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Modular Construction of Industrial Buildings and Lean Thinking—Identifying the Role of Daylight through a Case Study

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Abstract: This research looks at the optimisation of industrial buildings through the application of the principles of lean thinking and philosophy, with an emphasis on daylighting in the design of industrial buildings. With the use of multiparametric analysis tools, we provide a solution for the optimized design of a roof system for the provision of daylight, whilst maximising the benefits and minimising the cost during its lifetime, in different geographic and climatic regions in Greece. An optimisation algorithm has been proposed that improves the selection of the optimal roof opening type and geometry for industrial buildings in different geographical locations. The investigation of a roof system model was based on the maximum performance of daylighting, while reducing unnecessary energy use and cost. To reach our solution, we investigated the sawtooth roofing system in terms of energy cost (cooling, heating, and lighting), geography (orientation, location), and building variables (the opening dimensions and number). This has been achieved through the use of multi-parametric design, computational simulations, genetic algorithms, and the post-processing of results through statistical analysis. The use of natural lighting proved to be an effective sustainability strategy, providing energy savings of up to 20–30%, and offering economic advantages, hence presenting a comprehensive approach that benefits stakeholders and end-users by reducing the thermal loads, cooling requirements, initial HVAC costs, and overall waste. The developed algorithm has identified the optimal opening size and distance as ranging between 10 and 11 m for the conditions examined.

Keywords: artificial lighting; daylight; energy conservation; illuminance; industrial building; lean thinking

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1. Introduction

The construction and industrial sectors contribute to economic and social development [1–4], but can cause major environmental impacts. Research in collaboration between the two sectors of construction and industry offers multiple benefits. The construction industry has an important impact, both through its overall use of natural resources, and the pollutants it produces. Industrial buildings consume a large amount of energy, due to their size, complexity, and intensive use of energy for heating, cooling, ventilation, and lighting. So, the design, construction, and operation of industrial buildings have significant environmental impacts. Therefore, it is vital to assess the environmental performance of these buildings, and identify opportunities for improvement in the existing ones, as well as a proper design for the new ones. The parameters with the most weight are the building envelope, lighting, HVAC, and the production equipment, as they are the primary factors that contribute to energy consumption in an industrial building.

It is estimated that achieving this will require significant investment to reach net zero through energy-efficient buildings by 2050 [5]. In recent years, the construction industry has turned a page towards environmental friendliness. Nevertheless, the biggest subjects of this shift are office, residential, and commercial buildings, while the industrial building sector has been largely omitted from this focus. Sustainability assessment and design tools specific to buildings of industry are almost non-existent, resulting in a lack of literature and legislation on these buildings. While many studies have been carried out in terms of the pollution caused by production processes and activities in industry throughout the life-cycle of the building (through materials, heat, air, noise, water, etc.), as well as in waste treatment or recycling, less attention has been paid to the building envelope itself.

Worldwatch Institute [6] undeniably highlights the significant impact of the construction industry on the environment, emphasising its relentless demand for extracted materials from the Earth, which accounts for 60% of the total. Additionally, it is a major contributor to man-made CO_2 emissions, responsible for 50% of such emissions in the atmosphere. Moreover, [7] provides data indicating that the industrial sector is among the largest energy consumers, accounting for 26% of total energy consumption, as of 2011. In the United States, this figure rises even higher to 31% [8], with at most 7.5% of the energy obtained from sustainable sources in the same year [9]. In addition, research conducted in fifteen different divisions in the USA showed that about 15% of energy use in industrial buildings does not include production activities, while more than eighty per cent (80%) is spent on the air conditioning and artificial lighting of the space [10]. Due to the structural volumes of industrial premises, saving energy from lighting and air conditioning is a major concern, where even small energy optimisation interventions can scale up into reasonable savings in carbon footprint and operation costs. This work has made use of lean thinking as its guiding theory, based on its principal characteristics around waste elimination, and its close relationship with sustainability.

Daylight is one of the main application points of lean construction, and one of the main ways to save energy from artificial lighting [11]. On the other hand, with the penetration of natural light, one can argue that the building shell allows for an energy exchange between the internal and external environment that can lead to higher heating and cooling requirements, due to the solar gain and/or reduced u values of natural light openings against normal insulated panels. Tsangrasoulis et al. [12] have undertaken studies in order to examine a hybrid system of natural light, while Doulos et al. [13] investigated the correlation between dimming and natural light hybrid systems, whereas Kontadakis et al. [14] concentrated on the effect of dynamic daylight redirection systems. In addition to the above, various studies have been carried out on the research into daylighting systems within various types of buildings, and their results [15–18] provide evidence and scope to integrate these elements into a holistic approach towards an example design. If daylight design is left unchecked, it can create negative conditions in terms of the individual energy characteristics of the proposed solution to heating and cooling needs. As discussed earlier, if daylight entry is left fully unblocked, it can create negative conditions in terms of the individual energy characteristics of the proposed solution to heating and cooling needs. This indicates the need for the individual study of these characteristics, in order to achieve a possible reduction in the effect of natural lighting on them.

With the proper exploitation of daylight, up to 75% of the energy spent on building lighting can be saved. However, there are still many steps to be taken to maximise the use of daylight in construction design, as the effect of natural lighting, as part of solar radiation, is not included in the overall energy balance, to include the heating and cooling of the building, when calculating the benefits from a reduction in artificial lighting. Effective daylight exploitation solutions must follow an integrated approach to construction design [19]. In order to be efficient, daylight needs to be driven in a way that meets the required illuminance levels, thus minimising the installed light loads and lighting consumption, even for human-centric and biophilic design [20], thus reducing internal heat savings. Daylight design affects the requirement for air conditioning and ventilation. The additional capital costs for the improvement of daylight should be offset by savings in lighting operation costs and capital and operating costs for mechanical ventilation or air conditioning to remove the heat it produces. The above creates a need for a better understanding of, and investigation into, their interrelationships in the field of industrial construction.

The aim of this research is the investigation into, and development of, a methodology to optimise the design of industrial buildings, based on the principles of lean thinking and construction between electricity for lighting, the utilisation of natural lighting to reduce artificial lighting, the heating and cooling of the industrial building, and how they are affected by the design. The methodology will optimise industrial buildings using daylight in various regions in Greece; the creation of a multiparametric system, with the cost and optimisation parameters of daylight (ASE, UDI, sDA) is deemed necessary for the design optimisation of industrial units in terms of their sustainability. The early steps of this method were presented at the 8th International Light Symposium, Denmark, 21st–23rd September 2022 [11].

