POLITECNICO DI TORINO

Master of Science program in ARCHITECTURE FOR THE RESTORATION AND ENHANCEMENT OF HERITAGE

Thesis of Master degree

Evaluation and Optimization of Daylighting in Heritage Buildings; a Case Study at High Latitudes

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Abstract

Adapted reuse of heritage and historical buildings has been a major problem since the condition of degradation is generally severe, and recommended retrofitting is implemented with the great purpose of maintaining the building's authenticity. The main purpose of the thesis is to create users' daylight availability as well as make minimum changes on the historical building to penetrate daylight inside the building. Improvement of daylight adaptation strategies would influence space daylight conditions and would facilitate buildings to be more liveable.

However, the architectural solution for heritage buildings has its restrictions in that specific rules must be followed, particularly when the building looks to be the least maintained for many years. This research studied the daylight condition of the historical and iconic building in Trondheim (Norway) and discovered the most practical solutions for daylighting challenges in the present condition of the case study building. The daylight was measured using a luminance meter and the data collected was descriptively examined by comparing to the associated references in order to achieve the best possible result. Based on the measurements that have been conducted, it was shown that the daylight level on the base case was below the standard and the current solution for this problem was implementing the atrium. Although this research proposes several solutions to overcome the problems, the latter solution is considered as the most feasible solution to treat heritage buildings to be suitable daylight and visually comfortable buildings without major alterations in building fabrics as studied buildings are listed as National Heritage Monuments.

The daylight metrics of Spatial Daylight Autonomy (sDA), Annual Sunlight Exposure (ASE), and Daylight Factor (DF) was studied and results were compared. The daylight metrics used for this study were in accordance with the Leedv4.1 option1 and EN17037 rules, as well as some of the most extensively used certification methods in the construction sector. Simulations by using computer software Climatestudio and Honeybee in Grasshopper were conducted. for daylight availability in the case study. The parametric investigations were focused on six possible scenarios based on the atrium geometries in order to address the questions that led this inquiry. After comparison, the results of the best scenario in terms of providing efficient daylight were selected. The atrium in the selected scenario was optimized through genetic algorithms using Galapagos. The results after optimization were showed that daylight condition, sDA was improved from 14% in the base case to 50.2% after optimization.

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List of acronyms

ASE	Annual Sunlight Exposure [%]
DF	Daylight Factor [%]
sDA	Spatial Daylight Autonomy [%]
DA	Daylight Autonomy [%]
IES	The Illuminating Engineering Society
EPW	Energy Plus Weather files
GH	Grasshopper
HB	Honeybee
LB	Ladybug
U-value	Heat transmission coefficient [W/m²K]
Tvis	Visible Transmittance
m	meter

1. Introduction

The research has a strong emphasis on the intersection of cultural heritage preservation and environmental engineering, as evidenced by the thesis that accompanies the project activity.

Adapted reuse of old historical buildings had been a major problem because the condition of deterioration is frequently found to be severe, and suggested retrofitting is implemented with extreme caution in order to preserve the building's individuality. Furthermore, for changing the building function, extra considerations are required to meet the new needs. daylight availability for users has specific relevance in historical buildings for conceiving the huge artistic content within the interior spaces. To date, age of rapid technological advancement and numerous environmental challenges, it is becoming increasingly important to raise awareness of the values inherent in heritage buildings and also preserve these values while increasing daylight availability in large and deep buildings. In order to achieve this, the atrium plays a critical role in improving the lighting situation.

Today, the usability of the atrium is most usually linked with commercial or public buildings, as atria are commonly employed as significant architectural features in main entrances, public circulation spaces, or as specific destinations within a structure (*Atrium | WBDG - Whole Building Design Guide*, 2021). In fact, many of today's large-scale buildings are designed with atria.

An atrium is typically a large, multi-story, glass-roofed room used to bring daylight into large buildings where sidelight alone cannot penetrate enough (Norbert, 2015). The atrium provides many practical function for a building, such as a source of natural ventilation that can help maintain thermal comfort (Pilechiha et al., 2021), a buffer space to reduce energy losses and consumption, and introducing daylight into the building's core. The atrium's multifunctionality is what distinguishes it as a complicated object worthy of investigation.

There are numerous subjective and objective reasons for daylight buildings. Such as the quantitative energy savings, light quality, health and well-being, and environmental benefits of daylighting in buildings are undeniable. There are also other compelling reasons to promote daylighting.

Light is more than just a revealed of form, its rhythms are vital to existence. Every day, light resets our biological clocks and influences numerous biological and psychological processes in humans. The way architecture admits light puts us in contact with the sky and the horizon, allowing for a wide range of human interpretation and meaning. The most fundamental presence of nature in our existence is light's cycles, the length of the day, the strength of the sun, and seasonal patterns of sky cover (Dekay, 2010).

Therefore, the focus of this thesis is on daylighting and how various parameters influence the dispersion of daylight from the atrium into surrounding areas, as well as optimizing the daylighting condition in the early stage of the restoration process in historical buildings.

1.1. Background

Heritage is regarded as a highly precious treasure, and it is our responsibility to conserve it for future generations. Neglected heritage buildings may expose the heritage to further deterioration. Therefore, adaptive reuse of heritage was thought to be favorable to the preservation of the buildings. However, adapting to the new occupancy conditions is difficult, creating minimal alteration could help to keep the historical building's originality. With the goal of improving potential occupancy's positive experience, it is critical to provide daylit spaces that promote daylight conditions without sacrificing identity.

Using daylight as part of architectural design has always been critical, not only to reduce energy consumption for cooling and heating but also to improve interior environmental quality by incorporating passive design solutions early in the design process. Therefore, an atrium can be a significant source of daylight for deep and dark plans, as well as provide other environmental benefits like solar gain, reduced energy losses, and natural ventilation.

Bringing natural light into buildings is thus one of the many critical characteristics of a sustainable structure, and most environmental building certifications grant daylighting levels. However, designing atria to achieve an optimal degree of natural light within a building can be difficult because of the numerous aspects that influence light distribution. Spatially the case study is a heritage building.

This thesis aims to propose possible improvements in an atrium of the building located in the city center of Trondheim which was a dark and iconic building.

1.2. Research Objectives

This work will be useful for designers, architects, facade engineers, and students who are working on or researching daylight conditions in existing buildings.

The primary goal of the research was to develop simple, easy-to-implement approaches for improving daylight conditions in heritage buildings, as well as to assist architects and designers in easily comparing the percentage of daylight availability and other variables to choose between scenarios based on their needs and restoration rules.

In addition, this tool will help the designer to integrate the view matter at the very beginning of the project. The actual tendency in project design is to integrate all the study fields at the very beginning of a project, knowing that the daylight situation now has a significant impact on decision-making in architectural projects.

Therefore, the specific objectives were;

- Comparison of the simulation tools related to suitable daylight simulation.
- Finding the suitable alternative that can yield optimum conditions of daylight.
- Optimizing the alternative parameters
- Preparing recommendations in order to improve daylight condition in high latitude

1.3 Main research question and research sub-questions

2. How to improve daylight conditions in heritage building locations in high latitude?
3. Which simulation tools are most suitable for daylighting simulation?
4. Which scenario can yield optimum conditions of daylighting inside of the building?
5. How do daylight conditions optimize scenarios in terms of daylight availability?
6. How to achieve accurate results?

2. Literature review

Lighting comfort has a significant impact on visual functions in buildings. A suitable percentage of natural light is beneficial to occupants' health and productivity. Furthermore, a high level of daytime autonomy leads to lower operating expenses and reduces the electrical lighting demand. With the use of daylight(Bastian et al., 2022) questions about lighting may be answered early on in the design phase. The following text is devoted to research and literature pertaining to the thesis's topic.

An atrium can be a significant source of natural light and In the last 40 years, the atrium has become one of the most popular architectural forms(Medvedeva & Kolesnikov, 2021). it is a style that can be seen in a range of building types all around the world.

(Sharples & Lash, 2007) in their critical evaluation of daylight in atrium buildings, determined that supplementing artificial lighting consumption with daylight is a crucial component of environmental and sustainable solutions to a building's energy performance (Sharples & Lash, 2007). But designer achieves this in an efficient manner with atria buildings by creating: The roof fenestration system, the geometry of the atrium well, the reflectance of the well's surfaces, and the daylight levels achieved in spaces close to the well are the primary atrium components for daylight design. The amount of daylight in these locations is determined not only by the aforementioned characteristics but also by the daylight access (Samant, 2010).

In their study in atrium building design, they found that (Calcagni & Paroncini, 2004) Due to the considerable extension of openings and windows with high transmittance within the atrium wells, increasing reflectance values of atrium surfaces do not generate a substantial improvement in the daylight factor levels on the atrium's bottom floor. Because the number of surfaces that could potentially reflect light is so small, they have a negligible impact on the (Calcagni & Paroncini, 2004) daylight factor. This coincides (Cole, 1990). By reducing the size of the openings on the higher levels of the atrium well, more light can bounce off and down into the well. This was also (Susa-Páez & Piderit-Moreno, 2020) verified, he discovered that having smaller windows on the top levels of the atrium results in the atrium facade reflecting more light.

Also according to his research field (Cole, 1990), Increasing the reflectance of an atrium's ground floor has a significant impact on increasing daylight levels in neighbouring places.

(Du & Sharples, 2010) Physical measurements on a scale model and computer-generated daylight simulations on a 3D model using the raytracing program Radiance were used to compare the vertical sky component. Their findings revealed that the scale model's measured values matched the simulated data well. Indeed, as daylighting has become a significant aspect of sustainable/green building certification credits, and it is difficult to evaluate the quality and quantity of daylight in a space using basic rules of thumb, more and more emphasis has been paid to daylight simulation software in recent years.

(Christoph F. Reinhart & Fitz, 2004)A survey on the use of daylight simulation programs was conducted online. A total of 42 different daylight simulation software was listed by the 134 participants who used computer simulation tools for day-lighting design, according to the survey, which included 193 participants (from various countries) in the fields of architecture, engineering, daylight design consulting, and academic research. The Radiance tool or Radiance-based tools were the most popular.

In their research (Younis et al., 2019) Light from the sky, light reflected from the atrium walls, and light reflected from the atrium floor are the three most important components for daylighting rooms adjacent to an atrium well. As the angle to the direct sky increases in the lower levels of an atrium, reflected light sources become even more important. As a result, high reflectivity ratings on these surfaces, as well as the ceilings of surrounding spaces, are critical.

In a daylight building design guide published by the European Directorate-General for Energy, many architectural considerations for daylight optimization are discussed, including the advantages of using light shelves to divert incoming light towards the ceiling while also providing shade for the region of the room closest to the window. They also mention that the light shelf's underside can redirect light from a high-reflectance exterior ground surface onto the room's floor, and that a light shelf is most efficient when it is external, causes minimal obstruction to the window area, has specular reflective surfaces, and is combined with a high-reflectance ceiling. Furthermore, they claim that internal light shelves are ineffective since they block sunshine from entering the room while offering minimal compensation.

R. Saxon (1986) mentions in his book Atrium Buildings – Development and Design, that Within an overall volume, there is a trade-off between plan depth and story height, and boosting ceiling levels from 2.7m to 3.6m can provide good light up to 9 m into the plan.

Various parameters influence the distribution of daylight within buildings, and many methods are available for design and modeling, as evidenced by the research reviewed. The preceding literature analysis only highlights some of the sources that were used to determine which parameters to investigate for this thesis. The goal of this research is to confirm the effect of the parameters provided in the literature while also introducing other parameters of interest. The thesis also seeks to find a user-friendly simulation tool that is well-suited for replicating daylight within atria and adjacent places while also integrating effectively with the 3D modeling tool.

2.1. Basic concepts of daylight

A few terms utilized throughout this thesis and common to the study of daylight are discussed in the next section. Later on, more concepts will be introduced.

2.2. Sources of daylight

Direct and indirect daylight sources are the two types of daylight available. Direct daylight comes from diffuse skylight from the earth's atmosphere or direct sunlight, whereas indirect daylight comes from reflective surfaces like the pavement in front of a window or the wall opposite a window. Higher glazing ratios on southern façades allow more direct daylight to enter a structure, allowing for winter heating and a brighter environment, but also raising the danger of overheating in the summer and glare. An atrium with a wide view of the sky will allow both direct and diffuse daylight into the structure, while well-designed atrium surfaces that maximize the reflected component of daylight will improve the advantage of indirect daylight at lower floors. Direct daylight is used in the higher parts of an atrium, while indirect reflected daylight is used in the bottom parts.

2.3. Reflectance and transmittance

Light is reflected, transmitted, or absorbed as it reaches a surface. The reflectance factor is defined as the "ratio of reflected flux to incident flux" and ranges from 0 to 1. It determines how much light is reflected, whereas transmittance is a measurement of how much light flows through a surface. Finally, a surface's light absorbency is a measurement of how much light is absorbed by it. In most cases, the absorbed light is converted to heat. Some light will always be reflected by a surface. A white surface, for example, has a reflectance factor of 0.85, whereas a black surface has a value of 0.5. The reflectance of a surface can only tell you how much light is reflected, not how it is reflected.

The way light is reflected is determined by the surface feature. A highly polished surface, for example, will produce specular reflections, whereas matte surfaces will scatter light and produce diffuse reflections. Because the view to the sky is limited, we rely on indirect light reflected off the atrium surfaces to reach the surrounding rooms of an atrium well, especially at the lower floors. Choosing surfaces with high reflectivity but low specular values (to avoid glare) will help to bring light deep into a structure (Norouziasas, 2021). Furthermore, the amount of light in those adjacent spaces is determined by the percentage of light transmitted by the glazing through which the light flows.

2.4. Daylight aspects

A good daylighting strategy should have just as much focus on the quality of light as it does on the quantity of light within a space. In a design brief from the Architectural Energy Corporation on understanding daylight metrics, the quantitative and qualitative aspects of daylight are defined. The quantitative aspects of daylight are defined by metrics that shape the luminous environment, or in other words, metrics that give a sense of how we perceive light within a space. Metrics such as illuminance, the daylight factor, and various daylight autonomy hybrids are used to give a general sense of the daylight quantity, whereas the qualitative aspects of daylight are defined by metrics that shape the luminous environment, or in other words, metrics that give a sense of how we perceive light within a space. The color, contrast, and temperature of light within a room, as well as the homogeneity of light within a room, all influence the inhabitants' comfort in a daylit area.

The light environment is portrayed in a variety of ways. The color of the light chosen for an application is a significant part of how people experience light in a room (Lindahl et al., 2021). The color and temperature of light in a room are obviously important, and they should be kept at levels that do not inflict pain or strain on the eyes of people performing jobs in the space. "The color appearance of illumination is determined not only by the color of light, but also by the intensity of the light. The various types of illumination are assigned a color temperature." The appearance of illumination levels above 4000 kelvin is quite visible (K). This color temperature is commonly referred to as neutral white, while temperatures above 6000 K are referred to as daylight white (Davoodi et al., 2020).

The amount of light contrast in a room is also crucial. The ratio of background light to foreground light in a space is represented by the contrast of light within that space, where background light (or ambient light) is the light that provides back-ground illumination and foreground light (or task light) is the light required to provide the right level of sharpness within a room. The difference between the maximum and least brightness divided by the lower value is how light contrast is calculated mathematically. Ambient light levels should generally be kept between one-half and two-thirds of task light to achieve acceptable quality contrast levels in a setting (Medvedeva & Kolesnikov, 2021).

It's equally as crucial to keep certain homogeneity values. The ratio between the minimum illuminance (or daylight factor) value and the average illuminance (or daylight factor) value, both of which are measured over a horizontal working plane within a space, determines the homogeneity of light within that space. Maintaining adequate light homogeneity entails limiting high-intensity zones of brightness over the workplane5 while simultaneously ensuring that dark zones, typically in the back of a room, do not arise. High-intensity daylight zones, whether they appear on the work plane, the floor, or even the walls or ceiling, can make occupants uncomfortable. This is referred to as glare. Glare is defined as "a condition of vision in which there is discomfort or a loss in the capacity to perceive details or objects, as a result of an inadequate distribution or range of brightness, or excessive contrasts." (Dubois, 2003). Glare induced by daylight can normally be regulated with the proper installation of shade mechanisms, which should not cause patches of light (dark or bright) across the work plane, as this will aggravate occupants.

2.5. Daylight advantages in building

Atria are important components in introducing natural light into deep-plan structures, as has been highlighted multiple times, but what are some of the benefits of bringing the daylight into buildings? The aim of daylighting is well-explained in the LEED certification6 daylighting chapter. "The goal of the daylighting chapter is to connect building inhabitants with the outdoors, reinforce circadian cycles, and reduce the usage of electrical lighting by bringing the daylight into the area," says (USGBC, 2020). To grasp the significance of bright daylight in a structure, one must consider it in the context of sustainability. The following sections highlight three dimensions of sustainability: environmental, social, and economic, all of which are related to the benefits of bringing the daylight into a building.

2.6. Daylight and environment

One important aspect of the environmentally-conscious design is allowing for the reduction of artificial light in a building by introducing daylight into it. To put in perspective the amount of artificial lighting in use by today's society, one can simply look at the electricity consumption of this light source. The International Energy Agency states that artificial lighting represents almost 20% of global electricity consumption, which is similar to the amount of electricity generated globally by nuclear power on an annual basis (IESNA, 2018). Not only is the use of energy resources immense, artificial lighting systems also come with a great deal of waste. In an article on environmental repercussions of artificial lighting, (Russart & Nelson, 2018) highlights three forms of waste produced by artificial lighting, in terms of material waste (bulbs and the lighting system), energy consumption (heat, UV and electromagnetic radiation), and light pollution (Russart & Nelson, 2018). The excessive heat produced by artificial lighting systems increases the cooling loads on the mechanical cooling system of a building. Reducing the usage of artificial lighting can potentially reduce building cooling loads by 10–20% (Gregg D. Ander, 2016). Reducing the energy consumption of a building by implementing daylighting strategies create the potential for reducing carbon dioxide emissions, which ultimately reduces greenhouse effects.

2.7. Distribution of daylight in the atrium

The atrium is a design element that promotes the three components of building sustainability: social, environmental, and economic. Furthermore, it introduces a series of other benefits such as visual permeability between inner facades and inviting environments that are naturally lit into the spaces that face the atrium, thus positively affecting the occupants' productivity as well as introducing a series of other benefits such as visual permeability between inner facades and inviting environments that are naturally lit. (Samant, 2011). However, atria have not always been considered in architectural design. Although it was once widely used as a location to stimulate social contact in earlier civilizations, it was revived in the last 30 years primarily to improve the daylighting capacities of interior building areas (Sharples & Lash, 2007).

According to (Susa-Páez & Piderit-Moreno, 2020) Sky conditions, geometry, roof structures, and the characteristics of an atrium's enclosing surfaces are all essential considerations that can have a significant impact on the quantity and quality of daylight in the space. The sky plays a vital role because it is the source of light that is emitted towards the structure, whether direct or diffuse (Lorenz et al., 2019). Because some aspects, like as geometry, tend to follow the shape of the building, the atrium quality is frequently tied to the exterior envelope or the plan layout. Poorly constructed and aligned roof structures also reduce the amount of daylight available in adjacent spaces. (Sharples & Shea, 1999).

Finally, the atrium's surfaces can help with light reflection, especially on the lower levels, where the internally reflected component is the dominant (IRC) (Samant, 2011).

2.7.1. Geometry of atrium

The well index (WI) is a numerical method of describing the geometry of the atria. The height (H), width (W), and length (L) of the atrium can be used to establish the well index, which expresses the relationship between the light-admitting area, i.e. the area that is open to the sky, and the surfaces of the atrium well (Du & Sharples, 2010)(Calcagni & Paroncini, 2004). The equation was as follow:

Equation 1:

$$WI=.\ \frac{H*(W+L)}{2*W*L}$$

A greater well index indicates that the atrium space is deep and narrow, resulting in low levels of daylight at the atrium's base. A low well index, on the other hand, implies that the atrium is shallow and wide in proportion to its height, allowing more light into the atrium and its adjacent spaces (Wang et al., 2019).

There are more indicators for describing atrium geometry, such as the plan aspect ratio (PAR) and the section aspect ratio (SAR). The height-to-width ratio is defined as the SAR, whereas the width-to-length ratio is specified as the PAR. The well index can be expressed in terms of the SAR and PAR as follows:

Equation 2:

$$WI = \frac{H*(w+L)}{2*W*L} = \frac{1}{2}\frac{H}{W}\left(1+\frac{W}{L}\right) = 0.5SAR(1+PAR)$$

Because the well index incorporates the two aspect ratios, the WI is the most widely used geometric indicator.

2.8. Parametric design tools

When we say parametric, we're referring to a variety of different answers. We obtain them by manipulating various input parameters and changing them using algorithms. As a result, an algorithmic design process consists of a set of input parameters that are then passed through mathematical simulations to produce a set of outputs.

The parametric design method allows you to generate a large number of possibilities and visualize the final outcomes in record time. It is determined by the relationships between the various parameters and the design's aim.

2.9. Daylight in standards and certifications

This section outlines some of the thesis' concepts. The certification used in this study, as well as concepts connected to daylight metrics, are supposed to be quality indicators for the lighting performance and visual comfort of office buildings.

2.9.1. BREEAM

The BREEAM certification standard is a British certification standard. It mainly focuses on three factors: the environmental (66%), economic (5%) and social (29%) aspects and also on the use of resources, where the biodiversity for BREEAM is more important than in other certifications.

2.9.2. LEEDv4.1

LEED (Leadership in Energy and Environmental Design) is an American certification standard for sustainable building certifications. This standard considers energy usage, as well as occupant comfort and other factors. It focuses on the environmental (52%), economic (5%), and social (43%) aspects.

LEED presents criteria for dynamic assessment of daylight amount and quality through computer simulations in its most recent version. The criteria for good daylight can be met by selecting one of three choices presented in the certification. Annual computer simulations must be done in the first option to demonstrate that sufficient amounts of spatial daylight autonomy exist. and annual sunlight exposure (ASE) are obtained on particular floor regions the second alternative requires the designer to demonstrate through computer modeling that illuminance levels will be between 300 and 3000 lux for certain floor sections between 9 a.m. and 3 p.m. on a clear-sky day during the equinox. The last choice necessitates illuminance levels ranging from 300 to 3000 lux for a specific floor area at any time between 9 a.m. and 3 p.m. for a suitable work plane height. Two measurements must be taken as indicated in the certification for this option.

2.9.3. EN17037

The European Committee for Standardization (CEN) produced EN 17037, a unified daylighting standard, in 2018. (CEN 17037:2018). It includes four characteristics of daylight in buildings: daylight provision, perspectives, sunlight access, and glare prevention.

3. Methodology

3.1. Case study and location

This research has been studied one of the oldest and biggest wharfs namely Huitfeldtbrygga in Trondheim, Norway. Huitfeldtbrygga is currently vacant and undergoing renovations. It is listed as a protection class A building, which indicates it is regarded as one of Trondheim's most worthy of preservation.

The building is located in the center of the city. Kjøpmannsgata 13, also known as Huitfeldtbrygga, is one of the piers furthest south in Kjøpmannsgata. It also stands out in the row of wharves because it consists of three wharves built under the same roof that appears to be the most skewed.

The wharf has an area of about 1900 square meters. The building consists of four floors, basements, and an attic. The west wall facing the street which consists of two levels, separated, wide, and sloping central. In the middle, trees were planted that would also preserve as a spark trap. This was done to prevent the economically important piers from catching fire in the event of a fire in the city. but the east wall, facing the river Nidelva.

The building is special in itself as there are a few other wharves from the 18th century and this building is an important part of the building environment in Kjøpmannsgata which for many years the building was unused and appears to be the least maintained of the building in Kjøpmannsgata.

This thesis provided documentation that can be used as a proposal to improve daylight conditions in iconic and historical buildings. The research has a pronounced focus on improving daylight in heritage and architectural structures(*Huitfeldtbrygga - Huitfeldtbrygga*, n.d.).

In Figure 1, the photo was taken from Old Town Bridge that shows the view of the Nidelva river and Kjøpmannsgata.

Figure 1. Old storehouses flanking both sides of this river

Figure 2 and Figure 3 show the building from the street and river, respectively. The location of Huitfldtbrygga was shown in Figure 3 illustrates the position of the building in Trondheim and Norway.

Figure 2. Huitfeldtbrygga at Kjøpmannsgata 13

Figure 3. Situation of Kjøpmannsgata 13 in Trondheim

3.1.1. History and interventions

Figure 4. Maschius copper engraving, 1674

3.1.1.1. The 16th century

Trondheim saw a severe city fire in 1681. The king commissioned Johan Caspar von Cicignon to reconstruct Trondheim, and the row of wharves on Kjøpmannsgata was created according to his city design. To prevent any additional fire threats, fire safety measures were implemented, and the wharves on Kjøpmannsgata were erected at a lower elevation, parallel with a line of trees on the top of the hill. Trondheim has recently had multiple city fires, both huge and minor. Several of Kjøpmannsgata's older wharves were destroyed in both 1967 and 1983. As a result, Huitfeldtbrygga is regarded as a very valuable and significant reminiscence of a bygone age (*Historien - Huitfeldtbrygga*, 2022).

3.1.1.2. The 17th century

Kjøpmannsgata was the city's most significant street at the time, housing many of the city's traders ("Merchants' Street"). Henrik Hornemann (1644-1716) arrived to Norway from Germany and became one of the city's most powerful merchants. One of his relatives, Henrich Hornemann, was the first owner of Huitfeldtbrygga. From 1766, he is mentioned as the owner in the Fire Tax Register. Huitfeldtbrygga was erected in the 1740s for Governor

Hans Hagerup, according to the City Antiquarian. Later in the 17th century, many more proprietors were also documented(*Historien - Huitfeldtbrygga*, 2022).

3.1.1.3. The 18th century

In 1830, Nicolay Heinrich Knudtzon (1787-1837), a Kristiansund trader known for his fish exports, purchased Huitfeldtbrygga. He and his ancestors built a fortune through dried and salted cod exports (clipfish). Consul Arild Christopher Huitfeldt took over the wharf in 1840. (1813-1877). The wharf was in good shape and had substantially risen in value, according to the Fire Tax Memorandum of 1841. Huitfeldt resided in Huitfeldtgrden, Kjøpmannsgata 14 in Stockholm. He was a successful businessman. At several places in Trndelag, he was active in timber processing, extraction and export of other materials and pyrite from his own mines, fertiliser manufacture, brickwork, and pattern farming. Despite this, Huitfeldt's major interest was the factory on Kjøpmannsgata, which was created by Huitfeldt's father-in-law, but Huitfeldt was the principal stakeholder and manager. Huitfeldtbrygga built a steamboat and a locomotive, but during Huitfeldt's period, the company was most renowned for its timber industry. The first and second levels were united in 1878, according to the Fire Tax Register, most likely to make additional room for the timber industry. The significance of the wharf shifted around the end of the nineteenth century due to changes in transportation; the sea route was no longer the most significant. The wharves were now used as warehouses rather than ports(*Historien - Huitfeldtbrygga*, 2022).

3.1.1.4. The 19th century

Ivar Huitfeldt, Henrik's son, carried on his father's heritage. In the 1900s, the firm had a financial collapse, and Huitfeldt no longer used the dock alone, but also rented out storage space. The dock was sold to Master Glazier Andreas L. Riis in 1937 as part of the bankruptcy estate of A. Huitfeldt & Co. The change of ownership resulted in additional reallocation of space at the port. Because automobile ownership had grown increasingly common, the wharf was also modified to allow items to be backed in at ground level. Huitfeldtbrygga has had a variety of owners since Riis.

3.1.1.5. The 20th century

The wharf shows the marks of 40-50 years of neglect. The foundation alignment of the wharf's bearers supports, and tie beams are in catastrophic condition. The external timber walls are very decayed, and there are roof leaks. The wharf slopes towards the water, and where it is the worst, it appears to be 1.5 metres lower than it should be.

Lord Eiendom A/s acquired 100 percent control of the wharf in 2016. The wharf's foundation was reinforced with steel formwork supports in the autumn of 2016, and emergency repairs were performed. A three-year plan is being developed to restore the wharf to its original location. It has to be jacked up, and plans are being developed for new foundations, new wood walls, a new roof, and cladding and window repairs. The construction is scheduled to take place between 2018 and 2021.

Trondheim's City Antiquarian will provide helpful information and guidance. The National Antiquarian, the County Council of Sr Trndelag, the Cultural Heritage Fund, the Society for the Preservation of Ancient Norwegian Monuments, and the UNI Foundation have all provided financial assistance to make this restoration effort a reality(*Historien - Huitfeldtbrygga*, 2022).

3.2. Climate Data

Due to the special location of the case study, it is worthy to explain about climate data of Trondheim. In order to reach the satisfying output of the daylight situation in the case study, climate data was gathered.

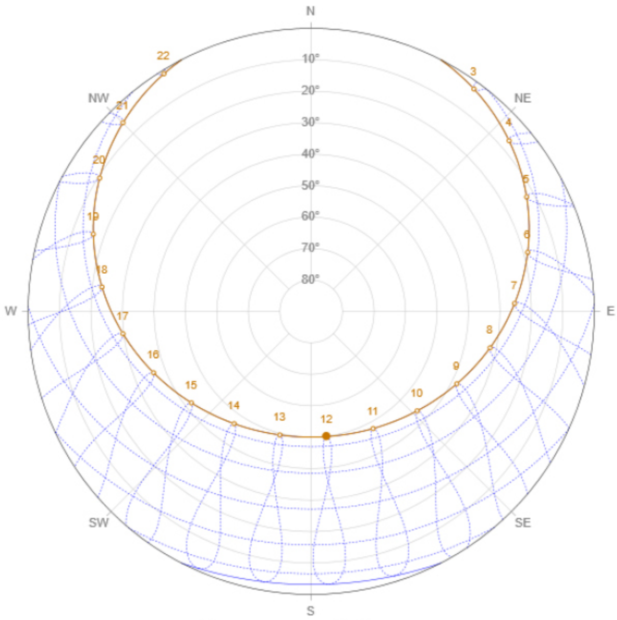
Trondheim defines a cold zone without dry season that average annual temperature and annual total solar radiation respectively are 6 degrees and 971kwh/m^2. As shown in Figure 5, the climate data is gathered from the EPW file from energy plus.

There are summer solstice and winter solstice that was illustrated in Figure 5. It shows Trondheim has short days and long nights with a short sun path diagram in November and December while in summer is vice-versa.

NOR_TD_Trondheim-Voll.012570_TMYx
Koeppen climate Zone: Continental, No Dry Season, Cold Summer (Dfc)
ASHRAE climate zone: Cold (6)
Average annual temperature: 6 °C
Annual total solar radiation: 971 kWh/m2

Cooling Design Conditions

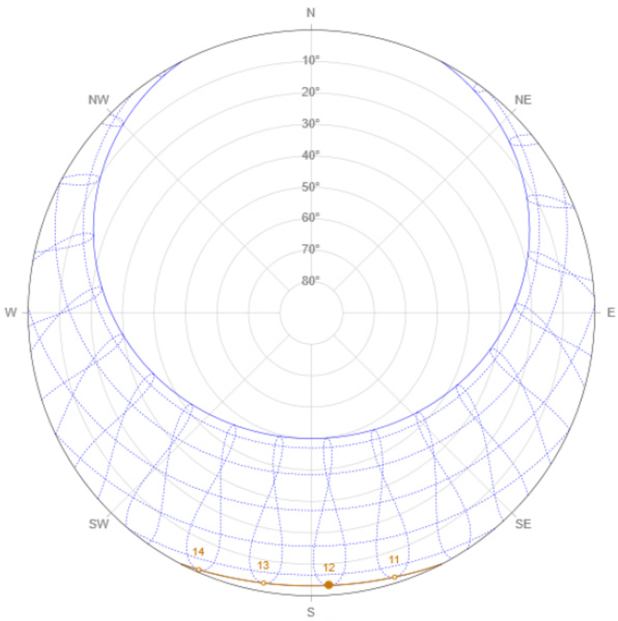
Hottest month: July
Hottest week: 6/29 - 7/ 5
Typical summer week: 7/ 6 - 7/12
Annual CDD for 10 °C is: 507
Design temperature 99.6%: 23.2 °C



Summer solstice
June 21 | 12:00
Trondheim Voll

Heating Design Conditions

Coldest month: January
Coldest week: 2/10 - 2/16
Typical winter week: 2/17 - 2/23
Annual HDD for 18 °C is: 4,255
Design temperature 0.04%: -10.3 °C



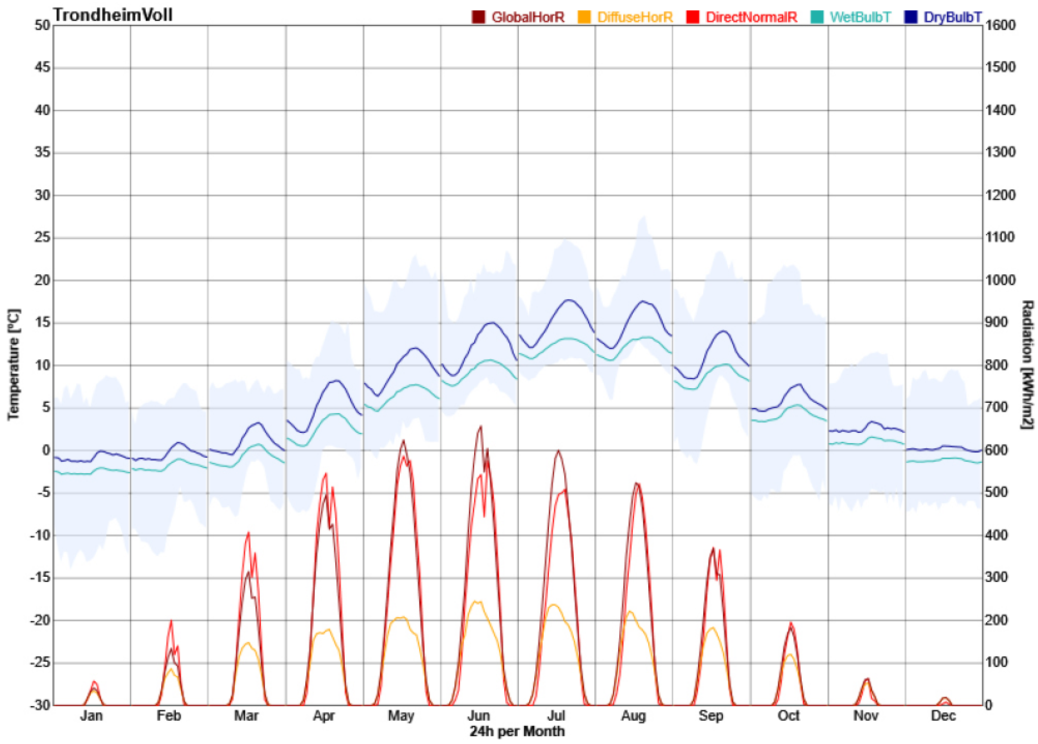
Winter solstice
December 21 | 12:00
Trondheim Voll

Figure 5. Trondheim climate data; Sun path in summer and winter

In Figure 6 there are two charts that show the number of different types of radiance during the year.

The amount of global horizontal irradiance in summer increased while during winter this amount decreased. The highest value of global horizontal irradiance was related to the months of May, June, and July with the value of 620 kWh/m^2,650 kWh/$m^{2,}$ and 600 kWh/m^2, respectively. However, the lowest value was 20 kWh/m^2 belonged to December and for the months of January and November was the same value of 50 kWh/m^2. As a consequence, in winter there was a very low amount of daylight condition compared to the summer, and should it be considered for designing and restoration of the place.

The second chart illustrates climate dry bulb temperature, during the year that most of the time average temperature fluctuated between -5 and +10 degrees. The Average Amount of humidity is start from 40% increased about 90%. Figure 6 shows more detail.



