DAYLIGHT OPTIMIZATION IN AN OFFICE BUILDING THROUGH ATRIUM IMPROVEMENTS

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Master thesis in Energy-efficient and Environmental Buildings
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Lund University

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

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

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Keywords: atria, daylight, optimization, office, atrium

Thesis: EEBD - 18/05

Abstract

Daylighting has become a fundamental measure not only to decrease the heating energy demand in buildings, but also to provide good indoor comfort for the occupants. Atria have been implemented in buildings since old times as a space to foster interaction and provide indoor comfort through ventilation and daylight. However, the implementation of this feature can be complex if good natural light levels are to be achieved, especially in tall buildings. Bearing that in mind, this thesis reviewed the studies that were developed in the field of daylighting in atria and proposed an investigation about the atrium parameters that affected the most the daylight conditions in a building project located in Gothenburg. In order to evaluate the current atrium and propose modifications that fit the architectural design, simulations were carried out in different programs. This evaluation concentrated in two main aspects of the building, which were the geometry and the wall reflectance values. Due to the size of the study case, the evaluation grid is located only along the atrium and the results are translated in area, so it is possible to draw a comparison between the different modifications proposed. Results showed that the geometrical volume alterations were the ones to increase the most the daylight quantity in the rooms along the atrium. Nonetheless, some of the modifications on the original project were followed by a floor area addition to compensate the losses brought by the alterations, therefore daylighting and property value were also analyzed. Lastly, a few options were investigated when it comes to the daylight quantity in each floor. Overall, the outcomes demonstrated that shifting the atrium characteristic from an enclosed one to a semi-enclosed can double the daylight quantity in the adjacent rooms.

Acknowledgements

The author is extremely grateful for all the support, suggestions and guidance from Marie-Claude Dubois. He also would like to thank Iason Bournas for the exchange of ideas, advices and support. In addition, he is thankful for the study case provided by White Arkitekter, as well as its aid regarding the hardware usage for simulation purposes. This longtime dream of pursuing a Master Programme in an international renowned university would not be possible without the support of the Swedish Institute, which provided a full scholarship for the author studies in Sweden.

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Terminology

AR	Adjacent rooms
ADF	Average daylight factor
BBR	Boverkets byggregler
BREEAM	Building Research Establishment Environmental Method
CIE	Commision Internationale de l’Eclairage
IES	Illuminating Engineering Society of North America
LEED	Leadership in Energy and Environmental Design
CBDM	Climate-based Daylight Modelling
DA	Daylight autonomy
DF	Daylight factor
ERC	Externally reflected component
IRC	Internally reflected component
MRD	Maximum room depth
PAR	Plan aspect ratio
SAR	Section aspect ratio
SC	Sky component
VDF	Vertical daylight factor
VSC	Vertical sky component
LRV	Light reflectance value
LTV	Light transmittance value
WE	Well efficiency
WI	Well index
WID	Well indexed depth
WWR	Window to wall ratio
UDI	Useful daylight illuminance
USGBC	United States Green Building Council

1 Introduction

1.1 Background and problem motivation

The construction sector accounts for 30% to 40% of the primary energy use worldwide, a factor that states the real estate market potential to foster a sustainable development with low energy demand (United Nations Environment Programme, 2007). According to Guzenski (2011), as the society evolves, buildings should improve at the same pace to bear the possible energy demand increase caused by existing buildings with low quality envelopes. In this sense, the architectural design has always been the key factor, not only to diminish the energy demand for cooling and heating, but also to improve the indoor environmental quality by applying passive design strategies at the early design stages. In cold climates, heating and electrical lighting have the largest share of the building energy demand, thus increasing the daylight component, especially in new buildings, is an effective approach to decrease the energy need and increase the user comfort (Wong, 2017).

The proper design of buildings coupled with innovative technologies to harvest natural light properly into the working zones might bring the electrical lighting need to considerably lower levels (Cammarano et al., 2015). Furthermore, daylight can increase the occupant's satisfaction and productivity (Lim, et al. 2017). Better color rendering, as well as the proper regulation of the circadian cycle are also essential benefits of natural light. However, office buildings located in dense urban zones, such as city centers and economical districts, can be a liability to daylighting strategies. Due to the proximity of buildings, the sky component can be only used on upper floors, hence leaving the bottom floors underlit and dependent on electrical lighting (Capeluto, 2003). In addition to providing side windows to fetch daylighting into the building, atria have been largely implemented in different parts of the world as a strategy. They provide not only natural light indoors, but also generate better comfort conditions, thus turning these places into pleasant environments where interaction between occupants are fostered (Samant, 2011).

With the increased awareness about sustainable practices in the construction market, developers have been launching architectural competitions in the recent years to be able to choose the projects that suit their needs in the best possible way. However, this type of competition can generate a series of non-feasible projects construction-wise, as well as further issues regarding legislation requirements (Sørensen et al., 2015). Since many of the competitions are set to bring ideas to a specific aim rapidly, the proposed projects lack analysis and therefore many fundamental aspects are left behind, such as the adaptability to the current microclimate and even the local culture and values. One aspect that is often neglected at the competition entry level is daylighting, therefore it is not rare that the proposals do not meet the topic's standards and regulations afterwards.

This thesis aims to propose possible improvements in an atrium of an office building which was submitted through a design competition. The project was previously assessed by White

Arkitekter and showed that the current daylight conditions in the atrium adjacent rooms were insufficient to meet the Boverket's Building Regulation (BBR) due to the building's height and its deep plans. The case study is located in Gothenburg in a rather dense cluster of buildings, which leads to a series of challenges when regulations are to be respected. The investigated building is part of an under-development Life Science Center, which entails in a diverse range of typologies such as a research center, a hospital and a business center.

1.2 Aims and assumptions

The utilization of atria is a valid and great strategy to increase daylighting in a building, especially in cases where the city block configuration fosters the creation of deeper plans, thus compromising the visual quality of the interior spaces. However, a proper atrium design is dependent on various factors such as geometry, height, surface reflectance, skylight and window aperture for example. The main objective of this thesis is to investigate how each parameter can influence the natural light harvesting into the adjacent rooms that face the atrium. Bearing this in mind, two research questions shape the framework of this thesis:

- Which parameter influences daylight quantity most significantly in the adjacent rooms?
- What atrium design would best suit the study case, considering the proposed design and its surroundings?

Considering both questions, some hypotheses were inferred based on the literature review, which pointed out some trends according to various studies. The main hypotheses are stated below:

- The atrium geometry is the parameter that most significantly affects the daylight quantity in adjacent spaces.
- The light reflectance values might affect the daylight quantity in the atrium adjacent spaces, however it has a limited impact on deep atria.

The simulations developed during the thesis project were structured so the above hypotheses could be investigated.

1.3 Limitations

Although atria have a considerable impact on the energy balance of a given space or building, this investigation focused only on how they influence daylighting distribution in the adjacent rooms (AR). Internal partitions as well as possible obstructions are not considered in the simulations. Moreover, metrics that evaluate the daylight quality are not investigated. The thesis solely focuses on daylight levels.

2 Atria in office buildings

2.1 Daylight in office buildings

The use of daylight in office buildings is important to displace electric lighting and enhance visual functions as well as occupants' health. It increases the user comfort for general tasks while reducing the electrical lighting demand and cooling loads during the summer season (Chen and Wei, 2013). However, it is fundamental to consider balancing both good daylighting levels and energy demand issues by wisely analyzing the orientation, the window-to-wall ratio (WWR), the window head height, the material reflectance, the ceiling height and the maximum room depth (MRD). By orienting the building towards north, for constructions located at higher latitudes, the rooms are protected from the sunlight. On the other hand, shading mechanisms to control overheating and possible glare effects become fundamental if the spaces are orientated to the south direction.

The WWR also plays a fundamental role for the energy demand of buildings, as well as for the daylight quality in the office spaces. Fully glazed facades are a liability in most cases, as it is a source of thermal losses in cold climates and a source of heat gains in warm climates. A sensitivity analysis using Radiance as the simulation tool and the Useful Daylight Illuminance (UDI) as one of the metrics was conducted by Dubois and Flodberg (2013). They found that the optimal WWR lied between 30% and 40%, showing that any additional glass in the facade would create glare problems for the occupants. Moreover, the reflectance of the surrounding walls was also assessed and according to the simulations, higher reflectance values created a better level of uniformity.

The maximum room depth is especially important in working spaces, as it influences the user ability to have an outdoor view, as well as the design of the electrical lighting system. A method developed by DeKay and Brown (2014), pointed out that if the depth of the space increases more than three times the ceiling height, the daylight factor (DF) in the deeper parts of the room might decrease below 1%. Nonetheless, the outdoor view can be considerably compromised in dense urban environments, where surrounding buildings could be tall and close to the analyzed room. As a consequence, the maximum room depth (MRD) tends to decrease on the lower floors, where the sky view angle measured from the working plane is noticeably lower. As investigated by Reinhart and LoVerso (2010), the MRD is determined by the no skyline equation, as it follows:

$$MRD_{\text{no sky line}} = (h_{\text{window-head-heigh}} - h_{\text{work-plane-height}}) \times \tan(\theta) \tag{1}$$

Where:

$MRD_{\text{no sky line}}$: Limiting depth of the room
θ: Sky angle
h: height

Although the WWR is an important component of the daylight equation, the surface reflectance values can also significantly affect light perception in a space. However, the surrounding environment is equally important, since it can notably limit the sky view angle from a specific window, which is a crucial element for the atria design.

2.2 Daylight distribution in atria

The atrium is an architectural element that fosters the three aspects of sustainability in buildings, namely social, environmental and economical. Moreover, it brings daylight 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 natural lit (Samant, 2011). However, atria have not always been part of the architectural design considerations. Although it was largely used as a space where social interaction was encouraged in older civilizations, its implementation was brought back in the past 30 years mainly to improve the daylight capabilities of the interior building spaces (Sharples and Lash, 2007).

According to Samant (2011), it is important to observe some critical elements that could substantially influence daylight quantity and quality of an atrium space, namely sky conditions, geometry, roof structures and the characteristic of its enclosing surfaces. Sky conditions play an important role, since it is the source that emits light towards the building, whether it is direct or diffuse (Erlendsson, 2014). Some features, such as the geometry, usually follow the shape of the building, therefore most of the times the atrium quality is bound either to the outer envelope or to the plan layout. Poorly designed and oriented roof structures also compromise the daylight levels in the adjoining spaces (Sharples and Shea, 1999). Lastly, the atrium's surfaces can contribute to light reflection, especially on the lower floors, which are dominated by the internally reflected component (IRC) (Samant, 2011).

2.2.1 Geometry

The atrium shape is one of the most influential aspects in the daylight quantity and quality in its adjacent spaces, as it substantially dictates how light will be distributed in its surrounding spaces. According to Erlendsson (2014), the circular atrium is the one which tends to distribute daylight in the most equitable way despite its difficulty to be arranged and constructed. One of the most common ways to evaluate the geometry in atria is by utilizing the Well Index (WI). It can also be expressed as the Plan Aspect Ratio (PAR), which concerns the width to length ratio, as well as the Section Aspect Ratio (SAR), which considers the height to width ratio.

Sharples and Lash (2007) pointed out that by combining the three measurements included in the PAR and SAR properties through the WI, it is possible to estimate which type of shape a given atrium has. Deep atria tend to have higher WI values, whereas atria that have lower SAR values tend to be shallower. The WI also draws an important relation among the atrium surfaces as it expresses the relation between the light admitting area and the light receiving area. According to Baker et al. (1993), the connection between the supply of daylight in the rooms that surround the courtyard and the shape of the atrium can be expressed in one value, which is the product of the following equations (Sharples and Lash, 2007):

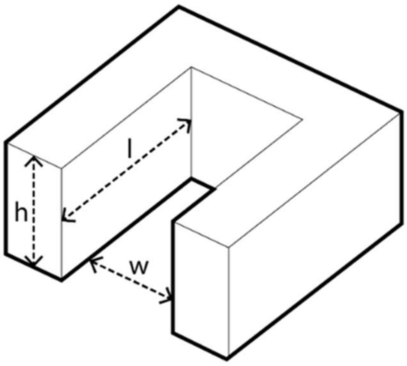


Figure 1: Atrium well index (WI).

$$PAR = \frac{w}{l} \tag{2}$$

$$SAR = \frac{h}{w} \tag{3}$$

$$WI = \frac{Height\ (Width + Length)}{2 \times Width \times Length} \tag{4}$$

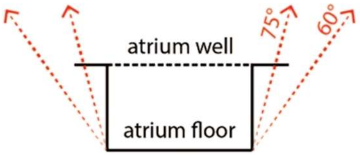
$$WI = \frac{1}{2}\frac{H}{W}\left(1 + \frac{W}{L}\right) = 0.5\,SAR(1 + PAR) \tag{5}$$

Liu et al. (1991) identified that illuminance levels can be fairly increased in atria with a lower PAR or rectangular, whilst four-sided and round ones tend to distribute the light more evenly. He pointed out in his investigation that the design of linear atria must be carefully studied as they have more exposed surfaces prone to receive light. As for the SAR, the shallower the atria, the higher the daylight amount in its center. Conversely, deeper geometries will produce a reduction of the natural light levels especially on the lower floors, where other important considerations have to be considered, namely wall reflectance and window to wall ratio.

Studies, such as the one performed by Liu et al. (1991) show that the proportion of the atrium can affect the distribution of daylight in AR. While natural light tends to increase in rectangular atria, the quadrangular ones seem to provide an equal amount of illumination on their surfaces. These hypotheses were confirmed in a physical model representing a linear atrium when its length was increased to twice the original measure in a study conducted by Matusiak et al. (1999). The daylight factor (DF) showed a substantial increase in the lower floors. In agreement with this statement, equation 4 can be applied to demonstrate that if the WI is lower, meaning the atrium is short and wide, the daylight quantity at the base of the space will be higher.

An investigation conducted by Calcagni and Paroncini (2004) claimed that simple but rather effective ways of simulating different atrium shapes could be used to guide architects at the early stages of design. Varying the WI in different ways could be beneficial or represent a liability to the spaces that share the atrium. Increasing the height or the WI of the building will most certainly generate a reduction on the daylight levels, whereas maintaining the height constant and increasing the atrium length or decreasing the WI will compensate the DF downward trend, as it will enlarge the admitting daylight area. By using a scale model under a heliodon, the results of Calcagni and Paroncini (2004) studies showed that the DF levels decreased as the atrium height increased, whereas the DF had an increase when the length was widened while the height was kept constant, which was expected since the light admitting area was enlarged.

Some studies, as the one performed by Laouadi (2004) investigated the splay angle of the atrium facades as a function of the well index and the well efficiency by using the SkyVision tool developed by the Institute for Research in Construction in Canada. According to the author, the well efficiency (WE) is “the ratio of the incident light flux on the well top surface to the exiting flux from the well bottom surface”. As the WI decreased, the WE also diminished proportionally for a splay angle of 90 degrees. However, the WE decreased in a slower pace as the splay angle became lower. Results showed the well efficiency to be at least twice for an angle of 60° for a well index of 1.



$$WE = \frac{light\ flux\ (atrium\ floor)}{light\ flux\ (atrium\ well)} \tag{6}$$

Figure 2: Well efficiency relation.

Strategies such as stepped sections might positively impact the AR of an atrium. Although the addition of interior balconies can lead to an enhancement in the atrium architecture quality, its consequences on the daylight factor were investigated by Alraddadi (2004) in a physical scale model in Riyadh. The building studied was composed of four floors and a north south oriented roof. The aperture was located on the north slope and the terraces, which overlapped four meters over each other, were built on the south wall. When compared to the base case, where the atrium had a regular shape from top to bottom, the upper two floors had an increase of 25,4% and 22,3% on the average daylight factor (ADF), whilst the bottom floor had an ADF decrease of 1%. This can be explained by the fact that lower floors are more dependent on the IRC and since the atrium floor area was reduced, the amount of surface reflectance also decreased. On the other hand, the conclusions drew by the author indicated that the balconies can still act as light shelves, thus improving the general daylight quality of the adjacent spaces.

Other computer simulations with Radiance, such as the one pursued by Yi et al. (2009), confirmed the conclusions of Liu et al. (1991). The authors analyzed two buildings located in subtropical climates with different atrium configurations, where one was enclosed, and one was linear. While the width was kept constant in the first case, a diverse range of volume heights were tested along with distinct lengths with the aim of increasing the WI constantly with multiple combinations of PAR and SAR. The authors confirmed that the height is the feature that affects the daylight conditions most significantly in enclosed atria. The results indicate that regardless of the length of the atrium, after a certain height, the lower floors will not be able to have access to the sky component, which is the fundamental element affecting the DF calculation. The daylight factor values in the atrium space ranged from 38% to 7% for a WI that scaled from 0,475 to 1,9.

Du and Sharples (2010) carried out a research where simulations were performed in atria with different WI and well-index depth (WID), which considers the distance from a specific point in the atrium wall to its top edge. The WID criterion was more important for this study, since it can be used to draw a relation from the measurement point to the top of the building, where the sky is more visible. The research was conducted in physical models, theoretical calculations and computer simulations in Radiance. The study indicated that the vertical sky component (VSC) not only diminished as the WID increases, but also decreased next to the atrium corners, therefore implying that the center is the best-lit spot. In addition, the study concluded that the SAR is more influential than the PAR of an atrium. Results have shown that the sky component (SC) value between the square and the longest plan achieved a maximum difference of 15%, whereas the impact of SC on an atrium which has its height equal to its width compared to a deeper one can go up to 173%.

Different PAR ratios were also tested in Radiance simulations performed by Du and Sharples (2011) under a CIE overcast sky. Results showed that the lower the PAR index, the higher the daylight levels in the AR, meaning that rectangular atria tend to increase the natural light distribution along its linear borders. Naturally, the DF was decreased as the distance from the window increased. Moreover, the study demonstrated that the lower the position of the room in the atrium, the more affected it is by lower PAR values, meaning that linear atria could increase the ADF at the bottom and middle floor rooms. Finally, as the lower spaces are dominated by the IRC, the surface reflectance is an important aspect to increase the daylight falling into these spaces.

2.2.2 Atrium facades

The last section showed that geometries play an important role affecting the daylight distribution in atria. In addition, the surfaces that cover this atrium can also improve dramatically its daylight performance. Their reflectivity and other characteristics will not only influence the atrium, but more importantly, they will drastically affect the quality of light that reaches the bottom floors. Although the best performing materials in terms of reflection could be the specular ones, they might introduce liabilities such as glare for the occupants.

Boubekri and Anninos (1996) also recommended auxiliary strategies, such as the gradual increase of opening sizes on the lower floors and the surface reflectance on the top pavements. Most importantly, the same authors found that the DF does not increase proportionally to the wall reflectance. It is also fundamental to notice that there is a close relation between the geometry and the reflectance of the inner atrium surfaces.

General but rather important considerations were brought up by Littlefair (2002) about optimization of daylight levels in atria. Although extremely bright surfaces contain higher reflectance levels, the average reflectance of the atrium can be steeply reduced if the amount of glazing is increased either on the roof or on the inner walls. He proposed to roughly estimate the level of illuminance penetrating the atrium’s AR by using the no skyline method. It simply implies that areas that lie across this limit will look gloomy, in case they are not lit from the other side of the atrium. This strategy can be also coupled with the increase on the window head height on the lower floors, since their sky visibility is compromised as the atrium becomes deeper.

An investigation by Calcagni and Paroncini (2004), where simulations were performed with Radiance under a CIE overcast sky, showed that the DF increased 4,8% in average in the AR when the wall reflectance changed from 30% to 70%. According to the author this low value is a consequence of the relative high WWR as most of the atrium facade was composed by large openings, therefore diminishing the reflectance potential to boost the DF in the lower floors. On the other hand, the DF values for the bottom of the atrium can increase drastically if the atrium walls are composed mainly by opaque surfaces with high reflectance and a lower WI.

Another investigation conducted by Samant and Yang (2007) assessed the wall reflectance potential for increasing the ADF in an atrium. The simulations were performed in Radiance under CIE overcast sky conditions, while utilizing a grid 85cm above the atrium floor. A physical scale model was also built. It is important to mention that a comparison between the measurements taken from the physical experiment and the results from Radiance presented a difference on the DF that ranged from 5-10%, which according to the author represents a good agreement. The investigation looked at the thicknesses and different colors of horizontal bands that were distributed from the top of the atrium towards its base. In addition, the authors also evaluated how these different arrangements influenced the ADF at the bottom of the atrium when the WI changed from 0.5 to 2. As expected, the reflectance has a limited influence on the lower parts of the atrium as its height increases. Nevertheless, a sensitivity analysis pointed out that the DF increased for a taller atrium if the band at the top of the geometry was white and large, meaning that more light from the sky could be reflected downwards.

A more recent study conducted by Du and Sharples (2010) investigated how different inner wall patterns (different reflectance) and depth affected the vertical daylight factor (VDF) and the IRC in a square atrium. The authors performed simulations under a CIE standard overcast sky using both Radiance and measurement data in a scale model under an artificial sky. They varied not only the WI ratios, but also the assortment of patterns along the atrium surfaces. Results indicated that the shallower the atrium, the lesser the impact of the reflectance distributions, as the VDF in this case is strongly responsive to the sky component. On the other hand, it was concluded that whenever the depth increases (WI>1), the surface reflectance starts to significantly affect the daylight reflected downwards towards the base of the atrium. To verify this effect, vertical and horizontal bands were tested on the vertical surfaces, by varying not only their amount, but also their thicknesses. Results were sorted according to horizontal band models and vertical band models and measurement points were placed in three different vertical positions. The outcome identified that the VDF is considerably affected by the color of the band which is placed at the top of the atrium. Conversely, an agreement was found between the models with a higher number of stripes and the base case model, indicating that the VDF is not so dependent on the increase of the reflectance distribution. As for the vertical bands, since the same band goes from the top to the bottom floor, the reflectance tends to be more constant along the height of the atrium.