2. Materials and Methods

This project was divided into two parts. In the first part, a systematic approach was used, in order to examine the characteristics and needs of buildings in industry. The scope was to determine the features of industrial buildings, and their connection with lean construction and sustainability regarding their shape optimisation. In the second part, a case study was investigated, in order to identify the role of daylight in industrial buildings in energy savings from avoiding artificial lighting, in the energy consumption for cooling and heating, and in the initial construction cost.

2.1. Industrial Buildings

An industrial structure is planned based on its functional requirements, regardless of morphological decisions (refer to Table 1). The primary characteristic of these buildings is their uncomplicated shape. They are designed as functional "shells", primarily driven by considerations of security, adaptability, and the utilisation of the prevalent construction methods and available building materials. Moreover, these buildings predominantly comprise linear forms, with a rectangular construction.

Table 1. Characteristics of buildings in industry, and their requirements at the early design stage [21,22].

Characteristics of Buildings in Industry	Requirements during the Design Stage of Buildings in Industry
Rectangular shape (simple geometries)	Needs of the production line
Volume of one dimension	Flexibility in current and future use
Short lifespan	Speed of construction
Vast land	Sustainability/environmental performance
Concrete/metal construction	Customer's corporate identity/aesthetic
Large size of roof	Maintenance requirements
Continuous changes	Specific material
Natural light from horizontal openings	

The idea of lean construction is based in the implementation of lean thinking and philosophy within the construction industry. Being a resource-intensive sector that generates significant waste, construction has a notable environmental impact [23]. Grohmann [24] highlighted that material and workforce waste can reach up to 30% of the actual construction process, especially in regions facing clean water scarcity and high costs. Additionally, ref. [23] revealed that such waste reflects in the labour costs, leading to a potential 6% increase in the total expenses. As a result, lean construction aims to revolutionise the production management system in the construction sector by eliminating all forms of waste, including time, costs, materials, and equipment, to deliver a superior final result, and enhance customer value.

Modular construction entails the creation and control of buildings within a factory environment, enabling high-quality finishes, and the use of diverse materials, such as steel, wood, or concrete [25]. Key features of modular construction include construction safety, a reduced project duration, waste reduction, flexibility for various building types, and reusability. While these structures historically followed simple designs, recent years have witnessed the evolution of modular construction into a more multiplex and aesthetically appealing system. It not only meets basic user needs, but also allows for continuous adaptation, based on emerging requirements. Yu et al. [26] identified modular construction systems as a combination of three discrete ideas: prefabrication, standardisation, and dimensional coordination. An effective flexibility and a reduced process complexity are among the significant advantages of modular products and their implementation [27].

One of the notable advantages of modular construction is the swift completion of projects, and the reduced time between project initiation and final delivery to the customer [28]. Moreover, delays because of extreme weather conditions can be minimised [29]. Modular construction saves approximately 40% of construction time, compared to traditional on-site techniques implemented in uncontrolled environments [29,30]. This construction method offers various benefits, including project time reduction and improved quality characteristics, compared to conventional on-site construction.

Hence, standardisation emerges as a highly advantageous process throughout the manufacturing journey. Modularity and flexibility bring developments to the construction of buildings all across their life cycles, from development to reuse or resale [31]. Embracing the modular philosophy in construction enables the balanced consideration of internal (production) and external (customer) needs, promoting construction flexibility, and reducing the complexity of the overall process [27]. Modular construction stands as the most effective approach for waste reduction in the construction industry. The important reduction in both material usage and time plays a crucial role in appointing this construction method as sustainable building. Furthermore, in combination with modular design principles, it allows for the potential deconstruction and reuse of elements in future construction projects beyond the original space, given the appropriate forecasting conditions [25]. The utilisation of modular construction brings multiple benefits, as identified by Nikmehr et al. [32], in terms of waste minimisation, while Boyd et al. [33] focus on the overall development in quality.

2.2. Role of Daylight

Daylight offers numerous advantages for both human wellbeing and the environment, including an enhanced productivity, reduced errors, and a decreased electricity consumption for lighting purposes [34]. Extensive research indicates that daylight can increase productivity by 10%, and decrease errors by 30% [35]. The correlation between lighting and user performance and health is particularly significant in industrial buildings. However, the improper utilisation of daylight can result in a subpar work quality, decreased productivity, and increased errors, leading to wastage. Inadequate lighting levels in the workplace can cause employee headaches, fatigue, accidents, and stress, while excessive lighting can pose health and safety risks. Light plays a vital role in regulating circadian rhythms, alertness, concentration, cognitive performance, and various non-visual functions [36].

Studies reveal that artificial lighting accounts for 20% of global electricity consumption, surpassing the consumption of total annual nuclear energy production globally [37]. Additionally, in the construction industry, artificial lighting contributes to approximately 11% of the energy use in residential buildings, and 18% in trading buildings [38], resulting in billions of tons of carbon emissions annually. The worldwide electricity consumption for lighting is projected to continue expanding, and is expected to double in the near future, further exacerbating the carbon dioxide footprint.

Although sustainability initiatives aim to conserve energy, and reduce the environmental impact, reducing the reliance on artificial lighting is a complex task [39]. Implementing a suitable daylight system can effectively decrease lighting consumption, and minimise cooling loads on internal equipment [40]. However, despite the reduction in artificial lighting consumption, additional energy usage for refrigeration may be necessary due to the solar gains resulting from daylight penetration.

In industrial buildings, daylight serves as a crucial parameter (Figure 1) that provides multiple benefits. However, a comprehensive study, incorporating elements of visual comfort and thermal gain, is necessary to fully harness these advantages. Through thoroughly examining the characteristics and elements of daylight, and integrating them into a holistic design, appropriate, comfortable, and energy-efficient systems can be achieved in industrial buildings. Consequently, conducting a case study is imperative to exploring these aspects further.

