TEM Journal. Volume 13, Issue 4, pages 2694-2702, ISSN 2217-8309, DOI: 10.18421/TEM134-07, November 2024.

Combined Approach to the Analysis of Lighting-Technical Parameters of Artificial Illumination at the Visual Task Area in the Production Hall

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Abstract **– Lighting is considered one of the physical key factors of environmental ergonomics in the workplace. The primary role of this factor is to maintain well-being at the workplace, increase productivity, and efficiency, and significantly influence visibility and visual conditions during task execution. To ensure the successful performance of manufacturing activities, it is essential to correctly set the lighting-technical parameters, particularly for areas involving visual tasks. This paper addresses this issue using a simulation program. The introduction of the paper describes the theoretical aspects of lighting conditions at the visual task area for proper subsequent interpretation of the conducted analysis. The second part details the execution of in-situ illumination intensity measurements, based on which a digital model of the real workplace is created. In the digital model, the characteristics of the lighting system, including a combined analysis of illumination intensity and uniformity, are examined. Additionally, within the virtual environment, luminance and glare are analyzed using the Unified Glare Rating (UGR) parameter.**

The conclusion of the paper evaluates the analyzed parameters to ensure suitable work performance during visual tasks, with an emphasis on reducing occupational health risks for employees.

Keywords **– Artificial illumination, DIALux, lighting-technical parameters, production hall.**

DOI: 10.18421/TEM134--7
https://doi.org/10.18421/TEM134-07

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Received: 01 July 2024.
Revised: 05 November 2024.
Accepted: 18 November 2024.
Published: 27 November 2024.

1. Introduction

Lighting-technical parameters that need to be analyzed and assessed when designing and modifying lighting systems in any workspace significantly impact the visual conditions in workplaces. If the necessary lighting characteristics are improperly set, it can lead to visual fatigue, cognitive dysfunction, and physical discomfort [1], [2], [3]. In production halls, it is crucial to ensure a proper lighting system, as inadequate lighting can have adverse effects not only on employees but also on the production itself, manifesting as high energy consumption, reduced productivity, or increased product defects [4], [5]. To prevent undesirable states and effects, it is essential to accurately analyze, evaluate, and subsequently design the work system incorporating the lighting system both as a whole and specifically for particular cases and activities at visual task areas. Given that this comprehensive process is time-consuming under real conditions, simulation tools are utilized in practice to reduce time and often high costs associated with the analysis and evaluation process [6], [7], [8]. The foundation of good lighting practice is to meet not only the required illumination but also other qualitative and quantitative requirements. Qualitative requirements for lighting are determined by satisfying basic human needs such as visual comfort, visual performance, and safety [9]. The main parameters for quantitative requirements defining the lighting environment are further listed [10].

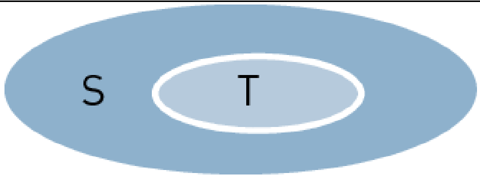
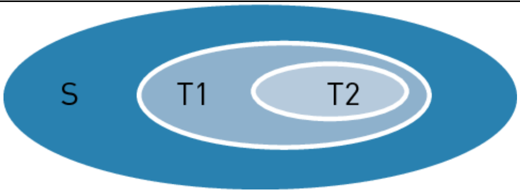
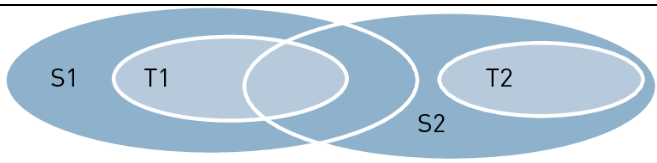
- Luminance distribution:
  - A parameter affecting visual adaptation, influencing task visibility.
  - Ensuring this parameter is necessary to enhance visual acuity, contrast sensitivity, and the efficiency of visual functions.
  - In lighting system design, high (or too low) luminance and high (or too low) luminance contrast should be avoided.
  - Determined by the surface reflectance factor.
- Illumination uniformity:
  - A quantitative measure of illumination.
  - For visual task areas, it is set to a value higher than 0.7.
  - In the immediate vicinity of the visual task area, it should be higher than 0.5.
- Illuminance:
  - A photometric physical quantity expressing the ratio of luminous flux incident on an elementary area to the size of that area.
  - It significantly impacts the speed, comfort, and safety of task performance and perception.
- Glare:
  - A sensation caused by overly bright light sources within the visual field.
  - Quantifiable through the Unified Glare Rating (UGR) factor.
  - Reducing glare to the greatest extent possible helps prevent errors, fatigue, and injuries.
- Colour rendering index (CRI):
  - A parameter identifying the objective characteristic of the colour quality of a light source.
  - The maximum value of this parameter is 100; values below 80 should not be used in interiors where employees stay for extended periods.
  - The lower the CRI, the poorer the representation of colours.
  - LED light sources with higher CRI do not achieve high luminous efficacy.
- Light colour:
  - Represented by the quantitative parameter of correlated colour temperature (CCT).
  - Defined in comparison with the black body and illustrated through the Planckian locus.
  - Increasing the black body temperature increases the blue component and decreases the red component in the spectrum.

