diffuse and directional diffuse reflection and

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<sup>1</sup> NURBS: Non-Uniform Rational B-Splines, are mathematical representations of 3-D geometry that can accurately describe any shape from a simple 2-D line, circle, arc, or curve to the most complex 3-D organic free-form surface or solid.

transmission in any combination to any level in any environment. The tool combines deterministic and stochastic ray-tracing techniques to achieve the best balance between speed and accuracy in the calculation methods. The primary advantage of Radiance over simpler lighting calculation and rendering tools is that there are no limitations on the geometry or materials that may be simulated. Radiance can be used to predict illumination, visual quality and appearance of spaces, as well as to evaluate new lighting and daylighting technologies. On the downside, Radiance is a complex tool to learn with adjustable settings and parameters that can be set according to the users and affect the quality of results obtained. Table 6 shows different Radiance parameters and their definitions, as well as values for each parameter depending on the level of detail desired.

Table 6: Radiance parameters' definition and settings

Source: Jacobs, 2016

Radiance parameters	Definition	Function	Radiance settings		
			Low	Medium	High
-ab	Ambient bounces	Controls the maximum number of diffuse bounces in the indirect calculation.	2	3	6
-ad	Ambient divisions	Controls the number of sampling rays sent from each point into the hemisphere which can increase the accuracy of the simulation.	512	2048	4096
-as	Ambient super-samples	Controls the number of extra ray used to sample areas in the hemisphere with high variability which improves accuracy of scenes with large bright and dark regions.	128	2048	4096
-ar	Ambient resolution	Sets the distance between ambient calculations by determining the maximum density of ambient values used in interpolation. It is used to avoid overloading the calculation with unimportant geometric details.	16	64	128
-aa	Ambient accuracy	Sets the maximum error permitted in the indirect irradiance interpolation. Lower values gives best accuracy.	0,25	0,20	0,10

### 3.2.5 DAYSIM

DAYSIM, developed by Christoph Reinhart in collaboration with the Fraunhofer Institute for Solar Energy Systems (ISE) and National Research Council (NRC) Canada, is a validated, Radiance-based daylighting simulation tool that models the annual amount of daylight in and around buildings based on the daylight coefficient and Perez sky models (Reinhart, 2016). By using DAYSIM, users can model dynamic facade systems, specify complex electric lighting systems and controls including manual switches, occupancy sensors and photocell controlled dimming systems. DAYSIM provides simulation outputs ranging from climate-based daylighting metrics and electric lighting energy use. DAYSIM produces hourly schedule for occupancy, electric lighting loads and shading devices which can be further coupled with thermal simulation engines, such as EnergyPlus (Reinhart,

2016). In this study, electric lighting loads generated from DAYSIM was used to analyze the electrical lighting consumption in all the studied rooms.

### 3.3 Daylight concept

This section discusses the daylighting metrics used in the study, daylight requirements in residential building based on Swedish building code and common environmental certification system, daylight levels recommendation, daylight model, simulation input and settings used throughout the study.

#### 3.3.1 The daylight factor method

The daylight factor method which was developed in the early 20<sup>th</sup> century in the United Kingdom, is a form of static daylight performance metrics (New Buildings Institute, 2016). The daylight factor method is widely used and considered as one of the simplest method to describe the amount of daylight received on a specific point in a room (Iversen, et al., 2013). Daylight factor is the ratio of the amount of the interior illuminance on a horizontal plane to the simultaneous outdoor illuminance under an unobstructed CIE standard overcast sky. The daylight factor (DF) is presented as percentage and can be expressed with the following equation:

$$DF = \frac{E \text{ indoor}}{E \text{ outdoor}} \cdot 100 [\%]$$

Where:

DF: the daylight factor of the measured point (%)

E indoor: the interior illuminance at a point on a given plane (lux)

E outdoor: the outdoor illuminance measured at the same time under an unobstructed CIE standard overcast sky (lux)

An example of DF calculation in a section of a simple room is shown in Figure 11.

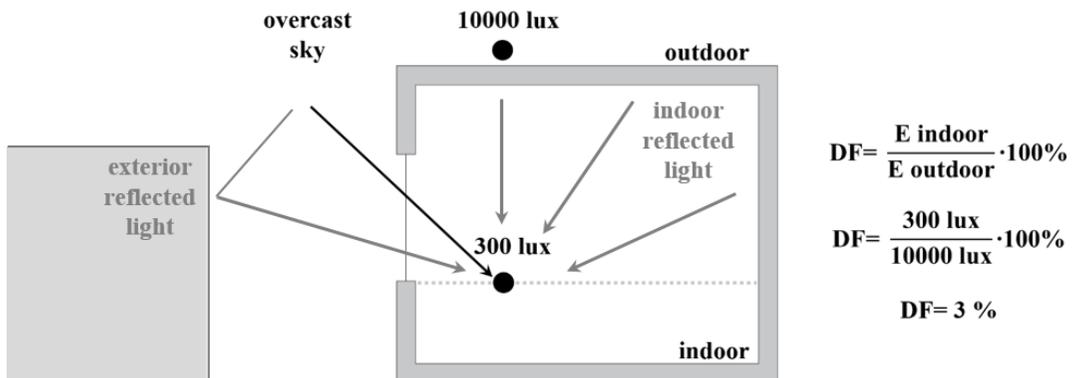


Figure 11: Example of daylight factor calculation in a simple room.

The interior illuminance is measured at work plane height and direct sunlight is excluded from the calculation. The overcast sky is used in this calculation due to the fact that it is the duller sky which represents the worst daylight conditions to be received in the evaluated space. By using the standard CIE overcast sky, DF calculation does not vary with azimuth, therefore orientation does not affect DF values (Mardaljevic, 1998). Since the overcast sky is isotropic, DF is also independent of orientation.

The daylight factor can be measured in two different ways. First, it can be measured at a specific point in the room to establish DF levels for specific tasks. The other way is to measure DF on a working plane or a specific floor area dependent on the function of the room. As stated in EN 12464-1:2011, it is recommended to use a measurement grid if the area approach is applied (Iversen, et al., 2013).

Another way to determine DF is by simulating the defined grid-based measuring points on the studied floor area using daylight simulation engines such as Radiance. To perform a reliable DF simulation, the materials surface light reflectance value (LRV) and glazing light transmittance (LT) in the studied space must be defined according to the real situation. Generally, DF are evaluated for uncluttered spaces, therefore only important structural features of the studied space are taken into consideration. Furniture are not taken into account in both DF manual measurements and simulations (Mardaljevic, 1998). Measuring points must always be unshaded from the surroundings.

Due to its intrinsic limitations, the DF method does not exist in the real world and it can never be measured, because buildings in reality never match 100 % with the assumptions used either in the manual measurements or simulations (Tregenza & Wilson, 2011). According to Cantin and Dubois (2011), other limitations of the DF method are:

- Light from the sun and non-overcast skies cannot be taken into account in the DF method.
- Impact of orientation is not affecting the calculation. So, north, south, east and west room will obtain the same DF values.
- DF values are very variable due to variable sky luminance distributions.
- The effect of mixed lighting (natural light and electrical lighting) is not taken into consideration in a DF calculation.
- The DF calculation is focused on horizontal light, which is not the only light perceived in reality.
- The DF is only applicable to areas with temperate climates where the sky is often overcast. The DF calculation has no relevance in very sunny climates.

Apart from the limitations mentioned before, the DF method also exhibits some benefits. Tregenza and Wilson (2011) lists the benefits below:

- The average DF can be used as an indicator of the appearance of a room (see Table 7). This is mostly applicable for areas in temperate climates, where particular rooms such as offices and classrooms, appear to have a good consistency in the relationship between average daylight factor and subjective assessment of daylighting.
- The average DF is a good basis for the early architectural design decisions. By adopting a particular value based on minimum DF value of certain room types (see

Table 8), the required window area can be determined. This will then influence the façade design of the building.

- The DF results can produce predictions of daylight availability in a room.

In addition, due to its relation to outdoor illumination, DF provides an indication of contrast between indoor and outdoor. As mentioned before, Table 7 presents the appearance of a room based on the average DF and Table 8 shows the minimum DF for different room types.

Table 7: Average daylight factor in a room compared with visual character of the room in temperate climate by using side windows.

Source: Tregenza and Wilson, 2011

Average DF	Rooms without electric lighting	Rooms with daytime electric lighting
1%	Gloomy appearance, harsh contrast with the view outside. Electric lighting is needed.	Electric lighting appears dominant.
2%	Areas distant from a window may appear to be underlit.	Appearance of daylit room even if electric lighting is the main light source for the task.
5%	The room appears to be brightly daylit. Visual and thermal discomfort may occur with large window areas.	Daytime electric lighting is hardly needed.
10%	The character of semi-outdoor space where the room is too bright and overlit. Visual and thermal discomfort occur.	Daytime electric lighting is unnecessary.

Table 8: Typical minimum DF based on room types.

Source: Lechner, 2008

Type of space	Minimum DF (%)
Art studios, galleries	4-6
Factories, laboratories	3-5
Offices, classrooms, gymnasiums, kitchens	2
Lobbies, lounges, living rooms, churches	1
Corridors, bedrooms	0,5

The DF method is commonly used as a threshold in some building regulations and certifications which is further discussed further down.

### 3.3.2 The daylight autonomy method

In reality, daylight is climate and time dependent and due to the limitations of the DF method, climate-based daylight metrics were developed to establish the annual daylight performance for a given space using hourly or sub-hourly calculations of the illuminance on every point of the measured work plane (Reinhart & Wienold, 2011). Climate-based daylight modelling (CBDM) is defined as the prediction of various luminous quantities: irradiance, illuminance, radiance and luminance, using both the sun and sky conditions that are determined by the standard meteorological datasets (Mardaljevic, 2006).

The daylight autonomy (DA) is one of the widely used CBDM which evaluates the daylight quantity associated with any given hour, specific geographic location and sky condition on

an annual basis. By using DA, it is possible to process a large amount of illuminance data up to 4380 hours for each point of the studied work plane. In this metric, the illuminance data is analyzed by establishing a schedule for a study and a suitable illuminance level for specific type of a visual task assigned in the studied work plane (Cantin & Dubois, 2011).

DA is expressed as the percentage of the year during which there is a minimum daylight illumination threshold reached (Reinhart, et al., 2006). The specific illuminance level is chosen based on the visual task and the required amount of daylight needed to perform the task. These values are usually obtained from standards, building regulations or some value to fulfill building certifications such as LEED and BREEAM. Daylight illumination levels are dynamic and time dependent, the influence of location and orientation strongly affect the daylight availability in the interior space. According to Mardaljevic (2006), in using DA method, climate file of a specific location is used to incorporate the global, diffuse and direct irradiance measurements that are used to obtain the luminance sky distribution, as well as to incorporate the global, diffuse and direct illuminance as hourly data. It is important to use the suitable climate file for each studied project.

### **3.3.3 Daylight requirements in residential buildings**

Every human has a unique perception of daylight conditions in buildings. Visual perception varies between individuals mainly due to age, gender, cultural background, shape of face, eyes, etc. The Illuminating Engineering Society of North America (IESNA) developed an illuminance level recommendation based on activities for every building types and rooms. The residential building lighting levels recommendation are presented in Table 9.

Table 9: Illuminance recommendation in residential buildings.

Source: IESNA Lighting Handbook 9<sup>th</sup> Edition, 2000

<b>Residential</b>	<b>Horizontal Illuminance</b>	<b>Vertical Illuminance</b>
General lighting	50 lux	
Conversation, relaxation, entertainment	30 lux	
Circulation	30 lux	
<b>Specific visual task</b>		
Dining	50 lux	
Handcrafts and Hobby		
Crafts	300 lux	50 lux
Sewing	500 lux	100 lux
Work bench	1000 lux	300 lux
Easel hobbies		300 lux
<b>Kitchen range</b>		
Cooking	500 lux	100 lux
Kitchen Sink		
Difficult Seeing	500 lux	100 lux
Cleaning Up	300 lux	50 lux
<b>Kitchen counter</b>		
Cutting	500 lux	100 lux
General	300 lux	50 lux
Laundry	300 lux	30 lux
Music	300 lux	50 lux
<b>Reading</b>		
In a chair (casual)	300 lux	50 lux
In a chair (serious)	500 lux	100 lux
In a bed (casual)	300 lux	50 lux
<b>Reading at desk</b>		
Casual	300 lux	30 lux
Serious	500 lux	100 lux
Table games	300 lux	50 lux

From this table, the average illuminance level that was taken as a threshold value for the annual daylight simulation and calculation for the electrical lighting consumption was 150 lux. The value of 150 lux was based on having an average value for spaces such as living room (low need of visual task of 30-50 lux for conversation and relaxation), kitchen (300-500 lux), workshop (300-500 lux), based on the IESNA guideline in Table 9 ( Illuminating Engineering Society of North America, 2000). The threshold value of 150 lux is recommended for general home lighting (excluding corridor), but also for spaces to perform

easy work or working areas where visual tasks are only occasionally performed (The Engineering Toolbox, 2016).

### **3.3.4 Daylight in building certifications**

Building environmental certification systems present various criteria for designing environmentally conscious buildings in many different aspects and one of the considered aspect is daylight prerequisites of the spaces in the building. The widely known rating systems, BREEAM and Miljöbyggnad in Sweden, state different criteria regarding the daylight conditions and each system has its own prerequisites regarding the required values, measurement methods and acceptable daylight metrics in the certification process.

#### **Swedish standards**

There are three Swedish regulations and standards with daylight recommendations, which are Boverket's Building Regulations (BBR), the Swedish standard of the European standard of lighting in work spaces EN 12464-1 and the Swedish standard SS 914201. BBR provides a general recommendation on daylighting which refers to the SS-EN 12464-1 which is mainly for office buildings, rather than residential buildings. It is stated in the most updated regulations, BBR 22, that rooms that are occupied more than occasionally shall be designed and oriented in a way so that the room has a good access to direct daylight. General recommendations are also given for the calculations of the glazed area using a simplified method in accordance with the Swedish standard SS 914201 which explains the method for the control of the required window glass area, valid for room sizes, window, sash, window placement and shielding angles as specified in the standard. It is also stated that according to this standard, the minimum window area of a room should be at least 10% of the floor area, which normally corresponds to a minimum DF of 1% at a point located 1 m from the darkest wall halfway in the room (Boverket, 2015). The requirement applies to all buildings, for rooms or separate parts of rooms that have a function for people to stay for more than temporarily, such as daily socializing, cooking, sleeping and resting. BBR also provides another method for calculating the window glass area with daylight factor which refers to "Räkna med Dagsljus", a publication by Löfberg (1987).

#### **BREEAM**

BREEAM which stands for Building Research Establishment's Environmental Assessment Method, is one of the world's leading and most widely used environmental assessment methods for buildings (BREEAM-SE, 2013). It sets the standard for best practice in sustainable design and commonly used to describe a building's environmental performance. BREEAM-SE, as one of the commonly used rating system in Sweden, is a Swedish adaptation of BREEAM Europe Commercial 2009 and is connected with relevant standards and rules in the environmental and energy areas. BREEAM-SE was developed by the Swedish Green Building Council (SGBC) in collaboration with BRE Global. In BREEAM, daylight assessment are included in the Health and Wellbeing category.

#### **Miljöbyggnad**

Miljöbyggnad is Swedish building rating system which is developed for Swedish conditions. The certification system can be used for new as well as existing buildings. Qualities of energy, indoor environment and materials are taken into consideration in the rating system. There are three categories, which are bronze, silver and gold (Sweden Green Building

Council, 2014). Almost all new building developments in Sweden are now aiming for Miljöbyggnad’s Gold rating.

More details about the prerequisite values of each building standards and certification systems that are widely used in Sweden are presented in Table 10.

Table 10: Comparison of building standards and certifications used in Sweden.

<b>Building standard</b>			
<b>BBR</b>	<b>Minimum Point DF*</b>		
	≥1,00%		
<b>Building certifications</b>			
<b>Miljöbyggnad</b>	<b>Point DF*</b>		
	<b>Bronze Level</b>	<b>Silver Level</b>	<b>Gold Level</b>
	≥ 1,00%	≥ 1,20%	≥ 1,20%*
<b>BREEAM Sweden</b>	<b>For latitude of 55° to 60°</b>		
	<b>Average DF**</b>		
	<b>First credit</b>	<b>Exemplary level</b>	
	All buildings	Single-storey buildings	Multi-storey buildings
	2,10%	4,20%	3,15%
	<b>Uniformity Ratio</b>		
	0,4		
	<b>Minimum Point DF</b>		
	<b>First credit</b>	<b>Exemplary level</b>	
	All buildings	Single-storey buildings	Multi-storey buildings
	0,84%	1,68%	1,26%
<b>BREEAM International</b>	<b>For latitude of 55° to 60°</b>		
	<b>Average DF**</b>		
Kitchen	2,10% ***		
Living areas	1,60% ***		
	<b>Uniformity Ratio</b>		
	0,3		
	<b>Average daylight illuminance</b>	<b>Minimum daylight illuminance at worst lit point</b>	<b>Occupancy time</b>
Kitchen	100 lux	30 lux	3450 hours per year
Living areas	100 lux	30 lux	3450 hours per year

Measuring criteria:

\* SS 914201 - Point is taken 1,00 m away from the darkest wall, 0,80 m above the floor, halfway from the exterior envelope.

\*\* Measurements are normally taken as 0,70 m above the floor.

\*\*\* 80% of the room has a view of sky from desk or table top height which is 0,85m in residential buildings.

### 3.3.5 Daylight model

To simplify the model for the daylight simulations in this study, each of the apartment models was simplified to only the studied spaces, such as the living room, kitchen and workshop along with the sunspace and balcony. Three steps of simplifications were achieved to study the impact of having a sunspace by firstly removing the sunspace and balcony, then the sunspace and balcony were attached to the apartment and at last the sunspace and balcony were simplified to simple rectangular boxes to be further studied and varied in the parametric study phase.

Figure 12 presents the daylight model for the west apartment. The simplifications on the east apartment also utilized the same methods.

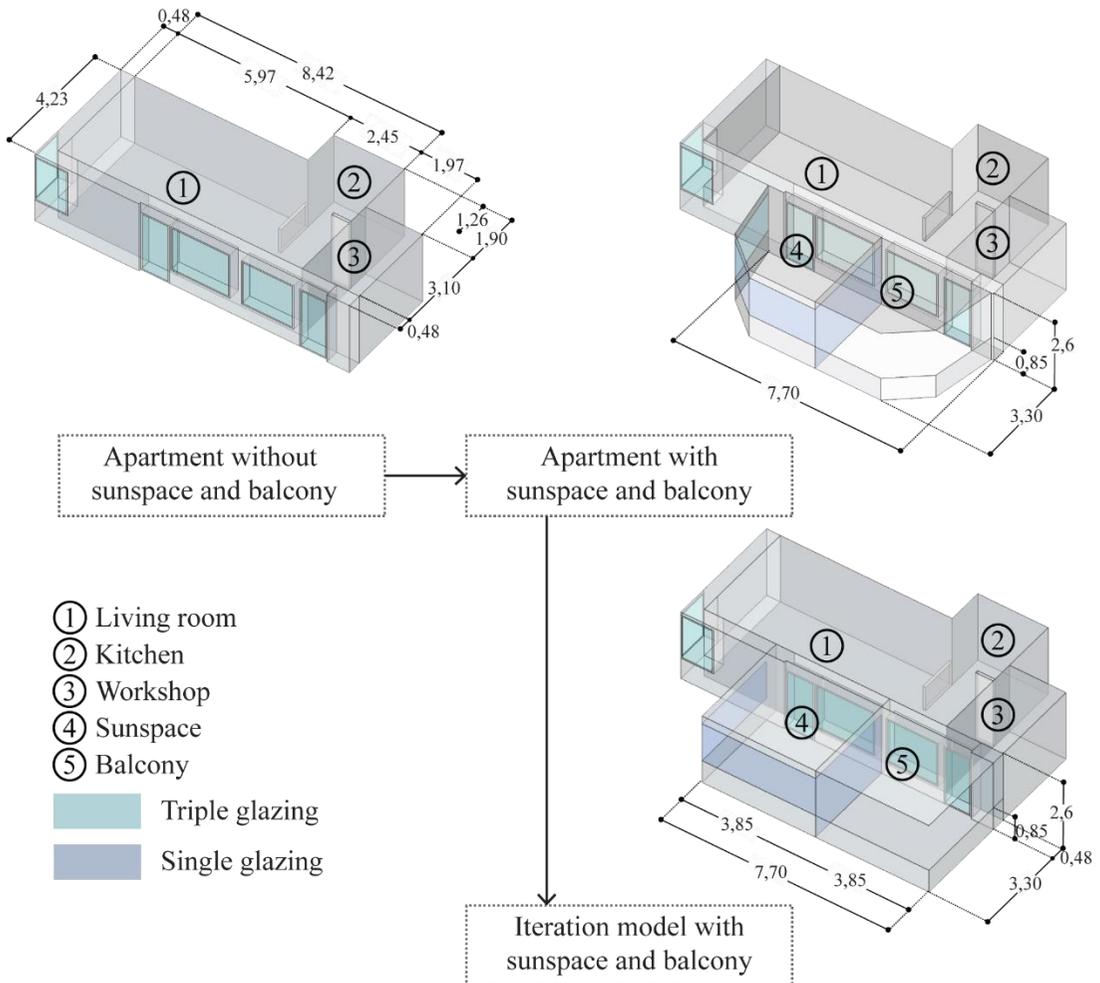


Figure 12: Simplified daylight model for the west apartment.

The apartment that does not have sunspace and balcony is called no sunspace and balcony model, the apartment with sunspace and balcony is called real case model and the iteration model with sunspace is called simplified model throughout this thesis.

The apartment had three different zones (living room, kitchen and workshop) with different occupancy schedules and electrical lighting loads that were determined by the space area and the lighting plan. Due to simplification purposes, all of these three zones were assumed to have the same illuminance threshold value which was 150 lux as mentioned previously.

### 3.3.6 Simulation input and settings

After preparing the model, to conduct both static and dynamic daylight simulations, the surface properties of the studied apartments needed to be set based on the actual building finishing of the Greenhouse project, as described in Table 11.

Table 11: Surface properties

Building Component	Material Type	Light Reflectance Value (%)	Light Transmittance Value (%)	Light Transmissivity Value (%)
Interior wall	Opaque	70	-	-
Interior ceiling	Opaque	80	-	-
Interior floor	Opaque	30	-	-
Glazing, triple-pane	Glass	-	59	64
Balcony wall	Opaque	70	-	-
Balcony floor	Opaque	20	-	-
Balcony ceiling	Opaque	20	-	-
Balcony glazing, single pane	Glass	-	90	98
Ground reflectance	Opaque	20	-	-
Surrounding building	Glass	30	-	-

Besides the surface properties, the next step was to set the simulation settings based on the results accuracy, as explained previously in Table 6. The simulation settings are presented in Table 12.

Table 12: Daylight simulation settings.

Parameter	Input
Climate file	Copenhagen, Denmark
<b>Static daylight simulation</b>	
Type of sky	CIE Overcast sky
<b>Dynamic daylight simulation</b>	
Illuminance threshold	150 lux
Occupancy schedule	See Table 4.
Electrical lighting load	3 W/m <sup>2</sup>
<b>Radiance settings</b>	
-ab	6
-ad	2048
-as	2048
-ar	64
-aa	0,2
<b>Grid settings</b>	
Simulation grids	0,5 m x 0,5 m
Point DF	1,00 m away from the darkest wall, 0,80 m above the floor, halfway from the exterior envelope

### 3.4 Parametric studies and studied parameters

To answer the second research question which was to develop sunspace design guidelines for improving daylighting performance, a series of parametric studies was conducted. The east and west apartments on the fourth and twelfth floor were studied. The parametric study diagram is presented in Figure 13.

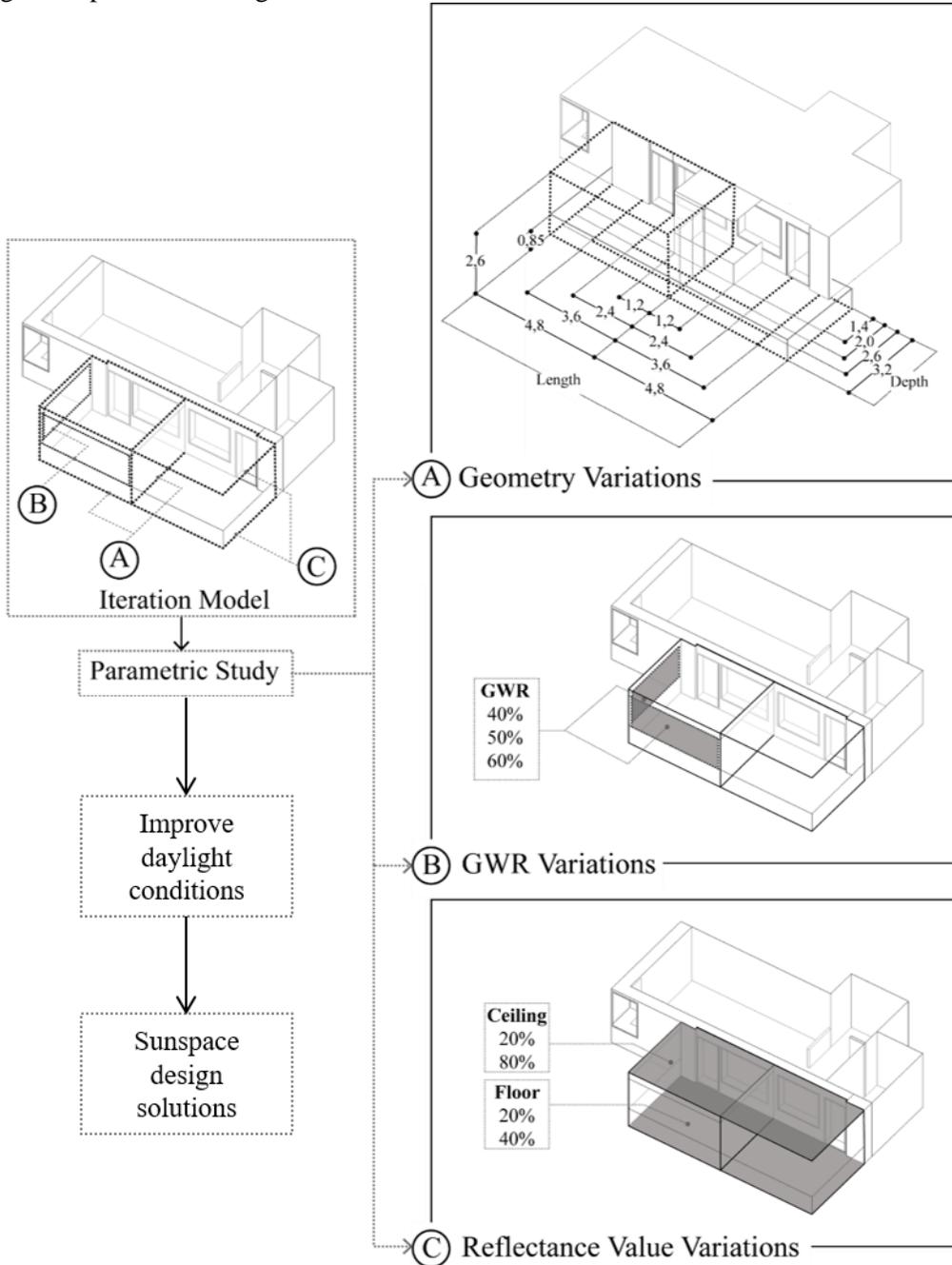


Figure 13: Parametric study diagram.

As shown in Figure 13, the parametric study took into account three different parameters to be varied, i.e, the sunspace and balcony geometry, the glazing-to-wall-ratio (GWR) and the light reflectance values (LRV) of the sunspace and balcony's floor and ceiling. First, the geometry had four different depths from 1,4 m to 3,2 m (with 0,6 m difference in each step). The minimum depth was assumed taking into account that a person needs 0,8 m to circulate in the sunspace balcony with an addition of 0,6 m of the cultivation area that was intended to be kept in the sunspace and balcony to maintain the Greenhouse urban-farming concept. Besides the depths, the lengths had also four different variations which started from 1,2 m up to 4,8 m each for the sunspace and balcony with the cultivation area included.

To study the effect of varying the GWR, three different GWR values were investigated. The maximum value could only reach 60% since the idea was to keep the cultivation area below the height of 0,85 m. The floor and ceiling of the sunspace and balcony reflectance values were also varied since the actual building only used raw concrete as the material. The values were then raised to 0,4 for the floor and 0,8 for the ceiling.

All of the variations were then combined into 96 different cases for each apartment which were simulated and analyzed individually. The average daylight factor (DF), average daylight autonomy (DA), point DF, daylight uniformity and electrical lighting use of every case were then analyzed in order to select the best performing cases based on the daylight conditions as the design solutions for each of the studied apartments.

## 4 Results

This chapter presents the selected results of this study that show the impact of sunspace design on daylight conditions of the adjacent living spaces. There are sections that consist of the base case study which was conducted to investigate the impact of the actual sunspace design as built in the Greenhouse project on the daylight conditions in the living room, kitchen and workshop. Then, there are also sections which present the results of the parametric studies regarding the sunspace geometry (length and depth), the sunspace glazing area (GWR) and the sunspace light reflectance value (LRV) on the daylight conditions in the living spaces. In the end, the best performing cases are selected and presented as the sunspace design solutions.

### 4.1 Base case study

This section presents the initial studies of the sunspace design of the Greenhouse project. As mentioned before, for each apartment, the sunspace and living spaces were modelled similarly as the actual apartment building. The impact of having sunspace on the daylight conditions and energy performance were studied by simulating and comparing two different building conditions. First, the simulations were conducted as if the whole apartment units did not have any balconies and sunspaces attached to it. Then, the sunspace and balcony were added and the simulations were performed again. As a part of the iteration that was used as a base of the parametric study, a simplified iteration model was also simulated and compared as the benchmark case for further parametric studies. The results of the different design conditions were compared and analyzed based on the daylight conditions.

The sections below presents the average DF, transversal DF, DF uniformity ratio, point DF, average DA and electrical lighting consumption for the studied living spaces.

#### 4.1.1 Sunspace and its effect on the average daylight factor

The following figures present the comparison between the average DF of the living room, kitchen and workshop for cases with and without sunspace as a base case study. The different apartment's floor heights (fourth and twelfth floor) and apartment's orientations (west and east) are also compared in the following figures.

Figure 14 presents the average daylight factor in the living room in three different building conditions.

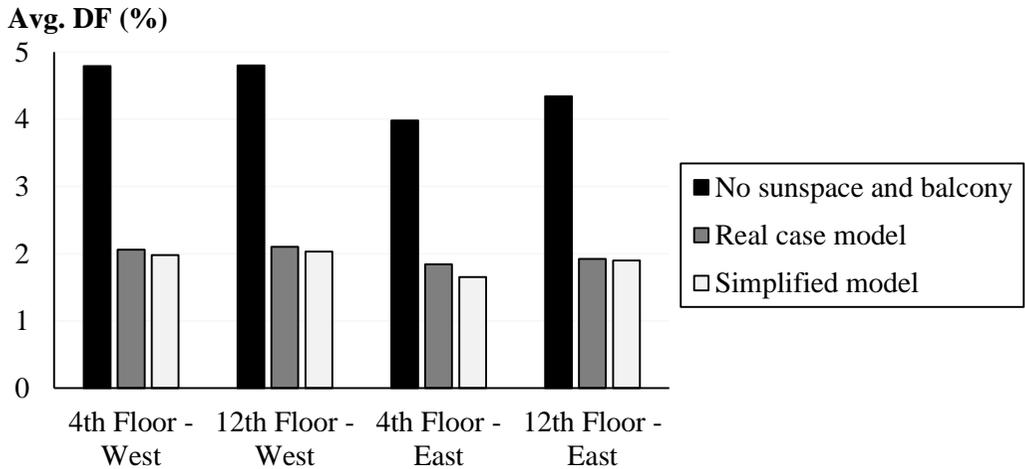


Figure 14: Average daylight factor in the living room.

Figure 14 shows how the average daylight factor in the living room was reduced after the sunspace and balcony were added. On the west oriented apartments, both on the fourth and twelfth floor, the average DF was reduced from 4,8% to almost 2,0%. For the east-facing apartments, the average DF was reduced from 4,0% to 1,8% on the fourth floor and from 4,3% to 1,9% on the twelfth floor. It can be seen that adding the sunspace and balcony reduced the living room’s average DF between 50 to 60% in all cases. The simplified model for each studied case had close values to the real case model with a maximum difference of 5% in the simulated average DF. This points out that the iteration model gave approximately same values as the initial building design (real case model), which was important in starting a parametric study which can be comparable to the real case.

Besides the living room, the kitchen was also studied and the results are shown in Figure 15.

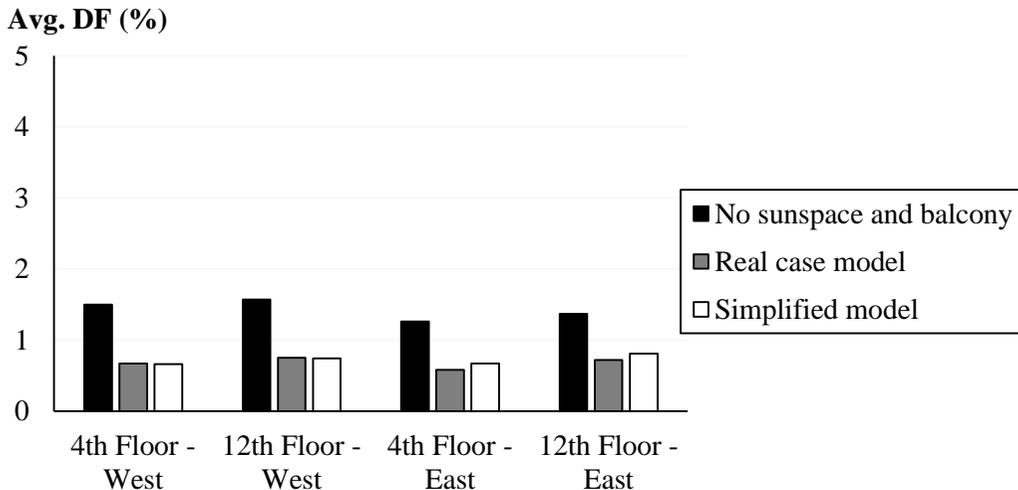


Figure 15: Average daylight factor in the kitchen.

Figure 15 shows that the kitchen in all floor heights and orientations had relatively close values in each of the conditions. For the west-facing apartments on the fourth and twelfth floor, the average DF in the kitchen was reduced from 1,6% to 0,7%. On the east side, the average DF was reduced from 1,2% to 0,6% on the fourth floor and from 1,4% to 0,7% on the twelfth floor, when the sunspace and balcony were added. The same trend in the living room also occurred in the kitchen that the average DF was reduced by at least 50% when the sunspace and balcony were attached to the building. For the simplified model on the east side, the average DF values slightly increased for both floors.

The workshop was also studied regarding the effect of the addition of sunspace and balcony which is presented in Figure 16.

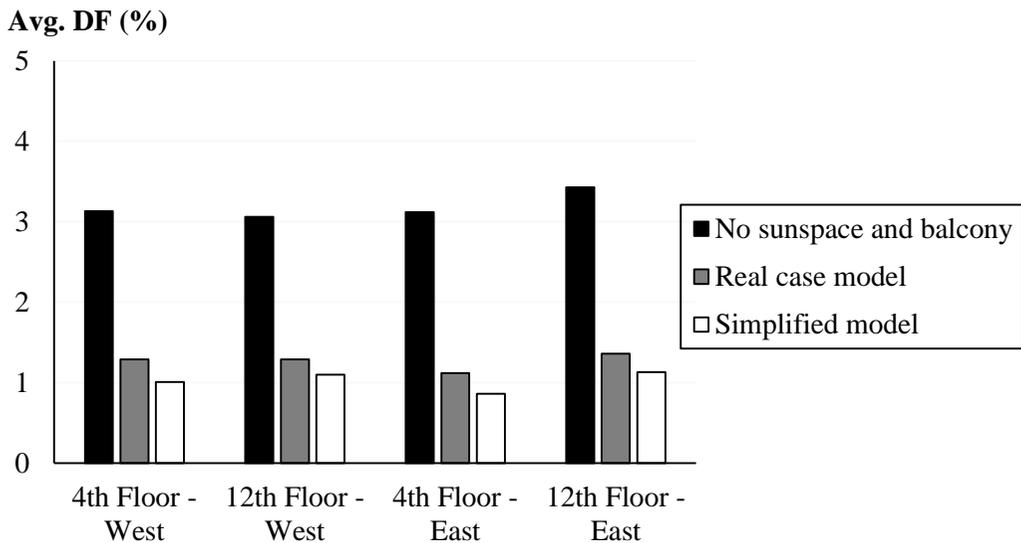


Figure 16: Average daylight factor in the workshop.

In Figure 16, it can be seen that by adding the sunspace and balcony, the average daylight factor on the west-facing apartments were reduced by up to 60%. Without adding sunspace and balcony, the average DF in the west-facing workshop could reach up to 3,1%, whereas when the sunspace and balcony were added, the value dropped to 1,3%. As on the east-facing apartments, the average DF on the fourth floor was reduced from 3,1% to 1,1% and from 3,4% to 1,4% on the twelfth floor when the sunspace and balcony were added. The average DF on the east facing apartments was reduced in the range between 60 to 64%, depending on the floor heights. For the iteration model, the values decreased slightly between 5 to 8%, which was still in the acceptable range.

#### 4.1.2 Sunspace and its effect on the transversal daylight factor

In order to investigate in detail how the addition of sunspace and balcony to each studied apartments affected the daylight conditions in the living area, two sections showing the DF transversally across the room for each orientation. The sections were taken from the center of the openings in the living room. Section A1 and B1 represent the living room of the west

and east apartment, whereas Section A2 and B2 represent the living room and kitchen for the west and east apartments. The results are shown in Figure 17 and Figure 18.

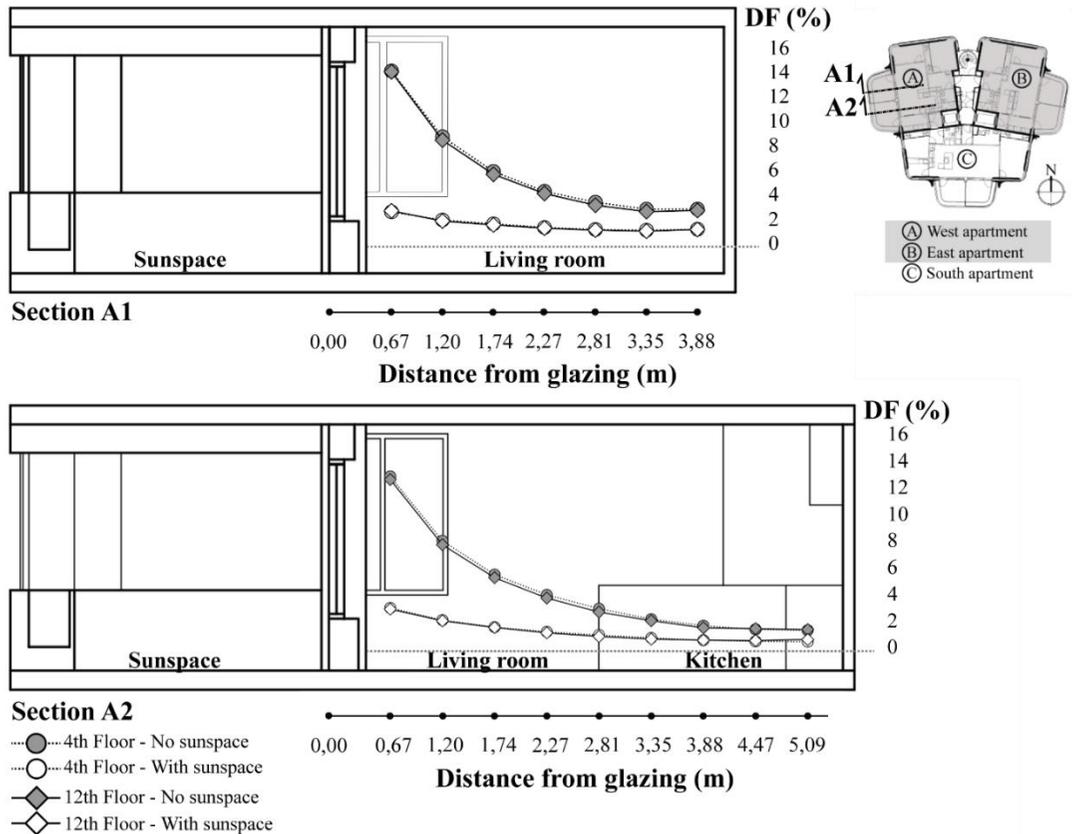


Figure 17: West apartment section and DF points.

Figure 17 shows how the daylight factor on each point dropped when the sunspace and balcony was added to the building in the living room (Section A1). The biggest drop was found on the areas nearest the windows where the DF was reduced by 80% on both floors when the sunspace was added. Looking at Section A2, which shows the living room and kitchen, the DF values at the back of the room (kitchen area) did not have an extreme drop compared to the areas near the windows, but the daylight levels were still reduced by at least 50%. This trend happened on both lower and higher apartment.

Figure 18 shows how the daylight levels were reduced in the living room and kitchen of the east-facing apartments when the sunspace and balcony were added to the building.

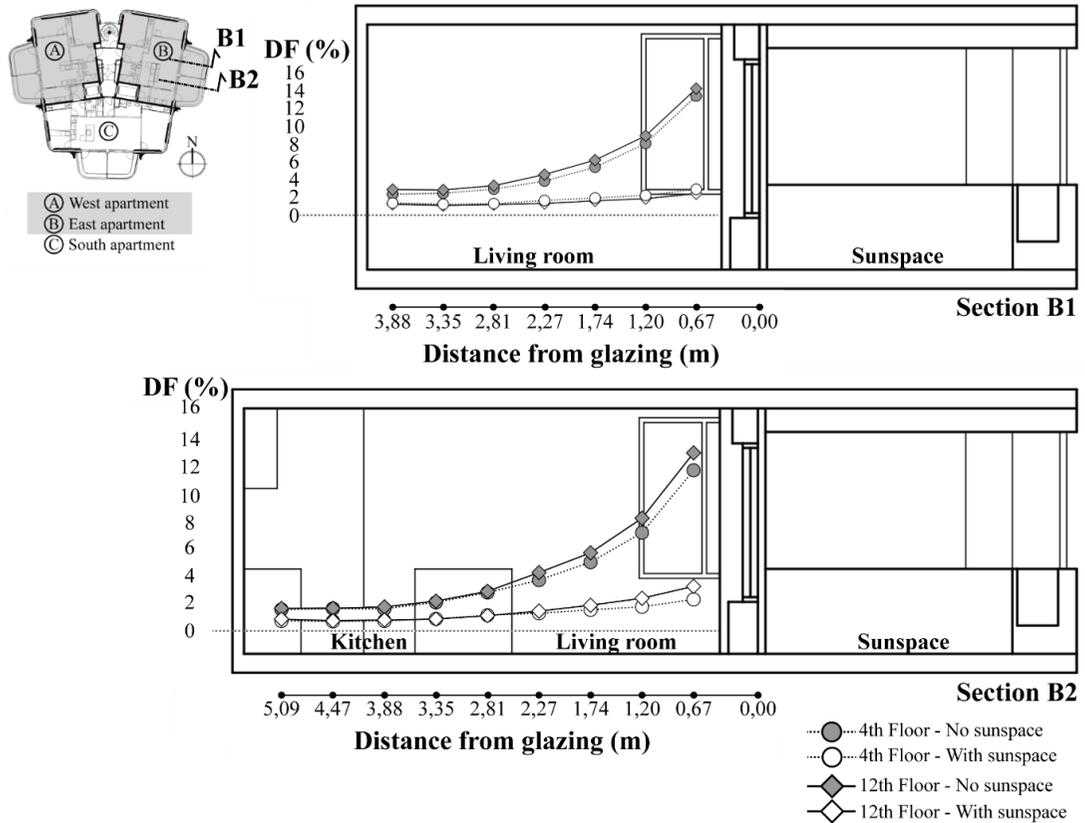


Figure 18: East apartment section and DF points.

It can be seen from Figure 18 that the twelfth floor had higher DF values on each point compared to the fourth floor, especially in the areas near the windows. On the fourth floor, the value dropped by 81% on the nearest point to the glazing when the sunspace and balcony was added to the building, whereas on the twelfth floor, 75% of the daylight was reduced. For the rest of the points, the DF values were reduced by the range of 48 to 70%, depending on the distance to the glazing.

For both orientations, it can be seen from Figure 18 and 19 that the highest reduction of DF occurred in the areas near the windows. This was because the areas near the windows received daylight mostly from the sky and more affected by the coverage of the sky close to zenith, therefore when the sunspace and balcony were added, this part of light that entered the space was blocked. For the back of the room, the amount of light received is from the horizon and light reflected from the surrounding surfaces, which also explains why the light deeper in the space was more uniform compared to the areas near the window. Looking at the previous figures, the daylight uniformity in the studied space increased when the sunspace and balcony were added to the apartment.

### 4.1.3 Sunspace and its effect on the point daylight factor

Figure 19 presents the point DF value in each studied apartments.

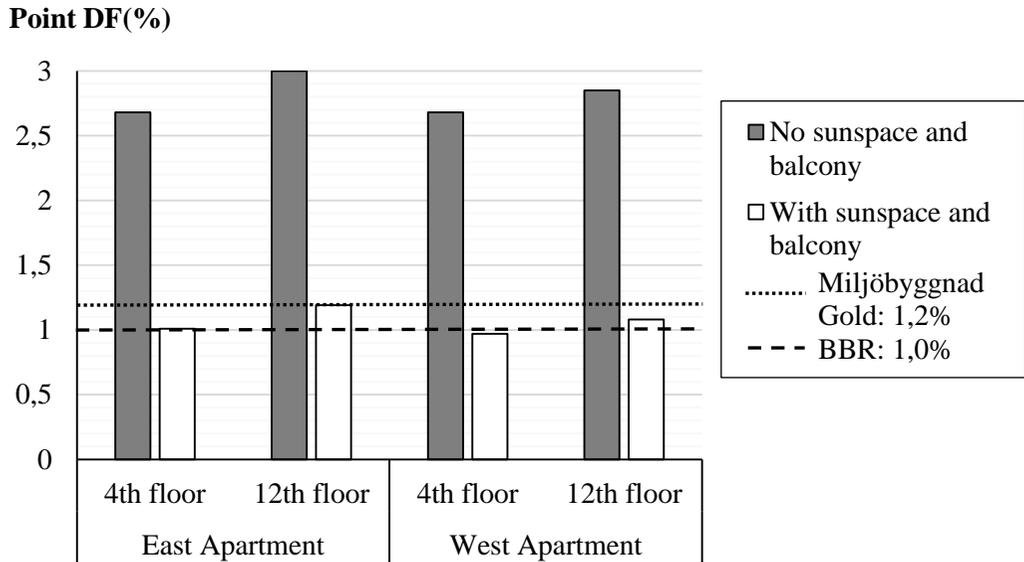


Figure 19: Point DF in the studied apartments.

