



Article

Daylight and Architectural Simulation of the Egebjerg School (Denmark): Sustainable Features of a New Type of Skylight

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Abstract: This article discusses the performance of a new skylight for standard classrooms at the Egebjerg School (Denmark), which was built ca. 1970. This building underwent important reforms under a European project to which the authors contributed. This research aimed to create a new skylight prototype that is useful for several schools in the vicinity, since there is a lack of educational facilities. The former skylights consisted of plastic pyramids that presented serious disadvantages in terms of sustainability matters. During the design process, the priority changed to studying the factors that correlate daylighting with energy and other environmental aspects in a holistic and evocative approach. Accordingly, the new skylight features promote the admittance and diffusion of solar energy through adroit guidance systems. In order to simulate different scenarios, we employed our own simulation tool, Diana X. This research-oriented software works with the effects of direct solar energy that are mostly avoided in conventional programs. By virtue of Lambert's reciprocity theorem, our procedure, which was based on innovative equations of radiative transfer, converts the energy received by diffusive surfaces into luminous exitance for all types of architectural elements. Upon completion of the skylights, we recorded onsite measurements, which roughly coincided with the simulation data. Thus, conditions throughout the year improved.

Keywords: skylight; daylighting simulation; radiative exchanges; sustainable school buildings

1. Introduction

The Model Educational Buildings for Integrated Energy Efficient Design (MEDUCA) Project for the Commission of European Communities proposed the renovation of some relevant educational facilities in Denmark. These buildings were inadequate as a consequence not only of the natural passing of time, but also of the demands resulting from increased migration from the neighboring country of Germany. The focus of this renovation was to make them sustainable through environmentally friendly and energy-saving strategies. During the renovation, the relationship between energy and daylighting in terms of issues of ventilation, acoustics, and insulation were the principle features [1].

The authors collaborated to predict the effects and results of a new type of skylight on the luminous and thermal performance of a typical classroom in Egebjerg School, which is located in the municipality of Ballerup (Copenhagen, Denmark). This public school, which was built in the 1970s, went through a core refurbishment within the framework of the said project (cofunded by the EU Directorate XVII for Energy (Thermie Program)). The research aimed to create a new skylight prototype for this school and other schools in the vicinity. The former skylight consisted solely of a conventional plastic pyramid that had serious disadvantages: a lack of insulation and imperviousness, glare, condensation, and undesired solar gains in summer. During the decision-making process, it was a priority to study

the factors that were correlated with light and energy dispositions, as well as other aspects such as ventilation and insulation. Many architectural designs pass for sustainable if they attain thermal regulations alone, even at the risk of subsequent energy waste in lighting devices and visual or physical discomfort. On the other hand, large glazed areas allow for more daylight into a space, but they often generate excessive heat gains or losses, which increases air-conditioning or heating loads [2]. Accordingly, the proposed new skylight improves the possibility of capturing solar energy in winter, and at the same time, internal louvers produce a uniform diffusion of light through the adroit guidance of impinging radiation.

Our participation in an international design team, which was formed from experts from various disciplines, was pivotal in the study of different solutions for such skylights, taking into account the possibility of direct sunlight and comparing climates as diverse as those of Egebjerg (Denmark) and Seville (Spain). We observed through our research an apparent contrast: in less sunny climates, there seems to exist a demand for the admittance of solar radiation irrespective of potential disadvantages, and therefore it is a requirement for future designs. On the contrary, users from southern Europe tend to neglect this attitude, avoiding sunlight if possible [3].

The proposed new “lantern” should overcome these constraints of obsolescence and environmental inefficacy, providing better performance. Some of its main features are a vertical south-oriented main surface double-layered with thick glazing and internal custom-designed louvers made of acoustical tiles (a compound of basaltic wool), vents, and opaque protections on the eastern and western sides. Rapidly, we assumed the need for establishing ventilation, daylighting, and improved acoustic behavior, and the authors conducted several trials in order to adjust the project. The design proposals were the bases for their substitution for the obsolete skylights, which consisted of a typical pyramid made of plastics that after some years showed problems with overheating and decay (Figure 1).



Figure 1. View of the no longer extant skylights consisting of a pyramid structure made of plastics.
Source: authors.

Methods of simulation for radiative transfer developed in other articles and books were employed for the diverse proposals that evolved in the hands of architects and engineers until an optimal design was reached from both an environmental and cultural point of view, as attitudes toward sunlight are very different within unified Europe [4–6]. The main goal was to get to know and control the performance of the skylights under conditions of direct sun. This, from a scientific point of view, had not been attempted before in northern latitudes.

In architecture, a great deal of projects, buildings, and competitions tend to emphasize the adequacy of a design regarding the aspects of control and utilization of light, but subsequent scientific studies to verify these good wishes have often been scarce and deficient. It is fair to recognize that such studies are not simple, but it is equally just to demand in the near future more sensibility about the question and changes in design trends that ensure that sustainability is truly fulfilled and not only covered by words or hypothetical design intentions, if sustainability represents a good objective for the project.

We demonstrated through monitoring that the contribution of sunlight to general lighting in a building could be well over 80% in quantitative terms for most countries [7]. However, the number of designers in the world familiar with the concepts and techniques of sunlighting is still low in comparison, and we intended to remedy this major fault with the help of the scientific advances under discussion.