According to (Samant, 2011), the atrium daylight performance is dependent on predominant sky conditions, roof configuration, geometry, enclosing surfaces and the properties of the adjacent spaces. However, in his investigation, he focused in finding the optimal glazing apertures on each floor of a five-story building. Despite the general claim that openings should progressively increase from top to bottom, ideal levels can be investigated to maximize the daylight potential and avoid overheating problems in the atrium's AR. The author carried out simulations using the Radiance program where geometry, wall reflectance and other criteria were constant while the wall openings were varying in length. In addition, the DF was measured at five different points that ranged from the middle of the atrium up to 5,8 meters from the window into the room. His findings suggest that rooms in the lower floors are slightly influenced at the furthest distance from the atrium wall. Moreover, smaller fenestrations on the higher floors improved the DF on the lower floor, as these spaces are highly dominated by the IRC. On the other hand, the DF variations after 3,2 meters inside the adjacent spaces are negligibly influenced by the window aperture. Although the results pointed out that an optimal internal facade option is composed of openings that range from 60% to 100% top down.

2.2.3 Skylight aperture

Since the roman ages, atria were an important feature of residential architecture, not only due to the fact that they could foster synergy between people, but also because they could provide daylight and ventilation (Murgul, 2015). However, its purpose has been slightly adapted to other functions and climates, which most of the times leads to a roof construction at the top, especially in cold regions. Therefore, working on an adequate roof design and aperture size may improve the sky visibility from the bottom and adjacent atria rooms, hence providing these spaces with the possibility to fetch daylight as much as possible (Littlefair, 2002).

An investigation carried out by Boubekri and Anninos (1996) pointed out the flat roof as the best performing option, while the sawtooth configuration tended to direct light only towards the walls opposing the apertures. According to this author, roofs should be designed in line with the specific locations. To maximize the illuminance in atria, Matusiak et al. (1999) investigated not only different inclinations for the glass cover, but also studied the contribution of nine different reflectors in an atrium that was 6m high and 8m wide. Results from measurements on a scale model under both artificial overcast sky and clear sky showed that the performance of the reflector is closely related to the sky type and mainly to the availability of the direct sun. They found that an inclined reflector placed at the top of the atrium, that was leaning outwards, performed the best, even though it could potentially block the lower sun path during the winter. By inserting a double-pitched glass cover in angles between 18° and 30°, the VDF on the facades decreased by 50% if compared to the flat roof of the base case.

Sharples and Shea (1999) carried out an analysis in an atrium where the WI was constant (2.0) and roof obstructions were modified under the glass pane that was covering the skylight. The authors built a 1:25 scale model, which represented a five-story building with internal walls painted with a special paint with an absorptance of approximately 0.98. Instead of using the typical DF, the researchers calculated the performance of each roof type by measuring the sunlight hours as a function of the internal illuminance values on the atrium floor. Moreover, the authors designed the structures of each roof type, namely flat, mono and double pitched, in order to make sure that regardless of their differences, their daylight blockage coefficient would be nearly 15%. Although the flat roof generally presented a higher performance for overcast skies, this research indicated that in the presence of sunlight, the double pitched roof was the type to provide higher illuminance values, as well as a smoother decrease on the sunlight hours along the day. This phenomenon can be explained by the fact that a roof with these features can increase the harvesting potential of sunlight as it provides two surfaces which are better oriented towards different sun altitudes and positions if compared to a flat and mono pitched surface.

Later, an investigation conducted by Laouadi and Atif (2001) focused on finding how different roof shapes would perform under different sky conditions for a latitude of 45°. The authors tested domes with different configurations as well as pitched, pyramidal and flat geometries. Although domes performed better in the winter due to the fact that the sun altitude was lower, this roof configuration might be a liability in the summer, as the optic characteristics of the glazing reflects more the direct sunlight than the flat skylight. The author’s results indicated that domes could transmit 78% and absorb nearly 150% more light than flat roofs at an incidence angle of 70 degrees.

An investigation conducted by Calcagni and Paroncini (2004), showed a comparative simulation of an atrium with and without roof. The structure has decreased the opening area by 11% and results have confirmed that the DF was reduced by 45% in the spaces facing the atrium.

By modifying the width and the clerestory height of a four-story atrium, where its adjoining rooms were facing south, the ADF of the different variations could be assessed in an investigation carried out by Ghasemi et al. (2015). Simulations were carried out by using IES Radiance and compared to results obtained from a physical model which simulated a 48m long/wide and 16m height building. The ADF divergences between the measured and simulated models ranged from 14% on the ground floor to 16% on the top floor. This discrepancy could be caused partly by the low amount of ambient bounces set for the simulation, since the results might underestimate the reflectance between the surfaces in the AR. As expected, the lowest clerestory height, measuring 1/8 of the total building height, presented the worst daylight performance in the atrium AR. Consequently, higher clerestory heights had a greater sky view angle, which boosted the difference between the ADF on the lower and top floors. In order to attenuate the large discrepancy between the results, techniques such as the reflectors could be considered.

Mohsenin and Hu (2015) worked with DIVA for Rhino to study daylighting in the inner building envelope comparing different roof apertures. The variations consisted in modifying the glazing monitor height according to a fraction of the atrium width, ranging from w/2 to w/10. In addition, different WIs and atrium types were also assessed in line with the previous criterion. Results showed that regardless of the atrium shape and type, the spatial daylight autonomy (sDA) and annual solar exposure (ASE) will have a tendency to also increase for larger monitor heights. In addition, as the WI increased, the difference on the amount of daylight falling into the AR according to each monitor type becomes higher in atria that are enclosed. On the other hand, the monitor roof heights do not substantially influence the natural light harvested in attached atriums, as it is possible to harvest daylight through its exposed lateral walls.

2.3 Energy efficiency in atria

In addition to its daylight aptitude, atria also have a potential to work as buffer zones depending on their placement and configuration. On the other hand, they might drastically increase the building's energy demand if conditioned and treated as regular indoor spaces that are regularly occupied. According to Hung and Chow (2001), atria can be classified in four different types, as shown in Figure 3.

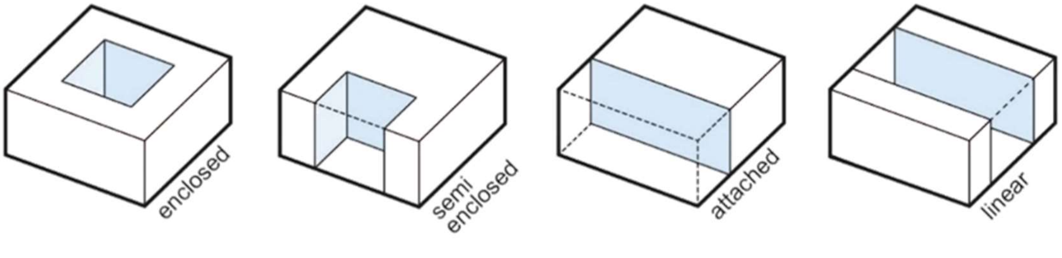


Figure 3: Types of atria.

He points out that centralized ones have a higher likelihood to keep the temperatures closer to its adjacent zones, as they are enclosed and share the boundaries with potentially heated or cooled spaces. On the contrary, atria such as the attached and linear ones are more prone to have higher heat losses to the surroundings. Most of the times, semi-enclosed and linear atria are wrapped in glazed panes, which can be beneficial depending on the climate. Atria with glazed facades can turn into not only buffer zones, which feature as transitional spaces between outdoors and indoors, but also into green houses that are naturally heated by sunlight, thus serving as pleasant gathering spaces during the winter. On the contrary, glazed facade atria can represent a liability in regions with warm climates, as the sun will bring additional radiation to theses spaces, thus transforming them into uncomfortable areas if not ventilated properly.

Wang et al. (2017) thoroughly studied the correlation between the SAR of atria and its energy performance, by utilizing field measurements and thermal simulations in Design Builder, in two existing enclosed atria in the city of Tianjin, located in a cold climate region in China. The two spaces were considered to be fully conditioned with setpoints adjusted to 20° and 26° for winter and summer, respectively. The shallow case showed to have more contribution of solar heat gain, especially at the bottom floor. The temperatures along the atrium height were more evenly distributed in the winter and in the summer, however more cooling capacity is needed during the warm season, as most of the atrium area is heated up by the sun. Although the deep atrium hardly had overheating problems, since its bottom is shaded most of the time during the year, the temperature gradient between its bottom and its top reached a higher difference. In terms of energy performance, the deep atrium reduces only the cooling need in the summer, while the shallow atrium reduces the heating demand, as a big portion of its area is heated up by the sun.

Another investigation conducted by Aldawoud (2013) focused in finding the relation between different atrium volumes and their thermal performance by using computer energy simulations in DOE 2.1E. The atria were assumed to be in thermal equilibrium at a temperature of 24° and had their only light admitting area through the skylight at their top. The atria shapes were tested only regarding their PAR, which varied from 0,15 to 1, whereas their height was kept constant. Among all the four geometries studied, the author found that the elongated shape had the worst energy performance, both in warm and cold climate regions. The energy demand of the adjacent spaces in a cold climate location increased up to almost 25% when compared to an atrium that had a square shape (PAR 1), due to its larger light admittance at the top. The investigation also pointed out that deeper atria tend to perform better in warm climates, as the middle and bottom floors are protected against direct solar radiation.

Moosavi et al. (2014) brought up several benefits of atria in buildings, one of them being their capacity to maintain acceptable comfort conditions inside its space and the adjacent rooms without necessarily using mechanical systems. Natural ventilation, temperature differences, solar radiation, wind properties of the region as well as internal loads have to be taken into account to design a space that adds value to the building. The temperature stratification along the atrium plays an important role and can drastically change according to the atrium WI and its openings for example.

Lastly, Laouadi et al. (2002) carried out computer simulations in ESP-r to verify the effect of different geometries on the energy performance of the adjacent atrium rooms in a building located in Ottawa, Canada. The energy demand studies were conducted in three different types of atria 1) enclosed 2) three-sided 3) linear. When compared to the base case, where there were no openings to the adjacent spaces, the cooling peak loads were significantly reduced to

41% 18% and 7% for the enclosed, three-sided and linear atria, respectively. The adjacent rooms were conditioned to a temperature of 21°, therefore contributing to a cool airflow from these rooms towards the atrium. Nonetheless, there was a substantial increase on the heating energy demand due to the heat losses and infiltration from the atrium towards the AR.

2.4 Summary

The previous sections were dedicated to the atria features that affect the daylight quantity and quality in the adjacent rooms and the space itself. As it was previously discussed, the geometry has been proved to play the largest role when it comes to daylight penetration and distribution in atria. As described by Baker et al. (1993), there is a strong relation between the well area at the atrium top, which can be described as the light admitting area, and the surfaces that receive the incoming light or the light receiving areas. This connection is described by the well index (WI) which is an equation that facilitates the comparison between different types of atria. Lower WI values mean that the atrium is shallow and more likely to fetch more daylight in their bottom and adjacent rooms. On the other hand, higher WI values indicate that an atrium is deep and probably gloomier at the lower levels. In addition, the SAR and PAR values are also good indicators of an atrium shape. Atria with lower PAR tend to be rectangular and have more surfaces exposed to daylight, thus having better chances of improving the daylight conditions in the AR, whereas aria with higher SAR are classified as deep, which leads to a consequent decrease on the natural light conditions in the AR.

Additionally, studies have showed that the wall reflectance properties of the inner atrium facades have the potential to increase the daylight quantity at the bottom floors, as well as expand their uniformity. However, the reflectance property starts to have limited impact as the atrium becomes deeper. The window to wall ratio is also an important feature of the atrium surfaces. Investigations, such as the one performed by Samant (2011), demonstrated that a proper combination of smaller windows at the top floors and larger ones at the bottom floors can improve the daylight scenario at the lower levels. Lastly, the roof type and aperture proved to considerably influence the daylight situation in the atrium. Flat skylights are more efficient under overcast skies, whilst pitched roofs offer the possibility to fetch more properly the sunlight, depending on their orientation and location.

Atria and their relationship with energy efficiency was also shortly addressed, since this topic is not included in the thesis project. The energy performance of an atrium is closely related to its shape. Enclosed ones tend to keep their surrounding temperature more stable, while linear types are more affected by the outdoor conditions. Shallower atria perform better in terms of daylight, nonetheless they are more susceptible to overheating problems and heat losses. A successful atrium case can be found in the Commerzbank project located in Frankfurt, where an atrium with side openings was implemented to facilitate penetration of daylight into the building core.

3 Daylight criteria

3.1 Daylight factor

The Daylight Factor is defined by the International Commission on Illumination or CIE (International Commission on Illumination, 2018) as “the ratio of the illuminance at a point on a given plane due to the light received directly and indirectly from a sky of assumed or known luminance distribution, to the illuminance on a horizontal plane due to an unobstructed hemisphere of this sky, where the contribution of direct sunlight to both illuminances is excluded.” The daylight factor is one of the most common criterion to verify the quantity of daylight in a given space and has been widely used not only by professionals, but also by a variety of standards to evaluate lighting conditions of projects and existing buildings. It is expressed as a percentage, which is a product of the following equation:

$$DF = \frac{E\ interior}{E\ exterior} \times 100\ [\%] \tag{7}$$

Where:
DF: Daylight factor of a given point (%)
E interior: Interior illuminance (lux) of a given point or plane (Normally horizontal at 0,7-0,85m from the floor with the light sensor pointed upwards)
E exterior: Exterior illuminance (lux) measured under a CIE Standard Overcast Sky

Although the daylight factor was established as the main criterion to investigate whether a building complies with some of the certification systems, one of its main drawbacks is the fact that no sunlight is taken into account in the calculations (Bian and Ma, 2017). Furthermore, this method cannot account for changes in orientation and location, thus disregarding two important considerations during the initial stages of the design. On the other hand, this method can be used both as a good indicator for the early design stages, and as an indicator for the daylight performance of a room or space (Tregenza and Wilson, 2013). The authors suggested that the minimum ADF suggested in office buildings is 2%. The following table connects ADF values to the appearance of spaces in office buildings.

Table 1: Average daylight factor for office buildings. Source: Tregenza and Wilson (2013).

Average daylight factor from side windows	Rooms without electric lighting
1%	Gloomy appearance, harsh contrast with view out
2%	Areas distant from window may seem underlit
5%	The room looks brightly daylit. Visual and thermal discomfort may occur with large window areas
10%	Visual and thermal conditions may be unsuitable for office-type tasks

As pointed out by Acosta et al. (2018), the daylight factor is influenced directly by the sky component (SC), the externally reflected component (ERC) and the internally reflected component (IRC). The DF can be calculated in different ways, through standard equations or computer simulations, where a grid can be used to determine the position of the sensors that will measure the availability of daylight.

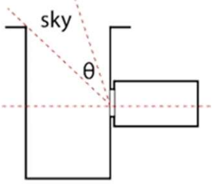
It is also possible to verify the DF at specific points, which is the case for one of the Swedish building regulations, the BBR. The code requires that a DF point of 1% is achieved and measured halfway towards the room depth and one meter from the darkest wall. However, the point location might be subjective, since some rooms have a particular shape that could bring difficulties in finding which walls could be used as a reference.

Additionally, the DF conditions in a room can be shown through the average daylight factor and the median daylight factor. Tregenza and Wilson (2013) highlighted that the ADF is a strong criterion to be used in the early phases of the design process, however this metric does not represent the uniformity conditions in the space, since higher values next to the window could sky rocket the average value. Conversely, the DF median seems to assess in a more reliable way the daylighting in a space, as the number can tell the amount of points that are above and below the arithmetical median (Mardaljevic and Christoffersen, 2017).

3.1.1 Sky component

The sky component is the element that has the greatest influence on the daylight conditions in the space. The DF level is substantially influenced by the portion of sky that is visible from the window or skylight and by any obstacles that might be placed in front of this fenestration, such as buildings, overhangs and balconies.

It is possible to have an idea if the space is well lit by estimating the visible portion of the sky from the window (equation 8).



$$D_v = \frac{\theta}{2}\ [\%] \tag{8}$$

Figure 4: Angle of visible sky in a building section. Source: Tregenza and Wilson (2013).

Where:
D_v: Vertical daylight factor
θ: Angle in degrees

Table 2: Conversion from vertical daylight factor (Dv) to vertical sky component (Dsv). Source: Tregenza and Wilson (2013).

Dv	5	10	15	20	25	30	35	40	43.5
Dsv/Dv	0.77	0.79	0.81	0.82	0.84	0.86	0.88	0.89	0.91

To understand how the calculations are performed in simulation programs, such as Radiance and DAYSIM, it is important to understand each type of sky that can be utilized in each analysis. The CIE has developed a series of sky models for different applications, but the standard overcast sky is the one used for the DF simulations (Mardaljevic, 2000). Despite its luminance variation according to the latitude, the overcast sky is always three times brighter at the zenith as devised by the Moon and Spencer equation, which was standardized by the CIE:

$$L_\theta = L_z \frac{1 + 2sin\theta}{3} \tag{9}$$

Where:
L_θ: Luminance of the sky at the elevation θ
L_z: Zenithal luminance

This sky has a more uniform light distribution compared to the clear sky and provides a smoother light along the building surfaces and streets. On the other hand, calculations handled by DAYSIM, make use of the Perez All Weather Sky model in order to generate metrics that take into account the weather conditions from a specific location to calculate the luminance distribution of the sky (AGi32, 2018). This sky model was created from a series of field irradiance measurements and can represent a large range of sky patterns through their different luminance distributions (Nabil and Mardaljevic, 2005).

3.2 Daylight autonomy and useful daylight illuminance

Reinhart and Walkenhorst (2001) defined the daylight autonomy as “the percentage of the occupied hours of the year when the minimum illuminance requirement at the sensor is met by daylight alone”. Unlike the daylight factor, the DA method is climate dependent, consequently being more likely to give a better daylight evaluation of the studied space. According to Dubois and Flodberg (2013), the consideration of parameters such as sunlight, user behavior and different types of skies make this approach more reliable. Moreover, the results obtained from the DA simulations might be used as an alternative metric to obtain credits and points in different certification systems, namely LEED and BREEAM.

This criterion fostered the development of new metrics based also on dynamic daylight simulations, such as the useful daylight illuminance (UDI) and the spatial daylight autonomy (sDA). Based on the user capability, the UDI establishes a range, so it is possible to evaluate whether the illuminance falling on the analysis plane is advantageous, so the occupant’s tasks can be performed with a proper level of daylight. While creating the UDI, Nabil and Mardaljevic (2005) established a range that goes from 100 lux to 2000 lux, meaning that a value that lies below that boundary implies a dark environment, whereas the ones that lie beyond the limit indicate that the space is probably overlit, thus indicating possible glare issues.

Table 3: UDI thresholds. Source: Nabil and Mardaljevic (2005).

Threshold	Description
< 100 lux	UDI fell-short (insufficient daylight)
100 – 2000 lux	UDI autonomous (total daylight autonomy; no need for electric lighting)
> 2000 lux	UDI exceeded (oversupply)

On the other hand, the sDA shows the percentage of the analyzed area that meets the DA previously established threshold for the occupied hours of the year. According to the Illuminating Engineering Society (IES), there are two levels for this metric: “Preferred daylight sufficiency” for an area that achieves a value of 75% and “nominally accepted daylight sufficiency” for an area that reaches a threshold of 55%. Table 4 shows the illuminance requirements according to each type of room.

Table 4: Lighting requirements for interior areas, tasks and activities. Source: EN 12464-1 (2011).

Type of room	Illuminance (lux)	Uniformity
Classrooms, tutorial rooms	300	0,6
Auditorium, lecture halls	500	0,6
Entrance halls	200	0,4
Circulation areas, corridors	100	0,4

3.3 Standards

3.3.1 Leadership in Energy and Environmental Design (LEED)

LEED is the most internationally well-known rating system for environmental-friendly buildings. The standard was designed by the U.S. Green Building Council (USGBC) and has certified nearly 100.000 projects around the globe, due to its flexibility as it comprises a wide range of categories that have different weights (USGBC, 2018). The certification levels are ‘Certified, Silver, Gold and Platinum’. Even the entry category has obligatory credits that shall be completed if the developer wants the building to be eligible for the certification scheme.

As for the daylight section, the computer simulations should demonstrate that an sDA with a threshold of 300 lux for at least 50% of the hours of the year can be achieved in 55% of the regularly occupied office areas. The accomplishment leads to two points on the overall certification. However, it is possible to score up to three points if an area of 75% is proven to meet the DA requirement. Moreover, not more than 10% of the floor area should display an annual solar exposure (ASE) of 1000 lux for more than 250 hours. Compliance can alternatively be demonstrated through illuminance calculations or measurements (USGBC, 2018).

3.3.2 BREEAM

The Building Research Establishment’s Environmental Assessment Method or BREEAM, was developed by the BRE Group that consists of a private institution focused in the research, generation and dissemination of knowledge about the built environment. The certification system was conceived in 1999 and since then it has been adopted by developers in the whole world (BREEAM, 2018).

The standard is divided into ten categories, ranging from management to innovation. The daylight category belongs to the section Health and Well-being and it contains three different criteria to evaluate not only daylight quantitatively, but also qualitatively. In this certification system, the building complies with the first and mandatory credit by reaching an ADF of 2,1% in 80% of the net lettable area or an average illuminance of 200 lux for 2600 hours along the year for latitudes between 55° and 60°. However, an exemplary credit might be achieved if an ADF of 4,2% in single story buildings or a 3,15% ADF for multiple stories are measured on the grid corresponding to the evaluated area.

Regularly occupied areas also need to be 7m distant at most from a window that should have a size of at least 20% of the total inside wall area. Lastly, a shading system should be installed so possible glare problems can be prevented, thus providing the users with more control over their visual environment (BREEAM-SE, 2013).

3.3.3 Miljöbyggnad

Miljöbyggnad is the main Swedish environmental certification system used in the Swedish market since 2011.The idea to develop a rating system for environmentally friendly buildings was initiated in 2003 by the Swedish Green Building Council (Sweden Green Building Council, 2018). The certification is provided based on three aspects, which comprise 1) energy, 2) indoor comfort and 3) materials. The achievement of a certain level of points can lead also to three ratings, namely gold, silver and bronze. Among the different methods for assessing daylight, the DF is the most adopted. The minimum thresholds to attain each rating category vary from 1% to 1,5% and since the calculations are performed utilizing computer simulations nowadays, it is acceptable by the standard that the simulated DF differs up to 0,2% from the requirement. The system accepts both a point DF (DFp) and a DF median in the version 3.0 (Miljöbyggnad 3.0, 2015).