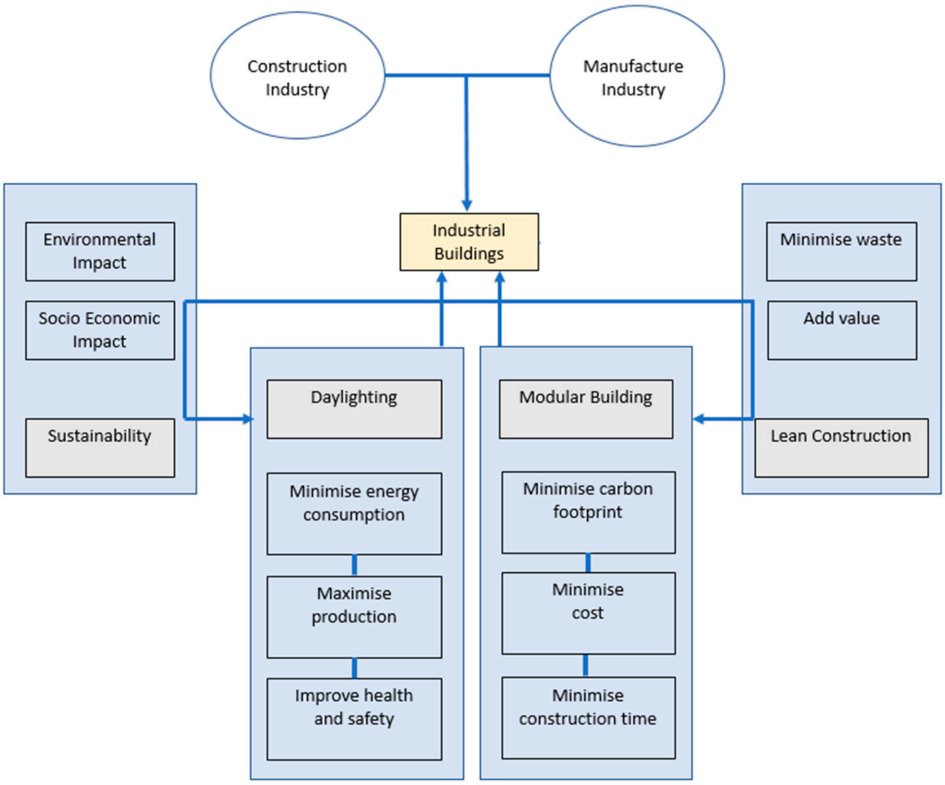

Figure 1. Sustainability, lean construction, and daylight interdependency.

3. Case Study

3.1. Building Selection

The building type selected is an industrial building in the category of low-nuisance laboratories, which have as a limit that their installed power is not to exceed 37 kW/h, based on the Greek Planning Law number 3982/2011. The industrial building model was created in detail, with the basic dimensions of 20 m width × 50 m length × 11 m height. Then, the corresponding type of roof opening was placed on the building shell (SawTooth roof, Figure 2) and, thus, the three different types being studied were created.

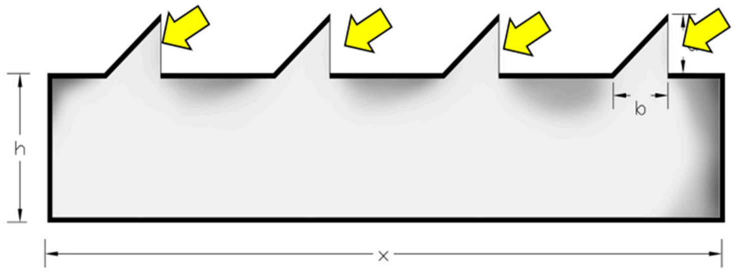

Figure 2. Model of the industrial building using a sawtooth roof (x = 50 m, h = 11 m, b = 4,5,6 m, a = 3,4,5 m).

The surface materials were chosen to have a reflection coefficient, as shown in Table 2. The construction type was chosen to be adiabatic, so that the energy used was not affected by the external conditions, but by the internal conditions and the respective roof system under consideration. The type of glass used was a 3 mm thick double glass, with a gap between the double glass of 12 mm. Through the choice of this glazing type, the typical needs for the considered climate zones of the selected cities were met [41].

Table 2. Characteristics of the model.

Surface	Reflectance	Transmittance
Floor	0.20	-
Walls	0.50	-
Ceiling	0.70	-
Glazing	-	0.80

The areas initially chosen to be studied are two extreme areas with regard to climatic conditions in Greece. The city of Heraklion, Crete, which is located in the southern part of Greece, and the city of Kastoria, which is located in the northwestern part of Greece, were chosen to be investigated. The climate data we used for Heraklion and Kastoria were produced with METEONORM, while the rest were sourced from the Energy Plus software website [42], as they were modelled through 10 years of processing relevant observations.

The parameters used, in respect of the dimensions of the openings and their number, are defined as dependent variables, while the parameters to be optimised were the daylight analysis indicators, the total energy use for cooling, heating, and lighting, and the cost. Scenarios will be checked for their orientation (N, E, S, W) for the regions of Kastoria and Heraklion. The steps are briefly described in Figure 3.

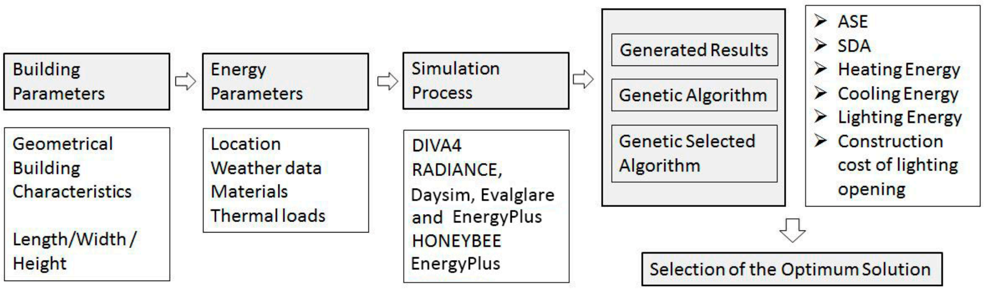

Figure 3. Flowchart of the simulation process.

Firstly, the parametric model was created in Grasshopper [43] for the Rhino computer program [44]. For the daylight simulations, DIVA4 [45] for Grasshopper for Rhino software was connected, and for the energy use simulations, Honeybee for Grasshopper for Rhino software was also connected. At the same time, an equation was created to measure the area of the glass curtains, which is linked to the model for calculating the cost. The optimisation was performed using the Galapagos genetic algorithm, which is linked to the dependent variables and the results of the parameters to be optimised.

A series of energy parameters were also evaluated, to provide a baseline understanding of how different openings affect the heating, cooling, and artificial light energy requirements for the investigated solutions. This was carried out to provide a clearer picture of how improvements in daylight conditions might affect other aspects of the building envelope's behaviour. This has been deemed important in order to address the overall requirements and provide a holistic view of design optimisation.

3.2. Simulation Parameters

Then, after we created the basic models, we parameterised them in terms of building and energy variables. The building variables are the building dimensions (width, height) and the number of openings, while the energy variables are the orientation and location (Figure 4).

