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Evaluation and Optimization of Daylighting in Heritage Buildings: A Case-Study at High Latitudes

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Abstract: Transforming historical listed buildings into workplaces is a serious challenge, particularly for buildings with relatively small windows in the façades, which determine scarce daylighting indoors. This paper studied how daylighting can be significantly increased in a case-study historical building through rooflighting systems, as the façade cannot be modified. The case-study was a historic and iconic warehouse built-in 1681 in Trondheim, Norway. The optimized configuration was analyzed in terms of daylight amount and view analysis, according to EN 17037 and to LEED v4.1 protocol. A critical evaluation of the actual applicability of the optimized Scenario in the real building was carried out along with the constructors. A 3D model was built in Rhinoceros, and daylighting simulations of the base-case (the building in the existing configuration) and for 6 alternative Scenarios were run through Climate Studio. The following metrics were calculated: Daylight Factor (DF), Spatial Daylight Autonomy (sDA), Annual Sunlight Exposure (ASE), and views. An optimized configuration was eventually identified through the Galapagos component in Grasshopper, with an average DF value of 2.7% (against 0.9% in the base-case configuration), higher than the target DF_m of 2.4% for Norway), and a sDA value of 50.2% (14.2% in base-case configuration).

Keywords: daylight simulation; atrium; corelighting; heritage retrofit; historical building; indoor environmental quality; view analysis; Nordic latitude

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1. Introduction

Historic, listed, or unlisted buildings account for 30% of the European building stock [1]. Heritage is regarded as a highly precious wealth, and its preservation for future generations is a big challenge. Neglecting the heritage buildings may expose the heritage to further deterioration. Therefore, adaptive reuse of heritage buildings is considered favorable to their preservation. However, adapting heritage buildings to new users with new occupancy conditions is a challenging task, concerned with implementing the new functions while keeping the historical originality of the building with only minimal alterations and in a sustainable way [2]. This implies a demand for retrofit solutions able to improve indoor environmental conditions while reducing energy use and preserving heritage significance. Improving the energy performance of the building envelope, such as roofs, walls, or windows, requires a more comprehensive analysis to balance out built heritage conservation, technical compatibility, health and comfort of occupants, and energy efficiency [1]. Daylighting particularly plays a crucial role in this process: with the goal of improving the positive experience for the occupants, it is crucial to provide internal spaces that promote daylight conditions without sacrificing the identity of the place. Moreover, a suitable amount of natural light is beneficial to the health and productivity of the occupants, as it regulates the circadian entrainment of individuals [3].

Heritage building reuse has been widely studied in previous research [4–8], which mainly dealt with green retrofitting and energy conservation whilst only partly including comfort-oriented strategies for the occupants [9,10]. The International Energy Agency IEA set up a dedicated project within the SHC Task 59, titled "Renovating Historic Buildings Towards Zero Energy", which was active over the quadrennium 2017–2021 [11]. It was mainly aimed at preserving the historic and aesthetic value of heritage buildings while increasing comfort, lowering energy bills, and minimizing the environmental impact [12].

Consequently, the energy issues have received the highest attention, but the visual comfort of the occupants must be guaranteed as well, to assure the successful reuse of heritage buildings. In a heritage building, evolving the original quality of daylighting through the extensive use of electric light can critically impact the visual character and the sense of the place [13,14]. Research in this regard strongly emphasizes the intersection of cultural heritage preservation and environmental engineering to change building usage and improve indoor daylighting. Thus, adaptive heritage reuse is considered beneficial for the well-being of the occupants [15,16]. Furthermore, a high level of daylight sufficiency leads to lower operating expenses and reduces the energy demand for electric lighting while increasing the indoor environmental quality for the occupants. Issues about daylighting should be addressed in the early design phase [17]. However, it should be stressed on the other hand that heritage-listed buildings present strong constraints that limit the opportunity to modify the façade layout, for instance by increasing the window area. In this regard, rooflighting is a promising strategy to admit daylight into a building by opening skylights on the roof [18,19]. As an alternative, the use of atria, attractive architectural elements that allow corelighting to be achieved, thus admitting daylighting into the core of the building, could be considered.

Over the last 40 years, atria have become a quite recurring architectural form [20,21]. They were used in a range of modern building types worldwide, to create the experience of openness and spaciousness inside buildings. An atrium is typically a large, multi-story, glass-roofed space that brings daylight into large buildings where sidelighting alone cannot penetrate enough [22]. Besides daylighting, atria can also provide other practical functions for a building, such as allowing natural ventilation to help maintain thermal comfort [23] or acting as a buffer space to reduce energy losses.

Nowadays, the usability of atria is usually linked to commercial and public buildings as they are commonly used as significant architectural features to emphasize main entrances, increase the usability of public circulation spaces, or highlight specific destinations within a structure [24]. In fact, many large-scale buildings are presently designed with atria.

Successful daylighting design of an atrium mainly depends on (i) the roofs fenestration system; (ii) the geometry of the atrium, typically expressed through the Aspect Ratio (height-to-section ratio); (iii) window-to-wall ratio WWR all along the vertical section of the atrium (typically higher at lower floors and smaller at top floors); and (iv) light reflectance of the atrium surfaces. The daylight availability can be evaluated in terms of daylight illuminance levels achieved in the atrium and, even more, in terms of daylight illuminance levels in spaces facing the atrium [21]. This in turn is a function of the daylight availability at the location [25].

Modern buildings use highly-glazed atriums more frequently because they offer pleasant architectural aesthetics and daylight [26]. In a work on atrium building design, Calcagni & Paroncini [27] found that increasing light reflectance R_v values of atrium opaque surfaces in atria with large daylight openings and high light transmittance T_v does not generate a substantial improvement in the daylight factor levels on the atrium ground floor. Differently, Matusiak et al. [21] examined different strategies for improving daylighting in buildings with atria. They found that with the variation of glazing reflectance across the atrium according to its height, a significant increase in daylight reaching the bottom of the atrium. Younis et al. [28] found that the light from the sky and the light reflected off the atrium walls and floor are the essential components for daylighting in rooms adjacent to an atrium well. In a similar study, Matusiak [29] found that the mean reflectance of the atrium surfaces had a significant impact on the distribution of daylight in the atrium: increasing atrium floor reflectance was a very efficient approach for improving daylighting in first-floor rooms, as well as increasing façade reflectance influences lower-floor daylighting very moderately but were quite successful for daylighting at the upper floors. As the view angle to the direct sky is lower at the lower levels of an atrium, reflected light becomes the most important component. Therefore, high reflectivity ratings on opaque surfaces are a crucial factor.

Most research has been focused on the performances of side windows [30–33], rather than on rooflighting systems. Low sun angles are a feature of high latitude regions, where electric lighting is essential for both visual and thermal comfort and daylighting needs to be optimized [34,35]. A reasonable illuminance level able to contribute to an impression of daylight presence in building cores and rooms without vertical windows was found to be equal to 50 lux [36]. Office buildings use about 40% of their energy for electric lighting, but this rate becomes even higher for other building types, such as commercial or industrial [34]. Therefore, providing daylight is vital and needs to be noticed, especially in high latitudes (greater than 55°). Daylighting is a particularly challenging topic to address in Nordic countries, due to its peculiar typical characteristics: (i) low solar elevation angles are prevailing during the year: up to 1/3 of the whole daytime during the year solar rays are nearly horizontal; and (ii) the frequency of sunny skies during the year is quite low, especially in winter. As an example, Figure 1 reports a map of the Scandinavian area, taken from Satel-Light, where the frequency of sunny skies is shown: it can be observed that the occurrence of sunny days is less than 25% on annual basis in Norway [37].

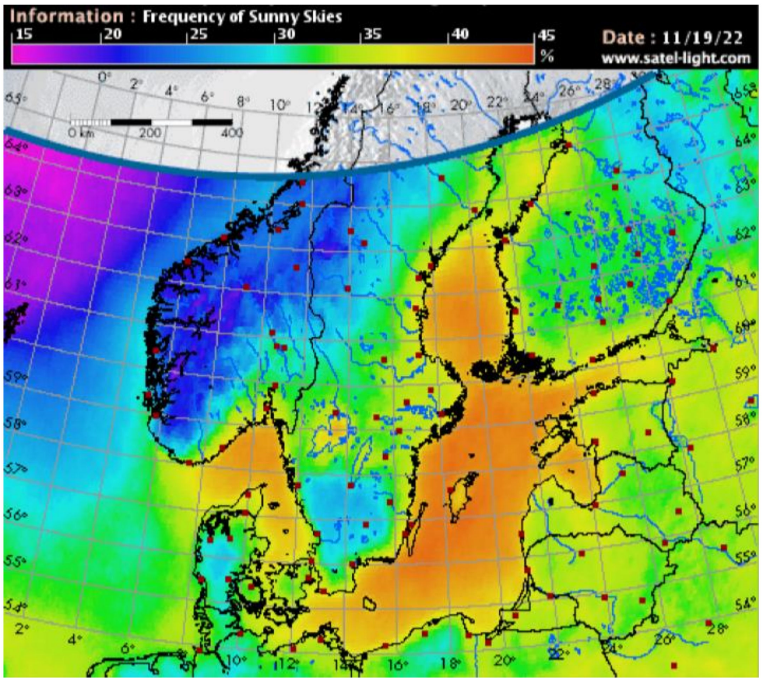


Figure 1. Frequency of sunny skies in Northern Europe (image taken from [37] with the permission of Barbara Matusiak).

In the retrofit process of existing buildings, additional elements are usually applied to windows to harvest, redirect, or even block the solar rays [38,39]. However, skylights make it possible to significantly increase daylighting without changing the visual character of the building since thy are hardly visible from the street level. The refurbishment of skylights in the NTNU university building (63° N) is an example showing how low sunlight can be both scattered and redirected down to the occupied room creating comfortable visual conditions with high daylight level during the year [37].

Within this context, this article focuses on how to improve daylighting in a heritage building through a specific case-study, which has poor daylighting conditions and presents strong constraints regarding the façades. Accordingly, the main research question was set as follows:

> *"How can it be possible to guarantee sufficient daylighting (according to international standards or protocols) in a heritage building located in a Nordic climate, where sidelighting cannot be incremented, so through corelighting?"*

To address this question, the study analyzed an existing building, located in Trondheim, Norway. Different alternatives of skylights and atria were explored to improve daylighting inside the building, quantifying its distribution into the adjacent areas (which are all dark in the original layout of the building), so as to find how daylighting conditions can be optimized since the early stage of the restoration process of historical buildings.

2. Materials and Methods

2.1. Case-Study

This research studied one of the oldest and biggest wharves, namely Huitfeldtbrygga, in Trondheim, Norway, at a latitude of 63.4° N and longitude of 10.4° E. Figure 2 shows the solar paths of Trondheim: it can be observed that at the winter solstice there are 4 h only of sunlight (from 11 until 14), with a maximum sun elevation angle as low as 3.35°. In the period from the 21st of December to the beginning of February, the sun elevation angle never reaches 10°; this value occurs for the first time on the 3rd of February. After this day, the number of hours when the sun is over 10° increases rapidly, but 30° sun elevation angle cannot be observed before the 30th of March.