It can be observed from Figure 19 that the point DF in all studied apartments were reduced by at least 60% when sunspace and balcony were added to the apartment building. Regarding the building requirements, for BBR, almost all apartments, except the fourth floor of the west apartment, reached the 1,0% point DF. For the Miljöbyggnad Gold requirement, all the apartments were below the 1,2% point DF requirement.

The point DF values were different between the east and west apartment. This can be explained by the slightly different geometry in the living space, as well as the position of the point DF.

#### 4.1.4 Sunspace and its effect on the daylight autonomy

The following figures present the daylight autonomy (DA) analysis results for the living room, kitchen and workshop. Each case with different building conditions, apartment’s floor heights and orientations are presented in each figure. The DA is based on the occupancy of the studied space and illuminance threshold of 150 lux, which were explained before in the previous chapter.

Figure 20 shows the average daylight autonomy in the studied living rooms, comparing the conditions with and without sunspace, as well as the iteration model for all studied orientations and different floor heights.

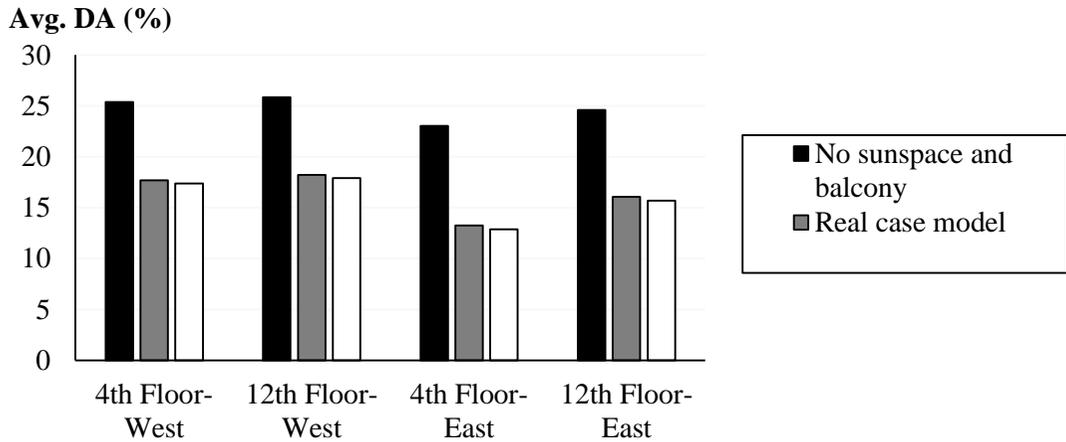


Figure 20: Average daylight autonomy in the living room.

It can be observed from Figure 20 that the twelfth floor west-facing apartment had the highest average DA in the living room compared to the other apartments in all conditions, whereas the lowest average DA occurred in the fourth floor east-facing apartment. For the west-facing apartments, the average DA in the living room was reduced from 25,4% to 17,7% for the fourth floor and from 25,8% to 18,2% on the twelfth floor when the sunspace and balcony were added. On the east side, the average DA in the living room was reduced from 23% to 13,3% on the fourth floor and from 24,6% to 16,1% on the twelfth floor. Adding sunspace and balcony to the apartment tower reduced the average DA in the living room by 30% on the west side for both floor heights, 43% on the lower east apartment and 35% for the higher east apartment. For the simplified model, the average DA value for the four studied apartments slightly decreased by 2%, which was a good threshold value to be comparable with the parametric study results.

The annual daylight simulation was also performed for the kitchen in four studied apartments. Figure 21 shows the average DA in the kitchen for the studied apartments for conditions with and without the addition of sunspace and balcony.

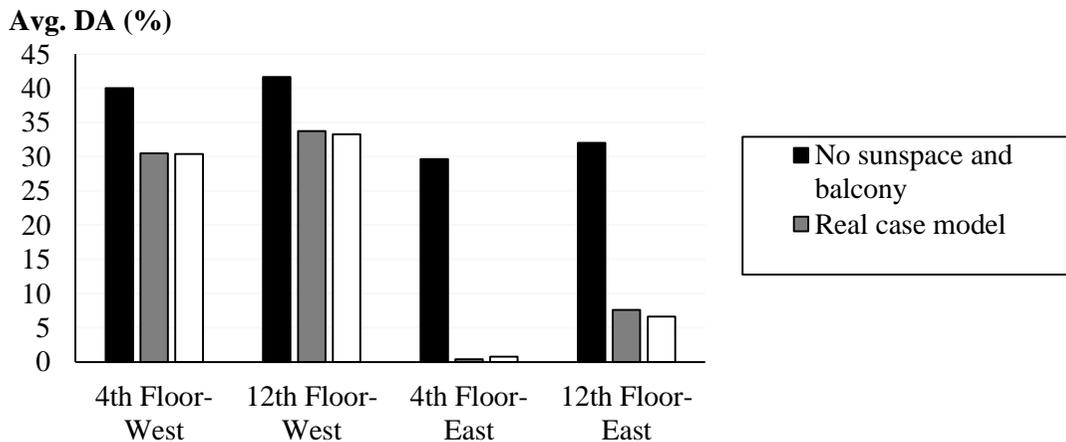


Figure 21: Average daylight autonomy in the kitchen.

As shown in Figure 21, the west-facing apartment could reach average DA of 150lux in the kitchen during the occupied time up to 40% on the fourth floor and 41,6% on the twelfth floor when the building was not attached to a sunspace and a balcony. At least a reduction of 24% occurred in the fourth floor’s kitchen when the sunspace and balcony was added, resulting in 30,5% average DA. Meanwhile, on the twelfth floor, the average DA was reduced by 19%, resulting in 33,8% average DA when the sunspace and balcony were added. On the east side, lower values can be observed in Figure 22. With no sunspace and balcony, the east-facing apartments could reach average DA in the kitchen up to 29,6% on the fourth floor and 32% on the twelfth floor. When the sunspace and balcony were added, the values dropped to 0,4% for the fourth floor and 7,6% on the twelfth floor, which means that the fourth floor’s kitchen for the east-facing apartment had almost never fulfilled the required threshold during the occupied period. This occurred mostly due to the occupancy hours assumed for the apartments.

The average DA in the workshop was also investigated based on the occupancy schedule assigned and the results are presented in Figure 22.

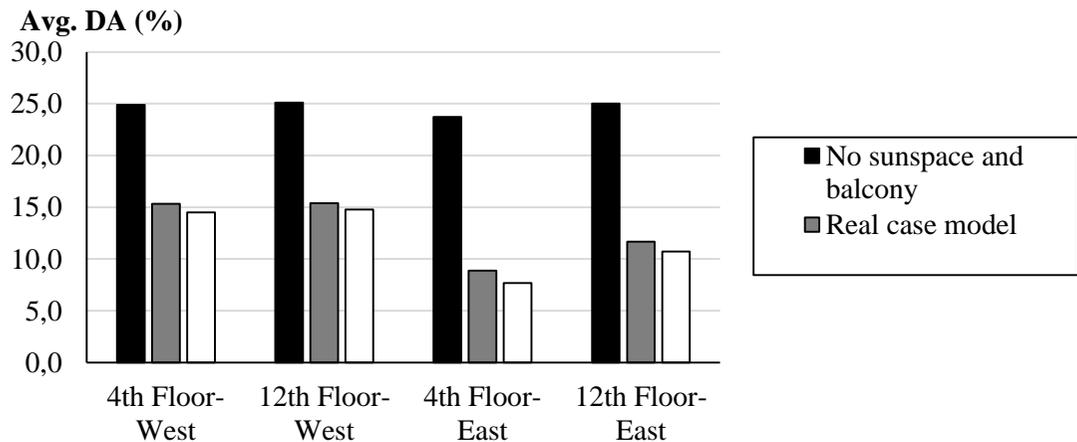


Figure 22: Average daylight autonomy in the workshop.

It can be seen from Figure 22 that the average DA in the workshop for all four studied apartments fell in the same range between 23% to 25% when there were no sunspace and balcony added to the building. The values dropped when sunspace and balcony were added, resulting in 15,3% for west-facing fourth floor workshop, 15,4% for west-facing twelfth floor workshop, 8,9% for east-facing fourth floor workshop and 11,7% for east-facing twelfth floor workshop. Looking at these values, the average DA in the workshop was reduced by at least 38% on the west side and 53% on the east side.

#### 4.1.5 Sunspace and its effect on the electrical lighting

The electrical lighting consumption was calculated in each room based on the occupancy schedules specified for each room, lighting level of 150 lux and electrical lighting load of 3 W/m<sup>2</sup>, assuming that the apartments are using LED lighting throughout the apartments.

The annual electrical lighting consumption in the living room, kitchen and workshop in the four studied apartments were also investigated and the results are presented in Figure 24, Figure 25 and Figure 26.

**Electrical lighting (kWh/m<sup>2</sup>)**

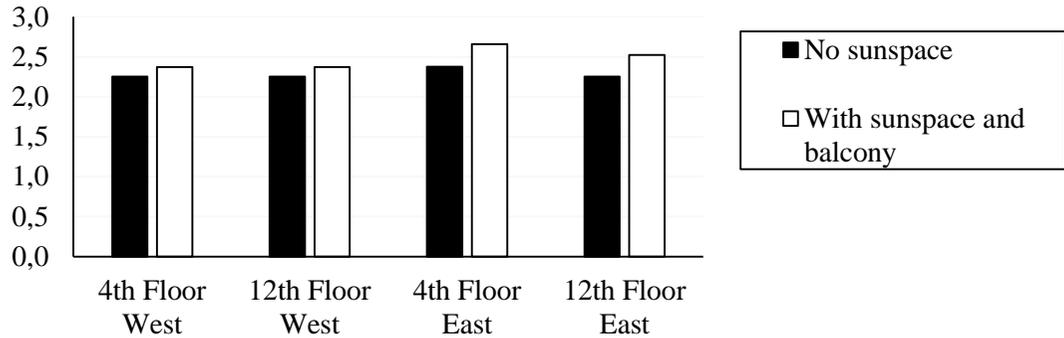


Figure 23: Annual electrical lighting use in the living room.

As seen on Figure 24, without having any sunspaces or balconies, both of the west apartments had annual electrical lighting consumption of 2,3 kWh/m<sup>2</sup>, year in the living room, whereas the east apartments had 2,4 kWh/m<sup>2</sup>, year on the fourth floor and 2,3 kWh/m<sup>2</sup>, year on the twelfth floor. Then, the electrical lighting use increased by 5% for the west side apartments and 12% for the east side apartments when the sunspace and balcony were added to the building.

**Electrical lighting (kWh/m<sup>2</sup>, year)**

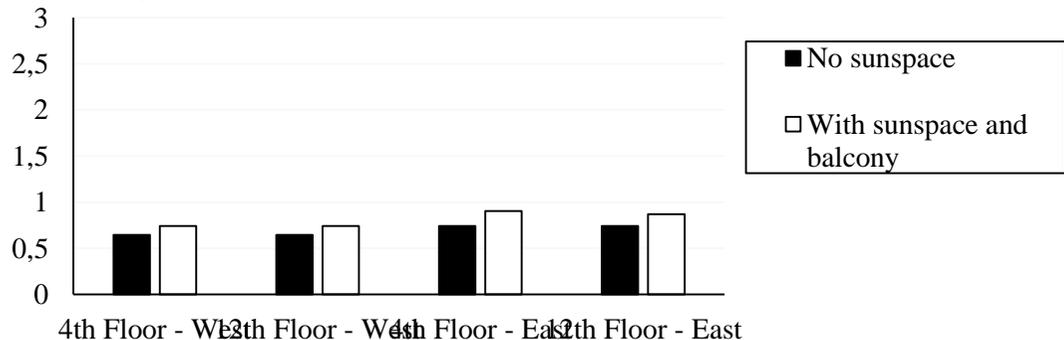


Figure 24: Annual electrical lighting use in the kitchen.

It can be observed from Figure 24 that the kitchen electrical lighting use on both of the west side apartments increased from 0,6 kWh/m<sup>2</sup>, year to 0,75 kWh/m<sup>2</sup>, year when the sunspace and balcony were added, whereas the east apartments increased from 0,75 kWh/m<sup>2</sup>, year to 0,9 kWh/m<sup>2</sup>, year on the fourth floor and to 0,87 kWh/m<sup>2</sup>, year on the twelfth floor.

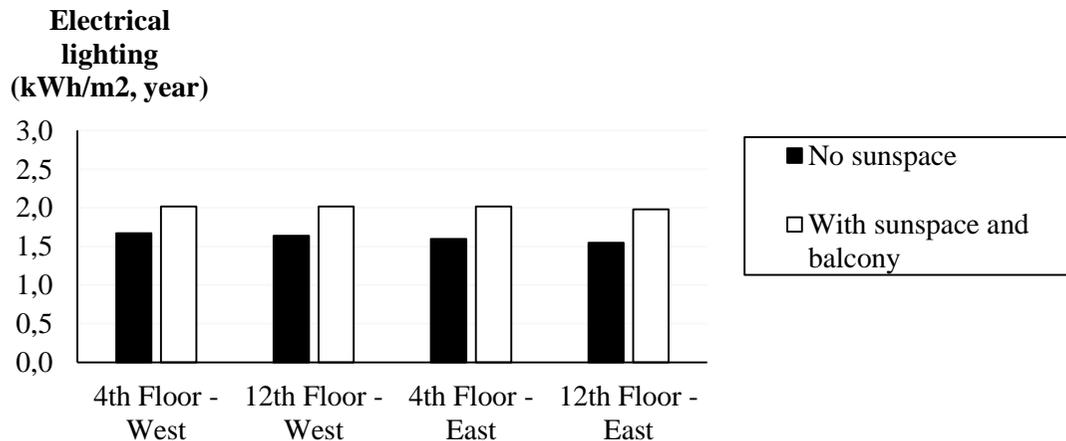


Figure 25: Annual electrical lighting use in the workshop.

Figure 25 shows how the electrical lighting use in the workshop increased when the sunspace and balcony were added to the building. For the west apartments and the fourth floor east apartment, it increased from 1,6 kWh/m<sup>2</sup> to 2,0 kWh/m<sup>2</sup>, annually. On the twelfth floor workshop of the east-facing apartments, it increased from 1,5 kWh/m<sup>2</sup> to 2,0 kWh/m<sup>2</sup>, annually.

## 4.2 Daylight parametric study

This section presents the results of the studied parameters that were simulated and analyzed in order to find the optimal sunspace design regarding the daylight performance in the living spaces of the four studied apartments. The purpose of the sunspace and balcony design iterations was to improve the daylight conditions in the living spaces for the four studied apartments. The overall results and specific results for each studied parameters are presented in the following sections.

### 4.2.1 Cases reaching 1,2% point DF

In Sweden, it is required to have at least 1,0% of point DF in the living space according to the BBR (Swedish's Building Regulations). Since the Greenhouse project was already certified with Miljöbyggnad's Gold, the required point DF is 1,2%.

In order to determine the most optimum sunspace and balcony position, all 96 possible iteration cases were simulated both in the actual position and flipped position. In the actual position, the sunspace was adjacent to only the living room and the balcony was adjacent to a part of the living room, kitchen and workshop. As in the flipped position, the balcony was adjacent to the living room and the sunspace was adjacent to the living room, kitchen and workshop.

Figure 26 presents the cases on both orientations that reached 1,2% point DF in the space out of a total of 96 iteration cases. The actual position is named normal case and the flipped position is named flip case.

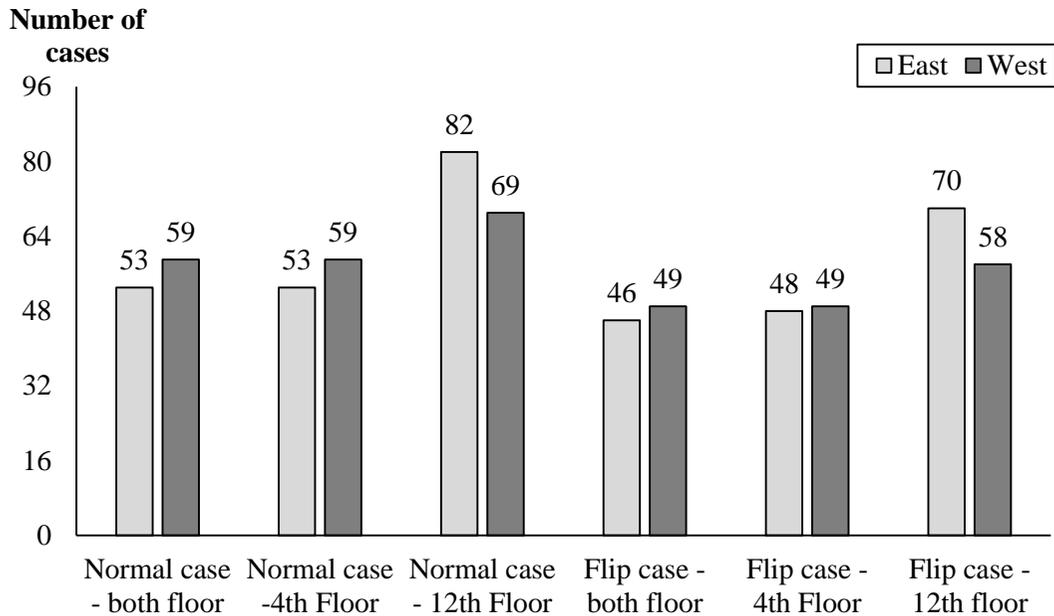


Figure 26: Cases reaching 1,2% point DF on east and west apartments.

In Figure 26, the orientation which had the most cases reaching 1,2% point DF was the west-facing apartments with the sunspace’s position according to the initial design. For the normal cases, on the east-facing apartments, 53 out of 96 cases on both floors reached the 1,2% point DF, whereas the west-facing apartments had 59 cases out of 96 cases. There were more cases on the twelfth floor apartments that reached the 1,2% point DF in both orientations. In all orientations, the flip case had less cases reaching 1,2% point DF, which indicated that no further investigations were conducted for the flipped sunspace and balcony positions.

#### 4.2.2 Effect of geometry on average and point DF

In this section, in order to analyze the effect of each parameters on the daylighting conditions in the adjacent living space, the simulation results of the average and point DF were sorted based on the sunspace and balcony geometry. D represents the depth (m) and L represents the length (m) of each sunspace and balcony. Each depth variations are presented by different shapes and the different lengths are presented by the different colors (dark grey presents the shortest length and white presents the longest length). Figure 27 and 28 present the average and point DF in the living space (living room and kitchen) of the four studied apartments.

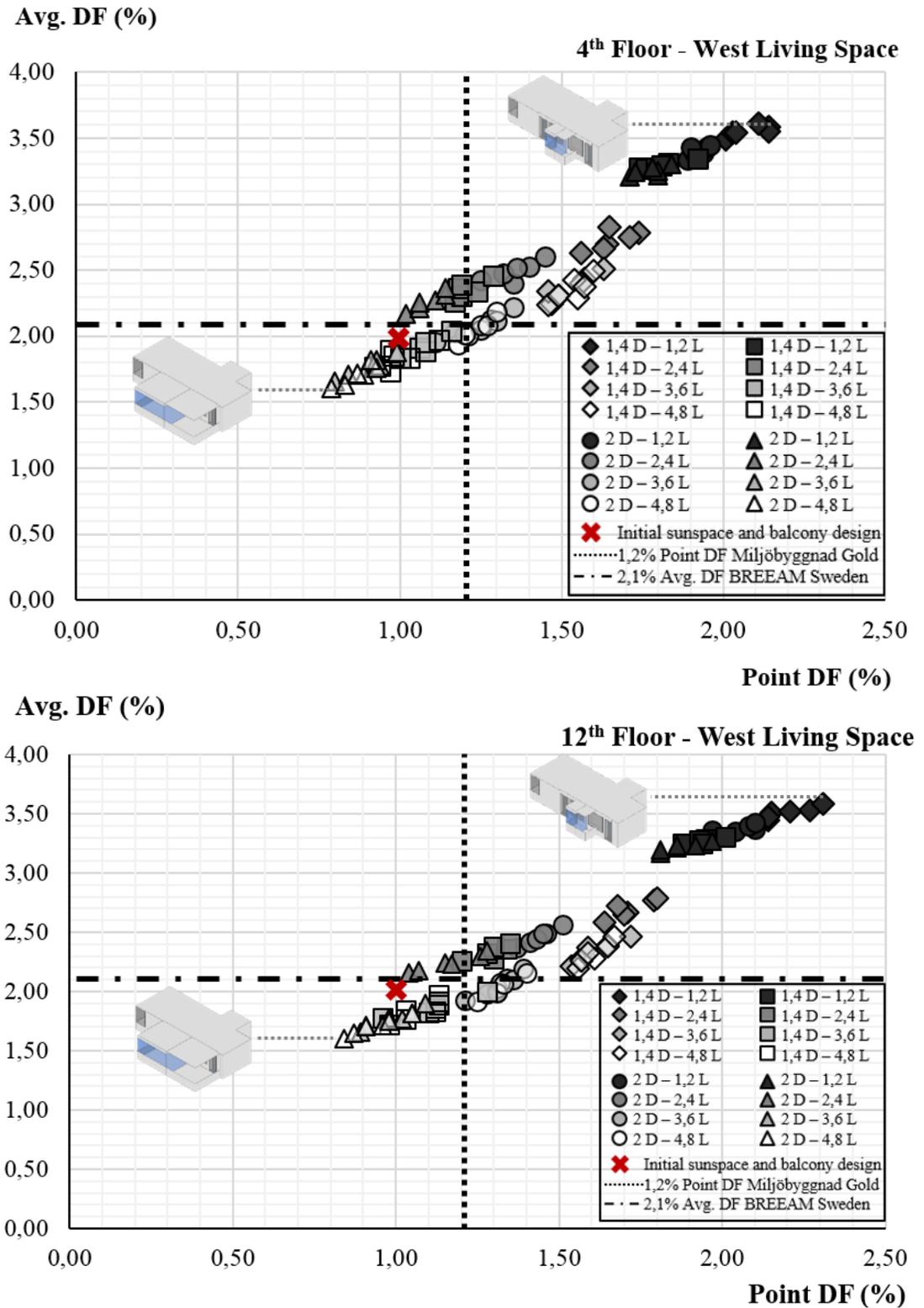


Figure 27: Effect of geometry on the average and point DF on the west apartments.