2. Methodology

We focused on an assessment of various skylight models to achieve an optimal design using an accurate and innovative daylighting simulation method that we have presented in former publications [8]. This method, which is based on a calculation of luminous radiative transfers, represents an advance in relation to the research of J. H. Lambert and his theorem of reciprocity [9], which was continued later by H. H. Higbie, J. Yamauchi, Moon, and Domina Spencer, among others [10–12].

The procedure extends the radiant properties of diffusing surfaces to luminous exitance of all kinds of building receivers (of whatever shape), which we treat accordingly and successively as radiative exchangers by means of the reciprocity theorem [13].

The former implies solving and balancing the general equation

$$\varnothing_{1-2} = (E_{b1} - E_{b2}) \int_{A_1} \int_{A_2} \cos \theta_1 \times \cos \theta_2 \times \frac{dA_1 \times dA_2}{\pi \times r^2} \quad (1)$$

for all emitters A_i involved in the space under consideration, where A_1 and A_2 are the two sources involved, r is the distance vector between the said sources, and $\cos\theta$ represents the angle between the distance and the normal to the respective surface. E_b stands for the irradiance expedited by each surface.

Once we know the initial intensity of a given boundary and the primary shape of the sources is fixed, successive interchanges can be obtained until a balance with the desired accuracy is achieved.

To simulate the performance of different scenarios, we employed our simulation tool, Diana X (which has been thoroughly validated). This research-oriented software deals with the effects of the luminous fraction of direct solar energy that conventional programs based solely on point-to-point exchanges for diverse sky conditions often underestimate. Our method feasibly encompasses the effect of sunlight both on radiation quantities and on the illumination field [14]. This daylighting simulation was developed in several phases following the different design possibilities of innovative skylights.

3. Objectives of the Simulation

As stated, it was necessary to introduce a model of radiative transfer capable of dealing with the effects of the luminous part of direct solar energy and to show its capabilities in a region not dominated by sunny weather. If we should need to discuss the results in terms of radiation, it is still possible, if required, to make conversions from the thermal to the luminous exchange. A caveat for the thermal domain is that Stefan–Boltzmann equations hold true when obtaining the internal temperatures of the surfaces involved once the principle temperatures are established by another procedure not detailed here.

Since the building sector is accountable for roughly 40% of global warming, it seems wise to control all sorts of energy transfers generated by the design and appearance of our architecture, and of course, this involves fenestration [15].

In this sense, it is our well-founded belief that for sustainability in architecture, solar energy must be used primarily in the openings of buildings. It is excellent to construct devices such as solar panels (which are sometimes expensive) to convert and store this natural energy, but why are we neglecting this for windows? Why is this not universal and included into normal (not additional) construction costs for all buildings?

By virtue of the above, we will be able to determine which shapes in a given situation produce adequate luminous effects, simultaneously avoiding overheating and undesired thermal responses [16]. In our humble opinion, the fight against climate change starts precisely here: in the measures implemented to control the energy use of buildings through design, avoiding as much as possible late and often doubtful additions.

4. Design Scenarios

Radiation values on horizontal and tilted surfaces are widely used around the world, and they can be measured with a certain ease. We have proposed in previous articles methods for calculating those values in the absence of real data. Thus, the former dependence on complex sky models has been reduced to a minimum, and design components using controlled direct radiation as louvers and light shelves can be analyzed much in the same way as unobstructed windows.

Bearing in mind the aforementioned issues, we designed and built a skylight prototype for the said classrooms (Figure 2). The so-called new “lanterns” were conceived of to control the incident solar energy in the building through the roof. We should note that this is the building surface with the highest incident solar radiation in all climates, and it allows for greater flexibility in connecting classrooms and other educational spaces with an outside environment.



Figure 2. Final skylight proposal for Egebjerg School: (a) general view; (b) row of skylights. Source: authors. Source: authors.

We evaluated various proposals for skylights in order to determine the forms with the best results for this particular situation. The paradoxical question was how to achieve a good daylighted environment and energy savings in winter without increasing the thermal loads in summer. This question was not an easy one and could not be treated as an isolated factor. We had to take into account that energy savings should not be obtained at the risk of visual discomfort or severe air conditioning loads leading to thermal stress.

With regard to this, we simulated two prominent situations: overcast conditions (deemed isotropic but with hourly/monthly variation) and sunny conditions (where orientation and hourly/monthly variation were mandatory). The first condition referred to more conventional models and old-fashioned features of the Nordic climate. The second condition was more innovative, as it was the core potential of our approach to the problem, as discussed above. It was forged for warm, arid regions, where some places reach 3000 sun-hours per year. We noticed in our research that in places with limited sunlight, as in the case of Denmark, where solar radiation is not as steady as it can be in southern Europe, direct exposure and glare do not seem to bother users in daily activities.

A basic concern here was energy use and thus luminous efficacy. However, energy savings should not be obtained at the cost of visual discomfort or severe cooling loads leading to thermal stress. Acoustics, which were also a relevant aspect of the design of the new elements due to their situation in

classrooms, are an important feature that are often disregarded in standard energy studies, and we ensured that the materials employed were more absorbent of sound than reflective.

Another balance question was how to achieve solar gains in winter, reducing at the same time the thermal load in summer. Due to this, in the final phase of the design, following the team leaders' advice, the east/west facets of the "lantern" were constructed as opaque to prevent overheating in summer.