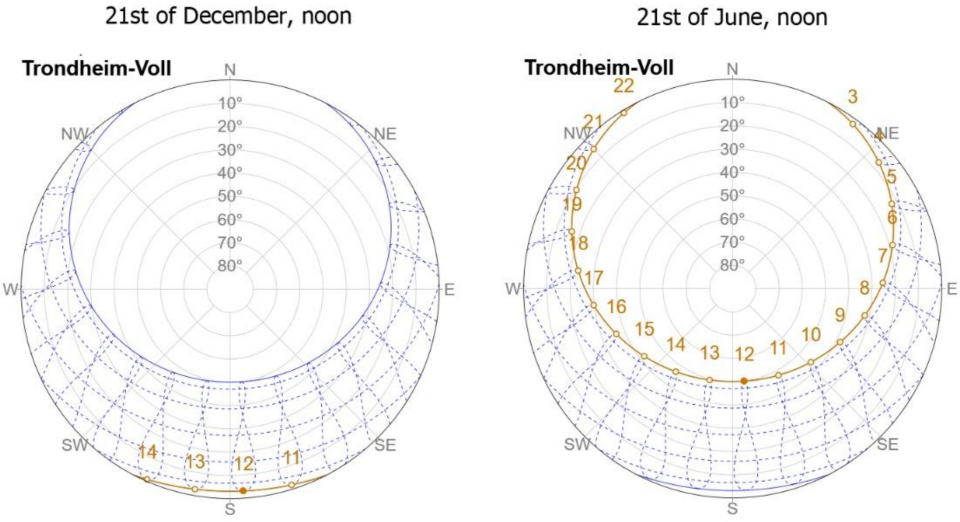


Figure 2. Solar paths for Trondheim.

In summer, the sunlight hours are 20 (from 3 until 22); the highest position of the sun is 50.1°, but this happens for only four days during the year, the 19th, 20th, 21st, and 22nd of June, and for a very short time: for instance, sun elevation angles higher than 50° lasts for 12 min only on 21st of June.

The Huitfeldtbrygga building strongly suffers from 40–50 years of lack of maintenance and use, and it is listed as a protection class A building, which indicates that it is regarded as one of Trondheim's most worthy of preservation. It is an outstanding building as it consists of three wharves built under the same roof, which also appears to be the most skewed one. The wharf has a total area of about 1900 m^2 and a very deep plan with small windows. Figure 3 shows some images of the case-study building.

Figure 3. Views of Huitfeldtbrygga in Trondheim, Norway (personal images by the Authors).

According to studies [40–42], a room with a depth of 4–6 m needs a window-to-wall ratio WWR of 60%. Therefore, WWR and WFR (window-to-floor ratio) play a crucial role in indoor space's daylight quality and quantity. In the building analyzed as case-study, the windows in the façades are relatively small, which results in low values of both WWR (18.4%) and WFR (2.4%).

The building consists of a basement, four stories, and an attic. The West wall is facing a street: they are separated by a sloping terrain, where trees were planted to transform it into a park. The building is currently undergoing a huge renovation, and the Authors of this paper support the optimization of daylighting inside the building, considering the constraint due to its architectural and historical character. The daylighting project was carried out through a continuous confrontation with the design team who realized the full renovation project of the building.

2.2. Research Framework

This study relied on empirical research and a quantitative strategy, which included modeling the building and investigating through simulations various alternative retrofitting Scenarios to optimize daylighting inside the building through core lighting (skylights and atria). The project was carried out through a sequence of steps, as shown in Figure 4.

The first step was the data collection and in-situ measurements. The plan and section drawings were provided by the architectural design team [43]. The architectural company working on the retrofit proposal for this building was interviewed, while luminance measures were taken inside the building to calculate the light reflectance of the materials (assumed as Lambertian), through the following equation:

$$\frac{R_{test}}{R_{ref}} = \frac{L_{test}}{L_{ref}} \tag{1}$$

In-situ measurement was taken to calculate the light reflectance (R_{test}) of the various surfaces inside the building. The luminance values of each surface (L_{test}) and of a reference grey card (L_{ref}) with known light reflectance (R_{ref}) were measured (Figure 5). The grey card was positioned in the same place and illuminated equally as the test surface. All measurements were done with using a luminance meter Konica Minolta LS-110.

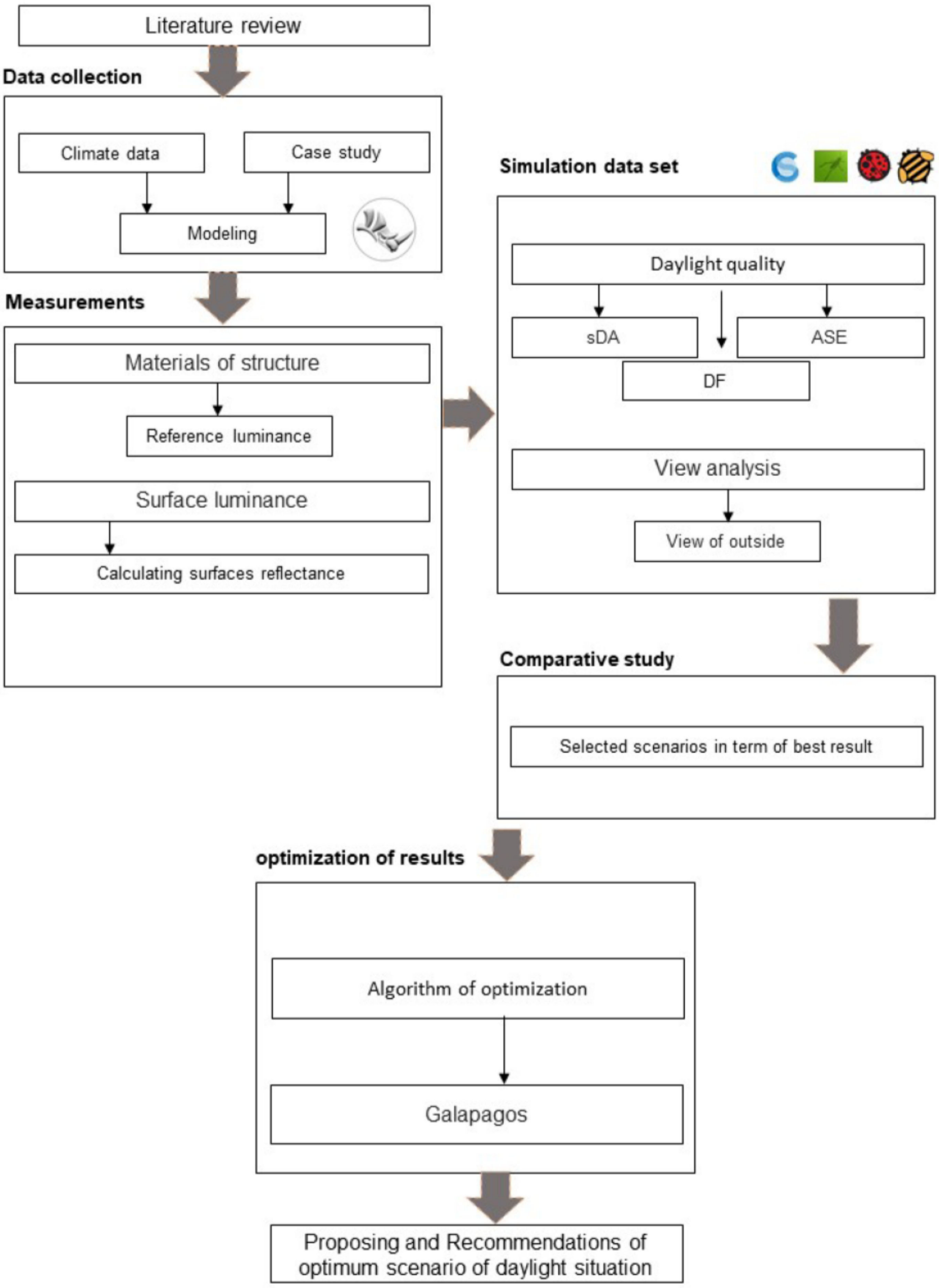


Figure 4. Conceptual framework of the study.

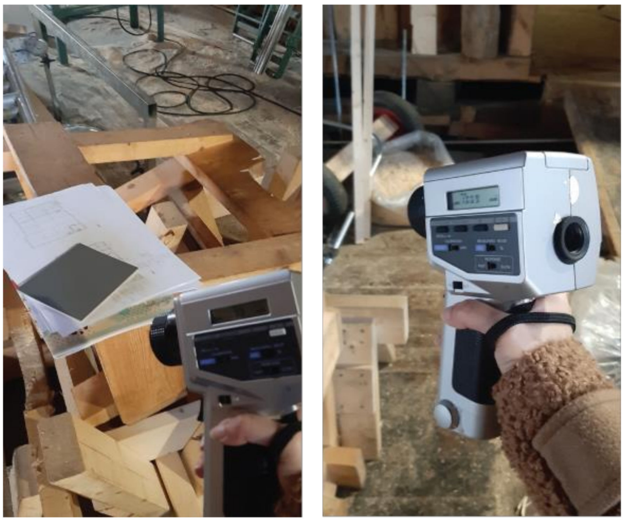


Figure 5. Field luminance measurement is used to calculate the light reflectance of real materials for simulations [44].

As the next step, the historical structure of the building was studied and a discussion was carried out with the design team on which acceptable Scenarios could be implemented into this heritage building: as a result, six alternatives were conceived, taking views, daylighting, and the solar exposure into consideration on an annual basis.

All alternatives were simulated using the Climate Studio (CS) simulation software package. This is a plug-in for the CAD modeler Rhinoceros and uses the validated Radiance algorithm [45] to calculate daylighting conditions in a space. Rhino was used to build the 3D model of both the existing building (base-case) and of the six Scenarios. Radiance-compatible materials were attributed through CS, by creating new materials with the light reflectances value that was measured in-situ for the various materials [46]. The EnergyPlus Weather File (.epw) of Trondheim was used as a source of meteorological data. The output of simulations was:

1. The daylight factor values in the building (at all floors), in accordance with what is required by the recent European standard EN 17037 [47] (mean and median DF); particularly, a mean Daylight Factor $DF_m \geq 2.4\%$ is required for the latitude and the climate of Norway.
2. The spatial daylight autonomy $sDA_{300,50\%}$ and the annual sunlight exposure $ASE_{1000,250}$; sDA quantifies the fraction of the regularly occupied area within a space for which the daylight autonomy (calculated for a threshold illuminance of 300 lx) exceeds a specified value (50%); ASE quantifies the fraction of the horizontal workplane that exceeds a specified direct sunlight illuminance level (1000 lx) for more than a specified number of hours per year (250 h) over a specified daily schedule with all operable shading devices retracted (excluding the sky) [48].
3. At all floors; the following targets were assumed, in accordance with the requirements set in the LEED protocol v4.1 [49]:
   - $sDA_{300,50\%} \geq 75\%$ for the regularly occupied floor area: 3 points are granted according to the EQ Credit: daylight
   - $sDA_{300,50\%} \geq 55\%$ for the regularly occupied floor area: 2 points are granted
   - $sDA_{300,50\%} \geq 40\%$ for the regularly occupied floor area: 1 point is granted
   - for any regularly occupied spaces with $ASE_{1000,250}$ greater than 10%, a strategy must be identified to address glare.