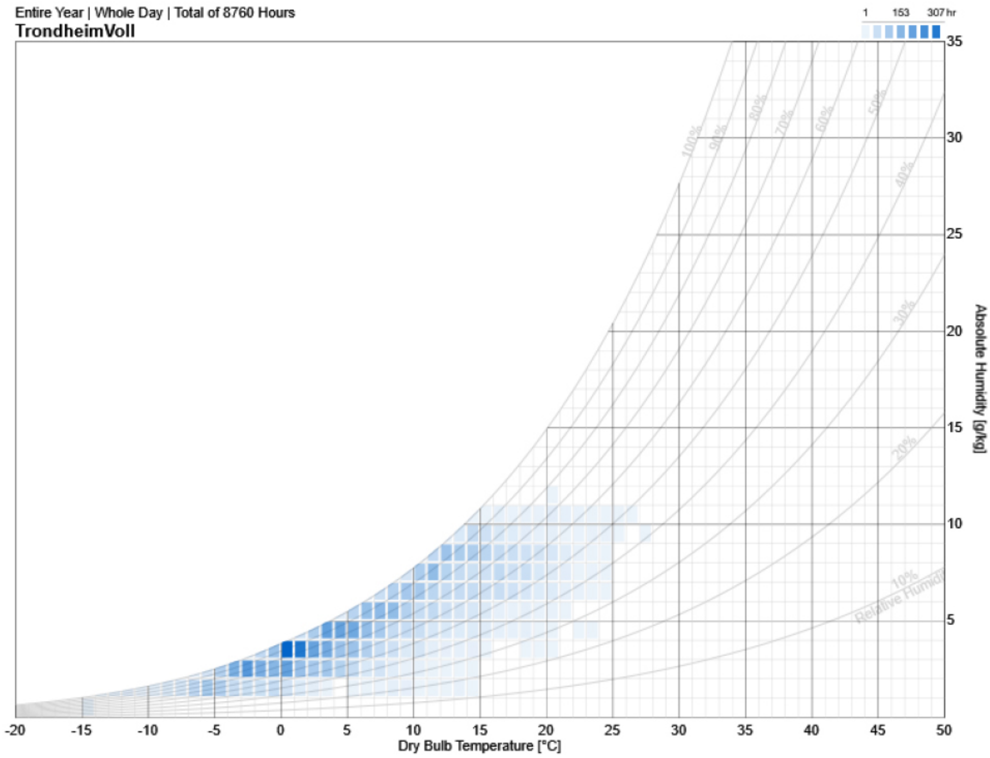


Figure 6. Climatic data of Trondheim; direct, diffuse, and global Radiation, dry bulb temperature, and wet bulb temperature (upper figure); Psychrometric chart (below figure)

3.3. Case study analysis

Although Huitfeldtbrygga consists primarily of three wharves erected under the same roof, in this project, as one becomes more familiar with analysis, buildings are viewed as a single massive structure, given the fact that the three components of the building have been joined together for a long time. Huitfeldtbrygga is oriented east-west, with the gable sides facing the river and Kjøpmannsgata was shown in Figure 7.

Figure 7. Exterior view of Huitfeldtbrygga building

The **roof construction** on the saddle roof is a combined ridge and barrier roof. The technical solutions are clearly marked by the combination of the three-building volumes. Roof trusses tie the construction together in the longitudinal direction. Towards the street, the roof is half vaulted. The originally patched gables in the middle wing are preserved under the current roof as shown in Figure 8.

Most of the **timber** in the middle wing is round timber, however, some coarser logs are edged1 while the wood was still raw. A striking feature, in terms of material use, is that the middle wing has mostly round timber, while the north and south wings are in edged timber. The use of round timber instead of edged timber can also be related to the available dimensions of the timber, economy, and a possible need for time savings. We know that there was a large export of timber in the 17th century and beyond the 18th century, a lot of the old, coarse pine forest was felled, which led to spruce, often of a smaller dimension, being used to an increasing degree. Trøndelag was an important area for the export of lumber, and beyond the 18th century, spruce took over as the dominant building material in Trøndelag2.

Another clear feature is that while all known walls in the middle wing have been repaired, several walls in the other two wings are half-timbered. We then disregard the areas where timber in recent times, probably due to rot damage, has been replaced with timber. Half-timbering became common only after the Building Act of 1845.

Windows: There are many different types of windows on the pier. Disregarding the larger windows with two frames; the empire windows and the functional window, the single-frame windows appear to be of mainly four types. Two of the types appear to be of an older variety, with profiled bars and equal hasps, but of two different sizes. The other two types are clearly newer, where the latest was complete without profiles and the other differs from the old ones in the type of hasps, hinges, and the way the frame and rails were designed. In the middle wing, where there were remnants of the room division with stalls, we see internal light windows in the partitions as shown in Figure 8.

All parts of the wharf have **pile foundations** in the area facing the river. Underwater, in the river outside the pile foundation, there was a dense row of posts, with posts 3-4 meters in length, which probably keeps masses and foundations from seeping into the river as shown in Figure 8.

Figure 8. Images of building elements; stair (a); roof construction *(b);* window(c); *foundations* (d)

The wharf was characterized by 40 - 50 years of lack of maintenance and empty of use. As Beygga is one of the important structures in Trondheim, restating and designing program dedicated in two phases for turning back iconic structures in the touristic area of Trondheim. Brygga's foundation with bottom beams, posts, and tie beams was critical. Exterior walls in the loft have been damaged by rot after roof and gutter leaks. The pier had a slope towards the river of approximately 1.5 meters in the northern corner. new wood walls, a new roof, and window repairing were being developed to restore the wharf. Further refurbishment and new use were divided into two phases:

- Phase 1: A 3-year plan has been drawn up with the intention of bringing the pier back into position and performing the necessary repairs on bottom beams, posts beams, lath, cladding, and windows as well as a new roof.
- Phase 2: Find tenants and designers for new use.

Figure 9. Longitudinal section

In Figure 9 the situation of the building in the context of urban with the section crossing from the river until another side of the street. It can be seen the situation of the foundation of the structure beside the river.

3.4. Description of the research methods and workflow

This chapter assembles all the steps of the methodology. Where the research questions, as mentioned in the first chapter, are:

- How to improve daylight conditions in heritage building locations in high latitude?
- Which simulation tools are most suitable for daylighting simulation?

- Which alternative can yield optimum conditions of daylighting inside of the building?
- How does the base shape of the atrium (6 scenarios) affect the daylight distribution?
- How eliminating a part of the interior wall (parallel with atrium) affect the daylight distribution?

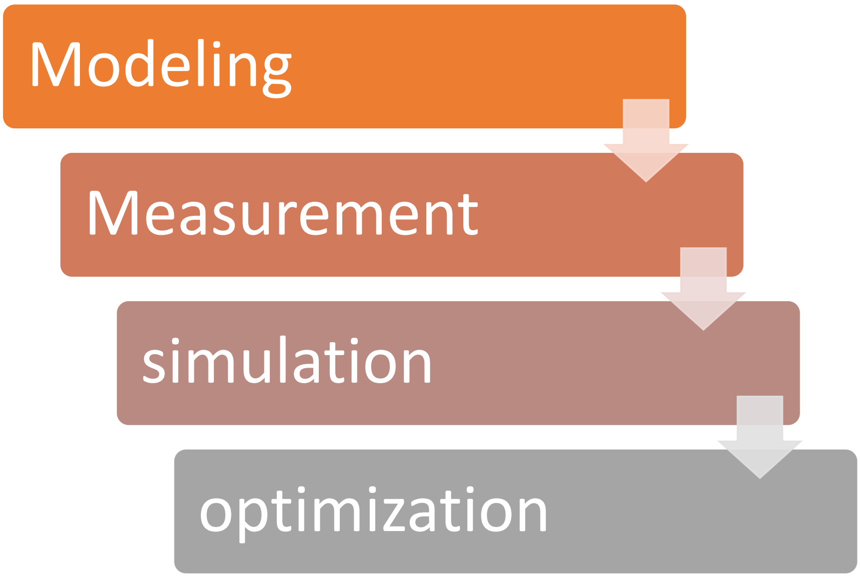


Figure 10. Thesis workflow

This study relied on empirical research and a quantitative strategy, which included modeling a case study and investigating simulations of various scenarios. Huitfeldbryga, a case study, has been chosen for this purpose. The meteorological data for Trondheim were obtained from the EnergyPlus weather data. The data was gathered through observation, modeling, measurement, and documentation study. Finally, the simulation's final results were optimized using the Honeybee plugin in Grasshopper. The findings have been suggested as best-case possibilities for improving the daylight situation.

The structure was divided into four major steps, beginning with modeling and concluding with results evaluation. Figure 10 depicts the simplified process of this research, which is explained in the next sections.

3.5. Conceptual study framework

The methodology of this thesis consists of 5 steps, as can be seen in Figure 11.

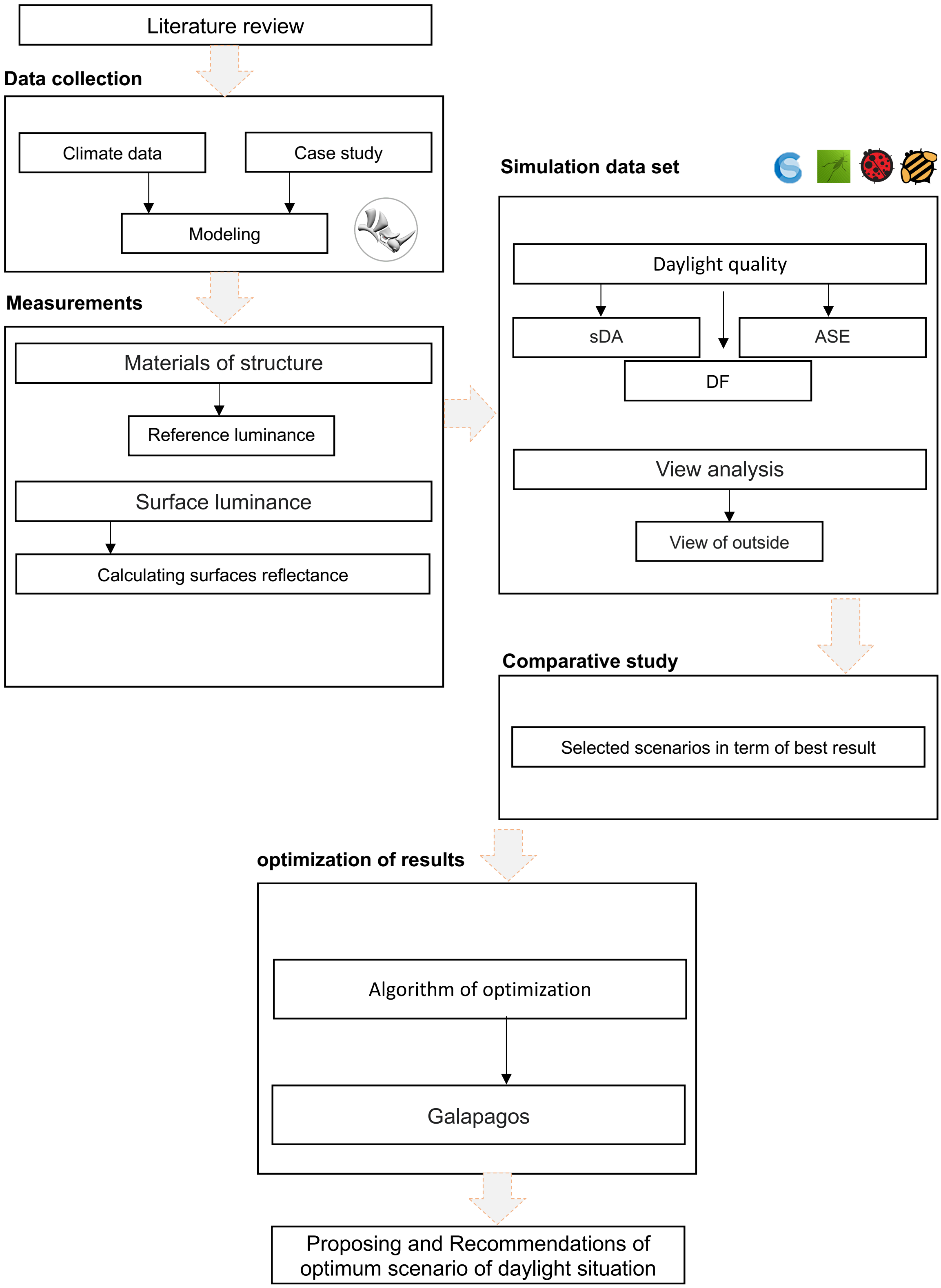


Figure 11. Conceptual study framework

Six types of alternatives have been explored and introduced in the title after visiting and studying historical structures and discovering some acceptable scenarios that can be implemented in heritage buildings. The first step in the thesis was data collection. After considering Huitfeldbrygga as a case study for this project, the EnergyPlus Weather File (EPW) for Trondheim was used as meteorological data. And Rhino was used to represent the data relating to geometrical and optical information from the base case. At the measurement stage, the type of measurement was taken. The light reflectance of the materials was measured. For reaching the reflectance of surfaces, A simple equation has been done. after measuring the luminance of the surface with a luminance meter and a reference gray card all data had been obtained and used for the equation: the Konica Minolta LS-110 was utilized as a luminance meter instrument for this purpose.

All of the information received has been simulated using Climate studio simulation software packages at the simulation data set the stage. This study simulated spatial daylight autonomy, daylight factor, and view analysis. The software outcomes from all scenarios were then compared. Following that, the two selected findings were chosen for the measuring view analysis, annual solar exposure, and implementing other alternatives to achieve the best result.

After a comparison, the optimum scenario for honey bee plugin optimization in grasshopper was chosen. And, in order to achieve a more accurate result, a more detailed model (including window thickness) was used, and the results were evaluated. Finally, some recommendations as potential tactics were presented based on the sDA and ASE, as this was the primary goal of the study.

3.6. Simulation software and modeling tools

To gain an understanding of the daylight behavior of buildings for this study, daylight simulation software tools must be used. This program aids in the evaluation of existing buildings' daylight behavior during operation or even forecast their behavior prior to construction during the decision-making stage.

There are daylight simulation software tools, such as Grasshopper, that might be used for this parametric study. These interfaces are meant to be simple to use. However, the simulated daytime is climate studio, and honeybee and ladybug have been employed for optimization. Grasshopper is used in conjunction with Rhinoceros (version 6) in this thesis.

3.6.1. Rhinoceros

Rhinoceros is a modeling program that is frequently used in architecture to design and plan building projects. It is possible to control shapes and geometry by combining the program with Grasshopper, a visual programming tool, with the purpose of analyzing them based on environmental conditions.

3.6.2. Grasshopper for Rhino

Grasshopper is a Rhinoceros 3D modeling software plugin(Roudsari & Pak, 2013). GH is a programming interface for developing information algorithms. It is the foundation for additional plugins such as Ladybug and Honeybee, among many more. Whereas each of their plugins is utilized for a specific purpose, it uses mathematics and geometry in programming as steps to construct a 3D model, basic or with extensive details, in a parametric manner. It is becoming one of the most popular platforms among designers.

Ladybug and Honeybee are the main Grasshopper plugins used for this investigation. EnergyPlus, OpenStudio, and Radiance are environmental design analysis plugins that are linked to certified simulation engines.

3.6.3. Honeybee for Grasshopper

The Honeybee is a GH plugin that uses Ladybug's climatic weather file. To obtain more advanced investigations, the Honeybee plugin is used(Kharvari, 2020). To create interior daylighting. The Honeybee plugin allows you to progress from early analysis to a more extensive and advanced analysis (Roudsari & Pak, 2013).

Grasshopper, with its plugins, is not an easy program to use. The rationale for selecting this program, however, is that it can adapt to the highly complicated architectural building design. Furthermore, we can add numerous details and variables to construct future tools.

3.6.4. Climate Studio

Climate Studio is a powerful Rhinoceros simulation plugin for analyzing daylighting, electric lighting(*ClimateStudio — Solemma*, 2021), and conceptual thermal. Solemma LLC's software assists in achieving accurate environmental performance outcomes for the Architecture, Engineering, and Construction (AEC) sector. It also aids in the creation of an optimal design with a user-friendly and straightforward interface. When compared to normal annual climate-based simulations, Climate Studio is the most accurate simulation software.

Climate Studio supports the calculation of LEED v4. Daylight was calculated using the Daylight Availability workflow, which includes presets for Option 1 (sDA-based) Option 1, described, simulates daylight availability throughout the entire year.

3.7. Work process

3.7.1. Data collection & representation

Result data is provided at sensor sites defined on an analysis grid at a user-determined distance (here, 0.8 m) above the floor of each building level. The outcomes included either daylight factor values for static simulations or daylight autonomy values for simulations. The analysis's grid size the grid determines the number of sensor points used in the simulation. As a result, it was decided to sensor spacing to 0.25m, in order to acquire pretty fine findings without having to run extremely long simulations. It is critical to remember that a finer grid would increase calculation time, especially in large-scale models like the one used in this thesis. Climate studio saves simulation results in CSR files, allowing the user to readily access them. The user has complete control over how the findings are shown, whether visually or mathematically. Components from Climate studio example files were utilized to depict the findings on a gradient color mesh, which was developed to separate the numerical and graphical findings of each floor plan, allowing the quantitative data and graphical interpretation to be examined independently for each floor plan.

The resultant daylight autonomy from the simulations was thus examined in two ways: visually by inspecting the color-mesh, and graphically by analyzing charts made in Climate studio. This allowed the benefits of the atrium (in terms of the parameters being evaluated) to be compared between floors as a function of distance from the atrium façade.

3.7.2. Measurements

3.7.2.1. Luminance meter

A luminance measurement can be used to determine a light source's visible energy output. Because luminance is a directional quantity, we must describe the acceptance angle of the instrument, measured area, and measurement geometry with regard to the source in order to effectively communicate the luminance data.

First, a Luminance meter was used to measure with Konica Minolta LS100 meter Luminance meter. Figure 12 depicts the Luminance meter used in this investigation to measure the intensity of light over time.

Figure 12. Luminance meter and Gray card

The baseline measurement was performed by pointing the meter at a gray card that reflects 15.5% of the light hitting it. Then, for about a second, measuring the brightness value that appear. The unit of this measurement was in candelas per square meter units of light. After recording the value, the value was registered and studied (Figure 13).

Figure 13. measurement with Luminance meter

The reflectance of the Gray card (reference card) was 15.5% then by the measuring amount of surface's luminance and in the same spot measuring the luminance of the Gray card. All gathered values where been calculated to obtain the reflectance of the test surfaces by proportion seen in Equation 3:

Equation 3:

$$\frac{\text{Reflectance}_{test}}{\text{Reflectance}_{ref}} = \frac{\text{Luminance}_{test}}{\text{Luminance}_{ref}}$$

3.7.3. Modeling

In this project, creating a model of Huitfeldtbrygga was a big challenge for the author. Since, the building was historical, under construction, and for many years, Brygga hadn't maintenance. Therefore, due to these reasons, some part of the building was demolished and the structure slope toward the river. Also, the structure does not have a straight line which made so much time for creating a model. Therefore, the following figures show the technical drawings on a scale of 1:100 that was used for creating a base case model. Then implementing different scenarios which will be explained in the next chapter was introduced.

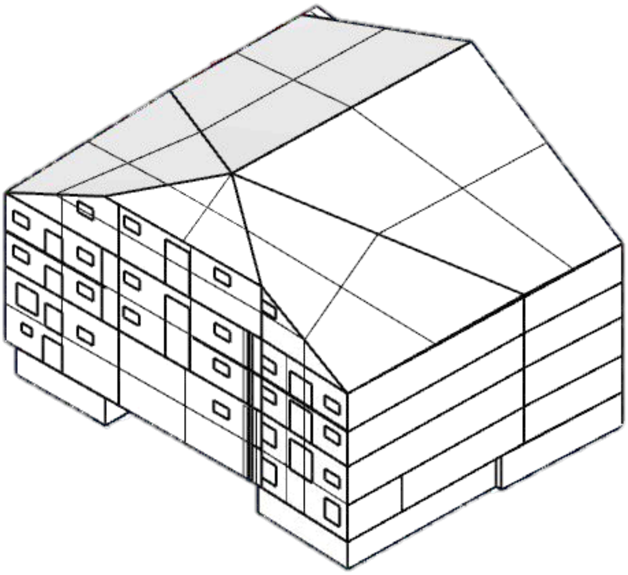


Figure 14. Huitfeldtbrygga isometric 3D model

All simulations in this investigation began with a model, which was depicted in Figure 14. Huitfeldtbrygga isometric 3D model. To reflect the information received, parameters such as glazing, height, length, and floor plan depth were set. Because the model was developed in Climate Studio, these parameters could be simply changed for each simulation. The model was described in the following section. Surface reflectance values were set as the quantity measured and stated in the preceding chapter.

Figure 15. East elevation

Figure 16. West elevation

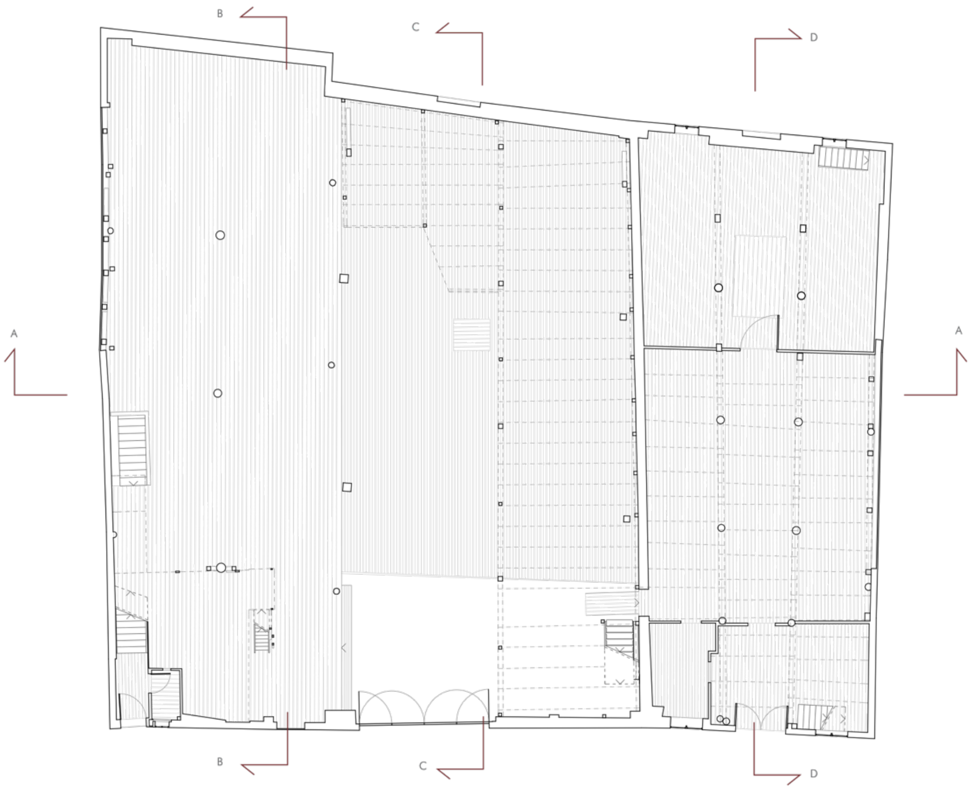


Figure 17. Ground floor

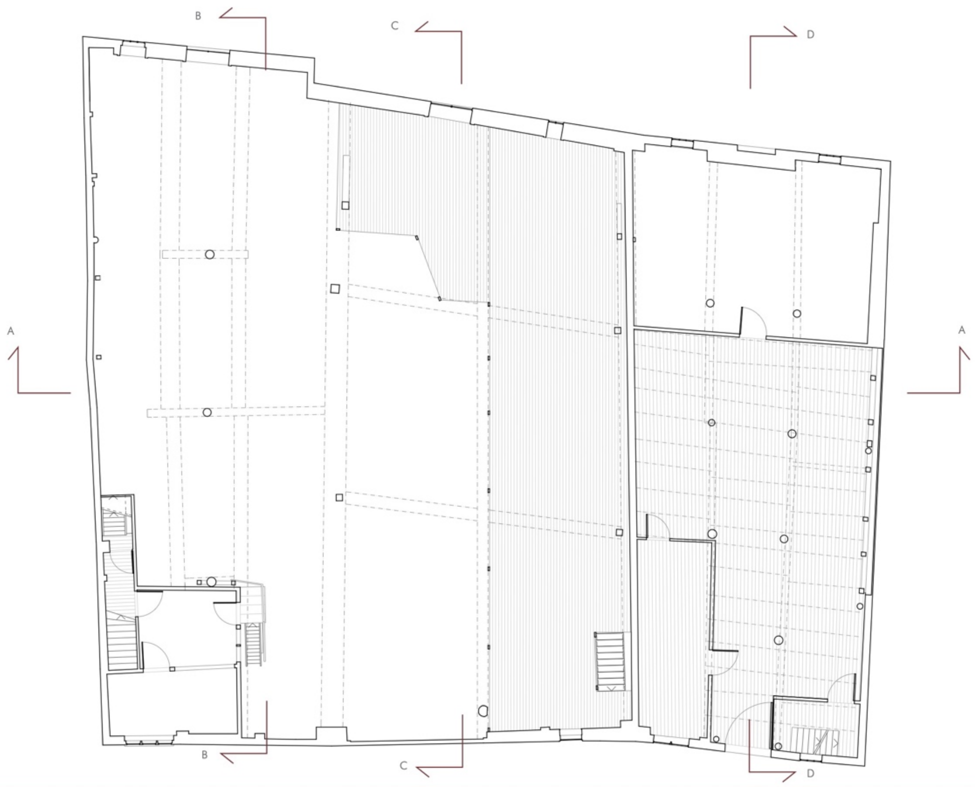


Figure 18. First floor

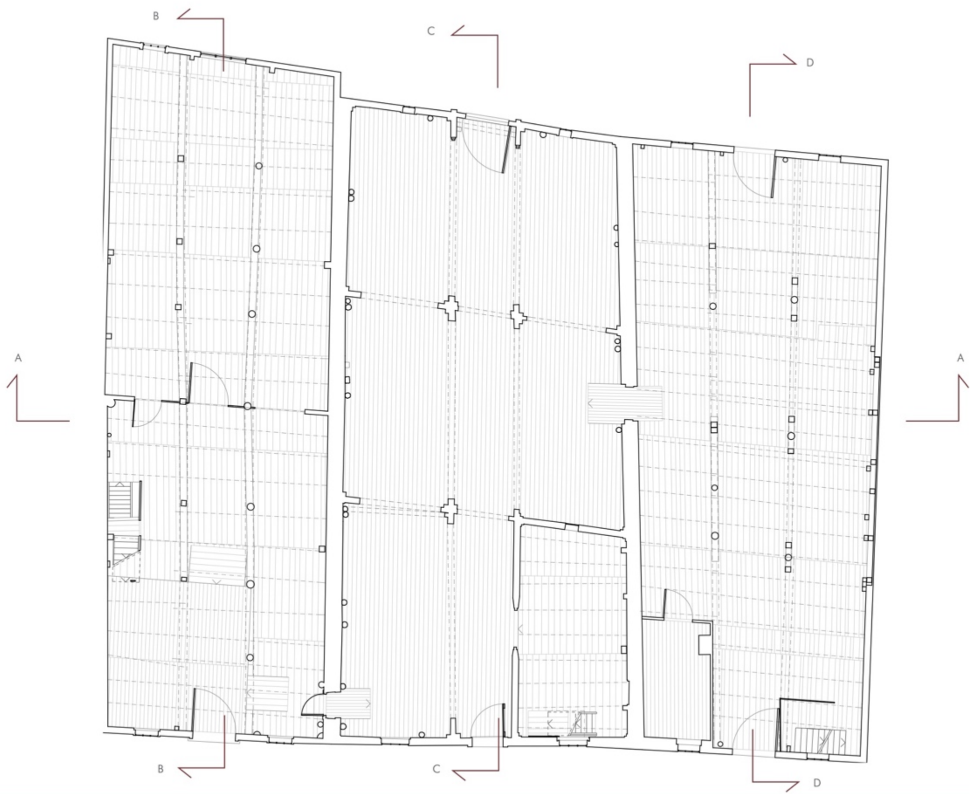


Figure 19. Second floor

Figure 20. Third floor

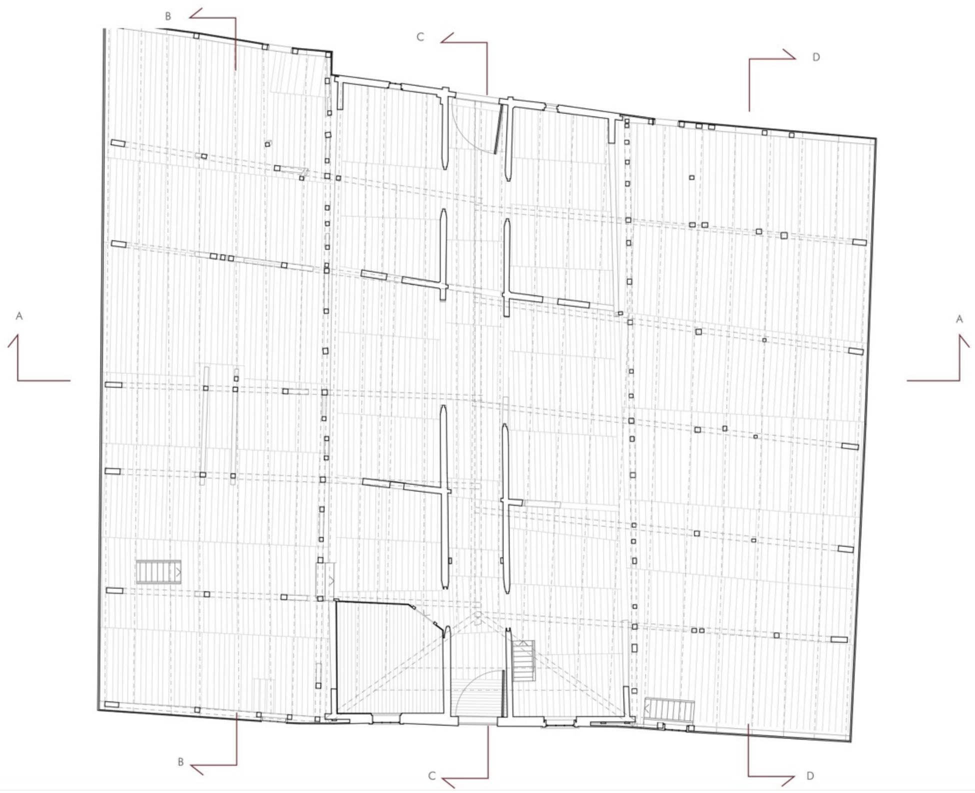


Figure 21. Fourth floor

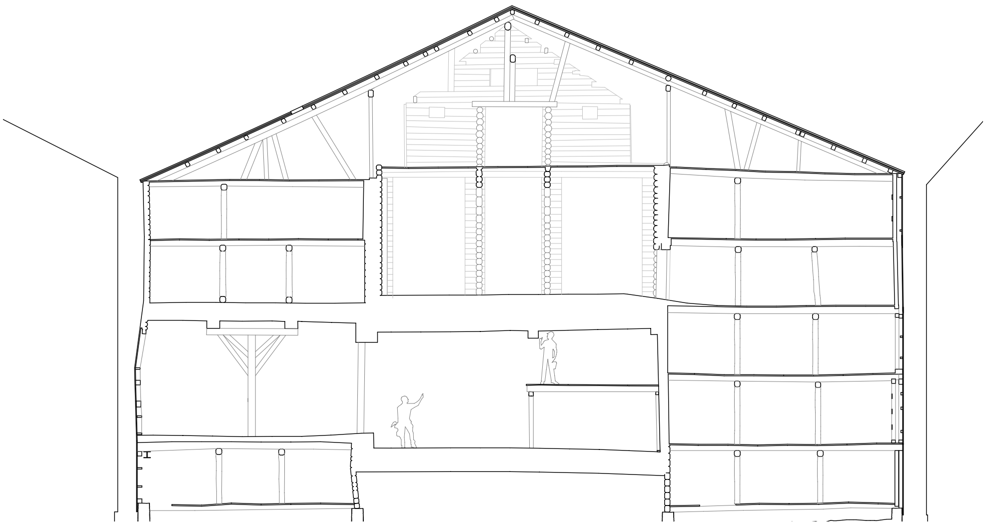


Figure 22. Section A-A

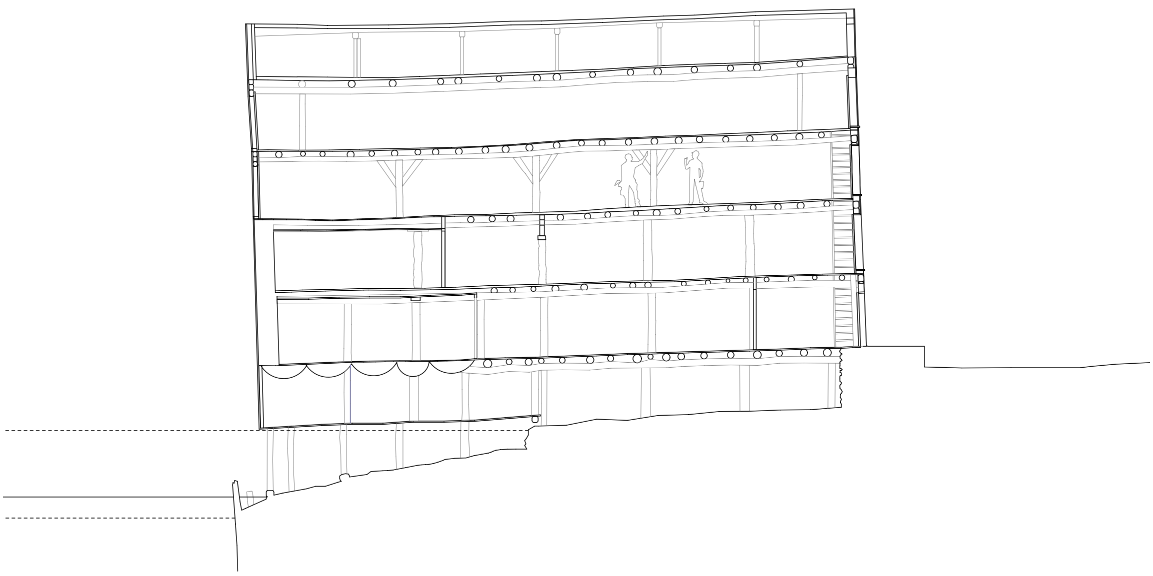


Figure 23. Section D-D

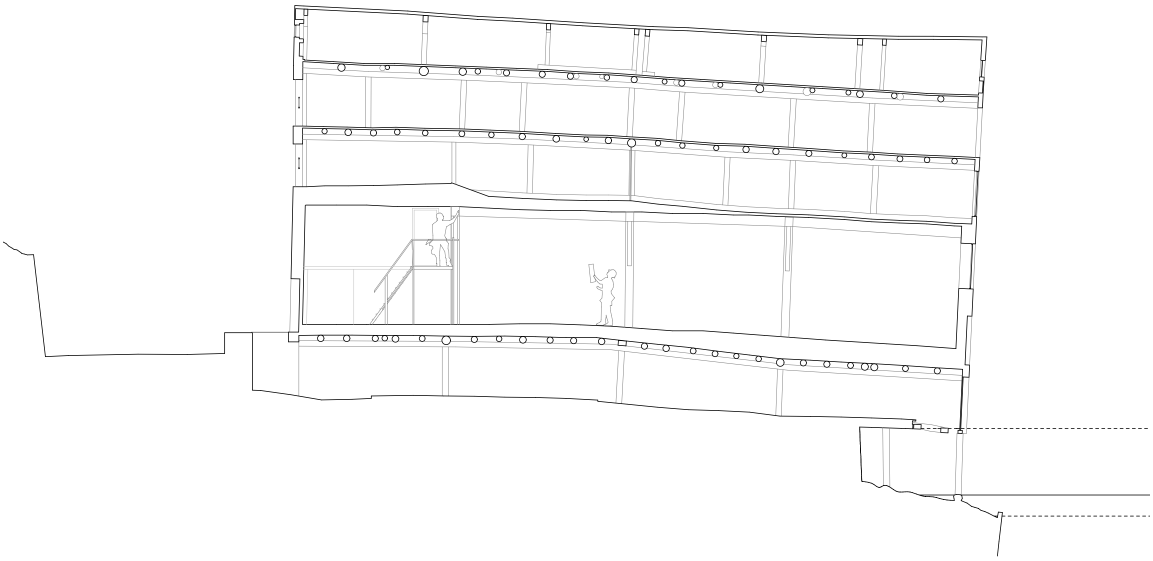


Figure 24. Section C-C

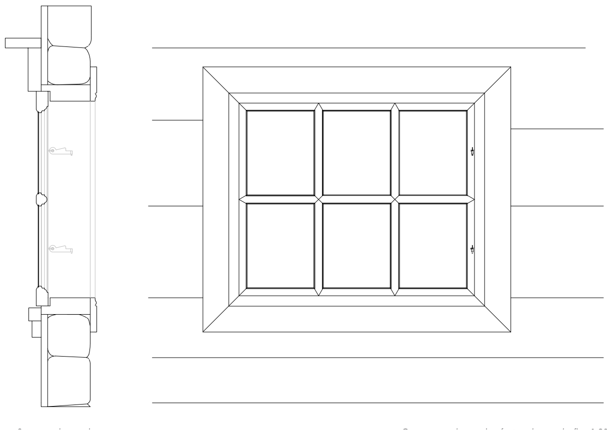


Figure 25. Window detail

3.7.4. Simulation data set

Initially, the simulation was performed in two software, Climatestudio, and Honeybee. In order to analyze the spatial daylight autonomy, annual sunlight exposure, view analysis, and daylight factor in Huitfeldbrygga. The simulation has been done for a year.