An additional protective measure was to display internal louvers in a way that represented functional solar geometry. Curiously, in Denmark, the sun's altitude angle is never over 60° . Under these conditions, deep horizontal apertures (often called lightwells) capture direct sunlight in their walls but do not allow it in the spaces underneath. In this fashion, visual comfort is ensured. Additionally, the material selected for the louvers was a kind of mineral fiber (basaltic wool) that had increased noise absorption, which dealt with the problem of excessive reverberation that partly glazed ceilings are prone to worsen. Among the diverse solutions considered, we present in Figures 3 and 4a design with the best estimates of performance in terms of light savings, visual and acoustic comfort, and the reduction of thermal loads.

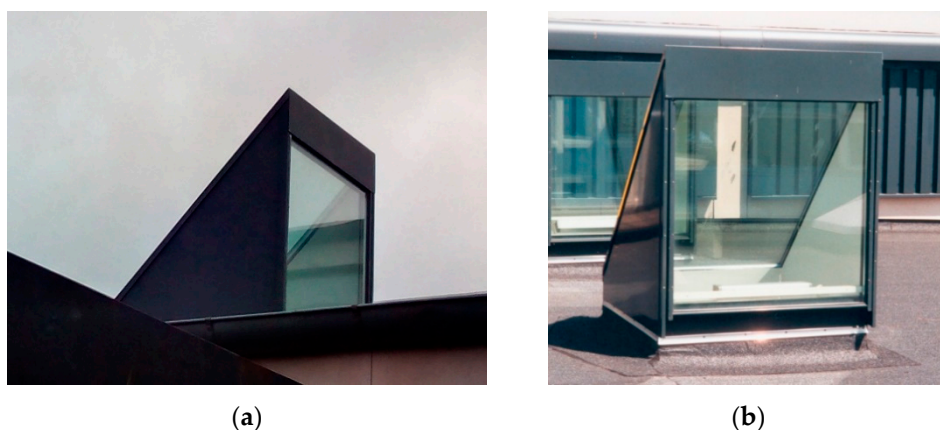


Figure 3. External details of Egebjerg School's new skylight: (a) west view of the model; (b) view from the south. Source: authors.

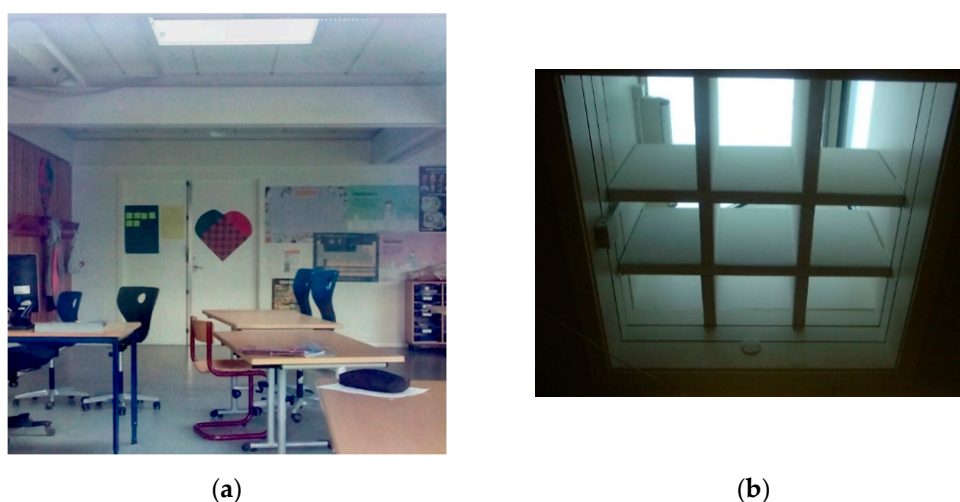


Figure 4. Internal views of Egebjerg School's new skylight: (a) regular classroom; (b) details of the internal reflective louvers made of basaltic wool. Source: authors.

A custom-designed solar chart was employed, and the different partitions and louvers of the skylight were accommodated to produce a uniform diffusion of light (a sort of functional specific solar geometry for this location) while redistributing direct radiation (Figure 5). This is the reason why the spacing of the absorbent slats is uneven.

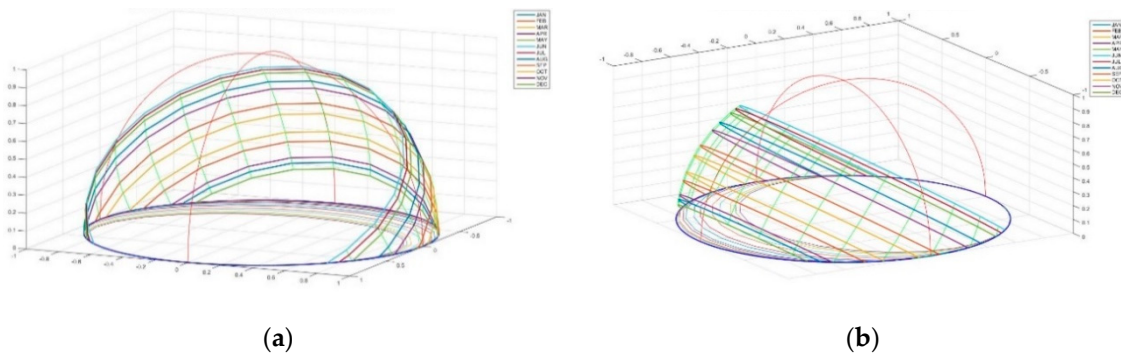


Figure 5. Ballerup’s solar chart (latitude 55.9° N), Diana X software: (a) summer solstice; (b) winter solstice. Source: authors.