The software outcome from all Scenarios was then compared and the two most promising alternatives were identified based on DF_m, sDA, and ASE results. These two optimal Scenarios were further analyzed according to the requirements set by EN 17037 [47] (see Section 2.5).

After a comparison, the optimum Scenario was chosen using the Honeybee plugin tool [50] in Grasshopper [51]. Finally, some recommendations for future strategies were presented based on sDA and ASE values.

All metrics were calculated for a grid of sensors positioned 0.8 m above the floor finishing and with a spacing of 0.25 m.

2.3. Simulation Data Set

Annual simulations were run to analyze the daylighting conditions inside Huitfeldbrygga, by calculating the following metrics: spatial daylight autonomy sDA, annual sunlight exposure ASE, daylight factor, and view out.

To understand the daylight behavior due to the changing geometry of atriums, all simulations were conducted in various Scenarios of atria space with considering the whole building of Huitfeldtbrygga. In order to do the simulation in ClimateStudio, laminated double-pane glazing was chosen for both the vertical windows in the façades and for the rooflighting systems (skylights and atrium). The window materials were selected based on conventional construction window material in Norway. Following up on the instructions received from the renovation design team, the light transmittance value T_v of a double-pane clear + clear glazing was used (clear Float glass 6mm, Krypton 13 mm, clear glazing 6mm), namely T_v of 0.70, with a corresponding U-value of 1.26 W/m^2K. It is worth mentioning that laminated glazing was chosen for its protective function.

2.4. Design Configurations

The shape of the atrium in the building fits the design of the existing plan and, at the same time, aims to provide a visual connection between the floors internally through an atrium. Figure 6 shows the plan of the third floor: the various design strategies to reach the standard level of daylight were defined taken the interior layout of the building into account. There are two long interior walls (side-to-side) that divide the building into three separated parts. As a result, separate atriums were implemented on both sides of the building to improve daylighting in these areas; besides, the middle part of the building was not blocked by the floors except in the second floor which is consistently connected to both sides. The six Scenarios that were designed to improve daylighting in the building relied on using as much secure glazing as suitable for transferring daylight as possible. Scenarios are shown in Figure 7. For all configurations, the atrium consisted of laminated glazing panes (1 m × 1 m in size) mounted on a galvanized steel supporting frame structure that is 0.06 m × 0.06 m in section. Also, the upper glazing that closes the atrium was conceived as an openable surface to allow ventilation to get activated (stack-effect) to reduce solar and internal gains in summer, with positive effects on thermal comfort for the occupants and reduced energy demand for cooling. It is worth pointing out, though, that the thermal performance was not in the scope of this paper. The six Scenarios are highlighted in orange in Figure 6. The main atrium in the various configurations was placed on the North-facing sloped roof rather than in the South-facing one to avoid the penetration of direct solar rays in the spaces adjacent to the atrium itself, especially at the top floors.

The first Scenario considered one massive atrium with plan sizes of 3.34 m × 8.50 m in the middle of the building. Similarly, to Scenario 1, Scenarios 2 and 3 had central atriums in precisely the same position and sizes, but in Scenario 2 there were three smaller separated atria with plan sizes 1.84 m × 1.70 m. In Scenario 3, there were united side atriums with side plans of 1.84 m × 10.10 m. In Scenario 4 there was a square atrium in the middle of the building with plan sizes of 3.34 m × 3.34 m, while Scenarios 5 and 6 had the same atrium plan sizes for both lateral wharves as atria 2 and 3.

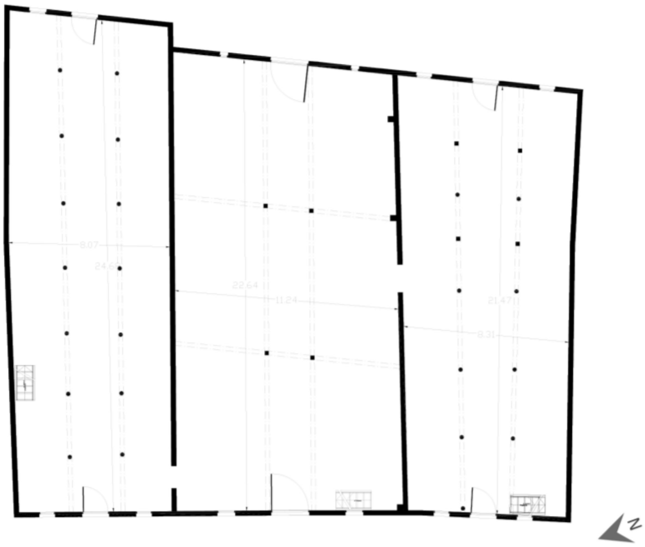


Figure 6. Plan of the 3rd floor of the case-study building, with the position of the structural elements.

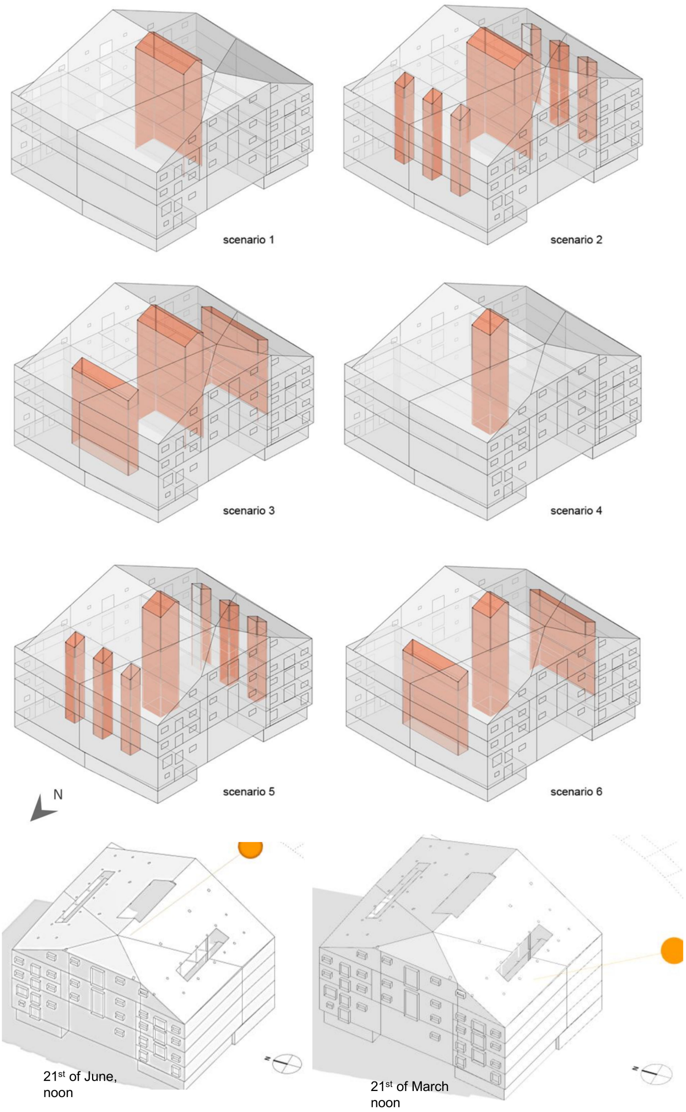


Figure 7. Schematic view of the six configurations that were defined for corelighting of the building through skylights and light atria. The position of the sun hitting the building is also shown.

Table 1 summarizes the following geometrical information: atrium volume, atrium roof area, percentage of the volume of each Scenario compared to the whole volume, and percentage of the roof surface of each Scenario compared to the total roof area. As shown in the Table, the atrium in Scenario 3 with 915.6 m^3 has the largest volume compared to the other Scenarios., whilst the atrium in Scenario 4, with a volume of 180.9 m^3, has the least space in the building. In between, Scenarios 1, 2, 5, and 6 had 462.1 m^3, 690.5 m^3, 408.9 m^3, and 634.4 m^3, respectively. It is worth mentioning that even if the spaces related to the atrium in each Scenario were quite large, each atrium geometry was considered functional spaces that could be used for different purposes, based on confrontation with the renovation design team.

Table 1. The detailed characteristics of considered atria area and volume in each Scenario.

Scenario	Atrium Volume (m^3)	Percentage of Atrium Volume Compared to the Building Volume (%)	Atrium Roof Area (m^2)	Percentage of Atrium Roof Area Compared to the Building Roof Area (%)
Scenario 1	462.1	4.9	31.1	4.4
Scenario 2	690.5	7.4	51.8	7.3
Scenario 3	915.6	9.8	72.6	10.3
Scenario 4	180.9	1.9	12.2	1.7
Scenario 5	408.9	4.4	32.9	4.7
Scenario 6	634.4	6.8	502	7.1

The total volume and total roof area of the case-study building (Huitfeldbrygga) were 9394.7 m^3 and 708.2 m^2, respectively.

2.5. View Analysis

The method evaluated the views for the occupants and determined eligibility for the EN 17037 European standard. View factors and distance to specific model layers or items of interest were also calculated for Scenarios with better daylighting (in terms of DF, sDA, and ASE), as well as for the optimized Scenario (see next section).

The results were provided at sensor places defined on an analysis grid distance of 1.20 m above the floor of each building level. The analysis grid size determined spacing 0.60 m to acquire precise findings. EN 17037 [47] covered four aspects of daylight in buildings, the second of which—View Out–was included in ClimateStudio view analysis workflow (as of Climate Studio v1.5).

Accordingly, in view result, CS shows the proportion of the building floor space that falls into each of four compliance categories: Failing, Minimum, Medium, and High. The compliance levels are determined by three assessments, which are performed for each point of view such as Horizontal Sight Angle, Outside View Distance, and the number of view levels (three, sky, ground, and landscape). A view position must observe:

1. at least the landscape layer, to achieve 'minimum' compliance
2. landscape layer as well as one additional layer (either ground or sky), to achieve 'medium' compliance
3. all three layers (landscape, ground, and sky), to achieve 'high' compliance
4. a point that does not benefit from any of the three view levels is labeled as 'failing' in the view assessment criterion.

2.6. Optimization

Grasshopper plug-in Ladybug and Honeybee were used to parametrize a Rhino model for daylighting simulation [52], and Galapagos was used to achieve the optimal solution [53,54]. Honeybee and Ladybug were validated and used in several studies [55–58] for daylight simulations. The simulation procedure started with creating the geometry and setting the parametric design variables. Throughout the parametric simulation process, each material of the real building was coupled to a specific Radiance materials component, by setting the material light transmittance T_v or reflectance R_v. After that, the building materials were linked to the daylighting simulation component, which takes the Trondheim's weather file, the position of daylighting sensors, and other simulation variables into consideration. Radiance creates a .rad file and simulates daylighting. Ladybug reads the daylight performance data and provides as output an annual lighting schedule, which is used by Honeybee to run an annual daylighting simulation and generate results in terms of daylighting metrics (DF, sDA, and ASE). The simulation results are then imported back into Grasshopper. Galapagos was utilized in the optimization process to determine the optimal atrium shape with the maximum sDA. To this end, different dimensions in the bottom and upper parts of each atrium were considered to test the variety of shapes in the optimization process. The boundary condition for maximum and minimum dimensions of atriums was also assigned to avoid unacceptable shapes. The assigned range of width was between 1.20 m and 3.60 m, and the length between 1.20 m and 15.80 m was adopted to achieve the optimum outcomes. These domains were set to control the optimal solutions according to the building floor area and the actual structure positions. The design variables were related to the Genetic input in Galapagos, and the sDA output was related to the Fitness input equal to 50. Each generation had a population of 100, with a population boost of twice the size of the first generation.