3.3.4 Swedish and European regulations and standards

The rules of Boverket’s Building Regulation (BBR) must also be respected when a new building or a renovation takes place in Sweden. Apart from the mandatory provisions, the regulation also provides several recommendations that can be followed in order to pursue ideal or minimal daylighting conditions in indoor spaces (Boverket, 2015). Section 6.322 on daylight, which is part of the health aspect, recommends that rooms which are occupied more than occasionally should be designed to allow exposure to direct sunlight. In addition, it states that at least one of the rooms shall have a view to the outdoors, thus ensuring that the occupants can follow daylight shifts along the day. In addition, the EN 12464-1 provides a further description and guidance concerning daylight quality in working environments. Aspects such as recommended illuminances, glare issues, color appearance and other properties of electrical lighting are also proposed.

4 Methodology

This chapter provides a description of the studied building and its current constraints according to its location, design and proposed functionality. Apart from providing good indoor visual comfort by maximizing the daylight conditions in the AR and the ground floor of the building, the additional aim is to seek compliance with the Swedish building regulations (BBR, 2015) and verify whether the current and new conditions are able to meet the requirements of environmental certifications, such as LEED, BREEAM and Miljöbyggnad. As a result, the current proposal was investigated and simulated to establish a base case scenario, followed by a series of parametric studies with the intention to verify how different geometrical transformations and surface reflectance values affect daylight levels in the AR.

As learned from the literature review, the geometry of an atrium is the main aspect influencing the daylight quantity in a building. As a consequence, this thesis mainly focused on analyzing the effect of this feature, which comprises not only the building shape, but also its skylight aperture. In addition, the surface reflectance is studied as it has the potential to increase daylight quantity and uniformity in a given space. Thus, different reflectance values are assessed.

Simulations and data analysis were performed using a combination of software: Rhinoceros, Grasshopper, Honeybee, Ladybug and Excel. The current building design was simplified for study purposes, as the initial geometry was complex, but without compromising the geometry and its current features. The dependent metrics used as basis for the evaluation include the daylight factor (DF), daylight autonomy (DA) and the useful daylight illuminance (UDI). These are further explained in the following sections.

4.1 Sahlgrenska Life Science Center

The Sahlgrenska Life Science Park is an expansion of the Sahlgrenska University Hospital located in Gothenburg. The enterprise is currently in the design process, which started in 2016, and has nearly 90.000 m^2 of gross floor area, comprising a variety of functions that range from offices to conference rooms with the main aim of integrating the medical community, companies of the field and the university hospital (Arkitema Architects, 2018). According to Moberger (2018), the development also pursues the objective to improve the urban attractiveness of the region by bringing together major stakeholders of the medical industry, while providing more job opportunities. Although the complex consists of two main buildings and a large passage that connects them, this thesis focused on analyzing a single building, which is described in the following chapters.

4.1.1 Location

The project is located in a cluster of buildings in the outskirts of Gothenburg between Annedal and Guldheden neighborhoods. The main idea behind the design is to embrace the existing edifices and create an urban pathway that crosses over Per Dubbsgatan, which is a relatively busy road. The connection between the buildings also occur at different levels and places, hence emphasizing the role of the new proposal as a connector between the functions that are already in place and the urban configuration, which tends to be slightly reorganized and improved. Bearing this in mind, the nearest existing buildings were modelled as they may influence the daylight conditions of the study case.

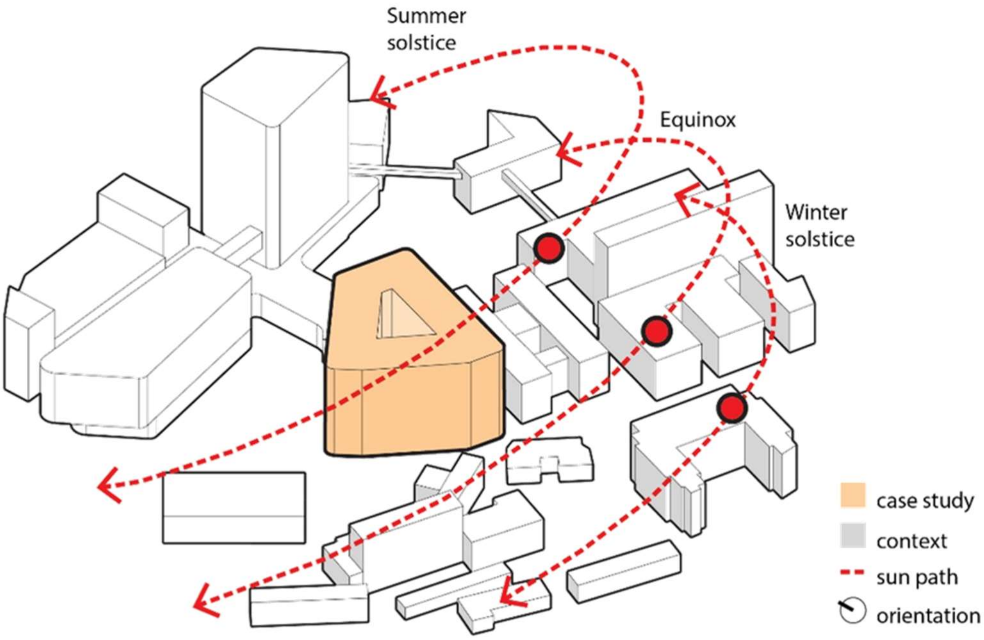


Figure 5: Location and surrounding context of the study case.

4.1.2 Geometry

Connecting interior and exterior spaces through smooth transitions was one of the goals of the project (Arkitema Architects, 2018). The shape of the building respects and dialogs with the existing lines and curves of the urban design 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.

The building consists of eleven floors, where functions as offices, laboratories and classrooms are distributed. Despite the contrasting nature of the functions which are developed on each floor, all activities taking place in these spaces are classified as working spaces, hence the daylight requirements according to standards and regulations apply equally to them as the spaces are used often. As the analysis (proposed by this thesis) is focused solely on the effect of atrium geometry and material properties on the daylight quantity in the AR, the area along the atrium border was the only climate zone considered for this investigation. The premise behind the analysis grid proposal can be found in the Daylight model chapter.

Considering the fact that the project is still under development, some functions can still be changed on the plans, yet the main activity zones are defined according to the schematic plan in Figure 6.

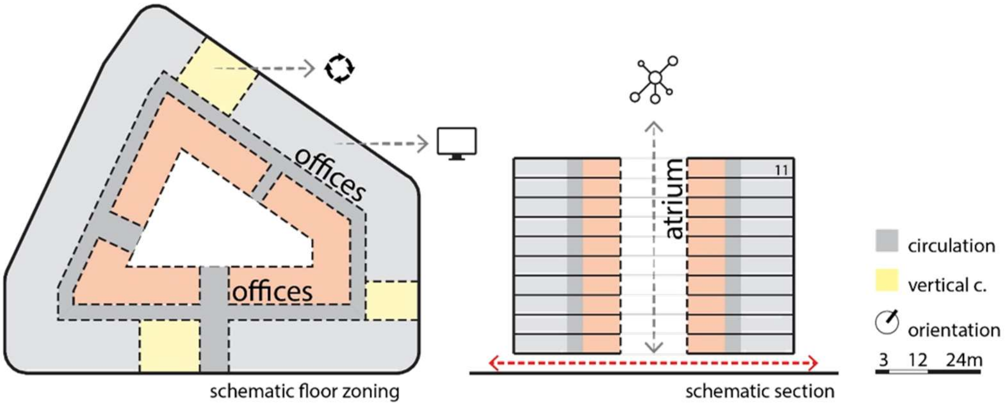


Figure 6: Schematic plan and section.

To understand the current daylighting situation, the proposed geometry (Figure 7) was simulated as a base case to allow a comparison with the parametric studies. More information about the reasons why the shape of the original project was broken down into four sections is provided in the chapter dedicated to the parametric scheme. The floor area has 4760m² and it is divided among the three wings as follows: a) 1270m² b) 895m² c) 1650m². Section d was not studied since it had a restricted facade towards the atrium.

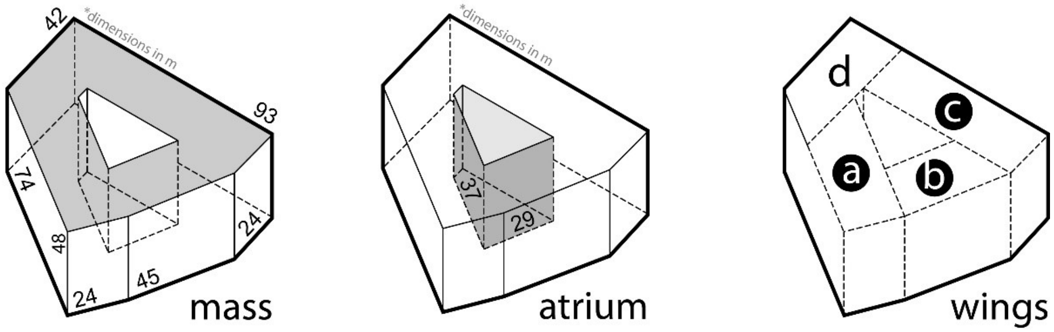


Figure 7: Current features of the base case.

4.2 Simulation tools and workflow

The main objective consists of analyzing the changes on the geometry and on the light reflectance values (LRV) that substantially affect the daylight levels in the AR. The results were also evaluated in terms of their potential to achieve the Swedish building regulations and some of the certification systems.

The eleven floors were analyzed in the simulations, yet the grid is only placed around the atrium perimeter, as previously discussed. To achieve the thesis objective, the following workflow (Figure 8) was established.

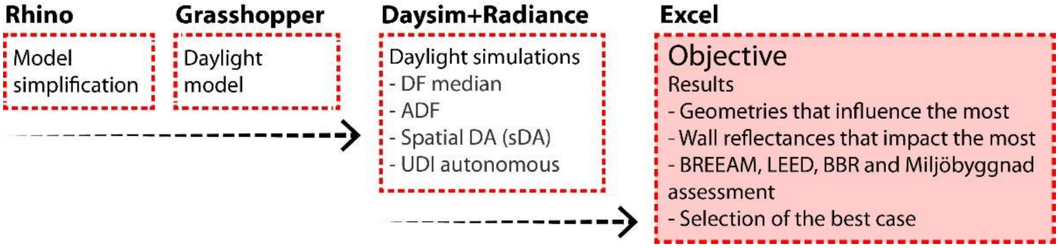


Figure 8: Thesis work flow.

4.2.1 Rhinoceros

Rhinoceros (2018) is a modeling software often used by the architecture industry to create and plan building projects. By integrating the program with Grasshopper (2018), which is a visual programming tool, it is possible to control shapes and geometry with the goal to analyze them according to environmental parameters. In this case, Rhino was used as the modeling tool to create the geometry that will be further investigated.

4.2.2 Grasshopper

Grasshopper (2018) is a tool for visual programming, which allows preparing and editing algorithms towards an environmental simulation. It is commonly used to perform parametric experimentations related to geometrical and material variations. It is the environment where a series of plugins such as Honeybee and Ladybug (Roudsari and Park, 2013) were deployed for use in this project. Moreover, Grasshopper is directly connected to Rhino, meaning that every geometry iteration triggered by Grasshopper will immediately affect the 3D model developed in the previous program’s interface.

4.2.3 Honeybee and Ladybug

Both Honeybee and Ladybug are plug-ins for Grasshopper that allow the user to run a wide range of environmental analyses, such as energy building performance, daylight availability, user comfort and shadow range, among others. These tools make use of validated engines for running the simulations, namely OpenStudio, EnergyPlus, Radiance and DAYSIM (Ladybug Tools, 2018). The platforms are usually employed to support the early design phases, nonetheless they can also be used to demonstrate compliance to environmental certification systems. For this reason, they were the main freeware used in the thesis project.

4.2.4 Radiance and DAYSIM

Currently embedded in many different interfaces, Radiance (Ward and Shakespear, 1998) is a well-known and validated set of lighting simulation programs based on a hybrid deterministic-stochastic backward raytracing technique, as it generates results that are displayed with a high degree of realism, either as numerical values or as images (Radiance, 2018). DAYSIM (2018) on the other hand is a Climate Based Daylight Modelling (CBDM) simulation tool that uses the Radiance engine at its core. DAYSIM allows to generate metrics that evaluate the space on an annual basis by using the daylight coefficient approach combined with the Perez all weather sky models. Daylight autonomy (DA), useful daylight (UDI), electrical lighting demand, as well as point-in-time and annual glare analyses are some of the outputs that the program can generate. For this specific investigation, the tool was used to calculate the spatial daylight autonomy (sDA) and the UDI.

4.3 Daylight model

4.3.1 Simulation input and parameters

Table 5 shows the Radiance settings used in the simulations. An accurate but rather optimized set of parameters were chosen due to the large size of the grid and the amount of simulations. In addition, a relative comparison of design alternatives yields more reliable results than the reporting of absolute simulation results (Reinhart, 2009). The following values give a solid rendering performance (Radiance Settings, 2018); however, the ambient bounces were increased from two to four in order to improve the ambient diffuse calculations.

Table 5: Rendering quality adopted for the thesis simulations.

Ambient bounces (ab)	Ambient division (ad)	Ambient sampling (as)	Ambient resolution (ar)	Ambient accuracy (aa)
4	512	256	128	0,15

Regarding the building configuration, the occupancy schedule for the annual simulations considered the evaluated areas to be occupied from 9h to 17h with a one-hour break during week-days. As for the material properties, the light reflectance values were chosen based on common construction practices, while the current light transmissivity value is for a double-pane glazing, as the atrium facades are not initially exposed to fully outdoor conditions. The window to wall ratio for the atrium facades was kept at 40% for all the simulations. Changing their values would not fit in the time constraints of this investigation.

Table 6: LRV and LTV of the materials adopted for the simulations.

Construction	Light reflectance value	Light transmissivity value
Glazing, double pane (WWR 40%)	-	0,73
External wall	0,40	-
Internal wall	0,70	-
Internal floor	0,40	-
Internal ceiling	0,80	-
Surrounding buildings	0,35	-
Ground	0,25	-

4.3.2 Parametric scheme

The parametric study was split into two main phases, where the first one assesses the impact of the changes in the geometry in different ways, while the influence of the surface reflectance values was explored in the second phase.

Figure 9: Tower option. shows the first set of modifications. In this case, the adjustment was conducted in each block separately in order to verify the effect of a larger opening in each orientation. It is important to consider that the geometry modifications triggered an area loss, which in most real cases compromise the project goals, since it was designed to fit all the requirements of the developer. To tackle this possible drawback, the adjustments of the geometry were followed by a volume addition, which varies according to each wing, thus increasing the height of the building in a specific spot. The towers that are added to the top contain the same number of floors of the wing that is being pulled down. Each step of the simulation decreases two floors at a time.

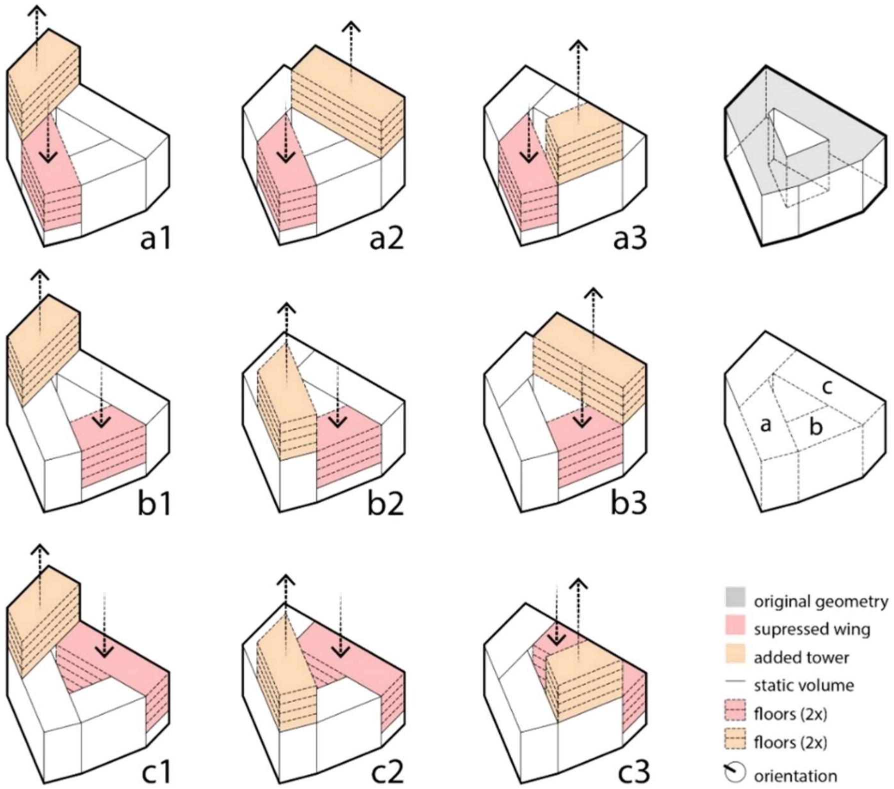


Figure 9: Tower option.

As it can be seen in the previous figure, there are many options to compensate the area losses and building a tower in one of the wings may represent one among many different ones that could be chosen for the architects responsible for the project.

The second series of simulations comprised additions that oppose the first tower options by creating geometries that rest over two wings and rely on fewer floors to make up for the area losses. However, for every two floors that are eliminated, only one floor is computed at the building top, as shown in Figure 10.

The potential of this option lies on increasing the sky view angle from the AR, as fewer floors will be added to the top. On the other hand, the atrium will be slightly more surrounded by floor area, which can technically block the sun path in a given direction. Architecturally, this alternative also pursues a higher degree of integration with its surroundings, keeping therefore the height of the cluster approximately at the same level.

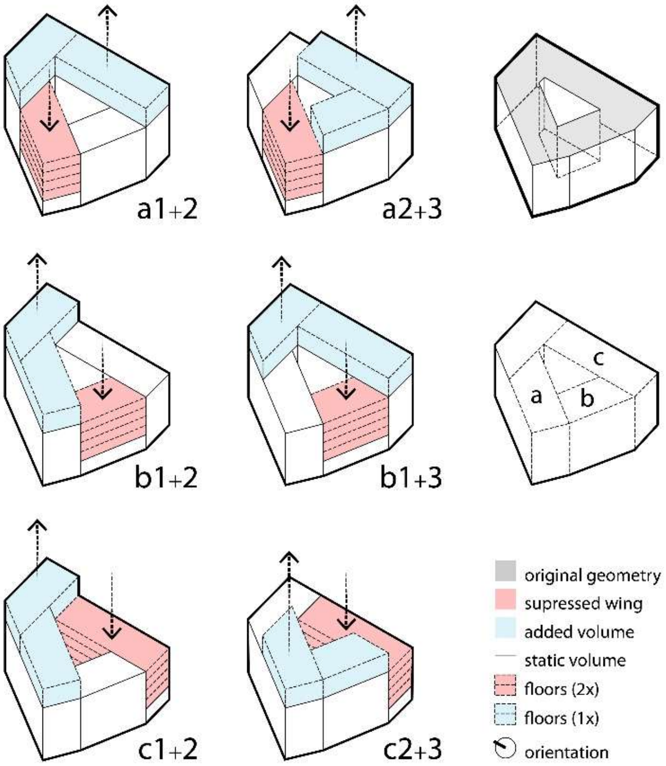


Figure 10: Combination of wings option.

In addition, these options also seem to be more realistic construction and structural wise. Their internal organization would also be easily spread over the wings that are not being suppressed, thus keeping the horizontal and vertical circulations more wisely organized. The combination of two wings has slightly the same area of the addition of two floors in the tower options, hence the floor space compensations are relatively similar in these two different ways of structuring the new volumes.

The third series of the geometry modifications, that can be seen in Figure 11, proposes a smoother transition between the heights of the different wings in order to compensate for the area losses of the volumes that are being pulled down. These solutions tend to be more architecturally appealing and it is a strategy often applied to fetch daylight into buildings that are constructed around large urban blocks, not to mention their likelihood to create terraces to be used as recreational spaces.

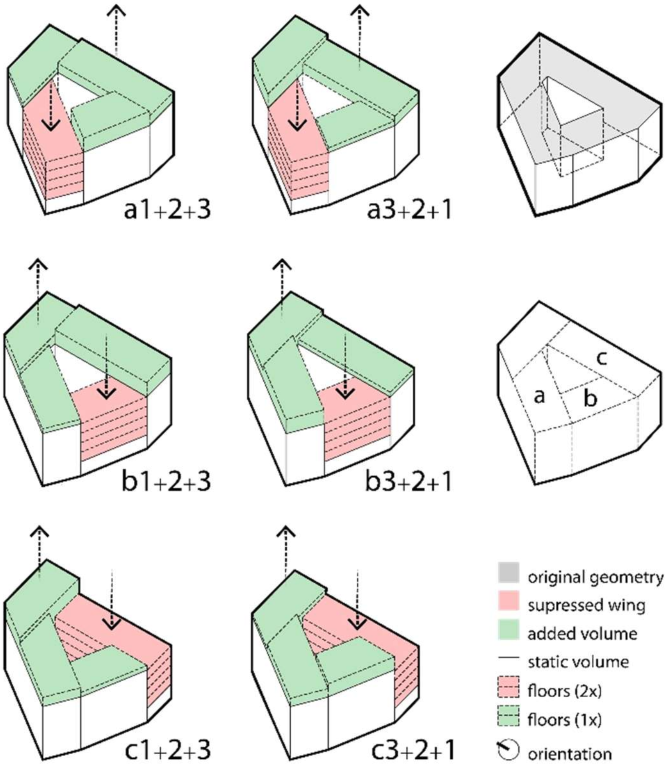


Figure 11: Counter and clockwise addition option.

Lastly, the plan aspect ratio or PAR was modified in angles of 5°, thus leading to a stepped section across the atrium in one specific orientation at a time. The angles range from 5° to 20°. The last angle was determined as it provided a minimum useful floor area on the top floor. This modification creates a small terrace for each floor and its dimensions varies according to each angle. The larger the angle, the deeper the terrace. This small balcony generates an additional outdoor floor area which acts as a reflector, thus increasing the potential distribution of daylight into the AR.

Differently from the previous options, the low angle inclinations do not extensively decrease the floor area of the case study, even though the 20° visibly reduces the top floor depth. In variance with the three precedent alternatives, no area compensation has been added to these modifications, thus avoiding an architectural disruption in the original volume.

The final geometry modification resides on the adjustment of all the three wings at the same time. Due to the combination of wings for this simulation stage, the 20° option could not be tested, as it does not leave any useful area on the last floor. Moreover, the area loss would be increased to an amount more than reasonable for any developer in real terms. The alternatives mentioned above can be seen in Figure 12.

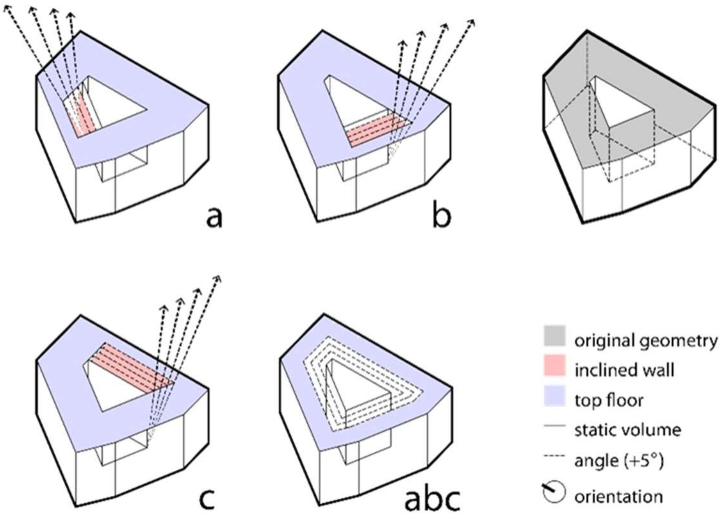


Figure 12: Wing splaying option.

The wall light reflectance values (LRV) were changed from 30% to 70% so the impact of modifying the material of the inner facade could be assessed. The literature review has pointed out that the LRV starts to have an important influence when the atrium becomes deeper. In this specific case, the base cases were chosen for the change of the LRV.

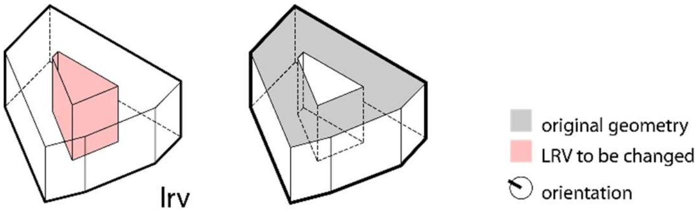


Figure 13: LRV modification option.

The area loss was calculated for each of the alternatives and compared with the gains in daylighting quality. Recent daylight analyses have shed light on the property value according, not only to their location, but also their potential to fetch daylight. Saratsis et al. (2017) analyzed how different block configurations could affect the natural light quantity of the neighboring buildings in New York. The author studied typologies ranging from perimeter blocks to double alleys and found that building them with different heights can improve the percentage of daylit area in a considerable amount on the lower floors. Furthermore, the studies showed that buildings that are constructed with different heights instead of one single block contributed for an increase of the Floor Area Ratio (FAR), meaning that larger floor area could be built with the same footprint.

This approach also enhances the property value, since more floor area is available for leasing. Following this methodology, the results are also compared in terms of property value according to the CBRE report for the last quarter of 2017, which showed that the value for the prime rents in the city of Gothenburg reached 3000 SEK/m² (Sweden Overall Property Market View, 2017).

4.3.3 Analysis grid

Since the atrium adjacent spaces consist of landscape offices and its area is the main subject of this study, the calculated grid depth followed the recommendations for work spaces proposed by Neufert and Neufert (2012). In order to comfortably accommodate two working desks next to each other, a room depth of 4,50m was chosen. The hallway was left behind, as it is not classified as a regularly occupied space.

In relation to the Swedish regulations, the DFp, which is measured half-way through the room's depth and one meter from the darkest wall, should not be lower than 1%. Instead of placing the points in each corner of the grid, the metric utilized for verifying the potential of each strategy was the area of DF above 1%. As it can be seen in Figure 14, the grid varies according to each geometry alternative. Nevertheless, the metrics adopted make it possible to compare the results among the different options. The grid surface is composed of sensors that are one meter distant from each other.

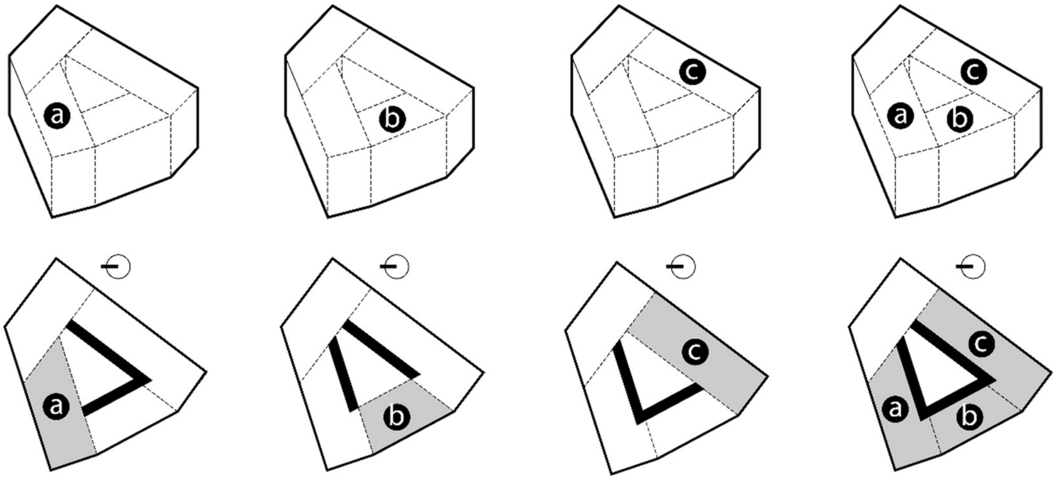


Figure 14: Grid combination for each case.

The evaluated grids are highlighted in black and are present in each of the eleven floors, while the wing that is being changed is indicated with the letter.

5 Results

Under the guidance of the two objective questions, the results of the current daylight situation in the building, as well as the proposals are presented in the following sections. Firstly, an investigation was carried out to verify how the AR in the current project were performing in terms of daylight quantity. Secondly, different qualitative proposals were developed utilizing parametric schemes, which considered the characteristics of the initial architectural concept. The scenarios, both current and future, were assessed using different metrics, consisting of ADF, sDA, DF median, UDI and specially the grid area that had a DF above 1%, which can be translated into areas that are potentially certifiable for the Swedish regulations and standards, such as BBR and Miljöbyggnad.

To answer the first research question, the study focused on geometry and wall LRV changes. According to the literature review, the atrium geometry showed to be the most influential aspect, hence this thesis project concentrated the investigations mainly on this atrium feature. Nonetheless, the walls LRV also demonstrated to considerably impact the daylight values mostly at the bottom floors, especially in atria with high WI. Secondly, an analysis was made to choose the optimal solution in terms of daylight quantity and less area losses. To wrap the study up, some options were chosen to be carefully studied in terms of daylight conditions per floor. The daylight metrics are assessed in absolute values, so comparisons could be drawn in an a more accessible way. General conclusions are discussed in the last chapter.

5.1 Base cases

The current daylight situation in the AR 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, and the evaluation grid was placed only around the atrium, so the simulation time was optimized, and the results of the improvements could be properly seen, as the outer facades could significantly distort the results. As for the present scenario, 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 perimeter of the atrium and changes according to each type of modification, thus leading to four different base cases. 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.

Shortly, the sDA shows the percentage of the area that has a daylight autonomy of 300 lux for 50% of the time of the year, while the daylight factor was quantified in terms of area that had a value of 1% or more. Lastly, the behavior of daylight was evaluated in each floor by using the ADF, the sDA, the DF median and the UDI autonomous. These metrics are utilized by certification systems, except the UDI, 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.

5.1.1 sDA and area of DF above 1%

The following graphs show an overview of the current daylight situation on the base cases in relation to the area of the proposed grid. The area that is seen in the vertical axis of Figure 15 is the sum of the grid along the perimeter of the atrium on eleven floors. Each grid varies according to the wing that is being studied, meaning that the rooms that are investigated are always located across and adjacent to the wing that is being modified. The letter indicates the wing that is being changed. The impact of the modifications in case a will be assessed by the opposite and adjacent rooms for instance, which are highlighted in black. The abc proposal does not follow the above-mentioned rule though, since there is no wing being suppressed, but rather splayed in angles, so all the atrium perimeter is being assessed.

As shown in Figure 15, none of the base cases present an sDA of more than 35%. However, this value decreases to the 29% on base case abc, which is expected as its grid area is bigger if compared with base case c. The values are presented in percentages, so comparisons among the grids could be drawn. It can also be noticed that both the amount of area of DF above 1% and the sDA decrease similarly as the grids are combined.

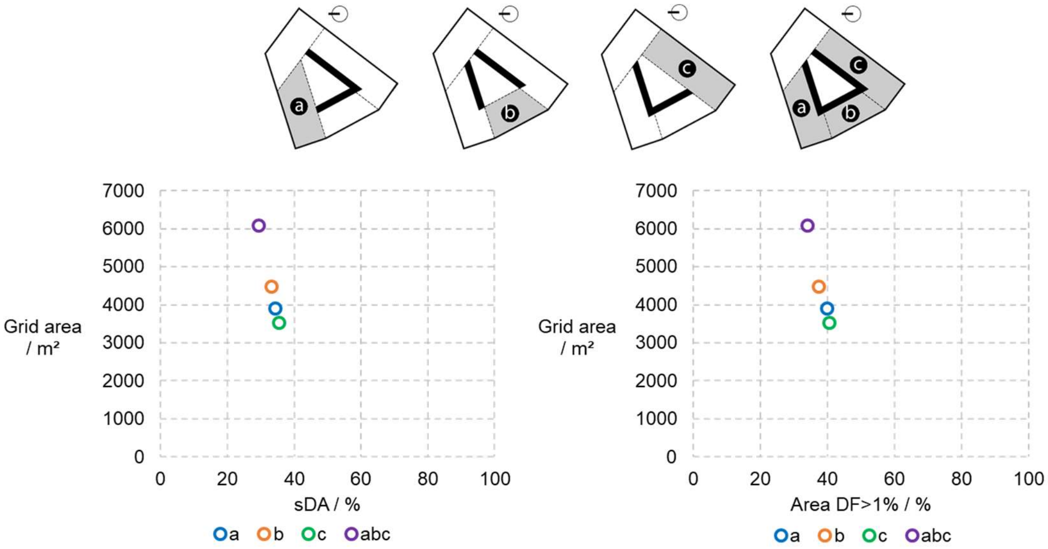


Figure 15: Grid area and area of DF above 1%.

As for the sDA metric, it is clear that the rooms that are located on the top floors and on the opposite side of wing c will have more advantage due to its south orientation. It can also be noticed that base case b had the lowest values, 33% for sDA and 37% for DF area above 1% if compared to the same family of modifications. Base case c performed the best, achieving an sDA value of 34,5%, while having 40% of its area with a DF above 1%. Base case abc achieved an sDA value of 29,3% and a portion of 34% of its area with a DF above 1%, thus being featured as the worst-case scenario.

5.1.2 ADF, DF median and dynamic daylight metrics

Figure 16 shows the daylight performance for the four base cases. The dot near the left lower edges of the graphs represents the 1st floor, while the one near the upper right bounds represents the 11th floor. The higher the floor, the higher the ADF, sDA and DF median values.

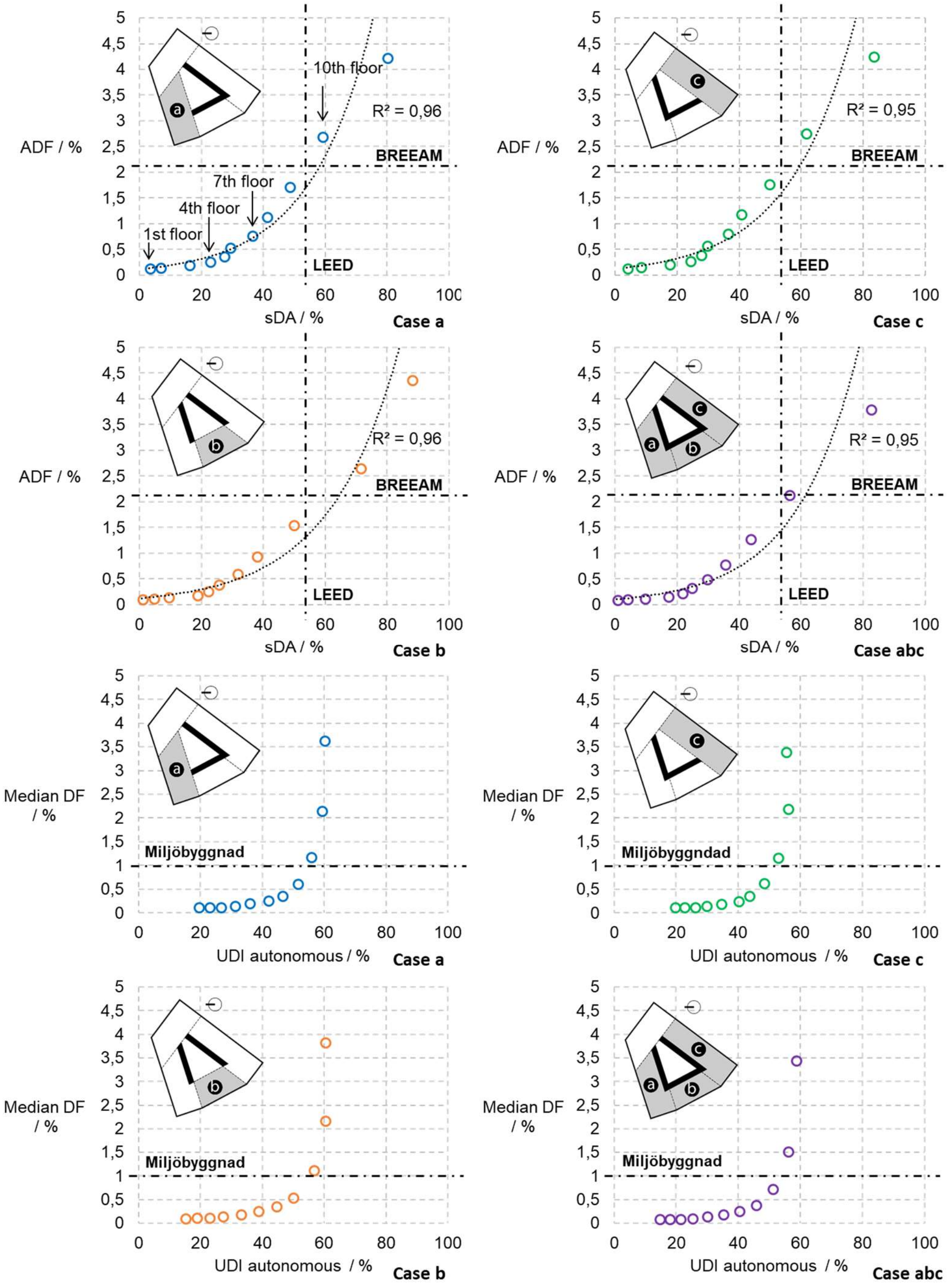


Figure 16: ADF, sDA, DF median and UDI autonomous per base case.

As it can be seen, all the cases behave in a similar way, where all the floors but the two upper ones are located below BREEAM and LEED requirements. Note that the ADF of 2,1% is the first BREEAM requirement, which precedes the demand of a daylight factor uniformity that is not analyzed in this thesis.

The upper floors that have their values lying on the right upper side of the graphs are complying with the certification requirements due to their higher sky view angle. This scenario is in line with the findings of an investigation conducted by Du and Sharples (2010), who claimed that the sky component dominates the region of the atrium where the distance from the top edge towards a point at the bottom equals the atrium width. Therefore, a vertical point in one of the atrium walls that equals the correspondent wing width represents the boundary where the SC is more influential. On the other hand, the IRC has more potential to generate a positive impact on the daylight conditions in the AR from that point downwards.

The ADF difference that ranges from 0,14% to 4,23% between the bottom and the top floors in base case a illustrates the strong imbalance between stories. To tackle this setback, the modifications will keep track on how many floors are able to reach the right upper quarter, meaning that the proposals are able to improve the daylight quantity in each floor and increase the chances of meeting the standards.

Base case c demonstrates a great potential to become autonomous in terms of daylight, as its grids have more access to sunlight due to the orientation of the building. The 10th and 11th floors reached sDA values of 61,4% and 83,2%, which are lower if compared to the same floors on base case b, 71,2% and 87,8%, respectively. However, most of its floors have higher values if compared to the floors in base case b. The ADF and sDA seem to be better distributed among floors in the options that included the grid on wing b. Lastly, case abc decreased somewhat the values, yet they follow a more uniform increase towards the top floors.

Regarding the DF median and the UDI autonomous, the top floor in all cases increased steeply if compared to the one underneath. The DF median reached a value of 3,85% on the 11th floor of case b, while its 10th floor presented a value of 2,18%. Increasing the number of bounces in the simulations would possibly lower the difference in the values between the floors, nevertheless this investigation aims to quantify the impact of changes in a broader way and increasing the quality of the simulations would drastically increase their time.

The DF median is a rather revealing metric and shows that while half of the values in a room are above a certain number, the other half is below. This metric is acceptable by Miljöbyggnad and illustrates in a better way the daylight conditions in a room in terms of distribution, whereas the ADF can be always boosted by the values next to the fenestrations. As it can be seen, just three of the base cases are able to achieve the certification system on the top three floors. Base case a presented DF median values for the 9th, 10th and 11th floors of 1,19%, 2,17% and 3,65%, respectively.

The maximum UDI of 60% is reached on the top floor of base case b. Some of the UDI values on base case c are slightly lower if compared to its alternatives. That can be explained due to the fact that the grids are facing south and east, therefore the upper floor values tend to fall on the UDI exceeded range.

5.2 Parametric study

The results from the parametric studies will be presented in the following chapters. Each investigation, namely geometry and LRV effects, were separated into their own sections, so their impact on the building daylight performance could be analyzed separately. The main idea of this parametric study is to test how different shapes and materials can affect this specific atrium design, however they also open a precedent for further investigations in atria that do not have regular shapes, where the interaction between the different components is not so evident, but rather complex to understand. In addition, the intention of these studies is to compare options and verify which could combine cost effectiveness with high daylight gains in the AR.

5.2.1 Effect of geometry

As reviewed in the literature about atria, the geometry is the most important factor when it comes to daylight quantity in the AR. It defines not only how the space embrace the building and its occupants, but also how light will be able to penetrate it, since this is one of the most desired characteristics of atria. Illuminating these areas with light is desirable, yet many atria also have the intention to illuminate the adjacent rooms. Due to its shape, the studied atrium has an aesthetical potential to surprise and create an interesting effect indoors. On the other hand, and as evaluated in the previous chapters, its shape and depth does not allow daylight to properly permeate the AR.

To tackle this setback, some proposals were created in line with the original project to avoid massive changes. Since the quantity of daylight in a room is strongly dependent on the portion of the sky that it sees, the main concept lies on the potential to maximize this view by pulling down different wings of the edifice and see how the illumination levels change according to every alteration. Each modification has a cost and therefore the proposals also account for area losses and additions.

5.2.1.1 Spatial daylight autonomy (sDA)

The first set of studies show how each modification affects the daylight conditions in the adjacent rooms by utilizing the sDA. This metric was particularly chosen as it considers the annual climatic variations and the location of the building. The sDA also provides the possibility to understand with only one number how the natural light situation improves or declines in the whole case study.

As the daylight quantity in the indoor spaces are mostly dependent on how much they can see the sky, the main goal was to gradually increase the sky view angle by decreasing the height of the building in steps of two floors at a time. According to the municipal regulations, it is possible to build up to 75m height on the site, so the proposals were developed according to this regulation.

The letter “a” stands for the wing that is being modified and the number next to it stands for the tower that is being stacked to make up for the area losses. The relation between area losses and daylight gains is shown in the area of DF above 1% chapter.

Figure 17 shows the first group of modifications that were proposed.

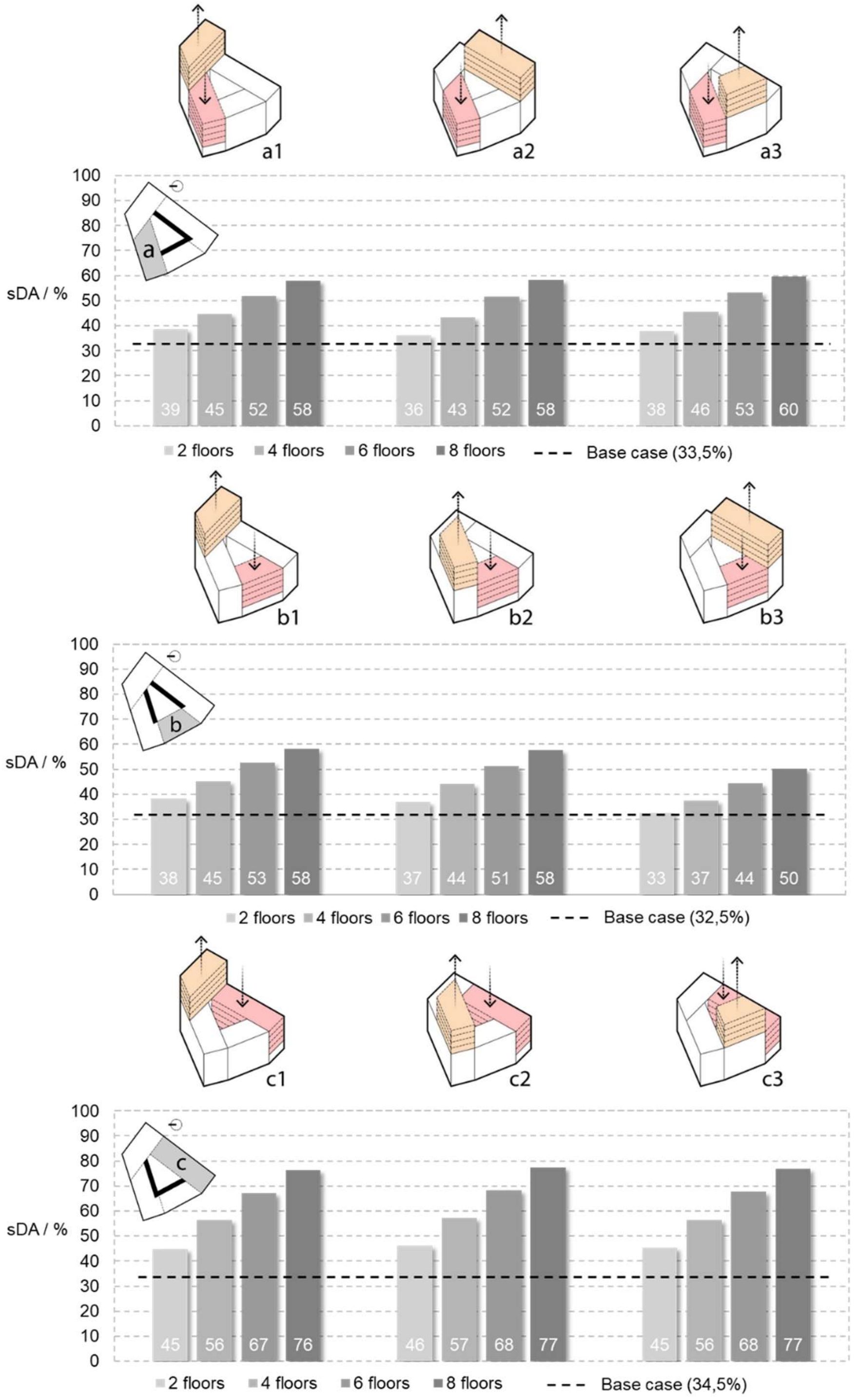


Figure 17: sDA for cases a1 to a3, b1 to b3 and c1 to c3.

As it can be seen, regardless of the tower position, the increase on sDA for the all the floors are substantial. By decreasing two floors on option a1, the sDA increased from 33,5% to 39%. Case a3 showed to have the best performance in terms of daylight autonomy.

Despite the fact that the grids are oriented towards north, a3 has the tower in a position that has less surface area blocking the visibility of the sky from the AR. If compared with the base case, bringing down eight floors increased from 33,5% to 60% the area that is achieving 300 lux for over 50% of the time during the year. LEED requires this area to be at least 55%, so the only options that have the potential to achieve this condition are the 8 floors step in each of the a cases.

The second set of investigations comprised modifications on wing b. Since the towers that are created to compensate the area losses on this wing have a larger floor area, all the options for this case will have an area surplus, which can be advantageous for the developer if the natural light conditions increase alongside as well. The first two recommendations increase in about the same level the daylight performance in the AR.

Cases b1 and b2 behaved similarly. The first one increased the sDA from 32,5% to 58% when eight floors were pulled down. Conversely, b3 appeared to underperform in relation to the previous cases, as its last modification presented a value of 50%. This option seems to demand a strong effort, as the building area is larger than the others and the rooms do not get the same good daylight conditions as cases b1 and b2. This could be explained by the fact that the tower which is located in the south side blocks most of the sky view and sun path from the rooms located in the opposite side of the atrium.

Wing c has the largest amount of floor space when related to the distinct wings and consequently has the largest potential to increase the natural light situation in the AR. Conversely, diminishing the number of floors in this wing will substantially decrease the area, which might represent a drawback for the developer.

The graphs show a dramatic growth of the sDA values regardless where the tower addition is being placed. Despite the building located in front of wing c, the analyzed areas are still able to take a great advantage of the east and southeast orientations. By pulling two floors on wing c towards the ground, the c1 values increased from 34,5% to 45%. The tower that is placed across wing b blocks most of its sky visibility, nevertheless its height does not represent a large impact in the universe of such a considerable improvement. Lastly, the suppression of eight floors has sharply rose the sDA from 34,5% to 77% in case c3. This steep growth can be explained as the inner atrium facades have mostly become an outdoor envelope, as they are more exposed towards the surrounding conditions. If compared to the actual scenario, the last modification has more than doubled the daylit area.

Overall, all the geometry adjustments within the tower alternatives significantly improved the AR daylight quantity. Although they all similarly contribute to a better well-lit indoor environment, it is important to consider the placement of the tower not only in terms of obstacle, but also in terms of aesthetical value. So far, the c family of modifications has presented the greatest improvements, followed by the cases a1, a2 and a3. In contrast to cases b1, b2 and b3, the rooms investigated in the previous alternatives are facing the sky directly, while the spaces in the second set of modifications are lying across each other.

Figure 18 illustrates the daylight behavior in the AR for the different geometry compositions.

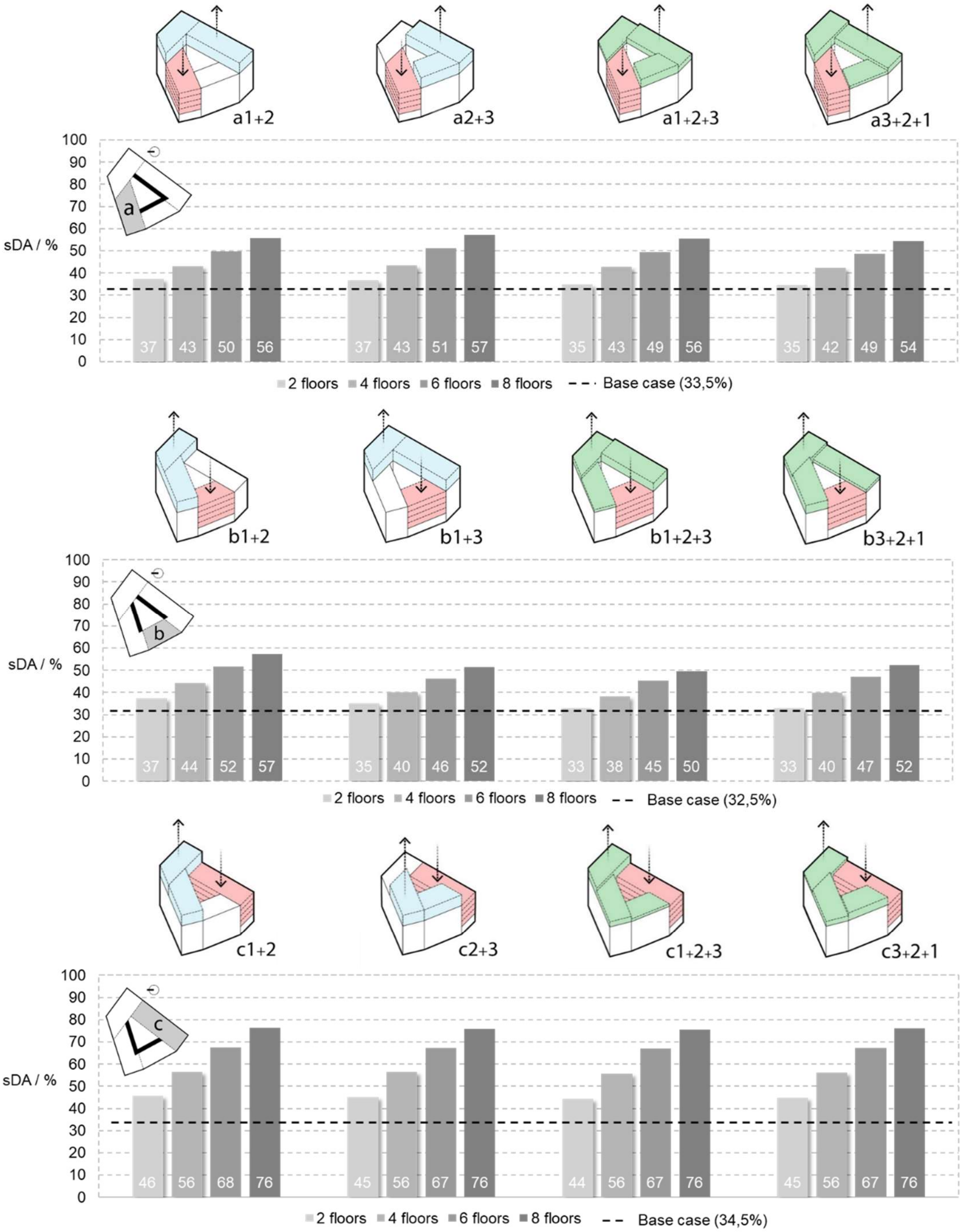


Figure 18: sDA for cases a1+2 to c3+2+1.

The idea of these alternatives was to verify whether these options would be advantageous over the tower arrangement.

The options that merged two wings (a1+2 and a2+3) to compensate the area losses are now increasing one floor at a time, whilst the wing that is being suppressed still decreases two floors. On the other hand, cases a1+2+3 and a3+2+1 increased in steps, which follow either a clockwise or counter clockwise direction. Both groups of changes increased the sDA alike, even though choices a1+2 and a2+3 showed a better performance than a1+2+3 and a3+2+1 when only two floors were deducted from the original volume. The lower values are probably due to the addition of all the free wings[1] one floor up in case1+2+3, which blocks more the sky view from the AR.

The arrangement a2+3 presented blandly higher values, which are in line with the lack of obstructions in front of the studied rooms. The same case also had a considerably growth that ranged from 33,5% to 57%, being slightly similar to case a2. It is noticeable though, that the volumes presented in this group of adjustments demonstrated to be less effective than the tower group a1, a2 and a3. When comparing a1+2+3 to a3+2+1, the first has overperformed the last in the eight floors change. By looking at the models, it is clear that the sky view angle is modestly wider from the AR in a1+2+3.

Option b1+2 showed the most excellent performance between the four new shapes by demonstrating an sDA that increased from 32,5% to 57% if compared to b1+2+3 that showed an increase that ranged from 32,5% to 50%. A closer look into the performance of the left grids for case b1+2 might reveal higher values regardless of the changes in the atrium shape, since they are oriented towards southwest. Cases in the b family are more sensitive to additions and subtractions in the original volume, even though in some cases, distinct configurations can present nearly the same results. This situation is illustrated by cases b1+3 and b1+2+3, where the values have a steady growth and both cases reached their peak with an sDA of 52% and 50%, respectively. Both cases also share the same obstacle creation in front to the sun path. It is also worth comparing these four cases with the tower options and as it can be seen, case b3 achieved similar results to b1+2+3. The difference between these two options is rather low.

Decreasing the number of floors on wing c revealed to be the most powerful strategy for the sDA metric, as it exposed a good portion on the atrium facade towards the surrounding and consequently towards daylight and sunlight from the south. These cases are specially interesting as they directly show that the building configuration on the free wings have little if no influence at all on the sDA. Concerning the suppression of eight floors, the four cases presented an increase from 34,5% to 76%, which is more than double. Since LEED requires a 75% sDA for achieving three points, all the options within this configuration are able to fulfill the demand.

By looking at the four different cases, option c1+2 showed the greatest improvement. The combination of the wings offered no obstruction and the starting sDA values in the first change substantially increased from 34,5% to 46%. The last two cases on the bar charts presented almost equal results, except for the first modification in case c1+2+3, where the sDA increased from 34,5% to 44%.

The four last geometry improvements came in the shape of a stepped section. They were designed to be splayed in angles of 5° to 20° in each of the wings that were studied before.

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[1] Free wings: Wings that are not being suppressed.

For the four following shapes, all the previous grids and adjacent rooms were investigated together, as there are no wings being diminished this time.

It is clear in Figure 19 that splaying the walls of the atrium brought an interesting increase of the sDA in the AR. In case a, the sDA ranged from 35% for an angle of 5° to 44% for an angle of 20°. Case b presented relatively lower values with an sDA of 33%, 35%, 39% and 41% for each angle. Case c reached a maximum sDA of 41% and apparently is the wing that takes more space of the building in order to be splayed. If all the wings are combined, the daylight scenario proved to advance sharply in relation to the changes in one wing only, even though it is important to consider that this option takes a higher effort to be implemented. A 20° angle was not feasible on the abc option, because it would not leave any available space on floors 10th and 11th.

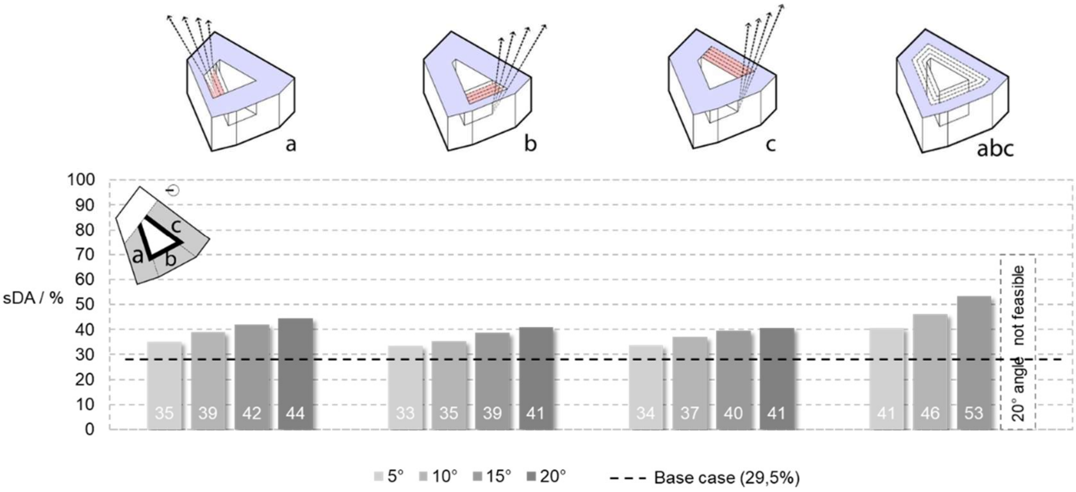

Figure 19: sDA for cases a to abc.

The first splay in case abc reached the same sDA value as the 20° splay in modifications b and c. Finally, the 15° splay accomplished a steep degree of natural light, with an sDA of 53%. Changes b and c correlate, as they show rather similar results. By splaying wing c though, the geometric features of the atrium change drastically and give a preferred and exceptional sense of higher quality for the occupants who sit in the AR. Option a demonstrated to be the best wing performer by fulfilling an sDA of 44% against the initial 29,5%.

The advantage of these new geometries is the establishment of an alluring atrium outline from the inside. Furthermore, the wall area along the atrium also increase, which consequently provides more spaces with a view to the outside, and most importantly with daylight. Bearing that in mind, the sunlight harvesting is a unique advantage of wing a. By decreasing the PAR in each floor, the light admitting area will increase, leading therefore to a drop on the WI.

5.2.1.2 Area of DF above 1%

Figure 20 displays the grid area with a DF above 1% as a function of the area losses. Each point on the graph corresponds to one modification step, that vary from the suppression of two to eight floors. The grid area is the sum of the values in the eleven floors. The area losses and gains are presented in relative values in relation to the original total floor area.

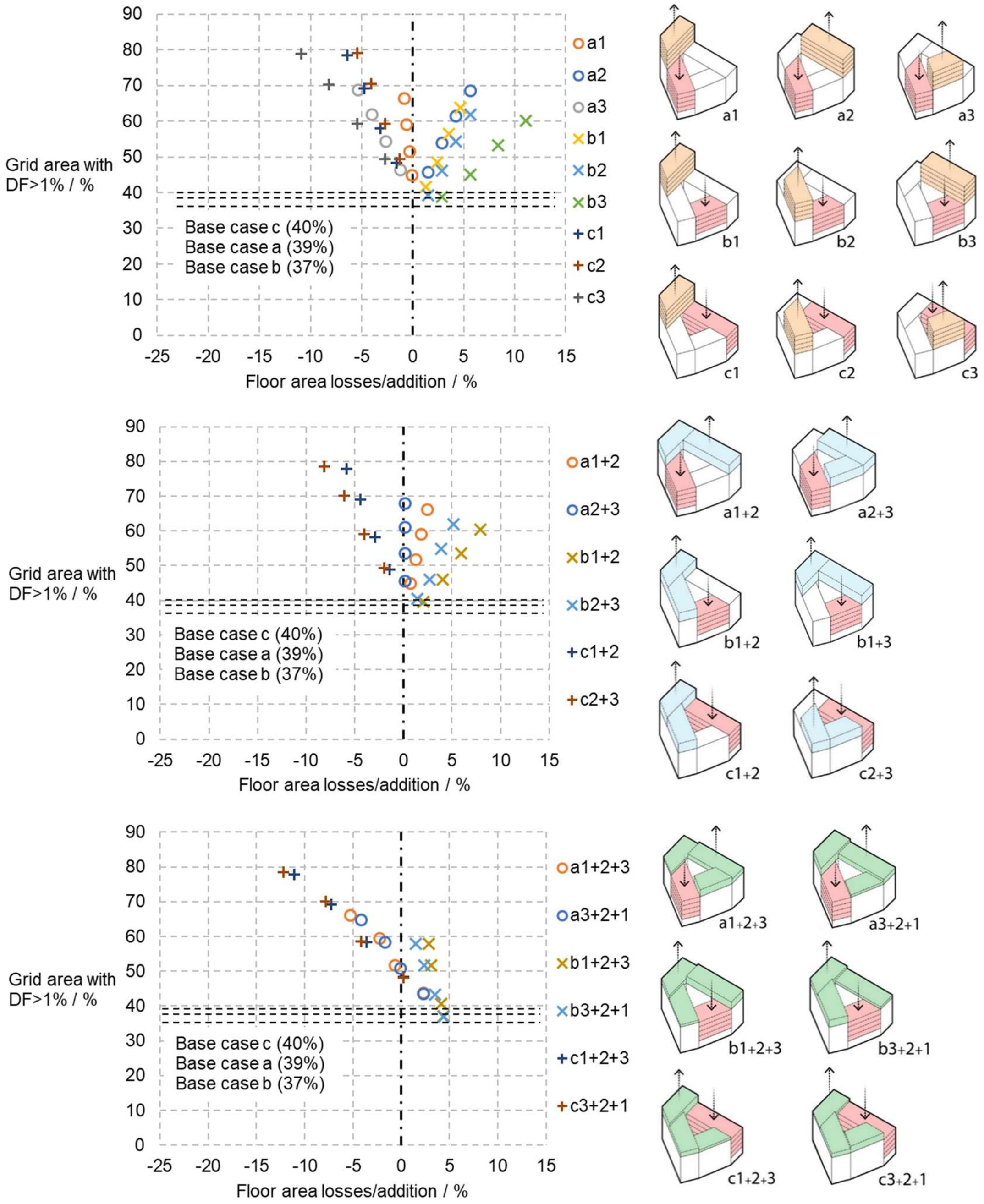

Figure 20: DF area and area losses/gains for the wing suppression arrangements.

The daylight factor is a well stablished metric and provides a good idea whether a given space has a potential to fetch daylight under overcast sky conditions. Although it does not take into account local climate factors, it is widely used by certification systems, such as Miljöbyggnad and BREEAM, as well as by some regulations, especially the BBR. As a consequence, this investigation has chosen to demonstrate the percentage of grid area that is achieving a DF above 1% due to the size of the study, which is considering a large amount of area, and due to the fact that this data is more comprehensive for this scale, as the whole building is being analyzed. Besides, the main goal is to compare the difference between the shapes and evaluate which could be more cost effective and improve the daylight conditions in the AR at the same time.

It is interesting to observe that group a is split into three different directions concerning area losses and additions. In terms of cost effectiveness, a3 lost approximately 5% of the project floor area to achieve the same DF results as case a2, which on the contrary, had an area gain of 5%. Considering the CBRE report for the last quarter of 2017, this addition could represent a potential leasing value of nearly 8,3 million SEK per year. Case a1 had the worst performance among the three, however the area losses were not so significant. It achieved a peak of 67% of DF area above 1% and a total area subtraction of 1%.

The area of DF above 1% in option b1 went up from 37% to 64% and had its area increased to 5% in relation to the base case. On the other hand, b3 demonstrated an enormous increase of 11% in the potential leasing area but did not perform as good as b1 in area of DF above 1%. The wing that is being added on this case is the largest, however it blocks most of the sky view from the opposite AR. The AR in group c were the ones that were affected the most, thus having the highest area of DF above 1%. The three cases within this family displayed nearly the same increase on DF values if compared to the base case, that ranged from 50% to 79%. Conversely, the area losses were large, particularly in option c3, where the area deficit reached 11% of the original floor area. This situation could represent a profit loss of approximately 18,3 million SEK per year.

The area of DF above 1% in cases a1+2 and a2+3 increased steadily, despite its similarities. The second one though, has neither lost, nor gained area. As a consequence of wing b having the smallest floor area, there is usually a leasing space surplus regardless of the volume arrangement to compensate its suppression. Yet, the escalation on the DF area above 1% is not as satisfying as in group a, for instance. Alternative b1+2 started with an area of DF above 1% of 40% and ended up at 61%. According to the chart, group c brought a great improvement in DF area in spite of its considerable floor space losses. Option c2+3 drastically increased the area of DF above 1% from 40% to 79%, almost doubling the base case value.

There is a downward trend for the counter and clockwise additions. As the area of DF above 1% increases, the area losses also increase, as in type c3+2+1, which reached an area loss of 12,5% of the original floor space. This percentage might represent a loss of nearly 19,9 million SEK per year. Concerning the area of DF above 1%, the last modification reached a value of 79%. Option b1+2+3 and b3+2+1 continued to have a rentable area surplus, but in these specific cases the volume diminishes whereas the DF area increases. On the last modification of type b1+2+3, the space loss tends to find an equilibrium with the original case by having an extra area of only 3%, yet it improved the area of DF above 1% from 37% to 58%.

Whilst presenting area losses of up to 5% in relation to the base case, the area of DF above 1% went up from 39% to 66% and 65% in types a1+2+3 and a3+2+1, respectively.

As for the volume alterations that concern the wing splaying, Figure 21 embraces the last stage of geometry modifications.

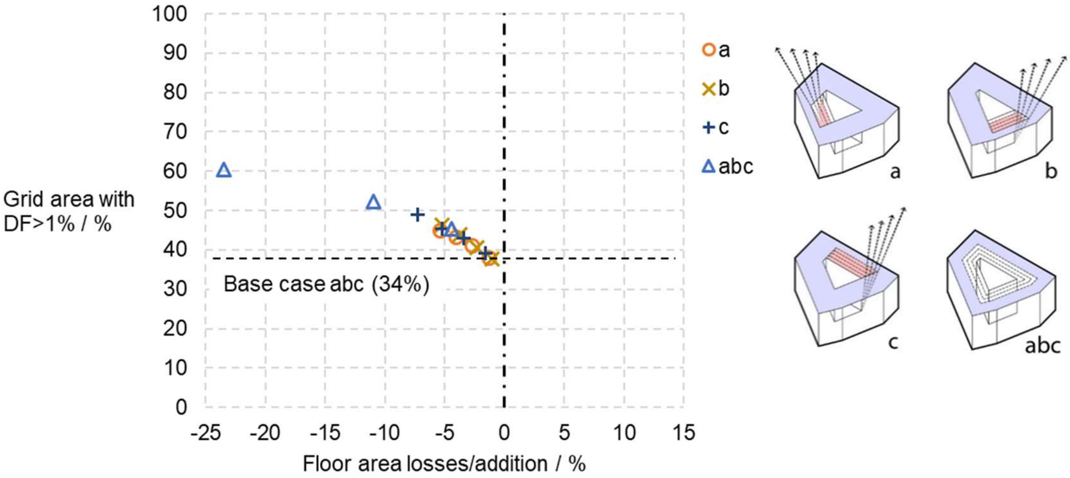

Figure 21: DF area and area losses/gains for the wall splaying options.

Although they do not offer any increase on the floor area, the idea was to test the potential of the stepped section and in what level they could boost the area of DF above 1% while splaying the walls in certain angles. Most importantly, a relation can be drawn between the families that work with wing suppression and the group that rely on the wall splay, showing their strengths and weaknesses. Whereas the grid remains constant in the past modifications, the angled volumetric alterations widely open the office area towards the atrium. Types a, b and c coincide to some extent in area losses. Case a presented an area of DF above 1% that increased from 38% to 45%, while losing a floor space that encompassed a range from 1% to 6% in relation to the base case.

Wing b demonstrated a great performance and peaked to an area of DF above 1% of 49%, whilst presenting a deficit floor space of 7% for an angle of 20°. In this specific scenario, the AR were elongated towards southwest, hence decreasing the PAR step by step on each floor. This occurrence is in line with the studies conducted by Liu et al. (1991), where his findings showed lower PAR values improved the DF conditions in the AR. Nevertheless, this type of shape could unevenly distribute the illuminance across the space. Alteration c has the largest facing wall towards the atrium and can consequently take a great advantage of the homogenous illuminance from the north orientation without any need of shading devices. It also demonstrated to be the most efficient option in area of DF above 1%, as it presented a value of 49% value, but with an area loss of 7% if compared to the original shape.

The cases that combined all the wings in the effort to fetch daylight as much as possible achieved an area of DF above 1% of 46% by inclining the walls 5°. Unfortunately, the last splay of 15° sharply expanded the area losses to 24% of the base case floor area.

5.2.1.3 ADF, DF median and dynamic daylight metrics

Due to the large amount of data and the limitation of time, four cases were selected to be investigated in relation to how the improvements affected each floor. It was also interesting to examine the same impacts on the wall splaying options. By looking at Figure 22, it is possible to compare the results of each increasing step. The code “2f”, for instance, represents the number of floors that are being suppressed.

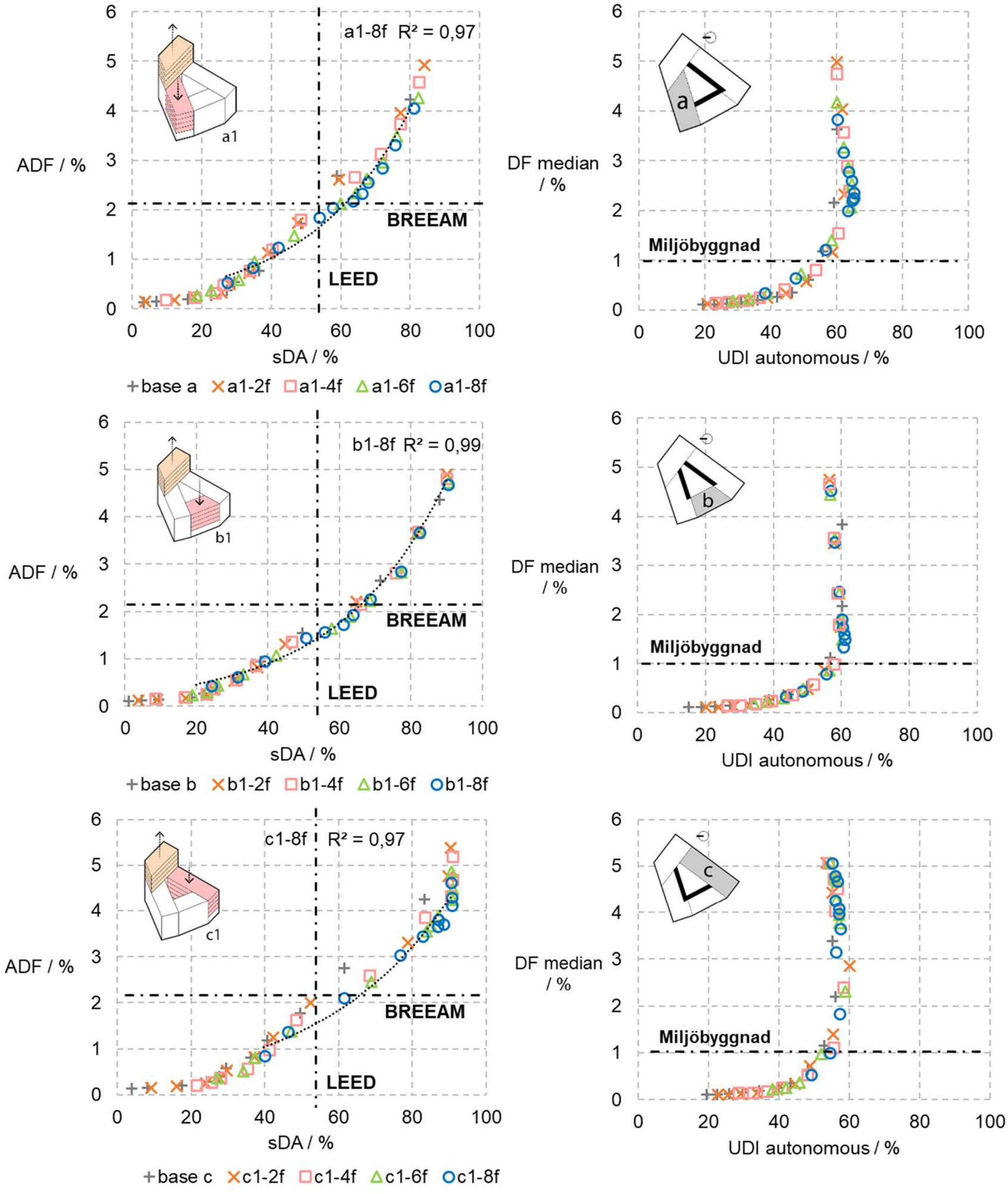

Figure 22: ADF, sDA, DF median and UDI autonomous for case a1, b1 and c1.

The points that lie on the upper right quarter on the graphs on the left are the floors that are complying with both BREEAM and LEED requirements. For the figures on the right, the threshold line for the DF median was placed at the 1% value, which is the minimum required for achieving Miljöbyggnad. As the floors on wing a are pulled down, the sDA and ADF started to increase at a steady rate. The highest numbers on the top floor for both metrics are reached when only two floors are suppressed.

As the number of floors decreased in case a, the tower increased in height, meaning that the sky view from the grid is being blocked. The ADF on the top floor decreased from 4,95% in modification a1-2f to 4,1% in modification a1-8f. On the other hand, most of the values for both metrics increased on the lower pavements as more floors on wing a were suppressed. This phenomenon can be noticed by a difference in the ADF between the sixth floor of a1-2f and the sixth floor of a1-8f that shifted from 0,75% to 2,2%, respectively. The a1-8f alteration brought six floors towards the first LEED requirement, whilst the base case had only two floors in compliance with the standard. Regarding the DF median and UDI autonomous evaluation, the base case had eight floors below the Miljöbyggnad threshold of 1%.

As the modifications took place, the number of floors with a higher DF median started to increase and reached a maximum value for the a1-8f alteration of 0,67%, 2,28% and 3,85% for the 2nd, 6th and 11th floors. Comparing to the base case values for the same floors, suppressing eight floors considerably increased the DF median in the lower and middle floors. As seen, the UDI for the base case follows a continuous upward trend until it peaks to approximately 59%. On the contrary, the a1-8f alternative shows a downward fashion towards the upper floors, a behavior that is aligned with the fact that the tower is serving as an obstacle, yet it does not compromise the UDI on the bottom floors.

In case b1, the situation differs from the preceding case in the sense that the modifications did not seem to affect drastically the daylight in the AR of the lower floors. A particular feature of alternative b1 is that the steep difference between some floors in relation to the ADF remains, such as the one between the 6th and 11th floors in modification b1-4f, with values of 0,88% and 4,82%, respectively. Nevertheless, as the floors on wing b were being removed, the middle floors on b1-8f responded with an increase on the daylight quantity and showed sDA values that ranged from 60% to 87% from the 6th floor up. In relation to the UDI metric, the maximum values were achieved in modification b1-8f, especially in the floors below the top ones. It can be speculated that some of the illuminance values could be falling on the UDI exceeded range. Regardless of the option, the UDI follows the same trend and decreases in a small scale before it reaches the upper most floor. This can be confirmed by the similar values between b1-2f, b1-4f, b1-6f and b1-8f on the 9th floor which are 59,3%, 58,4%, 58,8% and 58,8%. The base case had only three floors complying with a DF median of 1%, while b1-8f increased the number to eight.

Case c1 outperformed the anterior choices visibly, not only in ADF terms, but also in sDA and UDI. As the modifications were taking place, the values increased steeply, which can be illustrated by the bottom floor sDA of case c1-2f, that showed a value of 8,8%, against the bottom floor of case c1-8f that displayed an sDA of 39,6%. The ADF also increased significantly between the two alterations, from 0,18% to 0,86%. The trend of having lower ADF values on the upper stories as the tower is erected remains and it demonstrates that the volume that is being built to compensate the area losses does impact the daylight performance to some extent.

Step c1-6f, scored eight floors over the Miljöbyggnad requirement, while c1-8f scored almost the totality, leaving just one floor behind. The UDI autonomous peaked at 54,7% for most of the steps, which is relatively lower if compared to a1. Lastly, the UDI shows a uniformity among the majority of the upper floors for the last step (c1-8f), meaning that most of the times during the year, the illumination levels fall between 100 and 2000 lux and indicate that no electrical lighting is needed during the occupied hours.

As for the angle modifications, the results from each wing for the 15° splay and their combinations were merged into Figure 23.

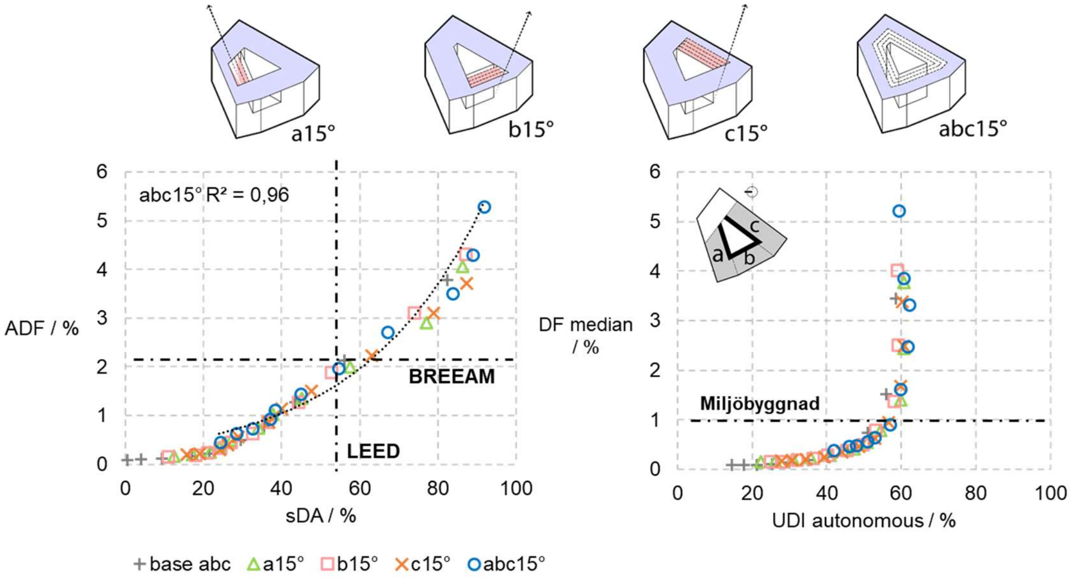

Figure 23: ADF, sDA, DF median and UDI autonomous from cases a to abc.

According to the sDA and DF area analyses, the combination and inclination of the walls along the atrium perimeter presented a great result, nonetheless the floor area losses were also significant. According to the chart that plotted the eleven floor values, the performance of case abc15° outworked the one wing splays by placing four stories on the upper right quarter on the left chart. The ADF in the 7th floor sky rocketed to 2% against 0,51% from the base case. The major contrast between the one wing splay options and the abc cases is that the bottom floors are also benefited if the whole perimeter is inclined. This phenomenon can be clearly observed in the chart, if one considers the higher ADF and sDA values of the lower floors of case abc15°. Almost half of the floors on abc15° had complying DF median values.

Option c15° leads the growth trend in sDA, except on the top floor. It is clear that by inclining wing c, the sky view is opening towards the southeast orientation, thus benefiting directly the rooms across and adjacent to that inner facade because of the sunlight access. The ADF is also greater in most of the cases. Looking at the UDI autonomous, the options presented a similar behavior for most of the floors and if compared to the base case, the numbers on the first floors increased dramatically.

5.2.2 Effect of light reflectance

For this specific thesis project, the aim was to study the potential of the reflectance values keeping the same WWR of 40% along the whole inner facade and compare these plans with the changes made on the geometry. For the present case, five diverse LRV were tested 1) 30% 2) 40% 3) 50% 4) 60% and 5) 70%. The second option is already adopted by the base case.

5.2.2.1 sDA and area of DF above 1%

The wall reflectance values were analyzed in the four base cases, so they could be compared with the geometry modification approach. The results shown in Figure 24 reveal a gradual but effective impact of higher LRV.

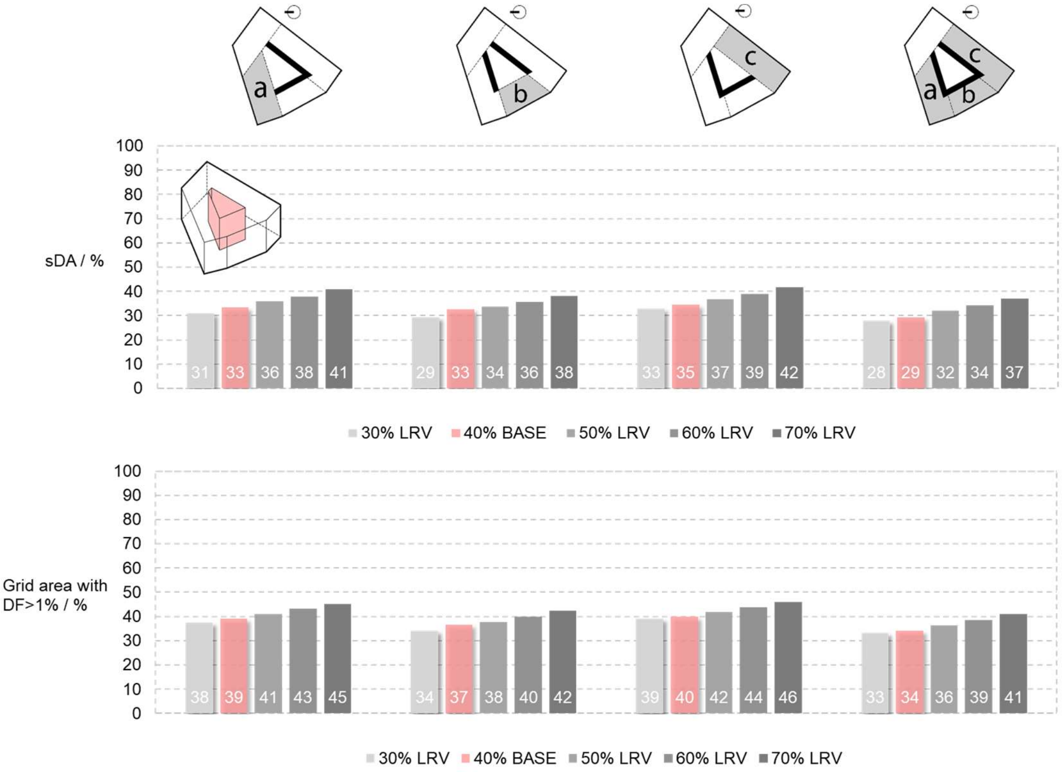

Figure 24: sDA for LRV cases.

By increasing the surface reflectance from 30% to 70%, an overall sDA increase from 33% to 42% could be reached in case c. The results among the four base cases vary without no notable divergences and follow the same upward trend. Base case c presented a slightly higher number. This combination of grids seems to be the most beneficial between the four, as both have a preferred cardinal orientation. However, case abc is the realistic approach, since the whole perimeter will be affected by the LRV, as the building structure remains originally the same. Looking closer into case abc, the sDA increased in a slow pace if compared with the massive effects caused by the volumetric changes. A material that could potentially contribute with a LRV of 70%, would increase the spatial daylight autonomy from 30% to 37%.

The area of DF above 1% was also analyzed for the LRV modifications, but since there was no area losses or gains, the main objective was to assess this strategy under a uniform overcast sky. The behavior of the enhancements coincides with the sDA evaluation and show the same upward trend among the different base cases. Type c is the one which shows the maximum area of DF above 1%, with 46%, whereas the combination of rooms abc underperformed by reaching its highest improvement with a value of 41%. According to the chart, it is apparently beneficial to locate office rooms along the perimeter suggested by type c, as it presented an area of DF above 1% that was higher than type abc. Option b, where the rooms analyzed are situated across each other, displayed the second lowest performance.

5.2.2.2 ADF, DF median and dynamic daylight metrics

Lastly, case abc was chosen to be further investigated when it comes to the daylight metrics in each floor, as it is composed of a group of grids that correspond to office rooms along the atrium perimeter. Figure 25 presents the evaluation of each floor and how the average daylight factor, sDA and DF median increase according to the enhancement on the wall LRV.

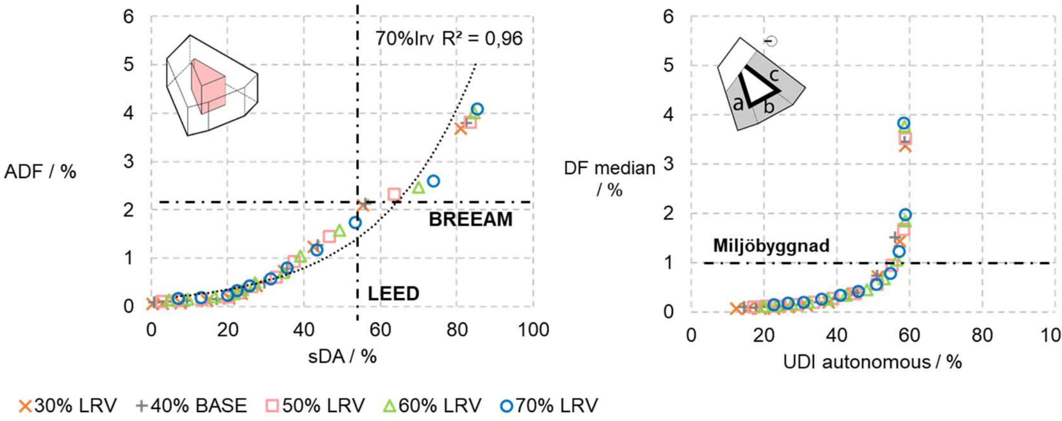

Figure 25: ADF, sDA, DF median and UDI autonomous for LRV cases.

Looking at the ADF at the bottom floor, the value stepped from 0,09% to 0,19%, but it took a LRV 40% higher to be able to raise it to that level. Despite the higher sky component influence on the top floors, these floors showed to be also sensible to LRV changes. The ADF on the upper rooms jumped from 3,71% with a LRV of 30% to 4,12% with a LRV of 70%. It can be also noticed that the reflectance values are most influential on the bottom floors, since these changes doubled the ADF on the AR.

The DF median shows the same fashion, where the highest floor has considerably higher values in relation to the 10th floor. Only the 60% and 70% LRV are able to push three floors towards the Miljöbyggnad achievement. As for the UDI autonomous, the digits tend to increase homogenously. The 11th floor showed a low difference in the UDI metric for different LRV, while the uppermost divergence was felt on the second floor, which the LRV of 30% reached an UDI of 15% and the LRV of 70% reached an UDI of 26%.

6 Discussion

This thesis aimed to evaluate the current daylight conditions of the building, as well as to propose changes to improve the natural light scenario in the AR. The discussion chapter was divided according to the results sections to facilitate their comprehension. As discussed before, the metrics chosen for this investigation are in line with the Swedish regulations and some of the most widely adopted certification systems in the construction sector. In order to answer to the two questions that guided this investigation, the parametric studies were concentrated in the geometry and LRV effects. As mentioned in the literature review, these were the most influential parameters affecting the atria studied. Most importantly, the split of the building into different wings was a product of the current design, so the proposals could offer a variety of forms to still keep the architectural dialogue with the surroundings, while improving the daylighting conditions of the building.

6.1 Base cases

The daylight assessment of the base cases consisted of adopting a perimeter grid along the atrium in four different ways according to each base case. Since the main objective was to study the influence of the building geometry on the daylighting in the perimeter offices, the original windows located on the outer building envelope were not considered. On the other hand, the original side fenestrations could be inserted for future studies to verify how the side lighting conditions could further improve the daylight conditions. Some of the LRV may also differ from the original project. However, the base cases analyses lay the ground for the parametric studies, so the results can be comparable. Consequently, this investigation lies on the relation of a specific atrium assessment and its urban context. This is useful for taking early decisions and guide the project process at the beginning of the design stage.

Results for sDA showed that none of the base cases complied with the LEED certification system, as all the values were below 55% for the grids analyzed. Moreover, the base cases presented different values for both sDA and area of DF above 1%. These variations could not only be due to different grid combinations, but also to the internal configuration of the building, which is relatively complex. Base case b, that combined the largest grids, was the second worst performer. Base case c featured as the best performer. The average values were negatively affected on base case b, as the AR have a lower sky view angle on the lower floors, especially when the evaluation points reach the narrowest side of the atrium. This phenomenon was previously discussed in the literature view, where it was pointed out that the DF values in the corner of rectangular atria are usually lower. The combination of the three grids for base case abc, which is the scenario that probably resembles reality, since most of the office rooms are potentially located along the atrium perimeter, presented the worst results. The proportional daylit area is lower than the other base cases, which could be due to the number of corners presented in this particular grid combination.

The evaluation of each floor showed that only the two top floors were complying with the regulations and certification systems. Their ADF, DF median, sDA and UDI were steeply increasing towards the top floors due to an open sky view angle. The analyses of the base cases also show that the current atrium configuration provides a great lack of daylight uniformity among the floors.

6.2 Parametric study

The parametric studies were divided into changes on the geometry and the LRV of the inner atrium facades. The following chapters discuss the main outcomes of the investigation. Figure 26 shows all the parameters investigated and their respective AR grids.

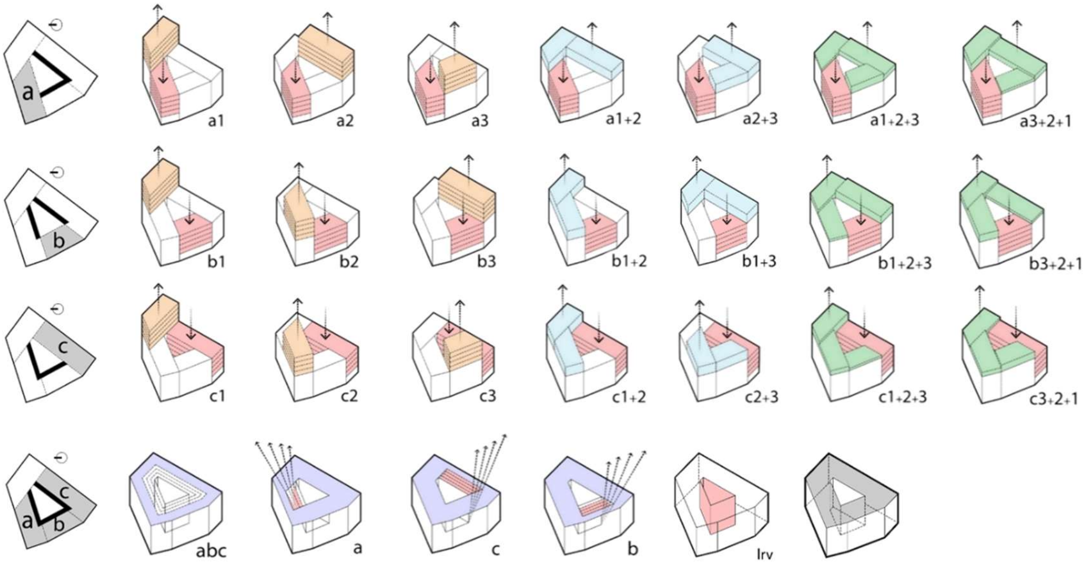

Figure 26: Geometry and LRV modifications.

6.2.1 Effect of geometry

According to the simulations carried out in this thesis, the geometry proved to significantly influence the daylight conditions in the AR. It can be generally observed that the sDA values dramatically increased as the number of floors were displaced in each wing (different geometries resulted in different outcomes). Option a2 performed worse than a1 while suppressing two floors, for instance. That reaction can be fairly understood since there is more mass surrounding the atrium than in the other cases and the tower that is being erected blocks the sunlight path on the south orientation. Option b3 faced the same problem, however this family of modifications presented lower results if compared to cases a and c. Most importantly, options b1 and b2 show that it is possible to increase the daylight penetration in different ways, as long as the atrium configuration shifts from an enclosed shape to a semi-enclosed one.

Surprisingly, the stepped height solution underperformed in relation to the tower cases. One could suggest that a higher tower resting over one wing could block a considerable portion of the sky, thus diminishing the potential of the grid to fetch daylight. On the contrary, the investigations demonstrated that distributing the volumes over the opposite and adjacent wings at the same time might represent a liability. If the tower is added in certain spots, it can probably help the light to penetrate on the rooms by contributing with its reflection. However, this would have to be further investigated in a more detailed study. It is confirmed that having only one higher volume resting over one wing is more beneficial than having more volumes added to the top of the free wings, even if they are shorter.

By drawing a relation between the tower cases and the other volume additions, one can see that the difference is small, yet the tower alternatives produced higher results. As mentioned before, surrounding the atrium again with a mass will produce the same effect of reducing the sky view angle, even though the height of the floors is distributed along the free wings. On the other hand, it is crucial that the tower is positioned in the right place, otherwise it might block the sky view and compromise the daylight performance in the AR. Looking at the big picture, regardless of the shape chosen, the increase on the natural light quantity is significant, especially on cases c, where the sDA increased from 34,5% to 76%.

Regarding the wall splaying options, there is no area compensation on these cases, as any addition on the top would most likely compromise the aesthetics of the initial proposal and create a conflict with the inclined walls. One of the advantages of the stepped section is the automatic creation of terraces in front of every wing that is being pushed inwards. The terraces can not only produce interesting places for social interaction, but also provide a reflective horizontal surface next to the office window.

To facilitate the comparison and understanding of how much area loss or gain each volumetric change is producing, the space changes were calculated as percentages in relation to the original building shape, so it was possible to draw an instant relation between area of DF above 1% and leasable area alterations. It is crucial to understand that the area of DF above 1% concerns only the perimeter of the atrium that is being analyzed, however the alterations to improve the daylight situation on the edifice take place in the whole volume.

Despite the substantial increase in area of DF above 1% in all c cases, they presented great area losses, since wing c has the largest floor space. Option a2+3 is an attractive choice, since the leasing area did not change. As previously mentioned, volume a2+3 offers no obstruction to the AR in the atrium, so it enhances their view to the sky, hence leading to a higher DF. Cases b1, b2 and b3 have all succeeded not only in elevating the DF area, but also in increasing the leasing area. In short, the b cases offered more advantage in terms of leasing space but lacked in terms of daylight quantity in comparison to the other alternatives.

Each floor was also evaluated for a1, b1, c1 and the wall splaying cases. It is clear that the daylight penetration does not reach a sufficient depth in the rooms in the b cases, as the wing that is being suppressed is located in their adjacencies and not across them. Consequently, the top floors remain with high levels of daylight and the lower ones show a slight increase as wing b is pulled down. On the other hand, the bottom floors evaluated in case c presented higher increase on their values. Although the LEED threshold of 75% is not drawn in the chart, it is possible to see that a great portion of the c1-8f points lie on the right side of it, meaning that most of them can even achieve three points in the certification. Conversely, the DF median values are high enough on the top floors to be considered satisfactory.

The simulations indicated that this option had higher values for the UDI exceeded metric, thus demonstrating that a shading system in this case would be valuable to avoid overheating, as the facades are fully exposed to the south and southeast directions. Lastly, splaying all the inner atrium walls together amplified the sky view from the AR, which can be confirmed since most of the floors on option abc15° indicated a growing uniformity between their DF median.

Overall, the original volume is rather complex, but it offers a number of possible combinations that can be interesting in terms of architectural design, as well as in terms of daylight for the occupied spaces along the atrium perimeter. The WI cannot be fully related to the modifications, as it considers atria that have regular shapes such as rectangular and square geometries. Even so, the results prove that it is possible to combine different heights and achieve exceptional outcomes in terms of daylight quantity.

6.2.2 Effect of light reflectance

Different LRV were also evaluated in the simulations. The light reflectance value is especially important in enclosed atria as it can improve uniformity in the AR and elevate the daylight levels at the bottom floors and ground. However, its effect can be rather limited as it was proven the DF levels are extremely influenced by the sky component.

The LRV qualifies as an important strategy if there is no space for major changes in the design, but it strongly depends on the properties of the materials and on the WWR. As previously examined, the larger the WWR, the lesser the influence of the wall reflectance. This balance is slightly complicated, as bigger windows will open the sky view, but at the same time decrease the number of reflective surfaces towards the atrium. Some strategies have already been discussed in the literature review and suggested that the openings on the top floors could be smaller to avoid glare problems, while they could be larger on the bottom rooms. This approach would be able to direct more reflected light towards the bottom, where the big openings would be ready to collect more daylight effectively.

By just changing the LRV of the inner walls from 30% to 70%, the sDA increased from 33% to 41% in case abc. Although it is discernible that the values considerably increased, it is evident that this strategy used alone is not sufficient to raise the numbers towards a full compliance with standards and regulations. Moreover, the results showed a daylight imbalance between the floors, as the difference in the ADF at the bottom floor and the top floor is steep, for example.

There is also a potential strategy that lies on the combination of both high LRV and one of the geometry modifications. However, a more dedicated approach has to be carried out in order to find which volume alterations could enhance this compendium. For this investigation, the internal walls and floors were set with a LRV of 70% and 40%, respectively, representing most of the materials available in the market and widely applied in office buildings. LRV higher than 80% are hardly achievable for external cladding, given the fact that materials get dirty with time, so they were left out of this investigation. Nonetheless, these values can be increased if necessary and according to the specification of project.

7 Conclusions

This thesis investigated the current daylight conditions in the adjacent rooms of an atrium in an office building located in Gothenburg, Sweden. This building is located in a dense urban cluster. The simulations were guided by two main questions: 1) The parameters that could influence daylight conditions the most in the adjacent rooms, and 2) The atrium design that would best suit the study case. Firstly, the geometry was speculated as the most influential parameter, followed by the idea that the light reflectance values would have a limited impact on the AR. Considering the questions and hypotheses mentioned above, it could be concluded that:

- The actual atrium configuration does not allow daylight to penetrate properly into the adjacent rooms, as the atrium and the floor plans are deep;
- The current atrium configuration allows only the grids on the 10th and 11th floors to comply with BREEAM and LEED thresholds for daylight. As for Miljögyggnad, the top three floors managed to achieve the bronze category in the certification system;
- There is a great difference in the DF, sDA and UDI values among the eleven floors, which can be explained by the portion of the sky that is more visible from the top ones, while the bottom floors rely on the internally reflected component (IRC);
- The geometrical alterations proved to dramatically increase the daylight quantity in the AR, specially the cases from group c, that increased the sDA values from 34,5% to 77%;
- Cases c presented the best performance, confirming that opening the atrium towards the southeast orientation is the best strategy to increase the sDA. For these cases, all the tower positions resulted in the same daylight outcome in the AR;
- Cases b did not perform as well as the ones from groups a and c. The wing that is being suppressed lies adjacently to the investigated rooms, therefore the sky view across some of the rooms remained similar;
- By opening the wing towards the northwest in cases a, the sDA and area of DF above 1% were higher than in the volumetric changes from group b, proving that there is an enormous potential if daylight is fetched from the north orientation as well;
- The combination of wings and the counter/clockwise additions did not perform as well as the tower options. However, the differences were not significant, hence giving the architects flexibility in design options;
- The wing splaying options showed a lower performance in terms of daylight quantity if compared to the wing suppression cases, however they offered an interesting volumetric effect for the rooms located on the atrium perimeter;
- The area of DF above 1% as a function of the area losses were also analyzed and according to the results, the cases presented in the b family were the ones which gained the largest floor area, but showed the worst daylight performance;
- Conversely, the c types were the modifications which presented the highest area losses among the wing suppression cases. Option c3 lost up to 11% of the original floor area;

- Option a2+3 showed the best cost effectiveness while increasing the daylight quantity in the AR, as it kept the exact same floor area;
- Case abc displayed a great amount of area of DF above 1% while splaying all the wings at the same time, nonetheless the area losses represented 23% of the original floor space;
- Looking at the sDA and ADF per floor, it could be seen that the cases included in group a demonstrated a better daylight uniformity between floors, while the b cases had higher values at the top floors and the c cases presented great daylight uniformity conditions in most of the floors;
- Option c1 was the only one to score eight floors towards the BREEAM and LEED compliance, whereas leaving just one floor behind the achievement of the bronze category in Miljöbyggnad;
- An LRV increase from 30% to 70% escalated the sDA from 33% to 42% on case c. These results show the potential of this strategy, but rather limited if applied without any change in the geometry;
- A closer look into the LRV effect on each floor showed that the increase is relatively substantial on the bottom floors. On the other hand, they are not sufficient to allow the compliance with the regulations and some of the certification systems;
- Overall, pulling down wing c was the most effective strategy, as the sDA and area above DF 1% doubled.

General conclusions

- Atria with asymmetrical shape do not follow the well index equation, therefore it is more complicated to predict their behavior in terms of daylight performance;
- Researches, such as the one carried out by Saratsis et al. (2017), pointed out that building with different heights is more beneficial than creating an atrium or courtyard surrounded by walls with the same height. This thesis confirms the hypotheses presented by the authors' work, since it showed that a semi-enclosed atrium with different geometry configurations yielded better daylight conditions in the adjacent rooms;
- Opening the geometry towards different cardinal orientations can also increase the useful daylight illuminance. Opening an atrium towards the north direction is beneficial as the light coming from this orientation is uniform and no shading devices are needed. On the other hand, the south orientation can take advantage of the sunlight to increase the level of illuminance in an office building, even though a shading system is extremely important in this case to avoid overheating and glare;
- Changing the geometry in the early stages of design revealed to have a great impact on the daylight performance of the AR. Conversely, the LRV strategy may not be qualified as a primary approach in deep atria, since it does not have the potential to dramatically increase the natural light levels in the atrium perimeter rooms.

Future studies and limitations

This thesis project focused on finding an atrium optimum solution for the study case located in Gothenburg. The investigation was limited to the perimeter office rooms along the atrium 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 four. It is important to mention that a higher number of bounces would not only boost the uniformity, but also the DF values. Although it is known that not all the construction is valued for leasing purposes, all the area that is being lost or added was considered as an asset to be traded, because it simplified the calculations for this thesis project.

Investigations regarding the daylight quality in the AR could be further developed in future studies, as well as a proper shading system design for the AR that were exposed towards more daylight and sunlight in the upper floors. It would be also interesting to assess the energy demand and verify how the new atrium configurations would affect the thermal conditions in the AR. Most importantly, future investigations could also address the potential of the whole building area to comply with the Swedish regulations and the certifications systems mentioned in this thesis.

Summary

Atria has been implemented as an architectural feature since ancient times in order to provide an inner space that protects the building users from the outdoor climate, encourages interaction and brings a good level of daylight into the atrium itself and the adjacent rooms. Daylighting has proven to decrease the energy demand and the electrical lighting need of the buildings. However, the relation among the atrium shape, its walls reflectance values and the daylight quantity on the adjacent rooms follow a rather complex relation, that can be simplified by the wall index for square and rectangular atria.

The literature revealed that the geometry is the most influential characteristic for the daylight conditions both on the ground level and adjacent rooms. In addition, many authors have investigated different atrium types, which can be divided into enclosed, semi-enclosed, attached and linear. The studies showed that the deeper the atrium, the worse the daylight conditions on the adjacent rooms. However, this type of atrium might be a good strategy in warm climates, since less floors have access to direct solar radiation, thus demanding less cooling. Shallower atria are prone to receive more daylight, but their adjacent rooms are more exposed to the outdoor climate, which results in more heat losses in cold regions.

Contemporary buildings have been incorporated atria often in their design, but their projects rarely analyze how the atrium should be designed in order to take the best advantage of the climatic conditions to fetch as much daylight as possible. Therefore, this thesis aimed to investigate which parameters influenced the daylight conditions in the adjacent rooms of a triangular atrium of a building located in Gothenburg. The methodology proposed consisted of dividing the building into four different wings, so the geometrical modifications could be separated into different orientations. Different light reflectance values of the inner walls were tested in the original atrium shape. The evaluation was conducted only in the perimeter of the atrium and many different metrics such as daylight factor, daylight autonomy and useful daylight illuminance were utilized to measure the daylight improvements. Furthermore, the area losses and gains were also evaluated.

Results showed that suppressing the wings, regardless of the orientation, increased the daylight factor values, as most of the floors had their sky view angle substantially increased. The spatial daylight autonomy simulations also revealed that even with the presence of an urban obstacle in the southeast direction, the sunlight could substantially contribute to the increase on the daylight conditions in the adjacent rooms (AR). A diverse range of shapes were tested in order to compensate for the area losses when one of the wings were pulled down. The outcome of the investigation demonstrated that the daylight in the AR is slightly influenced by how the new shapes are built around the atrium, however the largest differences in the natural light conditions were felt depending on the orientation of the wing that was being suppressed. The light reflectance values (LRV) of the inner facades were also changed from 30% to 70%. The outcome of the simulations demonstrated that the LRV had a limited impact on the AR due to the height of the atrium. Nonetheless, this strategy could successfully increase the daylight situation in the AR if combined with an appropriate geometrical alteration.

Overall, pulling down the southeast oriented wing showed to be the most powerful strategy, not only to yield good daylight conditions in the AR, but also to comply with the regulations and some of the certification systems assessed in the thesis.

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Appendix A

ADF, DF median and dynamic daylight metrics for the remaining cases.

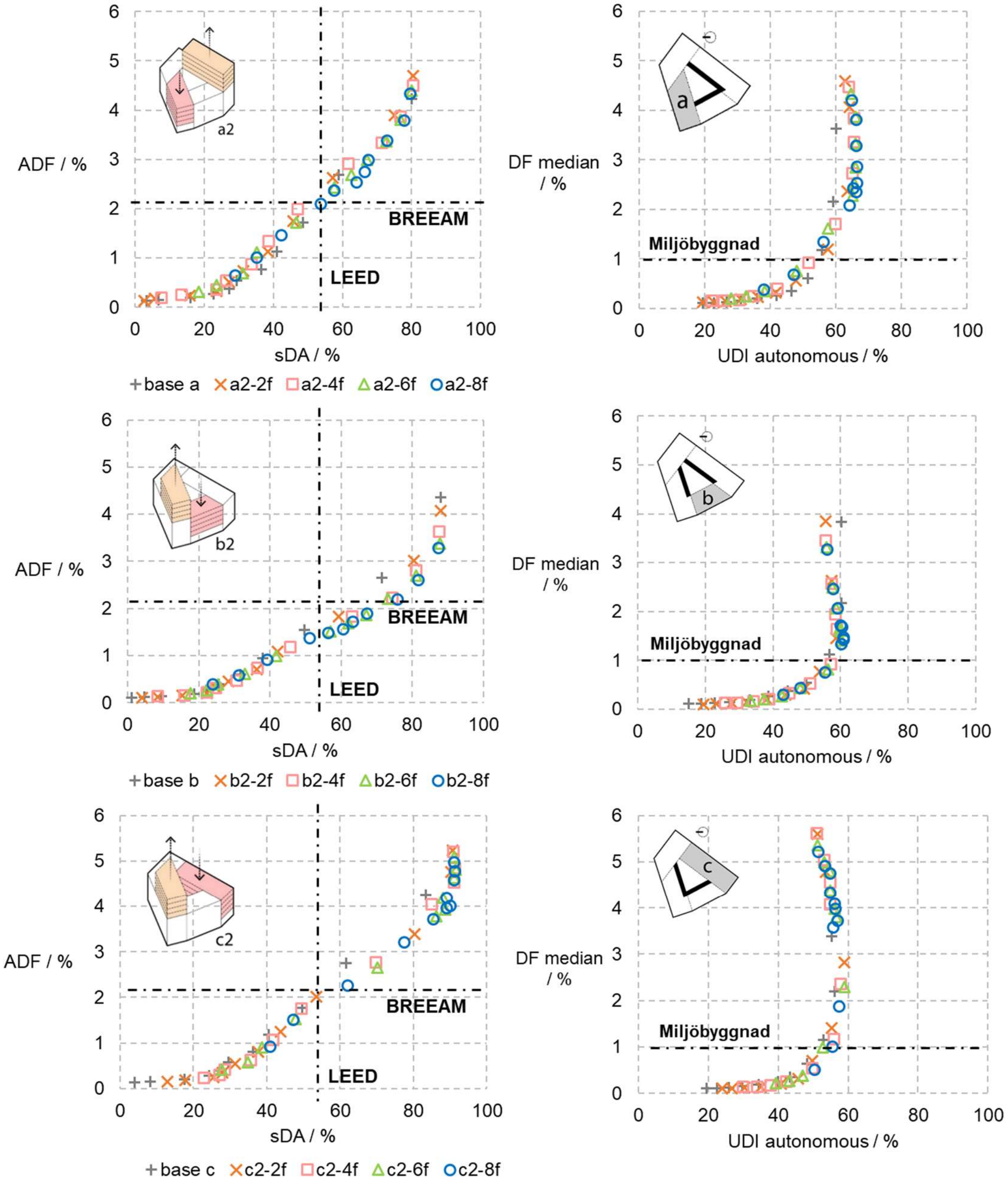

Figure A 1: ADF, sDA, DF median and UDI autonomous for cases a2, b2 and c2.