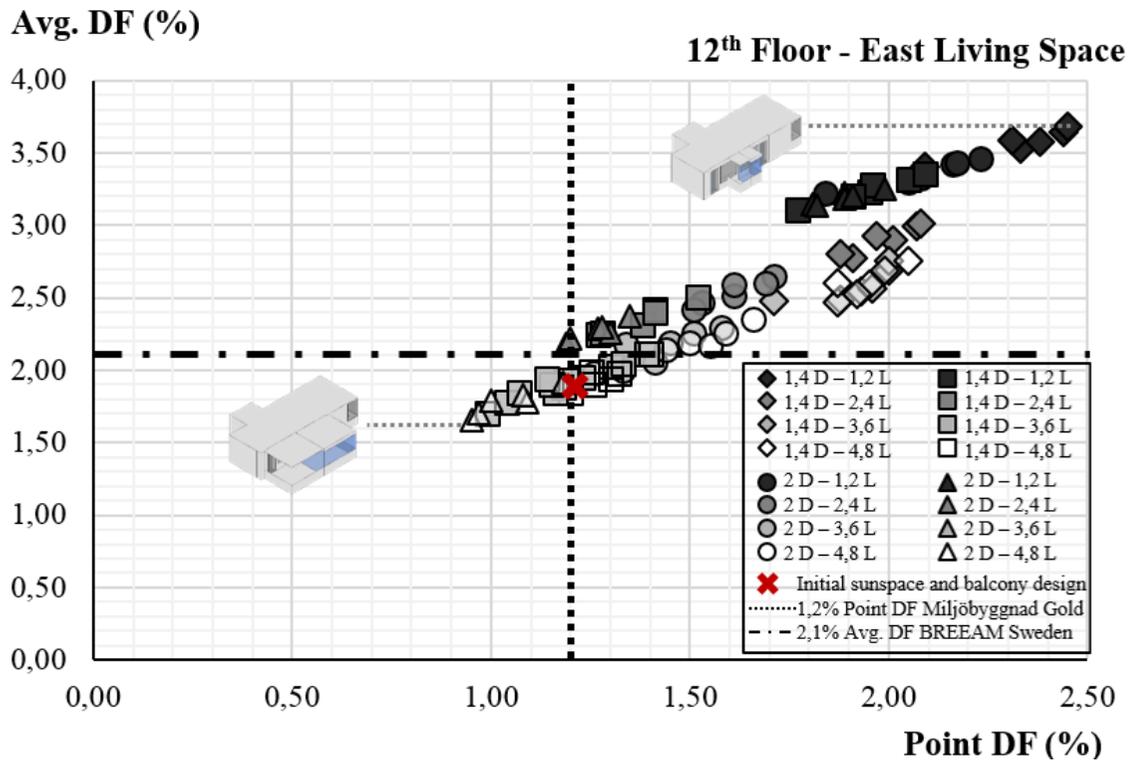
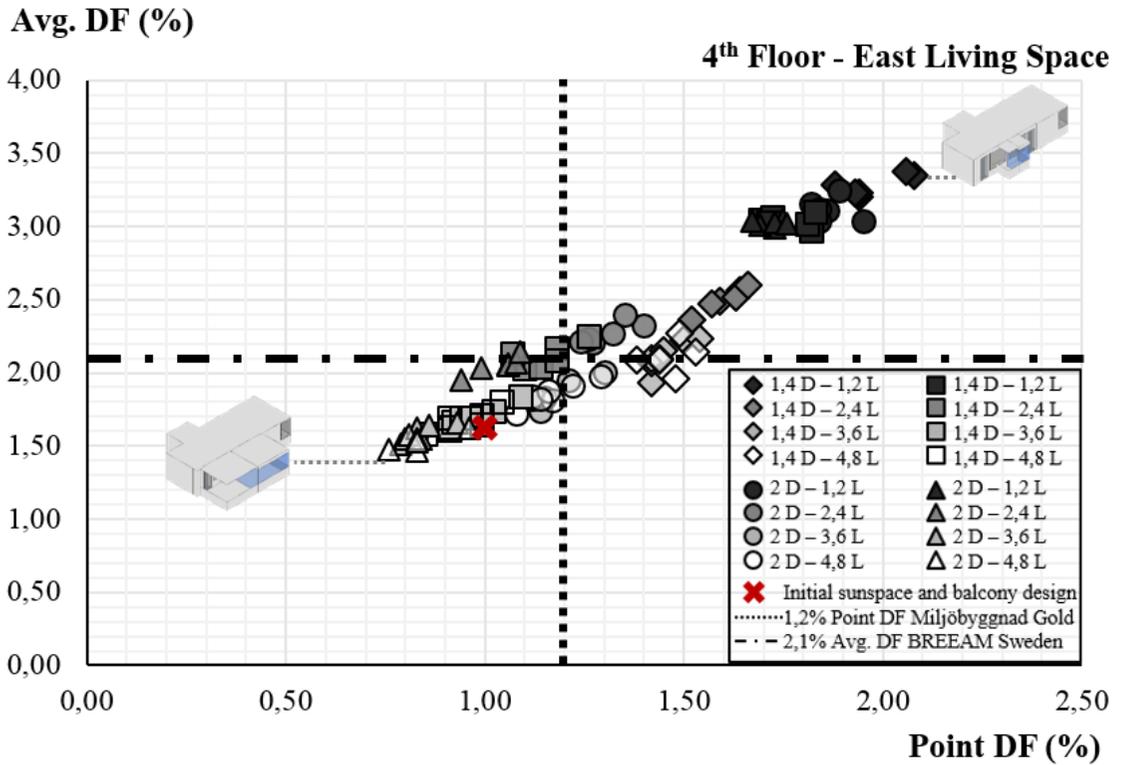


Figure 28: Effect of geometry on the average and point DF on the east apartments.

Looking at Figure 27 and Figure 28, in all studied apartments, having the least depth of 1,4 m with the shortest length, which was 1,2 m, gave the highest average DF and point DF in the living space. On both floors of the west living spaces, by having a geometry of 1,4 m deep and 1,2 m long (each for the sunspace and balcony), the average DF reached up to 3,6% with 2,1% point DF on the fourth floor and 2,3% point DF on the twelfth floor. Whereas on the east living spaces with the same geometry, the average DF was 3,4% with 2,1% point DF on the fourth floor and it was 3,6% average DF with 2,4% point DF on the twelfth floor.

Looking at all depth variations from 1,4 m to 3,2 m, combined with 1,2 m in length, these geometries were giving the higher values of average DF and point DF which were always above the assigned threshold values. These values then decreased when the depth and length of the sunspace and balcony were both increased simultaneously. For all four studied apartments, the geometry with the least depth, which was 1,4 m, could be combined with all the lengths and it could still achieve the thresholds, except on the fourth floor east-facing living space. In most cases that were combined with the sunspace and balcony length of 4,8 m, it was harder to achieve the threshold values. It was found that the twelfth floor of the east living space had the most cases reaching the thresholds and the fourth floor east living space had the least cases.

#### **4.2.3 Effect of geometry on average DF and daylight uniformity ratio**

The daylight uniformity ratio of all the living spaces were analyzed in order to investigate in how the daylight was distributed in each space. Figure 29 and Figure 30 present the average DF and the uniformity ratio in the living room.

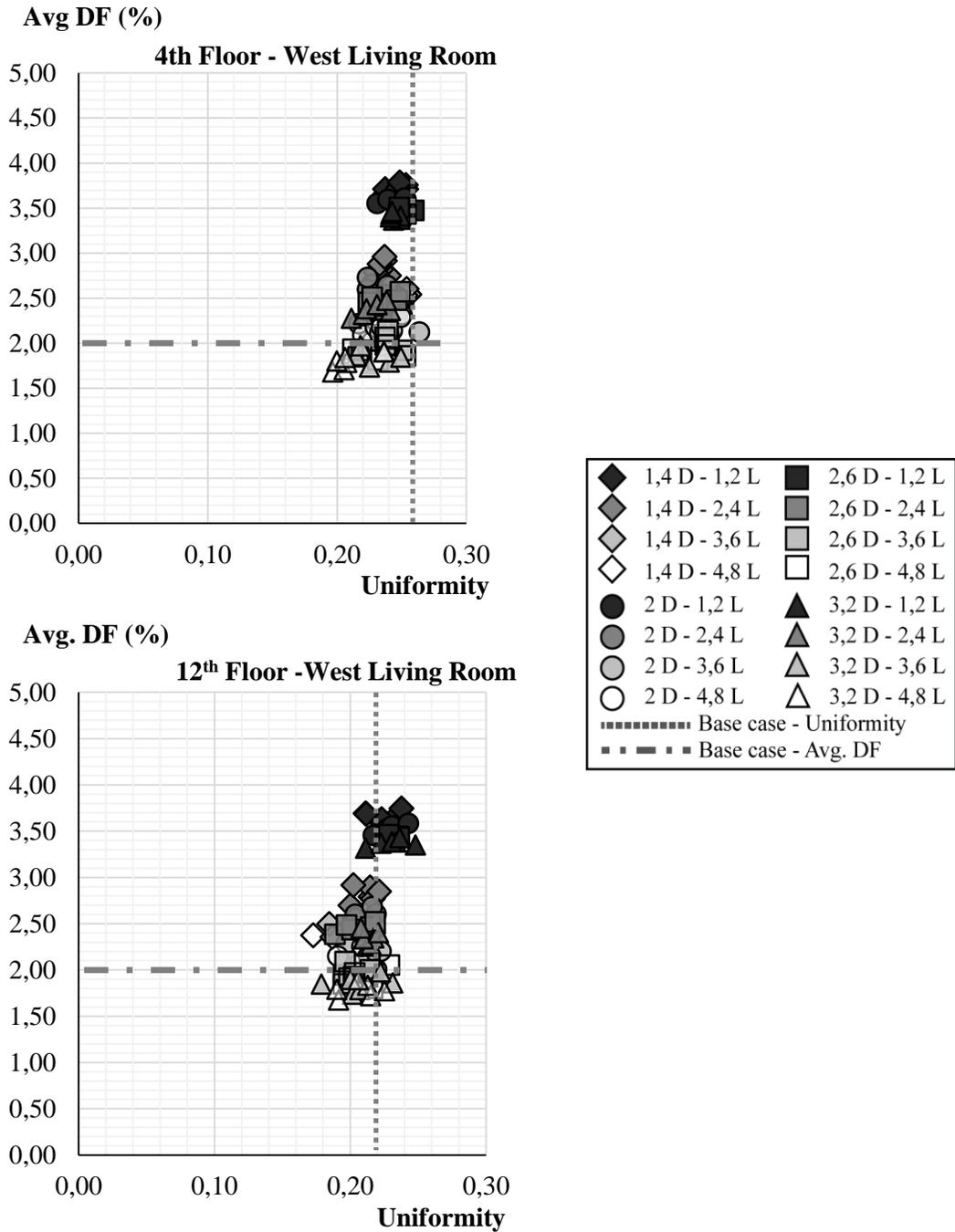


Figure 29: Effect of geometry towards the average DF and uniformity ratio on the west apartments.

For the west apartments, the base case had around 2,0% average DF on both floors and uniformity of 0,26 on the fourth floor, while it was 0,22 on the twelfth floor when the sunspace and balcony were added. Looking at Figure 30, the uniformity ratio on the fourth

floor was between 0,19 to 0,27, depending on the geometry, whereas on the twelfth floor, the values fell between 0,17 to 0,23.

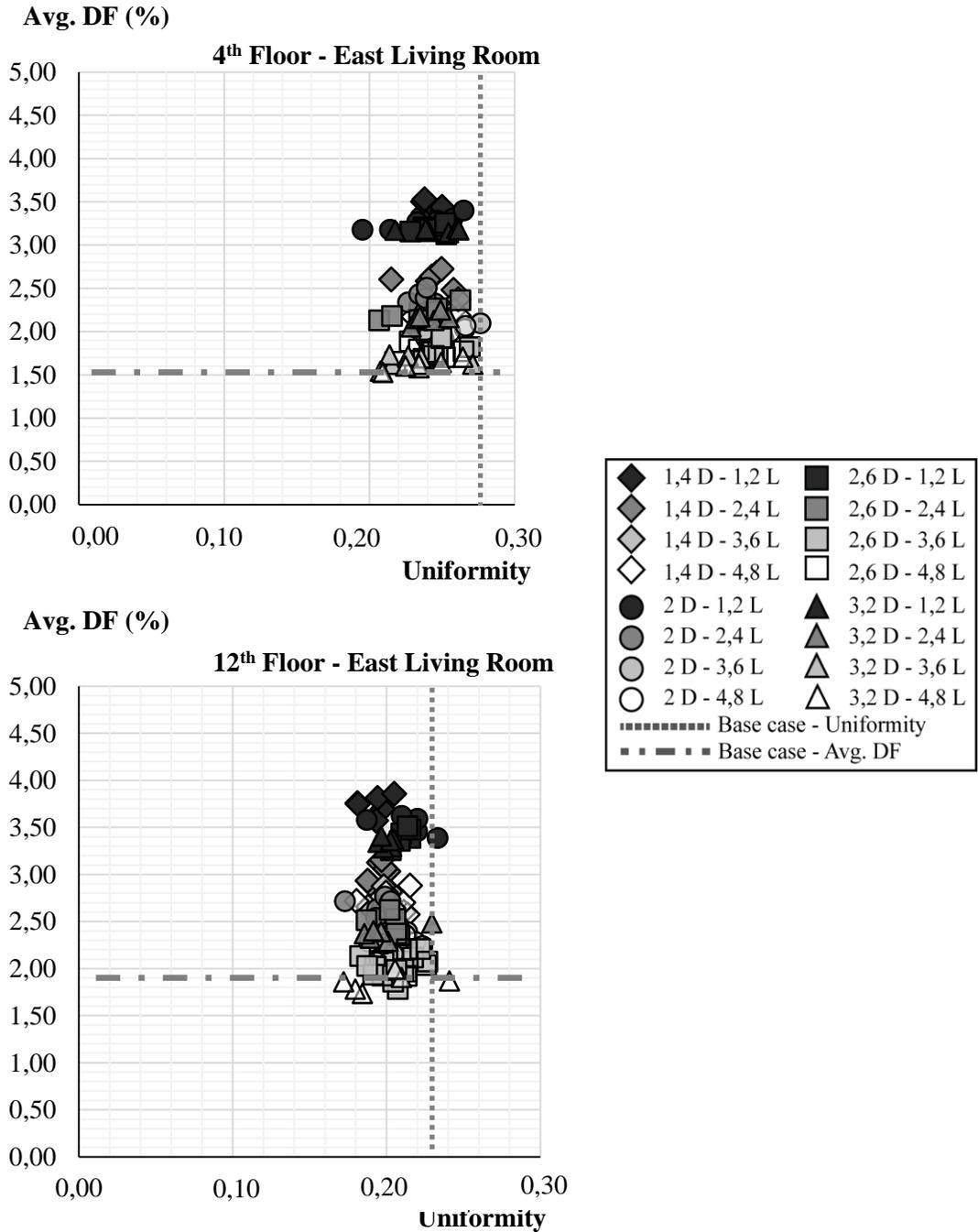


Figure 30: Effect of geometry towards the average DF and uniformity ratio on the east apartments.

In Figure 30, the fourth floor east living room had higher daylight uniformity compared to the twelfth floor. On the fourth floor, the daylight uniformity value ranged between 0,19 to 0,29 which was lower than the base case result. On the twelfth floor, the daylight uniformity was between 0,17 to 0,24.

#### 4.2.4 Effect of geometry on DA and DF

All variations for all of the four studied apartments were also analyzed based on the effect of the average DA in accordance with the average DF in each spaces. The DA values were based on the required 150lux illuminance threshold and the occupancy schedule of each spaces as explained in the previous chapter.

Figure 31 to Figure 34 shows how the geometry of the sunspace and balcony affected the average DA and average DF in the living room of the west and east apartments. In each graph, the base case average DA is presented by the dashed-dotted grey line, whereas the base case average DF is presented by the grey dotted line. The black dotted line represents the 2,1% average DF required by BREEAM Sweden as one of the threshold. These lines appeared in each graphs to determine the cases that can provide the average DA and average DF which are higher than the base case values and the required thresholds.

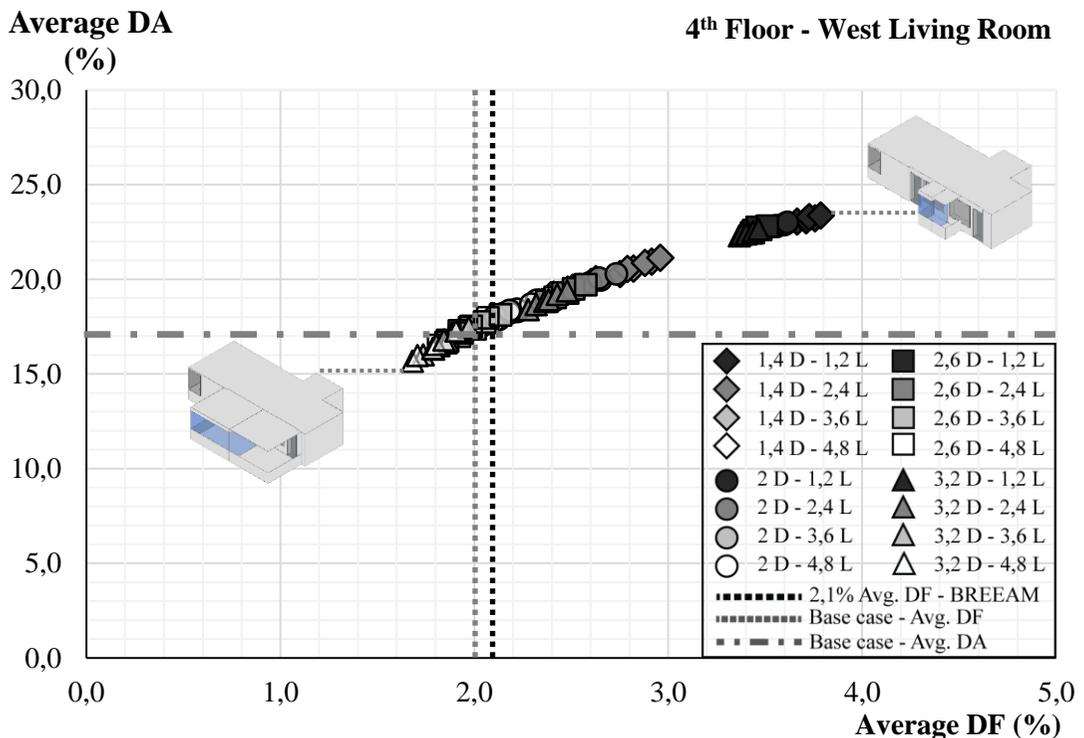


Figure 31: Effect of geometry on the average DA and average DF of the west living room on the 4<sup>th</sup> floor.

As shown in Figure 31, all the geometry which had 1,4 m to 3,2 m of depth in combination with 1,2 m in length, had the higher values of the average DA and average DF in the fourth

floor of the west-facing living room. The highest value was obtained by the sunspace and balcony which had 1,4 m in depth and 1,2 m in length, which resulted in 23,5% average DA and 3,8% average DF. Seeing all the cases for the fourth floor west living room, the values were ranging from 15,5% to 23,5% for the average DA and from 1,7% to 3,8% for the average DF. Almost all the variations were above the threshold lines, except the ones combined with 4,8 m in length.

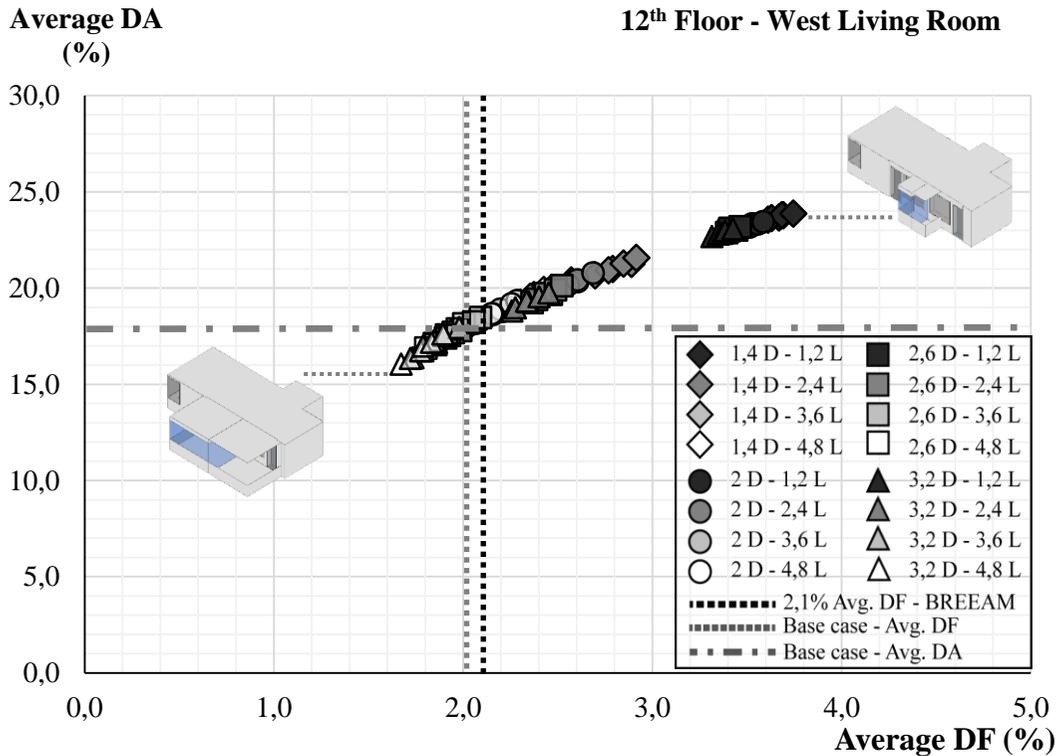


Figure 32: Effect of geometry towards the average DA and average DF of the west living room on the 12<sup>th</sup> floor.

Similar trend was also shown in Figure 32, all the geometry which had depths ranging from 1,4 m until 3,2 m in combination with 1,2 m in length, had the higher values of the average DA and average DF in the twelfth floor of the west living room. Looking at all the cases, the values ranged from 16,0% to 24,0% for the average DA and from 1,7% to 2,8% for the average DF. The highest average DA of 24,0% and average DF of 3,8% in the living room was reached by the sunspace and balcony that had a geometry of 1,4 m in depth and 1,2 m in length. For geometries that had longer lengths, such as 3,6 m and 4,8 m, the threshold values were harder to meet.