3. Results

Two key features distinguish the retrofit of a heritage building. The first component was related to the renovation process itself, as the original material asset should be preserved in the case of a historical building. The second issue was concerned with the historical feature buildings, which should be maintained in such a way that the authenticity of the asset was preserved with minimal modifications to the original construction.

This section reports all annual results from the Climate Studio and Grasshopper simulations. First, an inquiry was conducted to ensure that the final design tool with all iterations was given. Secondly, Scenario-based outcomes were evaluated using metrics such as mean and median DF, sDA, and ASE, highlighting the grid regions that were compliant with the LEED v4.1 protocol, option1, and the European standard EN17037:20218. Therefore, the general interaction with parameters and the effect of each variable input were explained using comparison and correlation studies. Finally, optimization was tailored to the parameters under consideration.

3.1. Analysis of DF, sDA, and ASE in the Base-Case

The simulation was initially carried out using two simulation tools, Climate Studio and Honeybee, to analyze DF, sDA, and ASE values within the Huitfildbrygga building. In order to improve daylight conditions in the existing building, it was necessary to quantify the daylight amount that was admitted in the base-case Scenario. Therefore, daylighting was evaluated at each floor by using mean and median DF, sDA, and ASE.

Figure 8 shows the simulation results for the base-case: it can be observed that daylighting levels in the building were quite limited at all floors, due to the reduced area of the vertical openings in the façades. This is testified by both DF (Figure 8a) and sDA (Figure 8b) values: the mean DF was 0.9%, while as for sDA, none of the floors in the base-case Scenario showed sDA value over 18%. The lowest daylighting level was observed on the ground floor, as expected: DF = 0.02% and sDA = 12.8%. The first floor and the second floor showed the same sDA results (17.1%), while the third floor showed the highest of sDA value (10.1%). On the other hand, the limited daylight penetration into the building yields ASE values that can be considered negligible (Figure 8c). The highest and lowest ASE values were observed on the lower floors (first and ground floors), with values of ASE = 5.1% and 3.1%, respectively.

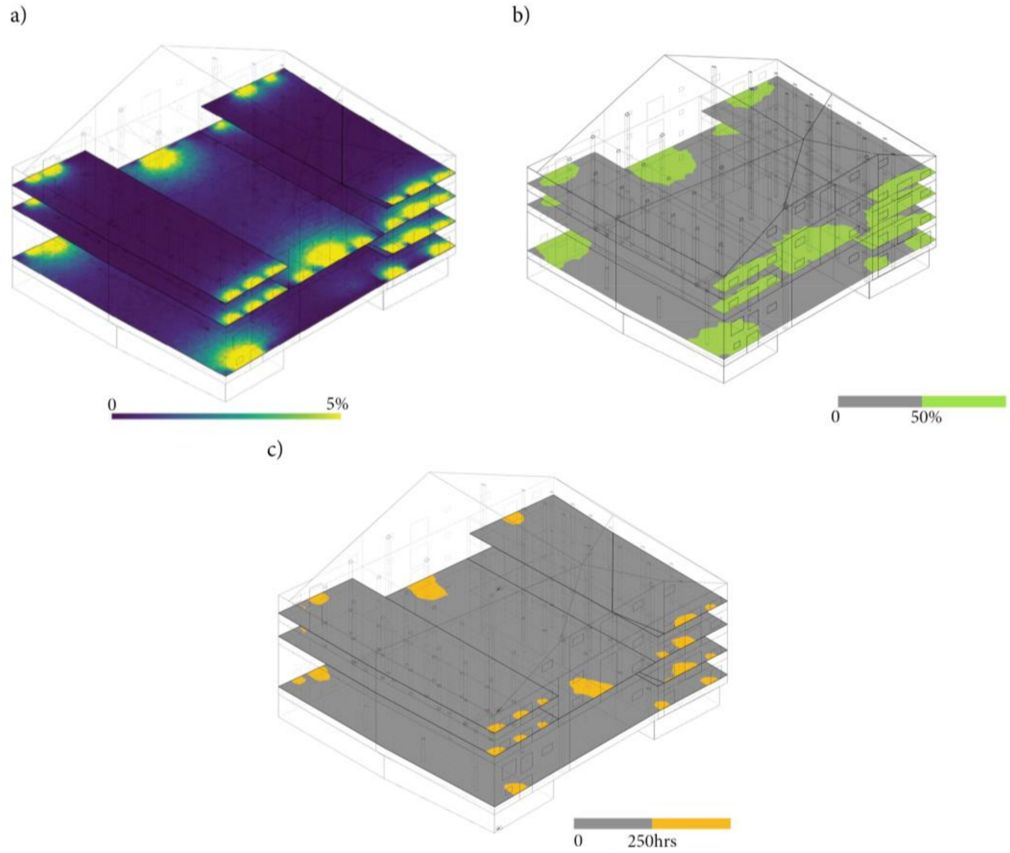


Figure 8. Simulation results in the base-case; (**a**) DF; (**b**) sDA$_{300,50\%}$; (**c**) ASE$_{1000,250}$.

The amount of sDA in winter was less than 10%. More specifically, sDA values were lower than 2% and close to zero in November, December, and January. On the other hand, sDA values exceeded 30% in May, June, and July. ASE values during a year were negligible in the base-case Scenario, especially in winter. The mean DF was quantified with a value of 0.9% and a median DF of 0.3%. As it typically happens in sidelighting configurations, point DF values decrease significantly as the distance from windows increases; however, they remain quite low also in the proximity of the façades, due to the reduced window area.

3.2. Comparison of DF, sDA and ASE in the Six Scenarios

Changing the atrium configuration affected how daylight penetrates deep down into the building. The simulation of the six Scenarios was intended to identify which Scenario resulted in the highest and most uniform daylight autonomy in the building spaces facing the atrium. Six Scenarios based on the number, shape, and size of atria were thus compared in the following sections.

Figure 9 illustrates and compares the DF, sDA, and ASE results that were obtained for each Scenario: the highest sDA values were observed for Scenario 3 (sDA = 28%), followed by Scenario 6 (sDA = 23%) and Scenario 2 (sDA = 21%). Scenario 4 offered a quite similar distribution of daylight autonomy to the base-case. Scenarios 1 and 4 were therefore the least favorable of the three shapes. The zones that received no light from the atrium were the largest for these atrium configurations, meaning that more electric lighting will be needed.

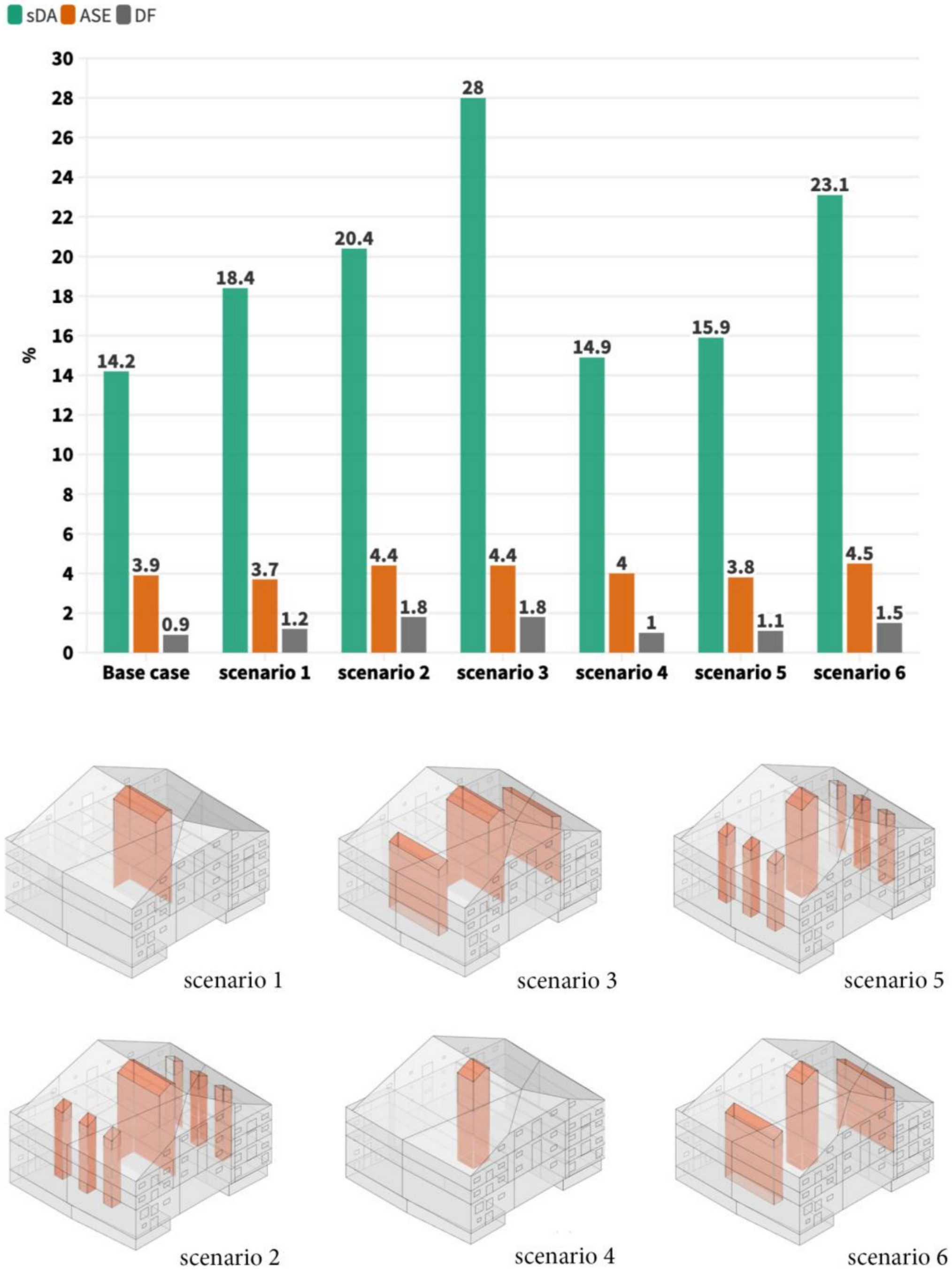


Figure 9. Results of $sDA_{300,50\%}$, $ASE_{1000,250}$, and DF in the six Scenarios.

As for the sDA metric, it was clear that the Scenarios with a united area of the atrium on the top and bottom had more advantages due to larger areas that face the external environment. It can also be noticed that Scenario 4 had the lowest sDA and DF values compared to the other Scenarios (absolute difference = 14.9% and 1% less, respectively). Scenarios 3 and 2 performed the best in achieving sDA with values of 28% and 20.4%, respectively. In contrast, DF in Scenarios 4 and 5 was 1% and 1.1%, and the sDA was 14.9% and 15.9%, respectively. These Scenarios yielded similar performances, thus being the worst-case Scenario among the six configurations, being closer to the base-case. In Scenarios 6 and 1, sDA was 23.1% and 18.4%, respectively. However, DF for Scenarios 6 and 1 was 1.5% and 1.2%. This means that these levels were not compliant with the requirement specified in EN 17037 and LEED v4.1.

Based on the comparative analysis of the six configurations, Scenarios 2 and 3 were thus identified as the best results, both in terms of sDA and of DF values, of daylight distribution inside the floor plan. Scenario 6 also showed high sDA, lower than Scenario 3 but even higher than Scenario 2. However, Scenario 6 was excluded due to a lower DF value and ASE value than Scenario 2. Note that Scenarios 2 and 3 showed the same DF value of 1.8%, which precedes the demand for daylight factor uniformity. Therefore, Scenarios 2 and 3 have been selected for more in-depth analysis.

3.3. Comparative Study of Selected Scenarios

According to the results, all the cases behaved similarly. Scenarios 2 and 3 demonstrate a great potential to become autonomous in terms of daylight, as their grids on the floor surface have more exposure to sunlight due to the atrium shape of the building.

3.4. Optimization of Scenario 3

Due to a large amount of data and time limitations, Scenario 3 was selected to investigate how the improvements affected the daylighting condition on each floor. Moreover, the amount of ASE was investigated to analyze glare amount.

The optimization process was carried out through the Galapagos component in Grasshopper [59]. Firstly, all building parameters, including walls, floors, windows, and atriums, were modeled in Grasshopper. Secondly, the materials related to each opaque and transparent surface were modeled. Finally, the algorithms of daylighting were designed in terms of optimization.

Galapagos was used to identify optimum fitness values and three parameters for each atrium through genetic algorithm optimization methods. The evolutionary algorithm was chosen since it was the only method to identify optimal solutions using Rhino and Grasshopper. Furthermore, this program was commonly used for architectural designs [60]. Galapagos was configured with three-parameter values and four variables to achieve circumstances similar to manual methods: Maximum Stagnant = 50; Population = 20; Maintain = 20%; Inbreeding = 50%. The Population value of 20 indicates that Honeybee simulates evolution 20 times for each generation, while the Maximum stagnant value of 50 computes up to 50 generations.

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

Figure 10 shows the optimized shape of the atrium for Scenario 3. The shape of the optimized atriums had two rectangles consisting of bottom and top rectangles. After optimization, the amount of each variable was defined, and the final and optimized shape of the atria was achieved. The atrium sizes yielded the bottom rectangle bigger than the top one. The atrium sizes atrium from North-West (left to right in Figure 10) were: 1.8 m × 12.21 m in the top rectangle, 3 m × 15 m in the bottom rectangle, for the central atrium 10.30 m × 1.92 m in the top and 15.10 m × 1.92 m for bottom one, another side of the building the dimension was 3.60 m × 9.00 m in the top, 11.25 m × 3.60 m for the bottom. The optimized slope shape of the atria was defined to compensate for the decreased daylighting at the bottom of the atria. This atrium shape allows daylighting to be guided into the building, thus improving the daylighting across the building. This rule was the same for all three atrium shapes; however, the optimized sizes of each atrium were different.

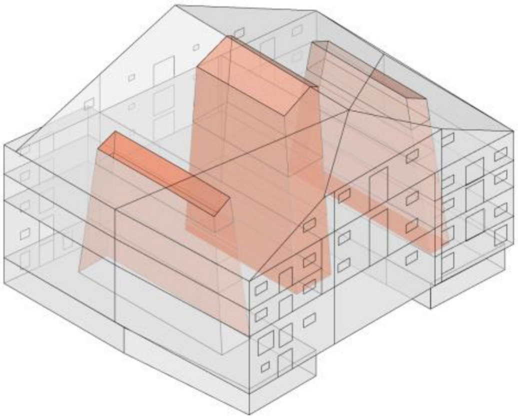


Figure 10. Configuration of atriums after optimization in Scenario 3.

In order to compare the daylight condition after the optimization, the optimized atrium was simulated, and the results of sDA, ASE, and DF were extracted.

Besides, the results of simulations of the optimized model, base-case Scenario, and Scenario 3 were compared in Figure 11, to better understand the effect of optimized atria on the building daylight condition.

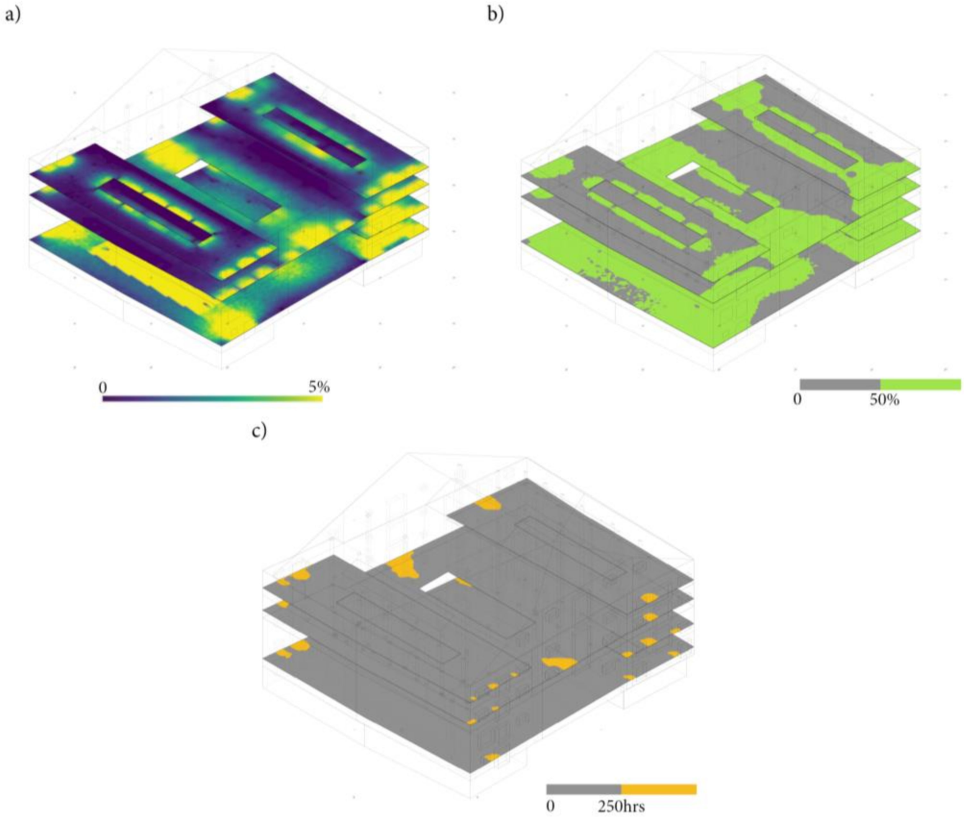


Figure 11. Simulation results in the optimized Scenario; (**a**) DF; (**b**) $sDA_{300,50\%}$; (**c**) $ASE_{1000,250}$.

The results shown in Figure 11 confirm that the value of sDA and ASE was 50.2% and 5.0%, respectively. The DF of optimized Scenario 3 was 2.7%, while a median daylight factor of 2.4% was obtained. Values of sDA and DF are higher on the ground floor than at the top floor. One reason for this is that the windows at the ground floor are much bigger than the equivalent ones at the top floor and the height of the ground floor is double as high. The second reason relates to the narrow shape of the atrium. High specularity of glass for light coming from slanted angles makes that the light from the sky is mainly reflected between glass with the vertical direction, which makes that the atrium glazing transports light from zenith effectively down to the bottom of the building. The light from zenith is a huge contributor at the location dominated by overcast sky condition with the yearly frequency of sunlight of about 20%. Additionally, the top floor was encompassed by the walls which blocked, and daylighting penetrations form the central part of building and the timber that was used for the top floor was much darker than the timber on the ground floor.

As indicated by the results, sDA in the base-case was 14.2%, increasing to 28% in Scenario 3 (Figure 12). After the optimization, the sDA exponentially increased and reached the value of 50.2%, with an increment of more than 32%. The ASE value in the base-case was 3.9%, while it slightly increased in Scenario 3, reaching the value of 4.4%. The ASE did not increase significantly even after optimization, reaching the value of 5%. According to the LEED protocol, the ASE should be lower than 10% to avoid glare occurrence based on the standard. After optimization, the low amount of ASE = 5% can guarantee a glare-free space within the interior space.

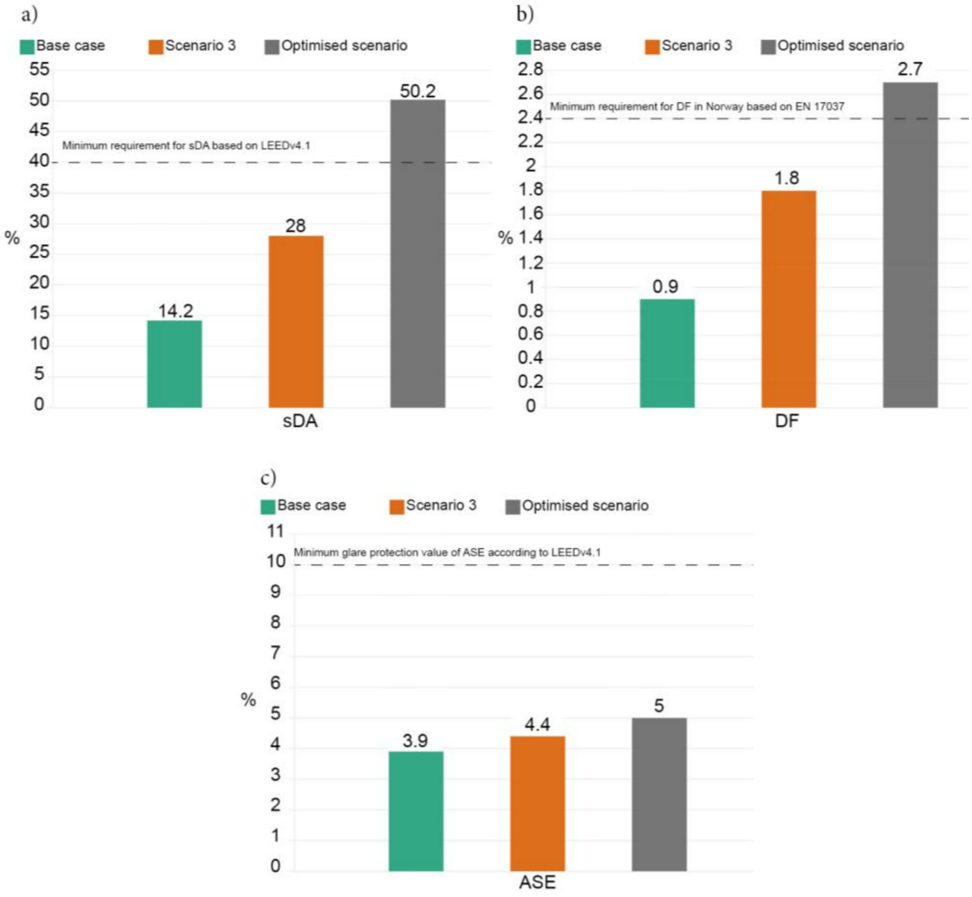


Figure 12. Results of simulated $sDA_{300,50\%}$, $ASE_{1000,250}$, and DF for Scenario 3 and optimized Scenario: (**a**) $sDA_{300,50\%}$; (**b**) DF; (**c**) $ASE_{1000,250}$.