Table 5 shows the Radiance parameters that were utilized in simulations Due to the vast size of the grid and the number of simulations, an accurate yet relatively optimized set of parameters was chosen. Furthermore, publishing relative simulation results gived more credible findings than giving absolute simulation results (C. F. Reinhart & Lo Verso, 2010). The following values provide a good rendering performance (*SETTING RENDERING OPTIONS*, 2022). Nevertheless, the ambient bounces were decreased from 6 to 5 to reduce ambient diffuse calculations.

In terms of building configuration, the occupancy schedule for the annual simulations assumed that the evaluated areas would be occupied for the whole year. The light reflectance values were chosen based on conventional construction procedures measured and assign as custom assigned material in Climatestudio, the present light transmissivity value is for a Double-pane window (clear Float glass6mm, Krypton 13mm, solar ban 60 on clear 6mm) with a u-value of 1.26 (W/m^2k) and Tvis: 0.696, and assigned the same glazing with laminate for the atrium to become protective. All assigned material was shown in Figure 26.

Software:	ClimateStudio v1.5.7955.284
Engine:	Radiance 5.3
Weather:	NOR_TD_Trondheim-Voll.01
North Offset:	10.4°
Ambient Bounces:	5
Passes Completed:	50
Primary Ambient Samples:	3200

Layer Materials

Layer	Objects	Material	Rvis	Tvis
fari_atrium_glazing	18	Clear - Solarban 60 (3) (Krypton)	11.9%	69.6%
fari_column_internal	298	Fari07_RHO_140	14.0%	0.0%
fari_floors_1.5	6	Wood Maple	35.9%	0.0%
fari_floors_F0	2	Wood Maple	35.9%	0.0%
fari_floors_F1	3	Wood Maple	35.9%	0.0%
fari_floors_F2	3	Wood Maple	35.9%	0.0%
fari_floors_F3	1	Wood Maple	35.9%	0.0%
fari_floors_F4	11	Wood Maple	35.9%	0.0%
fari_glazing_vertical	72	Clear - Solarban 60 (3) (Krypton)	11.9%	69.6%
fari_point01	12	Fari01_RHO_146	14.6%	0.0%
fari_point02	6	Fari02_RHO_500	50.0%	0.0%
fari_point03	33	Fari03_RHO_158	15.8%	0.0%
fari_point15	6	Fari15_RHO_402	40.2%	0.0%
fari_point16	5	Fari16_RHO_238	23.8%	0.0%
fari_point17	2	Fari17_RHO_124	12.4%	0.0%
fari_point9	5	Fari09_RHO_260	26.0%	0.0%
fari_poit14	4	Fari14_RHO_513	51.3%	0.0%
fari_roof	5	Fari07_RHO_140	14.0%	0.0%
fari_structure atrium	60	Aged Galvanized Steel	22.1%	0.0%
fari- inwall		Fari08_RHO_108	10.8%	0.0%
Ground		Exterior Concrete floor	22.0%	0.0%
wallpoint18		Fari18_RHO_078	7.8%	0.0%

Figure 26. Simulation data set

3.7.4.1. Ambient bounces

The parameter that determines the maximum number of diffuse bounces in the indirect calculation is the number of ambient bounces (-ab). In general, the value of -ab should represent the number of reflections required for a light to reach the place of interest. When the value of ambient bounces is set to 0, ambient calculations are disabled. When ambient computations are disabled, direct light will reach the point of interest if possible, but its contribution to the room will not be considered (Dubois, 2003).

3.7.4.2. Ambient divisions

The parameter ambient divisions (-ad) determines the number of sampling rays transmitted from each point into the globe. As a result, a value of zero suggests that no indirect computation was performed. Increasing this parameter, as well as the value for ambient super-samples, improves the simulation accuracy (Dubois, 2003).

3.7.4.3. Ambient super-samples

The ambient super samples (-as) parameter, which is typically set to roughly ad/2 or ad/4, is the number of extra rays used to sample locations of high variability in the hemisphere. By precisely sampling shadow borders, super sampling increases the realism of pictures with huge brilliant and dark parts (Dubois, 2003).

3.7.4.4. Ambient accuracy

The ambient accuracy (-aa) specifies the maximum inaccuracy that can be tolerated in indirect irradiance interpolation. Values between 1 and 0.1 are commonly utilized, with lower values providing the highest accuracy. When the value is set to 0, no interpolations are performed.

3.7.4.5. Ambient resolution

The ambient resolution (-ar) determines the maximum density of ambient values utilized in interpolation to determine the distance, S, between ambient calculations. At distances smaller than the maximum scene size divided by this value, the accuracy of the indirect computation begins to loosen. This parameter prevents the software from becoming overburdened with trivial geometric details (small objects)(Dubois, 2003).

The details of the Radiance parameters considered for the simulations in both software Climatestudio and Honeybee are presented in Table 1. It was worth mentioning that some of the parameters set as default and others like ambient bounces, Ambient divisions, and limit the weight of each ray were set as below.

Table 1. Radiance parameters details

Parameter	Description	Value
-aa	Ambient accuracy	0.1
-ab	Ambient bounces	5
-ar	Ambient resolution	256
-ad	Ambient divisions	1
-as	Ambient super-samples	1024
-dj	Direct jittering	0.5
-ds	Direct sampling ratio	0.25
-dc	Direct certainty	0.5
-dr	Direct relays	1
-dp	Direct- present density	256
-ps	Pixel sampling rate	4
-pt	Sampling threshold	0.1
-st	Specular sampling threshold	0.5
-lr	Limit reflections	6
-lw	Limit weight of each ray	0.01

3.8. Hypothesis

After assessing the heritage building to improve daylight availability in such historical buildings, considering atriums as the key to the desired outcome was studied in this research. The main challenge to this research was to find a reasonable way that has minimum damage and changes with maximum daylight penetration in the case study.

As in restoration plan was considered to renewing and replacement of the roof and also for having more daylight atrium cloud be the best option for such deep and dark plan like Huitfeldbrygga. The shape of the atrium in the building respects the design of the existing line and at the same time aims to provide a visual connection between the floors internally through an atrium, which is the object of this investigation. Therefore, six scenarios as architectural atrium were considered and designed in order to analyze daylight in the case study building. These six types of scenarios are shown with orange color in Figure 27.

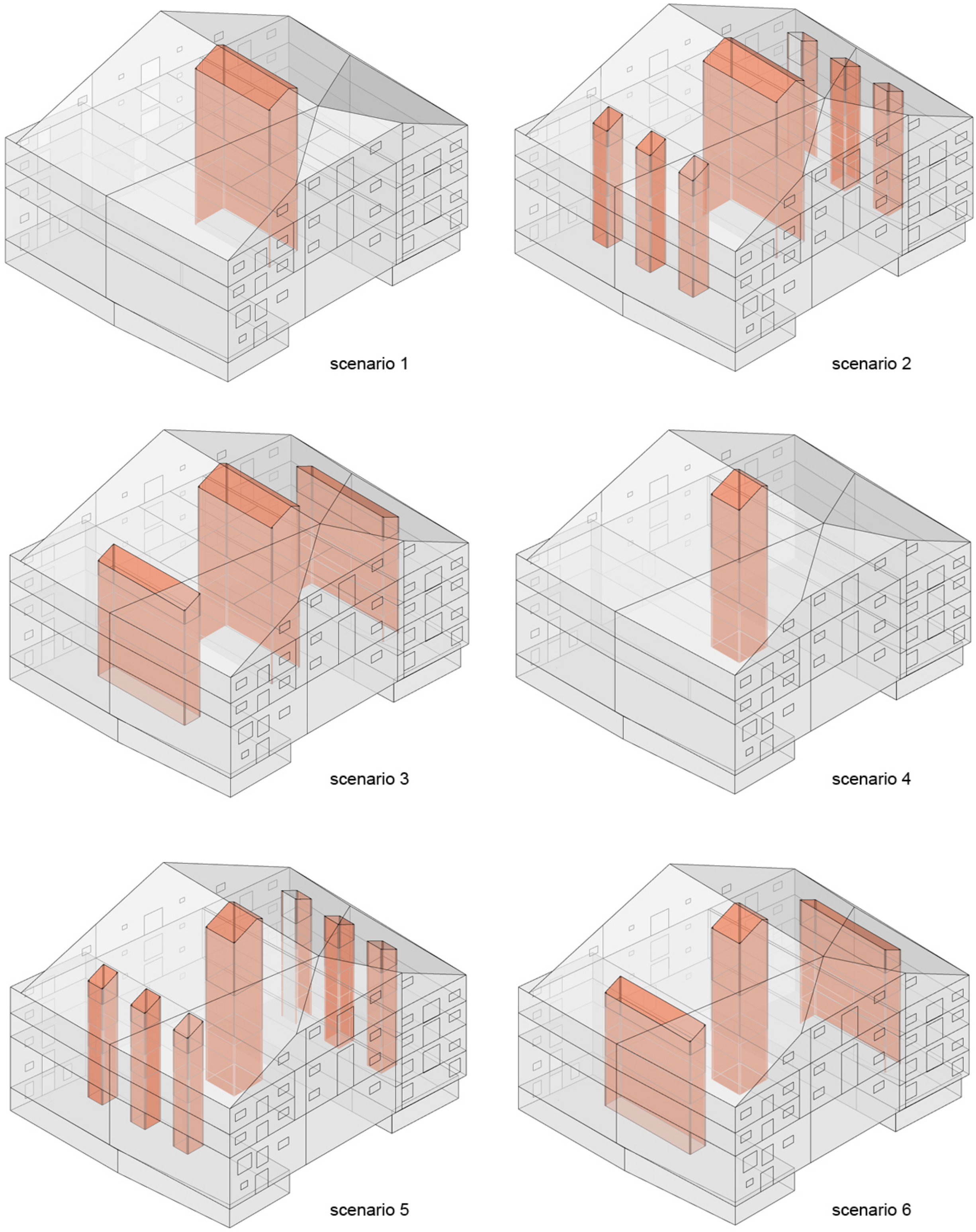


Figure 27. Six variations of the atriums (scenarios)

As a whole, the building consists of 3 huge wharves so the design and dimension of the atrium are aligned with the existing column in order to maintain as much as possible building materials.

In the first scenario, it just considered one huge atrium with a dimension of (3.34 m * 8.50 m) In the middle of wharves.

Same as scenario 1 in scenarios 2 and 3 are considered in exactly the same position. But moreover, in scenarios2 at two side wharves, there are three separated atria with a dimension of (1.84 m * 1.70 m) but in scenario3 there is a united atrium with a dimension of (1.84 m *10.10 m).

In scenario 4 there is a square atrium in the middle Wharfe with a dimension of (3.34 m *3.34 m) in turn scenarios 5 and 6 have the same atrium dimension for both sides wharves like atrium 2 and 3.

3.9. Atrium scenarios

Study question: How does the base shape of the atrium (6 scenarios) affect the daylight distribution?

Changing the geometry of an atrium affects how light is reflected within it. The goal of this simulation was to determine which design resulted in the most homogeneous daylight autonomy in the atrium's surrounding sections. Because of the massive structure, comparing the simulation results from the six scenarios is rather challenging. The size of the atrium walls will also be determined by the shape. In optimization, the volume of the atrium was therefore kept constant for first comparing simulation and selected scenarios made graphically between the bottom-, middle-, and top-floor of each shape. The models were built in such a way that there was minimal demolition in the roof and floors. This was done to guarantee that as little demolition as possible occurred.

3.10. Evaluation the effect of interior wall on daylighting

Study question: How does eliminating a part of the interior wall (parallel with the atrium) affect the daylight distribution?

To answer the research question, some simulation is done in terms of understanding improving daylight simulation inside the building. Therefore, in this step, the interior wall for all floors has been split and removed in the parallel atrium as highlighted in Figure 28 The orange color was the eliminated interior wall in the simulation. The aim of this step was for understanding it was possible to link all the areas together, what happen in the daylight situation.

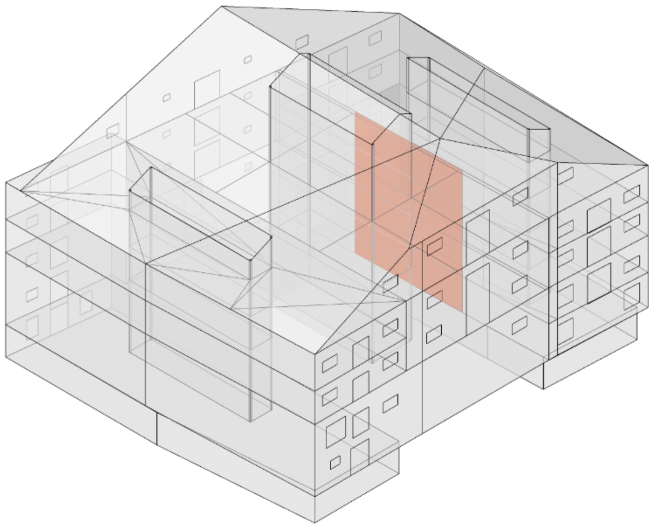


Figure 28. Highlighted the interior walls for modification

3.11. Daylight factor

The daylight factor (DF) approach is one of several types of static daylight performance measures. The technique, which was devised in the early twentieth century in the United Kingdom, is now one of the most extensively used daylight metrics. The daylight factor is a ratio that shows the amount of illuminance accessible indoors on a horizontal plane in comparison to the amount of illuminance available outside at the same time under an unobstructed CIE standard cloudy sky (*Home* | *Daylighting Pattern Guide*, 2020).

The daylight factor is given as a percentage and can be expressed with the following equation:

Equation 4:

$$DF= (\frac{E_1}{E_0})\times 100 \ [\%]$$

where

E_I is the illuminance at a point in the interior of the room being analyzed

E_O is the illuminance from the unobstructed sky on a horizontal surface outside

3.12. Spatial Daylight autonomy

Daylight autonomy (DA) is a modeling approach that calculates the yearly amount of daylight associated with each particular hour, geographic location, and sky condition. The first in a series of yearly daylight measurements, now known as dynamic daylight metrics, was daylight autonomy. It is expressed as a percentage of yearly daytime hours that a specific location in space is illuminated above a defined level (*Home | Daylighting Pattern Guide*, 2020). Furthermore, daylight autonomy employs work plane illuminance as an indicator of whether there is enough daylight in an area for inhabitants to operate only by (Christoph F. Reinhart & Fitz, 2004). Work plane illuminance thresholds are specified in certification standards such as LEED, with a minimum value of 300 lux. The daylight autonomy threshold of 300 lux was used in this thesis to match the LEED certification system criterion.

3.13. Annual sunlight exposure

Illuminating Engineering Society first used it in the 2012 (*Trials - MATLAB & Simulink*, 2021). The ASE measure considers direct sunlight to be a possible source of visual discomfort, measuring the percentage of floor area that exceeds a defined level of direct sunlight illuminance for a specified number of hours. The visual discomfort concerns may both be examined with ASE.

3.14. View analysis

This method evaluates occupant perspectives and determines eligibility for the EN 17037 European standard. View factors and view distances to specific model layers or items of interest were also calculated. Following the assignment of materials, a VisionGlass and Visionatrium tag were assigned to layers representing outside vision glazing and atrium.

Result data is provided at sensor sites defined on an analysis grid distance of 1,20 m above the floor of each building level. The analysis's grid size grid determines spacing to 0.609m, in order to acquire pretty fine findings without having to run extremely long simulations. Despite the fact that the materials selected in the Material column govern the optical behavior of the model's surfaces. EN 17037 is a unified daylighting standard published by the European Committee for Standardization (CEN) in 2018 (CEN, 2018). It covers four aspects of daylight in buildings, the second of which – *View Out* – is included in ClimateStudio's View Analysis workflow (as of ClimateStudio v1.5).

In order to achieve Minimum compliance, a view position must observe at least the Landscape layer. Medium compliance necessitates viewing the Landscape layer as well as one other. Seeing all three is required for high compliance.

3.15. Optimization

In Grasshopper, the process begins with parametric design variables and creating geometry. Ladybug and Honeybee perform daylight modeling procedures. The parametric building geometry is linked to the Radiance materials component throughout the daylighting modeling phase, with the setting of material transparency, reflectance, and so on. The building materials are then linked to the daylighting simulation component, which takes weather files, daylighting sensor placement, and other simulation variables into account. Radiance generates a rad file and runs a daylighting simulation. After the simulation, Ladybug reads the daylight performance metrics and provides an annual lighting schedule by importing the simulation result file back into Grasshopper. Galapagos is used in the optimization process to find optimal building designs with the highest sDA, which is the percentage of hours in a year that different dimensions in the bottom and upper parts of each atrium (width between 1.20 m and 3.60 m and the length between 1.20 m and 15.80 m) are adopted to achieve the optimum outcomes. The design variables are related to the Galapagos' Genetic input, and the sDA output is related to the Fitness input. Each generation has a population of 100, with a population boost of twice the size of the first generation.

4. Results

4.1. Introduction

When opposed to new construction, the refit of a heritage building is distinguished by two key features. The first component is related to the retrofitting process itself, as the original material asset in the case of a historical building should be preserved. The second issue is concerned with historical buildings, which should be maintained in such a way that the authenticity of the asset is preserved with minimal change to the original construction. The results of the current daylight situation in the building, as well as the proposals, are provided in the following parts under the supervision of the four objective questions.

This chapter will present the findings of the methods described in the preceding chapter. This chapter compiles all annual results from the Climate Studio and Grasshopper simulations. First, an inquiry was conducted to ensure that the final design tool with all iterations was given. Second, scenario-based outcomes were evaluated using several metrics such as sDA, DF median, ASE, and, in particular, the grid regions that are possibly certifiable under the LEED v4.1 option1 and EN17037 norms and standards. Then, using comparison and correlation studies, the general interaction with parameters and the effect of each variable input is explained. Finally, optimization is tailored to the parameters under consideration.

The first question of this study was:

Which simulation tools are most suitable for daylighting simulation?

4.2. Comparison of daylight simulation tools

In terms of understanding and finding the most suitable software simulation for assessing daylight behavior it was necessary to model a simple room and simulate daylight situation in the mentioned room. Four daylight software is studied, Velux, Relux, Honeybee plugin in Grasshopper and climate studio. The simulated daylight metrics in a simple room with a dimension of 3 m *5 m and one window on one side of the wall with a dimension of 1 m*1.20 m was modeled and simulated. Figure 29 shows the detail of the simulation results utilizing each software.

There was a similarity in four software like being open source free of use and fast simulation speed. Climate studio, Velux, and Relux are user-friendly and easy to use but using honeybee has the flexibility of using the complex model. Despite all of them, it is possible to simulate daylight metrics but, climate studio and honeybee provide more reliable daylight metrics (daylight factor, daylight availability, etc) as mentioned in Figure 29.

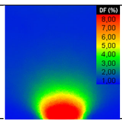
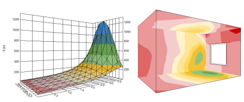
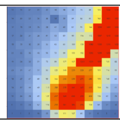
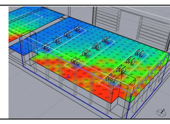
Parameters	VELUX	Relux	Ladybug Honeybee	ClimateStudio
Ease of use (Modeling)	User friendly and easy to learn	User friendly and easy to learn, compatible with CAD and BIM systems Daylight	Flexibility of using the same complex architectural model for daylight simulations	Rhino plugin, easy to use
Daylight metrics	• Daylight factor • Illuminance and luminance level at one point in time	• Illuminance levels for each evaluation area	• Daylight factor, • Annual daylight simulations • Aaylight autonomy • Glare • Single Thermal Zone Energy and Load Calculations	• Daylight factor • Annual & Individual Time Step Glare Analysis • Single Thermal Zone Energy and Load Calculations • View analysis
Simulation speed	Fast	Fast	Fast	Fast
Availability of software	Free	Free	Are two free and open source environmental plugins for Grasshopper	Free
Results visualization				

Figure 29. Comparison of daylight metrics analysis between four software

Figure 30 illustrates the pros and cons of four different software.

pros	Conceptual project	Suitable for artificial light	Easy to edit complex volume	Easy to edit complex volume
cons	Not realistic for considering, Daylight factor , Daylight autonomy	Not realistic for considering daylight metrics	Have some complexiteis	_

Figure 30. Pros and cons between four software

Velux and Relux as featured provide are suitable for the conceptual project and artificial light respectively. However, as results show with climate studio is much easy and faster to reach the result. Because creating a model is easier and more reliable compared to other software. More of is it possible to calculate view of outside and spatial daylight autonomy as we need for the case study. Therefore, Honeybee could optimize the model to find optimum output.

4.3. Analysis of sDA and DF, and ASE in the base case

How to improve daylight conditions in heritage building locations in high latitude?

The current daylight situation in the Huitfeldbrigga was assessed to be able to draw a comparison and most importantly, understand how the modifications affected and improve the building's natural light conditions. Due to the building's complex geometry, simplifications were made, so the simulation time was optimized, and the evaluation grid was placed in all fours floor. As for the base case, it is important to understand that the results from this investigation can be different from previous or future studies that have been or will be carried out, as the project is still under development and will go probably through great modifications.

The grid, which had its dimensions explained in the previous chapters, runs along the floor of the atrium and changes according to each type of modification, thus leading to six different scenarios.

Due to the high amount of data and the building area, it was important to show the general impact of each improvement using less data, but rather condensed in a few values that could be accessible. The metrics commonly used to evaluate the daylight conditions in adjacent rooms were adopted, however they were quantified in area, so all the proposals could be compared.

Initially, the simulation was conducted in two software, climatestudio and Honeybee, in order to analyze the sDA and DF in Huitfildbrygga. It is worth mentioning that simulations for this comparison were conducted also with ASE to comparing with optimum atrium and avoid glare. In order to improve daylight condition within the building, it was needed to understand how much daylight was existed in base case scenario. Therefore, this chapter explain the result of simulating daylight availability.

As shown in the results, Daylight availability has been conducted according to leedv4.1 with climate studio that introduced in methodology. The report gathered sDA and ASE for different scenarios with the same input and radiance parameters.

Lastly, the behavior of daylight was evaluated in each floor by using the ASE, the sDA, and mean and median DF. These metrics are utilized by certification systems, which is calculated as a percentage of the floor area that is complying with the criteria of the metric for at least 50% of the time along the year.

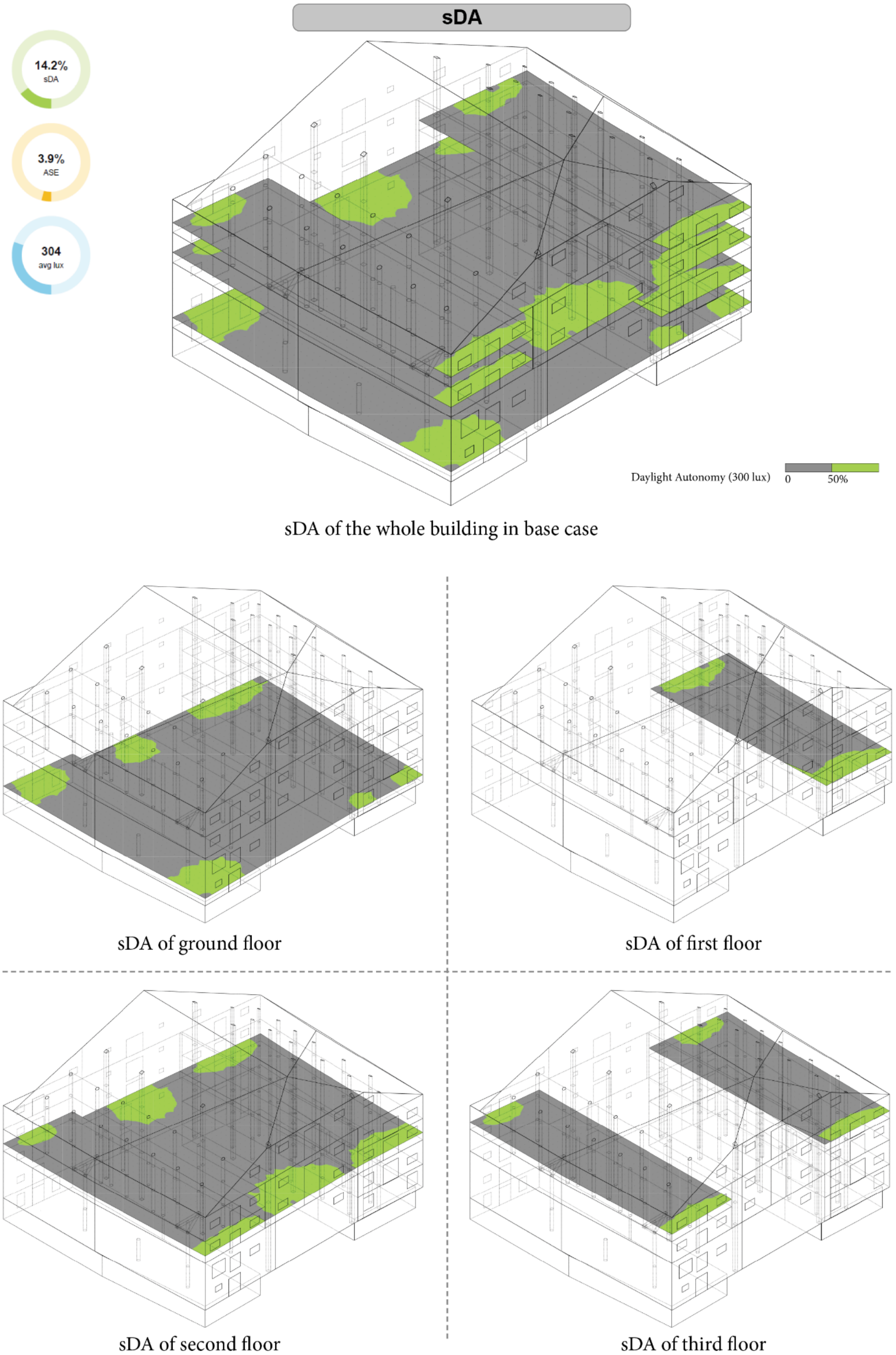


Figure 31. sDA of the base case

As shown in Figure 31 axonometric views of each floor and the values are presented in percentages. Based on the results, none of the floors in base case scenario had sDA value more than 18%. However, the recorded sDA value was 12.83% for the ground floor that was the lowest amount among all floors. First floor, and second floor with the same percentage of sDA with the value of 17.1%. The third floor with 19.09% had the highest amount of sDA. The high amount of sDA was expected in the last floor as its grid area are closer to the ceiling.

Based on the analysis results in Figure 32 the obtained values of ASE were very low. The highest and lowest ASE was achieved in first floor and ground floor with the value of 5.04% and 3.08%, respectively. ASE for the second and third floor was 4.75 % and 3.43%.

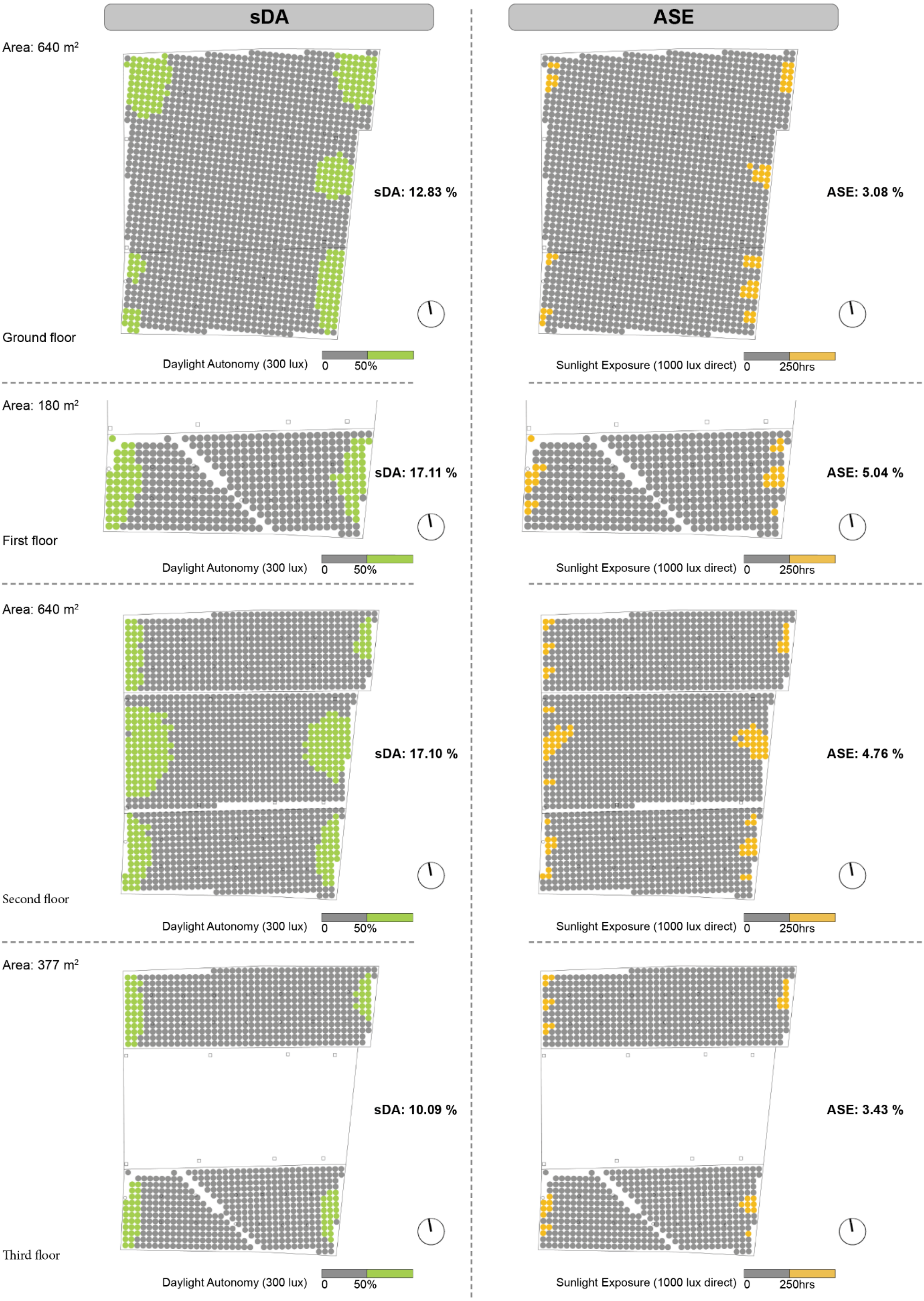
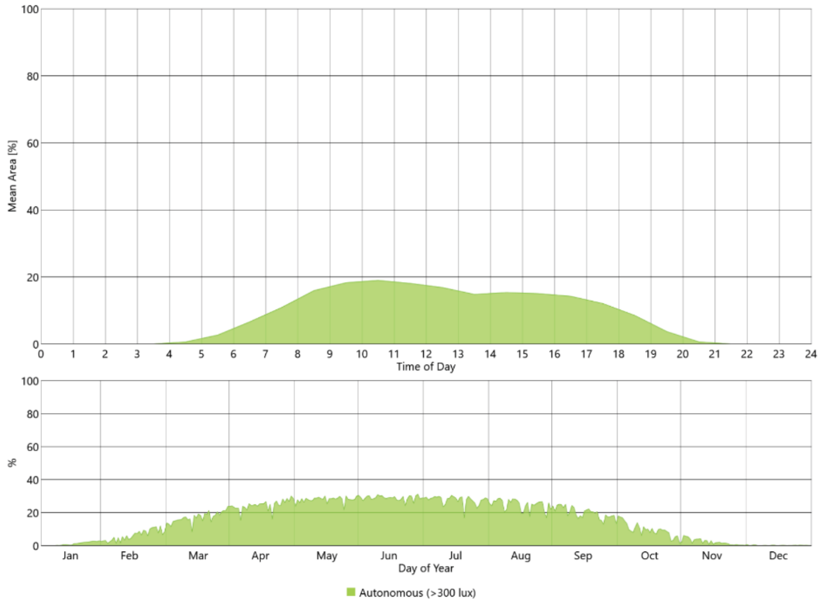
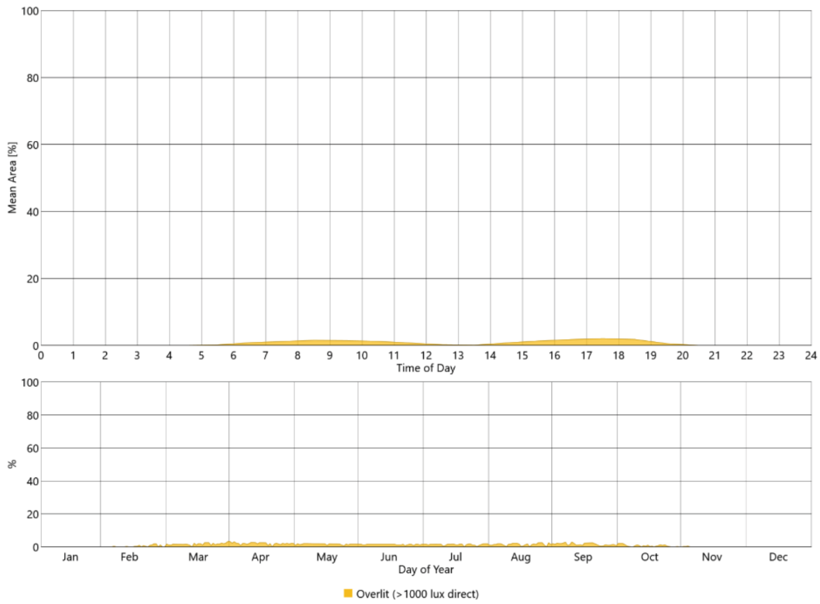


Figure 32. sDA and ASE values at each floor in base case

Figure 33 shows the annual amount of ASE and sDA in an annual basis and the hours during a day.



