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Integrated Lighting Efficiency Analysis in Large Industrial Buildings to Enhance Indoor Environmental Quality

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Academic Editor: Isaac Guedi Capeluto
Received: 2 May 2017; Accepted: 31 May 2017; Published: 5 June 2017

Abstract: We present observations from evaluation of internal environmental quality of industrial halls with priority on daylighting in combination with the integral lighting. The physical parameters related to indoor lighting in large industrial halls in winter and summer periods were analyzed using in situ measurements and computational methods. These are part of a comprehensive research on indoor environmental quality of industrial halls with the aims of saving energy and providing a comfortable environment for the workers while improving the productivity. The results showed that the procedures used for evaluation of residential or office buildings may not be used for industrial buildings. We also observed that the criteria of occupants' comforts for indoor industrial buildings may differ from those of other kinds of buildings. Based on these results, an adequate attention is required for designing the industrial buildings. For this reason, appropriate evaluation methods and criteria should be created. We found the measured values of daylight factor very close to the skylight component of the total illumination. The skylight component was observed on average 30% that of the measured daylight factor values. Although the daylight is not emphasized when designing the industrial buildings and its contribution is small, but it is very important for the workers psychology and physiology. The workers must feel a connection with the exterior environment; otherwise, their productivity decreases.

Keywords: industrial building; environment; lighting analysis; building physics; sustainable architecture; computational simulation; integrated lighting; solar radiation; luminance; sky components

1. Introduction

Global warming and protection of environment are increasing issues in the modern society. These serious concerns make the reduction of carbon emissions urgently necessary [1–4]. Energy production facilitates (such as, power plants) have major contribution in the problems; therefore, decrease of energy consumption, mainly electricity for lighting as well as energy for heating and cooling buildings, have been considered as one of the main targets for solving the environmental problems. The decrease of energy consumption in buildings should not violate the comfort and safety of occupants and interfere with the main functions of the buildings. The occupants must enjoy a safe and comfortable indoor and outdoor environment while energy-saving procedures are implemented.

The present trend of industrial development requires manufacturing halls with smaller environmental impact and further workers' comfort. In the past, people were spending and working most of their time in farms, construction sites, and other workplaces outdoor under daylight during productive hours. Such a situation was obviously limiting them to work only between sunrise and sunset in proper seasons. In later years, particularly after industrial revolution and development of cities with increasing the number of industrial workers, artificial lighting as well as creation of appropriate indoor environmental quality became necessary because many previous outdoor works were moved indoors and it was almost impossible to be operate outdoors. The progress in electric lighting and construction technologies resulted in improvement of productivity and made shift work in industries possible.

Many industrial buildings are particularly designed for light industries, such as textiles, electronics, foods, and automotive. The issues related to design, construction, and operation of industrial buildings have not been comprehensively studied in comparison with residential, educational, medical, and commercial buildings. In recent years, with the advances in technology and methods, it became possible to study these issues more seriously. Generally, criteria for residential or commercial buildings may not always apply to industrial buildings, it is therefore necessary to make certain modifications in models, methods, and approaches to evaluate a proposal of manufacturing buildings, particularly in light industries.

Research activities in design and evaluation of industrial buildings have been concentrated in several subareas. The first one focuses on evaluation of the impact of buildings on the environment in terms of their sustainability [5]. The modified criteria for assessment of the sustainability for industrial buildings have resulted in development of new models [6,7].

The second area includes the evaluation of the intensity of energy consumption of industrial buildings with attention focused on the impact of different climate zones on the energy consumption [8]. For instance, various HVAC systems were analyzed to decrease the energy consumption in the buildings [9–13]. Katunsky et al. studies the thermal energy demand in an industrial building with the aim of saving the total energy consumed for heating of a manufacturing hall [14]. Effects of window structures on the energy consumption of industrial buildings have been thoroughly analyzed to enhance the design of windows to save energy [15,16].

Lighting, along with heating, is a major element in buildings value and quality that strongly influence comfort, productivity, and health of occupants. These two elements should be considered together for design and optimization of buildings, making the whole process complicated. Although the occupants comfort and health are paramount matters, but in design and optimization of buildings, both form and performance must also be taken into account.

Natural lighting is one of the most important design elements for the internal environment of buildings, including manufacturing halls [17]. Although electric lighting systems can provide useful illumination in the absence of daylight, enabling the workers to work for a longer time, they create various physical, physiological, and psychological issues [18–27]. Daylighting is very important from the visual comfort point of view in the manufacturing halls of light industries. It is an effective stimulant to the human visual and circadian systems [28]. Different aspects of daylighting and illuminations have been investigated, such as analysis of lighting quality, modeling, lighting optimization, development of control systems, visual comfort, lighting in various types of buildings (office, residential, schools, etc.), lighting in commercial buildings with different activities, sky types, lighting in different climate zones, and lighting in building design [29–64]. Gou et al. studied the visual comfort and simulating effects of lighting in relation with the productivity and well-being of the occupants [65,66]. The authors focused on the performance of buildings occupants relating to the naturally- and artificially-lit illumination.

Regardless of these advantages and necessities, daylight cannot provide the best visual performance; it can cause visual discomfort through production of glare and distraction. Daylight can also weaken the performance of the visual system through masking reflections or shadows in the workplace. The effectiveness of daylight for visual performance depends on the quality of its illumination as similar as electric lighting; thus, there are both positive and negatives aspects in the daylighting. Boundary conditions of outdoor lighting for all weather model of sky luminance distribution and preliminary configuration and validation was studied by Perez et al. [67] and Igawa et al. [68]. Some aspects of integral lighting were designed [69]. Lighting conditions in workplaces have been investigated in both practical [70,71] and computational [72] methods.

The main objective of this research was to methodologically analyze the effects of daylight in industrial hall illumination with considerations of parameters for integrated dynamic light systems using measurements and simulation methods. The research was conducted on textiles halls in Kosice, Slovak Republic. In this paper, we report the observation related to one of the knitting halls in a textile factory. This work is a continuation of our comprehensive research on indoor environmental quality of industrial buildings. We previously studied the thermal energy required for heating of a manufacturing hall using measurements and dynamic simulations. The energy needed for heating was determined according to the Slovakian and Austrian national standard methods using a simplified computational method that was designed for non-residential buildings and the ESP-r and BuilOpt-VIE simulation programs [14]. We found that the clear definitions of the heat consumers inside the building, including all machinery and occupants, are very important for evaluation of thermal energy needed for heating. The results in that work also indicated that integration of lighting, in addition to heat recovery and door opening automation, can significantly reduce the energy consumption. Those observations motivated us to conduct the present research with focus on lighting system to enhance the indoor environmental quality and workers comfort while decreasing the total energy consumption in the studied factories.

Saving of energy consumed for artificial lighting inside the buildings using daylight mainly depends on clear understanding of the daylight distribution throughout the room as well as the system used as artificial lighting. In this regard, the subject of our research project was about the physical elements of internal environment and their mutual interactions in industrial buildings, typically of large halls. The specificity of the internal environment of industrial buildings and halls characterizes the non-homogeneity of the individual kinds of internal elements, including flow of non-stationary energy in the building in space and time. The qualitative and quantitative evaluation of these characters in a prediction level is not simple. One possible evaluation method is using integrated simulation technique. Within the framework of this research project, the focus was on selected physical elements of internal environment, especially thermal, humidity, and daylighting conditions related to the analysis of the total energy demand.