Nevertheless, sparse sunrays from a high altitude are permitted at selected times because it was deemed convenient to allow that in order to add dynamic qualities to the space. We carefully checked that those rays appear outside the normal range of vision of the students (Figures 6 and 7).

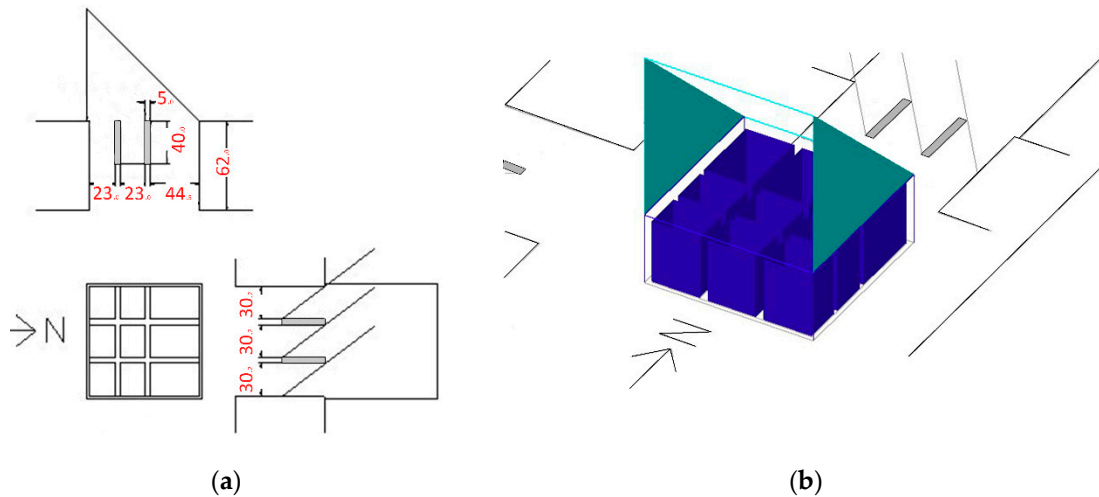


Figure 6. Final prototype for new skylights: (a) dimensions in centimetres; (b) model sketch. Source: authors.

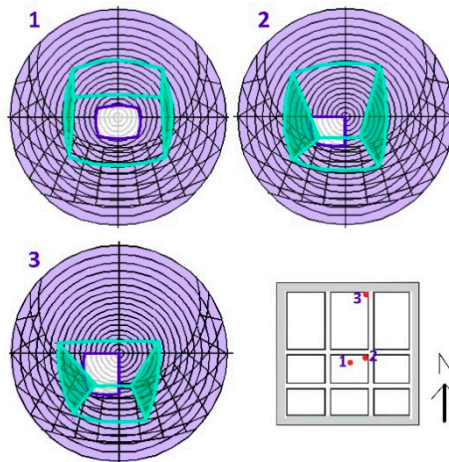


Figure 7. Stereographic projections of the model. Source: authors. As for the simulation performed, the times of the year selected were considered the most representative ones, especially the winter and summer solstices and the equinox. Within those periods, several hours were included until a complete knowledge of daylighting throughout the year was achieved.

The analyzed hours in June were 10:05, 12:00, and 13:55; the analyzed hours in December were 08:40, 12:00, and 15:20; and the analyzed hours in March and September were 09:20, 12:00, and 14:40.

5. Meteorological Data and Coefficients

The reflection coefficients of the walls were set at 0.5 and 0.6 (including maintenance) following the Illuminating Engineering Society of North America (IESNA) and European Reference Book recommendations. The perpendicular transmittance considered for the glazing was 0.60 plus a general cleaning factor for the hall of 0.90.

We used direct measures if they were available from the meteorological institute, which were tested to fare well with the algorithm proposed by Pierpoint et al. [17] to obtain daylighting intensities for vertical and horizontal surfaces as a function of the location's latitude.

We remark that in this case, the direct radiation on a surface perpendicular to the sun gives

$$E(\text{Klux}) = 127.5 \times e^{(-0.21/\sin\theta)}. \quad (2)$$

In the event of a partly cloudy sky, we obtain

$$E(\text{Klux}) = 127.5 \times e^{(-\frac{0.80}{\sin\theta})}. \quad (3)$$

The corresponding projections for horizontal and vertical surfaces are

$$E_h = E_n \times \sin\theta, \quad (4)$$

$$E_v = E_n \times \cos\theta \times \cos\Phi, \quad (5)$$

where θ = solar altitude in radians, and Φ = azimuth of the sun with respect to the vertical surface considered.

The horizontal illuminances under three frequent types of sky (clear, partly cloudy, and overcast) are, for a clear sky,

$$E(\text{Klux}) = 16.3 \times \sin^{0.5}\theta; \quad (6)$$

for a partly cloudy sky,

$$E(\text{Klux}) = 45.3 \times \sin\theta; \quad (7)$$

and for an overcast sky,

$$E(\text{Klux}) = 21.3 \times \sin\theta. \quad (8)$$

The clear-sky model of Gillette defines the vertical component of illuminance (in lux) for a clear sky as due to a half-hemisphere, which is determined by the equation below:

$$E_v = 4000\alpha^{1.3} + 12000 \sin^{0.3}\alpha \cos^{1.3}\alpha \left[\frac{2 + \cos\beta}{3 - \cos\beta} \right], \quad (9)$$

where β = azimuth, and α = the solar altitude. In the case of an overcast sky, similarly to the Commission Internationale de L'Eclairage (CIE) standard model, the former equation simplifies to

$$E_v = 8500 \sin\alpha. \quad (10)$$

As a result, we obtain the following values (Table 1).