Annual profile of sDA for base case scenario



Annual profile of ASE for base case scenario

Figure 33. Annual profile of sDA and ASE for the base case

As the chart shows the amount of sDA in winter was less than 10%. More specifically, during months of November, December, and January the value of sDA was reached to lower than 2% and were close to zero. However, in summer months the correspondents' values reached 30%. As an example, in months of May, June, and July the sDA was constantly more than 30%.

ASE values during a year was negligible in base case scenario, especially in winter. So that the ASE was recorded between months of mid of February until mid of October with the value less than 2%. While, in January, November, and December there was no ASE was recorded.

Figure 34 shows the results of simulation related to the DF in the base case scenario.

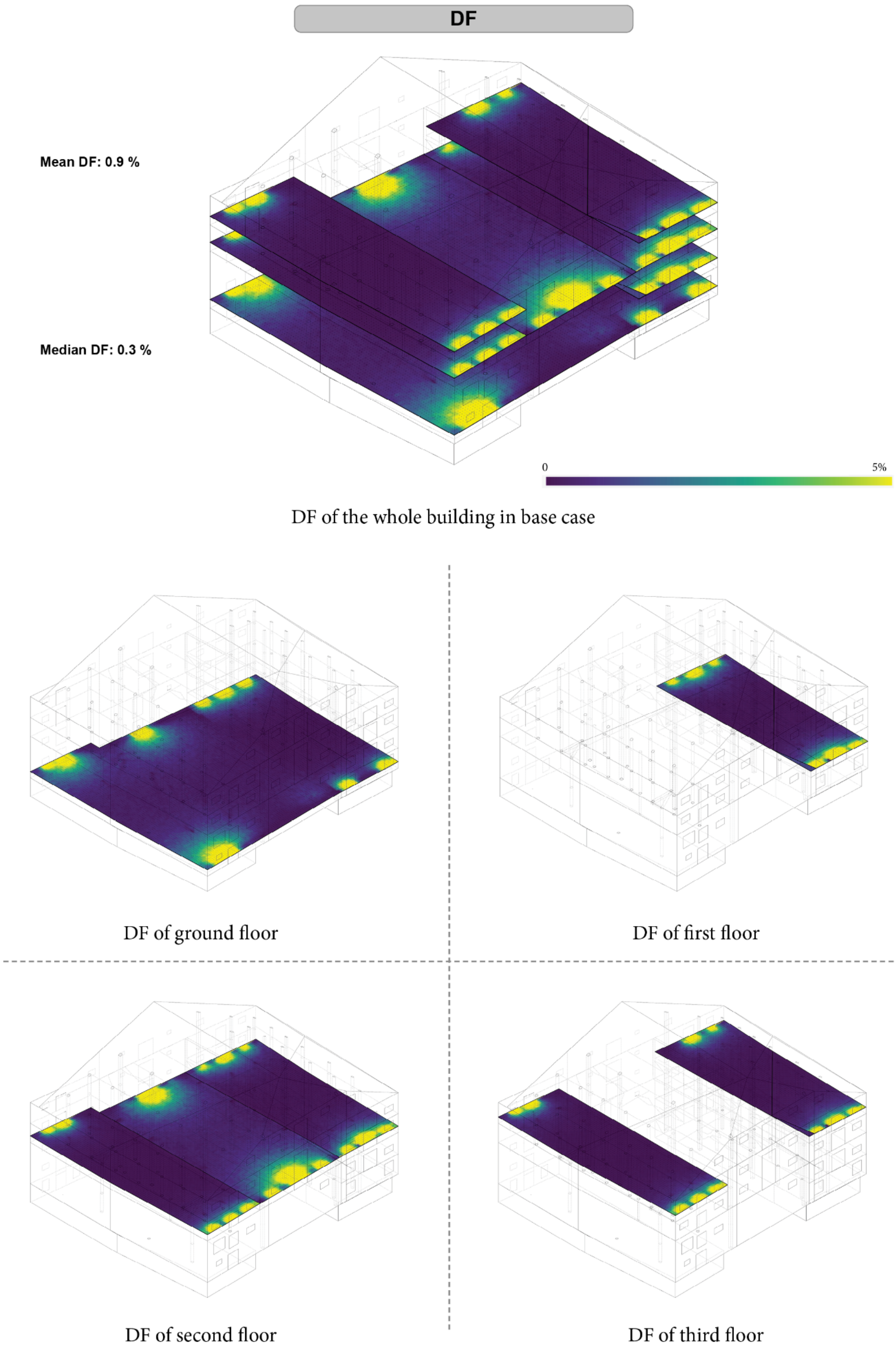


Figure 34. DF for each floor in base case

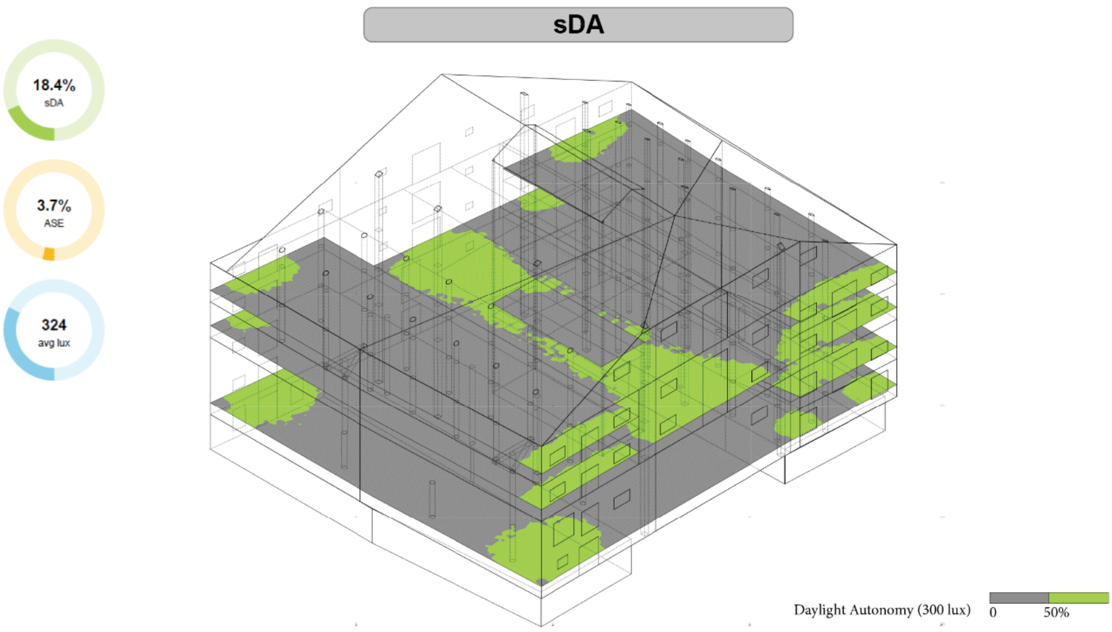
As indicated in the results, the mean DF was quantified with the value of 0.9% and median DF of 0.3%. It can also be noticed that the amount of area of DF is shown in Figure 34 for the whole building and all floors. As legend shows how much the distance from window became bigger inside the building especially in the middle of the building the amount of the building will be decreased noticeably. While near the window the amount of DF increased which is shown with yellow color in figure. Therefore, it can be concluded that the higher the distance from the window, the lower the value of DF will achieve.

Changing the shape of an atrium will affect how the light is reflected within the atrium. The intention with this simulation was to see which scenario resulted in the most uniform daylight autonomy in the adjacent spaces of the atrium. Six scenarios based on the number, shape, and size of their atrium were thus compared in the following sections.

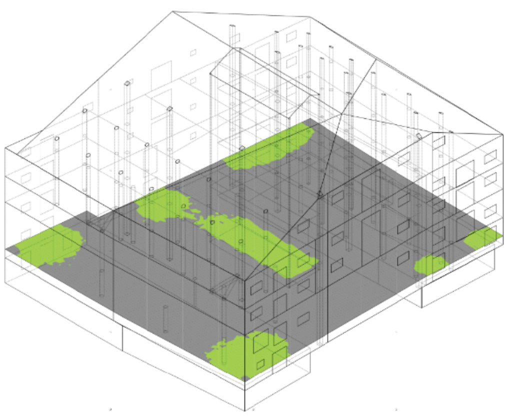
4.4. Analysis of sDA and DF, and ASE in scenario 1

Figure 35 shows the sDA throughout building’s indoor spaces in Scenario 1.

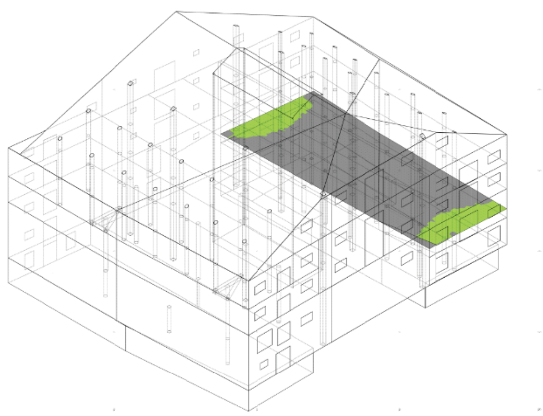
As it is obvious, the sDA condition was improved compared to the base case scenario. As figure shows sDA for whole the building reached to 18.4%, and the ASE of the overall in this scenario was 3.7%. In this scenario the atrium was located only in the middle of the building and the results shows that around the atrium in was in green color. It means that the atrium efficiently transmitted the daylight even to the ground floor.



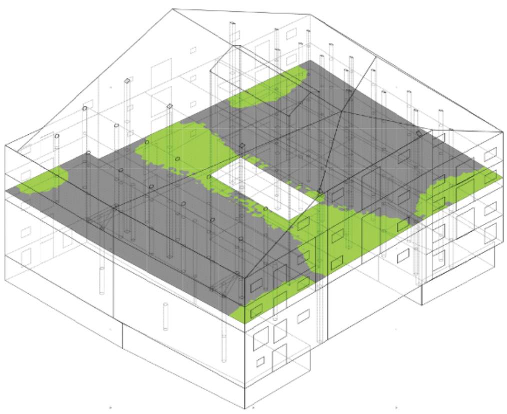
sDA of the whole building in scenario 1



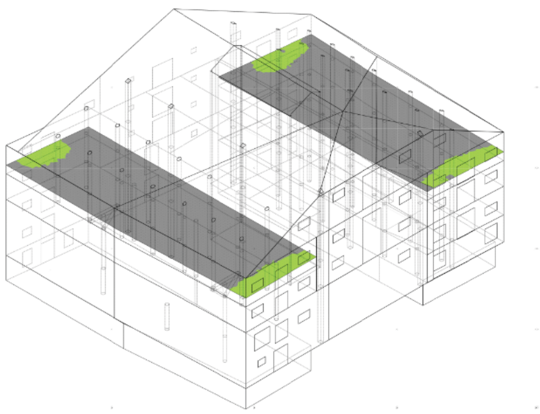
sDA of ground floor



sDA of first floor



sDA of second floor



sDA of third floor

Figure 35. sDA of the scenario 1

For more detail comparison, Figure 40 shows the sDA and ASE with their value at each floor. In second floor the obtained value for sDA was the highest amount compare to other floors with the value of 24.67%. While, the lowest amount was belonged to third floor with the value of 10.22%. In ground floor and first floor had very close values of sDA by 17.69%, 17.27%, respectively.

As the same, the highest amount of ASE in this scenario was related to the second floor with value of 4.98%. the lowest ASE was achieved in the ground floor with 2.55%. in first floor and third floor the ASE amount was 4.41% and 3.08%, respectively.

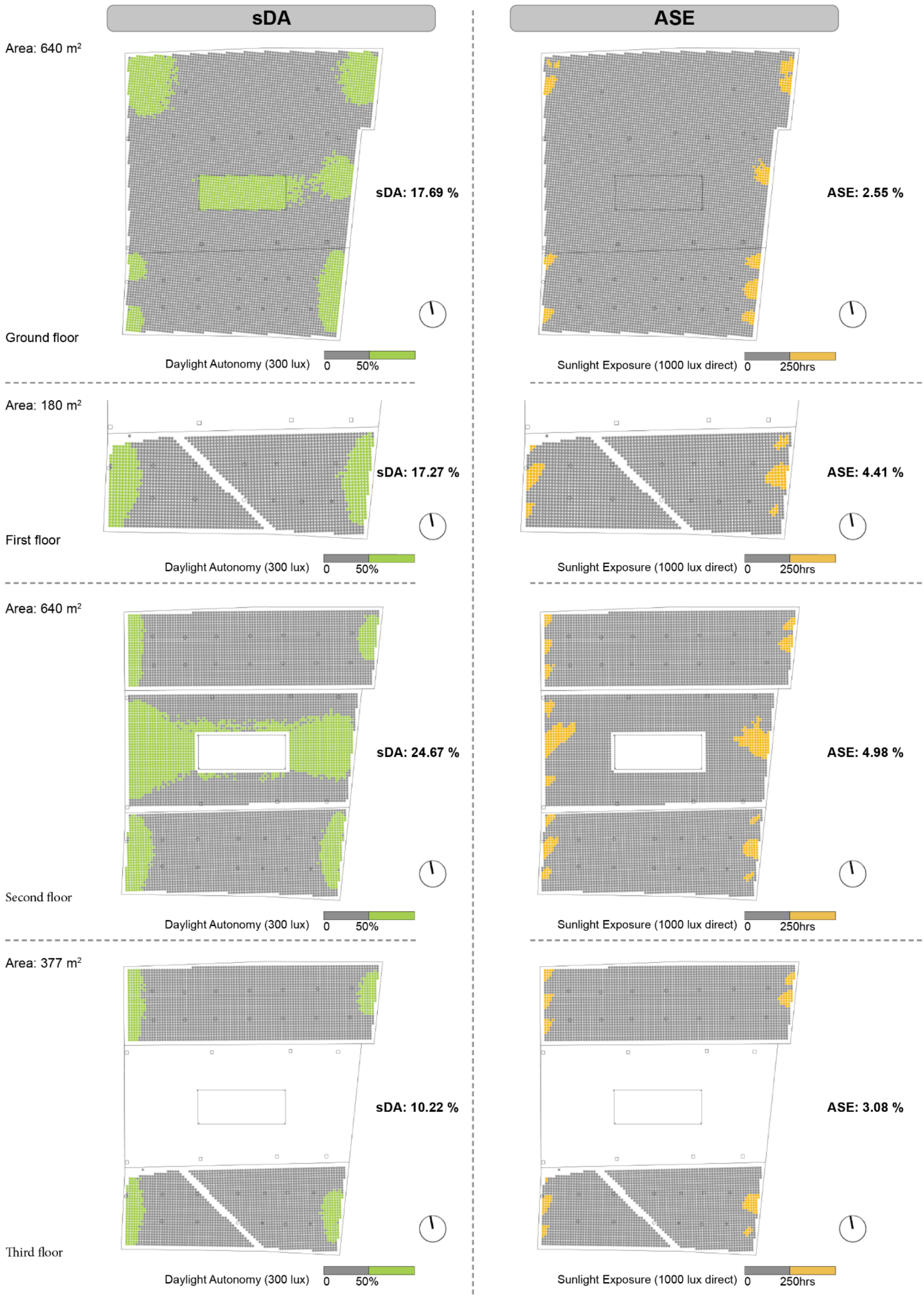
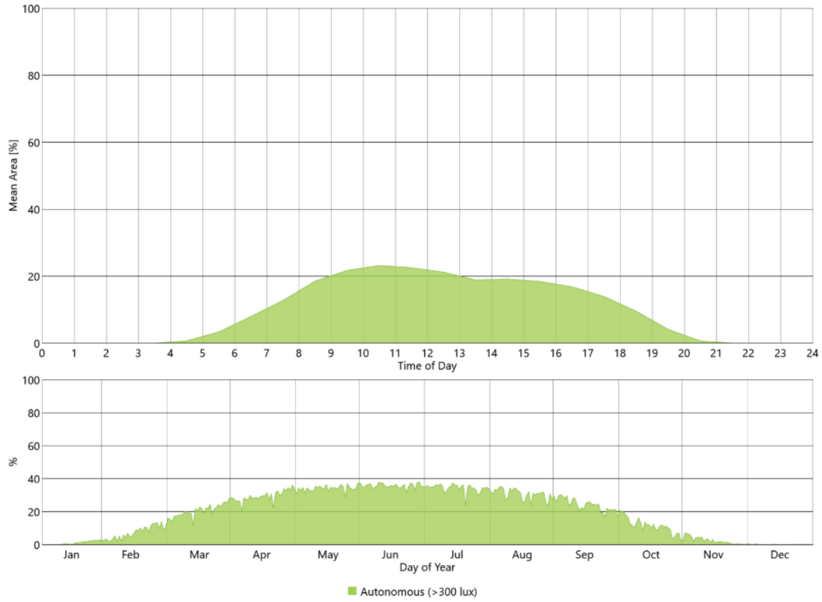
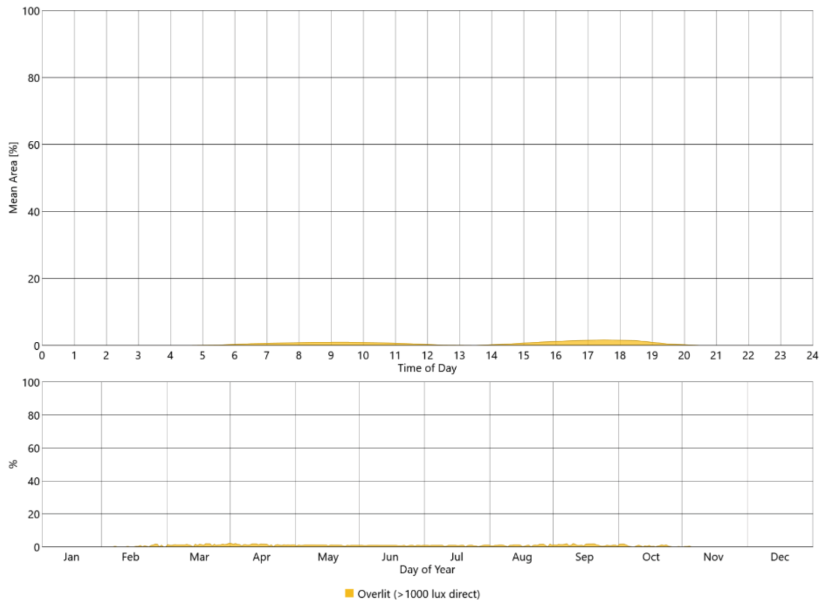


Figure 36. sDA and ASE values at each floor

Figure 37 shows the percentages of sDA and ASE during the year for the whole building in scenario 1.



Annual profile of sDA for scenario 1



Annual profile of ASE for scenario 1

Figure 37. Annual profile of sDA and ASE for the scenario 1

Based on the results, the sDA during months of May to August was reached to about 38% which was the highest in the year. The sDA value decreased to the zero in December and January. The ASE was constantly lower than 3% that the highest amount recorded in end of March and September. The reason for this increment in these months had similar behaviors which could be because of the autumn and spring equinox.

The DF for the scenario 1 is depicted in the Figure 38.

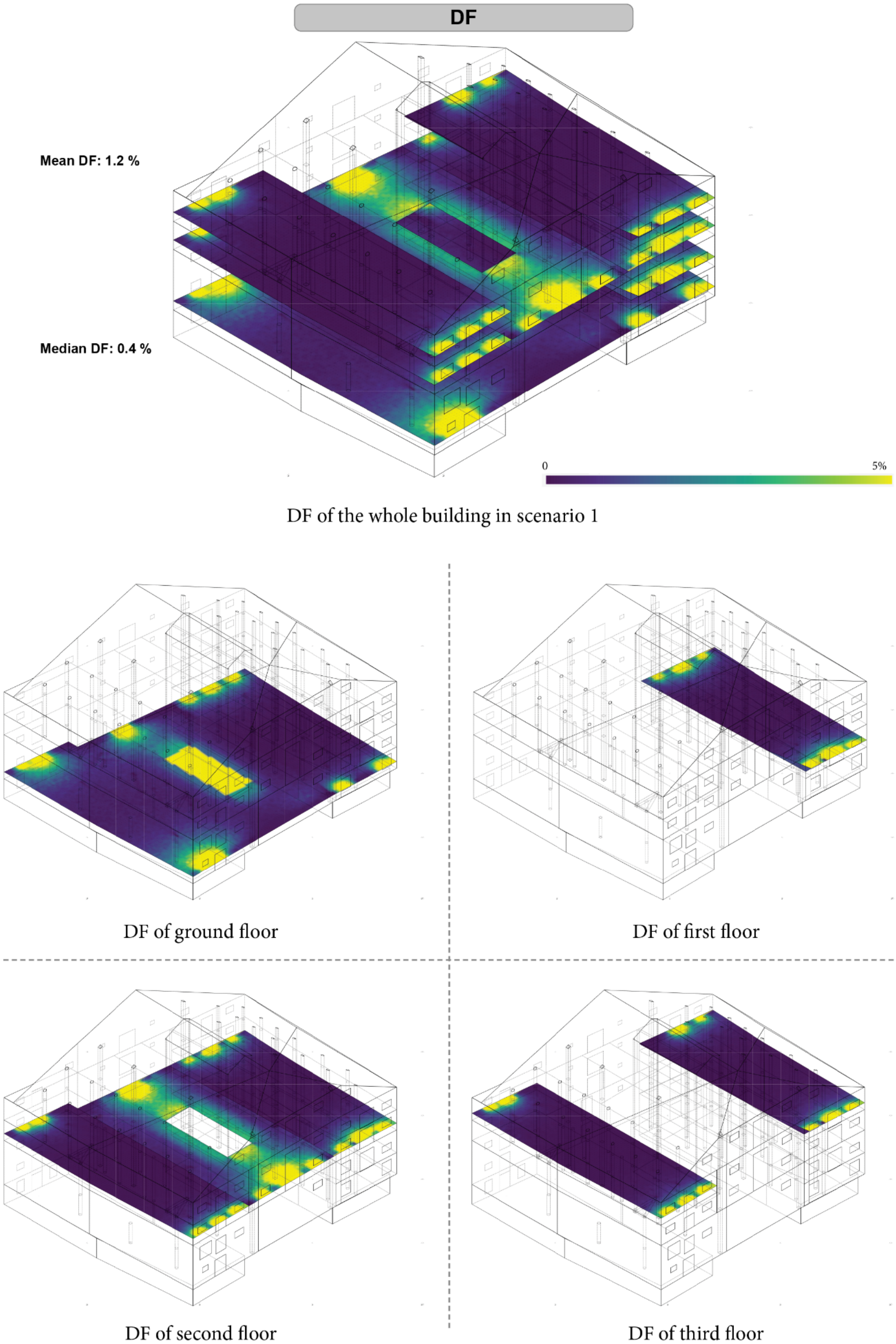


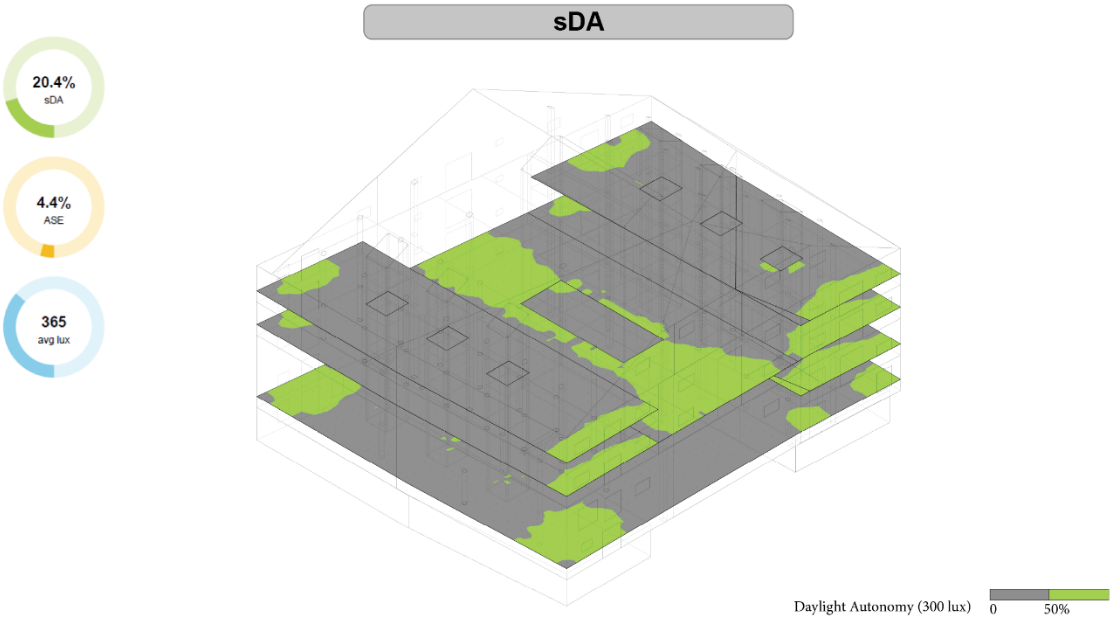
Figure 38. DF for each floor in scenario 1

The mean DF and median DF for this scenario was 1.2% and 0.4%, respectively. In the ground and second floor around the atrium the grids' color was changed to the green and yellow that shows atrium affect.

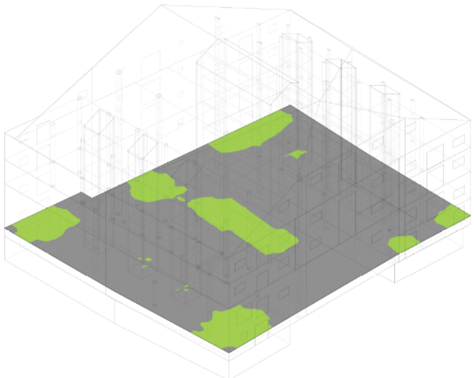
4.5. Analysis of sDA and DF, and ASE in scenario 2

Scenario 2 had the similar atrium with scenario 1 while had also three small atriums on both sides of the building. Therefore, in this scenario seven atriums implemented on the building with 2 geometry variations. The sDA analysis was conducted for this scenario and the results is presented in the Figure 39.

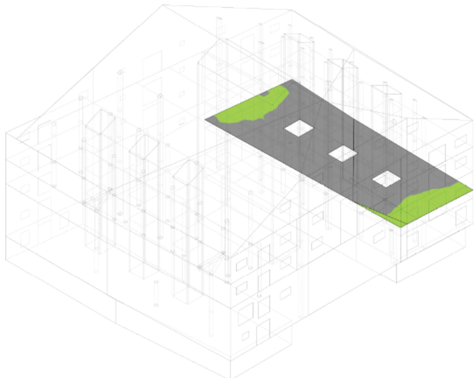
For the whole building 20.4% of sDA was obtained and the value of ASE was 4.4% during the year. the average illuminance of the space also calculated and it was 365 lux in average for the all gid points.



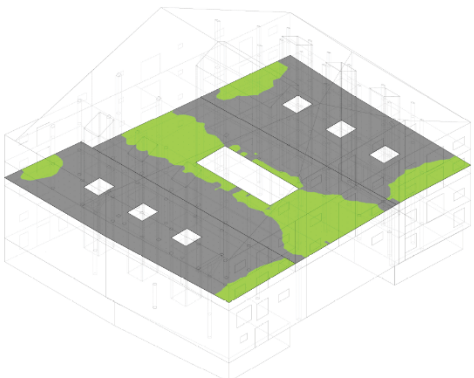
sDA of the whole building in scenario 2



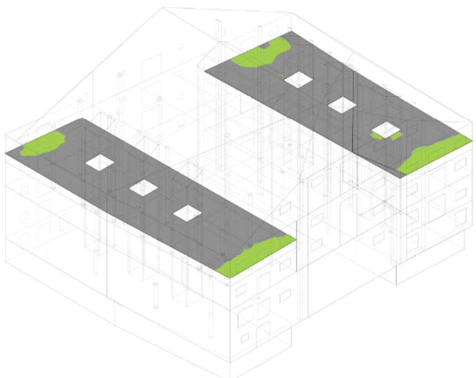
sDA of ground floor



sDA of first floor



sDA of second floor



sDA of third floor

Figure 39. sDA of the scenario 2

The results of sDA and ASE for each floor in Figure 40 shows that the highest amount of sDA was for the second floor with 26.91%. The second highest value of sDA was obtained at first floor by value of 19.22%. The highest and lowest value of ASE first floor and ground floor with the value of 6.08% and 3.13%, respectively.

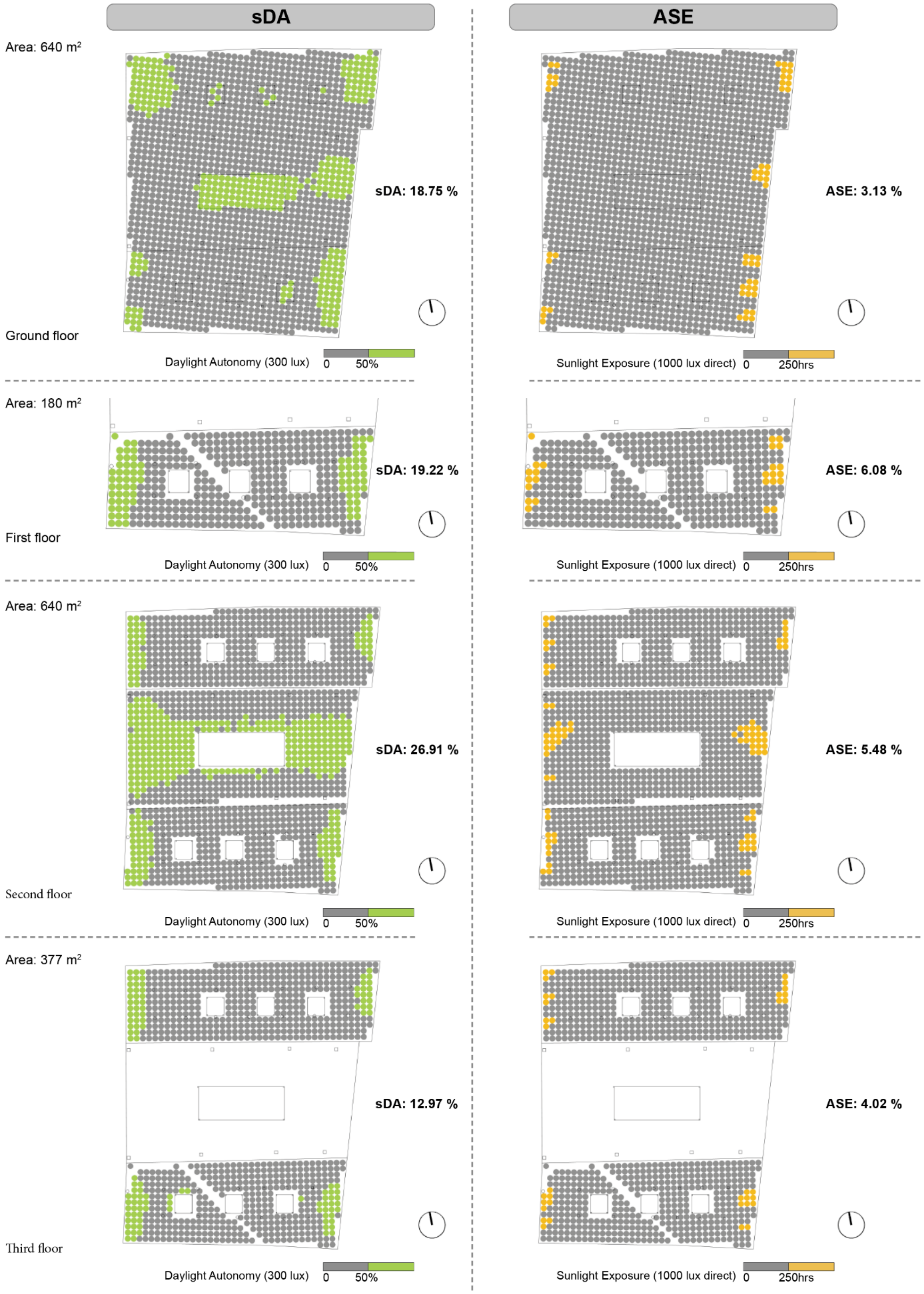
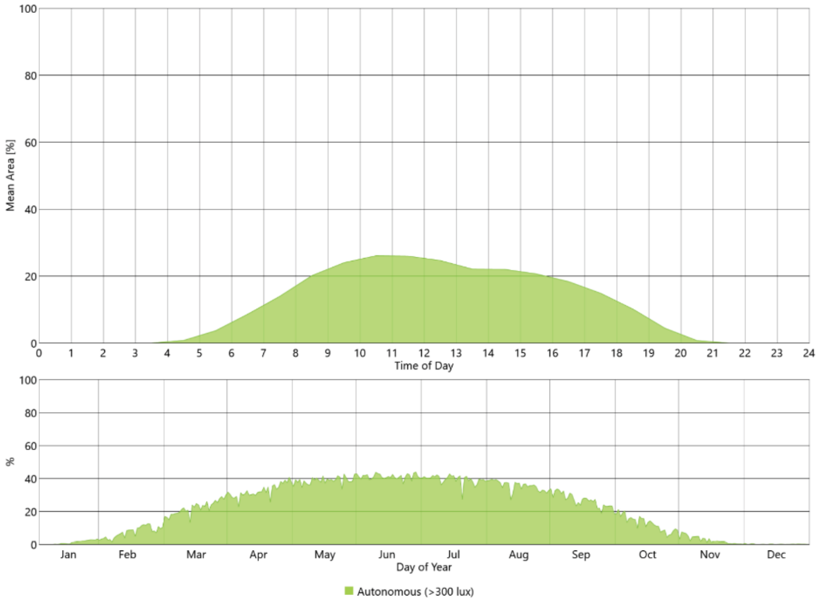


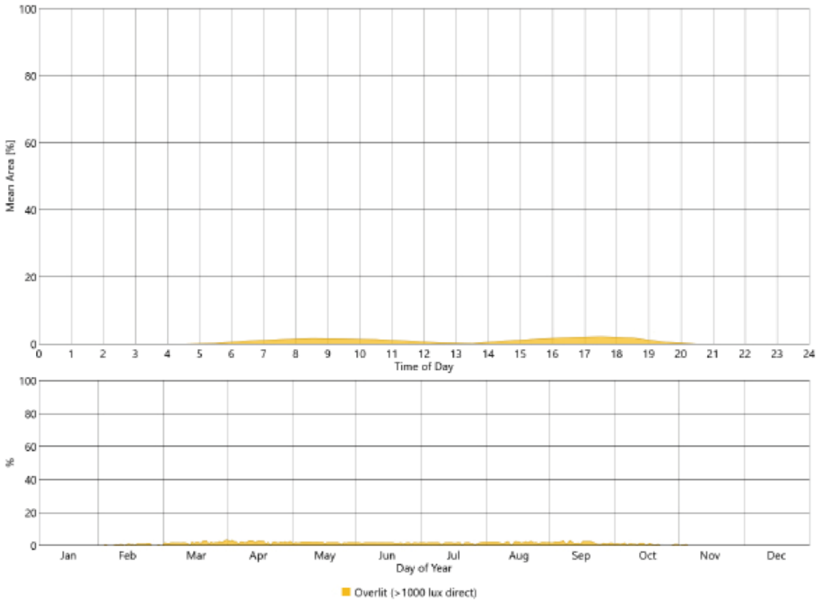
Figure 40. sDA and ASE values at each floor

Figure 41 represented the annual sDA and ASE in the scenario 2.

For the sDA from May to end of July was around 40%. While the value decreased to the below 5% in January and December. ASE value, however, was negligible from months of October to end of February.