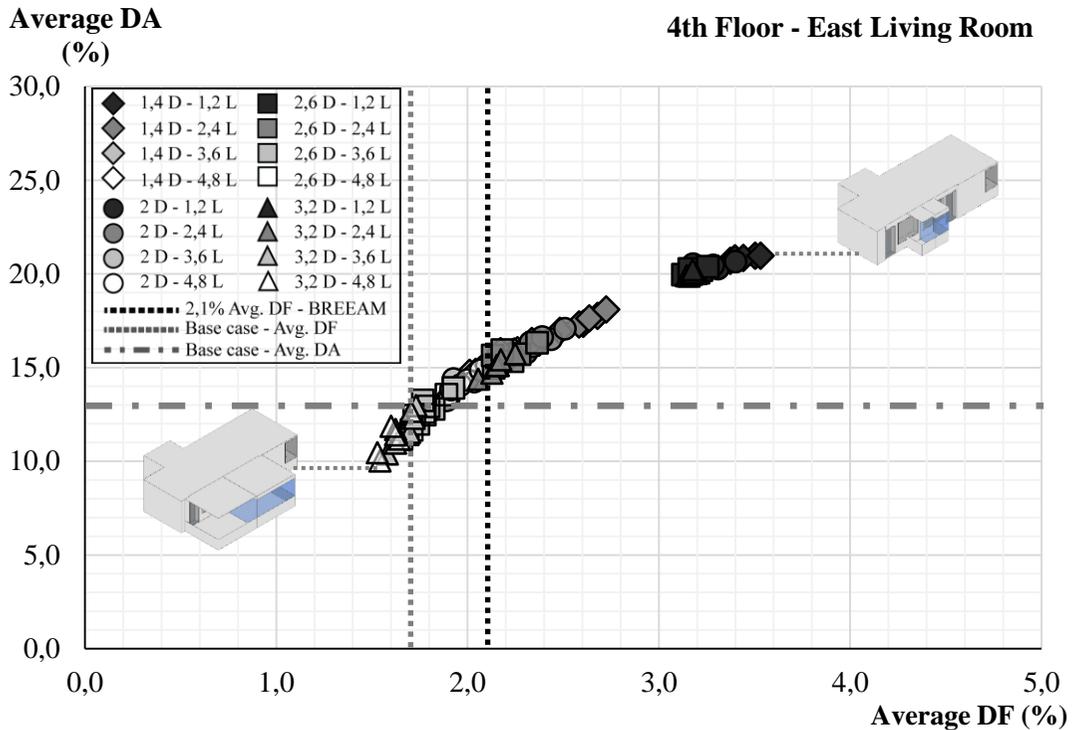


Figure 33: Effect of geometry towards the average DA and average DF of the east living room on the 4<sup>th</sup> floor.

On the east apartments, the average DA values were lower compared to the west apartments which explains why the average DA threshold value is lower for the east apartments. As shown in Figure 33, all the variations resulted in a range from 9,5% to 21% average DA and from 1,5% to 3,5% average DF, which in this case, only half of the cases reached above the threshold values. The highest value for the fourth floor east-facing living room was obtained by the sunspace and balcony that had 1,4 m in depth and 1,2 m in length, resulting in 21% average DA and 3,5% average DF.

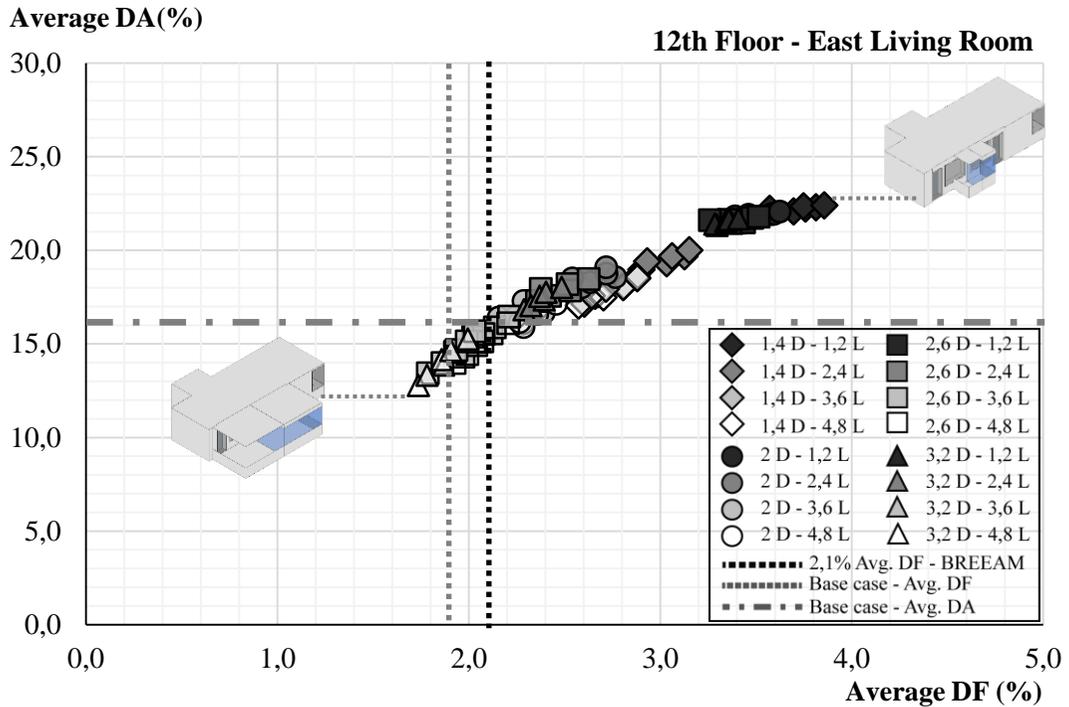


Figure 34: Effect of geometry on the average DA and average DF of the east living room on the 12th floor.

Compared to the fourth floor living room of the east facing apartment, the twelfth floor had more cases that met the threshold values. Figure 34 shows the results from all the cases for the twelfth floor east living room that fell between 12,5% to 22,5% for the average DA and 1,7% to 3,9% for the average DF. The same sunspace and balcony geometry as mentioned before gave the highest average DA and DF in the twelfth floor east-facing living room, which was 22,5% and 3,9%.

Besides the living room, the kitchen and workshop were also studied in order to study the effect of geometry on the DA and DF. Figure 35 and Figure 36 presents the average DA and DF results of all geometry variations in the kitchen of the four studied apartments.

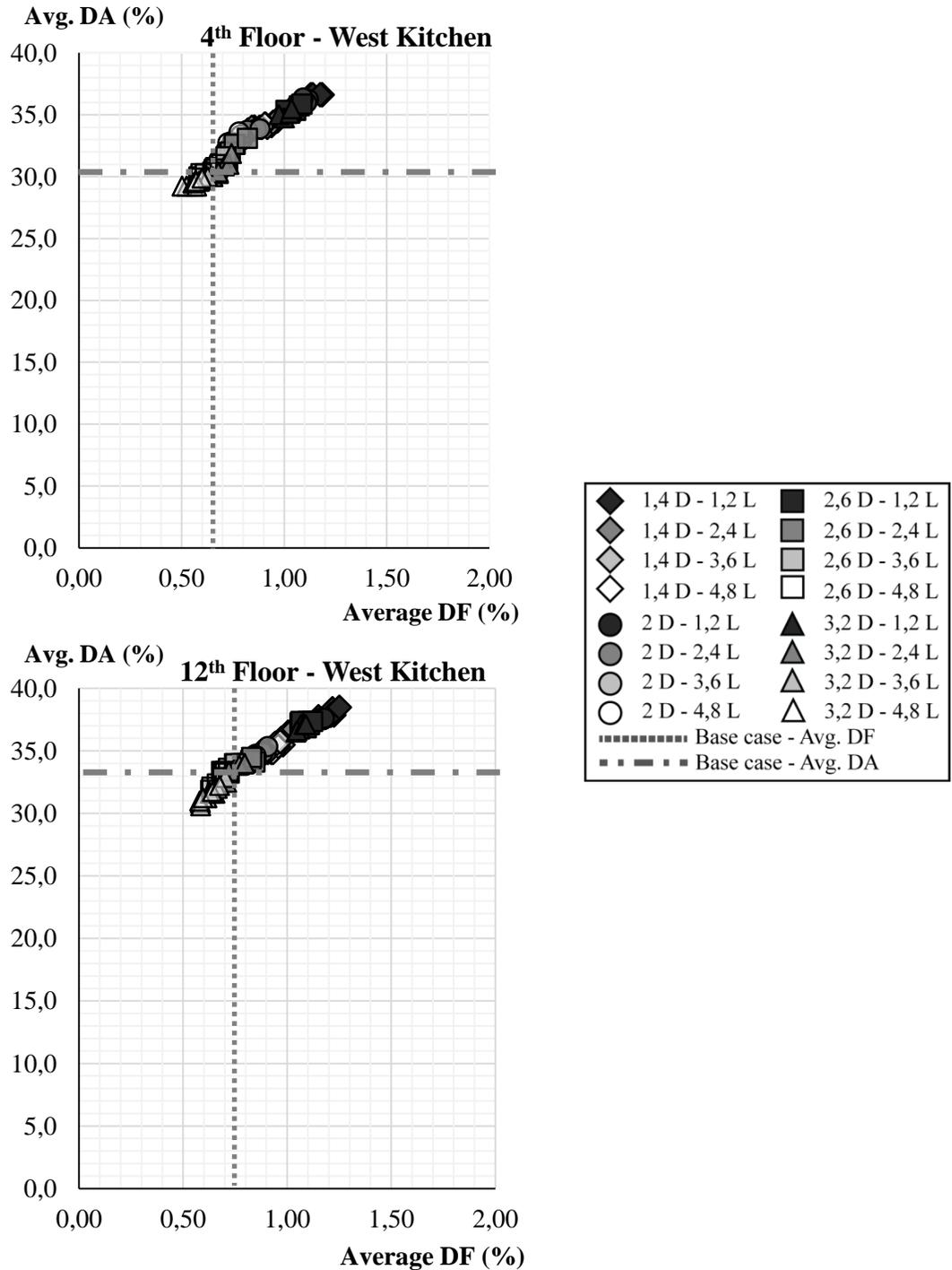


Figure 35: Effect of geometry on the average DA and average DF of the west kitchen.

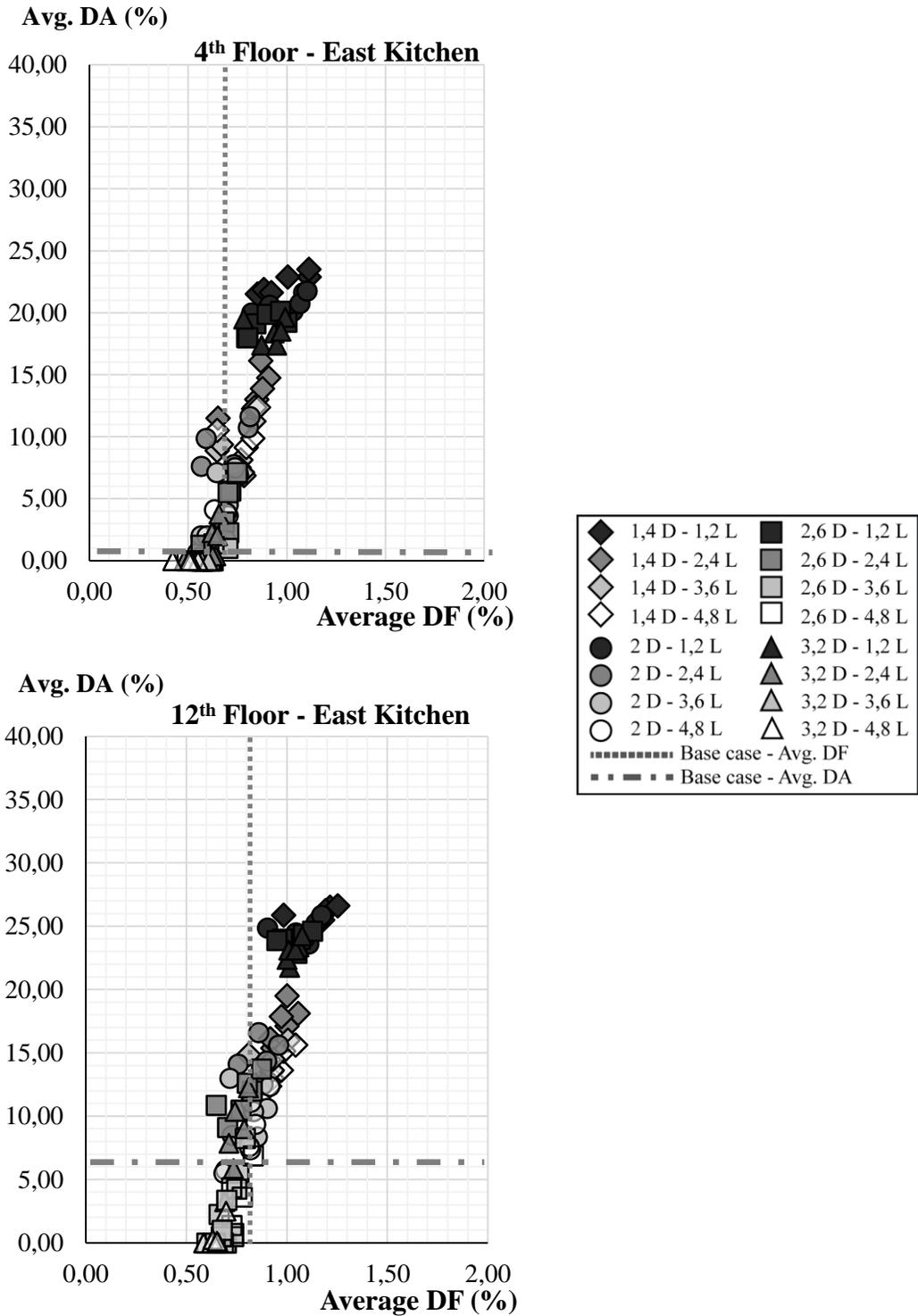


Figure 36: Effect of geometry on the average DA and average DF of the east kitchen.

As seen on Figure 35, the west apartment's kitchen on fourth and twelfth floor had higher average DA and average DF values compared to the east apartments which are presented in Figure 37. For the west kitchen, the values ranged from 28,0% to 36,5% average DA and from 0,5% to 1,2% average DF on the fourth floor, while on the twelfth floor the values reached up to 38% average DA and 1,3% average DF when least depth and shortest length were used as the geometry of the sunspace and balcony.

It can be observed from Figure 36 that for the east kitchen on both floors, the average DA values dropped to 0% when the sunspace and balcony had a large depth and length, which were 3,2 m in depth and 4,8 m in length. Having all the variations, the average DA was between 0% to 24% and the average DF was between 0,4% to 1,1% on the fourth floor, while on the twelfth floor the values were between 0% to 27% average DA and between 0,6% to 1,3% average DF. The less depth and length gave a higher average DA and average DF in the kitchen.

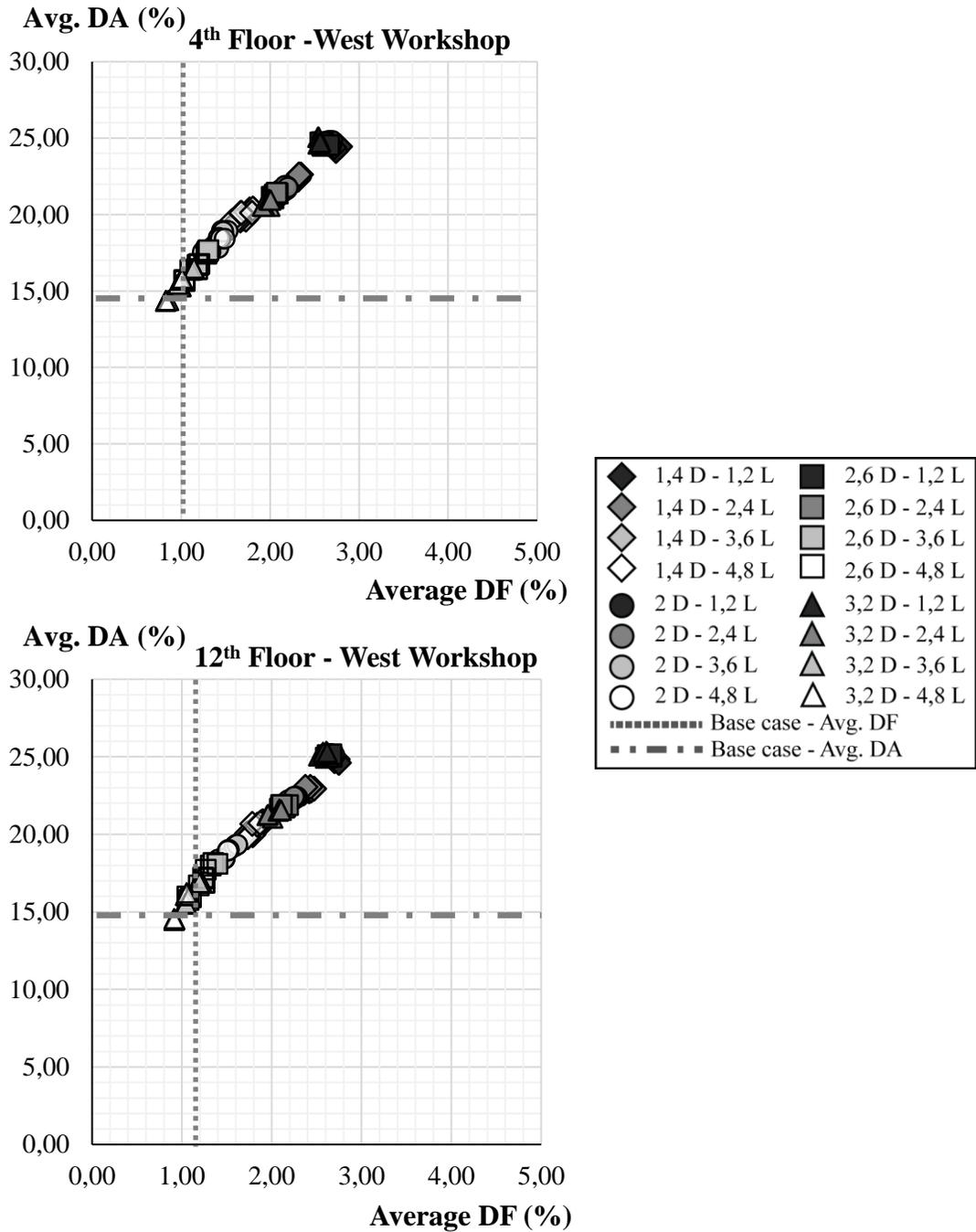


Figure 37: Effect of geometry on the average DA and average DF of the west workshop.

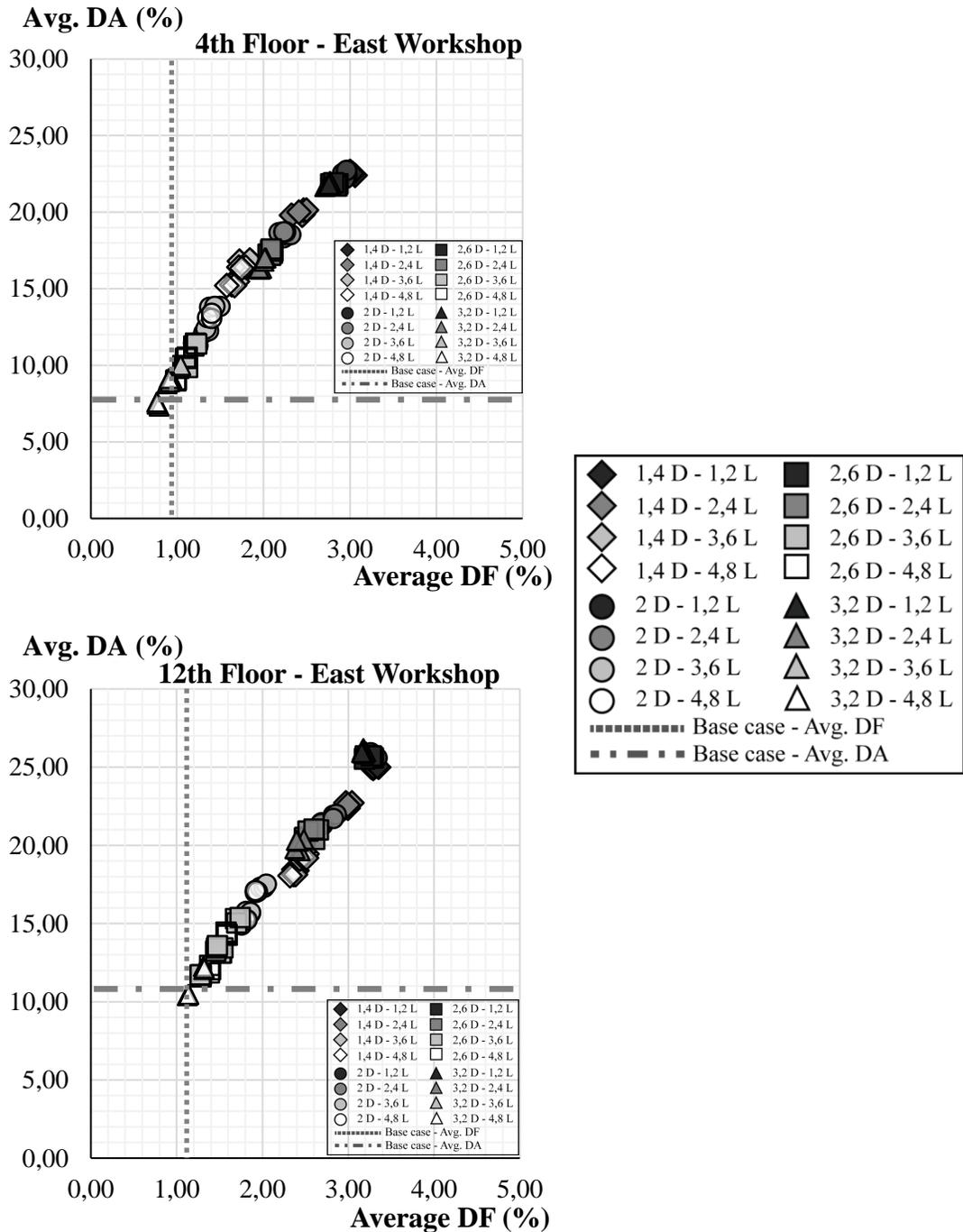


Figure 38: Effect of geometry on the average DA and average DF of the east workshop.

Comparing west and east workshop (see Figure 37 and 38), the west-facing workshop had higher average average DA values on both floors. For the west workshop, the values were between 14% to 25% for the average DA and from 0,8% to 2,8% for the average DF on both floors.

Looking at Figure 38, the east workshop on the twelfth floor had higher average DA and DF values compared to the fourth floor. The highest value on the fourth floor was achieved by having the least depth and length, resulting in 23,0% average DA and 3,0% average DF, whereas on the twelfth floor almost all depths reached the highest value of 26% average DA and 3,1% average DF when combined with the shortest length which was 1,2 m. The same trend also occurred in the workshop for all the studied orientations and floor heights that the value for the average DA and average DF increased when the sunspace and balcony had less depth and length.

#### 4.2.5 Effect of geometry, GWR and LRV on average DF and DA

Studying the effect of varying the glazing-to-wall-ratio (GWR) and the light reflectance values (LRV) on the average DF and average DA, the living room was taken as the studied space and the results are presented in the following figures. Only eight cases which exhibited large differences in geometry were chosen and presented in the following figures. The chosen cases were compared to two different cases, one which had the shortest length ( $L=1,2$  m) with two different depths ( $D=1,4$  m and  $D=3,2$  m) and one which had the longest length ( $L=4,8$  m) with two same depths ( $D=1,4$  m and  $D=3,2$  m) as well. The geometries and reflectance value of the chosen cases are listed below:

First comparison with the shorter length:

- 1,4 m deep and 1,2 m long with floor and ceiling LRV of 20% (1,4 D – 1,2 L – F20-C20).
- 1,4 m deep and 1,2 m long with floor LRV of 40% and ceiling LRV of 80% (1,4 D – 1,2 L – F40-C80).
- 3,2 m deep and 1,2 m long with floor and ceiling LRV of 20% (3,2 D – 1,2 L – F20-C20).
- 3,2 m deep and 1,2 m long with floor LRV of 40% and ceiling LRV of 80% (3,2 D – 1,2 L – F40-C80).