The aim of the whole research was to seek ways for optimization of the conditions regarding the design of a building envelope in close connection with the environmental issues and energy intensity reduction during their services. While the new halls are built according to recent design criteria and standards, but there are significant number of old halls being renovated and used in their original functions (e.g., manufacturing activities) as well as for new applications (such as sports halls and arts galleries). Therefore, it is necessary to evaluate not only the thermal, humidity and acoustic characters of the internal environment in industrial halls, but also to add more daylight in such spaces. Because the value of daylight factor (*DF*) is small by the daylight, it is necessary to include artificial lighting, that is integral lighting. There are regulations for daylight as well as for artificial illuminations, but for the associated lighting, there are no regulations. The solutions for these problems in interactions with architecture and formation of structural details of industrial buildings should lead to the change in approach for design of these kinds of buildings. The outcome is expected to be a stately architecture, environmentally appropriate, and economically efficient and sustainable industrial building, as illustrated in Figure 1.

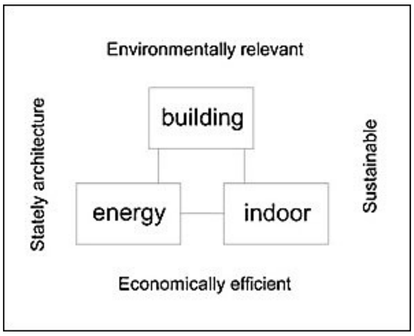


Figure 1. Scheme of requirements for industrial building design.

2. Design and Evaluation of Daylight in Manufacturing Hall

In design of buildings, it is necessary to sufficiently illuminate internal spaces to the level satisfying the standard requirements. This can be achieved through correct selection of lighting systems that would ensure the required light flux and consequently, efficient visibility during work, and provide visually comfortable environment for the building occupants. However, the lighting systems do not always ensure the required amount of daylight, especially when the area of the space is large, there is excessive dirt in the upper lighting system, or when the room is shaded by the surrounding buildings. In these cases, it is necessary to supplement natural daylight with an artificial lighting system. The combination of daylight with artificial lighting is determined by related standards under titles such as "Combined lighting of buildings" and "Integral lighting of buildings" [73,74].

In addition to natural daylight characters with its dynamics and variations during the year and each day, it is useful for every building and the occupants from various aspects. This fact is important not only from the physiological but also from psychological aspect. The selection of lighting systems for the given buildings depends on the load-bearing structural system, design of the object, and on the type of activities to be carried out in the building. In residential, civil, and light industrial buildings, where the individual departments are above each other, illumination is provided by light through windows. In heavy industry and single-storey workshops, various types of lighting systems and transparent surfaces with glass and plastic materials are used.

The indoor spaces without access to natural daylight in which lighting is provided only by artificial electric lamp system have not been successful for some reasons. For instance, in such circumstances, the connections between the interior and exterior parts of the building are interrupted. These spaces provide no natural ventilation and the ultraviolet component of solar radiation does not enter the inner spaces. The use of buildings with daylight has some benefits, as stated earlier, but a careful approach must be taken to their construction, proposal, and applications.

Recently, many light engineering standards have been revised with changes related to both natural daylight and artificial lighting. A new regulation of the problems for the formation of an internal space using combined lighting has been introduced [74]. This problem was dealt with in only a small number of selected sections of the earlier light standards. The requirements represent a qualitatively new formulation of standardization criteria including new approaches to design of lighting systems.

Daylight can be illuminated into the buildings in various ways from side, top, or combined from both directions, as shown in Figure 2. Side and top lighting can also be arranged in various forms, as presented in the chart in Figure 3. The standard CSN 360020 with a title of "Integral lighting of buildings" determines the minimum required values of *DF* for a single space in a building depending on its purpose [75]. These values are used as a basis to apply combined system of lighting (daylight and artificial illumination). The main starting point for determining the requirements on the level of combined lighting is the classification of the visual activities performed in the building, according to STN 730580 "Lighting of buildings during the day" and CSN 360450 "Artificial lighting of internal spaces" [76,77].

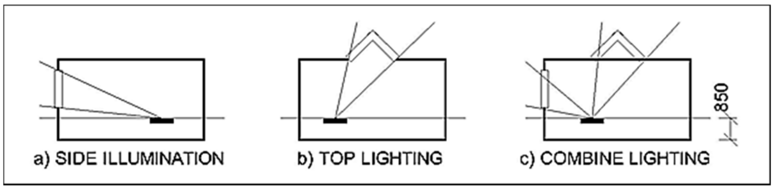


Figure 2. Daylight illumination directions: (**a**) single from one side; (**b**) top lighting; (**c**) combined lighting (dimension in millimeter).

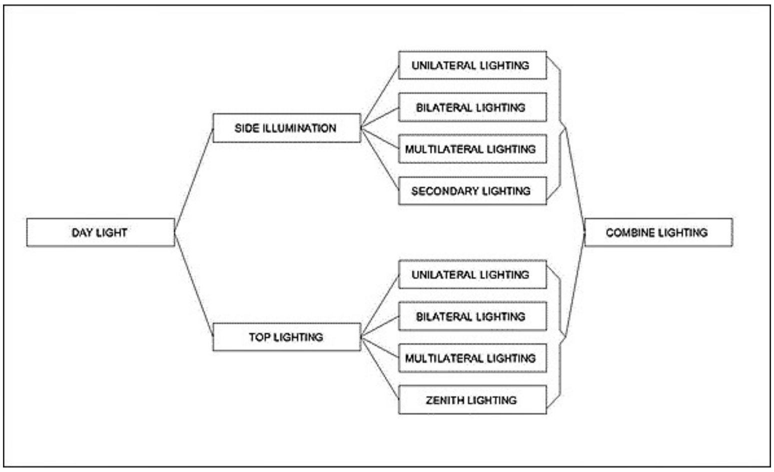


Figure 3. Possible daylight interior illumination.

The values of *DF* on the working places in which the workers permanently stay inside, the overall and graded combined illumination lighting must correspond to the values presented in Table 1, based on the national standard method of CSN 360020. In this standard, the buildings are classified into seven groups according to the intensity of the visual activities performed inside the building. Similarly, in the Slovak Republic standard STN 730580-1, the values of *DF* are grouped into seven categories representing human eye recognition for visual detail tasks. This standard classification spans from visual tasks with extreme accuracy (Category I) to those with no visual challenge (Category VII). The parameter for the observation relative distance is defined as the ratio of detail dimension to distance between detail and the observer eye, which is used for the categorization of visual tasks. For the permanently occupied indoor spaces, the *DF* value should be larger than 1.5% and 3% for the side-lit and top-lit illuminated spaces, respectively. To reduce or avoid glare, the brightness of window must be less than 4000 and or 60 cd·m^{-2} in the visual field of the observer for side-lit and top-lit illuminations, respectively. The observed ratio of luminance detail in the sky brightness should be less than 1:200th.

Table 1. Classification of buildings and corresponding *DF* values using integral illumination based on national standard CSN 360020 with minimum standard value, and minimum and mean recommended values for daylight factor (*DF*).