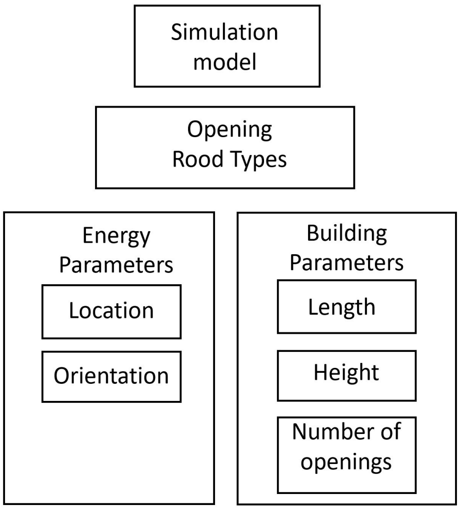

Figure 4. The types and variables of the simulation model.

Table 3 shows the type of opening present with the different cases considered. Previous work in the field identified the sawtooth type of roof opening as the superior one [46] in terms of daylight, and as a solution for optical comfort. As such, it was selected as the case study under investigation to further the work in terms of cooling, heating, and artificial lighting requirements. Table 3 provides an overview of the aforementioned cases examined.

Table 3. Characteristics of the examined case studies.

Opening Type	Height (m)	Width (m)	Number of Openings	Orientation	Location
Sawtooth	3, 4 and 5	4, 5 and 6	Varies	Four cardinal directions	Kastoria, Herakleio

The number of people was calculated according to the theoretical population of an industrial building according to Greek Presidential Decree for Fire Safety Regulations Number 71/88, according to which the theoretical population for industries and crafts is calculated with the ratio of one (1) person/10 square metres of gross surface. The installed power chosen for use is 37 kW, which is the maximum power allowed in low-noise laboratories in Greece, according to Greek Planning Law Number 3982/2011.

3.3. Artificial Lighting, Daylight, and Thermal and Cooling Loads

The artificial lighting power is 9.375 W/m^2. It was calculated according to the Relux program [47], while we chose to use the lamp Philips Lighting BY121P G3 1xLED205S/840 WB, which is suitable for industrial spaces.

One of the key control elements is the degree of autonomy in daylight, as defined by the percentage of the control surface that receives light above a certain illumination value. In the case of this study, this was chosen to be 300 lx, and over 50% of the operating hours in this space. The most important reason why we decided to use 300 lx as a guide is that we consulted EN 12464-1 [48] for industrial buildings, where the minimum lx required in the interior of industrial buildings is mentioned. The majority of work in a building of any industry requires 300 lx.

The thermal and cooling loads were evaluated only in terms of solar gains, and remained agnostic of the rest of the industrial building's functions (i.e., production line and equipment emissions, etc.). This allowed the researchers to concentrate on, and evaluate, the effects of the natural light openings on the thermal characteristics and, as such, provide an overview of the necessary adversarial considerations that should inform the design paradigms.

4. Optimisation

The optimisation parameters were selected in a way that catered for the diverse needs of the building, in terms of both lighting (natural and artificial) and HVAC (heating/cooling) energy needs, as summarised in Table 4, which presents the definitions of the examined parameters used.

Table 4. The considered metrics for the optimisation analyses.

Examined Parameter		Description
DF, daylight factor	DF	Ratio of the daylight levels inside a space to the daylight levels outside the interior space
UDI, useful daylight illuminance	UDI	% of the area surface with daylight between 100 and 2000 lx during scheduled hours
SDA, spatial daylight autonomy	SDA	% of the area surface with natural light levels greater than 300 lx for a period at least 50% of the annual scheduled hours of use
ASE, annual sunlight exposure	ASE	% of the area surface with natural light levels (caused only by sunlight) of 1000 lx and above for over 250 h annually
LEED V4	LEED	Two conditions: (1) ASE < 10%, (2) If SDA $\geq$ 55% (2 points) or 75% (3 points)
Heating/cooling energy		Annual energy simulations to calculate the end-use intensity (EUI) for heating/cooling
Lighting energy		illuminance simulations with IES light fixture definitions

The chosen opening dimensions adhere to multiparametric criteria, ensuring light uniformity as per EN 12464-1 [48], while making optimal use of the available daylight and economic considerations (Figure 5).

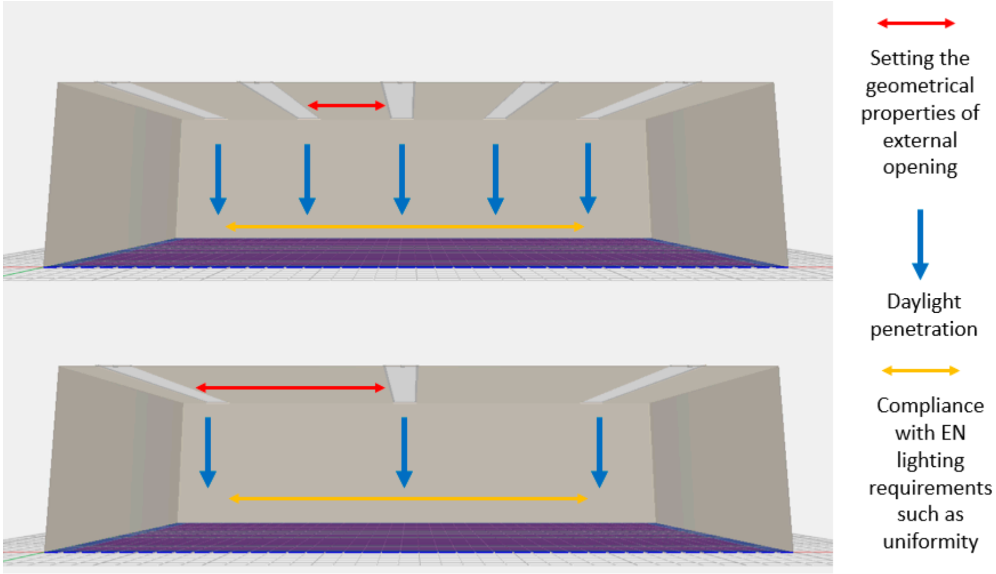

Figure 5. The spatial properties of vertical openings for a modular construction: (a) the European Norm lighting requirements, (b) considering the corresponding daylight data, and (c) minimising the total energy consumption (the heating, cooling, and lighting energy consumption).