Second comparison with the longer length:

- 1,4 m deep and 4,8 m long with floor and ceiling LRV of 20% (1,4 D – 4,8 L – F20-C20).
- 1,4 m deep and 4,8 m long with floor LRV of 40% and ceiling LRV of 80% (1,4 D – 4,8 L – F40-C80).
- 3,2 m deep and 4,8 m long with floor and roof LRV of 20% (3,2 D – 4,8 L – F20-C20).
- 3,2 m deep and 4,8 m long with floor LRV of 40% and ceiling LRV of 80% (3,2 D – 4,8 L – F40-C80).

Figure 39 presents the effect of varying the GWR and reflectance value with 1,2 m long sunspace and balcony towards the average DF in the living room.

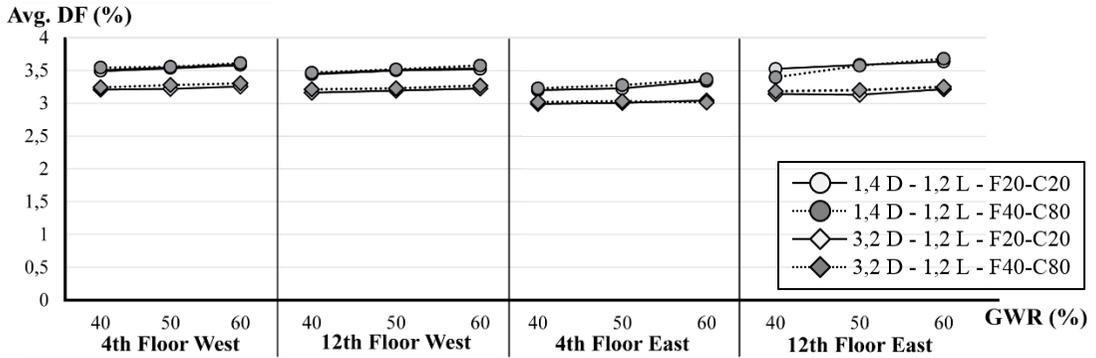


Figure 39: Effect of GWR and LRV on the average DF of the living room with shorter balcony and sunspace.

As it can be seen from Figure 39 that the average DF increased slightly when the GWR was increased. On the west apartments, both of the floors had similar average DF values, ranging from 3,5% to 3,6% for the sunspace and balcony which had 1,4 m depth and from 3,3% to 3,4% for the 3,2 m deep balcony and sunspace. The LRV did not have a great effect. For the east fourth floor, larger differences can be seen for the sunspace with 1,4 m depth when the GWR was increased to 60%. The increase of average DF value for the shorter balcony and sunspace length was not influenced greatly by the changes in GWR nor the LRV.

Figure 40 shows the influence of GWR and LRV towards the average DF results for the longer balconies.

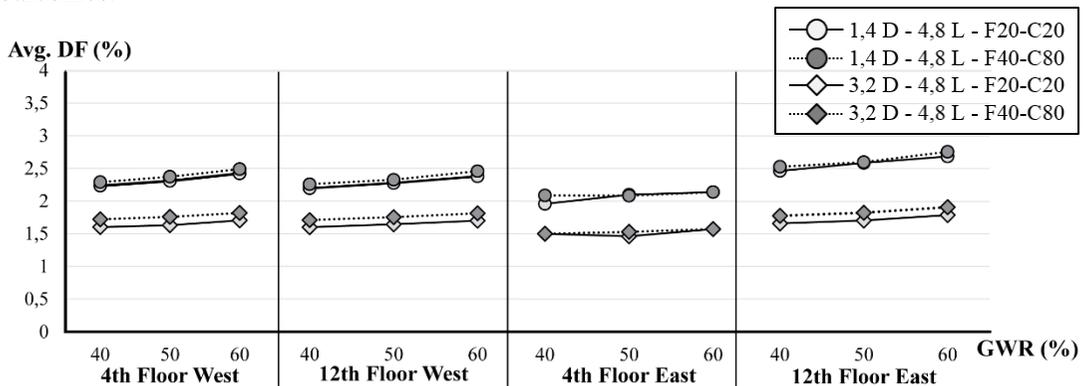


Figure 40: Effect of GWR and LRV on the average DF of the living room with longer balcony and sunspace.

Compared to Figure 39, the results shown in Figure 40 has larger increase when the GWR increases from 40% to 60% in all the apartments, except on the fourth floor east apartment where the increase was rather constant. This means that the GWR has more significant effect when the sunspace and balcony is longer, even though the differences is negligible in this case. For the west apartments, the average DF slightly increased when the LRV of the

sunspace and balcony's ceiling and floor were increased. Increasing the GWR from 40% to 60% can increase the average DF in the living room on the east and west apartments.

Figure 41 presents the effect of increasing the GWR and LRV in the shorter balcony and sunspace on the average DA in the living room

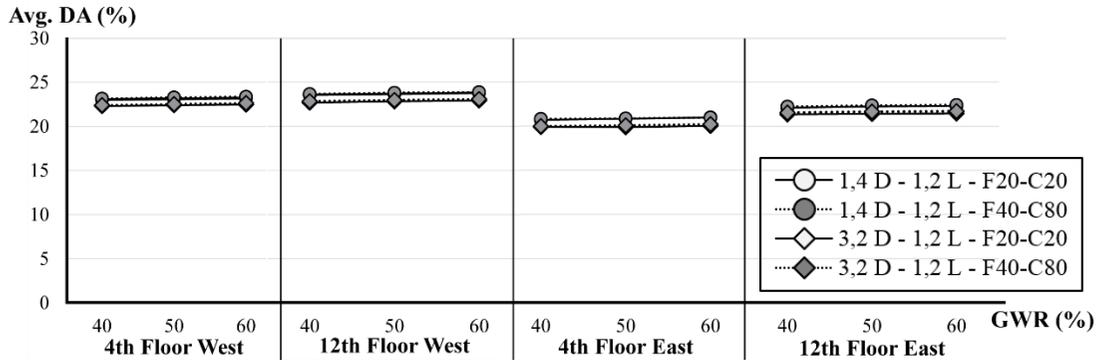


Figure 41: Effect of GWR and LRV towards the average DA of the living room with shorter balcony and sunspace.

Looking at Figure 41, increasing the GWR and LRV for the cases with shorter balconies only gave a slight increase which was also the same as it was for the average DF values. Larger differences can be seen in Figure 42 which represents the results for the balcony and sunspace which had longer length.

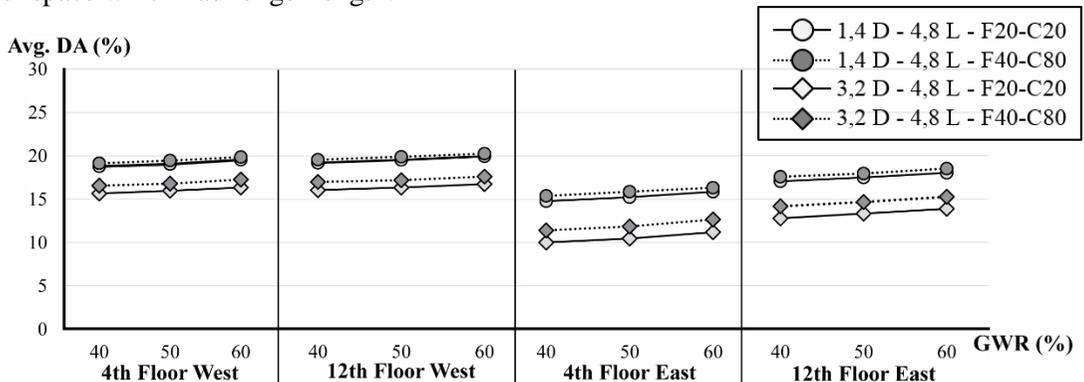


Figure 42: Effect of GWR and LRV on the average DA of the living room with longer balcony and sunspace.

As shown in Figure 42, the average DA values for all apartments were increased when the GWR and LRV were higher, especially for the east apartments. By having the larger depth (3,2 m) and longer length (4,8 m), it was beneficial to increase the GWR and LRV. On the west apartments, the average DA increased from 16% to 17% just by increasing the LRV and from 17% to 18% by increasing the GWR. Larger influence can be seen on the east apartments, where on the fourth floor by increasing the GWR and reflectance value, the average DA was increased from 10% to 13% and from 13% to 15% on the twelfth floor.

### 4.2.6 Effect of geometry on average DA and electrical lighting use

The effect of varying the geometry of the sunspace and balcony was analysed on the electrical lighting consumption in the living room, kitchen and workshop. Figure 43 and Figure 44 show the electrical lighting consumption in comparison with the average DA for all variations in the living room of the four studied apartments.

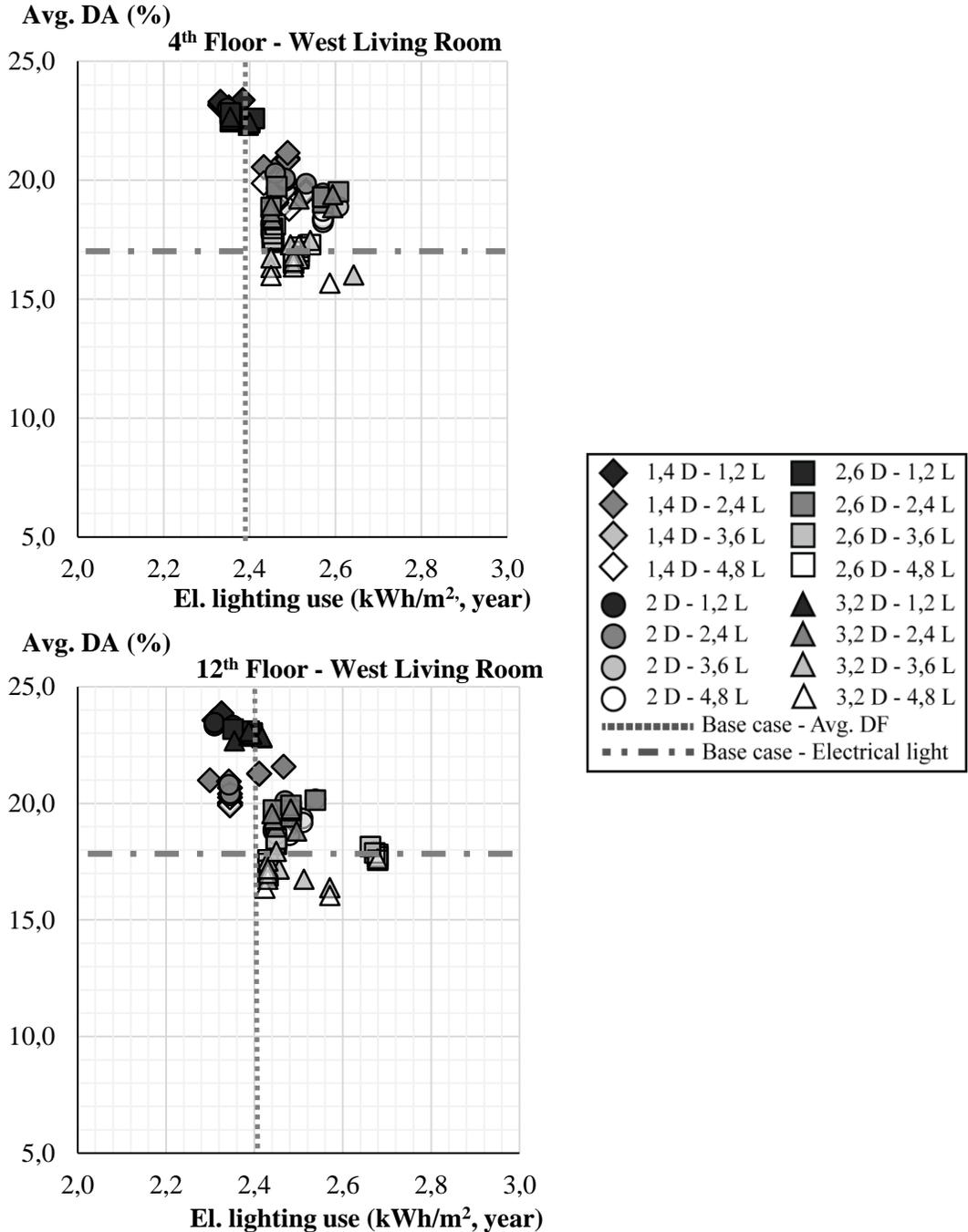


Figure 43: Effect of geometry on the average DA and electrical lighting use of the west living room.

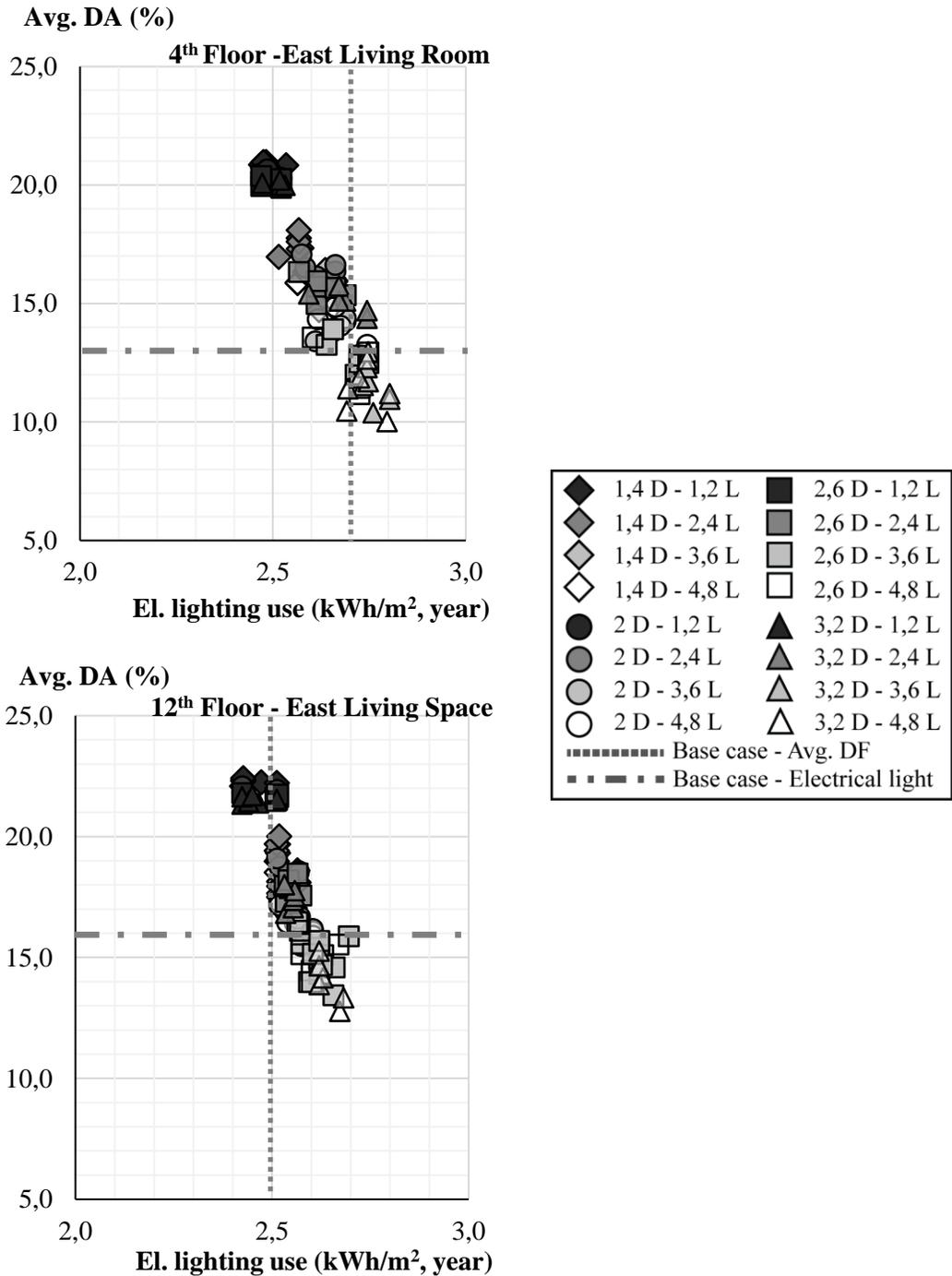


Figure 44: Effect of geometry on the average DA and electrical lighting use of the east living room.

From Figure 43 and Figure 44, it can be seen that in all studied apartments, the higher the average DA, the lower the electrical lighting consumption in the living room. On the west living room, the electrical lighting consumption was between 2,3 kWh/m<sup>2</sup>, year to 2,6

kWh/m<sup>2</sup>, year on the fourth floor and from 2,3 kWh/m<sup>2</sup>, year to 2,7 kWh/m<sup>2</sup>, year on the twelfth floor. For the east living room, the electrical lighting consumption was between 2,5 kWh/m<sup>2</sup>, year to 2,8 kWh/m<sup>2</sup>, year for the fourth floor and from 2,4 kWh/m<sup>2</sup>, year to 2,7 kWh/m<sup>2</sup>, year on the twelfth floor. These values were affected by the average DA on each studied apartment in conjunction with varied geometries.

Figure 45 and Figure 46 show the electrical lighting use in the kitchen for all studied apartments compared to the average DA.

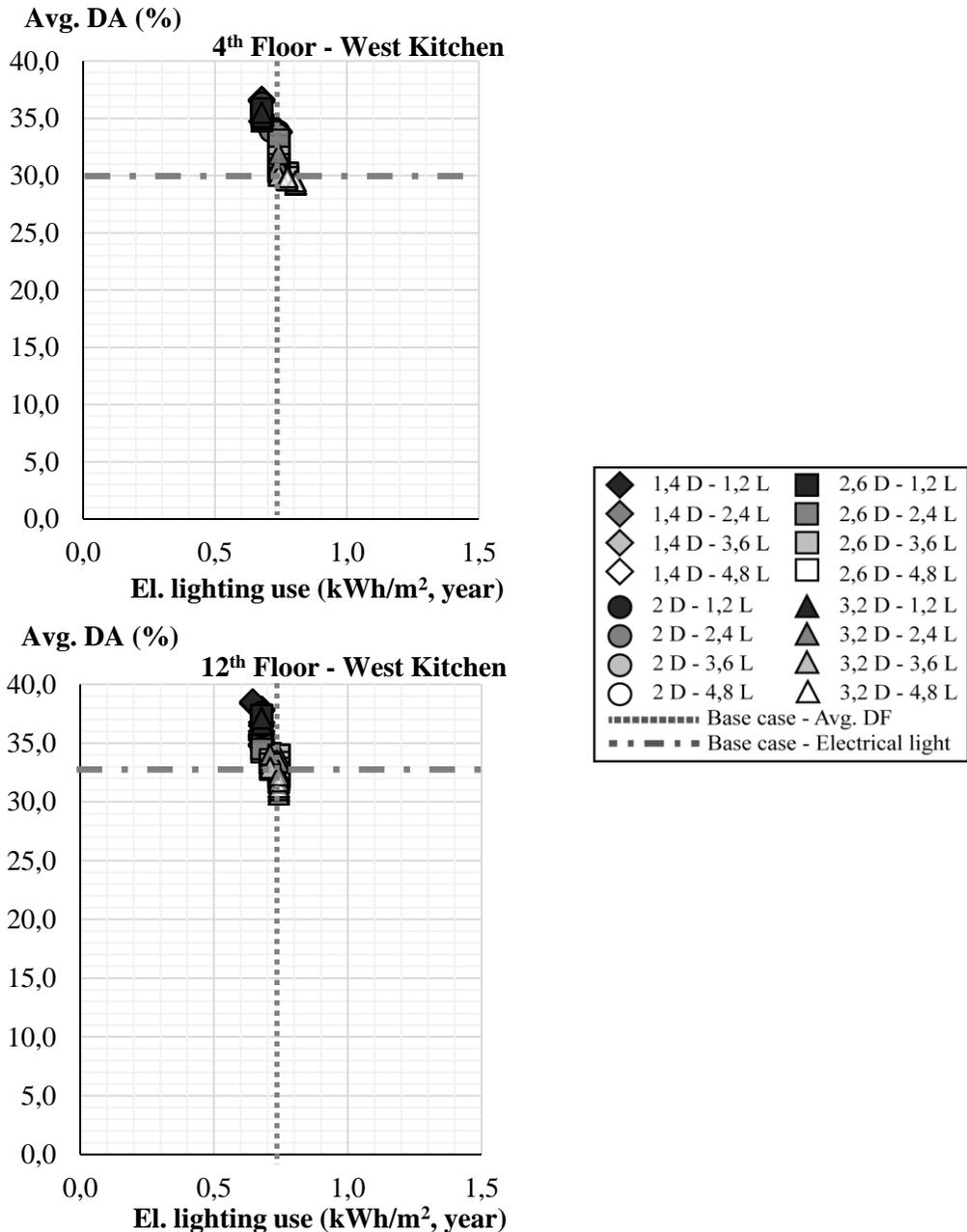


Figure 45: Effect of geometry on the average DA and electrical lighting use of the west kitchen.

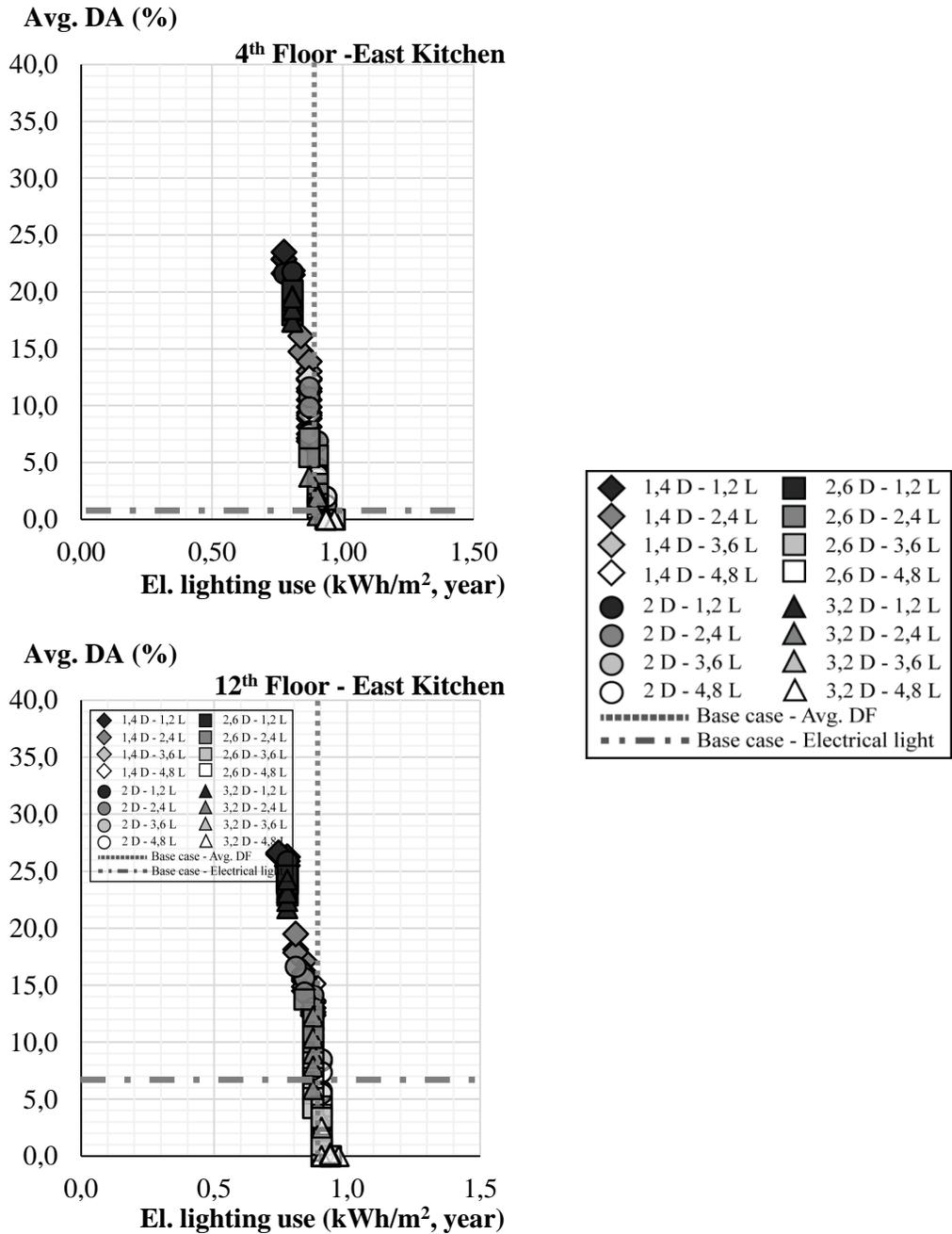


Figure 46: Effect of geometry on the average DA and electrical lighting use of the east kitchen.

As shown in Figure 45, the fourth floor west kitchen had electrical lighting consumption between 0,7 kWh/m<sup>2</sup>, year to 0,8 kWh/m<sup>2</sup>, year, whereas on the twelfth floor, it was between 0,6 kWh/m<sup>2</sup>, year to 0,75 kWh/m<sup>2</sup>, year. Figure 46 shows that the fourth floor east kitchen had the electrical lighting consumption between 0,8 kWh/m<sup>2</sup>, year and 1 kWh/m<sup>2</sup>, year, while on the twelfth floor, it was ranging from 0,7 kWh/m<sup>2</sup>, year to 1 kWh/m<sup>2</sup>, year.

The low electrical lighting consumption and high average DA in the space can be met by having the least depth and length for the sunspace and balcony.

Figure 47 and Figure 48 present the electrical lighting consumption in comparison with the average DA for the workshop in all studied apartments.

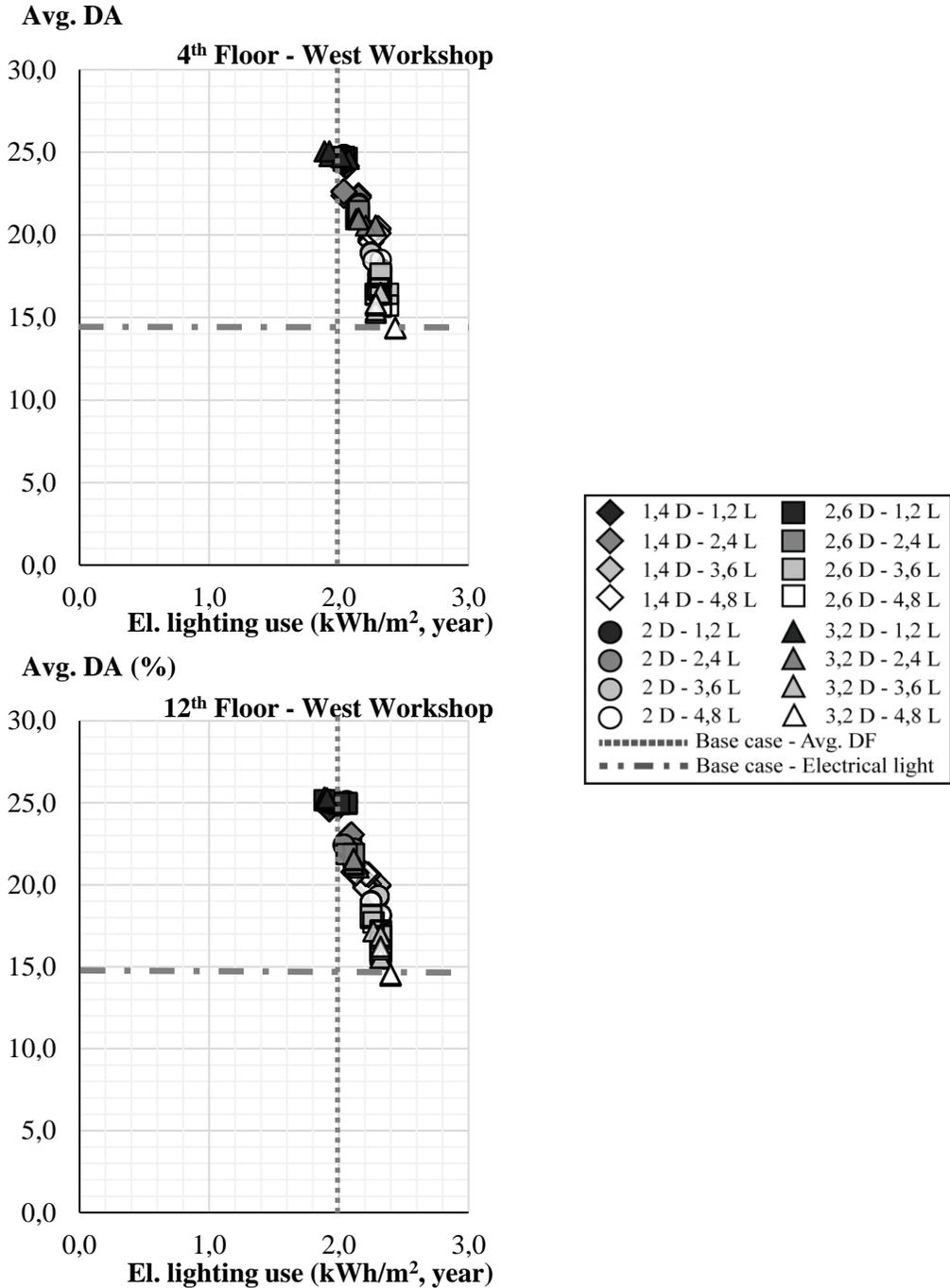


Figure 47: Effect of geometry on the average DA and electrical lighting use of the west workshop.

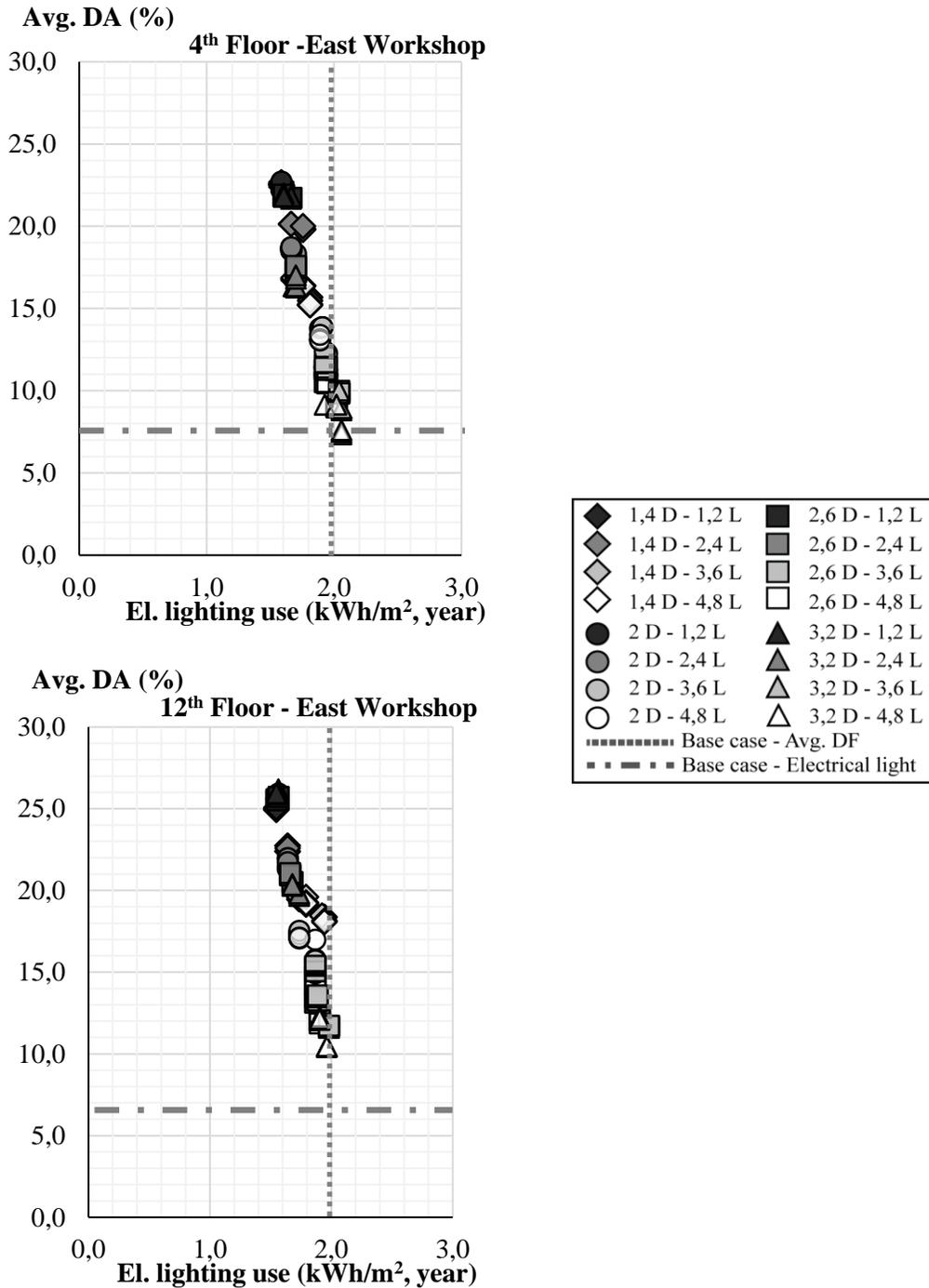


Figure 48: Effect of geometry on the average DA and electrical lighting use of the east workshop.

The same trend also occurred in Figure 48 for the east facing workshops, where the electrical lighting use of 1,5 kWh/m<sup>2</sup>, year on both floors was met by having the least length.

For all the studied apartments and the studied spaces, the electrical lighting use increased simultaneously when the depth and length were increased, which also caused the reduction of the DA in the space.

#### 4.2.7 Recommended cases based on overall daylight performance

After analyzing all the studied parameters and the impact on the daylight performance, Table 16 presents the listed cases that met the thresholds that were assigned previously: 2,1% average DF, 1,2% point DF, higher average DA and lower electrical lighting use. The recommended cases are highlighted in grey on Table 13.

Table 13: Cases that met the daylight prerequisites.

Studied Apartments	Above DF and Point DF Threshold		Above Average DA and Average DF						Above Average DA and Lower Electrical Lighting Consumption					
	Living Space		Living Room		Kitchen		Workshop		Living Room		Kitchen		Workshop	
	D	L	D	L	D	L	D	L	D	L	D	L	D	L
4th Floor West	1,4	1,2	1,4	1,2	1,4	1,2	1,4	1,2	1,4	1,2	1,4	1,2	1,4	1,2
	1,4	2,4	1,4	2,4	1,4	2,4	1,4	2,4	-	-	1,4	2,4	1,4	2,4
	1,4	3,6	1,4	3,6	1,4	3,6	1,4	3,6	-	-	1,4	3,6	1,4	3,6
	1,4	4,8	1,4	4,8	1,4	4,8	1,4	4,8	-	-	1,4	4,8	1,4	4,8
	2	1,2	2	1,2	2	1,2	2	1,2	2	1,2	2	1,2	2	1,2
	2	2,4	2	2,4	2	2,4	2	2,4	-	-	2	2,4	2	2,4
	-	-	-	-	2	3,6	2	3,6	-	-	2	3,6	2	3,6
	-	-	-	-	2	4,8	2	4,8	-	-	2	4,8	2	4,8
	2,6	1,2	2,6	1,2	2,6	1,2	2,6	1,2	2,6	1,2	2,6	1,2	2,6	1,2
	-	-	2,6	2,4	2,6	2,4	2,6	2,4	-	-	2,6	2,4	2,6	2,4
	-	-	-	-	-	-	2,6	3,6	-	-	-	-	2,6	3,6
	3,2	1,2	3,2	1,2	3,2	1,2	3,2	1,2	3,2	1,2	3,2	1,2	3,2	1,2
-	-	3,2	2,4	-	-	3,2	2,4	-	-	-	-	3,2	2,4	
-	-	-	-	-	-	-	-	-	-	-	-	3,2	3,6	
12th Floor West	1,4	1,2	1,4	1,2	1,4	1,2	1,4	1,2	1,4	1,2	1,4	1,2	1,4	1,2
	1,4	2,4	1,4	2,4	1,4	2,4	1,4	2,4	1,4	2,4	1,4	2,4	1,4	2,4
	1,4	3,6	1,4	3,6	1,4	3,6	1,4	3,6	-	-	1,4	3,6	1,4	3,6
	1,4	4,8	1,4	4,8	1,4	4,8	1,4	4,8	-	-	1,4	4,8	1,4	4,8
	2	1,2	2	1,2	2	1,2	2	1,2	2	1,2	2	1,2	2	1,2
	2	2,4	2	2,4	2	2,4	2	2,4	-	-	2	2,4	2	2,4
	-	-	-	-	2	3,6	2	3,6	-	-	2	3,6	2	3,6

	-	-	-	-	2	4,8	2	4,8	-	-	2	4,8	2	4,8
	2,6	1,2	2,6	1,2	2,6	1,2	2,6	1,2	2,6	1,2	2,6	1,2	2,6	1,2
	2,6	2,4	2,6	2,4	2,6	2,4	2,6	2,4	-	-	2,6	2,4	2,6	2,4
	-	-	-	-	-	-	2,6	3,6	-	-	-	-	2,6	3,6
	3,2	1,2	3,2	1,2	3,2	1,2	3,2	1,2	3,2	1,2	3,2	1,2	3,2	1,2
	-	-	3,2	2,4	-	-	3,2	2,4	-	-	-	-	3,2	2,4
	-	-	-	-	-	-	-	-	-	-	-	-	3,2	3,6
<b>4th Floor East</b>	1,4	1,2	1,4	1,2	1,4	1,2	1,4	1,2	1,4	1,2	1,4	1,2	1,4	1,2
	1,4	2,4	1,4	2,4	1,4	2,4	1,4	2,4	1,4	2,4	1,4	2,4	1,4	2,4
	1,4	3,6	-	-	-	-	1,4	3,6	1,4	3,6	1,4	3,6	1,4	3,6
	1,4	4,8	-	-	-	-	1,4	4,8	1,4	4,8	1,4	4,8	1,4	4,8
	2	1,2	2	1,2	2	1,2	2	1,2	2	1,2	2	1,2	2	1,2
	2	2,4	2	2,4	-	-	2	2,4	2	2,4	2	2,4	2	2,4
	-	-	-	-	-	-	2	3,6	2	3,6	-	-	2	3,6
	-	-	-	-	-	-	2	4,8	-	-	-	-	2	4,8
	2,6	1,2	2,6	1,2	2,6	1,2	2,6	1,2	2,6	1,2	2,6	1,2	2,6	1,2
	-	-	2,6	2,4	-	-	2,6	2,4	2,6	2,4	-	-	2,6	2,4
	-	-	-	-	-	-	2,6	3,6	-	-	-	-	2,6	3,6
	3,2	1,2	3,2	1,2	3,2	1,2	3,2	1,2	3,2	1,2	3,2	1,2	3,2	1,2
-	-	-	-	-	-	3,2	2,4	-	-	3,2	2,4	3,2	2,4	
<b>12th Floor East</b>	1,4	1,2	1,4	1,2	1,4	1,2	1,4	1,2	1,4	1,2	1,4	1,2	1,4	1,2
	1,4	2,4	1,4	2,4	1,4	2,4	1,4	2,4	1,4	2,4	1,4	2,4	1,4	2,4
	1,4	3,6	1,4	3,6	1,4	3,6	1,4	3,6	1,4	3,6	1,4	3,6	1,4	3,6
	1,4	4,8	1,4	4,8	1,4	4,8	1,4	4,8	1,4	4,8	1,4	4,8	1,4	4,8
	2	1,2	2	1,2	2	1,2	2	1,2	2	1,2	2	1,2	2	1,2
	2	2,4	2	2,4	-	-	2	2,4	2	2,4	2	2,4	2	2,4
	-	-	-	-	-	-	2	3,6	-	-	-	-	2	3,6
	-	-	-	-	-	-	2	4,8	-	-	-	-	2	4,8
	2,6	1,2	2,6	1,2	2,6	1,2	2,6	1,2	2,6	1,2	2,6	1,2	2,6	1,2
	2,6	2,4	2,6	2,4	-	-	2,6	2,4	2,6	2,4	-	-	2,6	2,4
	-	-	-	-	-	-	2,6	3,6	-	-	-	-	2,6	3,6
	3,2	1,2	3,2	1,2	3,2	1,2	3,2	1,2	3,2	1,2	3,2	1,2	3,2	1,2
-	-	-	-	-	-	3,2	2,4	-	-	3,2	2,4	3,2	2,4	
-	-	-	-	-	-	3,2	3,6	-	-	-	-	3,2	3,6	

Looking at Table 13, in all studied apartments, the geometry with the shortest length which was 1,2 m, met all the perquisites.

## 5 Discussion

This chapter discusses the effect of adding a sunspace on the daylighting performance in the studied apartments. The impact of the initial sunspace design is discussed in the following section along with the impact of the studied parameters.

### 5.1 Impact of the initial sunspace design

Adding the sunspace on the apartment building reduced the amount of daylight in the adjacent living space significantly. A more detailed explanation on each impact are presented below.

#### 5.1.1 Impact on the daylight factor

Adding sunspace and balcony which was deep and long gave a high reduction in the daylight factor of each studied spaces as it was expected. For all spaces in all four studied apartments, at least 50% of the daylight received in the space was lost due to the attached sunspace and balcony. This was then also affecting the result of the point DF which was required to be at least 1,2% according to Miljöbyggnad's Gold Building Certification in Sweden.

In the DF simulations, all orientations should give approximately the same value because it was conducted under a CIE overcast sky, which is isometric. But, another important factor is the surrounding context since this study was site and project specific. In this study, it was found that the average daylight factor on the fourth floor of the east-facing apartment was lower than the other cases. This was caused by obstructions from the nearby row houses on the southern side of the apartment tower and other buildings on the east side. This also explains that the twelfth floor of the east facing apartment had lower values compared to the west-facing apartments. On the west side, the apartment units do not have as many obstructions as on the east side.

Another important factor was the simplification of the studied model, since the iteration model was simplified into a rectangular shape, the area of the surface increased from the initial building model which caused even more reduction in the amount of daylight received inside the adjacent spaces. This explains why the simplified models had lower average DF values in most cases.

Looking at the transversal DF for all studied apartments that was also analyzed in the previous chapter, it was shown that the area closer to the glazing experienced the greatest reduction in the amount of daylight when the sunspace and balcony were added. The addition of sunspace and balcony blocked the light coming from the higher sky into the space, causing a smaller sky view angle to the area near the glazing. Although it can be seen from the transversal DF that the sunspace and balcony increased the uniformity especially in the living room as it was expected, the base case simulation results came out differently. The uniformity was rather the same. This might be caused by the northern windows that were not affected by the addition of the sunspace nor the balcony. The low daylight uniformity indicated that there were still high differences between all the DF values in the studied living spaces. The transversal DF only represents the areas that were directly

adjacent to the sunspace and balcony, therefore it could not be regarded as the overall situation of the studied space.

### **5.1.2 Impact on the daylight autonomy**

As discussed in the previous chapter, the addition of sunspace and balcony reduced the DA in all four studied apartments. The values were variable due to the studied space, occupancy schedule, orientations and floor heights. Lower values on the east apartments were observed. This was caused mainly by the occupancy schedule, which assumed that the living spaces in the apartment are mostly occupied in the evening. During the evening, the sun's position is more beneficial for the west-facing apartments, leaving the east apartments to have an extremely low values of DA in the kitchen, especially on the fourth floor apartment which was also shaded by obstruction from the surroundings. This is why performing parametric studies were important, to find the suitable solutions for each studied cases.

### **5.1.3 Impact on the point DF**

Without the sunspace and balcony, the point DF in each studied room reached the 1,2% point DF required by Miljöbyggnad Gold. After adding the sunspace and balcony, all the studied apartments were below 1,2% point DF which differs from the fact that the building is Miljöbyggnad Gold certified. This different values occurred because of different ways in determining the position of the point DF. In this thesis, the point DF of the living space was defined according to the Miljöbyggnad requirement, which was halfway of the room depth, 1 m away from the darkest wall and 0,8 m high above the floor. In this specific study case, the darkest wall was located in the living space which includes the living room and kitchen, both in the east and west apartments.

## **5.2 Impact of the studied parameters on the daylight conditions**

This section discusses the effect of the studied parameters, such as geometry, GWR, LRV, orientations and floor heights that were affecting the daylight conditions and electrical lighting consumption in the living room, kitchen and workshop.

### **5.2.1 The effect of varying geometry**

Overall, the geometry of the sunspace and balcony had the biggest influence on the daylight conditions in the adjacent spaces. The geometry is the most crucial aspect in designing an optimal sunspace according to this daylight study. The impact of geometry on each daylighting metrics are discussed separately.

#### **Daylight factor and point DF**

In general, increasing the depth and length of the sunspace and balcony, reduced the DF in all the studied spaces and point DF in the living spaces. For example, in the living space, if the 1,4 m depth and 1,2 m length was taken as the base value, then increasing the length to 2,4 m reduced the average DF by 26% and up to 40% when the length was increased to 4,8

m. When the depth and length were increased simultaneously to 2,0 m deep and 2,4 m long, the average DF was reduced by 50% and the reduction increased as the geometry was increased. The deeper and longer the balcony and sunspace were, the less daylight in the adjacent space. The same trend goes as well for the point DF, a reduction of the DF will lead to a reduction of the point DF of the living space because the position of the point is greatly affected by the sunspace and balcony.

### **Daylight Autonomy**

In all four studied apartments, the fourth floor east-facing apartment had lower average DA values compared to the other apartments, which was due to the shading by the surrounding buildings. The worst condition was found in the fourth floor east kitchen, but with varying the geometry, the average DA values increased when the sunspace and balcony geometry was reduced. For example, if the living room which had 1,4 m deep and 1,2 m long sunspace and balcony was taken as an example, increasing the depth to 2,0 m and length to 2,4 m, reduced the average DA up to 45% for the east apartments and 28% for the west apartments. Increasing the depth and length further resulted in larger reduction of the average DA.

### **Daylight uniformity ratio**

The higher uniformity was reached mostly by the cases which had higher GWR. It was expected that adding the sunspace and balcony would increase the daylight uniformity of the adjacent living space. But looking at the results, the sunspace and balcony did not have a significant effect on increasing the uniformity ratio. This is explained by the north corner windows that was not affected by the sunspace and gave the extra daylight in the living space.

### **Electrical lighting consumption**

The geometry had a large influence on the electrical lighting consumption, especially in the living room where the values were the highest. In all cases, increasing the depth and length of the balcony reduced the amount of daylight in the space which increased the needs of electrical lighting in the space when the 150 lux threshold was not achieved. During the day, the electrical lighting was less needed since the space was only occupied in the morning and in the evening during weekdays and for longer hours in the weekends. A higher average DA compared to the base case must be obtained to achieve a lower electrical lighting consumption. The geometry combinations that could ensure the lower electrical lighting consumption were the ones that had the shortest length (1,2 m). All the depths could still achieve a low electrical lighting consumption and high average DA by combining it with the length up to 2,4 m.