In production halls, it is essential to prioritize analyzing all the aforementioned parameters specifically for visual task areas. For the analysis and evaluation of lighting parameters, indoor workplaces are divided into the following zones [11]:

- Visual task area: The part of the workplace where the worker performs the activity; if the position and size of the visual task are unknown, the entire work area must be considered the visual task area.
- Immediate surroundings of the visual task: The section around the visual task area within the visual field.
- Visual task surroundings: The characteristic environment around the immediate surroundings of the visual task.

In production halls, the analysis of the visual task area focuses on work zones near or directly at workstations. Each workstation is arranged within one of the possible visual task (T) and immediate surroundings (S) configurations. These arrangement options are presented in Table 1 [12].

Table 1. Characteristics of visual task area arrangements within the workplace

Arrangement characteristics	Graphical Representation of Arrangement
Workstation with a single visual task area	
Workstation with overlapping visual task areas	
Workstation with overlapping immediate surroundings of visual task areas	

2. Material and Methods

For the purpose of analyzing and assessing the intensity of artificial lighting in indoor spaces, it is necessary to obtain data on the average illuminance in the workplace. The average illuminance of artificial lighting is expressed by the following mathematical interpretation, with its variables graphically situated in the layout shown in Figure 1 [13].

$$E_p = \frac{E_1 \cdot (n-1) + E_2}{n} \qquad (1)$$

, where:
E_1 – average value of lighting intensity in the room (average of values a, b),
E_2 – average value of the lighting intensity in the corners of the room (average of c values),
n – number of working lamps in the room.

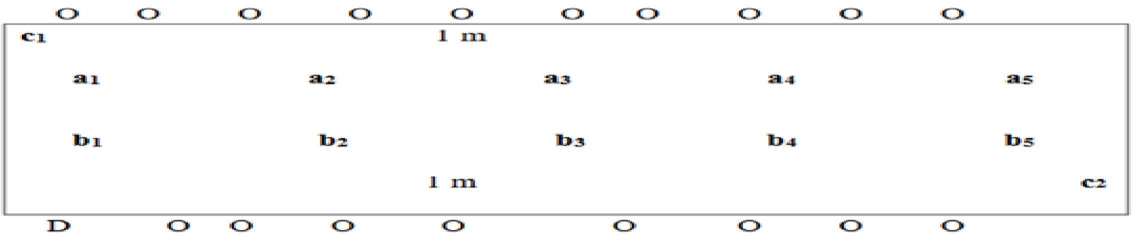


Figure 1. Graphical interpretation for partial factors of average lighting intensity

Illuminance, expressed in lux, cannot be perceived by the human eye and is thus considered a theoretical quantity. Illuminance can only be recognized when the emitted light strikes a surface (object, material) and subsequently reflects. This reflected light is terminologically referred to as luminance L (cd/m²). Mathematically, it can be interpreted using the following formula [14]:

$$L = \frac{d^2\emptyset}{d\Omega \, dA \, cos\theta} = \frac{dI}{dA \, cos\theta} \qquad (2)$$

If the luminance at the visual task area is excessive, it can cause visual discomfort for the worker, potentially impairing vision. This unsuitable, excessive luminance is described by a quantifiable measure – the glare index. The index is based on the assumption of a direct proportionality between the degree of glare and the luminance of the glaring source LzLz (which is in the direction relative to the control point) and the solid angle Ω (under which the glaring source is visible from the control point).