5. Results

Upon identification of the most efficient daylight opening types for the climatically extreme regions of Greece, the work focused on identifying the potential energy and cost implications associated with such an arrangement. To do so effectively, the cities of Heraklion (Crete, 33.3387° N, 25.1442° E) and Kastoria (Central Macedonia, 37.5193° N, 21.2687° E) were selected for the running of light and energy calculations, representing distinct climatological extremes in Greece, for the south and north, respectively.

For the energy cost calculations, a median cost of 0.1244 €/kWh was used, in line with pricing practices before 2021. Additionally, the environmental impact of the energy requirements was calculated according to the 2015 statistics of the Greek energy-mix environmental impact, which amounted to an average of 0.649 kg CO_2/kWh.

With the identification of the critical roof types, and opening numbers and geometries, 295 yearly simulations took place for a typical industrial building, with a plan of 20 m × 55 m, and a height of 11 m (excluding the sawtooth opening height), with the lighting conditions assessed at a level of 0.8 m from the floor, as per the representative working height conditions. The indicative results of the daylight calculations, along with the energy requirements due to heating/cooling and artificial lighting, are presented in Table 5.

For identification of the effectiveness of the proposed opening efficiency algorithm, the numerical simulation data were categorised in accordance with their energy efficiency for different opening distances. The results were compiled in Figure 6, showing the yearly energy cost in terms of the environmental impact of the two selected locations, according to the selected distance between openings.

Table 5. The indicative results from the simulations for the selected regions.

Region	Orientation	Opening Width (m)	Opening Height (m)	Opening Distance (m)	ASE	sDA	Lighting Energy (kWh/year)	Heating Energy (kWh/Year)	Cooling Energy (kWh/Day)
Heraklion	E	4	3	9	52	79.3	10,381	2624	80,325
	E	5	4	4	74	90.8	6157	10,668	102,576
	E	4	3	6	65	86	9979	5391	90,095
	W	4	4	4	78	91.3	6177	13,243	100,173
	W	4	3	9	54	81.1	7747	2492	79,719
	W	4	4	6	71	88.9	6828	8431	91,395
	N	4	3	9	0	51.9	10,123	1926	79,223
	N	4	4	4	0	85.9	5733	11,098	107,542
	N	4	5	4	0	88.5	5619	15,413	116,068
	S	4	3	9	61	85.4	8884	3246	65,237
	S	4	4	4	91	93.3	4638	16,081	71,400
	S	5	4	5	81	91.6	5836	10,422	68,679
Kastoria	E	4	3	9	49	80.1	11,507	11,287	62,691
	E	5	5	4	67	91.5	8295	51,659	82,993
	E	5	4	4	65	91.3	7592	38,191	76,369
	W	4	4	4	60	89.1	16,352	63,777	64,839
	W	4	4	5	56	87.8	16,042	53,792	61,631
	W	5	3	9	32	75.3	16,487	17,277	48,061
	N	4	4	4	0	83.1	7004	36,808	90,558
	N	5	5	4	0	85.4	6869	41,802	94,319
	N	4	3	9	0	28	14,927	8741	65,862
	S	4	3	9	62	84.5	16,487	19,955	38,511
	S	4	4	5	86	91.8	15,464	63,675	41,750
	S	5	4	4	87	92.5	15,247	63,757	41,732

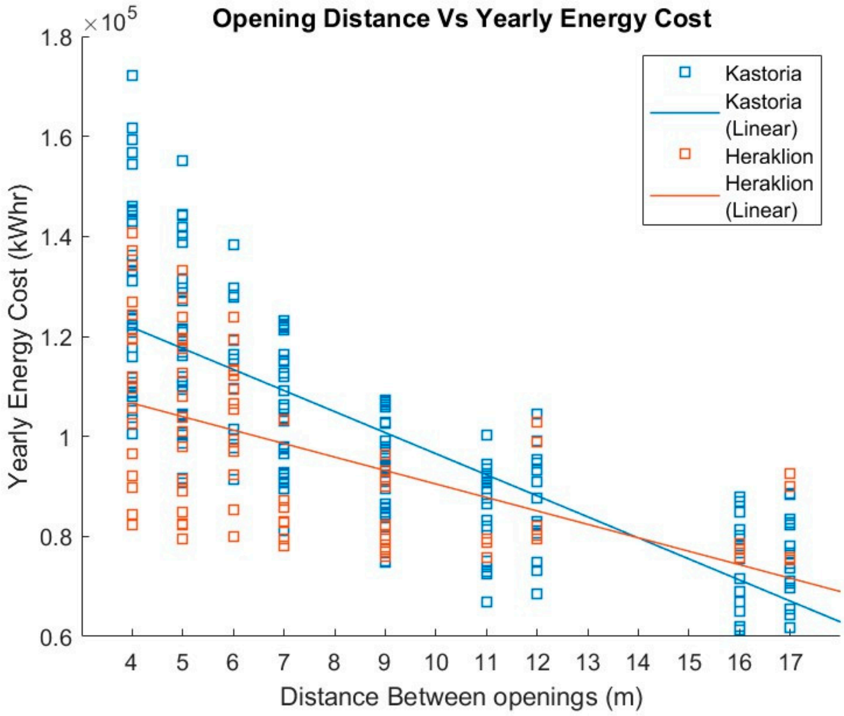

Figure 6. Opening distance vs. yearly energy cost.

If the desired selection had only to comply with the energy cost characteristics, then what the above graph shows is the relationship between larger inter-opening distances and lower energy costs associated with the roof openings. This is, indeed expected, as the modelling parameters call for an adiabatic industrial shell, where the major thermal gains and losses come from the nature, type, and size of the natural light openings. This is distinctly clear in the case of the northernmost city (Katoria), where the absolute lowest energy cost values are recorded at the opening distances of 16 m and 17 m. In the case of the southernmost city (Heraklion), such values seem to be present at 11 m, giving rise to the identification of the differences in climatic conditions and sunlight exposure between the selected locations.

In reality, architects and designers implementing natural light optimisation are keen to reduce direct glare and solar gain. As such, the selected cases have been re-examined, with those simulations showing ASE values above 40% being removed from consideration. In this case, the results seem to, again, follow similar patterns, as presented in Figure 7.

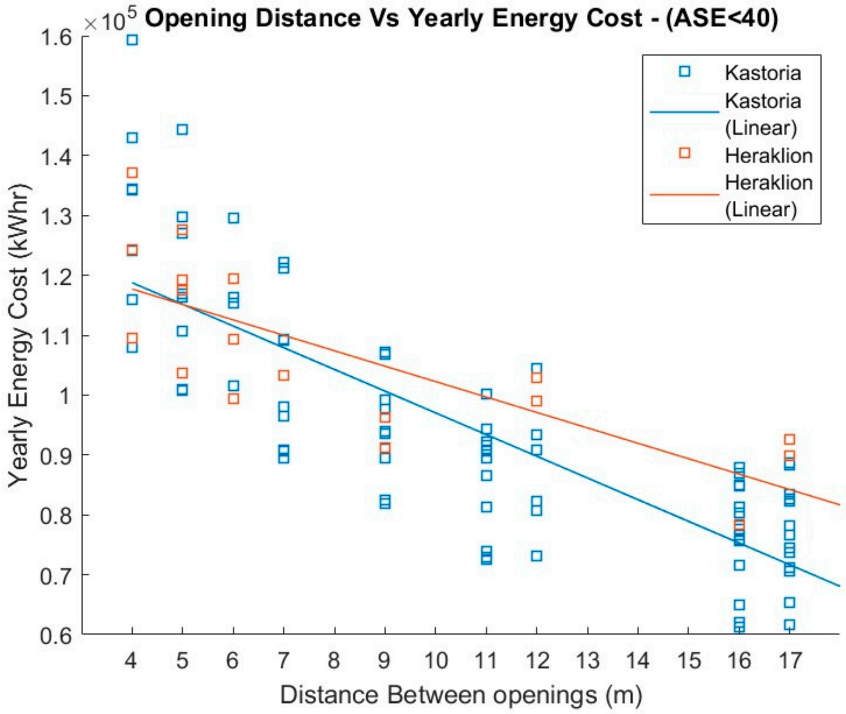

Figure 7. Opening distance vs. yearly energy cost for ASE < 40.

Once more, for the location of Kastoria city, the lowest energy cost values are present for the largest opening distances, of 16 m and 17 m, in the reduced-values dataset. In this case, for the city of Heraklion, the absolute lowest energy cost value is present at the inter-opening distance of 16 m, with the second lowest being that with the opening distance of 9 m.

The optimisation algorithm proposed used an adversarial condition scoring system that identified the suitability of natural light opening distances for industrial buildings, based on a multiparametric approach. The resulting selection algorithm, as presented in the work by Mavridou and Doulos [46], is presented in Table 6, to be benchmarked against the energy requirements and environmental impact.

Table 6. The results of penalty functions for the different opening distances simulated (higher is better).

Distance (m)	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
Penalty Function	8	8	8	8	7	10.5	10.5	9.5	9.5	8	5.5	5	5	5	3.5	4	4	4	2

6. Discussion

The primary aim of this methodology was to reduce costs, minimise the energy footprint, and enhance customer value, leading to significant changes in the design process. This research enables designers to develop a comprehensive understanding of how design choices influence the overall outcome, particularly concerning energy balance, and the influence of lean thinking processes and daylighting.

In terms of a project, lean thinking offers various advantages encompassing the environment, economy, and social aspects. The goal of sustainability in construction is to efficiently utilise resources throughout the building's design, construction, and use. In an industry that creates more waste than any other division of human activity globally [49], the above, along with modular design, allows for the creation of an improved future structure, and the extensive reuse of building elements in new construction projects [25]. Consequently, the construction industry's sustainability focus lies in achieving resource efficiency, while considering the environment, and user wellbeing. Therefore, when implementing a framework, it is vital to fully embrace production line requirements, adhere to sustainability principles, prioritise environmental preservation, and accommodate flexible usage. Notably, the principles of lean thinking in construction, which involve minimising material and time waste to maximise value, exhibit similarities with sustainable and modular construction concepts. Given that the construction industry is known for generating significant waste globally, this approach, combined with modular design, allows for the future deconstruction and reuse of building elements in new constructions elsewhere.

Although the inclination of the sawtooth roofs can have some influence on the atrium daylight quality [50], it was decided not to investigate this parameter in the parametric analysis of the presented research. The optimisation of the sawtooth inclination is also strongly related to the geographical position and the solar sun height; thus, the 90° inclination was selected, to exclude that factor. Most of the recent research uses the 90° inclination for sawtooth skylights [51,52], in order for the results to be comparable with other, future research works. Of course, this research can be a starting point for implementing the proposed methodology using other design parameters, such as the inclination, fabric coverage, daylight glare probability, etc.

The results show that designers should not look at only singular values (i.e., natural light, thermal comfort, energy use) when designing roof openings but, rather, approach the solution in a holistic manner that takes into account the different elements that contribute to successful interior design outcomes. The need to avoid overdependence on one particular parameter becomes apparent when the impact of different solutions is tested against the different parameters. Therefore, it makes little sense for the design to revolve around maximising natural light if this does not come along with visual comfort, as this can lead to issues in the production line, and worker fatigue. Similarly, when optimising for thermal comfort, it is easy to forget that natural light plays a much more important role in productivity that the traditional notion of reducing reliance to artificial lighting, and the associated energy expense. In the same vein, yearlong cooling and heating requirements are energy-intensive enough to warrant a separate look, to see whether natural light openings can offset some of the burden on a yearly basis.

In this case, two different locations within Greece were selected as representatives of the extreme latitudes experienced in the region, and the different weather patterns experienced in those two areas. In both cases, the energy/cost/natural light balance seems to converge, with the opening distances in the region of 10 m to 10.5 m producing the best results in terms of overall comfort, productivity, and energy requirements.

7. Conclusions

The authors of this study examined and analysed the philosophies of lean, modular, and sustainable construction, to identify common areas. In this work, natural lighting was found to positively impact safety, visual comfort, accidents, the health of the users, efficiency, and productivity. Moreover, the overall reduction in energy consumption directly contributed to lower pollution levels, which in turn affects the environmental impact and life cycle costing of the building. The use of natural lighting proved to be an effective sustainability strategy, providing energy savings of up to 20–30%, and offering economic advantages. Hence, it presents a comprehensive approach that benefits stakeholders and end-users by reducing thermal loads, cooling requirements, initial HVAC costs, and overall waste.

Given that lean thinking revolves around waste minimisation, it is crucial to leverage abundant resources, such as the sun and natural daylight. Therefore, utilising the sun for interior illumination and passive solar heating aligns with the principles of lean thinking, and should be employed to accomplish sustainable construction goals. The present research specifically focuses on applying lean construction through the optimisation of natural lighting in industrial buildings.

The results clearly demonstrate that the proposed algorithm for balanced daylight optimisation remains effective in terms of energy requirements.

- The opening distances of 10–11 m, which receive high scores of 10.5 in the selection algorithm, also exhibit a favourable energy consumption and environmental impact.
- Conversely, opening distances with a lower energy consumption do not provide sufficient natural lighting, and fall short in terms of lighting comfort.
- These findings align with the geographical and climatological conditions of the selected regions (Kastoria and Heraklion), indicating that the selection algorithm remains robust regardless of location, with the optimal values holding up under scrutiny regarding energy consumption.

Future research should focus on identifying the impact of selected industrial processes enveloped within the structural shell, to better identify the cooling and warming effects. Such work can lead to changes in the optimisation procedure, as they might create the opportunity for larger openings or different arrangements, leading to different optimal solutions based on the nature of the industry in question.

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References

1. Pacala, S.; Sokolow, R. Stabilization Wedges: Solving the Climate Problem for the Next 50 Years with Current Technologies. *Science* **2004**, *305*, 968–972. [CrossRef]
2. Smalley, R. Future global energy prosperity: The Terawatt Challenge. In Proceedings of the Materials Research Society Fall Meeting, Boston, MA, USA, 30 November–3 December 2004.

3. Abu, F.; Gholami, H.; Saman, M.Z.M.; Zakuan, N.; Streimikiene, D.; Kyriakopoulos, G.L. An SEM Approach for the Barrier Analysis in Lean Implementation in Manufacturing Industries. *Sustainability* **2021**, *13*, 1978. [CrossRef]
4. Aravossis, K.G.; Kapsalis, V.C.; Kyriakopoulos, G.L.; Xouleis, T.G. Development of a Holistic Assessment Framework for Industrial Organizations. *Sustainability* **2019**, *11*, 3946. [CrossRef]
5. IEA. *Net Zero by 2050*; IEA: Paris, France, 2021; Available online: https://www.iea.org/reports/net-zero-by-2050 (accessed on 12 July 2023).
6. Mastny, L. (Ed.) World Watch Institute 2005 Vital signs 2005. In *The Trends That Are Shaping Our Future*; W.W. Norton & Company: New York, NY, USA, 2005.
7. Eurostat. *Final Energy Consumption by Sector EUROSTAT*; European Union: Brussels, Belgium, 2013. Available online: http://epp.eurostat.ec.europa.eu/tgm/table.do?tab=table&init=1&plugin=1&language=en&pcode=tsdpc320 (accessed on 21 October 2013).
8. EIA. *Manufacturing Energy Consumption Survey*; U.S. Energy Information Administration: Washington, DC, USA, 2012.
9. EIA. *The Annual Energy Outlook 2012—With projections to 2035*; U.S. Energy Information Administration, U.S. Department of Energy: Washington, DC, USA, 2012. Available online: https://www.eia.gov/outlooks/aeo/pdf/0383(2012).pdf (accessed on 12 July 2023).
10. ORNL. ORNL/TM-2012/504. U.S. Manufacturing Energy Use and Greenhouse Gas Emissions Analysis. 2012. Available online: https://www.energy.gov/sites/prod/files/2013/11/f4/energy_use_and_loss_and_emissions.pdf (accessed on 12 July 2023).
11. Mavridou, T.; Doulos, L.; Nanos, N. Lean Thinking into the modular construction of industrial buildings. Identifying the role of daylight. *IOP Conf. Ser. Earth Environ. Sci.* **2022**, *1099*, 012020. [CrossRef]
12. Tsangrassoulis, A.; Doulos, L.; Santamouris, M.; Fontoynont, M.; Maamari, F.; Wilson, M.; Jacobs, A.; Solomon, J.; Zimmerman, A.; Pohl, W. On the energy efficiency of a prototype hybrid daylighting system. *Sol. Energy* **2005**, *79*, 56–64. [CrossRef]
13. Doulos, L.; Tsangrassoulis, A.; Kontaxis, P.; Kontadakis, A.; Topalis, F. Harvesting daylight with LED or T5 fluorescent lamps? The role of dimming. *Energy Build.* **2017**, *140*, 336–347. [CrossRef]
14. Kontadakis, A.; Tsangrassoulis, A.; Doulos, L.; Topalis, F. An active sunlight redirection system for daylight enhancement beyond the perimeter zone. *Build. Environ.* **2017**, *113*, 267–279. [CrossRef]
15. Song, J.; Dessie, B.B.; Gao, L. Analysis and Comparison of Daylighting Technologies: Light Pipe, Optical Fiber, and Heliostat. *Sustainability* **2023**, *15*, 11044. [CrossRef]
16. Sibley, M.; Peña-García, A. Flat Glass or Crystal Dome Aperture? A Year-Long Comparative Analysis of the Performance of Light Pipes in Real Residential Settings and Climatic Conditions. *Sustainability* **2020**, *12*, 3858. [CrossRef]
17. Mushtaha, E.; Kana'an, B.A.; Al-Jawazneh, R.A.; Hammad, R.S. Effect of using different light pipe parameters on the daylight quality in buildings: The case of Jordan. *Int. J. Green Energy* **2016**, *13*, 1590–1598. [CrossRef]
18. Mesloub, A.; Alnaim, M.M.; Albaqawy, G.; Alsolami, B.M.; Mayhoub, M.S.; Tsangrassoulis, A.; Doulos, L.T. The visual comfort, economic feasibility, and overall energy consumption of tubular daylighting device system configurations in deep plan office buildings in Saudi Arabia. *J. Build. Eng.* **2023**, *68*, 106100. [CrossRef]
19. Arasteh, D.; Selkowitz, S.; Apte, J.; LaFrance, M. *Zero Energy Windows (No. LBNL-60049)*; Lawrence Berkeley National Lab. (LBNL): Berkeley, CA, USA, 2006.
20. Madias, E.-N.D.; Christodoulou, K.; Androvitsaneas, V.P.; Skalkou, A.; Sotiropoulou, S.; Zervas, E.; Doulos, L.T. The effect of artificial lighting on both biophilic and human-centric design. *J. Build. Eng.* **2023**, *76*, 107292. [CrossRef]
21. Single-Storey Steel Buildings Part 1: Architect's Guide, The Design Guide Has Been Produced in the Framework of the European Project "Facilitating the Market Development for Sections in Industrial Halls and Low Rise Buildings (Sechalo) Rfs2-Ct-2008-0030". Available online: https://www.steelconstruction.info/images/d/da/SBE_SS1.pdf (accessed on 12 July 2023).
22. Design of Steel Structures II (Web Course), Indian Institute of Technology Madras Prof. S. R. Satish Kumar. Available online: https://civiltechnocrats.files.wordpress.com/2013/11/design-of-steel-structures-ii-prof-s-r-satish-kumar-prof-a-r-santha-kumar.pdf (accessed on 12 July 2023).
23. Pinheiro, M.D. Construção Sustentável—Mito ou realidade. In Proceedings of the VII Congress National of Environment Engineering, Lisbon, Portugal, 6–7 November 2003.
24. Grohmann, M.Z. Redução do Desperdício na Construção Civil: Levantamento das Medidas Utilizadas pelas Empresas de Santa Maria. In Proceedings of the VI Congress Internacional of Industrial Engineering, Anaheim, CA, USA, 15–20 November 1998; Universidade Federal Fluminense UFF: Rio de Janeiro, Brazil, 1998.
25. MBI. Using Off-Site Construction to Eliminate Waste in Design Phase Modular Building Institute MBI and BD+C Modular Advantage. 2011. Available online: http://www.modular.org/htmlPage.aspx?name=Eliminate_Waste (accessed on 10 October 2011).
26. Yu, H.; Al-Hussein, M.; Al-Jibouri, S.; Telyas, A. Lean transformation in a modular building company: A case for implementation. *J. Manag. Eng.* **2013**, *29*, 103–111. [CrossRef]
27. Marshall, R.; Leaney, P. A system Engineering Approach to Product Modularity. *Proc. Inst. Mech. Eng. Part B J. Eng. Manuf.* **1999**, *213*, 847–851. [CrossRef]
28. Kawecki, L.R. Environmental Performance of Modular Fabrication: Calculating the Carbon Footprint of Energy Used in the Construction of a Modular Home. Ph.D. Thesis, Arizona State University, Midsize City, AZ, USA, 2010.
29. NAHB. *Lean Construction. Report*; National Association of Home Builders: Marlboro, MD, USA, 2006.
30. Smith, R.E. *Prefab Architecture: A Guide to Modular Design and Construction*; John Wiley & Sons: Hoboken, NJ, USA, 2011.