Regarding DF, it increased from an initial value of 0.9% in the base-case to a value of 1.8% in Scenario 3, and further to a value of 2.7% after optimization. On the other hand, it is worth stressing that three large atria were needed to optimize daylighting, which resulted in less space available inside the building. Indeed, the optimized configuration will ensure effective usage with acceptable daylighting of the heritage building.

It is worth pointing out that both sDA and ASE are annual metrics that rely on threshold values. In more detail, sDA quantifies the fraction of space where the daylight autonomy

DA is over 50%, where DA quantifies the annual frequency of illuminances > 300 lx. It is a synthetic metric, which does not provide any information on the absolute illuminances. For this reason, a set of point-in-time simulations were run in ClimateStudio for some representative days (winter and summer solstice, and spring equinox), for an overcast sky and a clear sky, with the goal of visualizing the distribution of absolute illuminance inside the building for the base-case (Figure 13) and optimized atrium configuration (Figure 14).

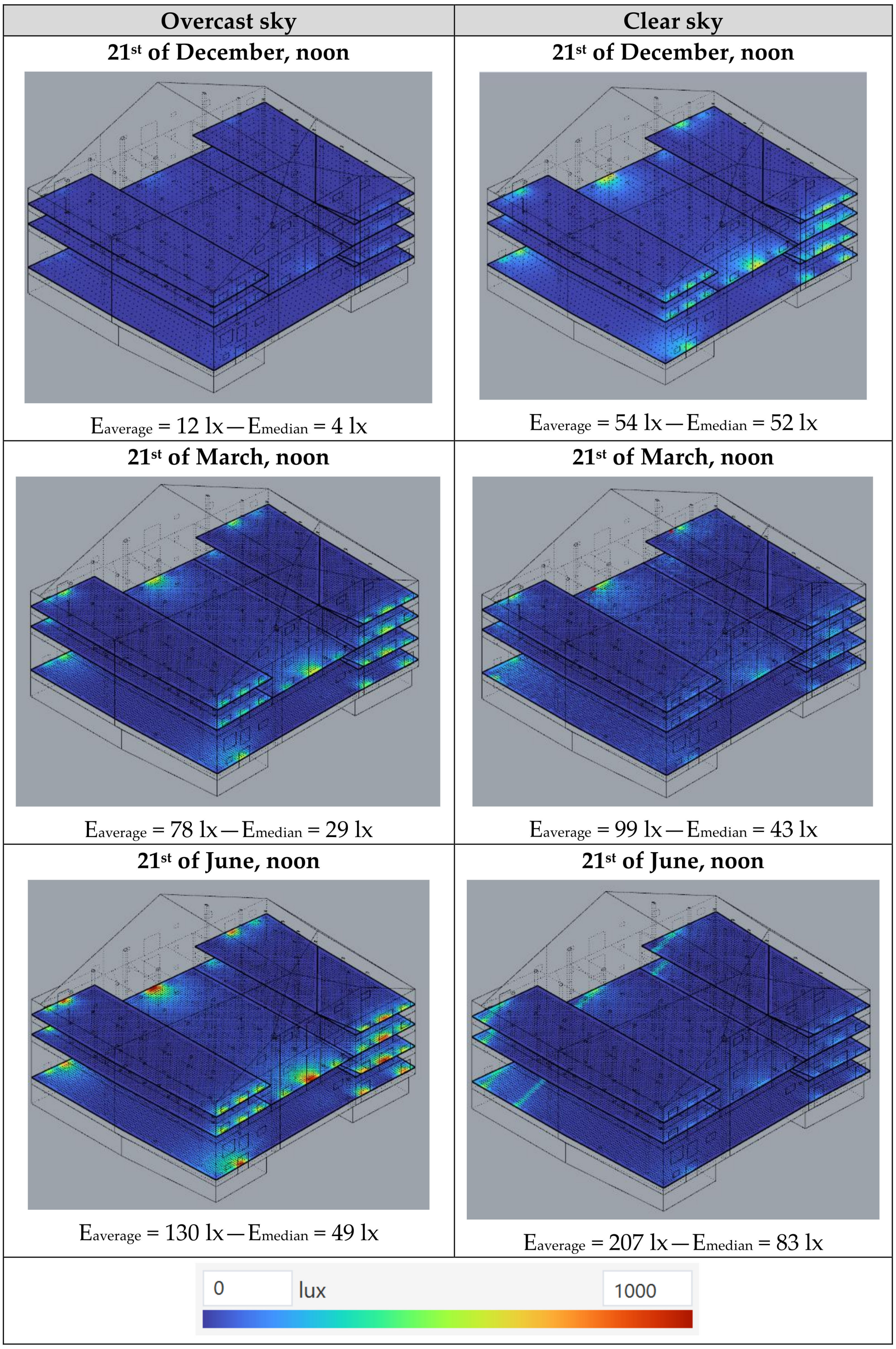
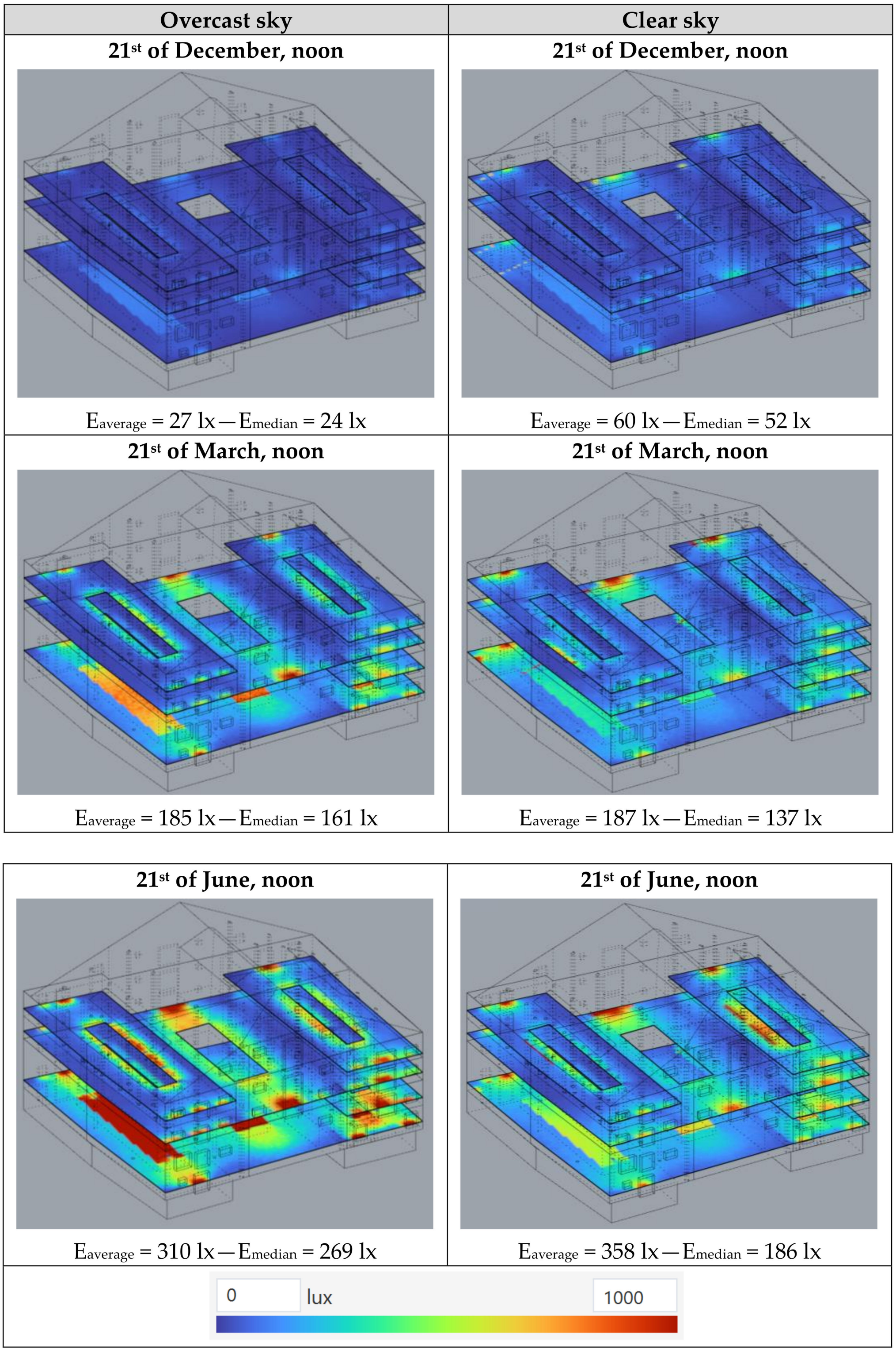


Figure 13. Point-in-time illuminances inside the building for the existing building (base-case).



Overcast sky

Clear sky

21st of December, noon

$E_{average}$ = 27 lx — E_{median} = 24 lx

21st of December, noon

$E_{average}$ = 60 lx — E_{median} = 52 lx

21st of March, noon

$E_{average}$ = 185 lx — E_{median} = 161 lx

21st of March, noon

$E_{average}$ = 187 lx — E_{median} = 137 lx

21st of June, noon

$E_{average}$ = 310 lx — E_{median} = 269 lx

21st of June, noon

$E_{average}$ = 358 lx — E_{median} = 186 lx

Figure 14. Point-in-time illuminances inside the building for the optimized atrium configuration.

Figure 13 shows the results obtained at noon for each day considered in base-case Scenario. According to the results, the highest average illuminance was achieved in June 21 under the clear sky with a value of 207 lx. However, for December 21, the average illuminance was 27 lx and 60 lx under the overcast and clear sky, respectively. The obtained results of point-in-time illuminance for the base-case Scenarios are as follow:

1. 21st of December, noon $E_{average}$ = 12 lx overcast sky $E_{average}$ = 54 lx clear sky
2. 21st of June, noon $E_{average}$ = 130 lx overcast sky $E_{average}$ = 207 lx clear sky
3. 21st of March, noon $E_{average}$ = 78 lx overcast sky $E_{average}$ = 99 lx clear sky.

As shown in Figure 14, the illuminance values remain low at the winter solstice, with an average illuminance of 27 lx for an overcast sky and 60 lx for a clear sky. Illuminance levels get increased at the spring equinox (similar average illuminance of 185 lx and 187 lx for an overcast and a clear sky, respectively) and results over 300 lx at the summer solstice, with an average value of 310 lx for an overcast sky and of 358 lx in the presence of a clear sky.

The point-in-time illuminances confirm that the poor daylighting in the baseline case was significantly improved through the optimized configuration.

4. Discussion

The study presented in this paper focused on the possibility of increasing daylighting levels in a real heritage building located in Trondheim (Norway) through rooflighting systems, which rely on a combination of skylights and corelighting systems (light atria). As is, the building has small windows and dark surfaces indoor, which determine scarce daylighting conditions in the internal spaces. Besides, as the building is listed, it is actually not possible to modify the layout of the façade by increasing the room area and therefore, the daylighting indoors through sidelighting systems. Therefore, rooflighting systems can represent the only way to admit daylight into the building, which is currently undergoing a deep renovation that will transform it from a warehouse (original usage) into a work area.