Annual profile of sDA for scenario 2



Annual profile of ASE for scenario 2

Figure 41. Annual profile of sDA and ASE for the scenario 2

Figure 42 is shown the mean and median DF of the building in case of scenario 2.

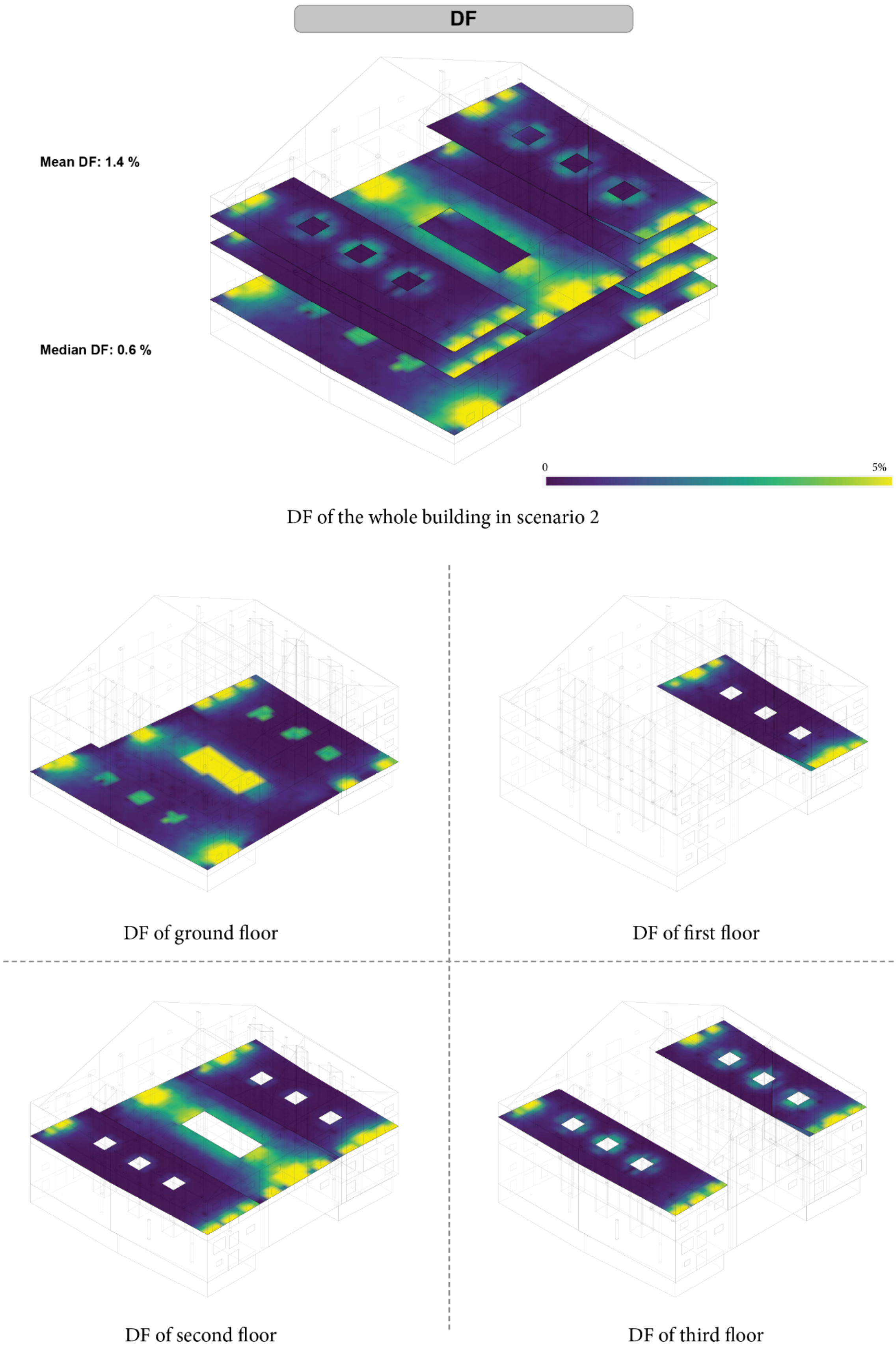


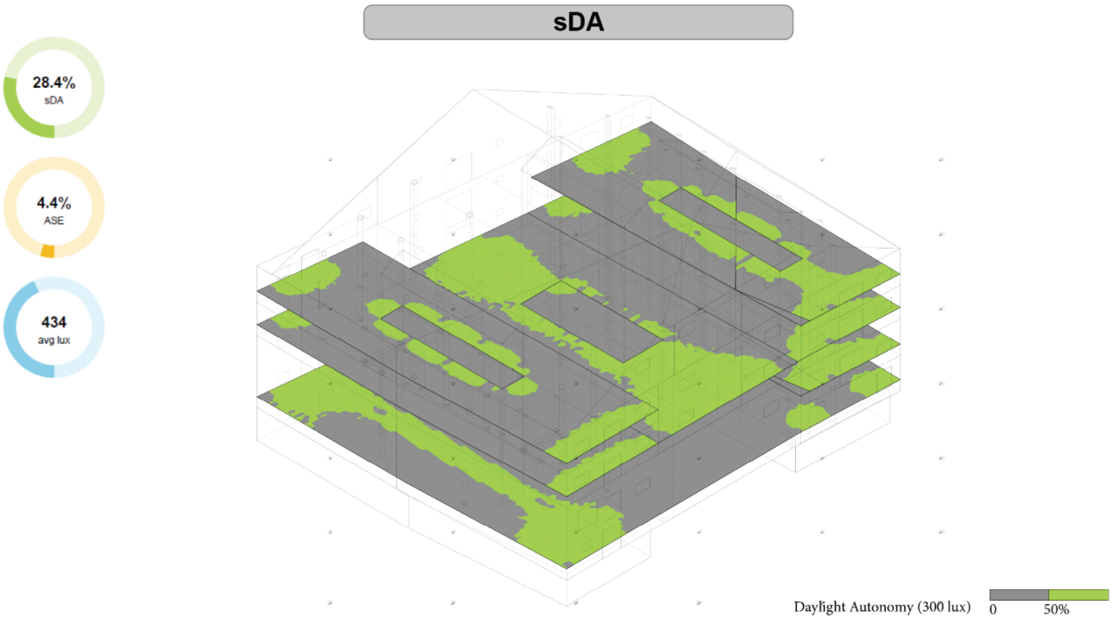
Figure 42. DF for each floor in scenario 2

In this scenario mean DF was 1.4% and median DF was 0.6%. the middle atrium sufficiently providing daylight in the building and around of this atrium is bright with green and yellow. However, in both sides of the building the atriums hardly provide the daylight. Based on the grid's visualization around of the side atriums are mostly dark that means low amount of DF. While, the sum of the area of three atrium were the same with the middle atrium, the DF was not improved sufficiently. Therefore, it can be concluded that the shape of atrium can strongly affect the DF in the building. One continuous shape atrium was more efficient in terms of improving DF in comparison with separated atriums.

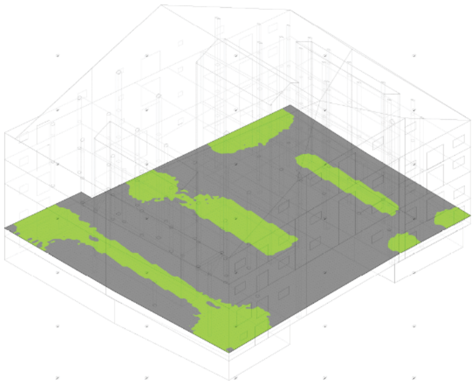
4.6. Analysis of sDA and DF, and ASE in scenario 3

The sDA, ASE, and DF was simulated in scenario 3 and the results are reported in Figure 44. In overall, the sDA for the whole building was 28.4% and ASE value was 4.4%. the average illuminance of the building for each grid point was equal to 434 lux.

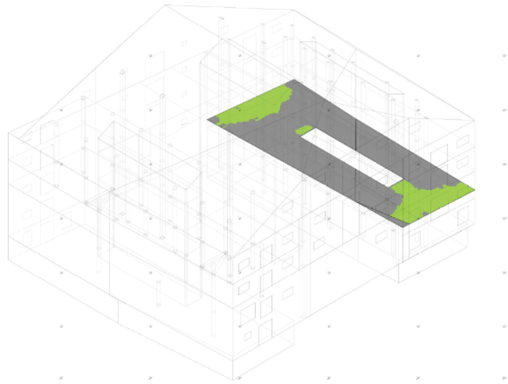
Figure 45 represented the results of sDA and ASE for each floor. As can be seen in the results, the sDA for the second floor was 30.74% which was the highest amount among all the floors. 29.3%, 26.76%, and 24.65% was the sDA values in order from highest to lowest related to the third, ground, and first floor, respectively. While the ASE was 5.65%, 5.425, and 5% for the second, third, and first floor, respectively. The lowest amount of ASE with the value of 2.66% was obtained in the ground floor in scenario 3.



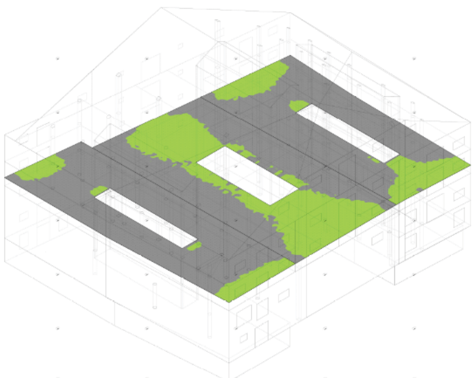
sDA of the whole building in scenario 3



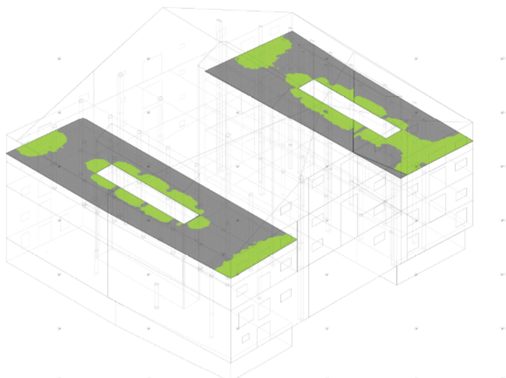
sDA of ground floor



sDA of first floor



sDA of second floor



sDA of third floor

Figure 43. sDA of the scenario 3

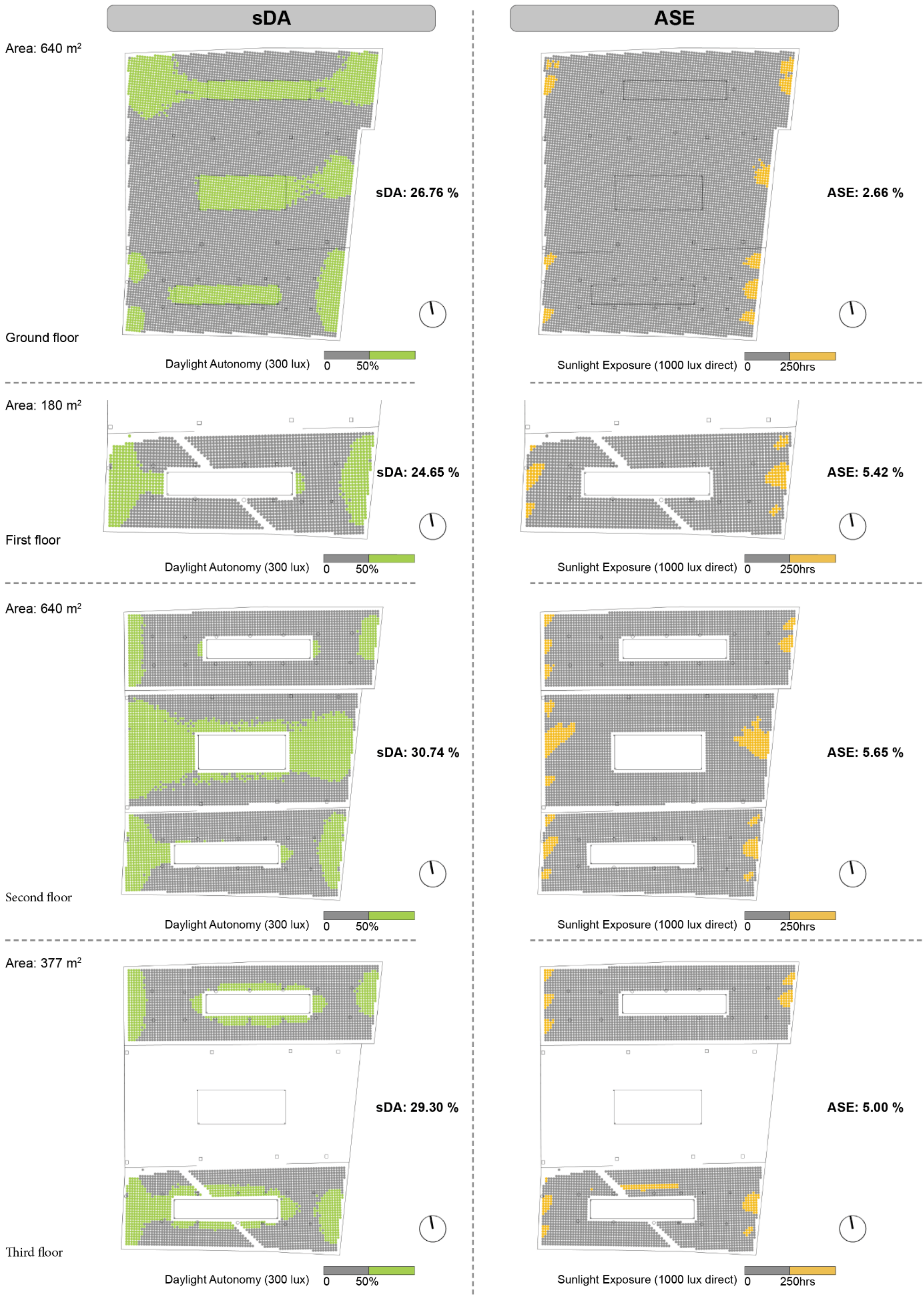
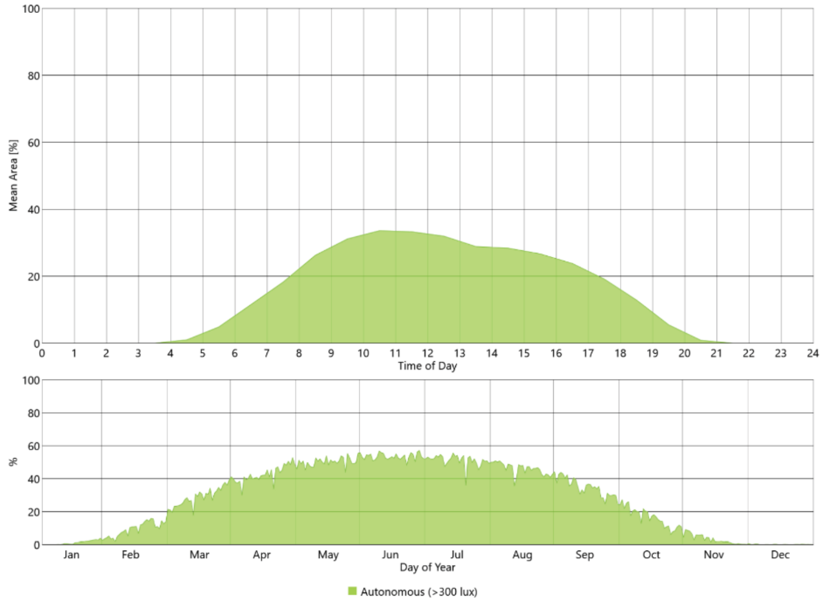
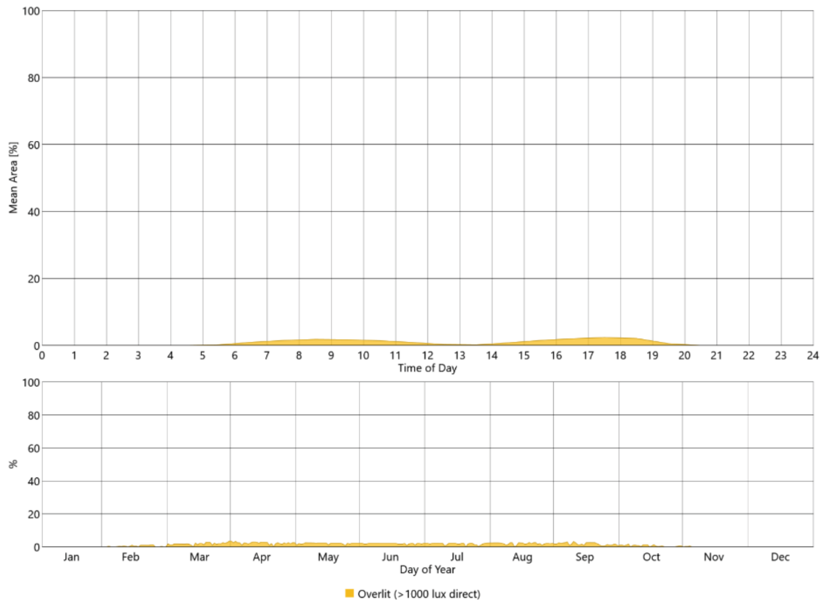


Figure 44. sDA and ASE values at each floor in scenario 3

Figure 45 shows the annual amount of sDA and ASE in each month and the day time for scenario 3.



Annual profile of sDA for scenario 3



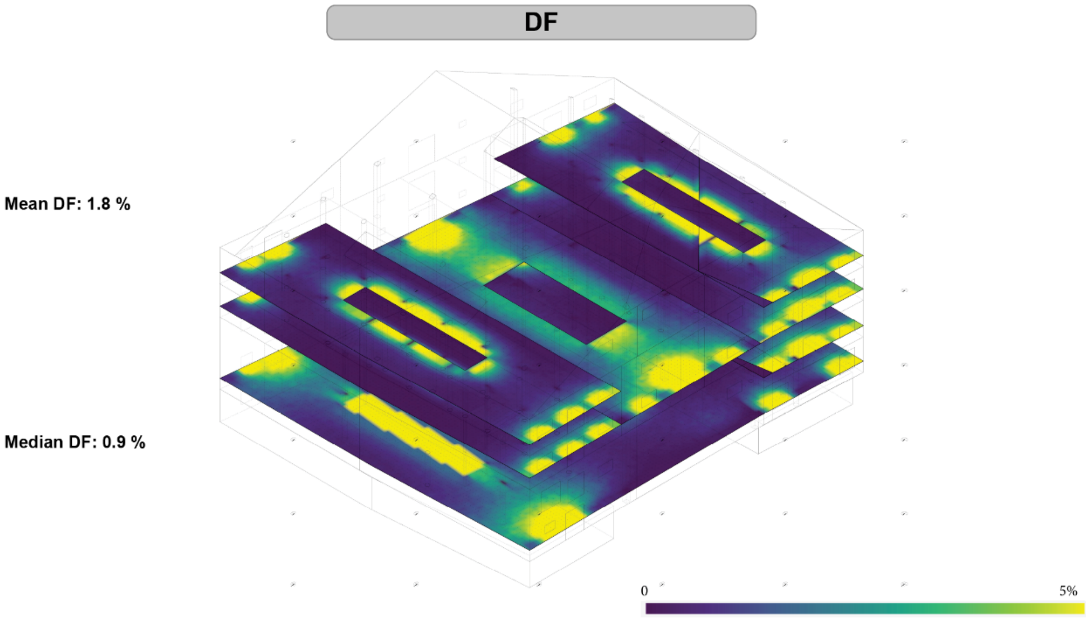
Annual profile of ASE for scenario 3

Figure 45. Annual profile of sDA and ASE for the scenario 3

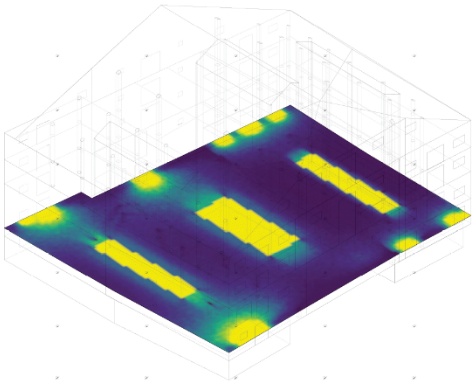
According to the results, the sDA was reached to about 50%during three months of May, June, and July. This value was decreased to lower than 10% in winter time when the lower solar radiation was occurred. The peak time of the day for sDA was from 10 am to 12 am when more than 50% of the area had received enough daylight.

The annual profile of ASE was shown that the value in most of the months was lower than 5% and decrease to zero in winter time. the peak hours of ASE value were between 8 am to 9 am in the morning and 5 pm to 6 pm in the afternoon.

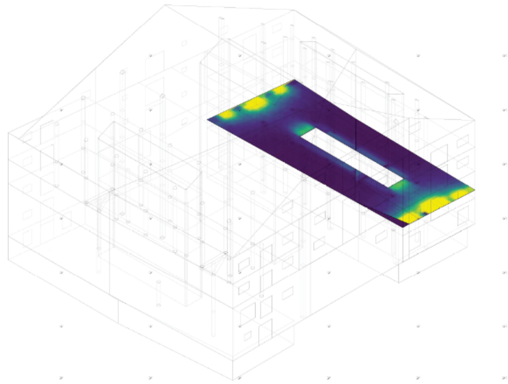
DF for scenario 3 is simulated and showed in Figure 46.



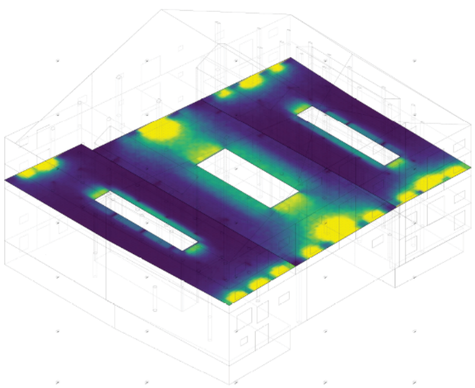
DF of the whole building in scenario 3



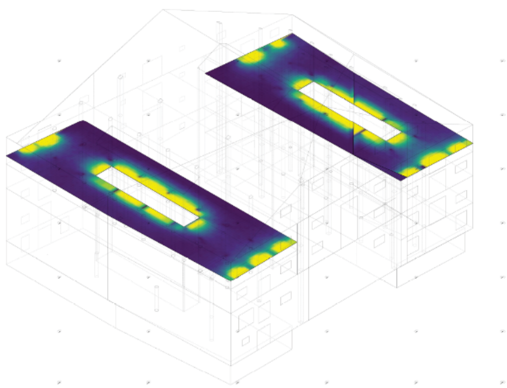
DF of ground floor



DF of first floor



DF of second floor



DF of third floor

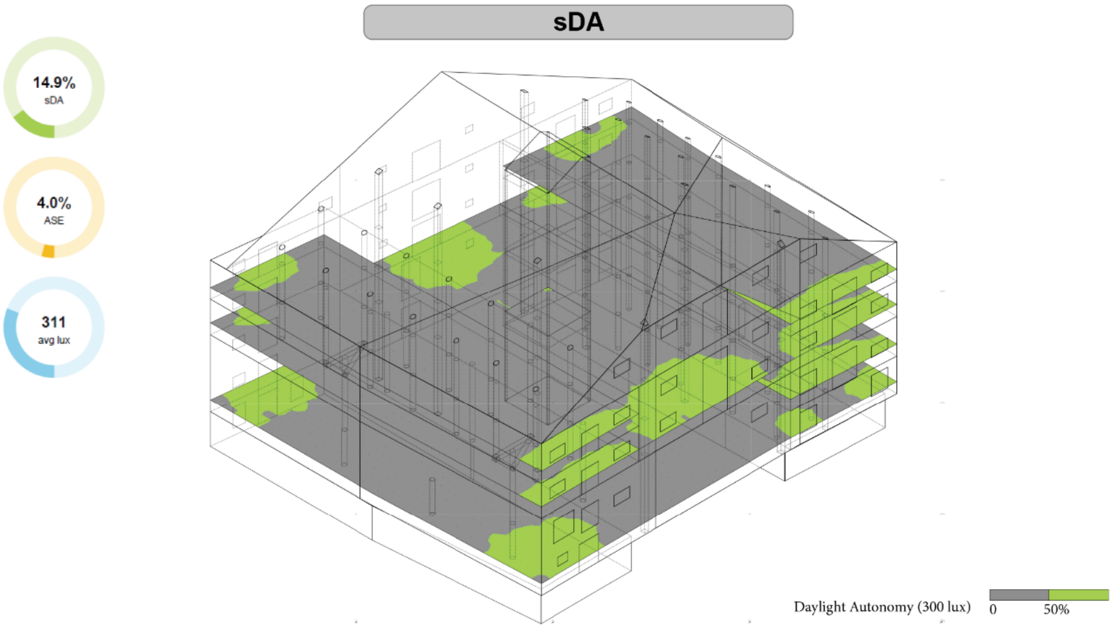
Figure 46. DF for each floor in scenario 3

The false color map of DF showed the mean and median DF with the value of 1.8% and 0.9%. in this scenario the sensors around atriums were in bright color that means the high value of DF. In this scenario the atriums perfectly increased the DF value compared to previous scenarios.

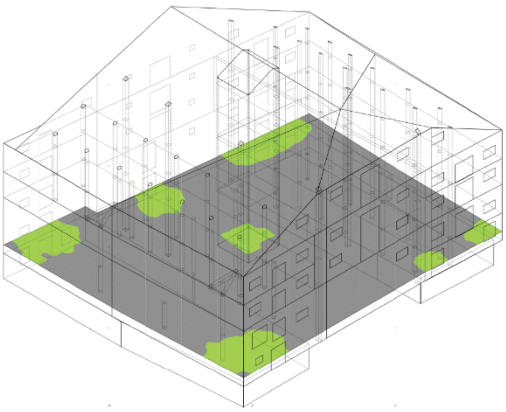
4.7. Analysis of sDA and DF, and ASE in scenario 4

Simulation of sDA and ASE was performed for scenario 4 which implemented with a rectangular atrium in the core of building.

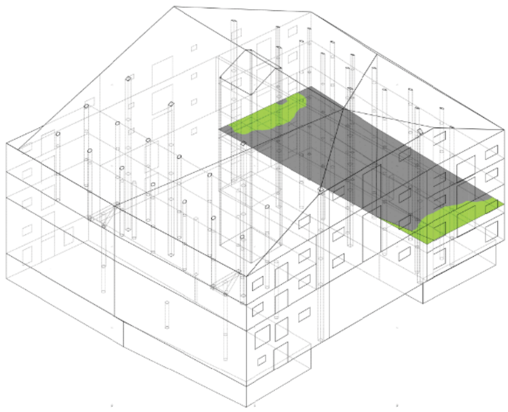
Figure 47 shows the sDA condition in the building in scenario 4. The overall sDA for all the building was 14.9% and ASE was 4%. The average illuminance of each grid sensors was 311 lux during a year. These values were shown that the atrium could not provide enough daylight for interior building.



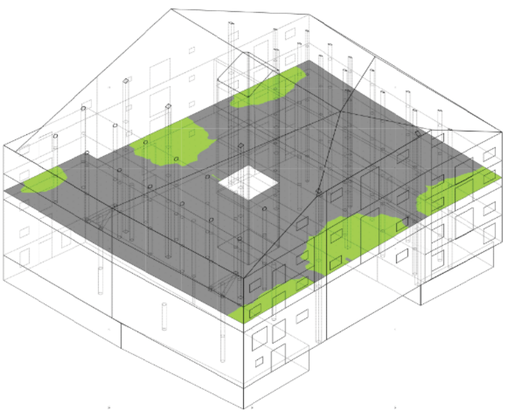
sDA of the whole building in scenario 4



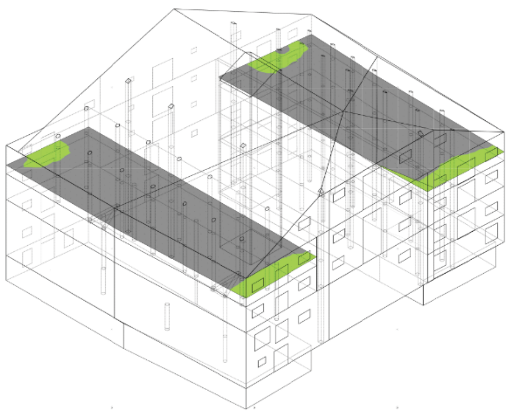
sDA of ground floor



sDA of first floor



sDA of second floor



sDA of third floor

Figure 47. sDA and ASE values at each floor in scenario 4

Figure 48 represented the sDA and ASE grids with the corresponding values at each floor in scenario 4.

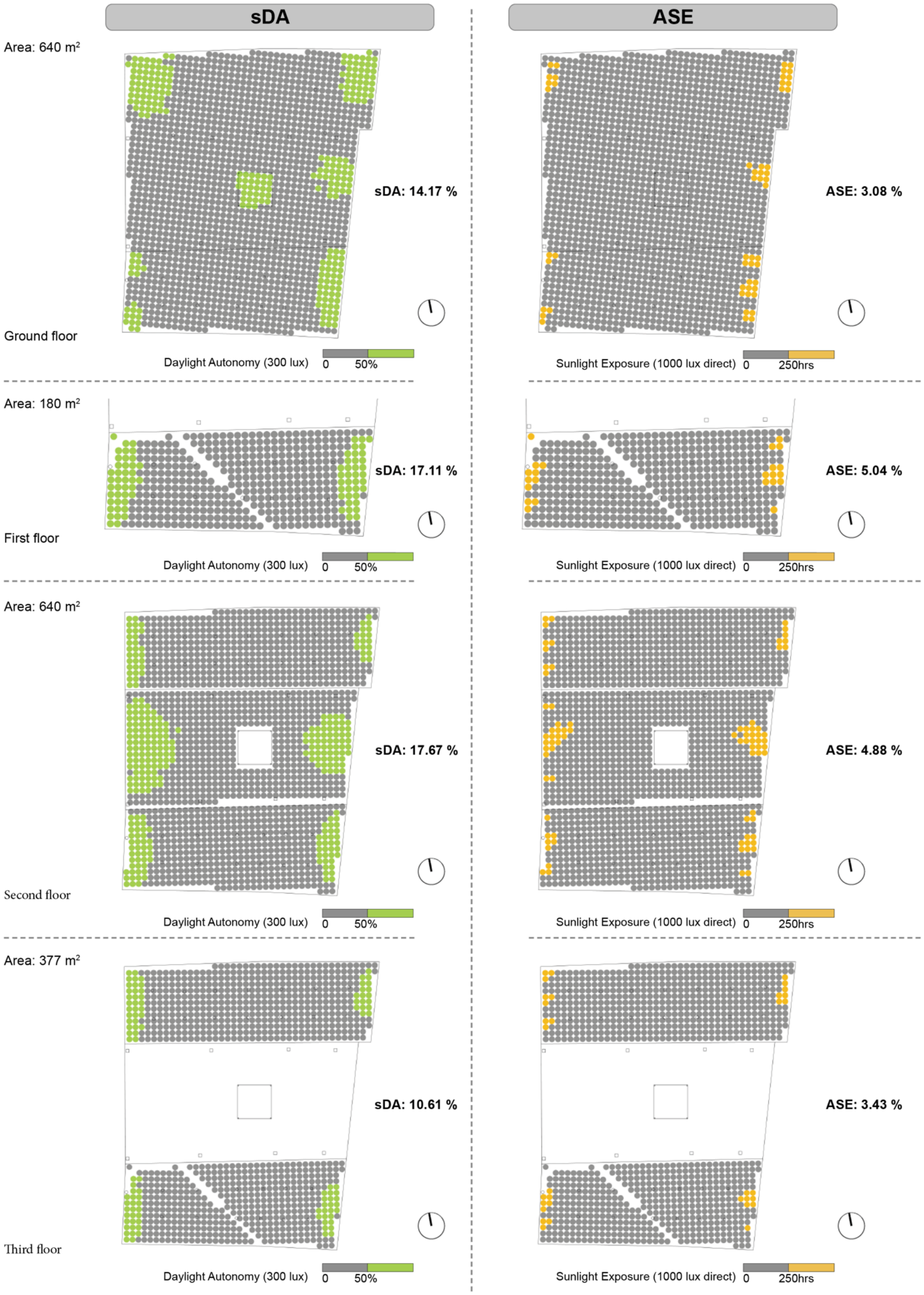
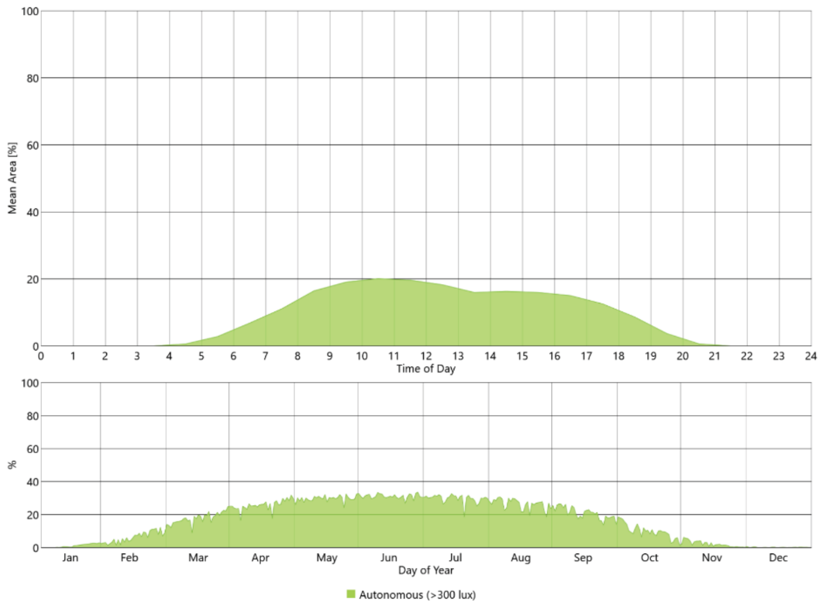


Figure 48. sDA and ASE values at each floor in scenario 4

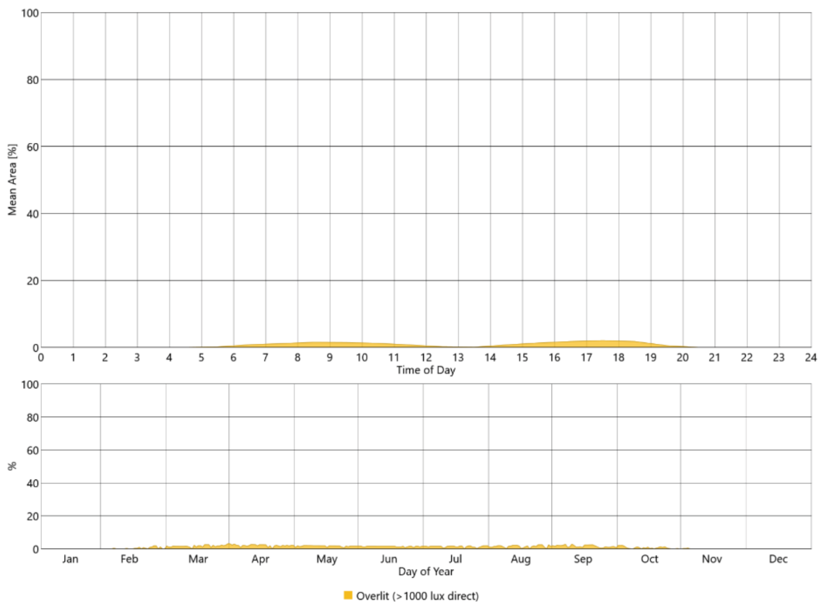
The highest amount of sDA in this scenario was 17.67% which happened at second floor. This value followed by 17.11%, 14.17%, and 10.61% in first, ground, and third floor, respectively.