Table 1. Radiation data at Ballerup, Denmark (lux).

Month	Time	Horizontal Global (Sun + Sky)	Horizontal Diffuse (Clear)	Horizontal Global (Overcast)
June	10:00	74,252.08	14,266.41	16,316.75
	12:00	83,244.56	14,927.37	17,863.68
	14:00	74,252.08	14,266.41	16,316.75
March/September	09:00	32,783.58	10,596.48	9001.76
	12:00	50,710.27	12,344.77	12,217.17
	15:00	32,783.58	10,596.48	9001.76
December	09:00	14,474.51	7870.61	4966.16
	12:00	30,891.28	10,208.98	8355.45
	15:00	14,474.51	7870.61	4966.16

Regarding the possibility of the occurrence of an overcast sky or sunny weather, we had the following values (Table 2).

Table 2. Probabilities of overcast and clear skies at Ballerup (Denmark).

Type of Sky	Sun + Sky	Overcast
March/September	76.40%	20.00%
August	86.30%	12.20%
December	78.60%	24.10%

6. Results of the Simulation

As previously expressed, two situations were investigated: overcast sky conditions (with seasonal variation) and sunny conditions (where orientation differences were significant). The first hypothesis refers to more conventional models (sadly still in vogue), but the second situation is innovative, and we believe that it can only be realized through our software. We needed to use it in order to save energy, as the luminous efficacy of free and overabundant solar radiation is much higher and more pleasant than that registered with artificial luminaires. Besides, with controlled beam radiation as the main lighting source, we were able not only to produce a more suggestive internal environment, but also to greatly reduce energy use, especially in air-conditioning overheads, as the size of the glazed apertures could be significantly diminished in comparison to conventional skylights [18]. These skylights do not control radiation, and therefore they admit excessive quantities of heat for an equivalent or even lesser luminous effect, as sunlight is not redistributed or tracked.

As we mentioned, for sustainability's sake it is better to use standard construction elements such as roof lights and windows to transmit solar energy that is able to be used and stored in the interiors in a straightforward mode, rather than to superpose collectors or other expensive makeshift devices.

Regarding the simulation that we developed, the times of year under study were the most representative ones, i.e., winter and summer solstices and equinoxes marking seasonal progression. Within each of these days, several hours were analyzed. Therefore, a complete knowledge of the performance of daylighting within the year is presented.

We show below some computer results of the simulations with commentaries (Figures 5 and 6). Horizontal daylighting values refer to a work plane located 1 m above the floor level, the normative table height. We should point out that 75% of the points studied showed a level of over 400 lux for all weather conditions, and 30% of the points considered were over 450 lux at all times, which was a fair representation of the combined design of skylights and windows. Note that the scales varied for the different moments analyzed.

6.1. March/September

6.1.1. Overcast

Levels below the new skylights were between 400 and 500 lux, which is considered adequate according to the European Reference Book (Figure 8).

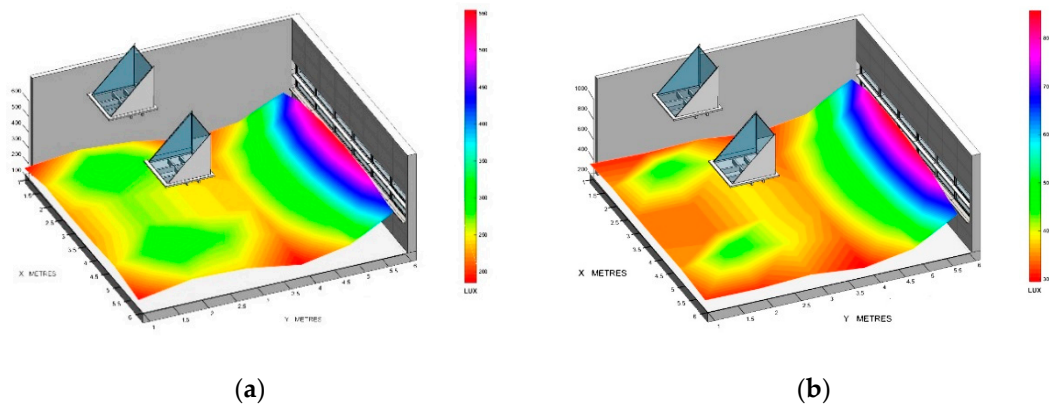


Figure 8. Overcast situation on 21 March: (a) 9:20/12:40; (b) 12:00. Source: authors.

6.1.2. Sunny Weather

The sunny weather values were from 600 to 500 lux, with a drop of 200 lux in the early morning and late afternoon (Figure 9).

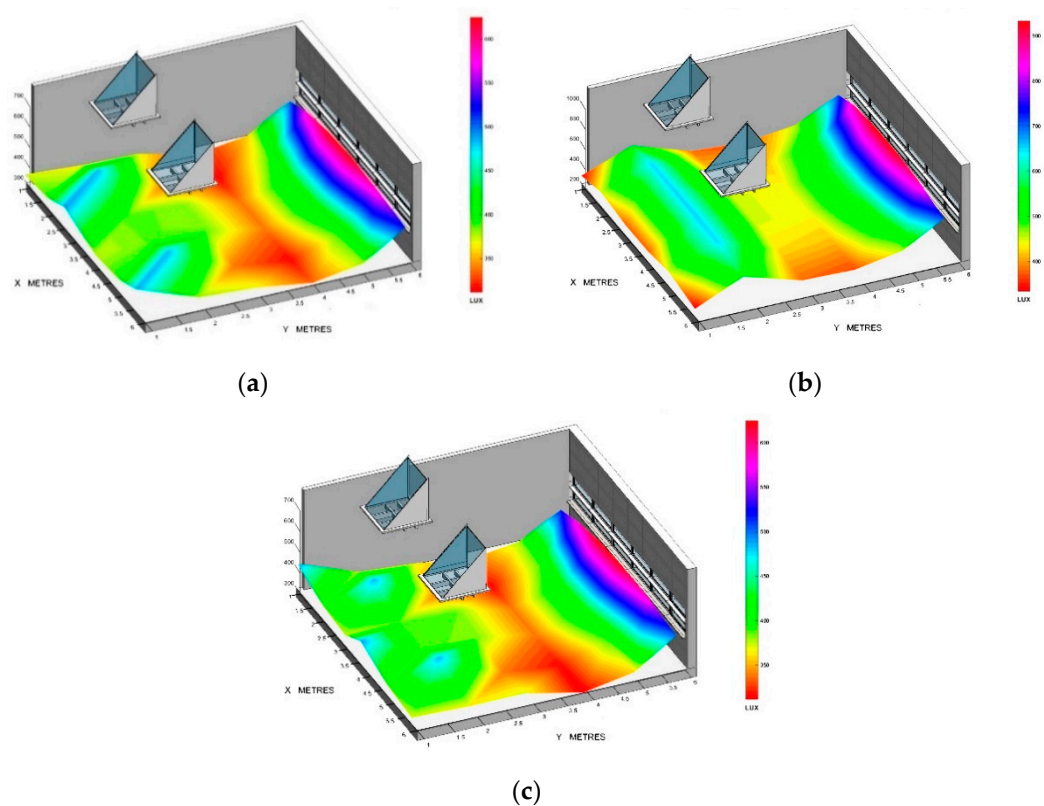


Figure 9. Sunny situation on 21 March: (a) 9:20; (b) 12:00; (c) 14:40. Source: authors.

6.2. June

Generally speaking, in June the values were high but well distributed around the lantern.

6.2.1. Overcast Situation

Daylighting levels below the skylights were around 500 to 550 lux in the morning (solar time) and more than 600 lux at noon (Figure 10).

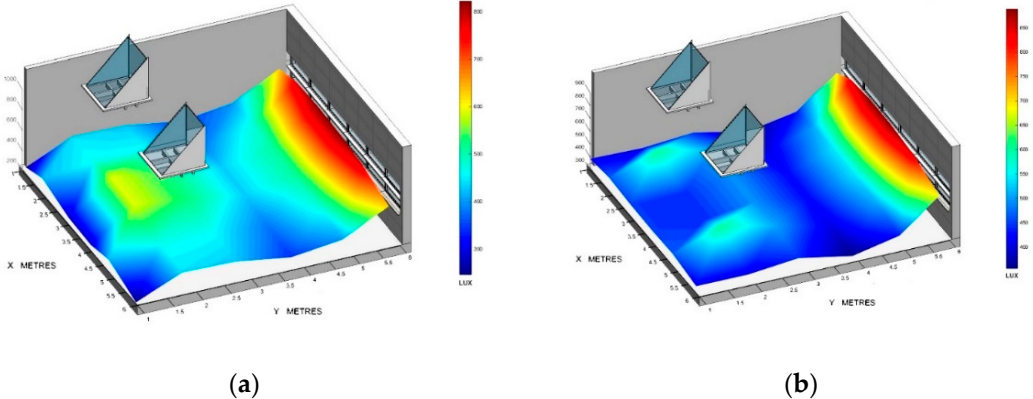


Figure 10. Overcast weather on 2 June: (a) 10:05/13:55; (b) 12. Source: authors.

6.2.2. Sunny Situation

In the sunny situation, the levels were over 500 lux. As a rule, the values showed a scattered distribution (Figure 11).

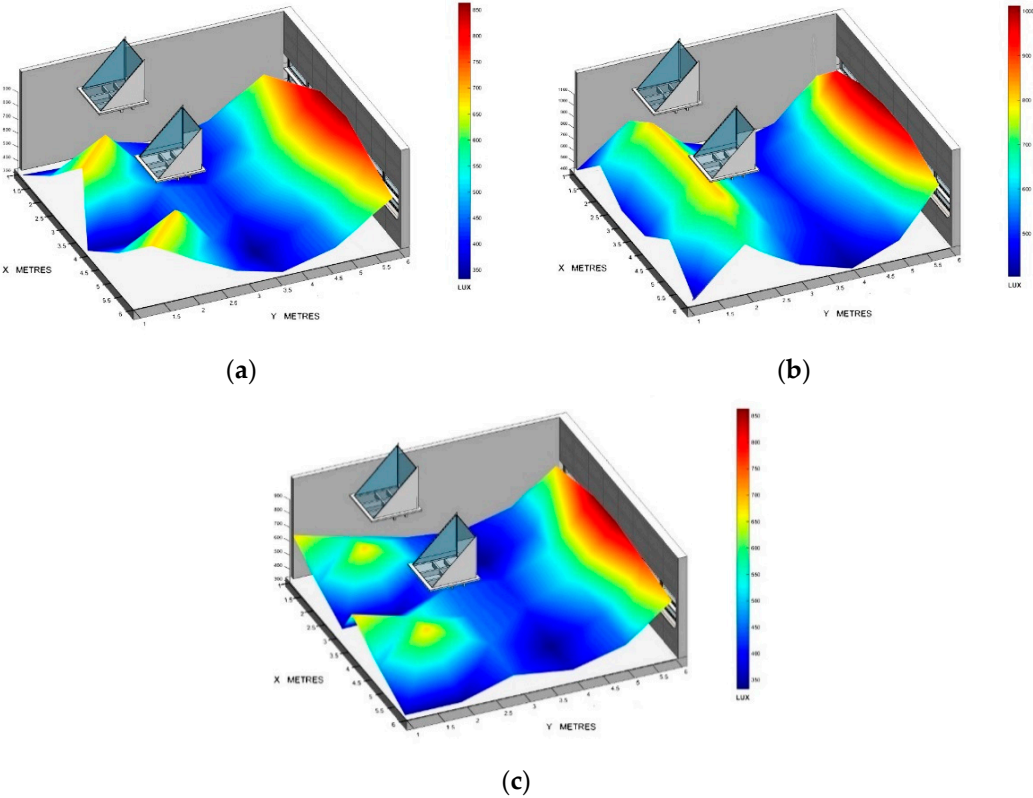


Figure 11. Sunny conditions on 21 June: (a) 10:05; (b) 12:00; (c) 13:55. Source: authors.

6.3. December

6.3.1. Overcast Situation

In this situation, less than 350 lux was reached, and a scant 200 lux was reached at 8:40 h in the morning (solar time) (Figure 12).

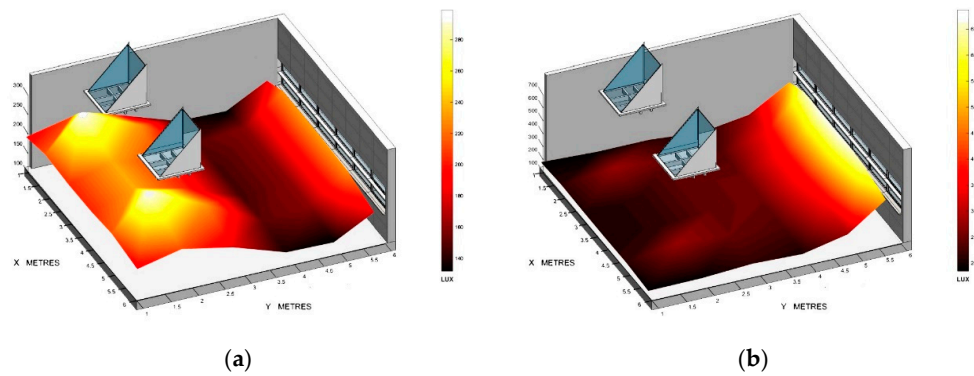


Figure 12. Overcast weather on 21 December: (a) 8:40/15:20; (b) 12:00. Source: authors.

6.3.2. Sunny Situation

In this situation, the range was 400–450 lux, and this latter value (450 lux) could be found at 12:00 solar time (Figure 13).

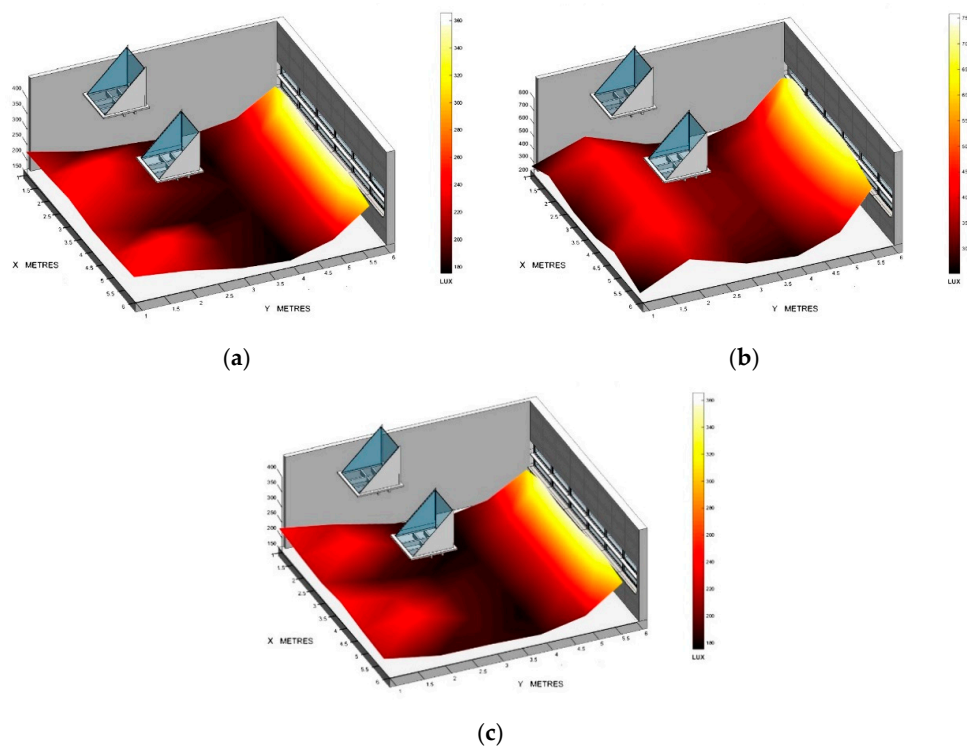


Figure 13. Sunny conditions on 21 December: (a) 8:40; (b) 12:00; (c) 15:20. Source: authors.

Daylighting in this new system is greatly dependent on solar illumination and is rarely dependent on diffuse radiation (overcast or not), and this is, in our opinion, an important innovation because it means that sunlight is being guided by virtue of a design based solely on scientific assumptions and not on convenient speculations.

7. Monitoring

The authors conducted a thorough monitoring campaign (only with reference to lighting) to modulate the range of the simulations and simultaneously check the usefulness of their outputs. An objective validation of our simulation program took place in other controlled experiments [19,20].

We took measures of light with a lux-meter PCE-170A with International Organization for Standardization (ISO) calibration, a measuring range from 0 to 120,000 lux, and an accuracy of $\pm 0.2\%$. Of these measures, we present a comparison to simulated values for a partly cloudy sky, which corresponded well due to not showing relevant discrepancies.

The slight differences registered between the simulated and measured data were presumably due to the sky being partly cloudy on the days the experiments were performed (Figure 14).

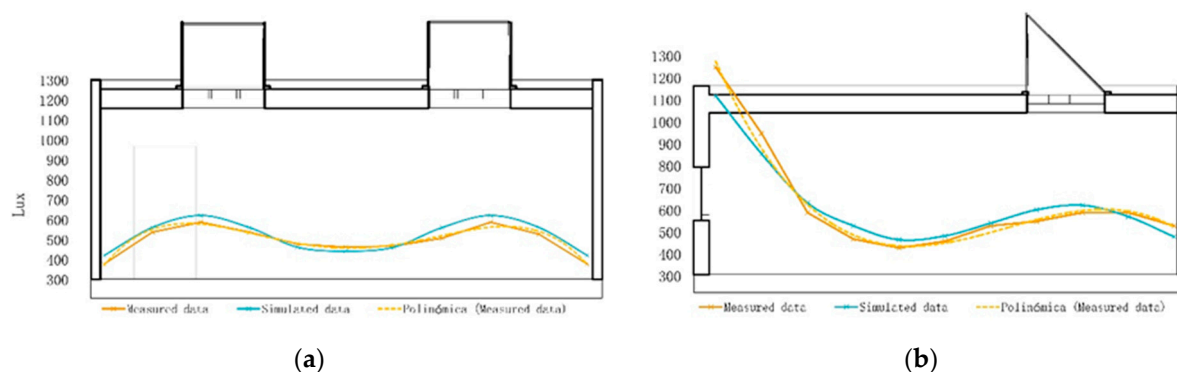


Figure 14. Comparison of measured and simulated data for partly cloudy sky at midday on 21 June: (a) east–west axis; (b) south–north axis. Source: authors.

8. Conclusions

With this research, a set of studies on natural lighting systems in Denmark was completed. The beginning was the competitive SOLAR HOUSE Project (contract JOU-CT92-0817), but it was never realized to our regret. After that, we continued with daylighting analyses for other educational and public facilities until finally reaching this application for Egebjerg. Once again, the skylights were built from scientific designs. They provided good results and closely followed our predictions, although we had no direct experience in such Nordic climates. This reveals the potential of our simulation tools.

One of the greater products of projects such as this is the significant contribution offered to the academic community’s knowledge about modern and historical skylights. This consists of recognizing the paramount fact that sunlight and solar geometry are key to the design of clerestories all over the world, as the majority of the earth’s population lives in sunny areas, and such regions are some of the most underdeveloped. If we are to avert climate change, we cannot continue disregarding this fact, and we need to reconsider models and concepts based solely on diffuse or sky radiation. Such contributions and advances were reflected at an early date, for instance, in the article “Scientific Design of Skylights”, which was presented by its authors in Brisbane (Australia) within the Passive and Low Energy in Architecture (PLEA) Conference [21].

On a more detailed level, we remark that in this project, relatively high and well-distributed daylighting levels were achieved inside the majority of the classrooms. The horizontal component of vector daylighting was above 400 lux, sometimes with higher values in winter than in summer (especially in terms of the skylights alone). The daylighting levels on the vertical planes were significantly lower, which is suitable for educational spaces. Additionally, the new skylights seemed to improve comfort levels both in winter and in summer, an advantage that was not obtained at the cost of visual discomfort (for a change).

The illuminance of the skylights was completely monitored, and the data show that they work properly and represent a valuable asset for their users. Therefore, they are still appreciated and are well maintained.

We have to stress that this example and many others that have been built in recent years validate and extend the results of the scientific determinations outlined above. Lighting design and predictions are an unequivocal benefit for the establishment of energy savings and the qualification of a space. In short, if such design philosophies are echoed, they will enhance and provide sustainable architecture for our endangered world.

Therefore, we firmly believe that the innovative skylights implemented represent a great advancement in the knowledge of design sources for natural light and a clear example of how predictions of the climate response of resilient architectural structures have fortunately produced real sustainability.

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