Category	Min. Standard *DF* (%)	Min. Recommended *DF* (%)	Mean Recommended *DF* (%)
I	1.0	1.2	3.0
II	1.0	1.0	2.5
III	0.7	0.7	2.0
IV	0.5	0.5	1.5
V	0.5	0.3	1.0
VI	0.5	0.1	0.7
VII	0.5	0.1	0.35

3. Evaluation and Computational Methods

The indoor environmental quality from the perspective of daylighting was evaluated based on *DF* values, which expresses the ratio of the indoor to the outdoor horizontal lightings of an unshaded plane. It is calculated through addition of the three components contributing to *DF*, including Sky component D_s, internal reflection $D_{i\rho}$, and external reflection $D_{e\rho}$. The illumination may take place in three ways, from side or top of the building or combined in both ways (Figure 3).

Values of *DF* in interior spaces of buildings are generally evaluated using two computational methods: flow (simulation) and point (graphical or numerical, manually or using computer) procedures. Choice of the computational method depends on the purpose. The most accurate method is using simulation programs, which can make photo-realistic image of an interior space. Generally, standards prefer the use of the point calculation method.

In other words, *DF* is a parameter expressed as a ratio of E_{iH}, the interior illuminance at a specific point on a given plane due to the light received directly and indirectly from the sky (with assumed or known luminance distribution), to E_{eH}, the exterior illuminance on the horizontal plane from an unobstructed hemisphere of the overcast sky, both quantities in lux (Equation (1)). Direct sunlight is excluded for both values of illumination.

$$DF = \frac{E_{iH}}{E_{eH}} \times 100 = D_S + D_i + D_e \tag{1}$$

where D_s, D_i, and D_e are sky, internally reflected, and externally reflected components of *DF* in percentage, respectively. These components are graphically shown in Figure 4. The *DF* value depends mainly on several parameters: Windows geometry and placement in facade, room walls and overhangs, light transmittance of glazing and shading devices, and reflectance of surrounding exterior and interior surfaces.

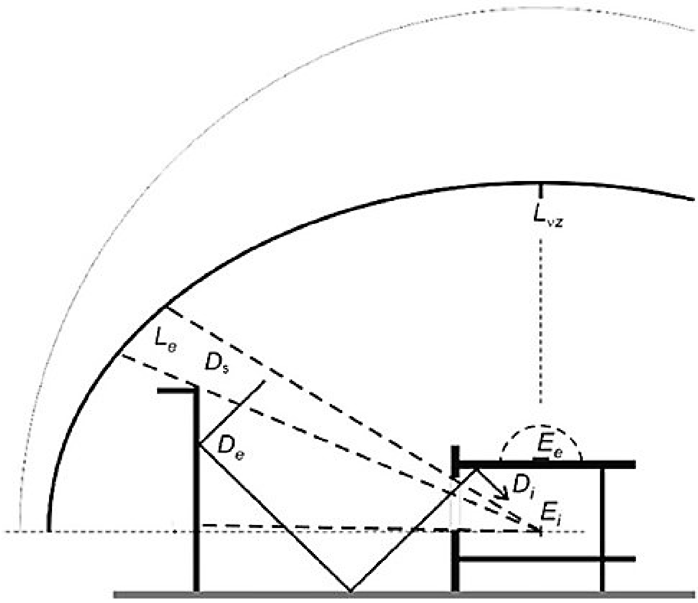


Figure 4. Diagram of the incidence of light beam on the examination area WP (working plane) and components of reflected light.

At present, there are several computational, graphical, and simulation methods to determine *DF* values and their components [73]. Various lighting simulation methods have also been proposed and validated with several tools; none of the methods are standardized. To calculate the alternatives to determine the required level of daylighting for different sizes of window (Figure 5), we used the numerical integration method for the sky component of *DF*, developed by Kittler et al. as Equation (2) [78–80].

$$D_s = \frac{3\tau_n}{7\pi} \int \frac{\cos^2 \Psi \cos v (1 + 2\cos v)(1 + 0.5 \sin^2 \Psi)}{l^2} dS_1 \quad (2)$$

τ_n: Normal light transmittance (τ_n is substituted by $\tau_{n,dif}$),
ψ: Angle of deviation of light beam from windows plane (degrees),
v: Angle of incidence of light beam in the examination plane (degrees),
l: Distance of examination point from elementary area dS_t of elimination orifice (m),
S: Window surface area (m^2).

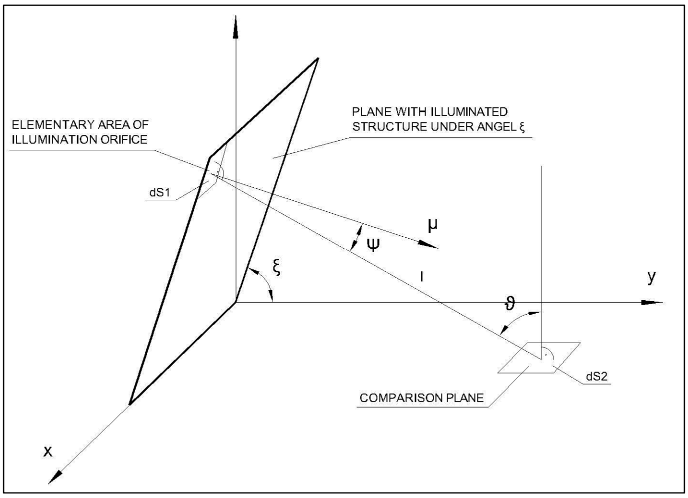


Figure 5. Geometry of light beam incidence on the observed desktop of working plane.

The basic geometry for incidence of light beam on the examination plane is presented in Figure 5. The internal and external reflection components of *DF* can be calculated from the empirical relations for the mean and minimum reflection components of *DF*, as presented in Equations (3) and (4), respectively:

$$D_\rho = \frac{85 S_W^{0.7}}{S(1-\rho)} [(0.785\rho_D) + 1.24\rho_D\, \rho_T (1 + 4\rho_T) \sin Z + 1.475\, \rho_T \rho_H \cos Z] \quad (3)$$

$$D_{\rho,min} = \frac{85 S_W^{0.7}}{S(1-\rho)} [(0.5\rho_D)(1 - \sin Z)^{1.5} + \rho_D\, \rho_T (1 - \rho_T) \sin Z (\rho_T \rho_H \cos Z)] \quad (4)$$

where S_W is window glass area (m^2), S is space area (m^2), ρ_D is light reflection coefficient on lower areas from windows axis (–), ρ_H is light reflection coefficient on upper areas from windows axis (–), ρ_T is light reflection coefficient from the terrain (–), ρ is average light reflection coefficient from all surfaces (–), and Z is angle of shadowing examined space by surrounding structures (degrees).

4. Case Study: Integral Lighting in Knitting Hall

In this section, we present information about the studied manufacturing hall, the measured and calculated results of *DF*, effects of various parameters (e.g., windows thicknesses and areas), contributions of natural and artificial illuminations. The experimental observations and simulations results are discussed.

To determine the required magnitude of lighting elements in the vertical plane of the circumferential jacket, we analyzed the lighting conditions in the selected industrial building with high levels of visually demanding work (knitting operation). The subject of the study was a textile plant in Kosice (located east of Slovak Republic) in which we selected the knitting Hall E with an aerial view shown in Figure 6a. Three photos of the investigated hall and internal Radiance images are illustrated in Figure 6. The activities in this hall are mainly production of fabrics through operating knitting machines by workers.

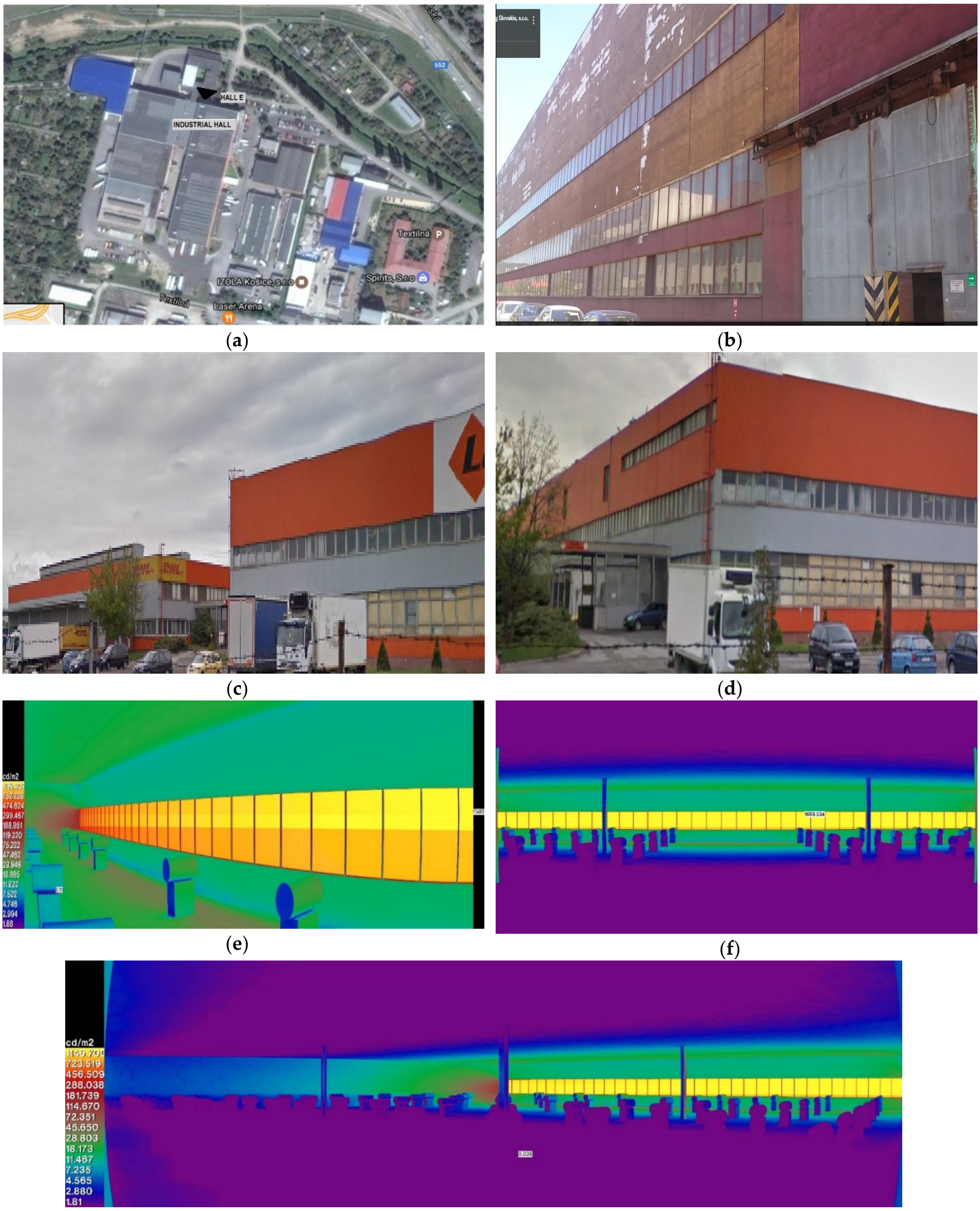


Figure 6. (**a**) Aerial view of textile factory building; (**b**–**d**) exterior view of knitting hall; and (**e**–**g**) internal Radiance images of hall revealing illuminance at various points of hall.

We considered the following boundary conditions for the calculations: Exterior horizontal illumination as 5000 lx; illuminated height 5100 mm and parapet 1200 mm. The size of the windows and the lining thickness were varied for the individual alternatives: Light loss coefficients were $\tau_1 = 0.92$, $\tau_2 = 0.74$, $\tau_3 = 0.80$, $\tau_4 = 1.0$. The light coefficients of reflections (ρ) for individual surfaces: White ceiling $\rho = 0.75$, glass areas $\rho = 0.10$, walls $\rho = 0.70$, external terrane $\rho = 0.15$ (no snow), light green mop board $\rho = 0.65$, light brown floor $\rho = 0.50$, and façade $\rho = 0.45$. Because the building is at a sufficient distance from the surrounding buildings (as shown in aerial photo of Figure 6a), the shade angle was taken as $Z = 0$.

Table 2 presents the windows sizes (the ratio of the width to the height of the window) and linings lengths. Hall E consists of 36 combined windows in a single envelope (external) wall. The floor plan of this hall is exhibited in Figure 7.

Table 2. Characteristics of six types of windows in Hall E.

Alternative	Hall E (36 windows) Size (mm)	Lining (mm)
1	1500/2400	150
2	1500/2400	250
3	1500/2400	300
4	1500/2400	400
5	1500/2100	400
6	1500/1800	400

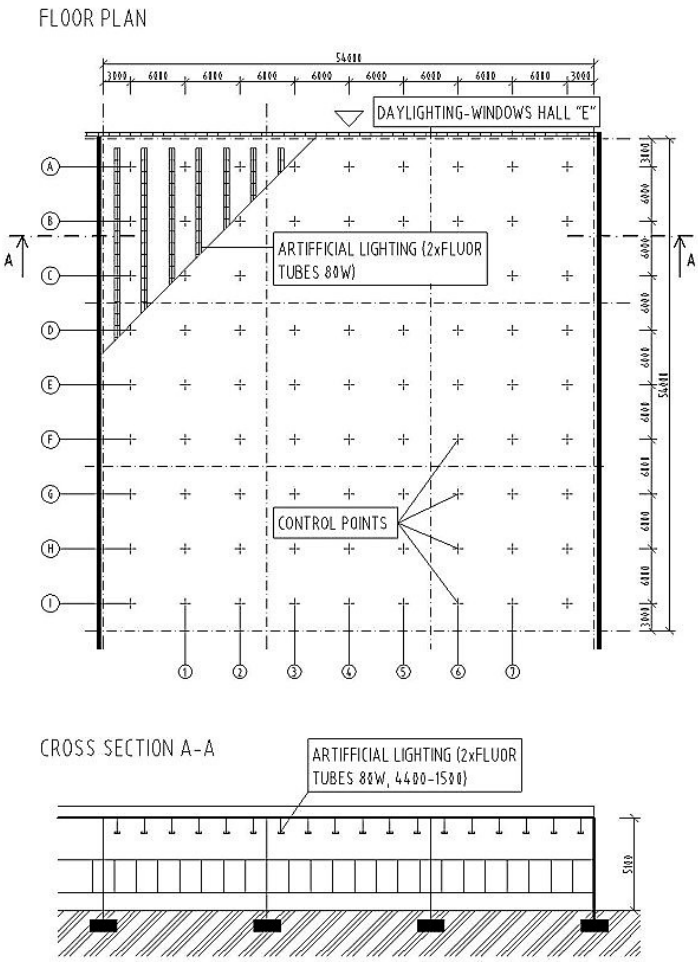


Figure 7. Floor plan and distribution of integral lighting system in Hall E (dimensions in millimeter).

Analysis of the calculated *DF* results for the inspected points (shown as control points in the floor plan of Figure 7) reveals that when using one-sided lateral illumination systems in the circumferential wall, the lines with the same *DF* values (shown in Figure 8) in the zone of working activity are not distorted and the resultant values are approximately equal in rows equally spaced in the circumferential jacket. Given decrease in *DF* value because of the tract depth, Table 3 presents the results of the selected alternatives for nine inspection points of A4 to I4 in the middle of the hall. Based on these results, it can be concluded that the effects of the lining thickness in the one-sided lateral illumination system is significant up to approximately 21 m from the windows structures, which is the point D4 in the floor plan. At points farther than D4, the effect of the lining thickness for the circumferential wall on the resultant *DF* value would be insignificant.

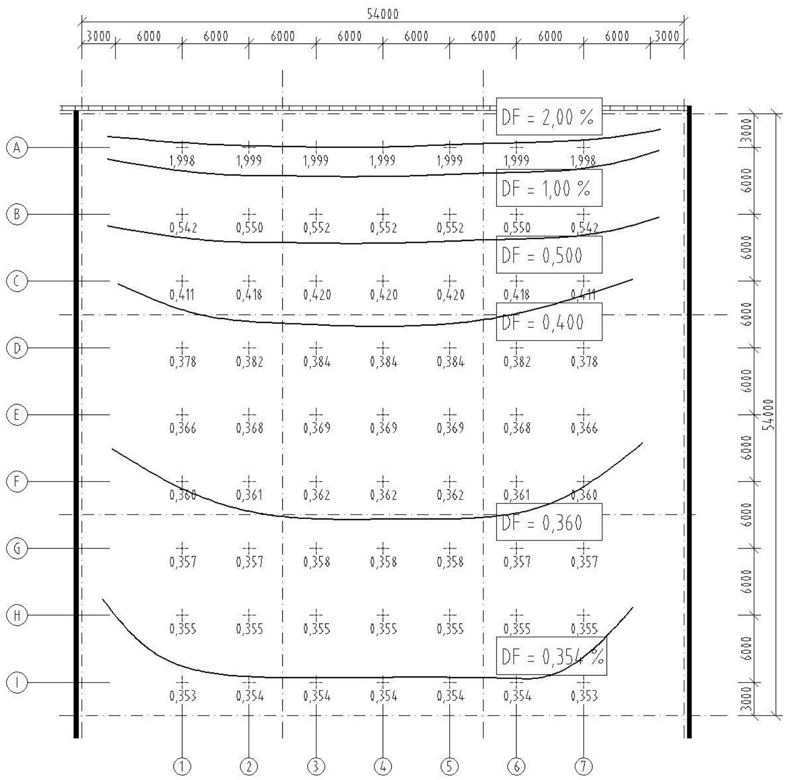


Figure 8. Distribution of daylight factor (*DF*) value at identical levels for window alternative 6 and design solution of selected areas of production zones for Hall E with contour lines for *DF* values of 2.00%, 1.00%, 0.50%, 0.40%, 0.36%, and 0.354% (dimensions in millimeter).

Table 3. Measured and calculated values of *DF* with sky lighting values in the middle points of Hall E.

Point	D_ρ (%)	D_s (%)	$D_{\rho,mean}$ (%)
A4	2.500	1.649	2.165
B4	0.400	0.202	0.670
C4	0.080	0.070	0.495
D4	0.050	0.034	0.420
E4	0.020	0.019	0.369
F4	0.015	0.012	0.330
G4	0.013	0.008	0.296
H4	0.010	0.006	0.268
I4	0.005	0.004	0.242

The measured values of *DF* at inspection points of A4 to I4 are presented in Table 3. Comparison of the measured and calculated values of the *DF* in Hall E indicates that the measured *DF* starts to approximate the skylight component at 15 mm from the window. The measured *DF* values differ from the calculated results, indicating that the reflection component of *DF*, which combines the internal and external reflection components, varies with the depth of the considered space and is not constant when calculated using Equation (3).

Measurements of the level of daylighting in Hall E were carried out at the center of the room because lines with the same level of daylight factor were mutually parallel to the external wall. The values of *DF* were also determined at windows with different thicknesses of lining and sill. When the window lining and sill thickness increased, significant decrease in the skylight component of *DF* was observed (Figure 9).

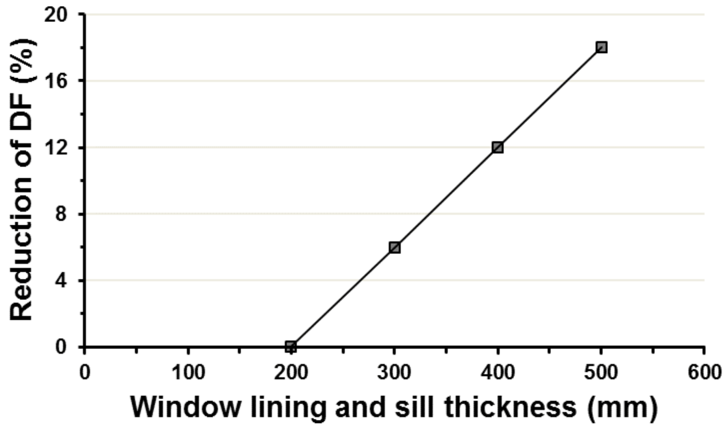


Figure 9. Dependence of decrease in skylight component of daylight factor (D_s) at various thicknesses of lining and sill for two-sided lighting illumination system.

Values of *DF* in Hall E at various distances for the six different alternative windows were determined (Figure 10). As the graph in Figure 10a reveals, the daylight factor rapidly changed at closer distances from the widows and levelled off after about 15 m. The details of variations in *DF* within 15 m from windows are shown in Figure 10b graph in comparison with minimum standard and recommended *DF* values. As the graph indicates, the *DF* values for all windows are above both standard and recommended values, which means the lighting conditions in this hall satisfy the standard requirements.

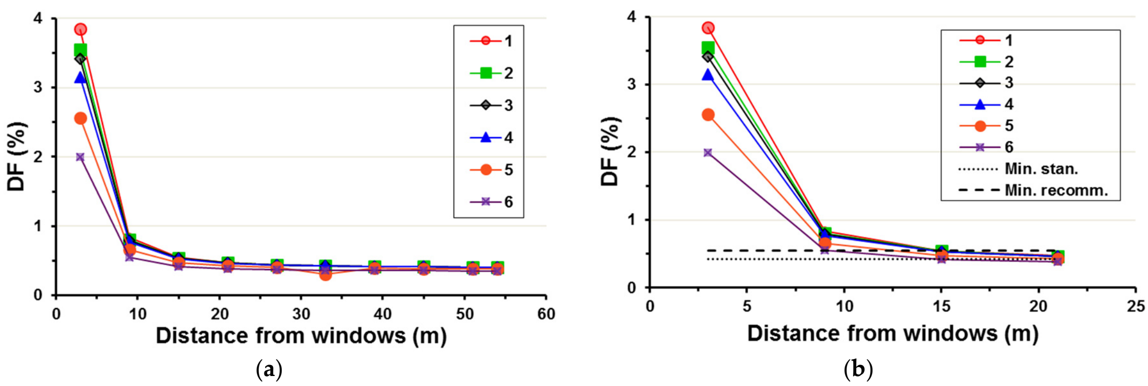


Figure 10. (**a**) Variations of daylight factor in Hall E at different distances of 3–54 m from six alternative windows; and (**b**) *DF* values within 21 m from windows are shown in more detailed in comparison with minimum standard and recommended *DF* values.

The values of *DF* components calculated with consideration of the change in *x* at the depth of the given working area are presented in Figure 11. The graph compares the individual curves of the decrease in the intensity of illumination determined based on calculations of *DF* with the curve of measured *DF* value in an actual interior space. It reveals the variation of these components at different distances from the windows compared with the measured values. The *DF* value only showed observable changes up to almost 15 m from the windows and after that the variation curves leveled off. While, at the distances closer to the windows, the measured *DF* was larger than the calculated components values, at farther distances, it was smaller. The further details of variations up to level-off onset are exhibited in Figure 11b.

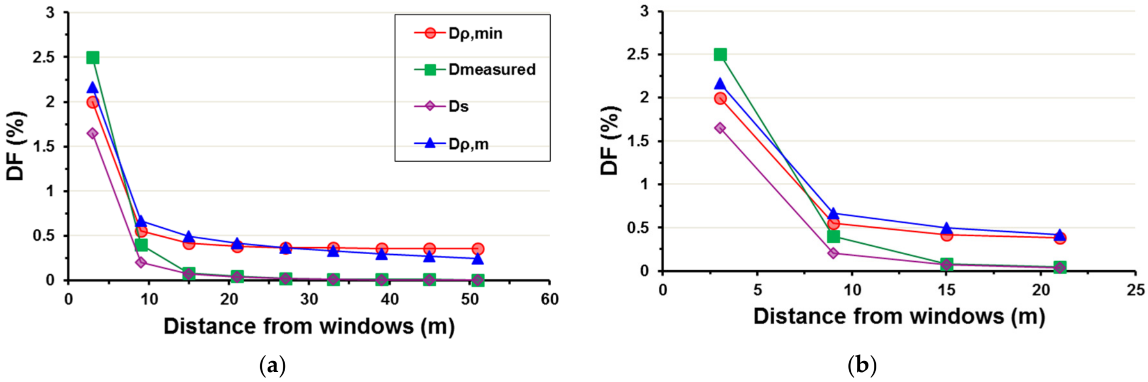


Figure 11. (**a**) Comparison of measured and calculated components of daylight factor at inspection points of Hall E from 3 to 51 m distance from the windows; and (**b**) detailed view at closer distances from windows of 3–21 m.

The artificial illumination was measured at night to exclude the impact of daylight. The average illuminance in Hall E was found as 552.06 lx with illuminance uniformity of 0.63. Figure 12 illustrates the illuminance values at different points of Hall E (see floor plan in Figure 7) and the recommended illumination value drawn as a thick horizontal line.

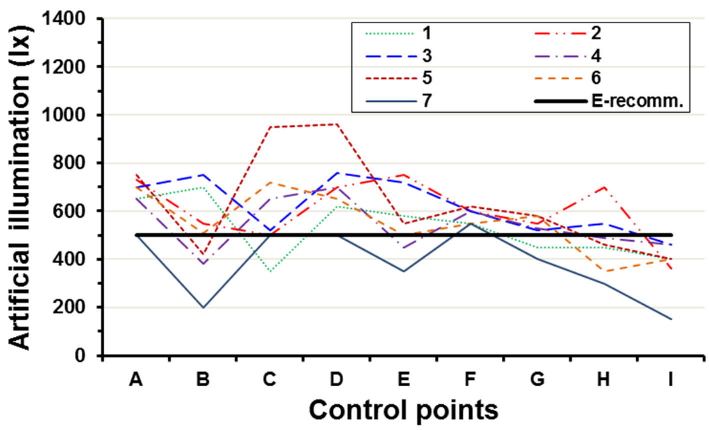


Figure 12. Dynamics of illumination with artificial light at night in control points in Hall E in comparison with the standard value.

Spatial distribution of *DF*, the distribution isocontour maps, and decrease of illuminance (minimum, mean, and maximum values) at different windows heights of 1800, 2100, and 2400 mm were determined using Radiance simulation program (Figure 13). In these graphs, *x* and *y* are distances in the directions of parallel and perpendicular to the windows, respectively.

Spatial Distribution of *DF*	Distribution of *DF* Isocontour Maps	*DF*

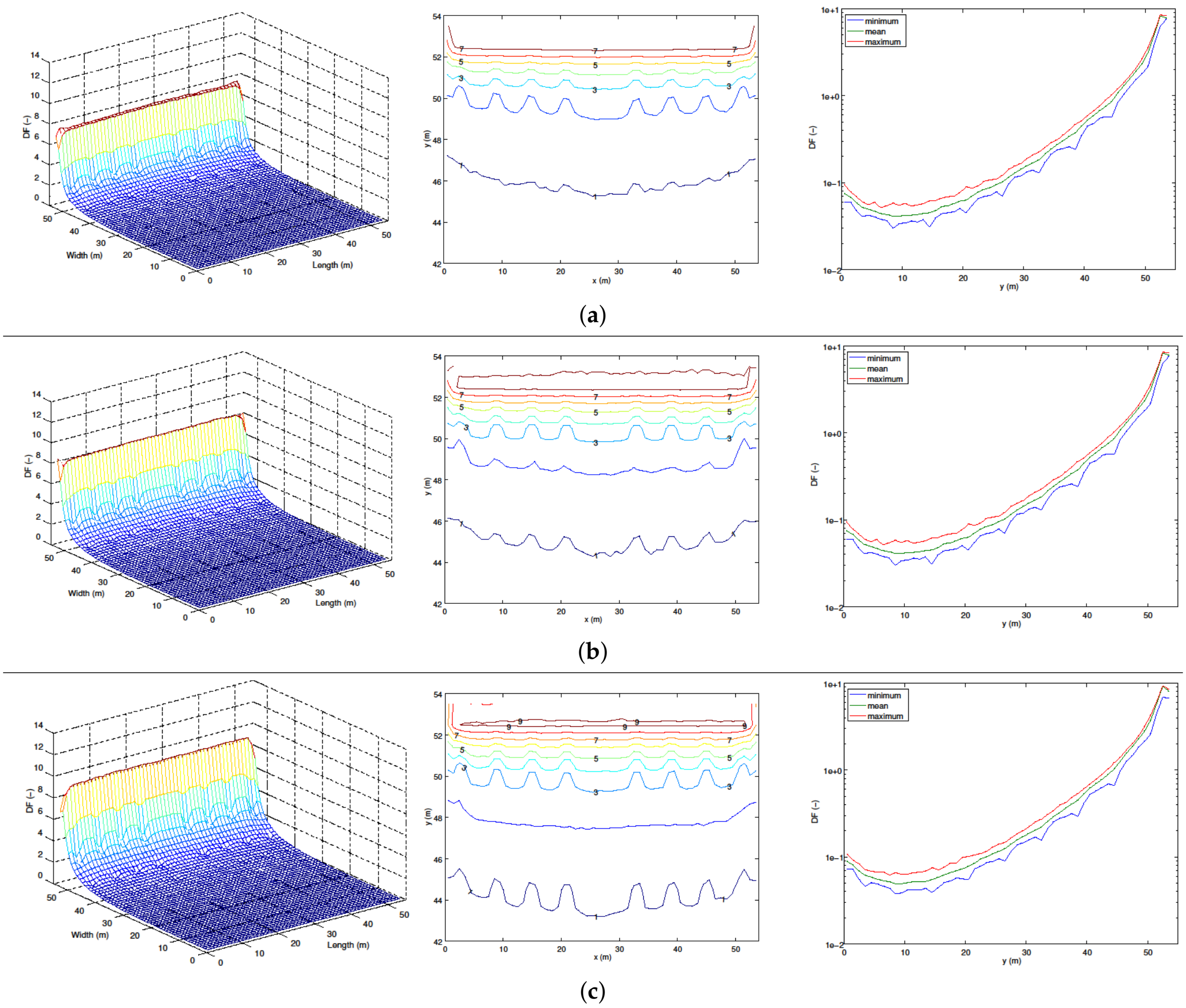


Figure 13. Spatial distribution of daylight factor (*DF*), distribution of *DF* isocontour maps, and decrease of illuminance at different windows heights of: (**a**) 1800 mm; (**b**) 2100 mm; and (**c**) 2400 mm using Radiance simulation program.

The *DF* value usually increases with the increase of windows area relative to the total floor area. The percentage p in Equation (5) represents this relation, which is representative of the relative magnitude of natural light entering the hall [81]. The relationships between p and *DF* at various distances from the windows are shown in Figure 14. At locations closer to the windows, the p value is more dependent on the daylight factor than at distances far from the windows. For instance, at 51 m from the windows, the effect of window area is almost insignificant; whereas, at 9 m distance, the *DF* value almost doubles when p increased from 4% to 6%.

$$p = \frac{A_w}{A_f} \times 100 \tag{5}$$

where p is the percentage ratio of windows area (A_w) to the total floor area (A_f) of the industrial hall.

The variation of the *DF* reflection component at distance x from the window is expressed by Equation (6) [69]. This equation can be used separately to calculate the reflection component of *DF* at distance x from the windows, which varies from $D_{\rho,min}$ to $D_{\rho,max}$ with an average value of

$D_{\rho,mean}$ positioned at the center of the considered space. *DF* is related to reflection component as in Equation (6):

$$DF = D_{\rho,\ mean} K^{\omega} \tag{6}$$

where K and ω in this equation are determined using Equations (7) and (8), respectively

$$K = \frac{D_{\rho,min}}{D_{\rho,\ mean}} \tag{7}$$

$$\omega = \frac{2x - h_m}{h_m - 2} \tag{8}$$

where x is the distance of the inspection point from the illumination orifice and h_m is the total depth of the considered space.

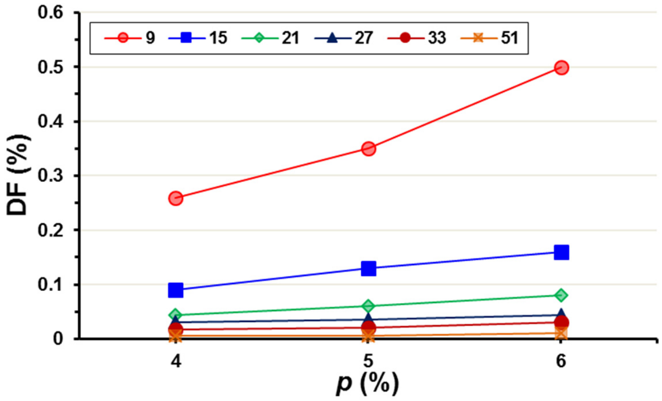


Figure 14. Approximate determination of daylight factor at various distances from windows (9–51 m) at different windows area ratio using the integral lighting system.

Once the glass surface area of the window was enlarged via increasing the height by 300 mm, the *DF* value increased by approximately 30% and its reflection components increased on average by only 5%–10%.

The course of integral lighting with exterior illuminations of 5000 or 20,000 lx in the middle of the industrial building in Hall E at points A4 to I4 (see Figure 7 floor plan) is shown in Figure 15 in comparison with the daylight illuminations in these points. The graph indicates that at almost all points in the middle of the Hall E, the illumination value is above the required value by national standard and recommended value (thick black line), whereas, in specific rare points, it is slightly below standard value.

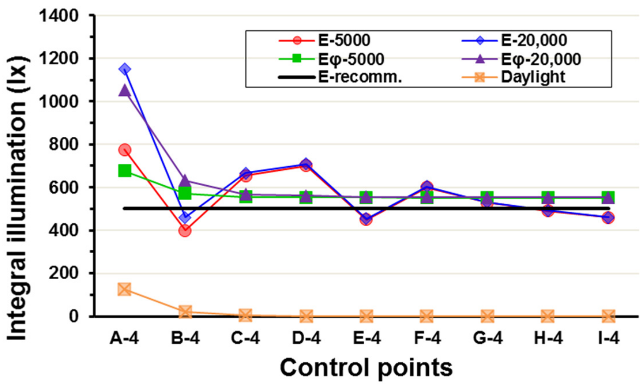
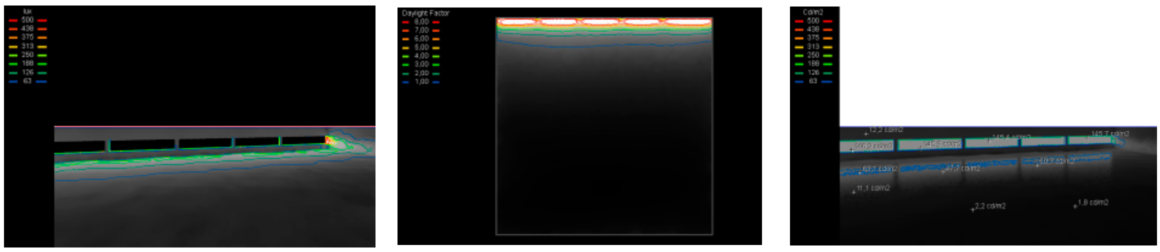


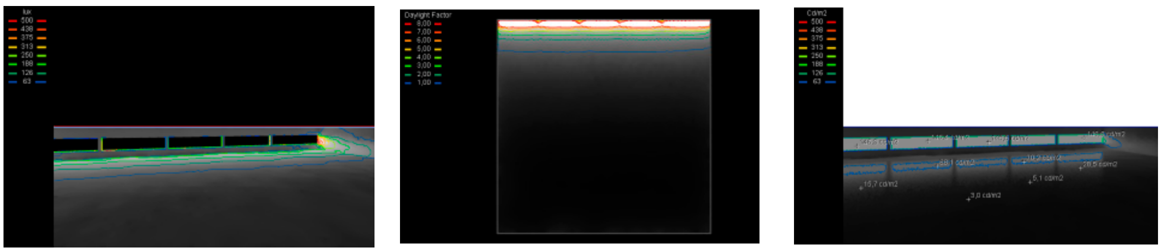
Figure 15. Integral lighting at exterior illumination of 5000 or 20,000 lx in the middle points of Hall E.

In the investigated industrial hall characterized by a large area with a lateral lighting system of daylight illumination, *DF* value decreased owing to the effect of the considered space depth. At critical points 1 m from the internal dividing structures at the largest distance from the windows, the final observed values of *DF* were very small, different from the calculated values. This phenomenon takes place because of the empty space for the calculations and the measurements were carried out in the furnished part of the interior space. Figure 16 exhibits the effects of windows heights on the illumination, daylight factor, and brightness obtained from the simulation program.

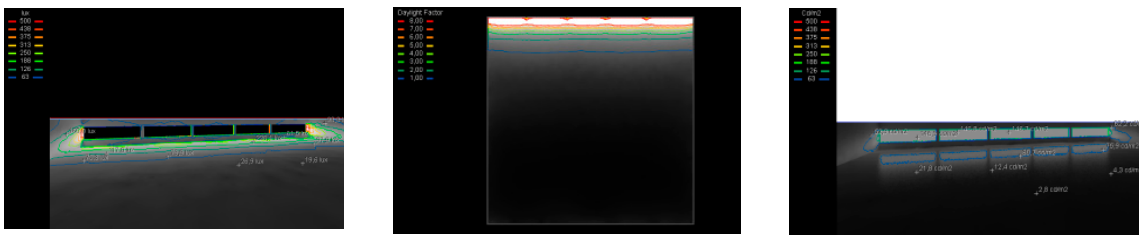
Illumination (lx)	***DF* (%)**	**Brightness (cd/m^2)**



(**a**)



(**b**)



(**c**)

Figure 16. Alternative results of illumination, daylight factor, and brightness in Hall E at three different windows heights of: (**a**) 1800 mm; (**b**) 2100 mm; and (**c**) 2400 mm.

Under the real conditions, the inspected points are shaded by objects; therefore, light-loss phenomenon occurs because of the light wave interference. When using the empirical relations for calculation of *DF*'s reflection components, the distribution of light waves after the first reflection is considered. The number of these reflections in the actual situation is greater. For this reason, the actual *DF* measured values differ from the calculated ones. The use of the computational relations for reflection components is limited and can be used only under specific boundary conditions. When we considered the change of D_x at distance x from the windows, the calculated *DF* values found in the immediate vicinity of the elimination structure at the distances up to 9 m were similar to the measured values.

Inspecting more remote points, we found the measured values of *DF* very close to the *DF* skylight component. The skylight component was on average 30% that of the measured *DF* values, as the graph in Figure 17 reveals. In large industrial halls, using the lateral system of daylight, we can determine the *DF* values with a sufficient accuracy if the skylight component of *DF* is multiplied by a coefficient of 1.3 in points deeper than 9 m from the windows as illumination of the system.

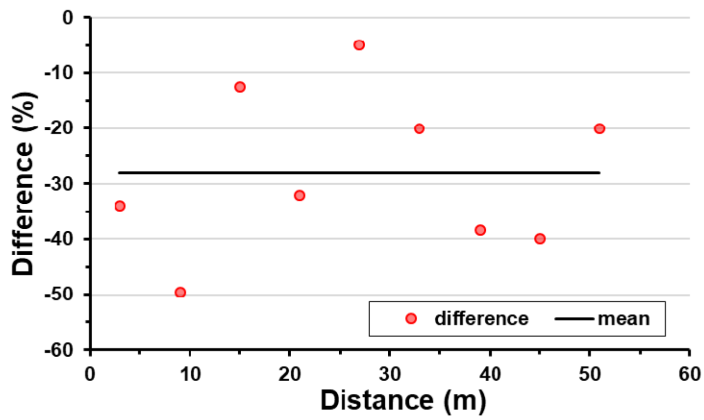


Figure 17. Variations of differences between $D_{calc.}$ and $D_{meas.}$ at different distances of 3–51 m from the windows and mean value.

Based on these results, we derived a graph for the dependence of *DF* on the percentage of glass areas at the depth of considered space of 9, 15, 21, 27, 33, and 51 m to determine the required window glass area that would ensure the existence of the required minimum values of *DF* as a basis for using combined lighting graph in Figure 14.

5. Conclusions

Optimization of energy consumptions in industrial buildings along with indoor environmental comfort for occupants is a crucial issue with considerations of new standards and regulations as well as energy costs. In this study, we investigated and analyzed efficiency and adequacy for integrated lighting in large industrial buildings with the aim to enhance indoor environmental quality and to satisfy the related standards. Emphasize was given to the use of daylighting to enhance the visual comfort of the examined industrial hall during daytime while saving energy. We observed that the daylighting in the examined knitting hall of the textile factory does not fulfill the required conditions in the entire working areas. In the points and locations that the values are below the required illumination magnitude, it is necessary to provide artificial lighting such as electrical lamps to supplement daylight to achieve the required levels.

The minimum required values of *DF* for the individual types of working activity were determined based on CSN 360020 national standard method. When the building designer does not have suitable computing method, it would be quite difficult to determine the required lighting area in the specific production plant. The investigated production area was very large, so it was necessary to calculate the *DF* values in many inspection points distributed in accordance with CSN 730580-1987 and CSN 730580-2000 standard methods. Design of the lighting system would meet the required *DF* at specific distances from the windows during day time. The measured values of daylight factor were found very close to the skylight component of the total illumination. The skylight component was observed on average 30% that of the measured daylight factor values. In designing the industrial buildings, the daylight is not emphasized and its contribution is usually small, but it is very important element for the workers psychology and physiology. The workers must feel a connection with the exterior environment; otherwise, their productivities decrease. We will report our further studies focusing on different orientations of windows and other influencing parameters as well as the visual comfort of workers and effects of natural lighting on their productivities in the future.

Acknowledgments: This paper was elaborated with financial support of the research project VEGA 1/0835/14 of Scientific Grant Agency, the Ministry of Education, Science, Research, and Sport of the Slovak Republic and the Slovak Academy of Sciences. The authors appreciate Bahareh Doroudiani of the University of Toronto, Physics Department for assisting in this work.

Author Contributions: Dušan Katunský coordinated the project, performed the field studies, conducted measurements of illuminations, and wrote the initial draft. Erika Dolníková conducted daylight simulations using the simulation computer program. Dušan Katunský, Erika Dolníková, and Saeed Doroudiani jointly performed analysis of the data and discussed the issues. Dušan Katunský developed the computational model. Saeed Doroudiani reviewed the literature, prepared the graphics, wrote the manuscript in collaboration with the co-authors, and edited the final manuscript.

Conflicts of Interest: The authors declare no conflict of interest.

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