The highest and lowest ASE in scenario 4 was at first floor by value of 5.04% and ground floor by the value of 3.08%, respectively.

The following figure represented the sDA and ASE in the year and also the accumulated amount of each metrics during a day hour.



Annual profile of sDA for scenario 4



Annual profile of ASE for scenario 4

Figure 49. Annual profile of sDA and ASE for the scenario 4

Based on Figure 49, the sDA in summer months reached to about 30% in scenario 4. Also, between 10 am to 11 am during a day was the peak of sDA with covering 20% of the building. However, in winter the sDA was reached to below 5% and even lower in January and December similar to the other scenarios.

The ASE value was constantly below 5% with the peak value in September and March.

The DF was simulated for the scenario 4 and the results is shown in Figure 50. The results showed that the atrium at this scenario hardly impacted the DF in the building. As in this scenario the atrium was only considered in the middle of the building, it was not changing the area which were far from the middle of the building.

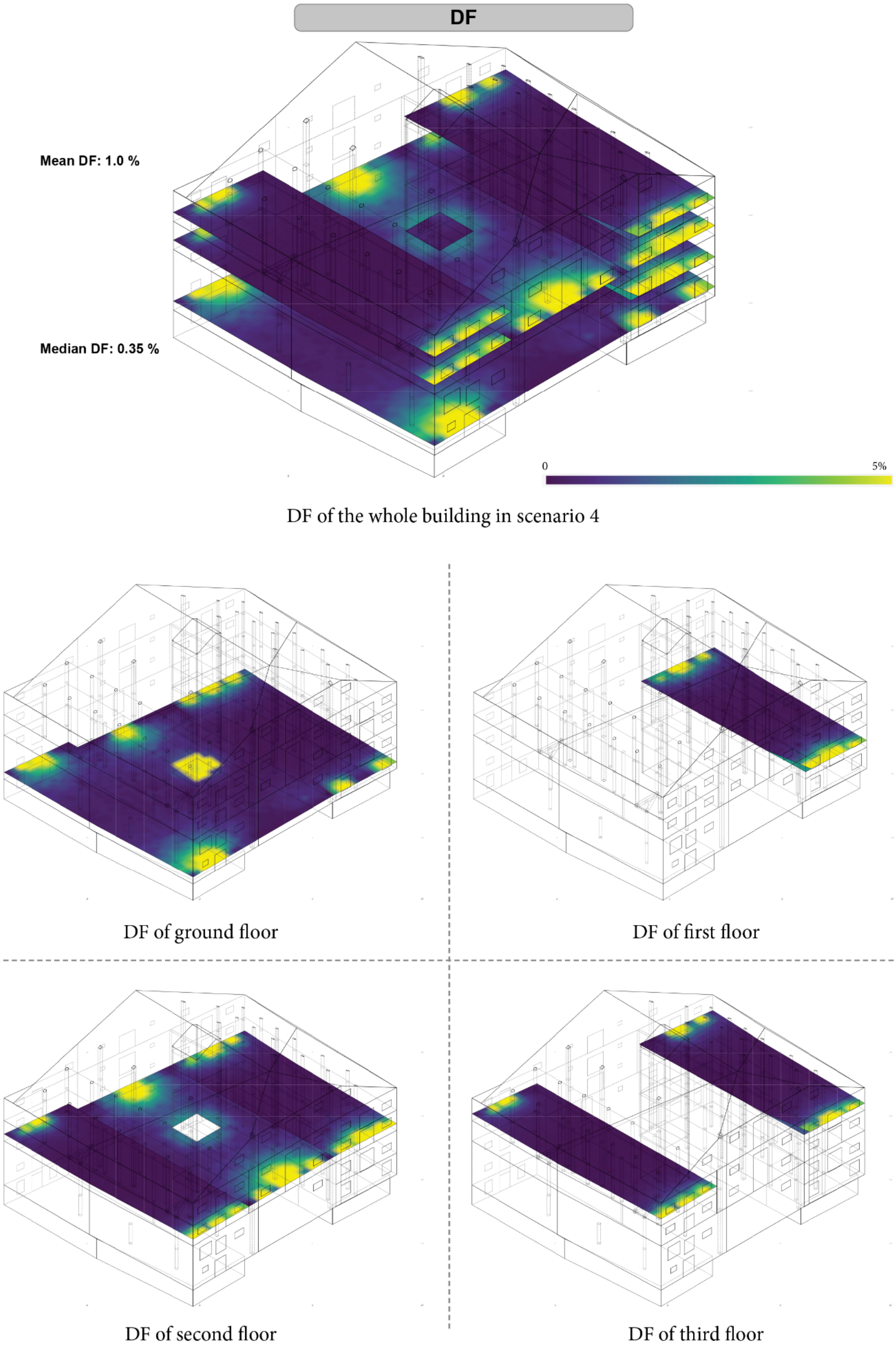


Figure 50. DF for each floor in scenario 4

4.8. Analysis of sDA and DF, and ASE in scenario 5

The results of simulations for scenario 5 are presented in Figure 51.

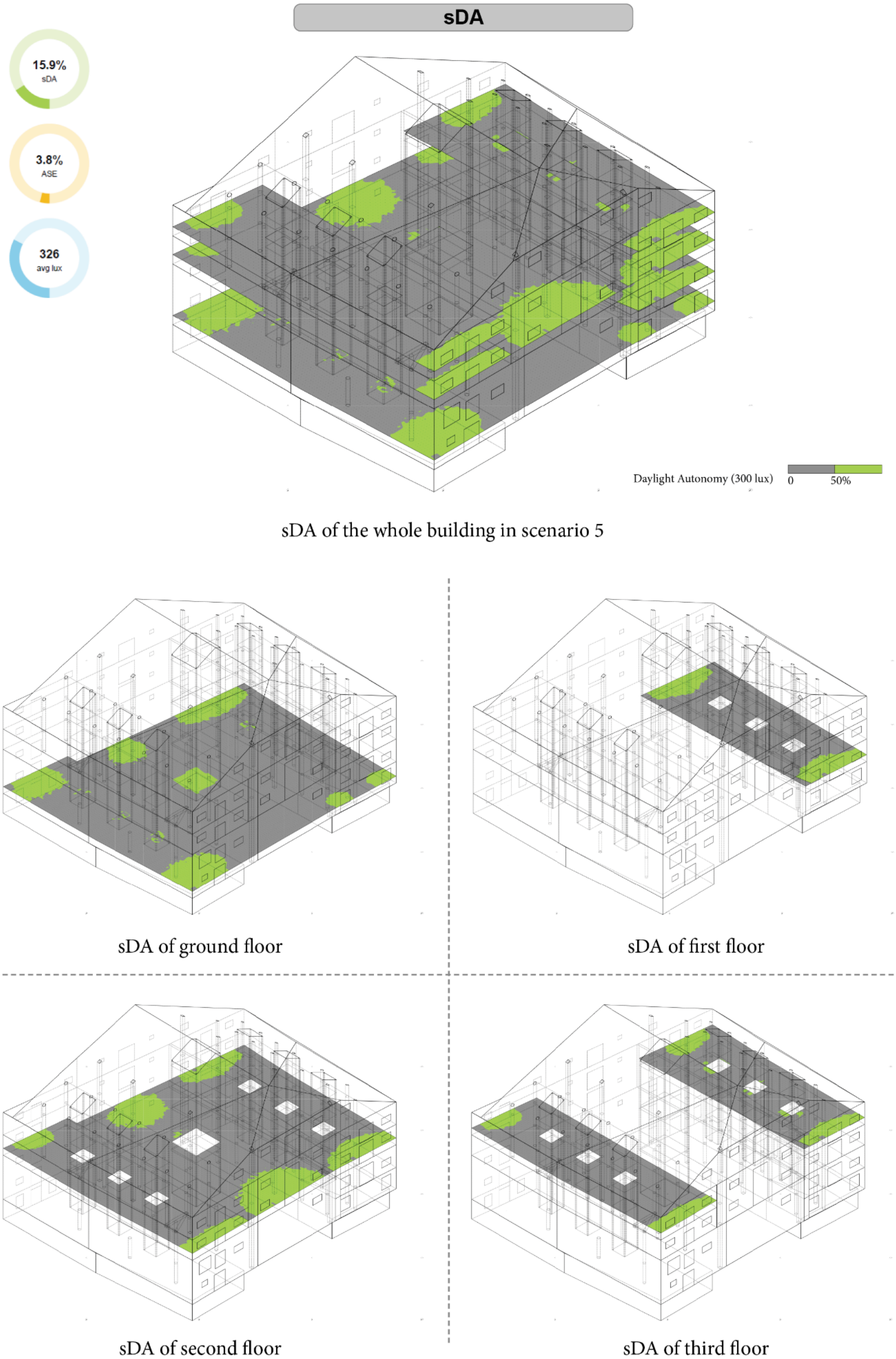


Figure 51. sDA and ASE values at each floor in scenario 5

As shown in the results, the sDA and ASE were 15.9% and 3.8% respectively. Also, the results were shown that the average illuminance in this scenario for the whole building was 326 lux.

For a more detailed analysis of sDA and ASE the results were presented for each floor separately and the values of sDA and ASE were shown in Figure 52.

The highest amount of sDA and ASE was related to the first floor with values of 19.27% and 4.91%. These values were decreased to the lowest amount on the third floor with the value of 12.2% and 3.42%, respectively. The sDA on the ground floor and the second floor was 14.25% and 18.86% respectively, however, the ASE value was 2.55% and 5.09% for these floors.

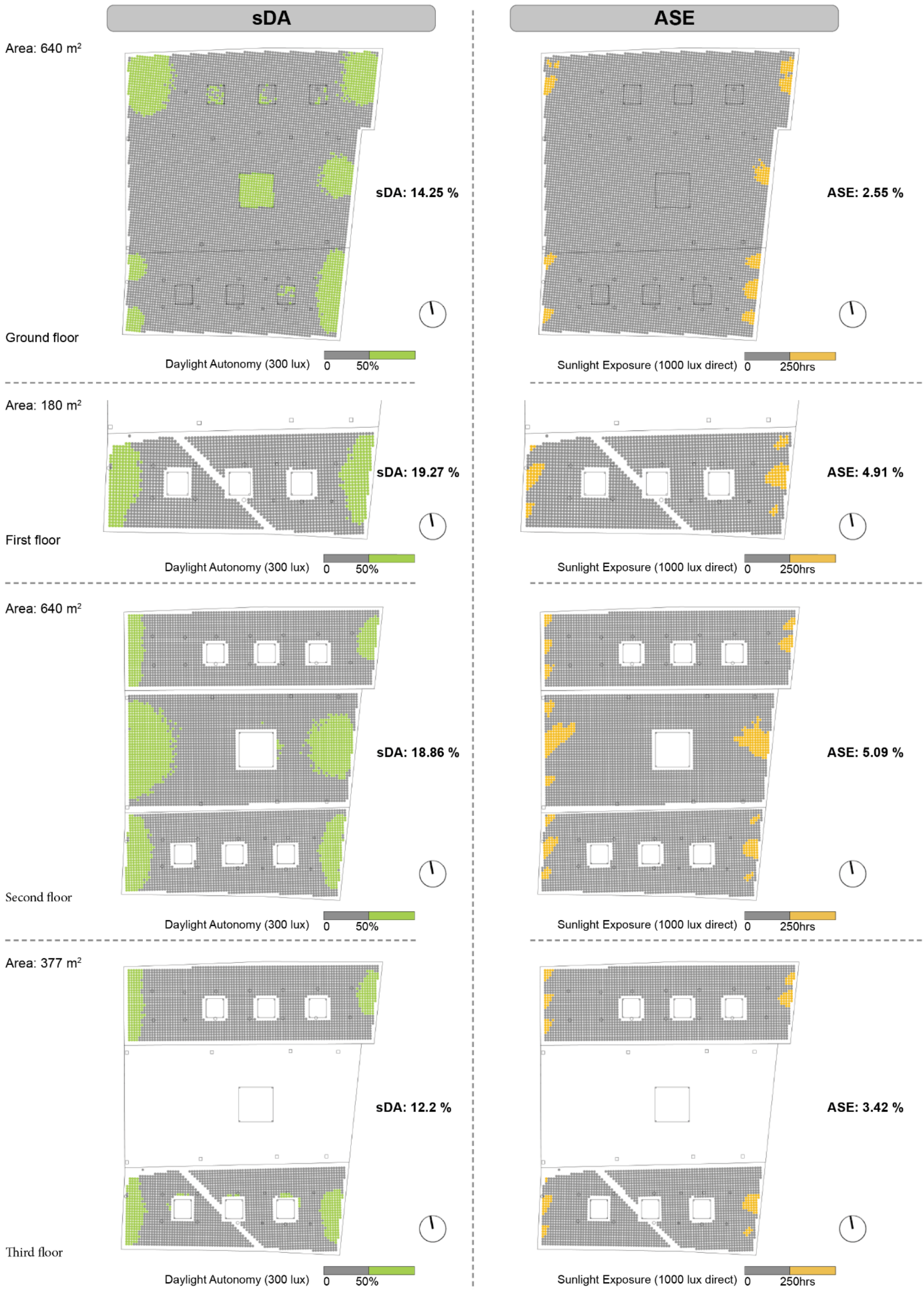
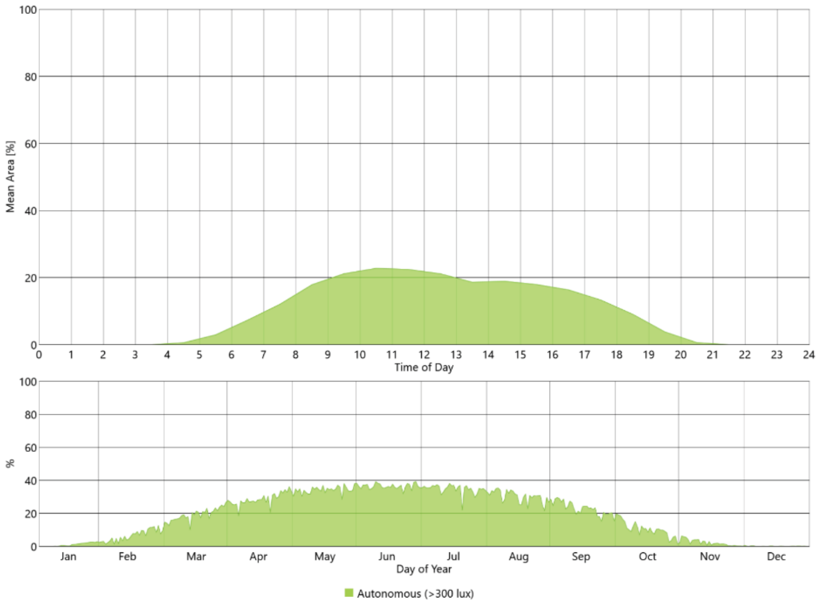


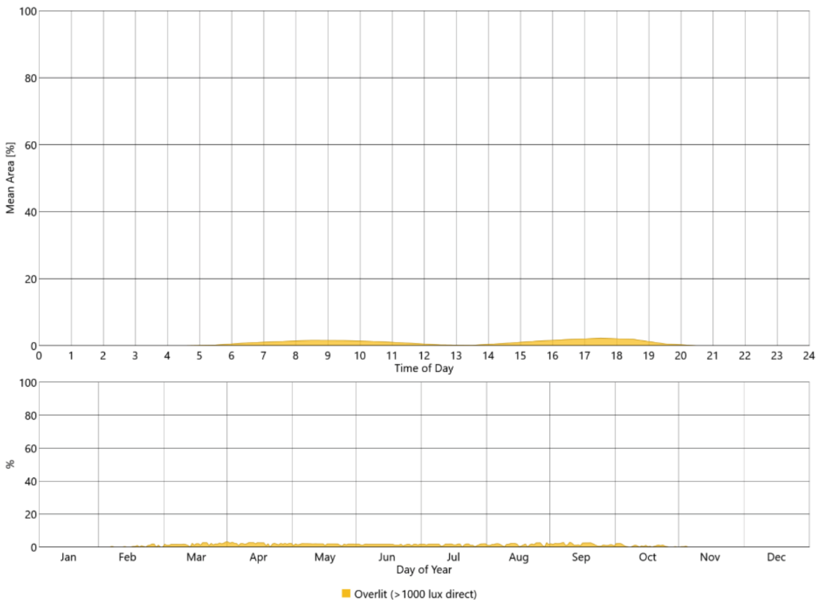
Figure 52. sDA and ASE values at each floor in scenario 5

Figure 53 depicts the annual profile of the sDA and ASE for each month during a year. the results demonstrated that around noon time the highest amount of sDA happened. Also, based on Figure 53, the sDA reached about 40% in the months of June and July. While the corresponding value in January and December reached near 0%. It could be because of the low amount of daytime during winter and also higher hours of daytime in the summertime.

The ASE value for scenario 5 was negligible and most of the time in a year was lower than 5% and during winter this value was about zero. Comparing the results of ASE showed that no glare condition happened in this scenario.



Annual profile of sDA for scenario 5



Annual profile of ASE for scenario 5

Figure 53. Annual profile of sDA and ASE for the scenario 5

The DF was simulated and analyzed for scenario 5 and the results is shown in Figure 54.

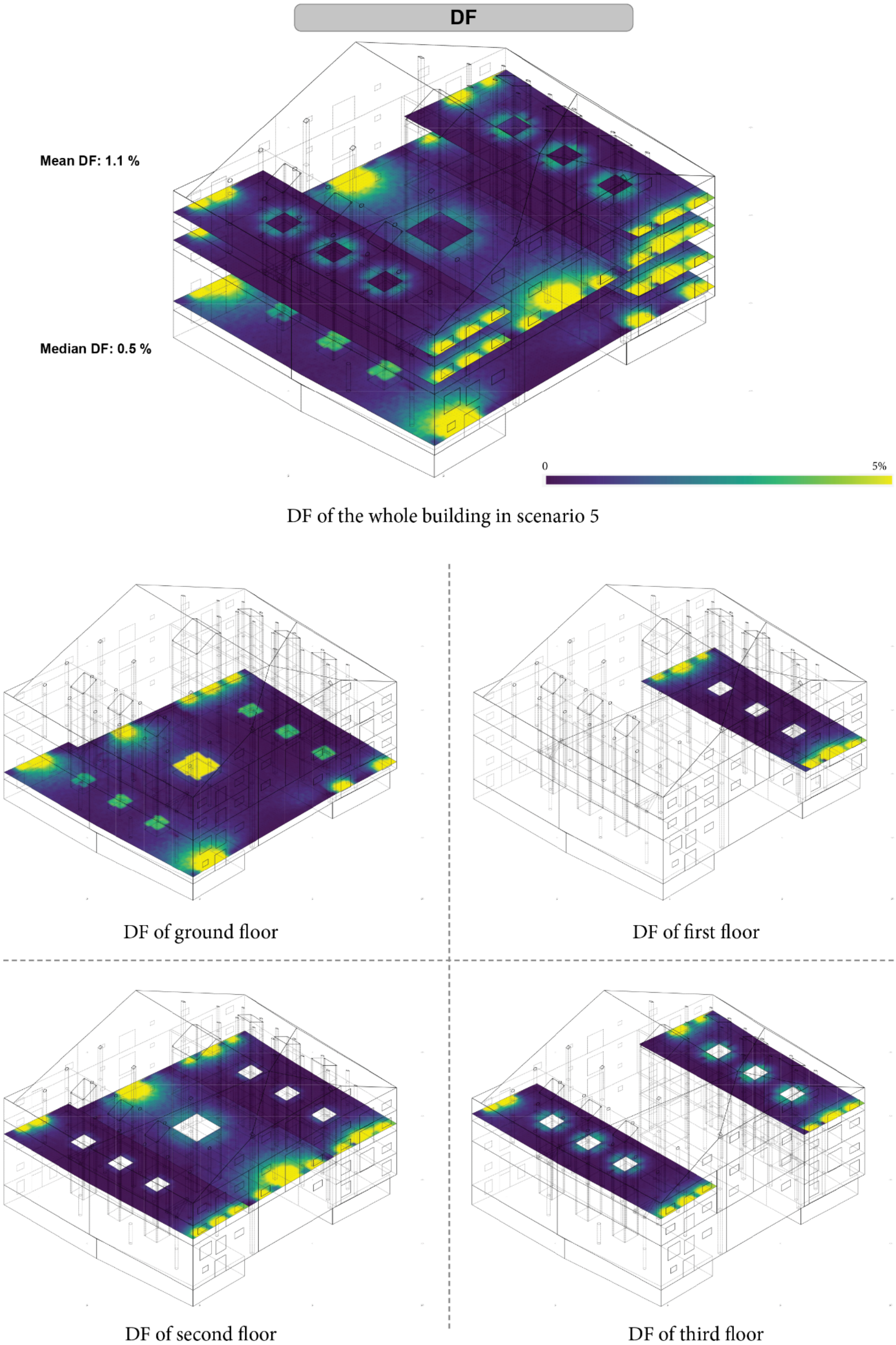


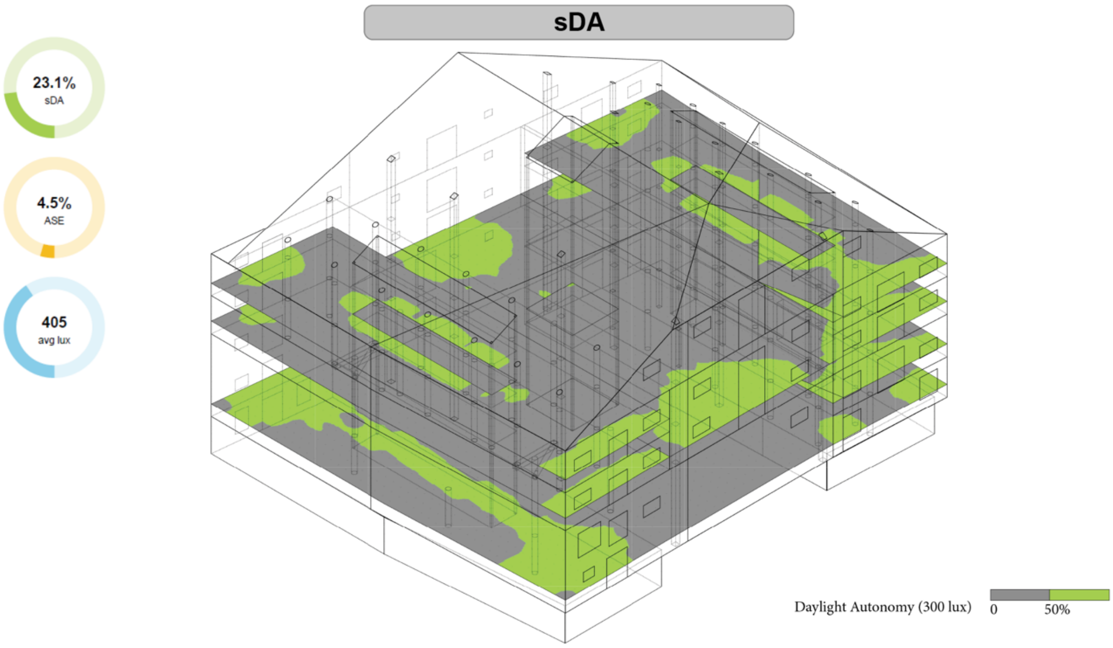
Figure 54. DF for each floor in scenario 5

DF analysis for this scenario showed that the mean DF was 1.1% and median DF 0.5%. According to the results, the atrium in scenario 5 could not improve the daylight condition in the building. Most of the areas with the highest value of DF were around windows and around the atriums were achieved the low amount of DF.

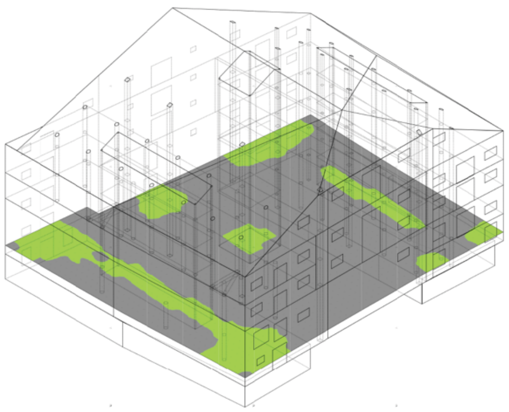
4.9. Analysis of sDA and DF, and ASE in scenario 6

The simulation of sDA and ASE was conducted for scenario 6 with three atriums. Two of them were the same shape and size and one rectangular atrium in the middle of the building.

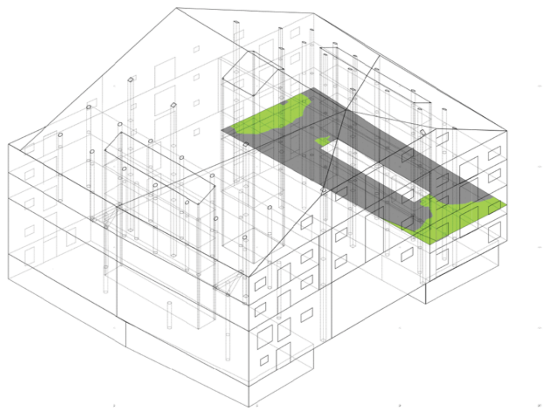
The results of sDA and ASE are shown in Figure 55. Based on the results the value of sDA and ASE was 23.1% and 4.5%, respectively. The average illuminance in the whole building was equal to 405 lux.



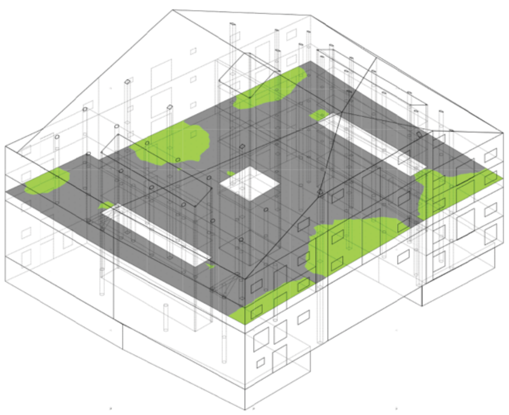
sDA of the whole building in scenario 6



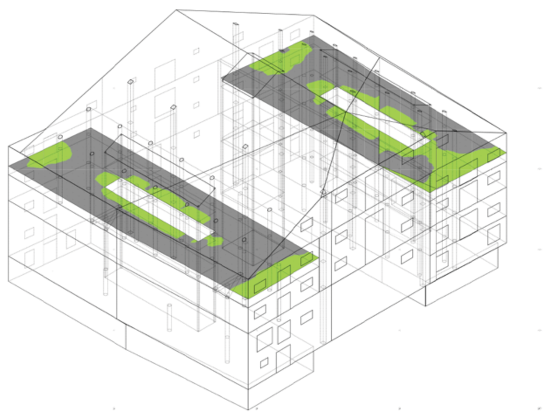
sDA of ground floor



sDA of first floor



sDA of second floor



sDA of third floor

Figure 55. sDA and ASE values at each floor in scenario 6

Figure 56 is presented the sDA and ASE in scenario 6 for each floor. The amount of sDA was varied between the lowest value of 20.79% which occurred on the second floor and the highest value of 26.78% related to the third floor. The corresponding value for the ground floor and the first floor was 22.89% and 24.23%, respectively.

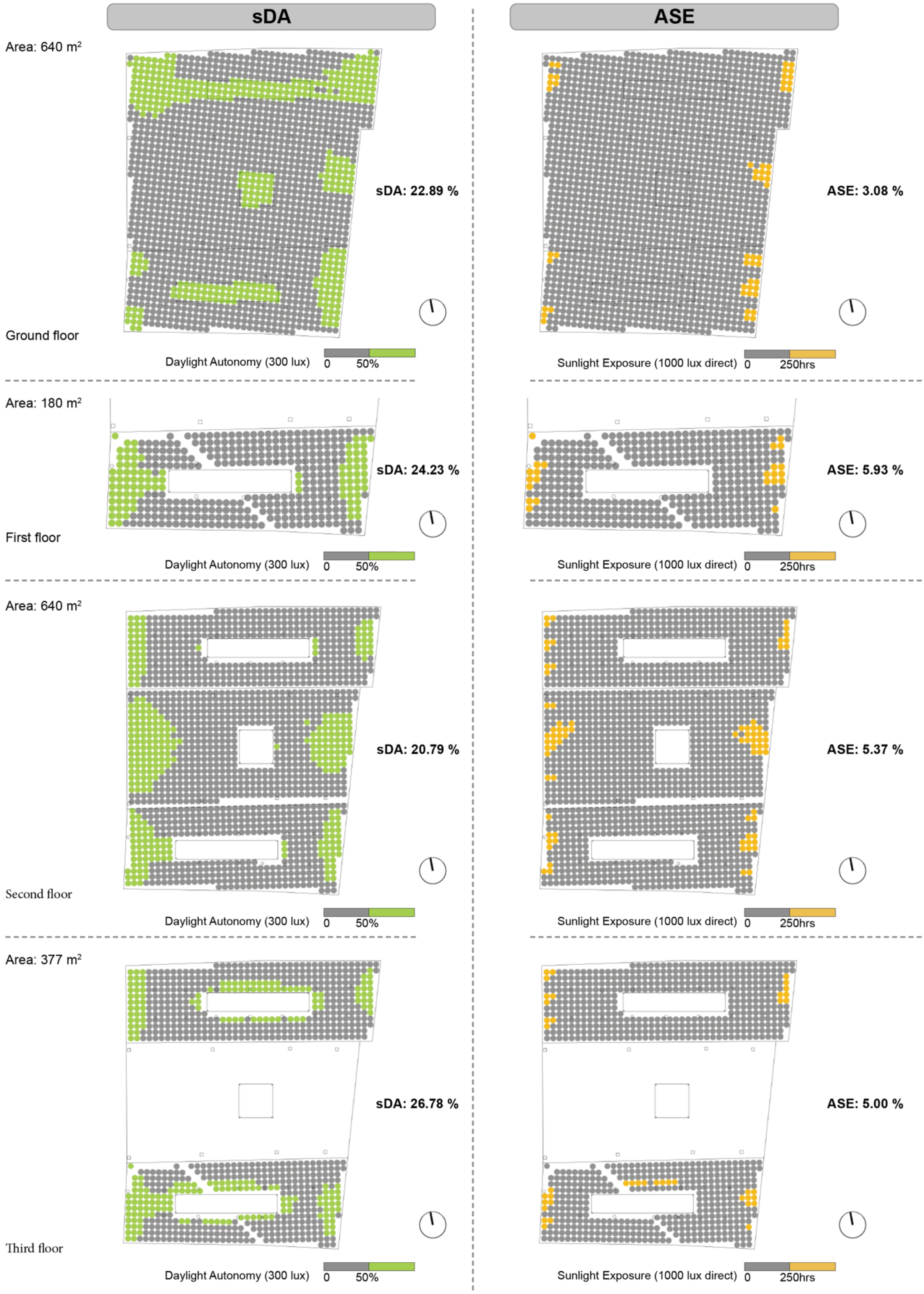
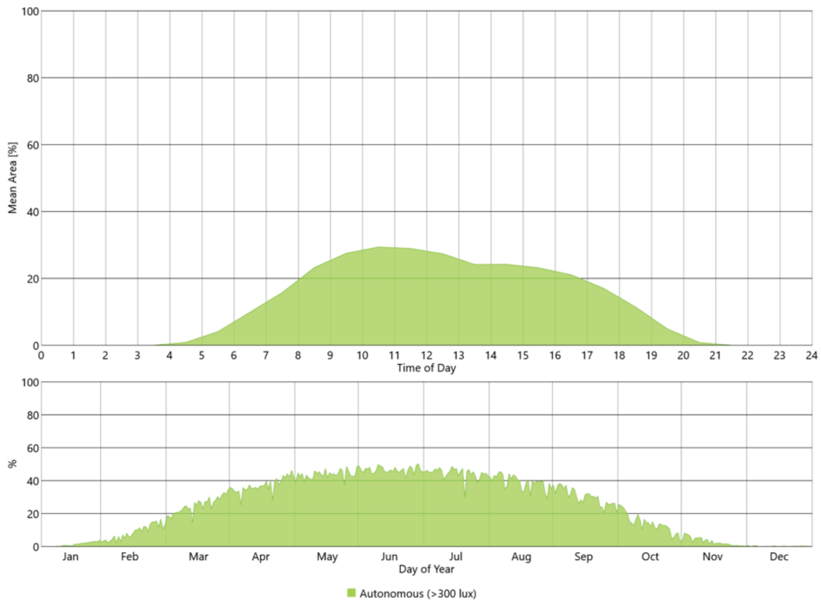


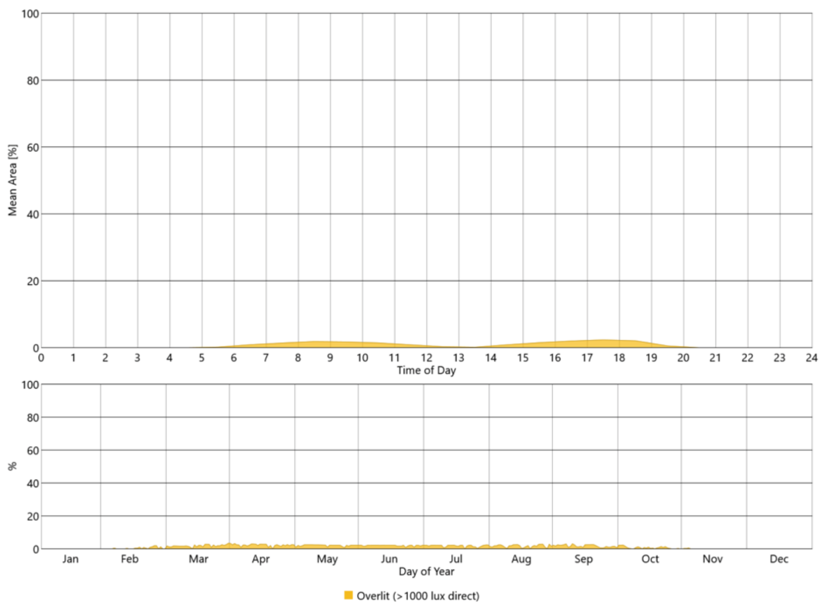
Figure 56. sDA and ASE values at each floor in scenario 6

However, the highest ASE value was recorded on the first floor with the amount of 5.93%. the second-highest amount of ASE was related to the second floor with the value of 5.37% and followed by 5% and 3.08% on the third and ground floor, respectively.

Figure 57 shows the annual profile of ASE and sDA on a monthly and hourly basis. According to the results, the highest amount of sDA happened during summer. From May to July the sDA was recorded about 50%. It shows that the performance of the atrium during these months was satisfactory. However, in January and November, this value decreased to lower than 5% and in December this value was about zero.