Daylighting inside the case-study building was analyzed through a combination of daylighting metrics:

1. daylight factor DF (point, average and median): although this is an obsolete metrics, it was included in the study as it is still assumed as a reference in many national regulations and legislations [61], including the latest European standard EN 17037 on 'Daylight in buildings'; besides, the calculation method included in the European standard EN 15193–1:2017 [62] to determine the energy demand for lighting relies on the daylight factor concept to determine the daylighting level in an indoor space [63] finally, as DF refers to an overcast sky condition, it seems particularly suitable for Nordic countries such as Norway, where the case-study building is located, where sunny skies occur less than 25% of the time on an annual basis and overcast skies are therefore predominant;
2. spatial Daylight Autonomy sDA and Annual Sunlight Exposure: unlike DF, which refers to an overcast sky and thus it does not include the dynamic variation of sunlight and skylight during a year, sDA and ASE are dynamic daylighting metrics that account for the presence of the sun on annual basis. Therefore, unlike DF, they account for all the factors that influence indoor daylighting and are more suitable to give preliminary information on the potential energy demand for lighting; besides, they are the metrics assumed in the LEED protocol for the credit on daylighting
3. point-in-time illuminances: as sDA and ASE are metrics with a threshold, they quantify the occurrence of time when illuminance values are over 300 lx (sDA) or over 1000 lx in direct sunlight only (ASE); no information is given on the absolute illuminance values during a year; for this reason, absolute illuminances were calculated for some reference days and sky conditions.

The research was conducted through a parametric approach to identify and optimize the shape and volume of different configurations of corelighting systems, using ClimateStudio and three Grasshopper tools: Ladybug, Honeybee and Galapagos. In order to answer the research questions that guided this investigation, the parametric study addressed six different Scenarios, which were defined by changing the atrium geometry (shape and volume). Therefore, after simulations, the sDA results showed that none of the Scenarios complied with LEED v4.1 and EN17037 requirements, as all the values were less than 50%.

Only the optimized configuration allowed minimum values of DF and sDA to be achieved in accordance with the standard EN 17037 and the LEED protocol.

As mentioned in the literature review, the shape and location of the atrium were the most influential parameters affecting the atria studied, along with the glazed area and the light reflectance properties of the atrium surfaces. Furthermore, genetic algorithm optimization has only recently been employed in designing new buildings and is rarely used in designing historical buildings [64,65]. Optimizing the building atrium has not been examined as thoroughly as optimizing other architectural variables such as form, side-lit openings, building façade, etc. To the authors' knowledge, parametric and optimization tools are quite new in their application to the heritage building. In this regard, an interesting study was carried out by Marzouk et al. [19]: in their study, the authors studied how to optimize skylights for an ancient building in Egypt, through Radiance, Daysim for daylighting analyses, and the multi-objective 'Octopus' component. The research presented in this paper addressed a similar problem, i.e., to admit daylight through rooflighting systems by relying on atria (corelighting).

In this regard, the Scenarios to enhance daylighting (starting from the base-case configuration with quite poor daylighting) and, even more, the optimized configuration result in relatively large volumes occupied by the corelighting systems. This resulted in a significant reduction of the available inner space (27% reduction in volume), which limits the exploitation of the internal layout in terms of usable space but guarantees better daylighting conditions in the exploited space; however, all the stages of the research were discussed and developed in accordance with the design team, which accepted the optimized configuration: such configuration will be built. Daylighting was conceived as one of the driving factors of the renovation, and the final, optimized solutions were considered satisfactory. Following adjustment, ASE was also tested to ensure visual comfort. The ASE increased to 5% after optimization, and the indoor daylight condition was greatly improved, and the risk of glare was averted.

Beside merits, the study also has some limits: for instance, the atrium shapes defined were quite simplistic from a geometrical viewpoint. Another issue was concerned with the fact that daylighting only was addressed in the research; other aspects of building physics (acoustics, thermal, energy demand) were not considered and should be the object of the following stages of the analysis. Increasing the window area in the roof (skylights + atria) may result in higher thermal losses in winter, with a potentially increased energy demand for heating, and in higher solar gains in summer, with a potential increase in the energy demand for cooling. As a solution to mitigate this latter problem, the upper surface of the atrium, as well as the skylights, were conceived as openable systems, so as to enhance natural ventilation in the summer period and to contrast the potential overheating problems due to direct sunlight. It would be interesting to analyze the overall performance of a building with rooflighting and corelighting solutions by integrating daylighting and thermal issues, as well as their related energy demands. At this stage of the research, though, the scope of the study was on daylighting only, as this was set as a primary design goal by the design team that is defining the retrofitting solutions: daylighting was given a priority over thermal and acoustical issues due to the high quality it brings in inside spaces, quality that is particularly important in Nordic climates.

Moreover, it is worth mentioning that the study is also limited by the extensive calculation time required to obtain high-quality results for large-scale building models with daylight simulation. Creating a model was a big challenge as the structure did not have single straight lines or angles. This affected both the size and complexity of the model, as well as the resolution of the results.

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

As far as future work is concerned, the present activity and its results only focused on the locations of the atriums; their sizes, the type of glasses, and their materials can be investigated in future work. Besides, another significant aspect of the atrium was that a considerable part of the atrium was transparent. Therefore, it results in heat losses or heat gain and overheating phenomena in the building. As a result, the thermal comfort and energy consumption when the atrium was considered can be investigated in future studies. More research is needed to develop strategies to improve daylight adequacy while achieving visual comfort utilizing diverse atrium arrangements.

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

5. Conclusions

This paper addressed a challenging task concerning heritage buildings: how to admit sufficient daylighting in a listed building, which means that no intervention in the façade can be considered. Particularly, an existing, listed wharf in Trondheim, Norway (L = 63° N) was selected as a case-study. Accordingly, the research question addressed in the study was: *"How to improve daylight conditions in heritage building locations in high latitudes?"*. Firstly, the base-case was a historical building with minimal modification to the original structure. Secondly, the base-case was deep and large, with small windows (WWR = 18.4%; WFR = 2.4%); for these reasons, this paper argued that an atrium should be used to increase daylight in construction.

To answer the research question, corelighting strategies were approached, and six configurations of skylights and atria were defined following the logic of the construction. Daylighting inside the six configurations was calculated using Climate Studio and Honeybee in Grasshopper simulations; surface reflectance measured in the building was used. Daylight metrics such as DF, sDA, and ASE were calculated and compared to discuss the daylight amount in the building using the target values required by the LEED v4.1 and EN 17037 regulations as benchmarks.

The simulations demonstrated that the ability to run dynamic daylight simulations for early-stage design was extremely viable. Therefore, supporting earlier studies and comparisons between computer-based simulations and physical models. After comparing the results, the optimal Scenario for supplying adequate daylighting was identified and this atrium configuration was optimized using Galapagos genetic algorithms.

The results showed that the sDA in the existing building (base-case) of 14.2% was increased to 50.2% after optimization, thus qualifying for the LEED credit. Accordingly, the initial average DF value of 0.9% was increased up to 2.7%, after the optimization, thus complying with EN 17037. Furthermore, ASE and views were also analyzed to guarantee visual comfort after the optimization. Results showed that the ASE value was 3.9% in the best case and increased to 5% after optimization. According to the standard, a value below 10% would provide a glare-free condition for building users. Based on the results, the interior daylight condition was improved adequately, and the risk of glare was prevented. On the other hand, the volume occupied by the atria was about 1290 m^3 which was equal to 13.7% compared to the whole building volume. Thus, implying a considerable reduction of the internal space available for activities.

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References

1. Buda, A.; De Place Hansen, E.J.; Rieser, A.; Giancola, E.; Pracchi, V.N.; Mauri, S.; Marincioni, V.; Gori, V.; Fouseki, K.; López, C.S.P.; et al. Conservation-Compatible Retrofit Solutions in Historic Buildings: An Integrated Approach. *Sustainability* **2021**, *13*, 2927. [CrossRef]
2. Sibley, M. Let There Be Light! Investigating Vernacular Daylighting in Moroccan Heritage Hammams for Rehabilitation, Benchmarking and Energy Saving. *Sustainability* **2018**, *10*, 3984. [CrossRef]
3. *CIE 026/E:2018*; CIE System for Metrology of Optical Radiation for IpRGC-Influenced Responses to Light. International Commission on Illumination: Vienna, Austria, 2018.
4. MIsIrlIsoy, D.; Günçe, K. Adaptive Reuse Strategies for Heritage Buildings: A Holistic Approach. *Sustain. Cities Soc.* **2016**, *26*, 91–98. [CrossRef]
5. Günçe, K.; Misirlisoy, D. Adaptive Reuse of Military Establishments as Museums: Conservation vs. Museography. *WIT Trans. Built Environ.* **2014**, *143*, 125–136.
6. Langston, C.; Shen, L.Y. Application of the Adaptive Reuse Potential Model in Hong Kong: A Case Study of Lui Seng Chun. *Int. J. Strateg. Prop. Manag.* **2007**, *11*, 193–207. [CrossRef]
7. Balocco, C.; Calzolari, R. Natural Light Design for an Ancient Building: A Case Study. *J. Cult. Herit.* **2008**, *9*, 172–178. [CrossRef]
8. Khalil, A.M.R.; Hammouda, N.Y.; El-Deeb, K.F. Implementing Sustainability in Retrofitting Heritage Buildings. Case Study: Villa Antoniadis, Alexandria, Egypt. *Heritage* **2018**, *1*, 57–87. [CrossRef]
9. Singh, M.K.; Attia, S.; Mahapatra, S.; Teller, J. Assessment of Thermal Comfort in Existing Pre-1945 Residential Building Stock. *Energy* **2016**, *98*, 122–134. [CrossRef]
10. Marzouk, M.; ElSharkawy, M.; Mahmoud, A. Analysing User Daylight Preferences in Heritage Buildings Using Virtual Reality. *Build. Simul.* **2022**, *15*, 1561–1576. [CrossRef]
11. IEA SHC | | Task 59 | | Renovating Historic Buildings Towards Zero Energy. Available online: https://task59.iea-shc.org/ (accessed on 30 September 2022).
12. Rose, J.; Thomsen, K.E. Comprehensive Energy Renovation of Two Danish Heritage Buildings within Iea Shc Task 59. *Heritage* **2021**, *4*, 2746–2762. [CrossRef]
13. Ahmad, S.S.; Ahmad, N.; Talib, A. Ceiling Geometry and Daylighting Performance of Side Lit Historical Museum Galleries Undertropical Overcast Sky Condition. *Pertanika J. Sci. Technol.* **2017**, *25*, 287–298.
14. Al-Maiyah, S.; Elkadi, H. The Role of Daylight in Preserving Identities in Heritage Context. *Renew. Sustain. Energy Rev.* **2007**, *11*, 1544–1557. [CrossRef]
15. Mehr, S.Y. Analysis of 19th and 20th Century Conservation Key Theories in Relation to Contemporary Adaptive Reuse of Heritage Buildings. *Heritage* **2019**, *2*, 920–937. [CrossRef]
16. Zaikina, V.; Moscoso, C.; Matusiak, B.; Chelli, A.; Balasingham, I. Users' Satisfaction of Indoor Environmental Quality Conditions in ZEB+ at High Latitudes. *IOP Conf. Ser. Earth Environ. Sci.* **2019**, *352*, 012001. [CrossRef]
17. Bastian, Z.; Schnieders, J.; Conner, W.; Kaufmann, B.; Lepp, L.; Norwood, Z.; Simmonds, A.; Theoboldt, I. Retrofit with Passive House Components. *Energy Effic.* **2022**, *15*, 10. [CrossRef]
18. Marzouk, M.; ElSharkawy, M.; Mahmoud, A. Optimizing Daylight Utilization of Flat Skylights in Heritage Buildings. *J. Adv. Res.* **2022**, *37*, 133–145. [CrossRef]
19. Marzouk, M.; ElSharkawy, M.; Eissa, A. Optimizing Thermal and Visual Efficiency Using Parametric Configuration of Skylights in Heritage Buildings. *J. Build. Eng.* **2020**, *31*, 101385. [CrossRef]
20. Medvedeva, N.; Kolesnikov, S. Specifics of Daylight in Atrium Spaces of Architectural Objects. *IOP Conf. Ser. Mater. Sci. Eng.* **2021**, *1079*, 022066. [CrossRef]
21. Matusiak, B.; Aschehoug, M.; Littlefair, P. Daylighting Strategies for an Infinitely Long Atrium: An Experimental Evaluation. *Int. J. Light. Res. Technol.* **1999**, *31*, 23–34. [CrossRef]
22. Lechner, N. *Heating, Cooling, Lighting: Sustainable Design Methods for Architects*; Wiley: Hoboken, NJ, USA, 2008.
23. Pilechiha, P.; Norouziasas, A.; Ghorbani Naeini, H.; Jolma, K. Evaluation of Occupant's Adaptive Thermal Comfort Behaviour in Naturally Ventilated Courtyard Houses. *Smart Sustain. Built Environ.* **2021**, *ahead of print*. [CrossRef]
24. Atrium | WBDG—Whole Building Design Guide. Available online: https://www.wbdg.org/space-types/atrium#spcatt (accessed on 12 February 2022).
25. Samant, S. A Critical Review of Articles Published on Atrium Geometry and Surface Reflectances on Daylighting in an Atrium and Its Adjoining Spaces. *Archit. Sci. Rev.* **2010**, *53*, 145–156. [CrossRef]
26. Dai, B.; Tong, Y.; Hu, Q.; Chen, Z. Characteristics of Thermal Stratification and Its Effects on HVAC Energy Consumption for an Atrium Building in South China. *Energy* **2022**, *249*, 123425. [CrossRef]
27. Calcagni, B.; Paroncini, M. Daylight Factor Prediction in Atria Building Designs. *Sol. Energy* **2004**, *76*, 669–682. [CrossRef]
28. Younis, G.M.; Abdulatif, F.S.; Mostafa, W.S. Impact of Design Characteristics of Daylight Elements to Creating Healthy Internal Environment for School Buildings Evaluation the Status of Schools in Mosul City. *Period. Eng. Nat. Sci.* **2019**, *7*, 1354–1372. [CrossRef]
29. Matusiak, B. Daylighting in Linear Atrium Buildings At High Latitudes. Ph.D. Thesis, Norwegian University of Science and Technology, Trondheim, Norway, 1998.

30. Ebrahimpour, A.; Maerefat, M. Application of Advanced Glazing and Overhangs in Residential Buildings. *Energy Convers. Manag.* **2011**, *52*, 212–219. [CrossRef]
31. Ochoa, C.E.; Aries, M.B.C.; van Loenen, E.J.; Hensen, J.L.M. Considerations on Design Optimization Criteria for Windows Providing Low Energy Consumption and High Visual Comfort. *Appl. Energy* **2012**, *95*, 238–245. [CrossRef]
32. Thalfeldt, M.; Pikas, E.; Kurnitski, J.; Voll, H. Facade Design Principles for Nearly Zero Energy Buildings in a Cold Climate. *Energy Build.* **2013**, *67*, 309–321. [CrossRef]
33. Yousefi, F.; Gholipour, Y.; Yan, W. A Study of the Impact of Occupant Behaviors on Energy Performance of Building Envelopes Using Occupants' Data. *Energy Build.* **2017**, *148*, 182–198. [CrossRef]
34. Obradovic, B.; Matusiak, B.S. Daylight Transport Systems for Buildings at High Latitudes. *J. Daylighting* **2019**, *6*, 60–79. [CrossRef]
35. Grynning, S.; Time, B.; Matusiak, B. Solar Shading Control Strategies in Cold Climates—Heating, Cooling Demand and Daylight Availability in Office Spaces. *Sol. Energy* **2014**, *107*, 182–194. [CrossRef]
36. Van Den Wymelenberg, K. Patterns of Occupant Interaction with Window Blinds: A Literature Review. *Energy Build.* **2012**, *51*, 165–176. [CrossRef]
37. Szybinska, B.S. Daylighting Is More than an Energy Saving Issue. In *Energy Efficient Buildings*; IntechOpen: London, UK, 2017.
38. Eltaweel, A.; Mandour, M.A.; Lv, Q.; Su, Y. Daylight Distribution Improvement Using Automated Prismatic Louvre. *J. Daylighting* **2020**, *7*, 84–92. [CrossRef]
39. Marzouk, M.; Eissa, A.; ElSharkawy, M. Influence of Light Redirecting Control Element on Daylight Performance: A Case of Egyptian Heritage Palace Skylight. *J. Build. Eng.* **2020**, *31*, 101309. [CrossRef]
40. Edwards, L.; Torcellini, P. *A Literature Review of the Effects of Natural Light on Building Occupants*; National Renewable Energy Laboratory: Golden, CO, USA, 2002.
41. Xue, P.; Mak, C.M.; Cheung, H.D. The Effects of Daylighting and Human Behavior on Luminous Comfort in Residential Buildings: A Questionnaire Survey. *Build. Environ.* **2014**, *81*, 51–59. [CrossRef]
42. Acosta, I.; Campano, M.Á.; Molina, J.F. Window Design in Architecture: Analysis of Energy Savings for Lighting and Visual Comfort in Residential Spaces. *Appl. Energy* **2016**, *168*, 493–506. [CrossRef]
43. Huitfeldtbrygga. Available online: https://www.huitfeldtbrygga.no/#sidewidgetarea (accessed on 12 February 2022).
44. Piraei, F. Evaluation and Optimization of Daylighting in Heritage Buildings: A Case Study at High Latitudes. Master Science's Thesis, Politecnico di Torino, Turin, Italy, 2022.
45. Ward Larson, G.; Shakespeare, R. *Rendering with Radiance: The Art and Science of Lighting Visualization*; Morgan Kaufman: Burlington, MA, USA, 1998.
46. Mardaljevic, J. Validation of a Lighting Simulation Program under Real Sky Conditions. *Light. Res. Technol.* **1995**, *27*, 181–188. [CrossRef]
47. CEN. *European Standard EN 17037*; Daylight in Buildings. Comité Européen de Normalisation: Brussels, Belgium, 2018.
48. IESNA Daylighting Metrics Committee. *Spatial Daylight Autonomy (SDA) and Annual Sunlight Exposure (ASE)*; Illuminating Engineering Society: New York, NY, USA, 2012.
49. U.S. Green Building Council. *LEED v4.1 Building Design and Construction*; U.S. Green Building Council: Washington, DC, USA, 2020.
50. Kharvari, F. An Empirical Validation of Daylighting Tools: Assessing Radiance Parameters and Simulation Settings in Ladybug and Honeybee against Field Measurements. *Sol. Energy* **2020**, *207*, 1021–1036. [CrossRef]
51. Roudsari, M.S.; Pak, M. Ladybug: A Parametric Environmental Plugin for Grasshopper to Help Designers Create an Environmentally-Conscious Design. In Proceedings of the BS 2013: 13th Conference of the International Building Performance Simulation Association, Chambéry, France, 26–28 August 2013.
52. Wong, I.L. A Review of Daylighting Design and Implementation in Buildings. *Renew. Sustain. Energy Rev.* **2017**, *74*, 959–968. [CrossRef]
53. Mahdavinejad, M.; Nazar, N.S. Daylightophil High-Performance Architecture: Multi-Objective Optimization of Energy Efficiency and Daylight Availability in BSk Climate. *Energy Procedia* **2017**, *115*, 92–101. [CrossRef]
54. Susa-Páez, A.; Piderit-Moreno, M.B. Geometric Optimization of Atriums with Natural Lighting Potential for Detached High-Rise Buildings. *Sustainability* **2020**, *12*, 6651. [CrossRef]
55. Rastegari, M.; Pournaseri, S.; Sanaieian, H. Daylight Optimization through Architectural Aspects in an Office Building Atrium in Tehran. *J. Build. Eng.* **2021**, *33*, 101718. [CrossRef]
56. Rastegari, M.; Pournaseri, S.; Sanaieian, H. Analysis of Daylight Metrics Based on the Daylight Autonomy (Dla) and Lux Illuminance in a Real Office Building Atrium in Tehran. *Energy* **2023**, *263*, 125707. [CrossRef]
57. Erlendsson, O. Daylight Optimization: A Parametric Study of Atrium Design. Master Science's Thesis, Royal Institute of Technology, Stockholm, Sweden, 2014.
58. Norouziasas, A. Active Transparent Facades: Experimental and Numerical Evaluation on Daylighting. Master Science's Thesis, Politecnico di Torino, Turin, Italy, 2021.
59. Rutten, D. Galapagos: On the Logic and Limitations of Generic Solvers. *Archit. Des.* **2013**, *83*, 132–135. [CrossRef]
60. Yi, Y.K.; Kim, H. Agent-Based Geometry Optimization with Genetic Algorithm (GA) for Tall Apartment's Solar Right. *Sol. Energy* **2015**, *113*, 236–250. [CrossRef]

61. Nigra, M.; Lo Verso, V.R.M.; Robiglio, M.; Pellegrino, A.; Martina, M. 'Re-Coding' Environmental Regulation–a New Simplified Metric for Daylighting Verification during the Window and Indoor Space Design Process. *Archit. Eng. Des. Manag.* **2022**, *18*, 521–544. [CrossRef]
62. CEN. *European Standard EN 15193-1*; Energy Performance of Buildings—Energy Requirements for Lighting—Part 1: Specifications, Module M9. European Committee for Standardisation (CEN): Brussels, Belgium, 2017; pp. 1–140.
63. Lo Verso, V.R.M.; Pellegrino, A. Energy Saving Generated Through Automatic Lighting Control Systems According to the Estimation Method of the Standard EN 15193-1. *J. Daylighting* **2019**, *6*, 131–147. [CrossRef]
64. Shahbazi, Y.; Heydari, M.; Haghparast, F. An Early-Stage Design Optimization for Office Buildings' Façade Providing High-Energy Performance and Daylight. *Indoor Built Environ.* **2019**, *28*, 1350–1367. [CrossRef]
65. Chen, X.; Yang, H.; Zhang, W. Simulation-Based Approach to Optimize Passively Designed Buildings: A Case Study on a Typical Architectural Form in Hot and Humid Climates. *Renew. Sustain. Energy Rev.* **2018**, *82*, 1712–1725. [CrossRef]