31. Rogan, A.L.; Lawson, R.M.; Bates-Brkljac, N. *Value and Benefits Assessment of Modular Construction Report*; Steel Construction Institute: Berkshire, UK, 2000.
32. Nikmehr, B.; Hosseini, M.R.; Rameezdeen, R.; Chileshe, N.; Ghoddousi, P.; Arashpour, M. An integrated model for factors affecting construction and demolition waste management in Iran. *Eng. Constr. Archit. Manag.* **2017**, *24*, 1246–1268. [CrossRef]
33. Boyd, G.; Zhang, G. Measuring improvement in energy efficiency of the US cement industry with the ENERGY STAR Energy Performance Indicator. *Energy Effic.* **2013**, *6*, 105–116. [CrossRef]
34. IESNA. Illuminating Engineering Society of North America. In *The IESNA Lighting Handbook*, 9th ed.; IESNA: New York, NY, USA, 2000.
35. ILO. Physical Hazards, Indoor Workplace Lighting. International Labour Organization OSH Brief No. 3c. 2014. Available online: http://www.ilo.org/wcmsp5/groups/public/{-}{-}-americas/{-}{-}-ro-lima/{-}{-}-sro-port_of_spain/documents/presentation/wcms_250198.pdf (accessed on 12 July 2023).
36. Vandewalle, G.; Maquet, P.; Dijk, D.J. Light as a modulator of cognitive brain function. *Trends Cogn. Sci.* **2009**, *13*, 429–438. [CrossRef]
37. IEA. *World Energy Outlook IEA Publications*; 9 rue de la Fed Eration; 75739 Paris Cedex 15; IEA: Paris, France, 2012.
38. EERE. Building Energy Data Book Office of Energy Efficiency & Renewable Energy. 2011. Available online: https://openei.org/doe-opendata/dataset/buildings-energy-data-book (accessed on 12 July 2023).
39. Leslie, R. Capturing the daylight dividend in buildings: Why and how? *Build. Environ.* **2003**, *38*, 381–385. [CrossRef]
40. Ander, G. Daylighting. 2016. Available online: https://www.wbdg.org/resources/daylighting (accessed on 12 July 2023).
41. *Greek Energy Efficiency Regulation of Buildings*; N.3661/2017, TOTEE_20701-1/2017; KENAK: Athens, Greece, 2017.
42. Energy Plus. Available online: https://energyplus.net/weather (accessed on 12 July 2023).
43. Davidson, S. Grasshopper-Algorithmic Modelling for Rhino. Available online: http://www.grasshopper3d.com/ (accessed on 12 July 2023).
44. McNeel, R.; Others. *Rhinoceros 3D, Version 6.0*; Associates: Seattle, WA, USA, 2010.
45. Reinhart, C.F.; Lagios, K.; Niemasz, J.; Jakubiec, A. DIVA for Rhino Version 2.0. 2011. Available online: http://www.diva-for-rhino.com/ (accessed on 12 July 2023).
46. Mavridou, T.; Doulos, L.T. Evaluation of Different Roof Types Concerning Daylight in Industrial Buildings during the Initial Design Phase: Methodology and Case Study. *Buildings* **2019**, *9*, 170. [CrossRef]
47. Relux Software. Available online: https://reluxnet.relux.com/en/ (accessed on 12 July 2023).
48. *EN 12464-1*; Light and Lighting—Lighting of Work Places—Part 1: Indoor Work Places. International Organization for Standardization: Geneva, Switzerland, 2021.
49. Meadows, D. Designing Out Waste. Environmental Design & Construction. 2011. Available online: http://www.edcmag.com/articles/87434-designing-out-waste#comments (accessed on 12 July 2023).
50. Xue, Y.; Liu, W. A Study on Parametric Design Method for Optimization of Daylight in Commercial Building's Atrium in Cold Regions. *Sustainability* **2022**, *14*, 7667. [CrossRef]
51. Acosta, I.; Navarro, J.; Sendra, J.J. Daylighting design with lightscoop skylights: Towards an optimization of shape under overcast sky conditions. *Energy Build.* **2013**, *60*, 232–238. [CrossRef]
52. Yi, Y.K.; Tariq, A.; Park, J.; Barakat, D. Multi-objective optimization (MOO) of a skylight roof system for structure integrity, daylight, and material cost. *J. Build. Eng.* **2021**, *34*, 102056. [CrossRef]