Annual profile of sDA for scenario 6

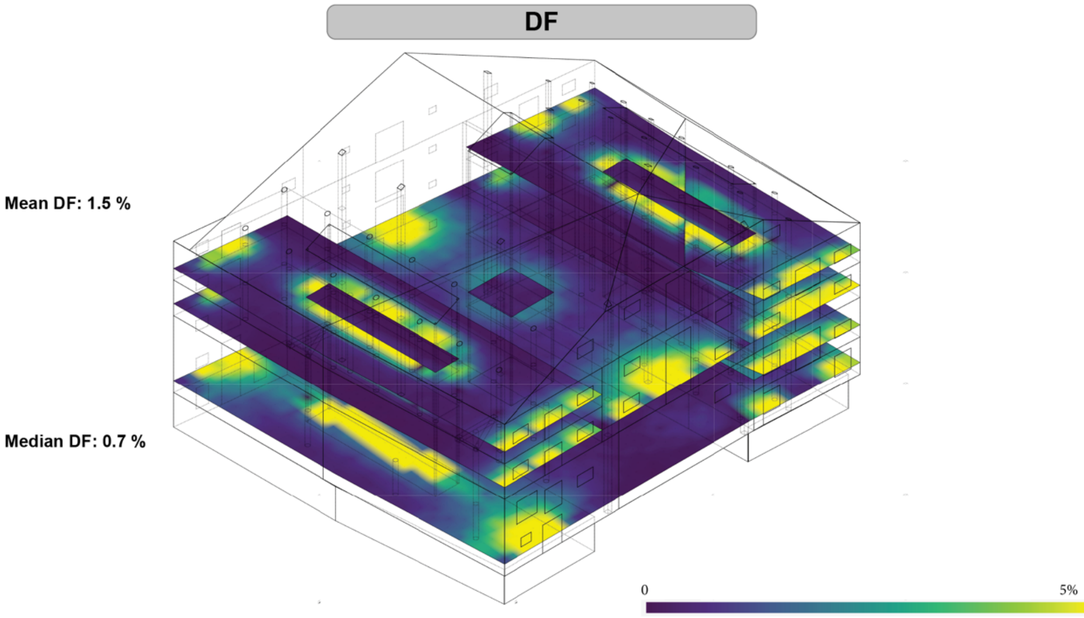


Annual profile of ASE for scenario 6

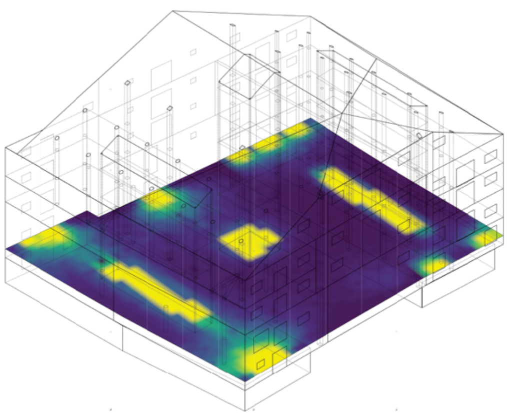
Figure 57. Annual profile of sDA and ASE for scenario 6

On the other hand, the ASE in scenario 6 was constantly lower than 5% during summer and in winter reached zero percent. Therefore, it can be concluded that in this scenario in none of the floor the chance of glare will not occur.

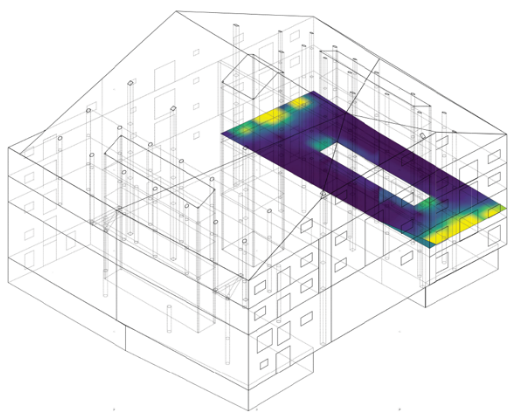
The DF of scenario 6 is presented in Figure 58. The mean daylight factor of 1.5% and median daylight factor of 0.7% were obtained in this scenario. As results illustrated the DF condition at each floor, not only around the window area DF reached 5% but also at third and ground floor around the atrium, the grid sensors showed the yellow color. It means that in scenario 6 the atriums provided daylight within interior space.



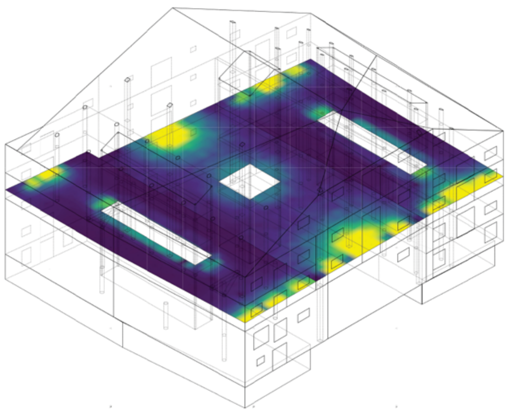
DF of the whole building in scenario 6



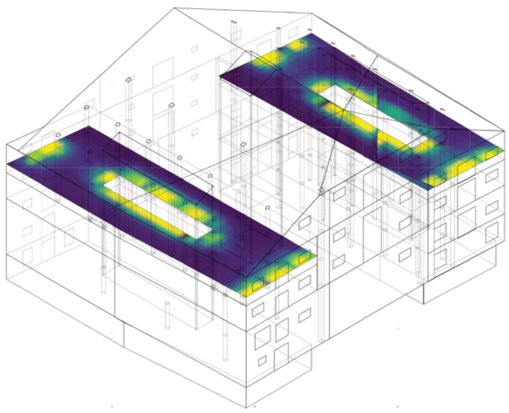
DF of ground floor



DF of first floor



DF of second floor



DF of third floor

Figure 58. DF for each floor in scenario 6

4.10. Comparison of sDA, ASE, and DF analysis in all scenarios

Changing the type of an atrium will affect how the light is reflected within the atrium. The intention of this simulation was to see which scenarios resulted in the most uniform daylight autonomy in the adjacent spaces of the atrium. Six geometric shapes were thus compared (six scenarios). Comparing the simulation results from the different scenarios is quite difficult due to the fact that the glazing distribution will vary depending on the shape. The area of the atrium walls will also depend on the shape.

Figure 59 is presented and summarized the results of sDA, ASE, and DF in all scenarios.

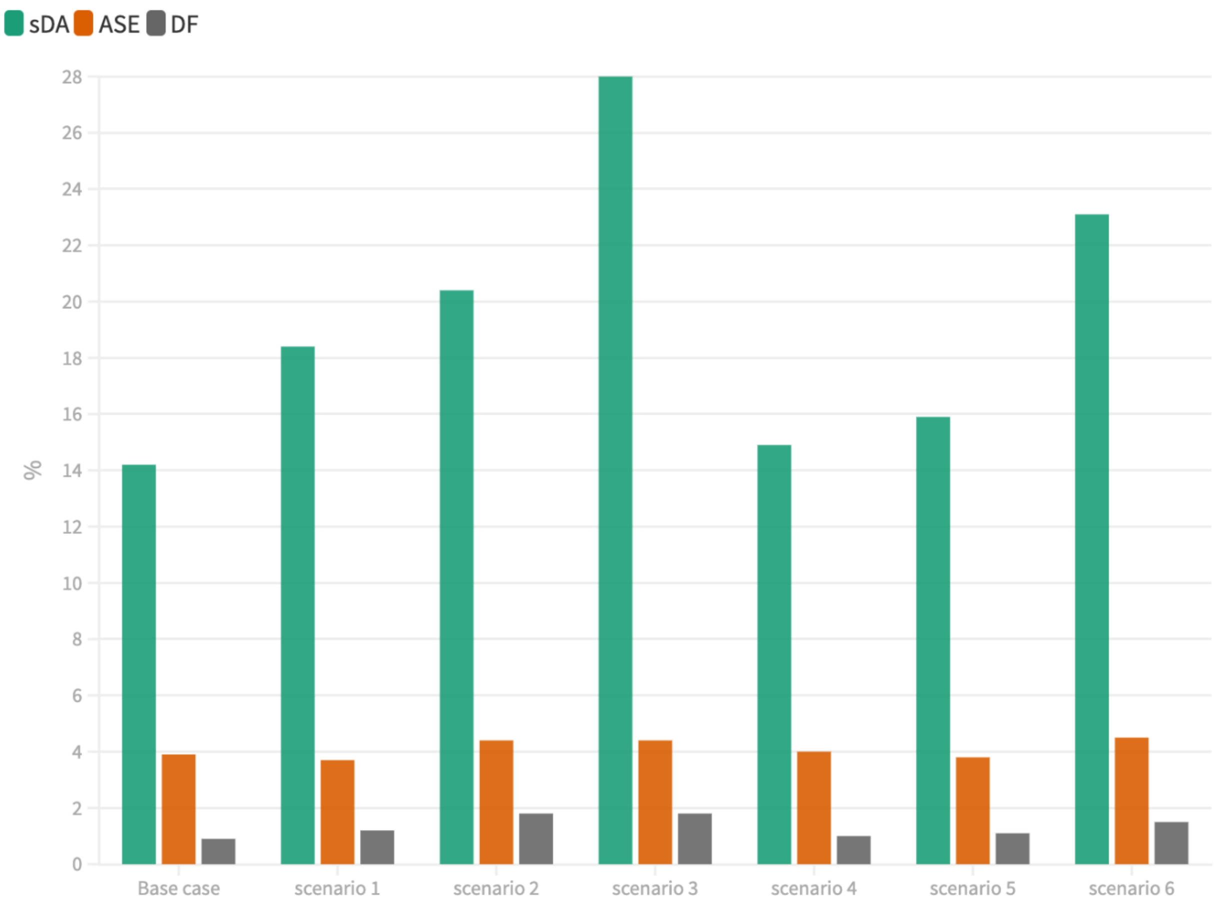


Figure 59. Results of sDA, ASE, and DF at all scenarios

The highest amount of sDA was related to scenario 3 with a value of 28%. The second rank of sDA was for scenario 6 by 23%. Scenario 2 with about 21% of sDA was the third-highest value among all scenarios. Scenario 4 offers a quite similar distribution of daylight autonomy to the base case. scenario number 1 and 4 is the least favorable of the three shapes. The zones which received no light from the atrium were the largest for these shapes, which means that more artificial lighting will be needed in these zones.

As for the sDA metric, it was clear that the scenarios with a united area of the atrium on the top and bottom had more advantages due to areas that were faced to outside. It can also be noticed that scenario 4 had the lowest value of sDA by 14.9% and 1% for DF compared to the other scenarios. Scenarios numbers 3 and 2 performed the best, in achieving sDA with the value of 28%, and 20.4%, respectively. While having 1% and 1.1% of DF in scenarios 4 and 5 and 14.9% and 15.9% for sDA, in turn. These scenarios behaved similarly and thus being as the worst-case scenario and more close value to base case.

In scenarios 6 and 1, sDA defined 23.1% and18.4%, respectively. However, DF for scenarios 6 and 1 was1.5% and 1.2% which was not meet the requirement of EN 17037 and LEEDv4.1.

In order to summery all the results, scenarios 2 and 3, were introduced the best results of light distributed to the inside of the floor plan. Note that the DF of 1,8% is the same in both scenarios 2 and 3 which precedes the demand of daylight factor uniformity that is not analyzed in this thesis. It can however be argued that scenarios 2 and 3 could be selected scenarios for more analysis.

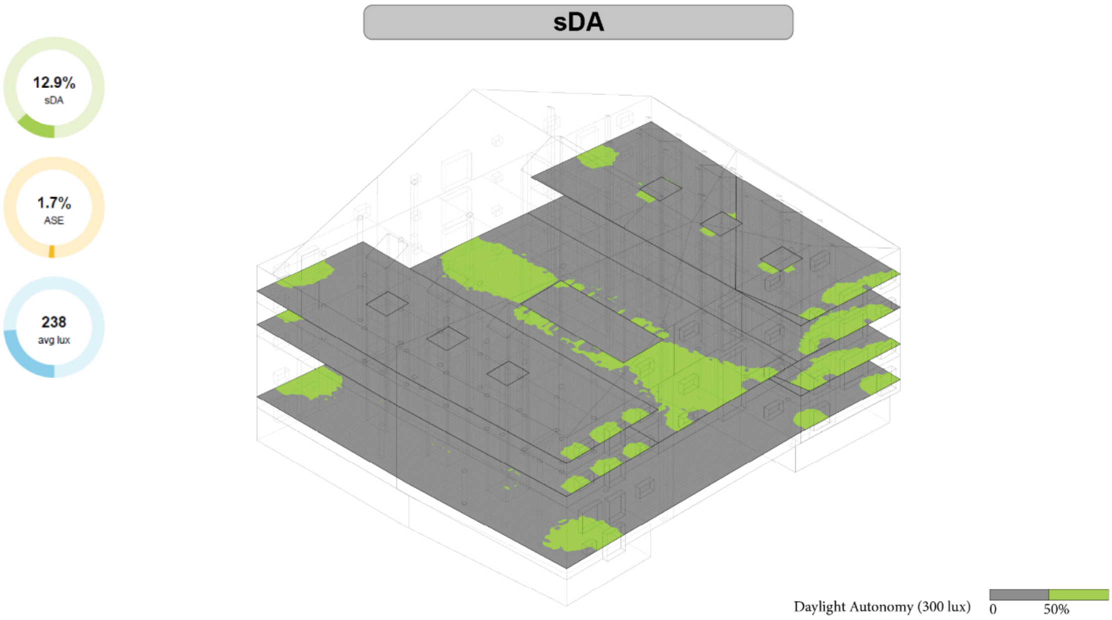
4.11. Comparative study of selected scenarios

According to the obtained results, all the cases behave in a similar way, scenario 3 and 2 demonstrate a great potential to become autonomous in terms of daylight, as their grids have more access to sunlight due to the orientation of the building.

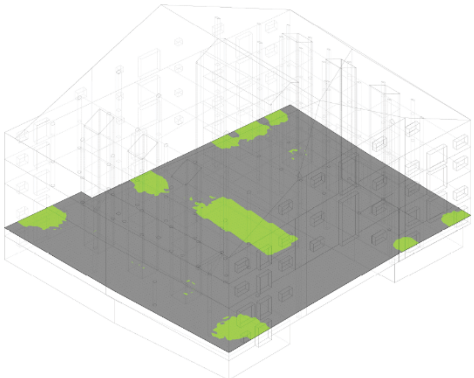
4.11.1. Comparison of sDA and ASE analysis in scenario 2 and scenario 3 with consideration of wall thickness

For the simulation in real conditions, two selected scenarios (scenario 2 and scenario 3) have been simulated with consideration of the wall thickness. In the reality, the window was located on the wall with thickness. In terms of achieving the results with high accuracy close to the real condition, the simulation for two selected scenarios had been done with the thickness. In this building, the wall thickness was 0.3 m. Therefore, this amount was added to the building simulation model in order to compare and analyze the effect of wall thickness on the value of sDA and ASE.

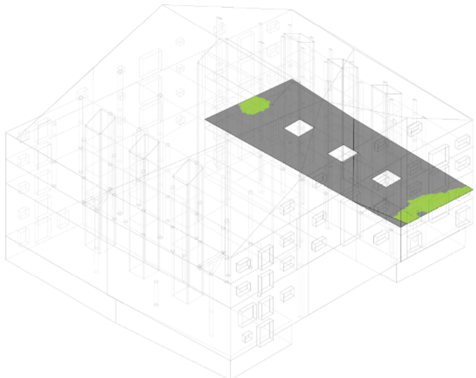
Figures 59-60 show the results of sDA when the wall thickness was considered in scenario 2. The overall sDA for the building decreased to 12.9%. Also, the value of ASE decreased to 1.7% for the whole building in the year. The simulation results for each floor showed the highest value of sDA was related to the second floor with a value of 18.32%. The lowest amount of sDA was related to the third floor with 6.43%. The ASE was lower than 3% on all floors, with the highest value of 2.43% on the first floor and the lowest value of 1.30% on the ground floor.



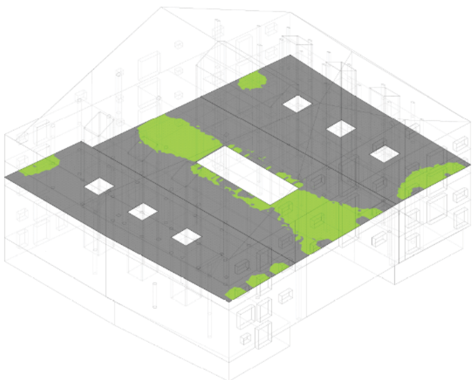
sDA of the whole building in scenario 2 with consideration of windows thickness



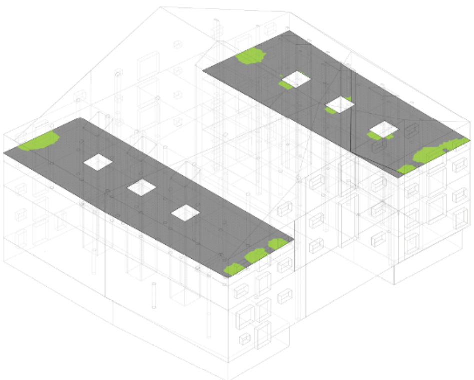
sDA of ground floor



sDA of first floor

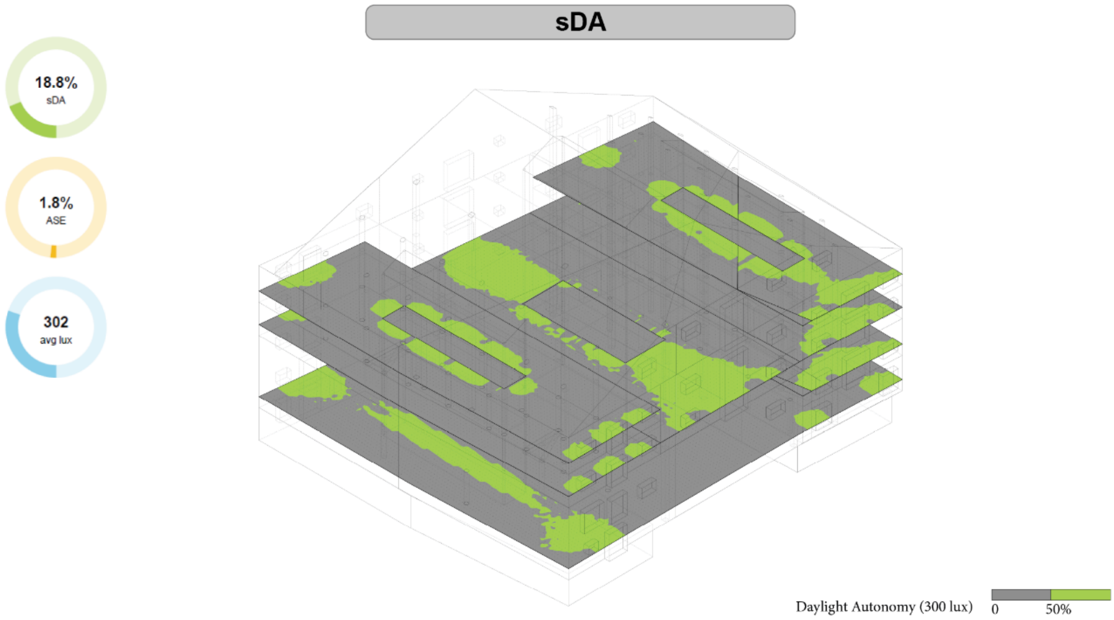


sDA of second floor

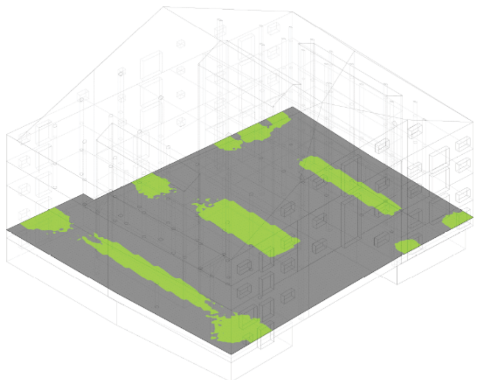


sDA of third floor

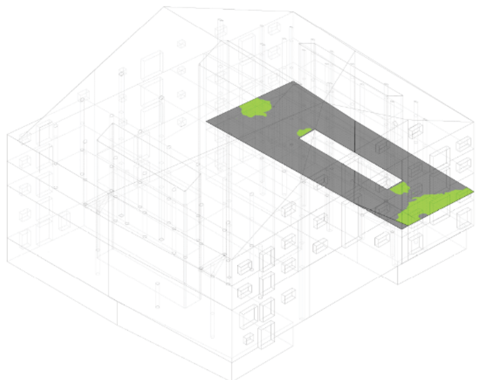
Figure 60. sDA and ASE values at each floor in scenario 2 with cnsideration of wall thickness



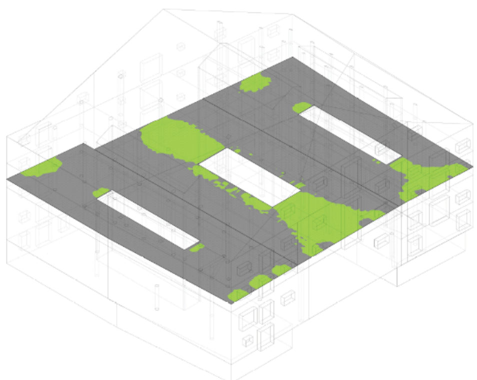
sDA of the whole building in scenario 3 with consideration of windows thickness



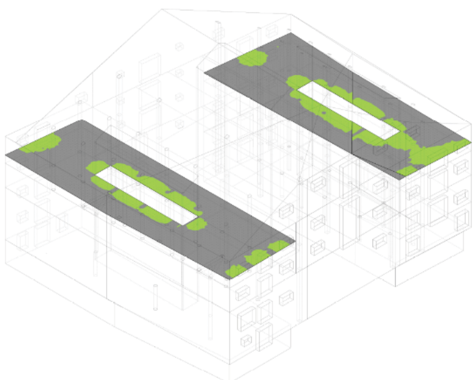
sDA of ground floor



sDA of first floor



sDA of second floor



sDA of third floor

Figure 61. sDA and ASE values at each floor in scenario 3 with consideration of wall thickness

Figure 60 shows the value of sDA and ASE with and without walls on each floor of scenario 2. As can be seen, the highest sDA was related to the second floor by 27% however this value decreased to 18.2% when the wall thickness was considered. The highest value of ASE was recorded on the first floor which was 6 %. After adding the wall thickness, the correspondent value decreased to 2.1%.

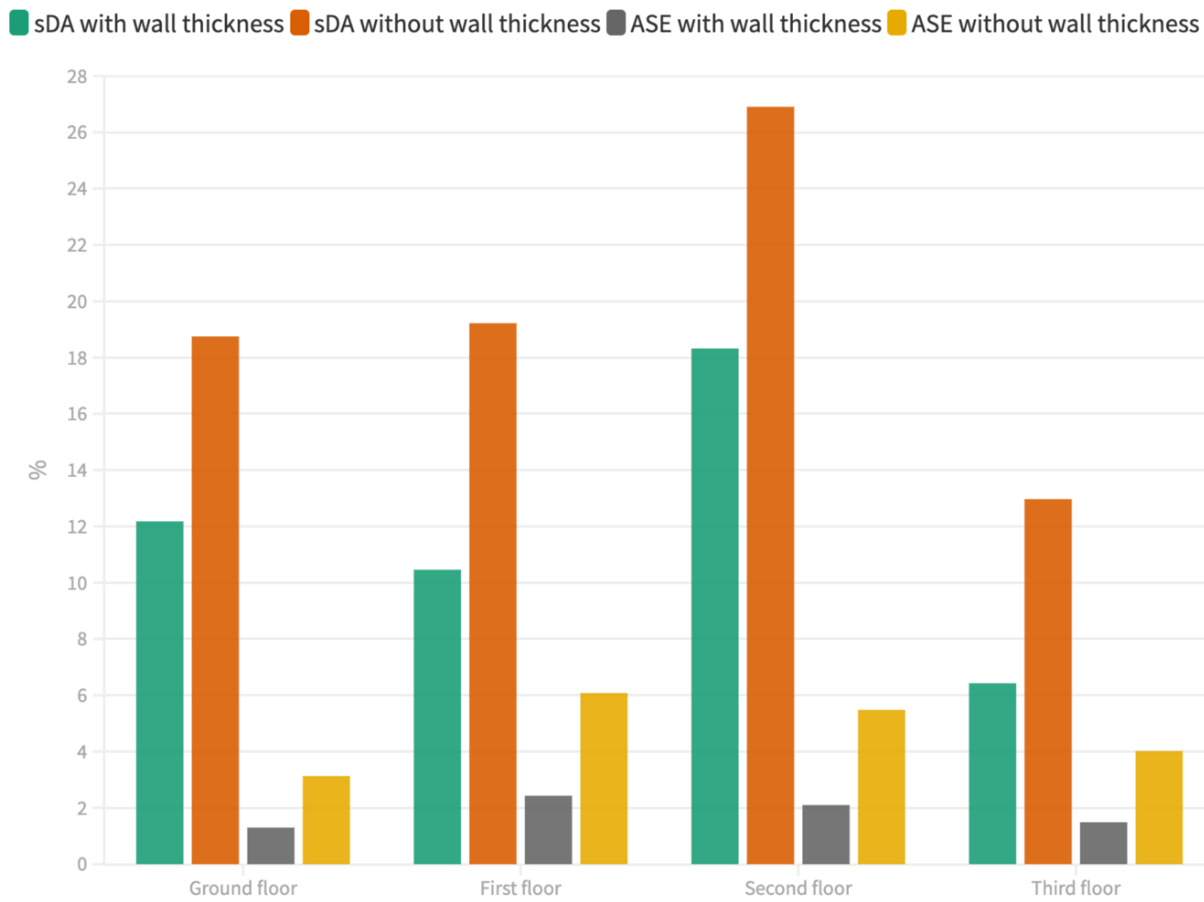


Figure 62. The sDA and ASE in scenario 3 with and without consideration of wall thickness

As similar the sDA and ASE for scenario 3 were presented in Figure 61 before and after considering the wall thickness. The highest and lowest value sDA in this scenario was 32% and 24.8% for the second and first floor, respectively. These values decreased to 19% and 14%.

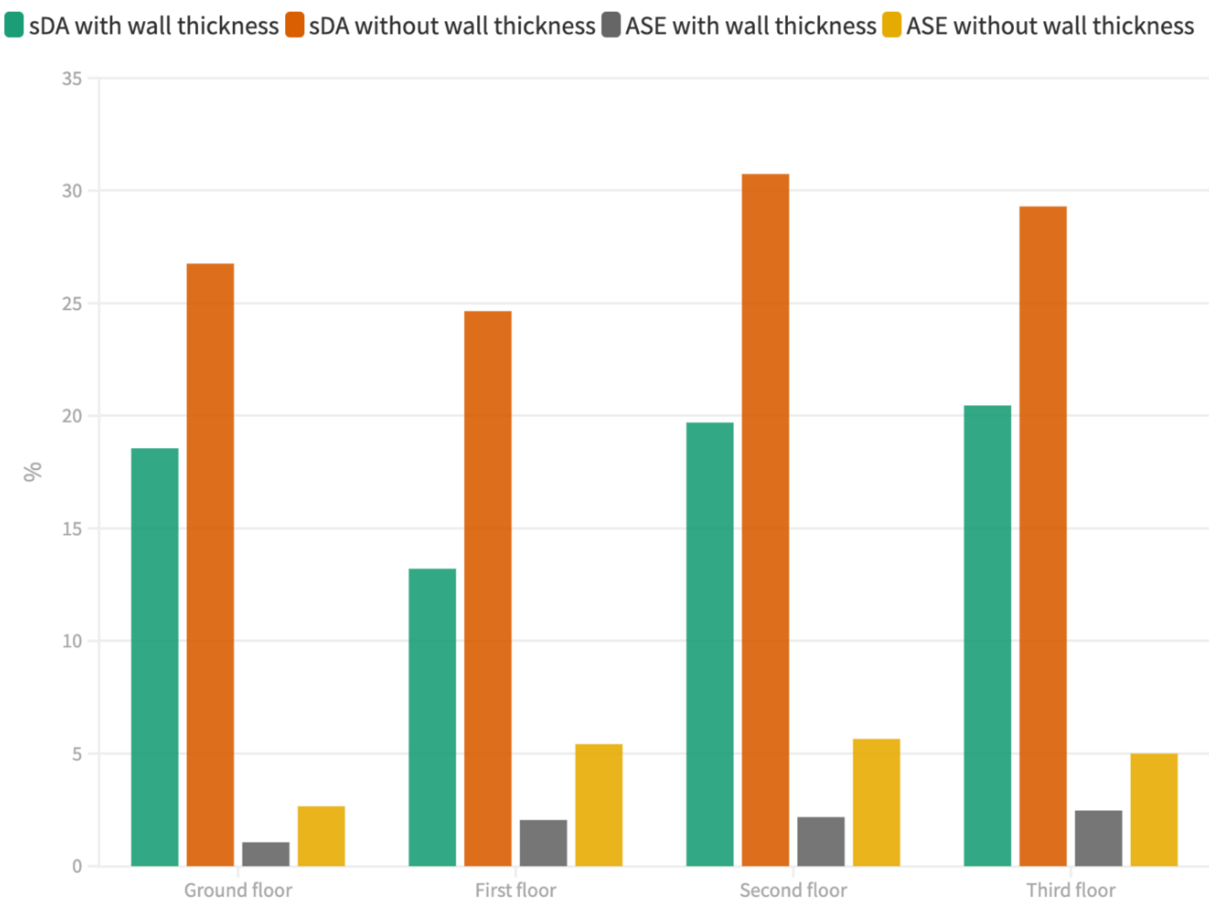


Figure 63. The sDA and ASE in scenario 3 with and without consideration of wall thickness

4.11.2. Effect of interior wall on daylighting in scenario 2 and scenario 3

The second set of investigations comprised modifications on the interior wall. The interior wall located in front of the atriums was blocking the daylight transmission. Therefore, the aim of this section was to understand how much daylight could improve by eliminating the interior walls in front of the atrium. As a result, in both selected scenarios (scenarios 2 and 3) sDA and ASE were simulated with and without the modified interior walls.

Figure 64 is shown the comparison of sDA and ASE in scenario 2 and scenario 3. The sDA value in scenario 2 was 20.4% and after the modification increased to 20.8%. As a result, the sDA value by modification and eliminating part of the interior wall only changed by 0.4% in both scenarios. However, the ASE did not change before and after the modification of interior walls neither for scenario 2 nor for scenario 3. The differences were negligible and, in the reality, the interior wall did not impact the interior daylight.

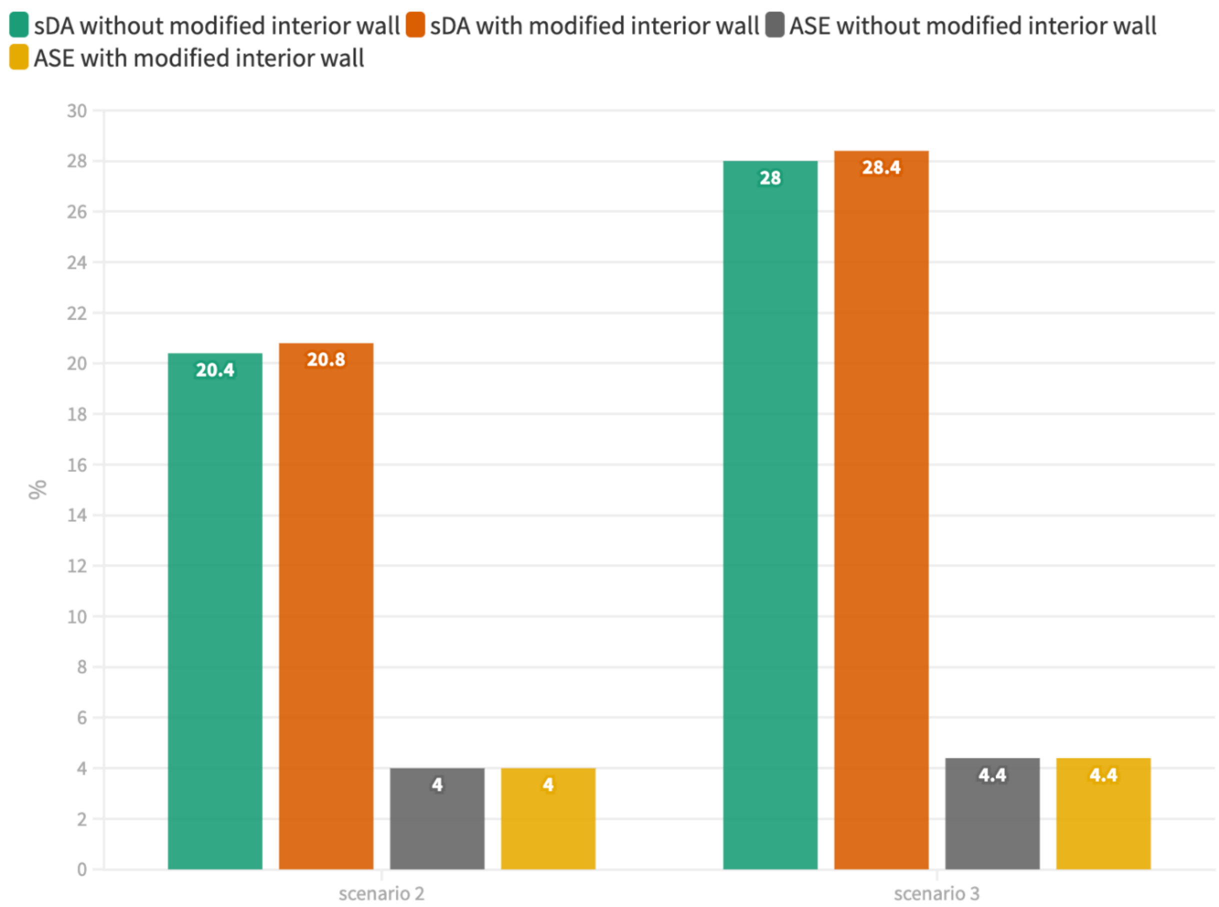


Figure 64. The sDA, ASE with and without modification of interior wall in scenario 2 and scenario 3

Therefore, because of the fact that the case study considers a historical building, removing the part of the wall was not the right choice in order to improve daylight conditions.

4.11.3. View analysis

After selection of the scenario 2 and scenario 3, the view condition in these scenarios was analyzed.

The view analysis was conducted according to the EN 17037 (CEN, 2018). This standard analyzes the view building in four areas as mentioned below (Velux Commercial, 2020).

- Daylight provision
- Assessment of the view out of windows
- Access to sunlight
- Prevention of glare

To this end, the second area of the standard was taken into account for analyzing the view in the building. As defined in standard 1. Building occupants should have a broad and unobstructed view of the outside. EN 17037 takes into account the view's breadth and outer distance, as well as landscape 'layers' (sky, landscape, and ground). The vision should appear crisp, undistorted, and neutrally colored. A thorough or simplified technique might be used to determine the width of the view. Outside distance and number of layers are each measured by a single approach.

Accordingly, in climate studio View result shows the proportion of the building's floor space that falls into each of four compliance categories: Failing, Minimum, Medium, and High. The compliance levels are determined by three assessments, which are performed for each point of view:

Horizontal Sight Angle: The overall horizontal angle subtended by windows from the viewing location (in the XY-pane). Minimum compliance necessitates an angle of at least 14 degrees. Angles of 28 and 54 degrees are required for medium and high levels of compliance, respectively.

Outside View Distance: The median view distance between the window and the objects visible outside the window. Minimum, Medium and High levels of compliance have thresholds of 6, 20, and 50 meters, respectively. All pixels containing through-window views to the outside from the viewing point are used to calculate the median. The sky and unmodeled regions of the ground hemisphere are thought to be endlessly far, thus if these elements make up more than half of the outside view, the median distance will be limitless as well.

The number of view levels: is defined by EN 17037 as three, sky, ground, and landscape. The Landscape layer encompasses both natural and man-made elements — in other words, everything except the sky and man-made ground. To obtain Minimum compliance, a view location must be able to see at least the Landscape layer. Medium compliance necessitates viewing the Landscape layer as well as one additional. Seeing all three is required for high compliance. ClimateStudio considers all outside objects that are not designated with a ground tag (as described in the setup instructions) to be part of the Landscape layer. ClimateStudio additionally includes in the Landscape layer ground-hemisphere view rays that exit the picture within five degrees of the horizon. The reasoning for this is that distant, near-horizon vistas must include either buildings or natural scenery, even if neither is modeled explicitly.