Conversely, it decreases with increasing average background luminance Lp (adaptation luminance). The glare index is mathematically expressed as follows [15]:

$$UGR = 8log\left(\frac{0.25}{L_p}\sum\frac{L_z^2\Omega}{p^2}\right) \quad (3)$$

, where
L_p is the background luminance, quantified by the following mathematical interpretation [15]:

$$L_p = \frac{E_{nv}}{\pi} \quad (4)$$

L_z denotes the luminance of the illuminated part of each luminaire in the direction of the observer's eyes, interpreted through the luminous intensity (I) of the luminaire in the observer's direction and the projection area (A) [15]:

$$L_z = \frac{I}{A} \quad (5)$$

Ω is the solid angle of the illuminated part of each luminaire relative to the observer's eyes, and p is the position factor.

To identify the basic input microclimatic conditions, a FLIR measuring device was used with a relative humidity range of 0% – 100% and a basic accuracy of 2.5% RH, and an air temperature range from 0°C to 50°C with a basic accuracy of ±0.6°C.

Monitoring the illuminance at the visual task area was conducted using a luxmeter with a measuring range of 0.1 – 200 klux, a working temperature range from 0°C to 50°C, an error limit of less than 6%, and linearity of less than 5% (Figure 2).

Figure 2. Device for in situ measurement - Kimo

The values recorded at the visual task area using a luxmeter were exported into a spreadsheet via specialized software and subsequently processed for further use in the creation of a digital workplace model. The model was developed using the software tool DIALux Evo.

3. In Situ Measurements

The measurement of the selected physical factor of the work environment was conducted at a machining workstation. The machining workstation consists of a CNC milling machine and a workstation where all auxiliary tasks necessary for processing the component according to the prescribed production procedure are performed. These tasks are carried out by an employee who operates the machine.

Figure 3. Assessed visual task area in the production hall

During the measurements, attention was focused on the main quantitative lighting parameters – uniformity and intensity. The measurements were conducted during the morning work shift, and the conditions under which the individual measurement series were performed (Table 2).

Table 2. Condition of measurement

Parameter	Value
Temperature	21.6 °C
Relative humidity	41.3 %
Frequency of data collection	5 s

The measurements were carried out from 12:29 to 12:39, with a sampling interval of 5 seconds.

During the measurements, no significant decrease or increase in lighting intensity was recorded, as can be observed in the graph showing the lighting intensity over time, depicted in Figure 4.

The observed fluctuations and non-linearity are, however, caused by outdated light sources and insufficient maintenance of the lighting system.

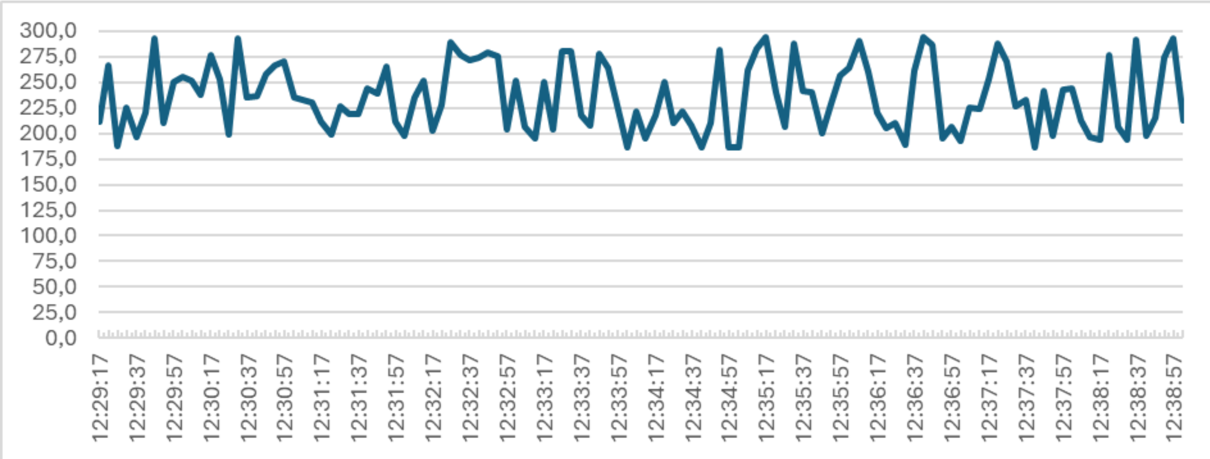


Figure 4. