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Lighting Quality of Indoor Environment in Large Floor Buildings in Light Industry

Dušan Katunský [a,*] and Erika Dolníková [b]

[a] Department of Architecture and Building Structures, Institute of Architectural Engineering, Faculty of Civil Engineering, Technical University of Kosice, Slovak Republic
[b] Department of Building Physics, Institute of Architectural Engineering, Faculty of Civil Engineering, Technical University of Kosice, Slovak Republic

*Corresponding Authors. E-mail addresses: dusan.katunsky@tuke.sk

E-mail addresses: dusan.katunsky@tuke.sk (D. Katunský), erika.dolnikova@tuke.sk (E. Dolníková)

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ABSTRACT

The paper highlights the problems associated with the application of daylight and integral lighting in industrial facilities. In the case study of a multi-storey textile plant, we show how combined lighting (daylight and integral illumination) can be evaluated in production halls labelled F and G. These halls have large areas 54 × 54 metres, and are more than 5 meters high. There is daylight only on side through connected windows in a vertical position. In this paper we want to present case studies of these two production halls in the textile factory located in Kosice (Slovakia). These are halls that are lit through by daylight from two sides through external walls that are opposite or next to each other. The results of the case studies can be applied in similar production halls illuminated by a "bilateral"—a double-side daylight system and natural illumination through windows on two sides in a vertical position. Such a situation is typical of multi-storey buildings in light industry. The proposed approach of daylight factor calculation can also be applied to floor space in other similar buildings.

1. Introduction

Daylight should be a significant source of illumination for all rooms with the possibility of installing lighting fill structures. In areas with insufficient daylight it is necessary to illuminate with artificial electric light [1]. Daylight is increasingly preferred by building users as a way to adequately illuminate indoor surfaces and save energy for electric lighting. It is especially preferred for physiological as well as psychological reasons. People feel very uncomfortable in places without daylight. Daylight can provide good illumination inside, with high colour rendering. It has great variability that changes during the day and with seasons. Daylight opening structures provide views and connections to the external environment and contribute to people's psychological well-being. A daylight opening can also provide exposure to sunlight indoors, which is important, for example, in dwellings, hospital departments, nurseries and schools [2].

In an area where activities such as reading, writing, using imaging devices, observing small details, and so on take place, a shielding device should be provided to reduce visual

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discomfort by glare. The proposal of a new EU "daylight" standard [4] deals with day lighting throughout the year. Providing daylight depends mainly on the availability of outdoor daylight – sky conditions. It depends on the prevailing climate in the place, and then also on the surrounding environment, the components immediately around the openings for daylight and the arrangement of interior space. Daylight should illuminate space during a significant part of annual daylight during the year.

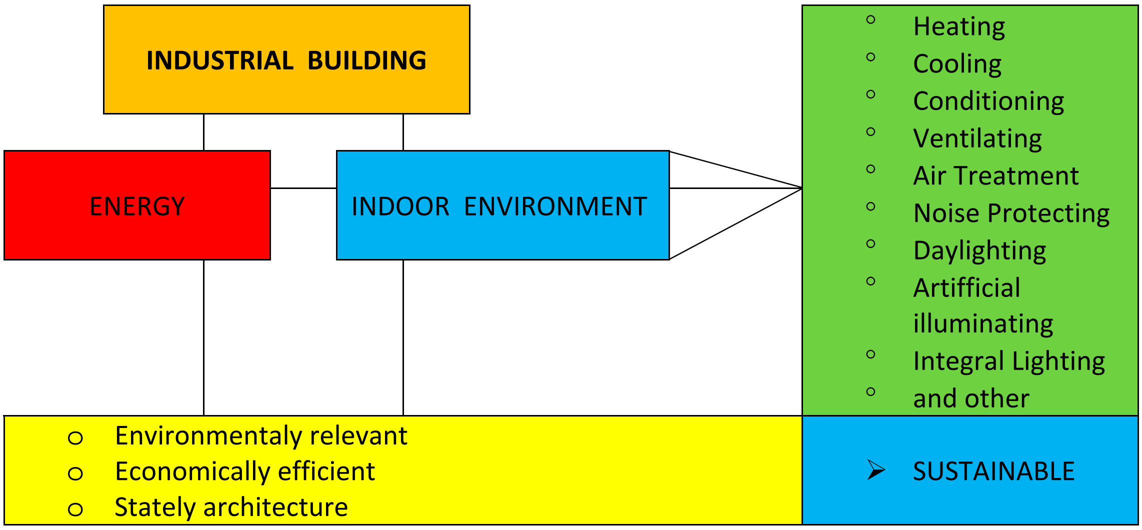

Figure 1. Creation of an industrial building and requirements for indoor environment

If we consider the environment, it can include internal and external environmental space. Buildings that meet all the prerequisites of not endangering the environment – that is, outdoor environment, can sometimes be found in a town's central part. We know of many cases where an industrial building is built in the centre of a city. Here it is necessary to take into account the shading of the surrounding area in terms of day sovereignty. Mostly, however, a building requires a location – location outside the city (transport, connection, supply, waste, etc.). In this case, the building is in an open area with a free horizon, and there is no danger of being shielded by any obstacles. That is our situation. In this article, we are considering a light industry building (textile combination) outside the city, where one of its operations can be over another and there is no shielding. We are only interested in one part of the indoor environment and lighting. It is not possible to meet daylight requirements for visibility at distant locations with unilateral (one-side) day illumination. A combination of daylight and artificial lighting must be applied here. The case study in this contribution will show how it is with bilateral (i.e. double-side) lighting.

The interior space forms building structures in combination with the building's technical equipment, which must create optimal (or appropriate to the surrounding environment) boundary conditions of the physical components of the environment. Thermal comfort consists of heating (in winter) and cooling (in summer) air conditioning, ventilation (air supply), air conditioning, daylight (windows, lights), artificial lighting (artificial sources of artificial lighting) and the associated combination of day and artificial lighting illumination. An industrial building must be environmentally relevant, economically efficient, with stately architecture so that it leads to sustainability even in industry (see Figure 1).

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2. Methodology and evaluation of indoor light quality

Classification of the internal daylighting indoor-environment according to Slovak technical standards is based on the work, its complexity and the basic requirements that are placed on the complexity of the visual activity.

Table 1. Classification of human eye recognition of visual detail tasks according to the Slovak national standard STN 730580 [3].

Human eye recognition category		Visual detail tasks
I.	Extreme accuracy	The most accurate visual work with limited use of magnification, with the requirement to eliminate errors in definition, stringent control
II.	High accuracy	Very precise production and control activities, high-precision drawing, hand engraving with very small detailing, fine art work
III.	Precise operation	Precision manufacturing and inspection, regular drawing, technical drawing, consuming laboratory, labor-intensive investigations, fine sewing, embroidery
IV.	Medium accuracy	Medium precision manufacturing and inspection, reading, writing (by hand and machine), routine laboratory work, examinations, treatments, using machines, thicker sewing, knitting, laundry, cooking class, reading room, teaching cabinet, kitchen, doctor's surgery, office, meeting room, conference room
V.	Low accuracy	Approximate works, manipulating objects and materials, food consumption and service, leisure activities, physical education, dining room, living room, lounge, hall, gymnasium, swimming pool, storage room, waiting room
VI.	Very rough work	Maintenance cleaning, showering and washing, changing, walking on public roads open to the public, cloakroom, toilets, corridors
VII.	Only spatial orientation	Walking, material transport, storage of raw material, supervision

The rule of minimum and average DF daylight factor for all seven light-technical recognition categories according to the Slovak national standard can be seen in Figure 2.

In the draft of the European standard, the rules are slightly different from national standards. Other factors are taken into account here. This standard evaluates permanently inhabited areas, classifies buildings' premises according to function and work activities, and defines areas with day lighting requirements. The daylight assessment features are applied mainly to industrial areas, office, civic, school, health, business and apartment buildings, prisons and care homes. Daylight availability is determined by the median of horizontal diffuse illumination at location E_{med}. Daylight is intended to provide levels of natural light higher than critical visual daylight lighting level of 300 lx. Daily lighting requirements should be adequate, with an acceptable minimum of 100 lux. Target factor D_T is the daily lighting factor to be achieved in a certain portion of an area in order to meet the daylighting criterion. On the working plane, the illumination level is 300 lx. Daylighting factor D_{TM} is the minimum daylight target factor. This is the minimum DF value in a specific location that corresponds to the illuminance level of 100 lx (see Tables 2, 3, 4):

Table 2. Recommendation of daylight provision by daylight openings in vertical and inclined surfaces [4]

Level of recommendation for vertical and inclined daylight opening	Target illuminance E_T (lx)	Fraction of space for target level F_{plane},%	Minimum target illuminance E_{TM} (lx)	Fraction of space for Min target level F_{plane},%	Fraction of daylight hours F_{time},%
Minimum	300	50%	100	95%	50%
Medium	500	50%	300	95%	50%
High	750	50%	500	95%	50%

NOTE: Table A.3 in [4] states the target daylight factor (D_T) and the minimum target daylight factor (D_{TM}) corresponding to the target illuminance level and the minimum target illuminance, respectively, for the European CEN capital cities.

Table 3. Recommendations of daylight provision by daylight openings in a horizontal surface [4]

Level of recommendation for horizontal daylight opening	Target illuminance E_T (lx)	Fraction of space for target level Fplane,%	Fraction of daylight hours Ftime,%
Minimum	300	95%	50%
Medium	500	95%	50%
High	750	95%	50%

NOTE: Note that for spaces with horizontal daylight openings, there are no minimum target illuminance recommendations. The table is only for horizontal daylight openings with diffusing material.

Table A.3 in standard [4] shows values of DF for daylight openings to exceed an illuminance level of 100, 300, 500 or 750 lx for a fraction of daylight hours F_{time},% = 50 % for 33 capitals of CEN national members, and Table A.4 in [4] shows values of DF only for horizontal daylight openings with diffusing material 1) to exceed an illuminance level of 100, 300, 500 or 750 lx for a fraction of daylight hours F_{time},% = 50% for 33 capital cities of CEN national members [4].

Table 4. Assessment of the view outwards from a given position [4]

	Parameter a)		
Level of recommendation for view-out	Horizontal sight angle	Outside distance of the view	Number of layers to be seen from at least 75% of utilized area: - sky - landscape (urban and/or nature) - ground
Minimum	≥ 14°	≥ 6.0 m	At least the landscape layer is included

Medium	≥ 28°	≥ 20.0 m	Landscape layer and one additional layer are included in the same view opening
High	≥ 54°	≥ 50.0 m	all layers are included in the same view opening

a) For a space with room depth of more than 4 m, it is recommended that the respective sum of the view opening(s) dimensions is at least 1.0 m x 1.25m (width x height).

2.1 Daylighting according to Slovak standards

Recently, many light engineering standards have been revised with changes related to both natural daylight and artificial lighting. A new regulation for the problems of the formation of internal space using integral lighting has been introduced [1]. 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 lighting systems design. In standards, daylight is determined by DF daylight factor %

$$DF = \frac{Internal\ illuminance}{External\ illuminance} 100\ \% \tag{1}$$

Prescription of DF according to a Slovak standard can be seen in Figure 2.

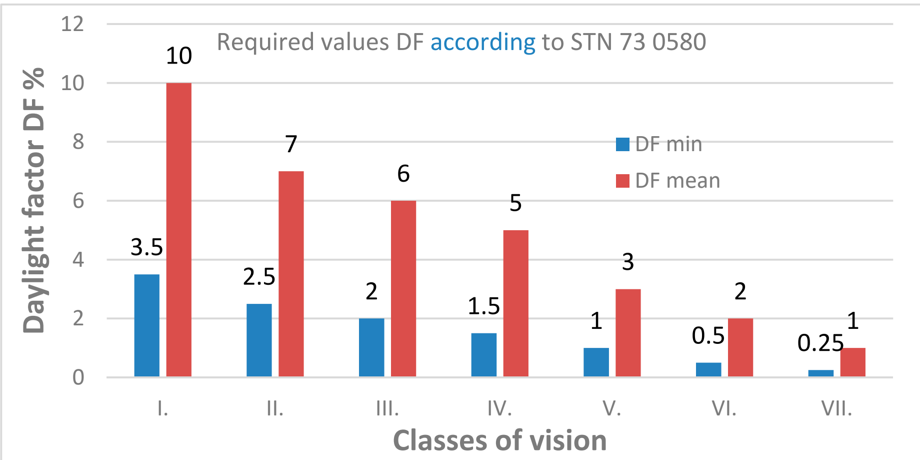

Figure 2. Prescribtion of DF according to Slovak standard STN 730580

Daylight can illuminate buildings in various ways, i.e. from the side, top, or from both directions. Side and top lighting can also be arranged in various forms. Standard integral lighting of buildings determines the minimum required values of DF for a single space in a building depending on its purpose [1]. These values are used as a basis to apply a combined system of lighting (daylight and artificial illumination together). In this standard, buildings are classified into seven groups according to the intensity of visual activities performed inside a building. Similarly, in the Slovak standard [3], values of DF are grouped into seven categories representing human eye recognition for visual detail tasks. The main starting point for determining the requirements at the level of combined lighting is the classification of visual activities performed in a building according to [3] (*Table 1, Figure 2*).

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The values of DF in workplaces in which workers permanently stay inside, the overall and graded combined illumination lighting must correspond to the values presented in (*Table 1, Figure 2*) [3]. This standard classification spans from visual tasks with extreme accuracy (Category I) to those with no visual challenge (Category VII). The parameter for observation-relative distance is defined as a ratio of detail dimension to distance between detail and the observer eye, which is used for the categorization of visual tasks. For permanently occupied indoor spaces, the DF value should be greater than 1.5% and 3% for side-lit and top-lit illuminated spaces, respectively. To reduce or avoid glare, the brightness of a window must be less than 4000 $cd \cdot m^{-2}$ and 60 $cd \cdot m^{-2}$ 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 5. The maximum permissible brightness (luminance) of the subject observed and the brightness of the illuminating opening positioned 60° from the normal viewing direction

Class of visual activities	The ratio of the luminance of the observed object to the luminance of the illuminating opening (windows)
I,II,III	1 : 40
IV	1 : 100
V,VI,VII	not intended

Note: The usual direction of view is a view of the subject of work or other view related to the activity and the relaxation view in the horizontal direction. Finally, for each hour and each space luminance contrast (or contrast of luminance) between window and environment can be calculated as follows:

$$C = \frac{Luminance_{windows} - Luminance_{environment}}{Luminance_{environment}} \ (-) \qquad (2)$$

The first step is to evaluate light contrast. Is it low, medium or high? When contrasting, we compare the highest and the lowest brightness of the scene. A low contrast is characterized by the fact that there is not much difference between the brightest and the darkest place. The dynamic range of the entire scene is narrow. A high contrast occurs when there is much difference between the brightest and the darkest place, often outside the dynamic range.

Many industrial buildings are specifically 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 compared to residential, educational, medical and commercial buildings. In recent years, with the advances in technology and methods, it has become 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 for manufacturing buildings, particularly in light industries.

3 Sustainability in industrial building design

Design, construction and operation of industrial buildings is described in various publications. We are particularly interested in indoor microclimates focusing on light and heat-humidity microclimate with an emphasis on saving energy in operation. Last but not least is the area of building sustainability.

Lighting, along with heating, are major elements of 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 occupants' comfort and health are paramount matters, in design and optimization of buildings, the form and performance of both must also be taken into account.

As it has been said, natural lighting is one of the most important design elements for the internal environment of buildings, including manufacturing halls. Although electric lighting systems can provide useful illumination in the absence of daylight, enabling workers to work for a longer time, they create various physical, physiological and psychological issues.

Research activity in design and evaluation of industrial buildings has been concentrated in several points. The first focuses on evaluation of the impact of buildings on the environment in terms of their sustainability – Alarcon, B. [5]. The modified criteria for assessment of industrial buildings' sustainability have resulted in the development of new models – Lombera, J.T. [6], Yan, B. [7]. The second point includes evaluation of industrial buildings' intensity of energy consumption with attention focused on the impact of different climate zones on energy consumption – Bawaneh, K. [8]. For instance, various HVAC systems were analyzed to decrease energy consumption in buildings – Zhivov, A.M. [9]. Katunský et al. [10] studies the thermal energy demand in an industrial building with the aim to save the total energy consumed by heating a manufacturing hall. Effects of window structures on industrial buildings' energy consumption were analyzed to enhance the design of windows to save energy – Wang, H.W. [11]. One of the authors dealing with daylighting and its impact on users is Belia, L. [12, 13].

Daylight impacts on human health – Veitch, J.A. [14] Shishegar, N. [15] Fribourg [16], affects physiological and biological processes in the human body – McColl, S.L. [17], Smolders, K.C. [18], as well as visual comfort inside buildings – Yao, J. [19], Fabi, V. [20], and in industrial operations. Gou, Z. et al. studied visual comfort and simulated lighting effects in relation to the productivity and well-being of the population [21, 22]. The authors focused on the performance of a building's population in relation to a naturally and artificially illuminated environment.

Human-oriented research focusing on access to daylight assessment in buildings for non-visual health potential, visual interest and observed behavior is in works by Amundadottir, M.L. [23], and visual perception is described by Lee, J.H. [24].

The influence of direct sunlight and shielding is investigated by Wang, N. [25], Yokoya, M. [26], Lee, K.S. [27], protection against dazzle and unpleasant glare is described by Hirning, M.B. [28, 29]. Shen, H. [30] monitors a synchronized daylight-shading operation using simplified model-based control.

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Research is also focused on different types of microclimate, in Švajlenka, J. [31], [32], as well as overall assessment of the internal environment. In terms of indoor lighting, various types of buildings requiring demanding visual activities are examined in the literature. Educational buildings and schools are dealt with by Ferencikova, M. [33], Moazzeni, M.H. [34], Kruger, E.L. [35], Piderit Moreno, M.B. [36] and others. Residential buildings are followed by Xue, P. [37], Nebia, B. [38], apartment buildings by Iringova, A. [39], atrium building by Mohsenin, M. [40] et al., Berrardi, U. [41], Gonzales, J. [42], Pellegrino, A. [43], Costanzo, V. [44], Konis, K. [45].

Research activities in this field are also monitored by different types of light or lighting. Mistrick, R. [46] deals with computer modelling of daylight-integrated photocontrol of electric lighting systems. Simulation and modelling in the field of daylight is conducted by Nasrollahi, N. [47], energy performance by Reinhart, C.F. [48], the use of natural light vs. cold LED lighting by Amorim, R. [49], energy and visual control by Shen, E. [50], side and view atmospheres by Uriarte, U. [51]. Adaptive light is followed by Gunay, H.B. [52], and simulation for pre-visualizing and tuning lighting controller behavior by Jia, L. [53].

It follows that daylighting is also very important in the manufacturing halls of light industries from the visual comfort point of view. It is an effective stimulant to the human visual and circadian systems. 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 by masking shades or shadows at the workplace. The effectiveness of daylight for visual performance depends on the quality of lighting similar to electric light. Therefore, negative aspects are also positive in daylight. The boundary conditions of external lighting for all meteorological models of sky brightness distribution and preliminary configuration and validation were studied by Perez et al. [54] and Igawa et al. [55]. Certain aspects of integral lighting have been proposed already in [56] Katunský, D. Lighting conditions at workplaces were examined using both practical and calculation methods [57, 58], and incorporation of methods of daylight assessment into urbanization was studied by Sokol, N. [59] and Chen, K.W. [60]. These comments motivated us to carry out the current research focusing on lighting systems to improve the internal quality of the environment and workers' comfort while reducing overall energy consumption – Labat, M. [61], Gourlis, G. [62], Pham, K. [63]. Katunský, D. et al. [64] examined the effectiveness of daylight and artificial lighting in an industrial textile factory in Košice (Slovakia). The results were published for Hall E, unilaterally illuminated as in the case study. In this text, the authors want to outline the continuation of the research.

3.1 Aim of research

The main objective of this research was to methodologically analyse the influence of daylight on industrial hall illumination with regard to parameters of integrated dynamic lighting systems by means of measurement and simulation methods. The research was carried out in textile halls in Košice. As part of this work, we observed two knitting factory halls in a textile factory that differ in the location of windows. This work is a continuation of our comprehensive research on the quality of indoor conditions (indoor microclimate quality) of

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industrial buildings. Previously, we studied the heat-humidity microclimate and the energy needed to heat the production hall by means of measurements and dynamic simulations. Continuing insight is offered by the assessment of daytime and artificial light conditions which also uses measurement and dynamic simulations, leading to design optimization and industry sustainability monitoring.

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

The aim of the whole research was to seek ways of optimizing conditions regarding a building envelope design in close connection with environmental issues and energy intensity reduction during their service. While the new halls are built according to recent design criteria and standards, there is a significant number of old halls being renovated and used for their original purpose (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 characteristics of the internal environment in industrial halls, but also to add more daylight in such spaces. Because the value of daylight factor (DF) is low for daylight, it is necessary to include artificial lighting, that is integral lighting. There are regulations for daylight as well as for artificial illumination, but there are no regulations for the associated lighting. Solutions to these problems in interactions with architecture and formation of structural details of industrial buildings should lead to a change of approach to designing these kinds of buildings.

4 Case study – textile factory halls F and G

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 in the eastern part of the Slovak Republic) in which we selected the knitting halls. In this contribution we evaluate two halls, namely hall F and hall G, which are illuminated with daylight from two sides. In Figure 3, you can see the situation and the indoor daylight simulation by the Radiance program. The activities in this hall are mainly production of fabrics through operation of knitting machines by workers.

In this paper, we want to show case studies of similar light industry factories that are illuminated by a double-bilateral daylight illumination system of aligned bands of windows:

- The windows are next to each other in adjacent peripheral walls. (Hall F)

- The windows are opposite each other in opposing peripheral walls. (Hall G)

Similarly to the previous example, it is a confrontation of traditionally calculated and simulated daylight situations:

- The calculation is considered according to prescribed rules.
- The calculation is performed by a simulation program without a device.
- The calculation is done by a simulation program with the hall equipment.

a) Situation of case study b) Bilateral daylight system c) Luminance – Brightness in bilateral daylight system

Figure 3. The situation of a textile factory placement, lighting simulation results near windows in double-side window day illumination

It is against this background that we attempt to determine the level of minimum DF factors as the basis of integral lighting. The point is that we are considering a new methodology (i.e. conversion of DF daylight factor to absolute illumination in lux). It is then the superposition of daylight and artificial light flows that together form a combined, integral lighting system.

We considered the following boundary conditions in the calculations:

Exterior horizontal illumination of 5000 lx; illuminated height of 5100 mm and parapet of 1200 mm. The size of the windows and the thickness of the lining varied for the individual alternatives: Light loss coefficients of $\tau1 = 0.92$, $\tau2 = 0.74$, $\tau3 = 0.80$, $\tau4 = 1.0$. Coefficients of reflections (ρ) of the light of 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 $\rho = 0.50$, façade $\rho = 0.45$. Because the building is at a sufficient distance from the surrounding buildings (as shown in the situation and photo in Figure 3a), the shade angle was taken as Z = 0.

Analysis of the calculated DF results for the inspected points (shown as control points in the floor plan of Figure 4) reveals that when using one-sided lateral illumination systems in the circumferential wall, the lines with the same DF values in the zone of working activity are not distorted and the resultant values are approximately equal in rows equally spaced in the circumferential jacket. (shown in Figure 4)

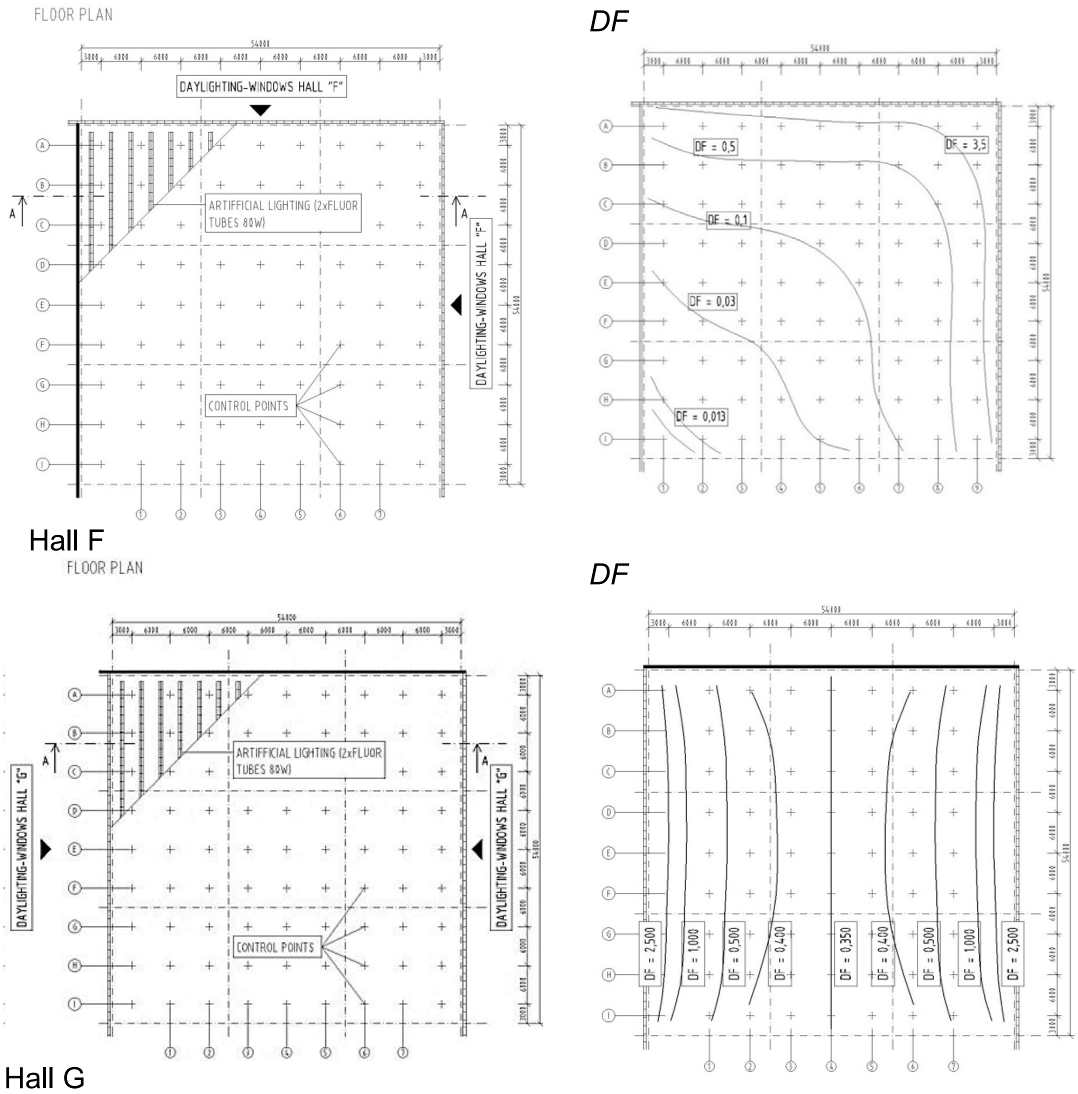

Figure 4. Floorplans and DF in halls F, and G bilateral daylight system The calculated lines with the same *DF* values in the zone of working activity in hall F

DF values in hall F (double-sided daylight system of windows next to each other) and Hall G (double-sided daylight system of opposite windows) are measured and computed. Halls reduce the DF due to the depth of the tract. The article presents the results of selected alternatives for nine control points A4 to I4 in the center of hall G and in points A9 to I1 in the F symmetry axis (diagonal).

On the basis of these results, it can be stated that the effects of the thickness of the lining in the one-side lighting system are significant up to a distance of approximately 21 m from the window structures, which is point D4 in the plan view. At points beyond D4, the thickness of the lining on the perimeter wall would be insignificant for the resulting DF.

The results of DF and lighting calculated in the F and G halls and the brightness (cd/m^2) in halls F and G calculated without a space device can be seen in Figure 5.

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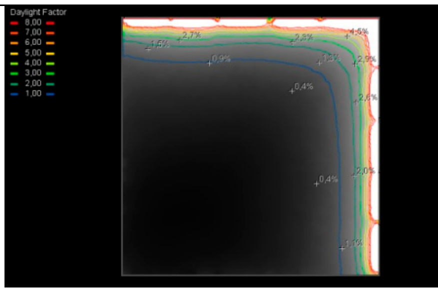
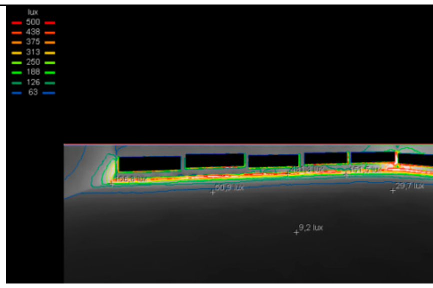
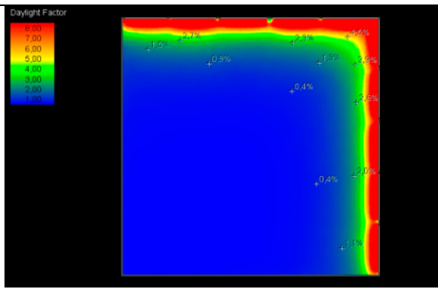
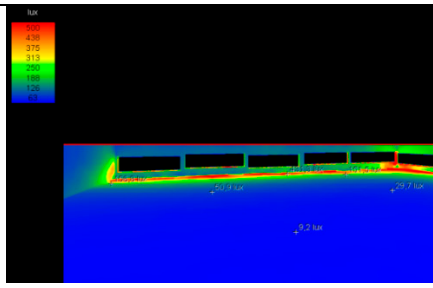
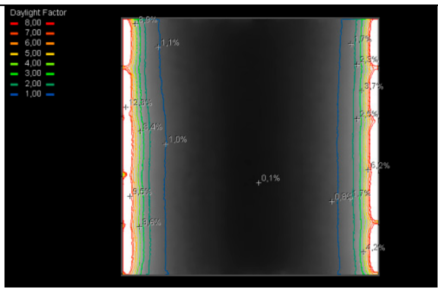
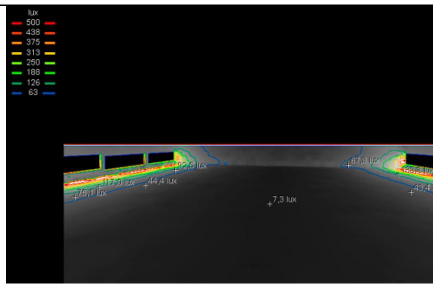
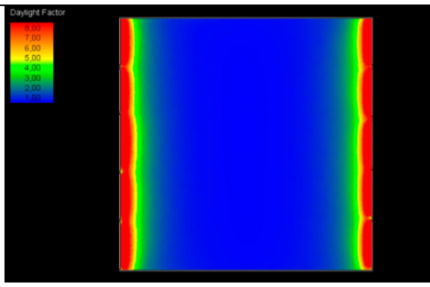
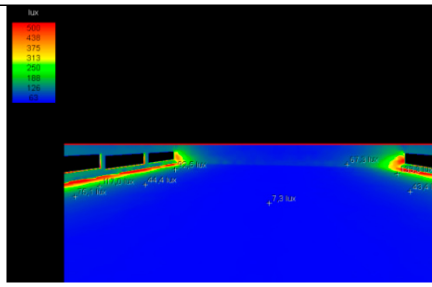
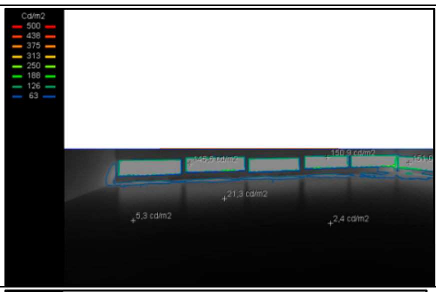
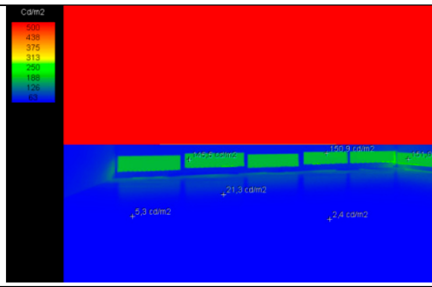
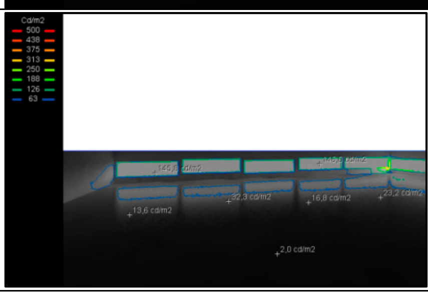
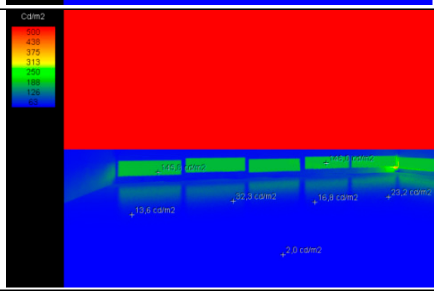
A/ Bilateral daylight	DF (%)	Illumination (lx)
Hall „F“		
Hall „F“		
Hall „G“		
Hall „G“		
Hall „F“ luminance (cd/m^2 Cloudy (overcast) sky		
Hall „F“ luminance (cd/m^2 Cloudy sunny sky		

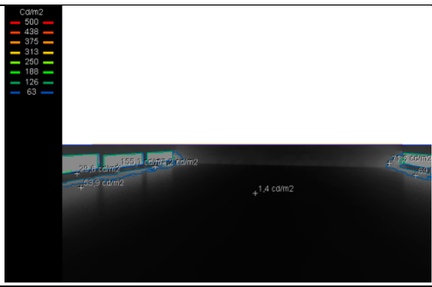
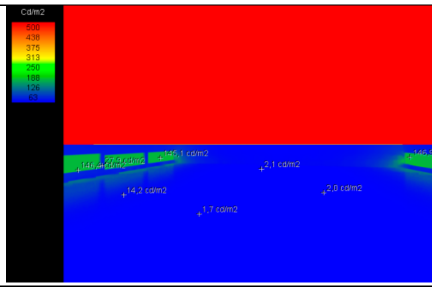
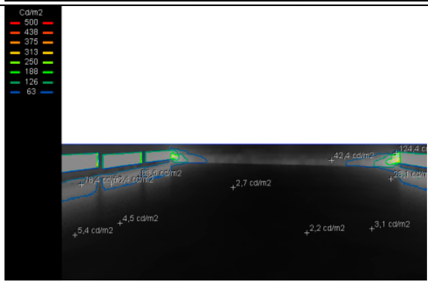
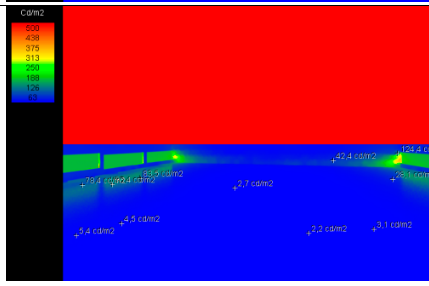
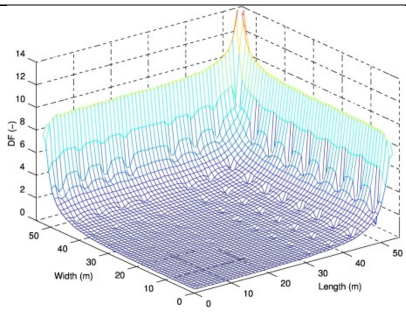
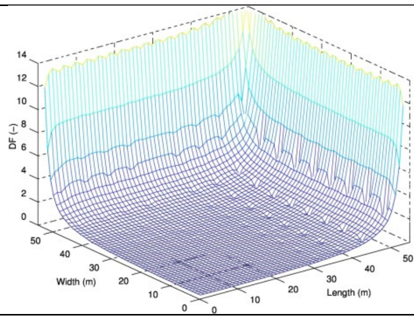
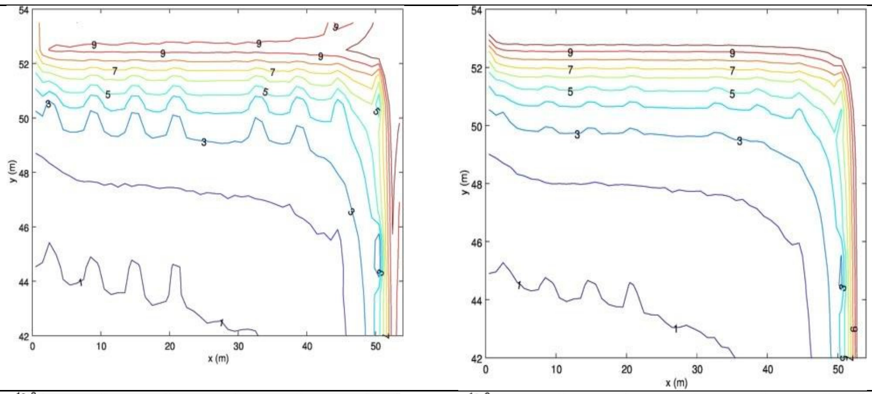
Hall „G“ luminance (cd/m² Cloudy (overcast) sky		
Hall „G“ luminance (cd/m² sunny sky		

Figure 5.
Results of daylight factor *DF* (%), illumination *I (lx)* and luminance (cd/m^2) in halls F and G calculated without a space device.

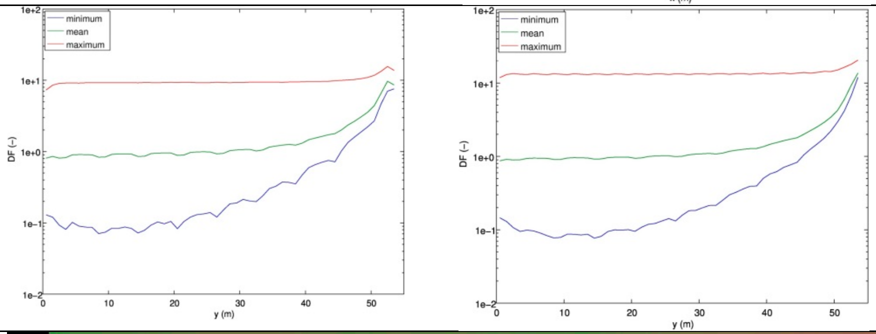
In Hall E, daytime lighting was provided on one side only. The results are similar to those in the F and G halls, except that symmetry is different. In Hall F, the symmetry axis is diagonally across points A9 to I1, in Hall G in the center through points A4 to I4. In Hall F there was no duplication of results in any points, despite the fact that lighting is from two sides. In hall G, daylight factor can be determined by superposition of values. It is the sum of the highest value near the windows and the lowest value at the extreme point. In other points, the results are mirrored. When it comes to simulation programs, it is different. The results depend on the program used and the exact specification of the input data. Some programs also take into account the interior and the production process. In the industry, it is quite difficult to simulate a situation that would correspond to reality. We tried to simulate especially the visual perception of the interior, the observed detail and the view of the windows. The results using simulation programs for the unfinished as well as the furnished interior can be seen in Fig. 6.

	DF (%) Window height 2400, wall 300 mm	DF (%) Window height 2400, wall 100 mm
In space 3D		

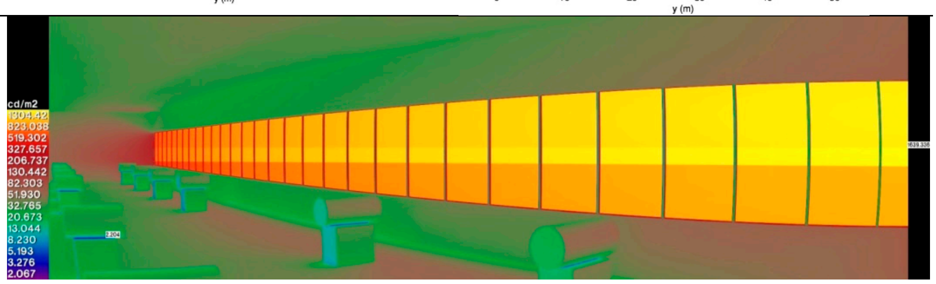
In floor plan



In cross section



Sunny sky
Cloudy (overcast)
sky near windows



Cloudy (overcast)
sky overall view

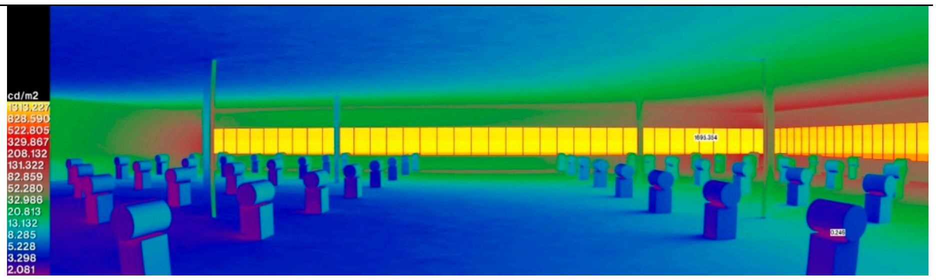
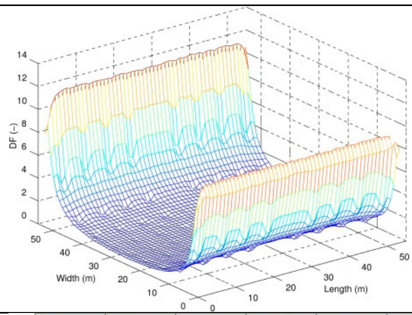
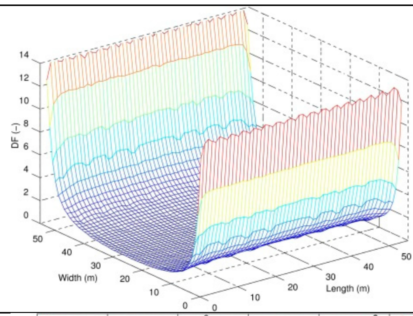
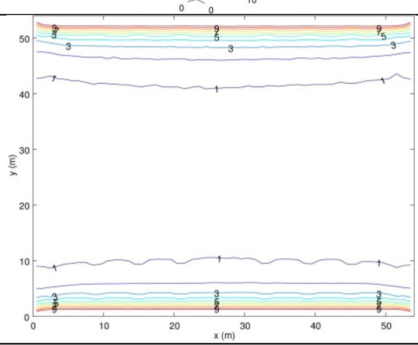
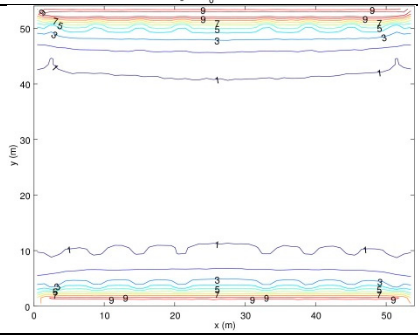
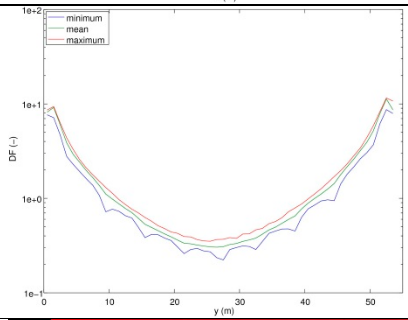
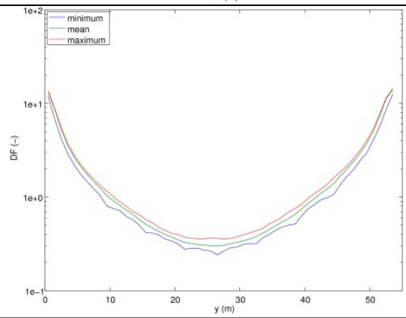
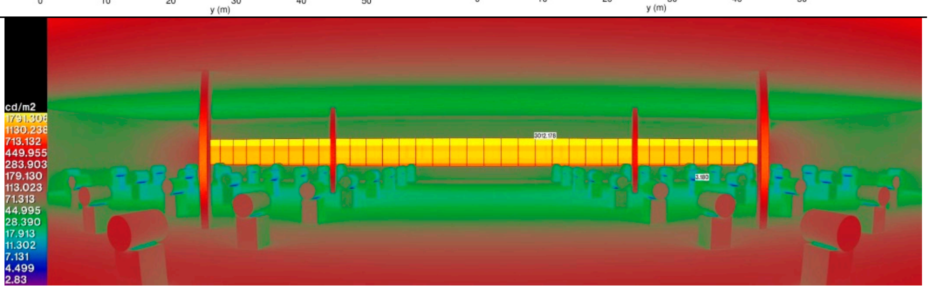
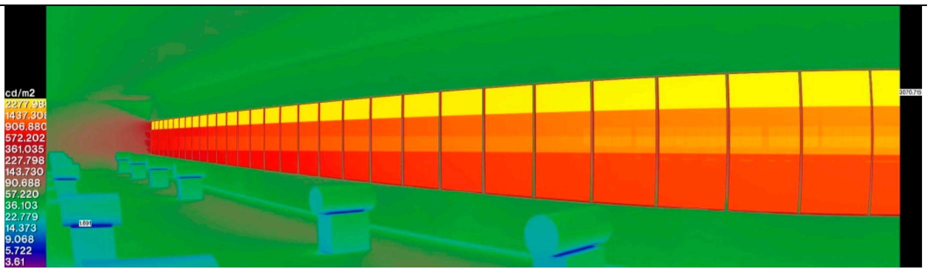


Figure 6. Results of daylight factor *DF* (%), illumination *I (lx)* in hall F calculated by a simulation programe without a space device, and results of luminance (cd/m^2) in hall F with the hall equipment calculated by the Radiance simulation program

Figure 6 shows the distribution of daylight factor DF in space (3D), floor plan (2D) and in section (1D) for alternative calculations with wall thickness variations of 300 mm and 100 mm. Interesting are the results of brightness, where the values reach 2.204 cd / m2 in detail and 1639 cd / m2 when looking at the combined windows. The ratio of these values is almost 800. It is not appropriate from a visual point of view. Of course, it is necessary to improve the indoor light microclimate using artificial lighting. In that case it will not be so bad, the ratio of brightness will be more acceptable. Figure 7 shows the outputs obtained by the same procedure for Hall G.

	DF (%) Window high 2400, wall 300 mm	DF (%) Window high 2400, wall 100 mm
In space 3D		
In floor plan		
In cross section		
Luminance (cd/m^2)		
Luminance (cd/m^2) Sunny sky Detailed view		

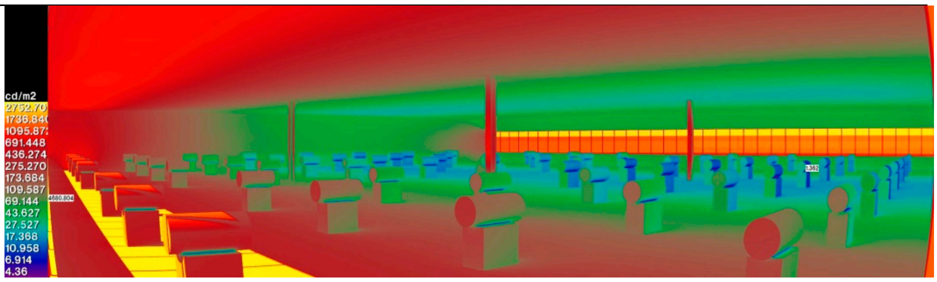
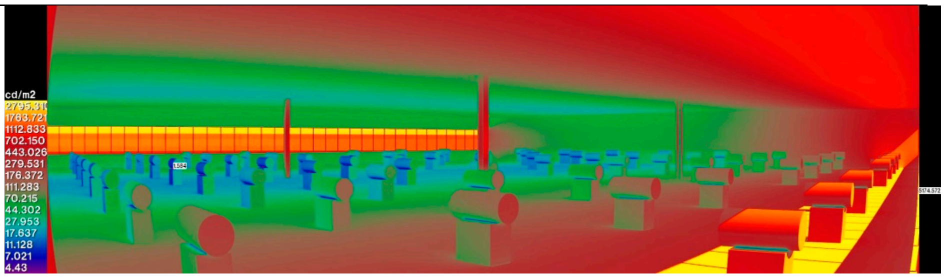
Luminance (cd/m²) Sunny sky View left side	
Luminance (cd/m²) Sunny sky View right side	

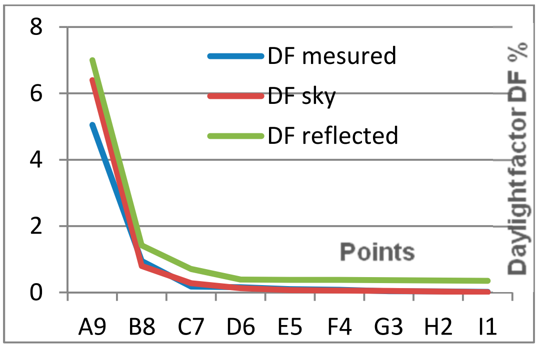
Figure 7. Results of daylight factor *DF* (%) illumination *I (lx)* in hall G calculated by a simulation programe without a space device and results of luminance (cd/m^2) in hall G with the hall equipment calculated by the Radiance simulation program.

The calculation that tracks the results for hall G (Figure 7) was done with the same simulation programs as for hall F. This G Hall has a two-sided illumination system with windows facing each other. Alternatively, daylight factor DF (%) for window height of 2400 mm and wall thickness also 300 mm and 100 mm can be seen in the 3D space, in the plan view and in the cut. Interesting is the luminosity in the furnished interior. For luminance results, values from 1.362 cd/m^2 when viewed in detail and 3180 cd/m^2 when viewing compound windows were observed. The ratio of these values is about 1000. In terms of visual perception, this is not acceptable, as it creates visual discomfort.

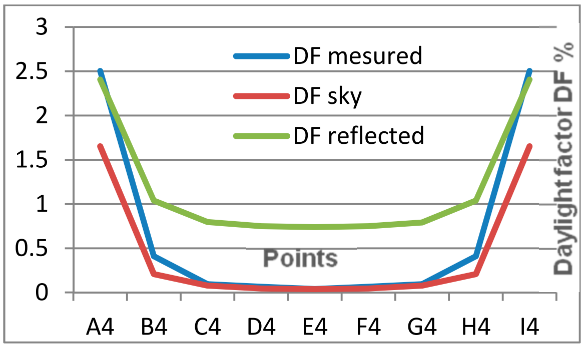
5 Evaluation and discussion

Comparison of the measured and calculated values of the DF in Halls F, G can be seen in Figure 8. It indicates that the measured DF starts to approximate the skylight component of DF 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.

Measurement of daylight levels in Hall F was done diagonally – in the symmetry axis of the room, because lines with the same level of daylight were parallel to each other's outer wall. DF values were also set for windows with different thicknesses of the outer wall. When the thickness of the outer wall increased the thickness of the sill, this caused a significant decrease in the DF sky component (see Figure 8).



Hall „F"



Hall „G"

Figure 8. The measured, calculated lines of "sky and reflected components" of *DF* values in cross section in the midle of working activity in hall F and G

The variation of the *DF* reflection component at a distance from the window opening D_w is expressed by Eq. (3) [64]. This equation can be used separately to calculate the reflection component of *DF* at distance D_w 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 Eq. (3):

$$DF = D_{\rho,mean} K^{\omega} \tag{3}$$

K and *ω* in this equation are determined using Eqs. (4) and (5), respectively

$$K = \frac{D_{\rho,min}}{D_{\rho,mean}} \; (-) \tag{4}$$

$D_{\rho,max}$ Maximum internal reflected daylight factor %
$D_{\rho,mean}$ Mean (average) internal reflected daylight factor %
$D_{\rho,min}$ Minimum internal reflected daylight factor %

$$\omega = \frac{2D_w - T_d}{T_d - 2} \; (-) \tag{5}$$

D_w Distance from daylight opening m
T_d is the total depth of the considered space.

The resulting DF also influences the peripheral wall structures. Figures 6 and 7 have documented the results of DF and illumination for alternative wall thicknesses of 300 mm and 100 mm in the 3D space in the plan view and in the cut. Figure 9 shows the dependence of the wall thickness on the DF at the points of the symmetry axis. For hall F there are points A9 to I1. The influence of the wall thickness on the DF level is that for every 100 mm the DF drops by about 7%. These values are shown in Figure 9.

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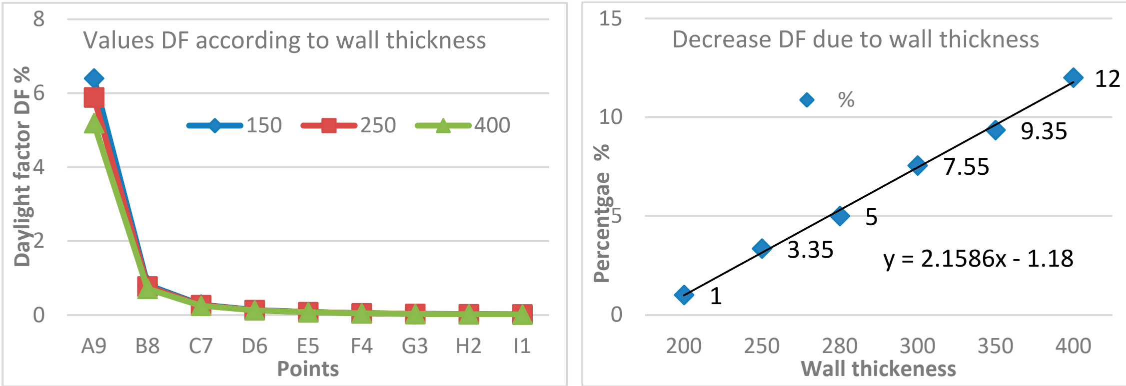

Figure 9. The calculated lines of "sky components" of *DF* values in cross section in the midle of working activity in hall F

Based on this analysis, we can in this case also calculate DF relationship, which uses the percentage of glazing P

$$P = \frac{A_{glazing}}{A_{floor}} \ (-) \tag{6}$$

We can express daylight factor as:

$$DF = \left(2.926 D_w{}^{-2.115}\right). P^B \tag{7}$$

where B can be calculated:

$$B = 1.287 + 0.126 D_w - 6.6 \times 10^{-3} D_w{}^2 + 9.8 \times 10^{-5} D_w{}^3 \tag{8}$$

The DF results, depending on the distance from daylight opening Dw and percentages of the glazing P can also be seen in Figure 10. 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 only by 5%-10%.