#### **5.2.2 Impact of varying the sunspace glazing ratio**

In general, DF and DA increased when the sunspace GWR increased. But in this study, the base case already had a high GWR, which was almost 60% on the outer balcony walls and 88% on the wall dividing the balcony and sunspace. This value of GWR is considered the maximum percentage if the original concept of having a greenhouse in the balcony is

respected. This also explains why 40%, 50% and 60% were the chosen variations to be studied for the GWR of the sunspace, because the less the GWR, less daylight is received in the adjacent living space. On smaller balconies with the least depth and length, the effect of varying GWR was not significant, because the living room windows that were adjacent to the balcony and sunspace were less obstructed. It has more impact on the larger balconies and sunspaces with the larger depth and longer length that were covering and shading the whole living room windows adjacent to the balcony and sunspace. For example, the increase from 40% to 60% GWR can increase the average DA by 12% and the average DF by 9% in the living room.

For the daylight uniformity, the variation in geometry had the most influence even though the results did not vary much. But, in each geometry combination, there were three different GWR that were analyzed. The higher uniformity in each geometry was mostly reached by the highest GWR, since the adjacent living space was still receiving high amount of daylight from the northern windows. The larger GWR the sunspace has, the more amount of daylight comes in to the adjacent living space, the more uniform the daylight conditions in the space is.

### **5.2.3 Impact of varying the light reflectance value**

Since the rest of the balcony already had high LRV for the surfaces and the single glazed sunspace already had a large light transmittance (LT) value, the surfaces that could be improved were the floor and ceiling LRV. The values were simultaneously increased to 40% for the floor, which was a high value for a floor, and the ceiling was increased to 80%. Studying the results, the increase of the balcony and sunspace LRV did not have a significant effect on daylighting, especially for smaller sunspace and balcony. It had more influence for cases with larger balconies, with deeper depth and longer length, for example 3,2 m deep and 4,8 m long, which allows more light to be reflected when it enters the balcony and sunspace to be distributed to the adjacent space.

So all in all, LRV is an important parameter when the main part of the daylight contribution comes from the internally reflected component, as is the case with the deep and long balcony.

### **5.2.4 Impact of varying the orientations and floor heights**

In a site and project specific study, orientation and floor height play important roles in the results, especially for the annual daylight simulations. It was observed that the east apartments had lower DF compared to the west apartments due to the obstructions on the east side. Orientation and floor height had larger influence on the annual daylight simulation. Since the studied building was an apartment, the studied living spaces, such as living room, kitchen and workshop, were only occupied during the morning before work and in the evening after the occupants got back from work. This explains why the east apartments, especially the fourth floor had lower average DA values compared to the other apartments. In the evening, when the living space was occupied the most, the sun is already setting down on the west side, giving the east side less amount of daylight due to the sun's position and the shading caused by the southern apartments that blocks light to come into the east apartments. The twelfth floor of the east apartment had higher average DA values

due to the less obstructions caused by the surroundings. For both floors on the west apartments, the average DA and DF were in the same range, which explains that in a less obstructed area, the different floor heights did not have a great impact.

### **5.2.5 Recommended sunspace and balcony design**

Based on Table 17 presented in the previous chapter, the recommended sunspace and balcony design for the four apartments are listed below:

- 4<sup>th</sup> floor west apartment
  1. 1,4 m deep and 1,2 m long
  2. 2,0 m deep and 1,2 m long
  3. 2,6 m deep and 1,2 m long
  4. 3,2 m deep and 1,2 m long
- 12<sup>th</sup> floor west apartment
  1. 1,4 m deep and 1,2 m long
  2. 1,4 m deep and 2,4 m long
  3. 2,0 m deep and 1,2 m long
  4. 2,6 m deep and 1,2 m long
  5. 3,2 m deep and 1,2 m long
- 4<sup>th</sup> floor east apartment
  1. 1,4 m deep and 1,2 m long
  2. 1,4 m deep and 2,4 m long
  3. 2,0 m deep and 1,2 m long
  4. 2,6 m deep and 1,2 m long
  5. 3,2 m deep and 1,2 m long
- 12<sup>th</sup> floor east apartment
  1. 1,4 m deep and 1,2 m long
  2. 1,4 m deep and 2,4 m long
  3. 1,4 m deep and 3,6 m long
  4. 1,4 m deep and 4,8 m long
  5. 2,0 m deep and 1,2 m long
  6. 2,6 m deep and 1,2 m long
  7. 3,2 m deep and 1,2 m long

In all four apartments, the depth that was combined with the length of 1,2 m, met all the prerequisites of the assigned daylight thresholds. These cases answered the second objective of this study which was to determine the sunspace design solutions which ensures acceptable daylighting based on building certification systems. The least the length and the depth of the sunspace, the better the daylight conditions in the building.

## 6 Conclusions

This study was conducted to investigate the impacts of having sunspace and balcony in multi-storey residential building on the daylighting performance in the adjacent living spaces. A second objective consisted of providing design solutions based on the parametric studies to improve the daylighting conditions. The series of parametric studies were performed using validated daylight simulation tool, Radiance and Daysim, which were integrated in Honeybee and Grasshopper along with Rhino3D.

From the simulation studies, having the actual sunspace (3,4 m deep and 3,8 m long) and balcony (3,4 m deep and 3,8 m long) attached to the apartment building, daylighting decreased by at least 50% on an overcast day. Since this study is a residential study and most of the spaces are unoccupied during the day, the threshold value for the daylight autonomy even for the building without a sunspace is relatively low compared to office buildings which could achieve a maximum DA value up to 80%. In the studied apartment building, without the sunspace, the living room in the west apartments had 26% average DA on both floors, whereas the east apartments had 23% on the fourth floor and 25% on the twelfth floor. These values were then the maximum average DA that could be reached by the sunspace design parametric studies.

After conducting the parametric studies to improve the daylight conditions by setting the threshold to reach the 1,2% point DF, 2,1% average DF, higher average DA and lower electrical lighting consumption, it was found that geometry was the most important factor affecting daylighting in the adjacent spaces. The next important factors were the glazing area and reflectance values. Orientation and floor heights had a larger impact on the results of the daylight autonomy study. The existing conditions, such as the surrounding buildings and type of ground surfaces had also large influence on the results.

Varying the geometry with different lengths and depths for the sunspace and balcony influenced the daylight conditions in the adjacent living space. Increasing the depth and length of the sunspace, reduced the amount of daylight received in the adjacent space which lead to an increase in the electrical lighting consumption. Based on the parametric studies, it is recommended to design sunspace with the least depth and the shortest length which gave the highest average DF and average DA in all spaces in all of the four studied apartments. The worst design for the daylight conditions was to have the sunspace and balcony with the largest depth and longest length, which caused a large reduction in the amount of daylight received in the adjacent space and an increase in the electrical lighting consumption.

The GWR and LRV in this study only gave a large difference when the sunspace and balcony had a large depth and length. The higher the GWR and LRV in the sunspace, the better the daylight conditions in the adjacent space.

The next studied parameters were the variation of orientation and floor heights, which also showed a large difference, especially on the east apartments, since this study was a site specific study. The west apartments had the same range on the results, but the east apartments had different values on the fourth and twelfth floor. This was caused by the site conditions with the surrounding buildings as obstruction to the lower east apartments. The surrounding conditions was also another factor affecting on the results.

In conclusion, in designing a sunspace and balcony, geometry is the most affecting parameter on the daylight conditions of the adjacent space. Other factors such as the sunspace GWR and LRV, apartment's orientation, floor heights and surrounding obstructions, are also affecting the daylight conditions in the adjacent space. Designing a sunspace and balcony should also consider the function of the space. The least depth and least length of the sunspace and balcony give the least daylight reduction in the adjacent space, but on the other hand it limits the function of the space due to the least space available. It is always important to take into account all affecting aspects to have a well performing sunspace and balcony.

### **Limitations and future work**

There were some limitations that were not taken into consideration in this study, such as the occupant behavior in the sunspace, shading caused by plants and the south oriented apartments. These limitations will of course affect the results when they are included in the simulations and analysis of generating best sunspace design solution. In the future, it is best to consider all the affecting parameters.

Another possible future work is to make the study more general and applicable to other projects. The study can be done in an unobstructed area for all the orientations. In this way, all orientations can have the recommended design based on the orientation solely. Besides that, there were northern windows that were not affected by the sunspace and the windows were placed in the northwest corner for the west apartments and northeast corner for the east apartments. This gave a really high amount of daylight received in the north corner area compared to the rest of the area in the living room and kitchen, which means that the daylight was not evenly distributed in the space and the uniformity value stayed low. To improve the uniformity, a future work that studies the placement of these windows needs to be conducted.

Another limitation was that no field study was conducted due to the actual building was still in the construction phase during this thesis work. A future work on having a validation study of the base case simulation result with on-site measurements study will be beneficial to determine the results validity of this study.

Besides the daylight studies, it is also important to analyze the impact and optimization of sunspace design based on the energy performances. Apart from this thesis, the ongoing research project at White Arkitekter analyses the energy performance of the living space adjacent to the sunspace. With the results from both daylight and energy performance, optimized sunspace design solutions for multi-storey residential building will be obtained. It will both provide adequate daylight conditions, as well as lower heating demand and overheating hours in the adjacent living spaces.

## 7 Summary

When it comes to low energy housing, especially in Northern European countries, conflicting topics in balancing daylight and energy in building arise. The energy performance is often prioritized, rather than the daylighting. Therefore, there is an immense need of studies that optimize both daylight and energy potential in buildings, especially in the residential sector. This thesis is a part of a research project at White Arkitekter AB which aims to develop design solutions for balancing the daylight and energy performances in the MKB's Greenhouse project in Malmö, Sweden.

MKB Greenhouse is a Miljöbyggnad Gold and Feby-Passive House certified multi-family housing that encourages urban-gardening in each apartment using the sunspace and balcony as the cultivation area. The literature studies showed that adding sunspace in buildings can cause serious problems, such as higher energy demand, overheating issues in the summer and reduction of daylighting in the adjacent spaces. On the contrary, if the sunspace is designed accordingly to the local climate and surrounding conditions, as well as taking into account the function and user behaviour, integrating a sunspace in a multi-storey residential building can provide benefits to reduce heating loads during the winter period, provide extra living and urban gardening spaces.

The lack of sunspace studies, especially about the impact on the daylighting conditions in the adjacent spaces formed this thesis research questions and objectives. Even though the main research idea is to balance both energy and daylight performance, this thesis only focused on the daylighting issues caused by the addition of sunspace and balcony in the Greenhouse apartment. Four apartments with different floor heights (fourth and twelfth floor) and orientations (west and east) were studied, simulated and analysed throughout this thesis. The first research question to be answered was the impact of the actual sunspace and balcony design on the daylight conditions in the adjacent living space, which were the living room, kitchen and workshop. The second research question is to develop design solutions based on the parametric studies to improve the daylighting conditions in the adjacent living spaces.

Answering the first research question, adding the sunspace on the apartment building reduced the amount of daylight in the adjacent living space significantly. For all spaces in all four studied apartments, at least 50% of the daylight received in the space was lost due to the attached sunspace and balcony. The worst condition was observed in the fourth floor east apartment's living spaces because of the existing buildings and southern apartments that shade and block the apartment from daylight. Looking at the transversal DF, where there were two sections cutting through the living room and kitchen, the greatest daylight reduction was found in the area nearest to the apartment's glazing when the sunspace and balcony were added to the building. Analyzing the point DF results, the simulations showed that only the fourth floor of the west apartment reached 1,0% DF according to BBR requirement and all the studied apartments were below the 1,2% point DF Miljöbyggnad Gold requirement. These findings were contradicting with the fact that the MKB Greenhouse is Miljöbyggnad Gold certified.

The average DA was also reduced in all studied apartments when the sunspace and balcony was added. For example, in the living room of both west apartments, the average DA was

reduced by 30% compared to the apartments without sunspace and balcony. The reduction of the average DA in the east apartments was even higher. The worst condition of the average DA was found in the fourth floor east apartment's kitchen. Reduction in the average DA caused higher electrical lighting consumption in all of the adjacent living spaces, since most of the daylight coming into the spaces was reduced by the sunspace and balcony addition.

Overall, looking at the actual sunspace and balcony design which is deep and long (3,30 m in depth and 3,85 m in length for each balcony and sunspace), there were serious issues with the daylighting condition in the living spaces, as expected. For that reason, it was even more crucial to perform parametric studies to provide sunspace design solutions that improve the daylighting conditions in the adjacent living space. Various geometry, glazing to wall ratio (GWR) and light reflectance value (LRV) of the sunspace and balcony were conducted in order to answer the second research question in developing sunspace and balcony design solutions to improve the daylighting performance in the adjacent living spaces.

Varying the geometry, GWR and LRV, there were 96 sunspace and balcony iteration cases in total. After conducting the parametric studies to improve the daylight conditions by setting the threshold to reach the 1,2% point DF, 2,1% average DF, higher average DA and lower electrical lighting consumption, it was found that geometry was the most important factor. The deeper and longer the balcony and sunspace were, the less daylight in the adjacent space. The next important factors were the glazing area and reflectance values. Orientation and floor heights had a larger effect more on the daylight autonomy study the surrounding and existing conditions on site have a large influence.

From this study, it is recommended to design a sunspace and balcony considering the geometry, with the least depth and length, while also considering the function of the sunspace and balcony. As an extra living and cultivation space, a sunspace and balcony should also still provide enough space but also not reducing most of the daylight that comes into the adjacent space. This is why the iterative process of the geometry of the sunspace plays important role in this study, since it was the most affecting factor compared to the other studied parameters.

In the future, the whole study in this thesis contributes to a larger research project at White Arkitekter AB, where the simulated daylight conditions results will then be compared with the actual measured ones and discussed further more with the energy performances. Other than that, the findings of this thesis will add knowledge about daylighting impact of sunspace design in one of the Scandinavian countries to the residential building and research sector. Improvements that can be done to this study is to include the energy part along with the daylight study, so an optimized result can be achieved as early as possible and also to include more affecting factors, such as different occupancy profile, different climate conditions, different surrounding conditions and shading from the vegetation in the sunspace and balcony.

All in all, in designing a functional and high-performing sunspace and balcony that do not cause issues to the adjacent space should always take into account all the determining aspects, climatically and functionally.

## 8 References

- Aelenei, D., Leal, H. d. A. & Aelenei, L., 2014. The use of attached-sunspaces in retrofitting design: the case of residential buildings in Portugal. *Energy Procedia*, pp. 1436-1441.
- Architecture 2030, 2016. *2030 PALETTE*. [Online]  
Available at: [http://2030palette.org/swatches/view/indirect-gain-sunspace/institute\\_for\\_forestry\\_1.jpg](http://2030palette.org/swatches/view/indirect-gain-sunspace/institute_for_forestry_1.jpg)
- Bailkey, M. & Nasr, J., 2000. *From Brownfields to Greenfields: Producing Food in North American Cities*, s.l.: Community Food Security News.
- Bataineh, K. M. & Fayez, N., 2011. Analysis of thermal performance of building attached sunspace. *Energy and Buildings*, pp. 1863-1868.
- Bioregional, 2016. *BedZED*. [Online]  
Available at: <http://www.bioregional.com/bedzed/>
- Bournas, I. & Haav, L., 2016. *Trade-offs between heating and daylighting when considering fenestration solutions for residential spaces*, s.l.: s.n.
- Boverket, 2015. *Boverkets byggregler*, Karlskrona: u.n.
- BREEAM-SE, 2013. *English Manual for New Construction and Refurbishment*, Sundbyberg: Sweden Green Building Council.
- Brown, G. Z. & DeKay, M., 2001. *Sun, Wind & Light: Architectural Design Strategies*. 2 red. New Jersey: John Wiley & Sons.
- Building Research Establishment, 2016. *What is BREEAM*. [Online]  
Available at: <http://www.breeam.com/>  
[Använd 10 August 2016].
- Bülow-Hübe, H., 2001. *Energy-Efficient Window Systems - Effects on Energy Use and Daylight in Buildings*, Lund: Lund University, Lund Institute of Technology.
- Cantin, F. & Dubois, M.-C., 2011. Daylighting metrics based on illuminance, distribution, glare and directivity. *Lighting Research and Technology*, pp. 291-307.
- CIE, 2016. *International Commission on Illumination*. [Online]  
Available at: <http://www.cie.co.at/index.php/LEFTMENU/About+us>  
[Använd 10 August 2016].
- Davidson, S., 2016. *About Grasshopper*. [Online]  
Available at: <http://www.grasshopper3d.com/>
- Efficient Windows Collaborative, 2016. *Window Technologies: Glass*. [Online]  
Available at: <http://www.commercialwindows.org/vt.php>  
[Accessed 10 August 2016].
- EnergyPlus, 2016. [Online]  
Available at: <https://energyplus.net/>

- European Commission, 2016. *Energy*. [Online]  
Available at: <http://ec.europa.eu/energy/en/topics/energy-efficiency/buildings/nearly-zero-energy-buildings>
- Fritz, R. & McNeil, A., 2016. *About Radiance*. [Online]  
Available at: <http://www.radiance-online.org/about>
- Howard, B. C., 2016. *Urban Farming Is Growing a Green Future*. [Online]  
Available at:  
[http://environment.nationalgeographic.com/environment/photos/urban-farming/#/earth-day-urban-farming-new-york-rooftop\\_51631\\_600x450.jpg](http://environment.nationalgeographic.com/environment/photos/urban-farming/#/earth-day-urban-farming-new-york-rooftop_51631_600x450.jpg)  
[Accessed 10 August 2016].
- IEA Task 20, 1999. *Solar Energy in Building Renovation*, London: James and James.
- Illuminating Engineering Society of North America, 2000. *Lighting Handbook: Ninth Edition*. New York: IESNA.
- Inhabitat, 2008. *BEDZED: Beddington Zero Energy Development in London*. [Online]  
Available at: <http://inhabitat.com/bedzed-beddington-zero-energy-development-london/>
- Iversen, A. o.a., 2013. *Daylight Calculations in Practice*, Copenhagen: Danish Building Research Institute.
- Jacobs, A., 2016. *Radiance Tutorial*. [Online]  
Available at:  
[http://www.jaloxa.eu/resources/radiance/documentation/docs/radiance\\_tutorial.pdf](http://www.jaloxa.eu/resources/radiance/documentation/docs/radiance_tutorial.pdf)
- Jaure, S., 1998. *Energy efficient renovation of buildings in Lyon and Marseilles*, s.l.: European directory of sustainable and energy efficient building.
- Jeffries, J., 2013. The use of Light Reflectance Values (LRVs) in achieving visual contrast. *Architectural Ironmogery*, Issue 130.
- Johansson, D., Bagge, H. & Lindstrij, L., 2011. *Measured Occupancy Levels in 18 Swedish Apartment Buildings-Application to Input Data for Building Simulations*. Sydney, Building Simulation, pp. 1730-1736.
- Jorgensen, O. B. & Hendriksen, O. J., 2000. *Glazed balconies and sunspaces - energy savers or energy wasters*. Copenhagen, u.n.
- Lechner, N., 2008. *Heating, Cooling, Lighting: Sustainable Design Methods for Architects*. New Jersey: Wiley.
- Lund Institute of Technology, 2016. *Derob-LTH*. [Online]  
Available at: <http://www.ebd.lth.se/english/research/software/derob-lth/>
- Löfberg, H. A., 1987. *Räkna med dagsljus*, Gävle: Statens Institut för Byggnadsforskning.
- Malmö Stad, 2016. *Ekostaden Augustenborg*. [Online]  
Available at: <http://malmo.se/English/Sustainable-City-Development-2016/Sustainable-City-Development/Augustenborg-Eco-City.html>  
[Accessed 10 August 2016].
- Mardaljevic, J., 1998. *Rendering with Radiance: A Practical Tool for Global Illumination*, Orlando: u.n.

- Mardaljevic, J., 2000. Simulation of annual daylighting. *Lighting Research and Technology*, pp. 32: 111-118.
- Mardaljevic, J., 2006. *Examples of climate-based daylight modelling*. London, CIBSE National Conference.
- Mihalakakou, G., 2002. On the use of sunspace for space heating/cooling in Europe. *Renewable Energy*, pp. 415-429.
- MKB Fastighets AB, 2016. *Greenhouse*. [Online]  
Available at:  
[https://www.mkbfastighet.se/globalassets/nyproduktion/greenhouse/faktablad-gh-150224\\_eng.pdf](https://www.mkbfastighet.se/globalassets/nyproduktion/greenhouse/faktablad-gh-150224_eng.pdf)
- NCC Construction Sverige AB, 2014. *Energiberäkning: Greenhouse, Malmö-Byggnad 1*, u.o.: u.n.
- New Buildings Institute, 2016. *Analysis Methods*. [Online]  
Available at: <http://patternguide.advancedbuildings.net/using-this-guide/analysis-methods/daylight-factor>
- Reinhart, C., 2016. *Highlights*. [Online]  
Available at: <http://daysim.ning.com/>
- Reinhart, C. F., Mardaljevic, J. & Rogers, Z., 2006. Dynamic daylight performance metrics for sustainable building design. *Leukos*, pp. 3: 1-25.
- Reinhart, C. & Wienold, J., 2011. The Daylighting Dashboard: A simulation-based design analysis for daylighted spaces. *Building and Environment*, pp. 46: 386-396.
- Robert McNeel & Associates, 2016. *Rhino 5 Features*. [Online]  
Available at: <https://www.rhino3d.com/features>
- Sadeghipour Roudsari, M. & Pak, M., 2013. *Ladybug: a parametric environmental plugin for grasshopper to help designers create an environmentally-conscious design*. Lyon, u.n.
- Santamouris, M. o.a., 1994. Energy characteristics and savings potential in office buildings. *Solar Energy*, pp. 59-66.
- Solem LLC, 2016. *What is DIVA-for-Rhino?*. [Online]  
Available at: <http://diva4rhino.com/>
- Sweden Green Building Council, 2014. *Miljöbyggnad - Bedömningskriterier för nyproducerade byggnader.*, Stockholm: Sweden Green Building Council.
- The Engineering Toolbox, 2016. *The Engineering Toolbox*. [Online]  
Available at: [http://www.engineeringtoolbox.com/light-level-rooms-d\\_708.html](http://www.engineeringtoolbox.com/light-level-rooms-d_708.html)  
[Använd 23 12 2016].
- Tregenza, P. & Wilson, M., 2011. *Daylighting: Architecture and Lighting Design*. Oxon: Routledge.
- U.S. Department of Energy, 2016. *EnergyPlus Energy Simulation Software*. [Online]  
Available at: <http://apps1.eere.energy.gov/buildings/energyplus/>

- Vanhoutteghem, L., Skarning, G. C. J., Hviid, C. A. & Svendsen, S., 2015. Impact of facade window design on energy, daylighting and thermal comfort in nearly zero-energy houses. *Energy and Building*, pp. 149-156.
- Wilson, M. P., Jorgensen, O. B. & Johannesen, G., 2000. Daylighting-energy and glazed balconies: a study of a refurbishment project in Engelsby, near Flensburg, Germany. *Lighting Research & Technology*, pp. 127-132.
- Zitzler, E., Marco, L. & Lothar, T., 2001. *SPEA2: Improving the Strength Pareto Evolutionary Algorithm*, Zurich: Swiss Federal Institute of Technology.



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