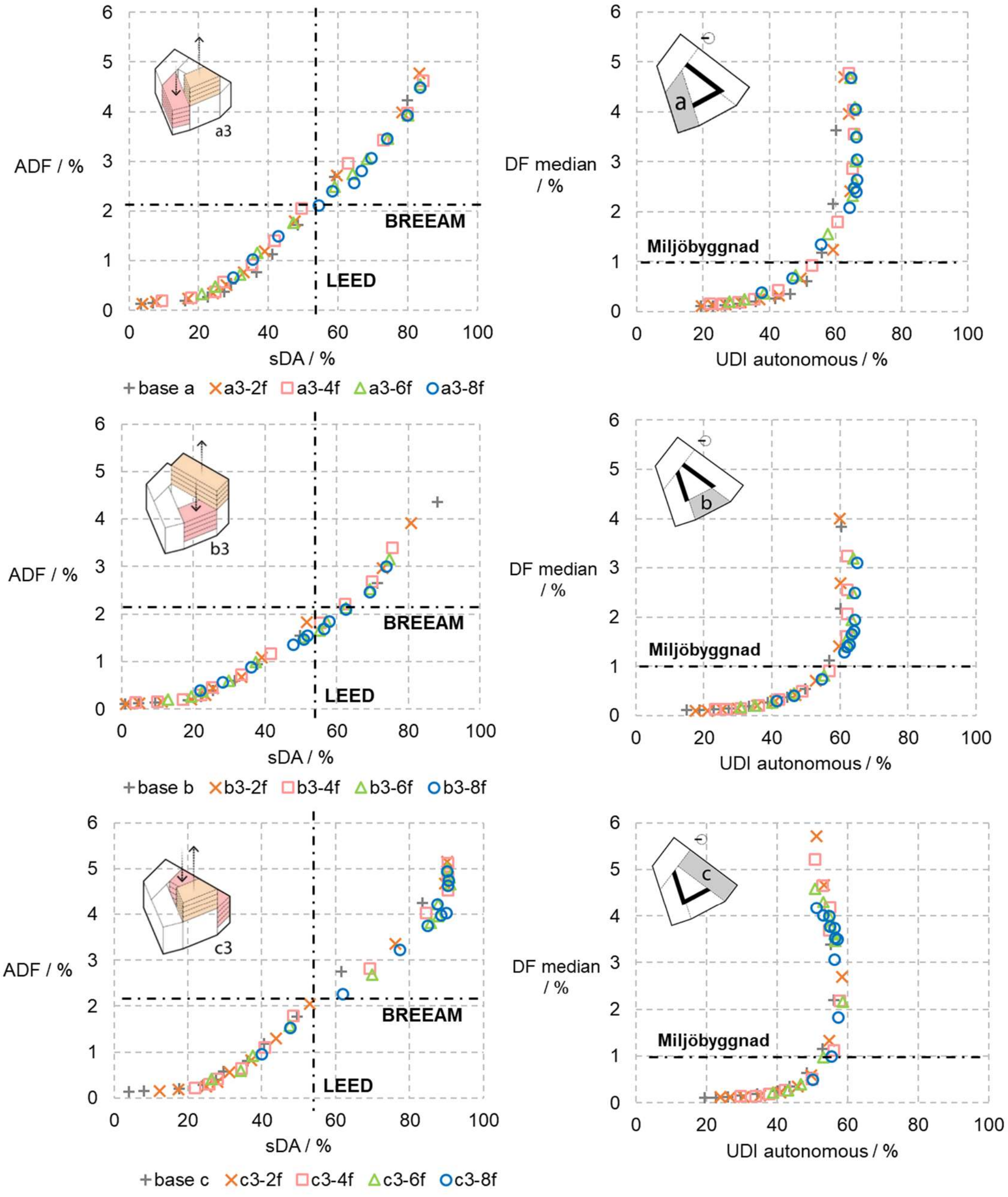

Figure A 2: ADF, sDA, DF median and UDI autonomous for cases a3, b3 and c3.

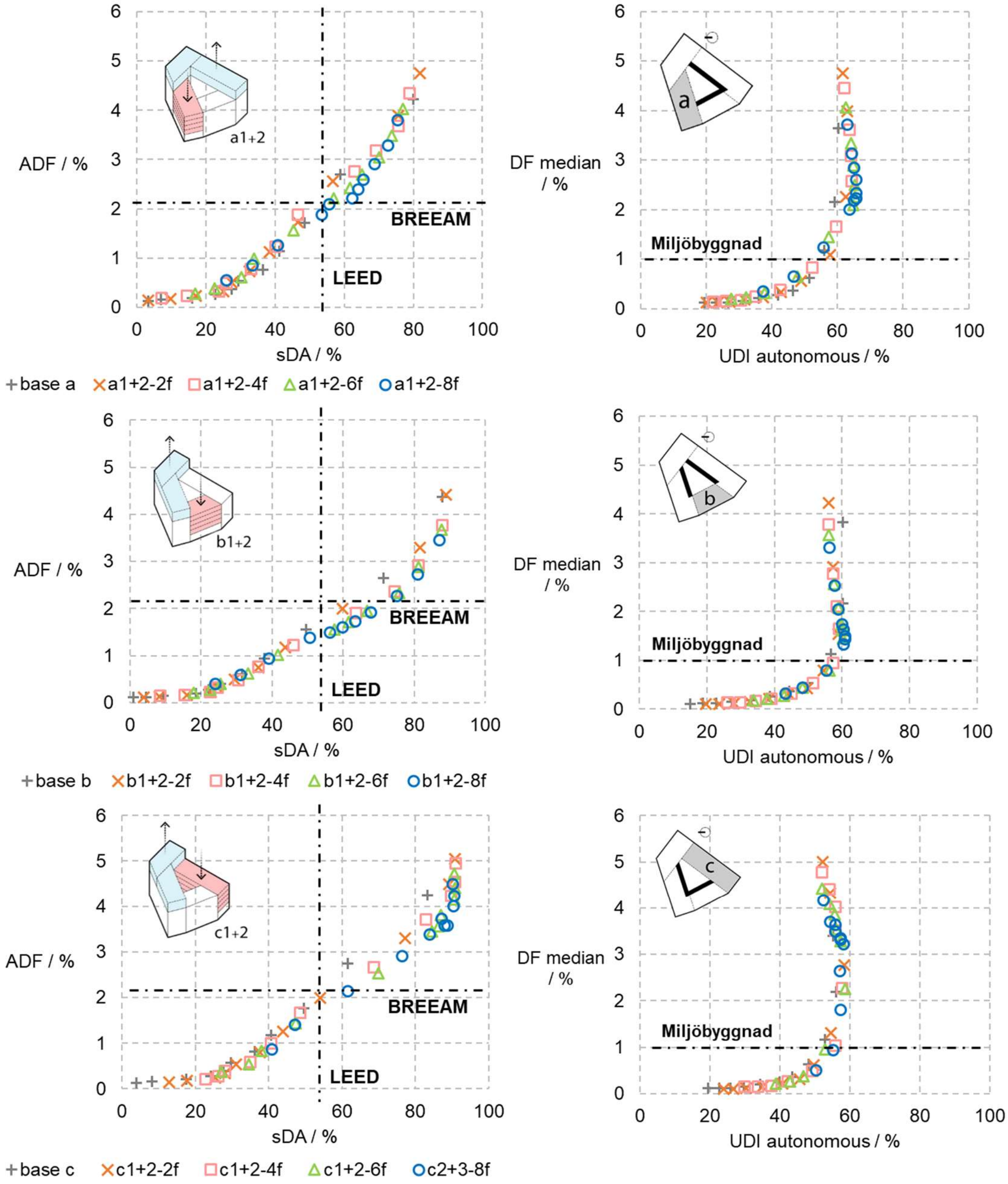

Figure A 3: ADF, sDA, DF median and UDI autonomous for cases a1+2, b1+2 and c1+2.

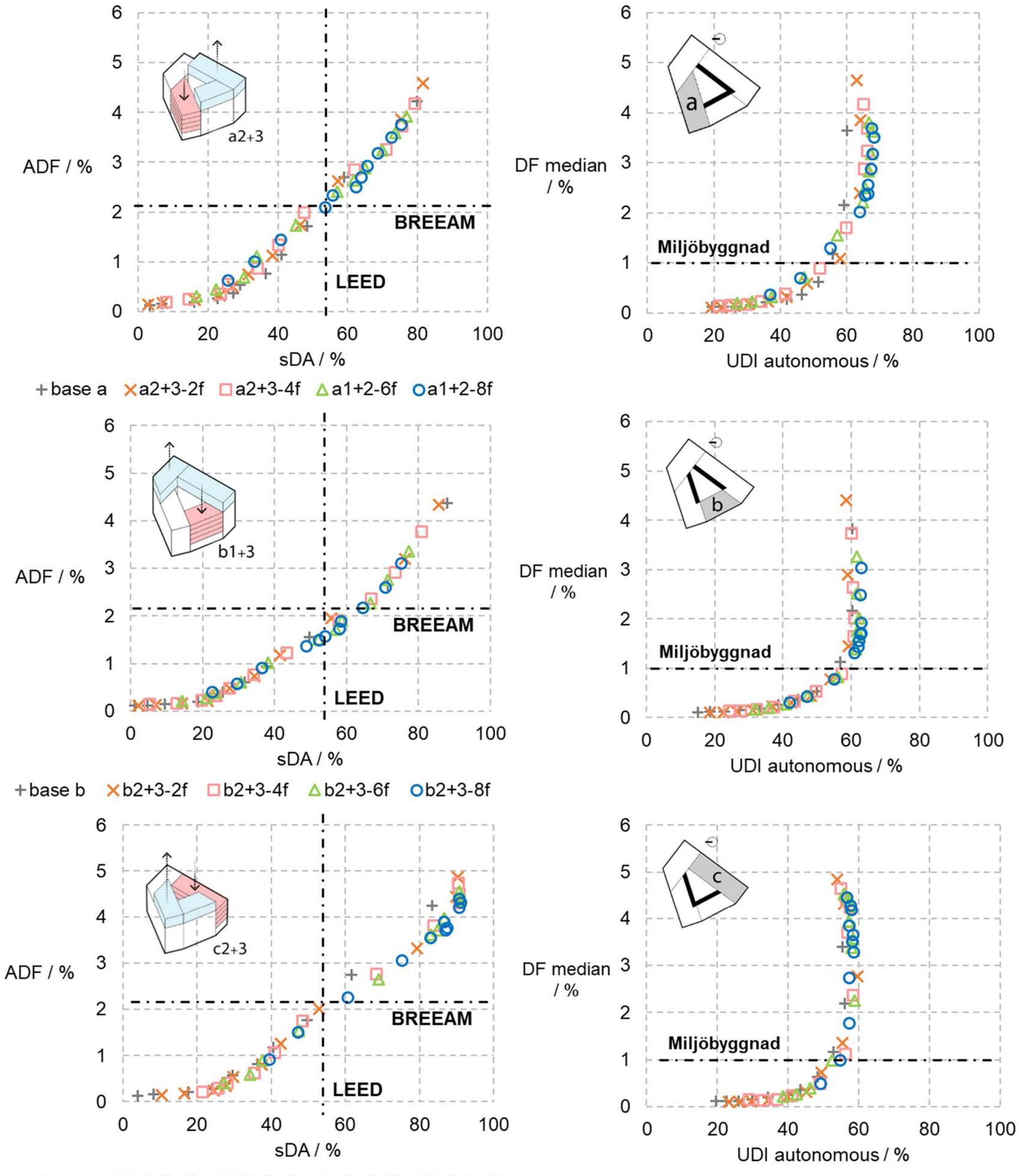

Figure A 4: ADF, sDA, DF median and UDI autonomous for case a2+3, b1+3 and c2+3.

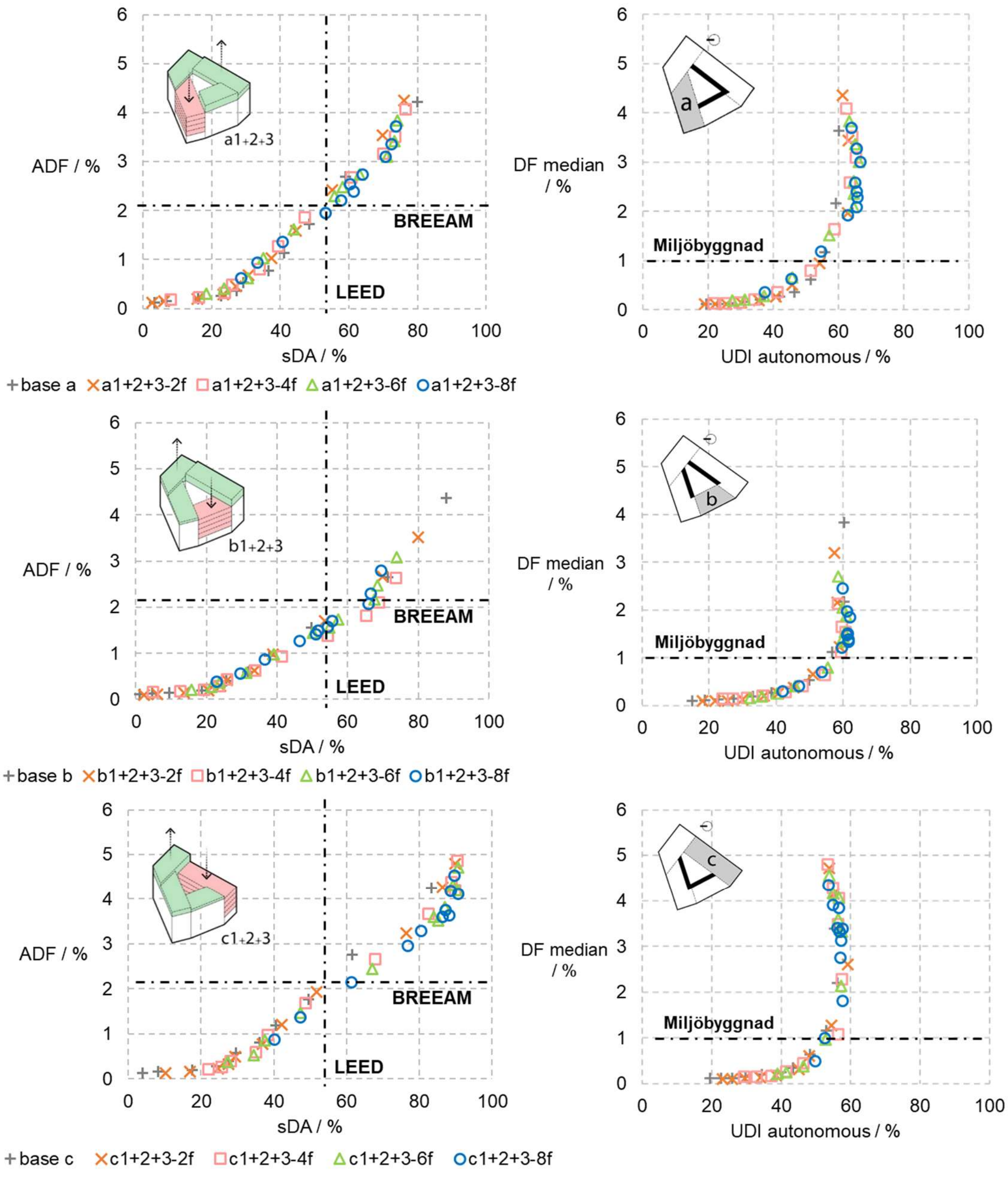

Figure A 5: ADF, sDA, DF median and UDI autonomous for cases a1+2+3, b1+2+3 and c1+2+3.

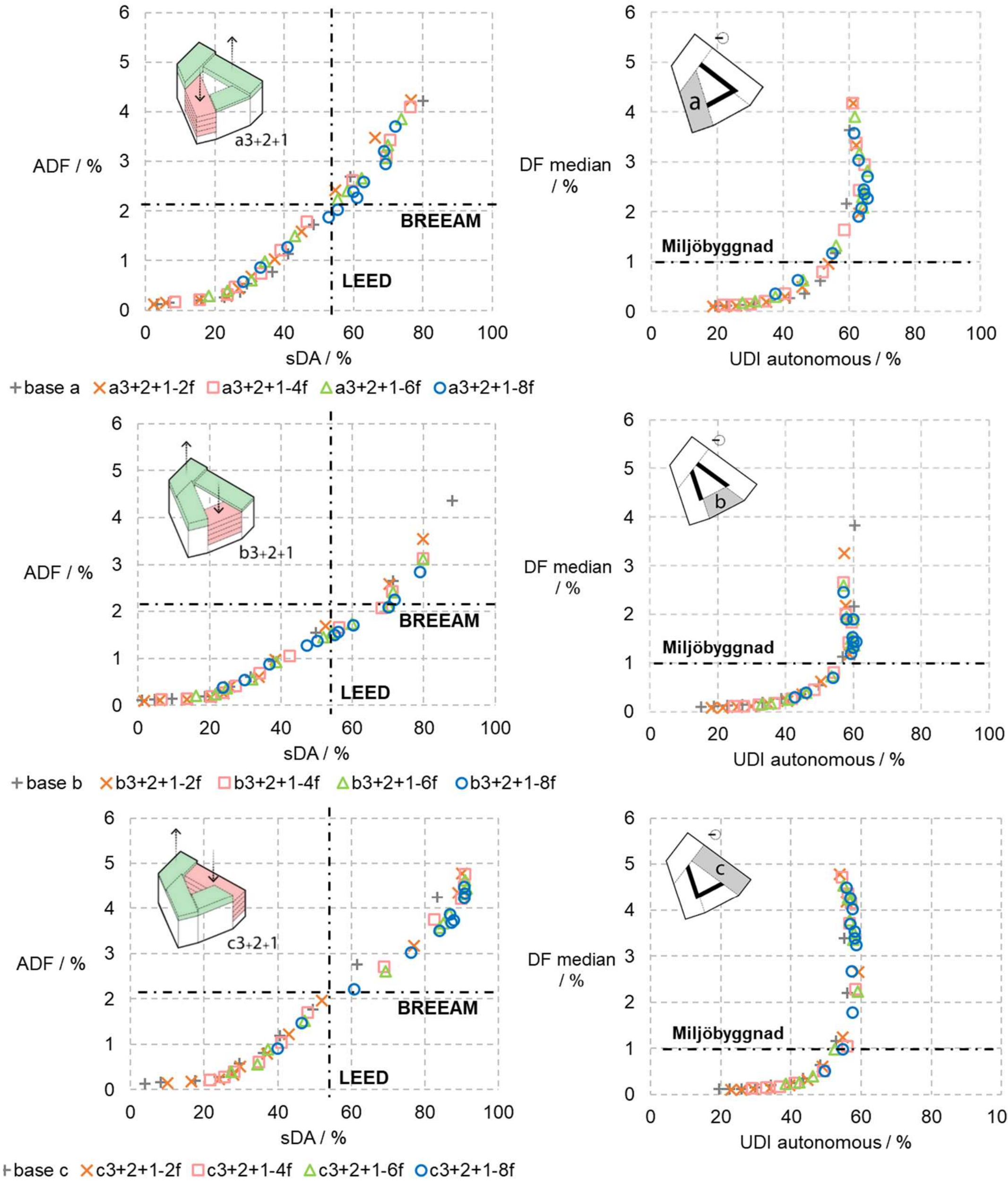

Figure A 6: ADF, sDA, DF median and UDI autonomous for cases a3+2+1, b3+2+1 and c3+2+1.

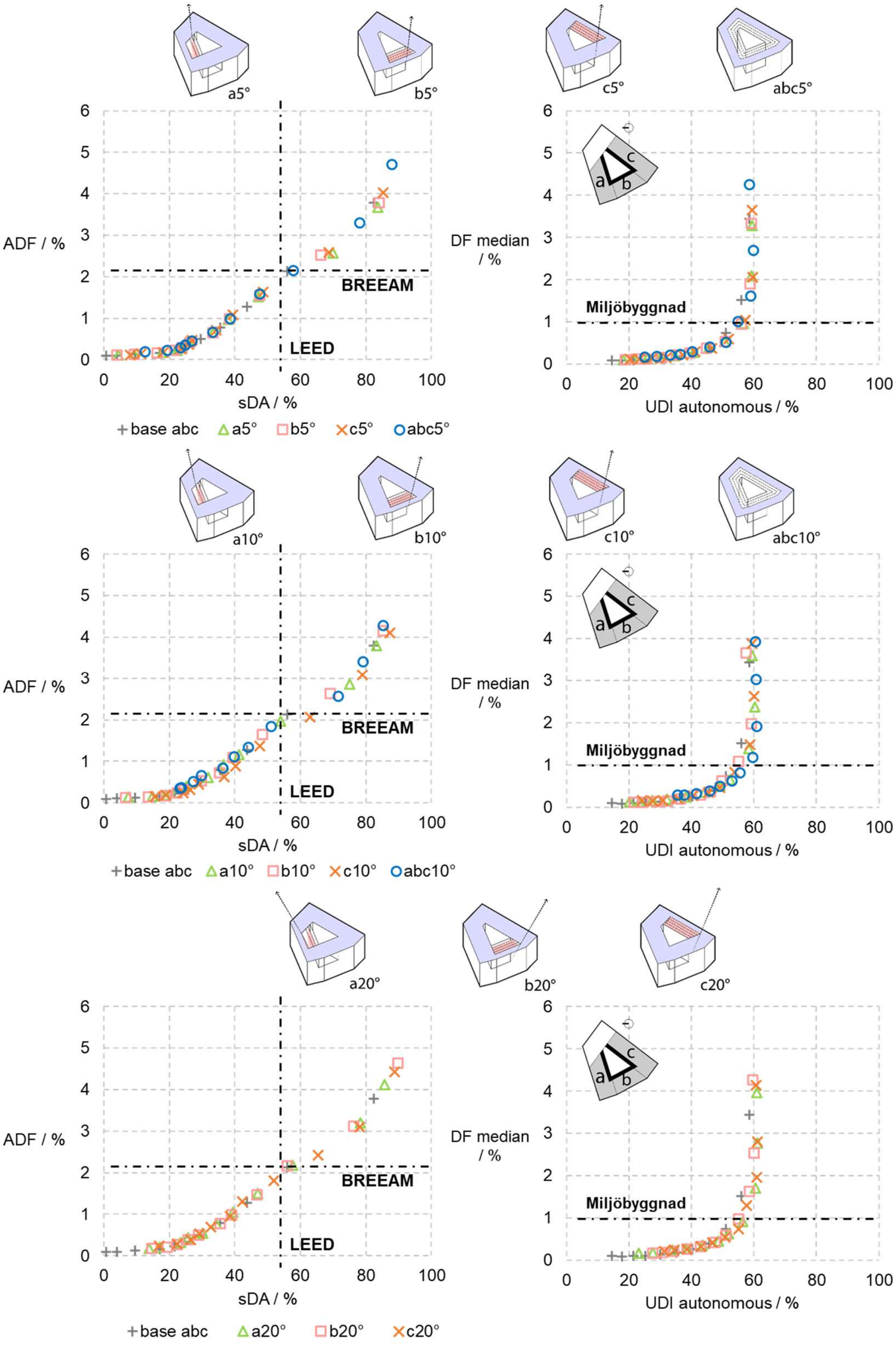

Figura A 7: ADF, sDA, DF median and UDI autonomous for cases a,b, c and abc..

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