Based on the abovementioned definitions, the false-color map shows the area with four colors, fail, minimum, medium, and high. Figure 65 illustrated the view in scenario 2 on each floor. In this scenario, 80.2 % of the area failed and 5.6%, 4.8%, and 9.4% with the minimum, medium, and high view, respectively. The average view factor for the whole building in this scenario was 22.37% and the average view distance of 4.21 m.

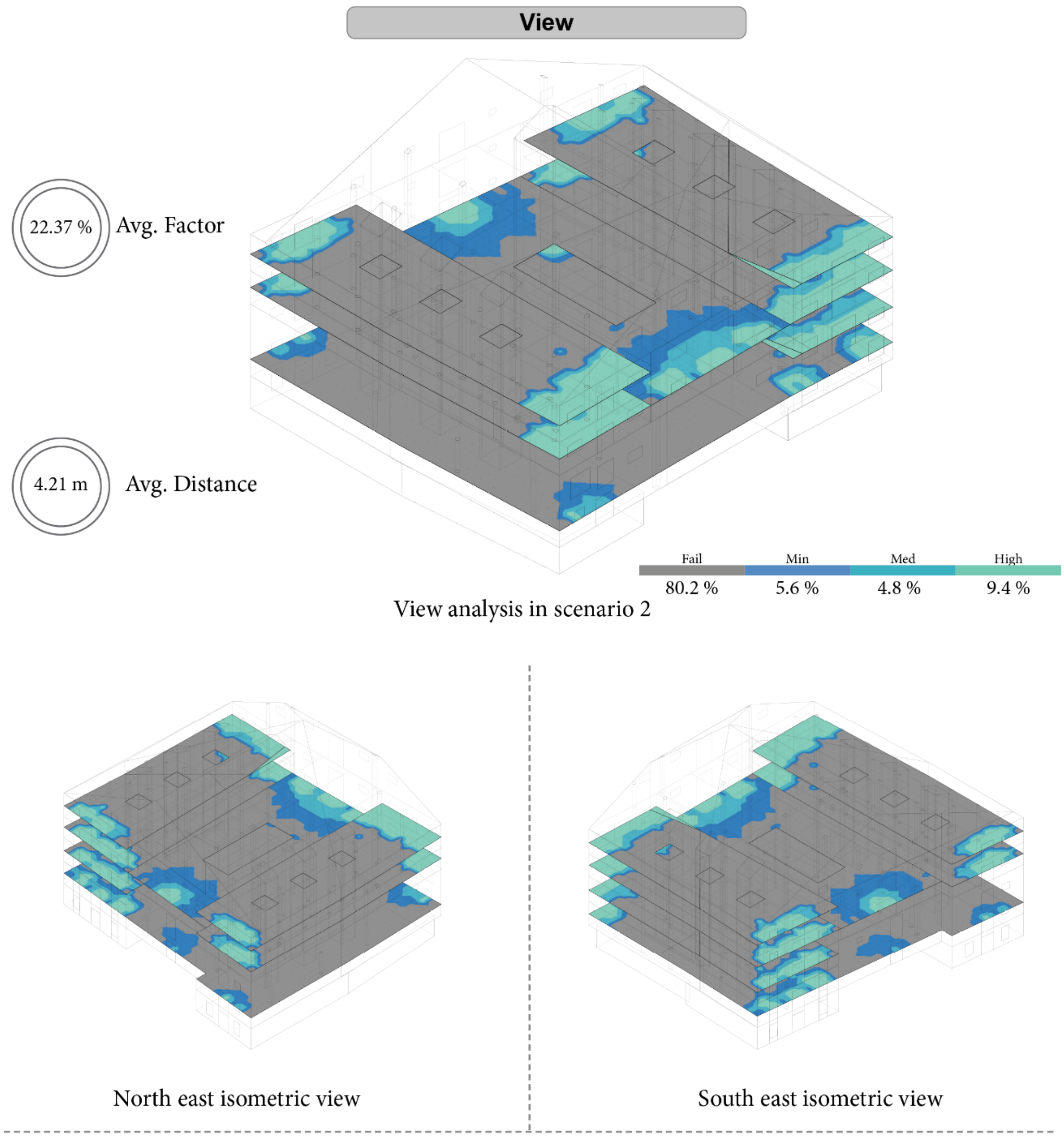


Figure 65. The view analysis of scenario 2

The view analysis for scenario 3 was simulated and the results presented in Figure 66. As can be seen in the results, 74.1% of the area had the fail view condition, 9.1% with minimum view, 5.6% with medium view, and 11.2% with high view. Also, the average view factor for this scenario was 25.21% and with 4.16 m average view distance.

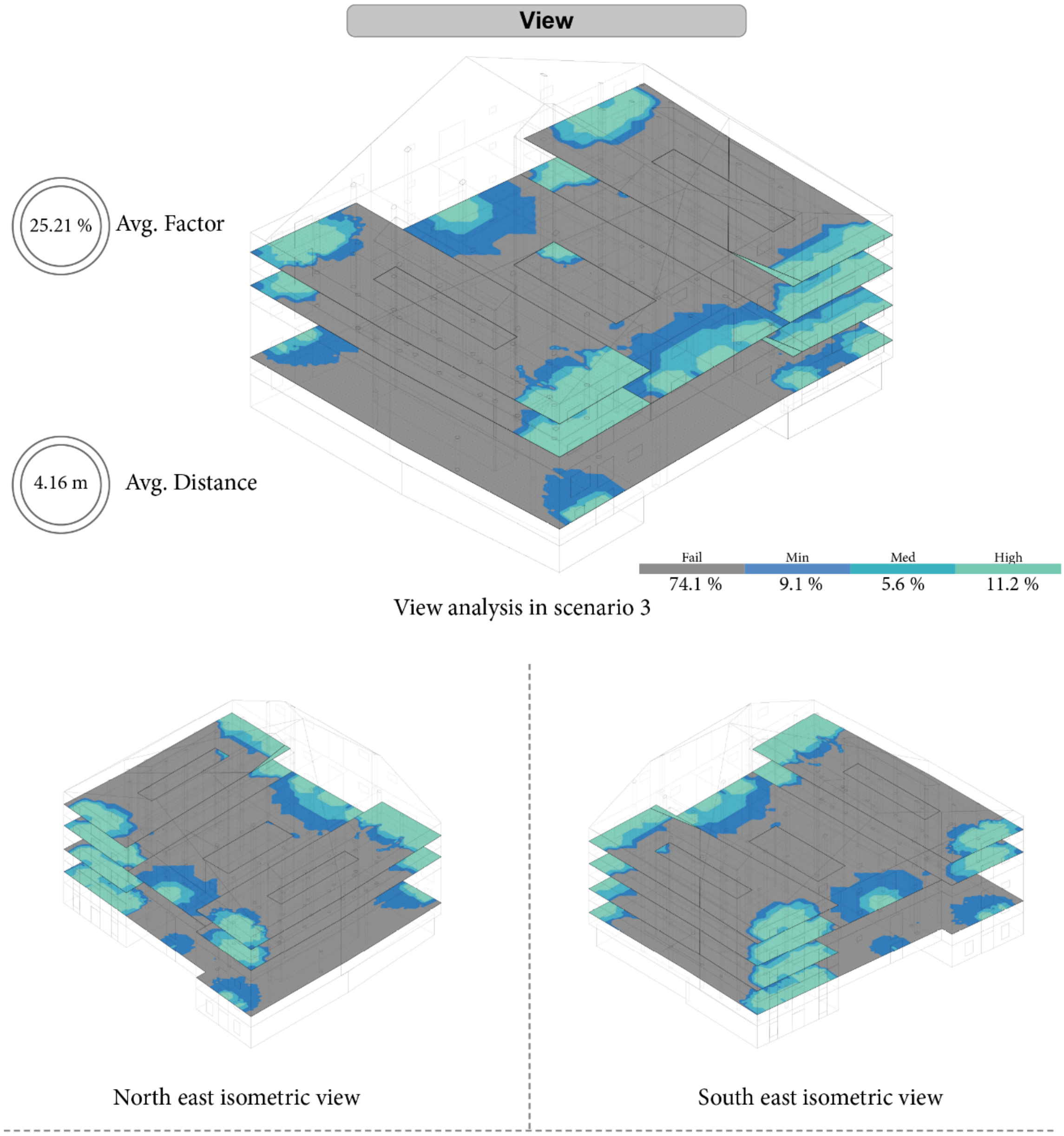


Figure 66. The view analysis of scenario 3

For general comparison between scenario 2 and scenario 3, Figure 67 summarized all the obtained simulated results. The web chart shows the sDA, ASE, view analysis, DF, and the sDA with and without modification of interior walls.

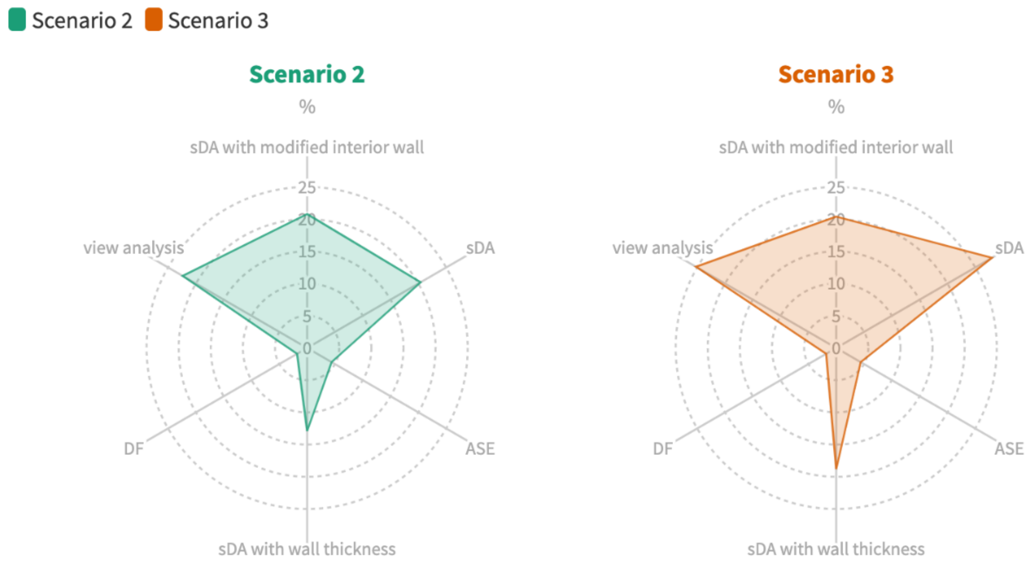


Figure 67. Web chart of scenario 2 and scenario 3

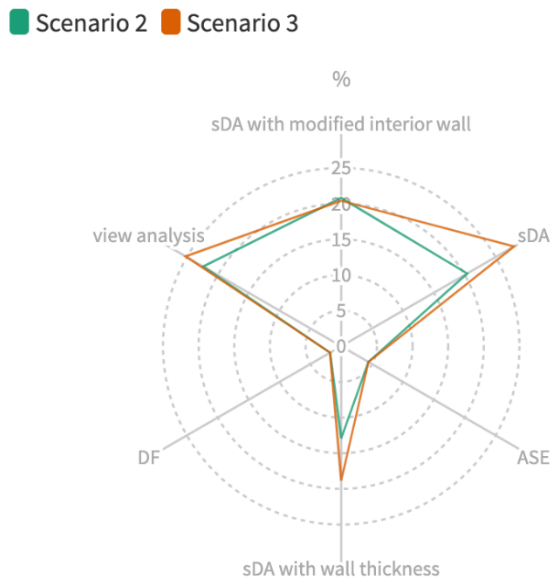


Figure 68. Combined web chart of scenario 2 and scenario 3

According to the results, the DF and sDA seem to be better distributed among floors in scenario 3 compared to scenario 2. Also, the combined web chart in Figure 68, the higher values regarding the sDA, DF, and view. Regarding the mean DF, the top floor in all cases increased steeply if compared to the one underneath. Comparing the results showed that consideration of the wall thickness influenced mostly the areas near the window and did not impact the depth of the building. Therefore, these results were considered for comparison of the real condition and simulation boundary condition. Since the focus of this study was mainly on the impact of atriums on the daylight conditions the results for view and optimization without wall thickness were considered.

According to the abovementioned results and analysis, scenario 3 had more efficient performance in terms of improving daylight and view in the selected case study building. Therefore, scenario 3 was chosen for conducting the optimization process in the following sub-sections.

4.12. Optimization of scenario 3

Due to a large amount of data and the limitation of time, scenario 3 was selected to be investigated in optimization relation to how the improvements affected the daylighting condition at each floor. Moreover, the amount of ASE was investigated to analyze glare amount.

The optimization was conducted through the Galapagos component in Grasshopper (Rutten, 2013). Firstly, all parameters of the building including walls, floors, windows, atriums were modeled in Grasshopper. Then the materials related to each opaque and transparent surface were defined. After that, the algorithms of daylighting were designed in terms of doing the optimization. Figure 69 represented the screenshot of the algorithms created in Grasshopper.

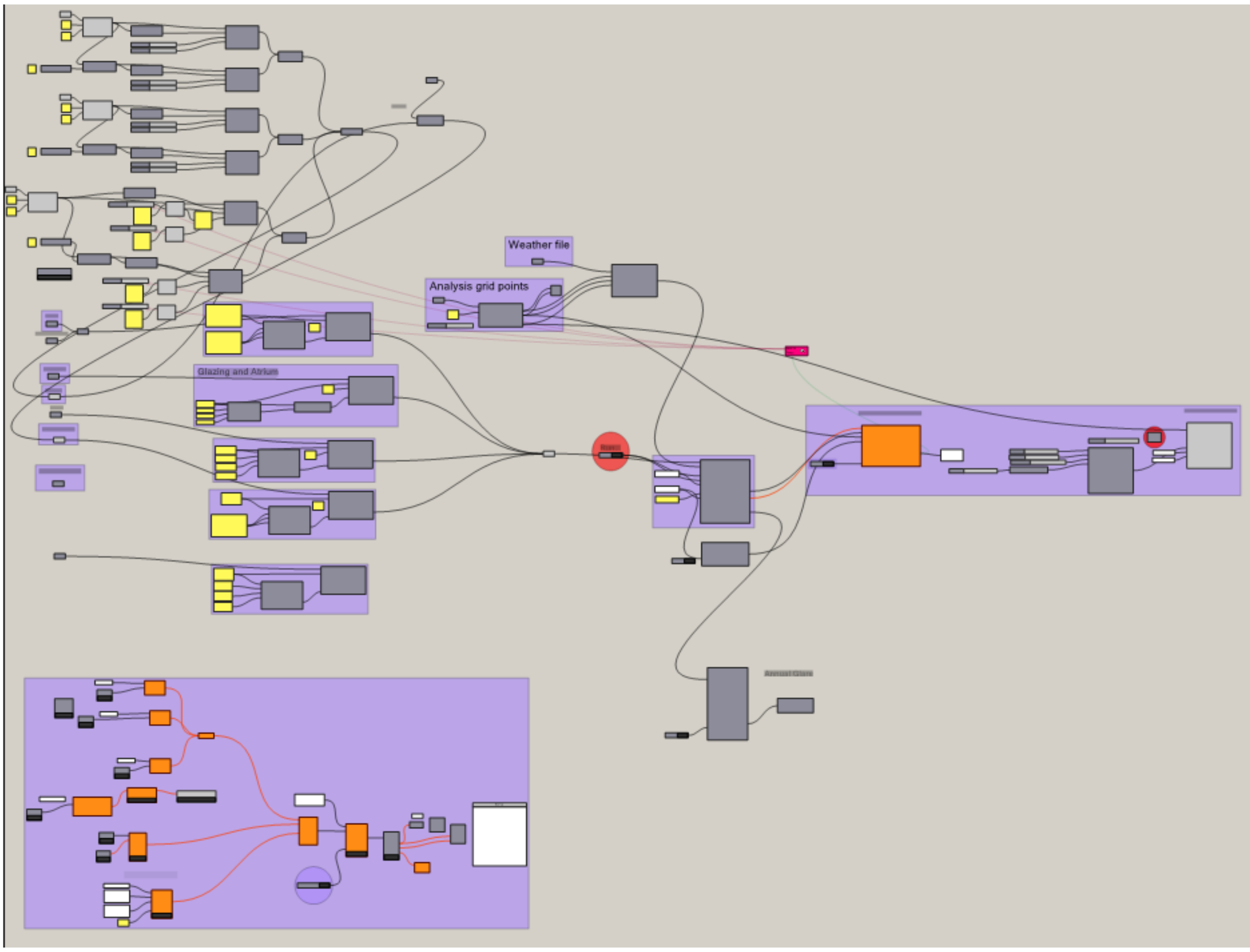


Figure 69. screenshot of optimization algorithm in Grasshopper

The Galapagos was utilized to identify optimum fitness values and three parameters for each atrium utilizing genetic algorithm optimization methods. The evolutionary algorithm was chosen since it was the only method that can identify optimal solutions using Rhino and Grasshopper software. Furthermore, this program was commonly used for architectural designs (Yi & Kim, 2015). Galapagos was configured with three-parameter values and four variables to achieve circumstances similar to those of manual methods: Maximum Stagnant: 50, Population: 20, Maintain 20%, Inbreeding: 50%. The Population value of 20 indicates that Honeybee simulates evolution 20 times for each generation. In this scenario, the Max. Stagnant value of 50 computes up to 50 generations.

Because of the fact that this study focuses on sDA as an objective for optimizing the atrium, most probably the highest area of the atrium on their boundaries could have opted. Therefore, for each atrium, two rectangles were considered to create an atrium. The length and width of each rectangle are connected to the Galapagos component as variables. For controlling the size of the atrium, the highest value for length and width of atriums based on their positions among columns was also considered. It is worth mentioning that for the lengths and width of each atrium as variables, three steps were considered to decrease the number of simulations. As a result, the total number of simulations should be 1000, and the skip and filtering-method technique was designed to eliminate duplicates. By 20 percent of the population has remained stagnant. However, in this study, each atrium had 36 examples, and the highest value of fitness may be found within 30 generations.

Figure 70 is shown the optimized shape of the atrium (highlighted areas) in scenario 3. The shape of the optimized atriums had two rectangles consisting of bottom and top rectangles.

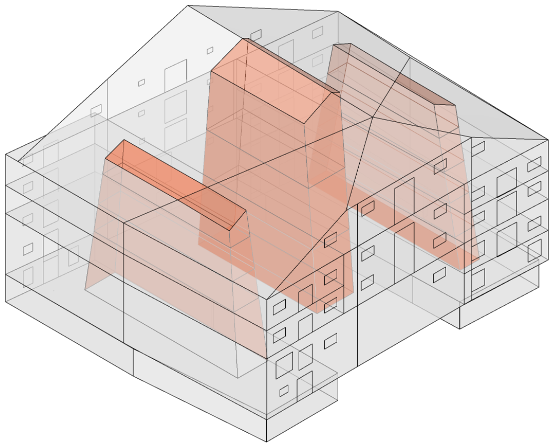


Figure 70. the optimized shape of the atrium

The atrium dimension after optimization yielded the bottom rectangle bigger than the top one. The dimension of the atrium from northwest (left to right Figure 70) respectively were:1.8m*12.21m in top rectangle, 3m*15m min bottom rectangle, for middle atrium 10.30m*1.92m in top and 15,10m*1.92m for bottom one, other side of the building the dimension was 3.60m*9.00m in top, 11.25m*3.60m for bottom. The optimized slope-shape of atriums could be because of the low-lit area on the lower floors compared to the upper floors of the case study building. As mentioned in the literature, this shape of the atrium guided more light into the building and help the daylight condition. This rule was the same for all three atrium shapes, however the optimized dimension of each atrium was different.

After the optimization process using Galapagos, the amount of each variable was defined, and the final and optimized shape of atriums was achieved. After that, to testify and compare the daylight condition before the optimization, the obtained atrium was simulated and the results of sDA, ASE, and DF were extracted.

The results of sDA and ASE are shown in Figure 71. Based on the results the value of sDA and ASE was 50.2% and 5.0%, respectively. The average illuminance in the whole building was equal to 632 lux.

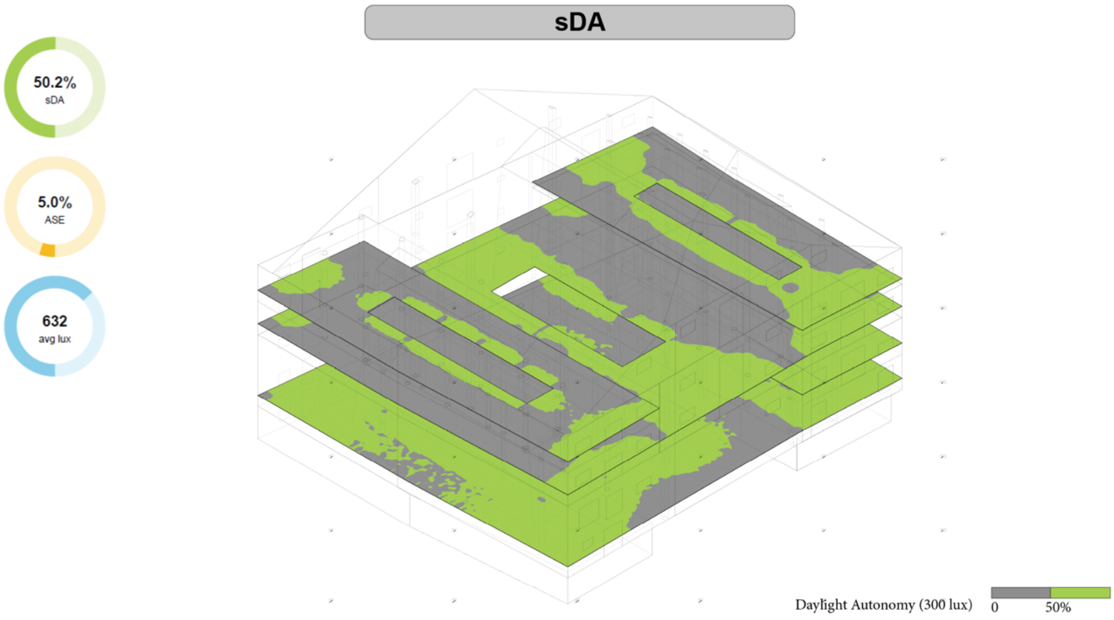


Figure 71. sDA of the whole building after the optimization

The DF of optimum scenario 3 is presented in Figure 72The mean daylight factor of 2.7% and median daylight factor of 2.4% were obtained in this optimum scenario.

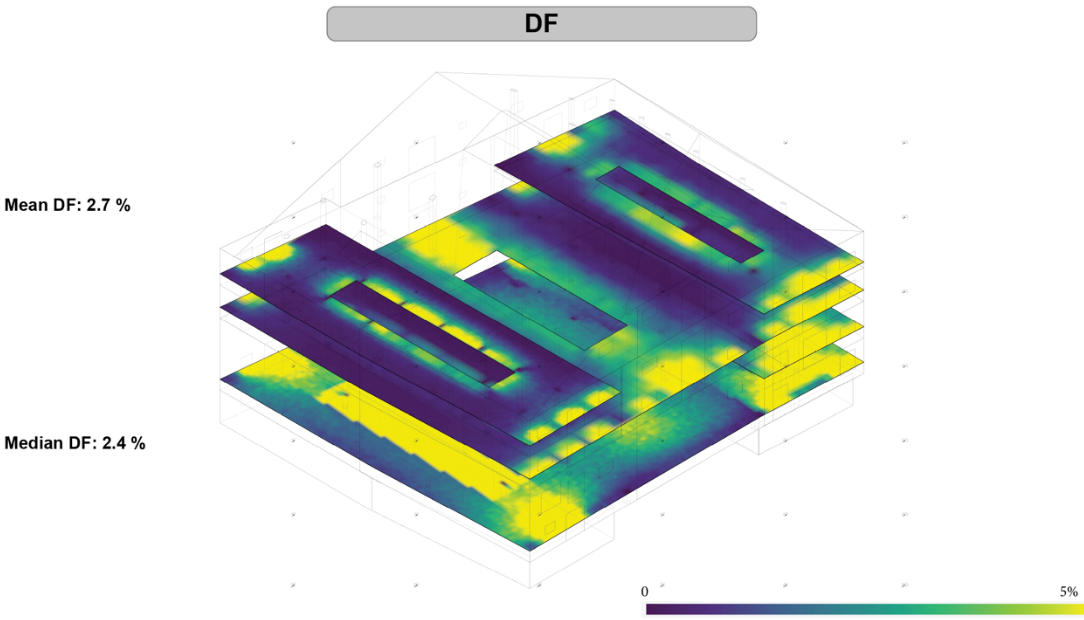


Figure 72. DF of whole building after optimization

Figure 73 is shown the comparison of sDA, ASE, and DF in the base case, scenario 3, and optimized scenario.

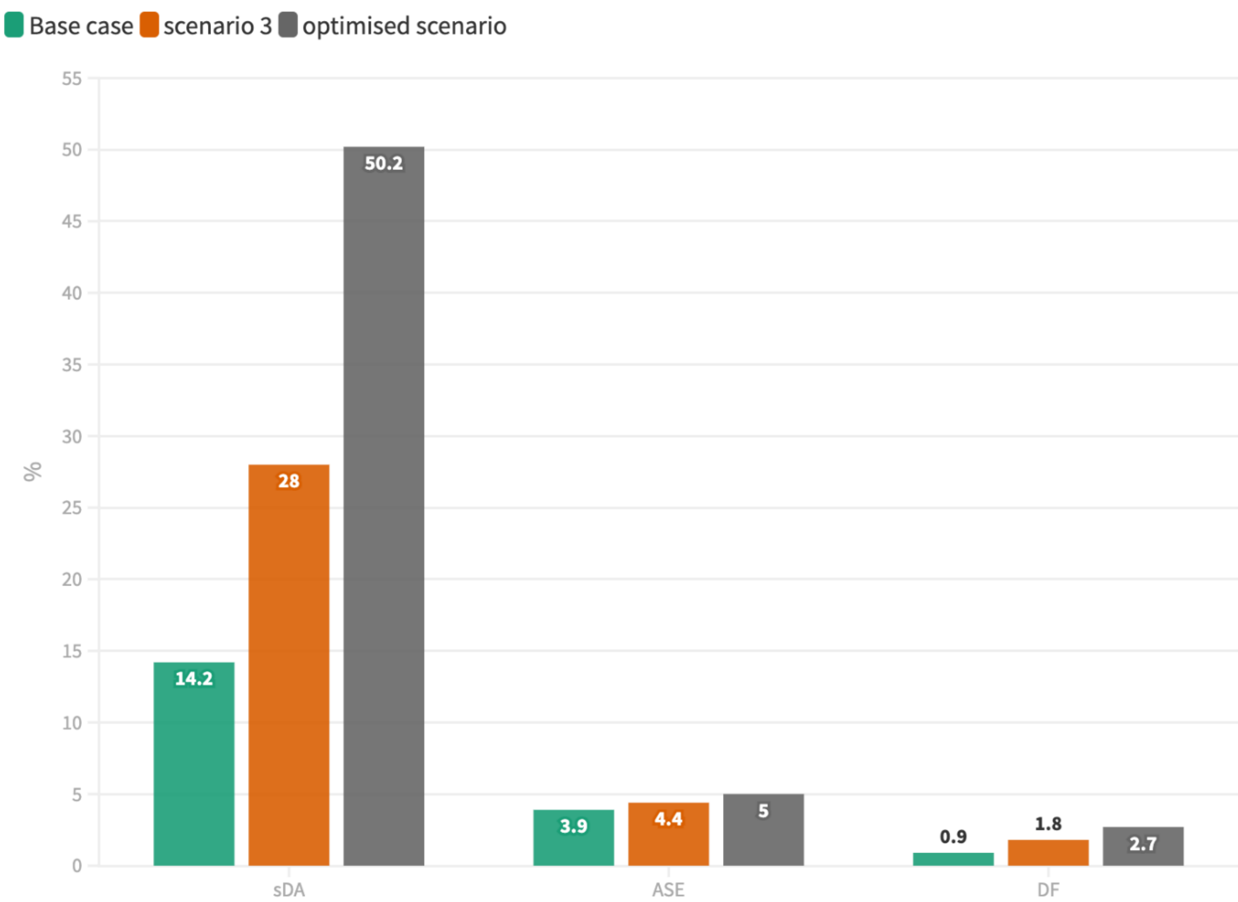


Figure 73. Results of simulated sDA, ASE, and DF for the base case, scenario 3, and optimized scenario

As indicated in the results, sDA in the base case was 14.2% which increased to 28% in scenario 3. After the optimization, the sDA exponentially increased by more than 32% and reached the value of 50.2%. The ASE in the base case was 3.9% and in scenario 3 increased to 4.4%. While, after optimization, the ASE did not increase too much and it was 5%. Based on the standard, the ASE should be lower than 10% for avoiding glare occurrence. The low amount of ASE (6%) can guarantee a glare-free space within interior space after optimization. Regarding DF, from 0.9% in the base case and 1.8% in scenario 3, this value increased to 2.7% for the whole building.

According to the achieved results, it can be concluded that the daylight condition in the case study building was successfully optimized and improved.

5. Discussion

The purpose of this thesis was to examine the current daylight conditions of the building and to recommend adjustments to improve natural light in the historical building. The discussion chapter was divided according to the results sections to facilitate their comprehension. This chapter contains an overview of the major findings. It will next go over various metrics and factors that influence decision-making.

As discussed before, the metrics chosen for this investigation are in line with the Leedv4.1 option1 and EN17037 regulations and some of the most widely adopted certification systems in the construction sector. In order to answer the questions that guided this investigation, the parametric studies were concentrated in 6 different scenarios which were defined based on the atrium geometries. As mentioned in the literature review, the shape and location of the atrium were the most influential parameters affecting the atria studied.

Indeed, the potential occupancy visual comfort will ensure the heritage building's effective usage. Furthermore, genetic algorithm optimization has only recently been employed in the design of new buildings and is rarely used in the design of historical buildings (Chen et al., 2018; Shahbazi et al., 2019). Optimizing the building atrium has not been examined as thoroughly as optimizing other architectural variables such as form, side-lit openings, building façade, and others.

Comparing the simulation results from the six shapes of the atrium was quite difficult due to the fact that the glazing distribution will vary depending on the shape. The area of the atrium walls will also depend on the shape.

The sDA results showed that none of the scenarios complied with LEED and EN17037 certification systems, as all of the values for the grids evaluated was less than 50%. Furthermore, the scenarios provided various values for the sDA and DF areas. These variances could be attributed not only to different atrium types but also to the building's unusually complex internal configuration. The worst performance was the base case, while the second-worst performer was scenario 4. Scenario 3 was the greatest performance. As a result, scenario 3 was picked for optimization in Grasshopper using the Galapagos plugin.

Selected scenarios 2 and 3 presented optimum outcomes as compared to other scenarios in the preceding chapter, leading to significantly more daylight penetrating the building smoothly.

Selected scenarios 2 and 3 yield in time savings for assessing research questions and obtaining results, such as the influence of modified interior walls, view analysis, and simulating with wall thickness.

Despite the fact that Huitfeldbrygga was a historical structure (trying to conduct minimal renovation), simulating scenarios 2 and 3 with the outputs insignificant influence of modifying internal walls on enhancing daylight conditions was shown.

5.1. Strengths and limitations of the study

The study is limited by the extensive calculation time which is required to obtain high quality results for large scale building models with daylight simulation. It was a big challenge to creating model as structure does not have a single straight line or angle. This had an effect both on the size and complexity of the model, as well as the resolution of the results.

Moreover, the building was considered as a heritage building so finding the best way to minimize changes in the structure of the building was so challenging that took time to find a solution.

The author also did not have prior knowledge of the simulation and modeling tools with Climatstudio, which meant that a lot of time was associated with familiarizing with the aforementioned tools.

The expected outcome of the thesis is a document, containing answers to proposed study questions, results from simulations, and other relevant information. The document will be formulated as guidelines for the early-stage design of atria for daylight autonomy optimization in a historical and iconic building.

Furthermore, at the end of this study, the author also has obtained a good knowledge of the simulation and modeling tools used in the thesis work and will be able to apply the tools in future works.

5.2. Future works

This thesis project focused on finding an atrium optimum solution for the study case located in Trondheim in Norway. The investigation was limited to the improving daylight situation heritage building as the main objective was to assess the daylighting improvements fostered by the atrium modifications. The number of ambient bounces utilized in the simulations was five. It is important to mention that a higher number of bounces would not only boost the uniformity, but also the DF values.

The results only focused on the locations of the atriums and their sizes, the type of glasses, and their materials can be investigated in future work.

Also, other aspects were important when the atrium was considered and implemented in the building as a huge part of the atrium was transparent. Therefore, it results in heat losses or heat gain and overheating phenomena in the building. As a result, the thermal comfort and energy consumption of the building when the atrium was considered can be investigated in future studies.

More research is needed to develop strategies to improve daylight adequacy while achieving visual comfort utilizing diverse atrium arrangements.

Investigations regarding the daylight quality in the atrium could be further developed in future studies, as well as a proper sensitivity analysis of atrium design for the inputs and outputs daylight metrics that were exposed towards more daylight availability. It would be also interesting to assess the energy demand and verify how the new atrium configurations would affect the thermal conditions in a heritage building. Most importantly, future investigations could also address the potential of the whole building area.

6. Conclusions

This thesis looked into the existing lighting conditions in a heritage building in Trondheim, Norway. The simulations were led by a single crucial question: 1) How to improve daylight conditions in heritage building locations in high latitude? Firstly, because the base case is a historical building asset with minimal modification to the original structure. Second, the base case was deep and large, with a small window; for these reasons, this thesis argued that an atrium should be used to increase daylight in the construction.

The daylight metrics of sDA, ASE, and DF were investigated and compared. The daylight measurements employed in this study were in compliance with the Leedv4.1 option1 and EN17037 regulations, as well as some of the most widely used building certification techniques. Simulations were carried out utilizing the computer tools Climatestudio and Honeybee in Grasshopper. In order to answer the problems that prompted this analysis, the parametric investigations were centered on six different scenarios depending on atrium geometries. The performed simulations in this study demonstrated that the ability to execute dynamic daylight simulations for early-stage design was extremely viable, hence supporting earlier studies and comparisons between computer-based simulations and physical models. After comparing the results, the optimal scenario for supplying effective daylight was chosen. The atrium in the chosen situation was optimized using Galapagos genetic algorithms.

The results showed that the sDA in the base case was 14.2% which increased to 50.2 % after optimization which shows daylight was exponentially increased. The DF was 0.9% in the base case and 2.7% after the optimization. The achieved results show that DF meet the requirement of the standard. Furthermore, ASE was analyzed also to guarantee the visual comfort after the optimization. Results showed that ASE value 3.9% in the base case and increased to 5% after optimization. According to the standard the value below 10% would provide the glare free condition for building users. Based on the yielded results, not only the interior daylight condition was improved adequately but also the risk of glare was prevented.

Followed by the idea Considering the questions and hypotheses mentioned above, it could be concluded that:

- Increasing in bottom rectangle dimension of the atrium compared to top rectangle dimension (width and length) of the atrium caused the improving daylight.
- Glazing technology has mostly contributed to the improvement of sDA circumstances, such as increasing light transmittance and u-value of glazing, which leads to an improvement in the daylight situation.
- Creating The atrium for each of the Huitfeldtbrygga's wharfs was expanded to allow for more daylight.
- The modified interior wall had no effect on improving the lighting situation inside the structure.
- Simulating with wall thicknesses caused the declining daylight situation and to be more accurate results.
- Scenarios 2 and 3 were considered as the most suitable options, and in order to save time, scenario 3 was optimized and achieved LEED and EN requirements.

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