The combined lighting of the workplace is implemented as a single system with regard to directionality, shading, glare blocking, contrast of brightness in the field of vision and other requirements specified in the following technical standards:

STN 73 0580-1 Daylight building lighting. Part 1: General requirements.

STN EN 12464-1 Light and lighting. Illumination of places for work. Part 1: Places to work in the interior.

When a 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 the 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 daytime. 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 industrial buildings, daylight is not emphasized and its contribution is usually small, but it is a very important element for workers' psychology and physiology. Workers must feel a connection with the exterior environment; otherwise, their productivity decreases. 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 productivity in the future.

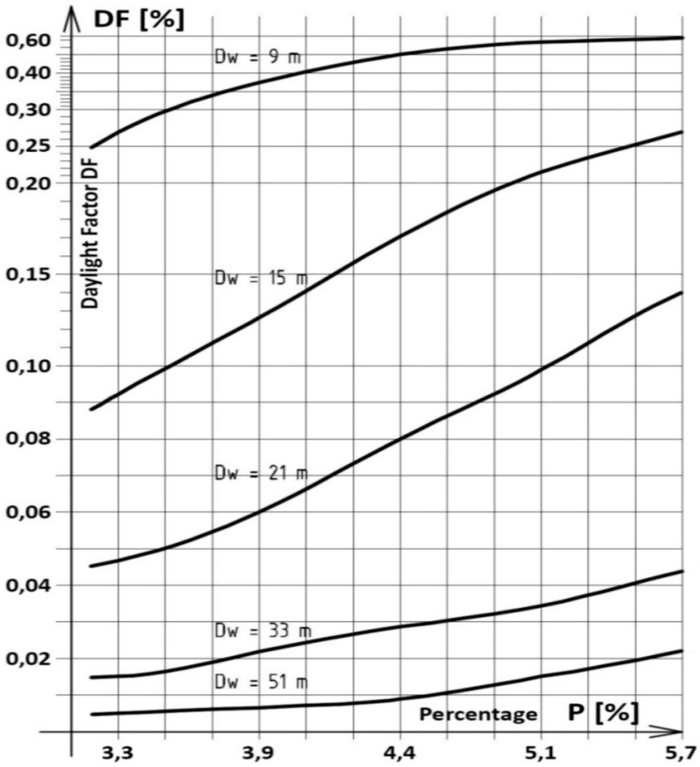

Figure 10. Approximate determination of DF depending on D_w (m) – the distance from the daylight opening and P (%) – the percentage of glazing.

In this study, we investigated and analyzed efficiency and adequacy of integrated lighting in large industrial buildings with the aim to enhance indoor environmental quality and to satisfy the related standards. Emphasis 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 fulfil the required conditions in the entire working area. In the points and locations where 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 for integral lighting
- Combined lighting is used indoors or in their functionally defined areas where the daylighting factors are lower than those required by standard, but at least 1/3 of these values.
- Workplaces in premises with illumination openings where the condition under the first point is not met are considered as workplaces without daylight.

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- The combined lighting of workplaces shall be designed so that the brightness ratio (1:40, 1:100) in the field of vision shown in the Table 5 is not exceeded.

If the brightness of the illumination holes is more than 4000 cd.m^{-2} up to 60º from the normal view, it is restricted by suitable control devices (e.g. blinds, curtains).

6 Conclusions

The contribution points to assessing visual well-being in large spaces. In this case, it is an industrial operation with ground planes of 54 x 54 metres with a height of about 5 meters. This type of “halls” can also be compared to large-sized spaces in other construction (not only in light industry). Such spaces are also typical of administrative and other buildings in civil construction, where there is a free layout without partitions built in. In this work, the relationship can be applied to predict the size of the glazed parts in the external wall in the given spaces. Since daylight illumination represented by the daylight factor is small, it is necessary to bring distant places into artificial light. For the application of daylight illumination with artificial ones, the physical conditions are not normative. Artificial light always dominates there. Therefore, in absolute terms, we can determine the required value of luminosity in lux, but daylight is suppressed here. As it is known, daylight is at least physiologically and psychologically necessary. A person inside must feel a connection of the enclosed interior with the exterior. This is sometimes only a visual idea that can not be mathematically described, though. Therefore, the need for daylight is small in the conditions we have described. The DF's daylighting factor is of little value. It is prescribed only in some national regulations. When calculating by standard methods, the calculation is based on outdoor lighting of 5000 and 20,000 lx. The new draft of the European Standard is based on the specific conditions of the external lighting of individual countries. It is represented by the outdoor illumination of the capital city.

The calculations we performed and confronted with measurements in a real interior point in a case study of a large-sized interior. It is necessary to emphasize that the results are different if we take into account normative boundary conditions, and are different if we calculate with a simulation program, but in an unadjusted interior, and are yet different if we take into account the prediction of the interior equipment. Any situation of preliminary determination of the layout of the fitting and built-in objects in the interior will be represented by another interior and the calculated results will only be approximate. They will come closer to the values we can expect in a real interior.

The contribution also shows the possibility of approximate determination of DF by glazing. In residential buildings, glazing (windows) is about 10% of the floor area. In industry (mainly light industry buildings) it is about 3 to 6%. For the preliminary determination of the DF, it is possible to use the equation (7) or the graph depicted in Figure 10. The overall situation is particularly interesting from the viewpoint of visual perception, i.e., illumination and luminosity. Luminosity should not be such that the ratio between the luminosity of the observed detail and the luminosity of the surroundings is greater than that shown in Tab. 5. See the overall lighting situation in the F and G halls in Figure 11.

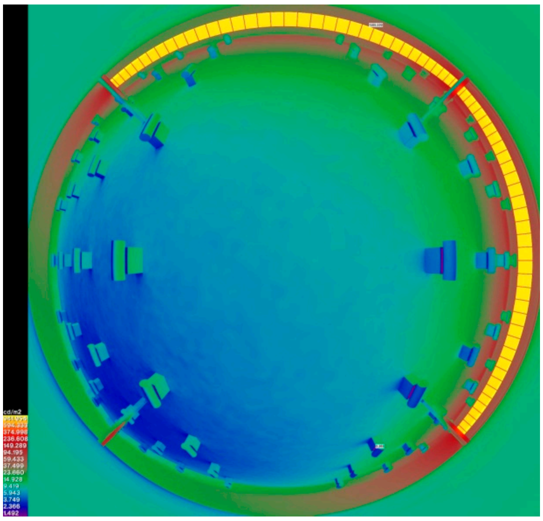
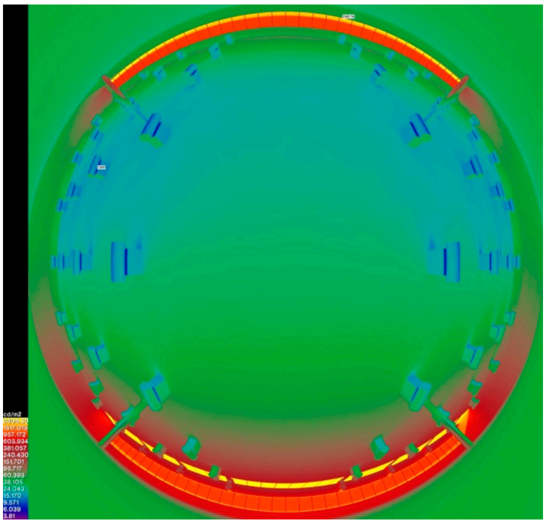
 F  G

Figure 11. Luminance in Hall F and G in the overall situation acording to the Radiance program (during the day without artificial illumination)

When assessing building sustainability based on computational programs, the daylight element becomes just one of the sustainability assessment indicators. At the same time, the need for daylight is essential for sustainability, and its emphasis should be highlighted in evaluation programs. Of course, it is not a simple matter to find a compromise between ecology, environment, economics and energy requirements. But this is the role of all of us in the future, because getting closer to sustainable development is our goal.

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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, jointly performed analysis of the data and discussed the issues. Dušan Katunský developed the computational model.

Conflicts of Interest
The authors declare no conflict of interest.

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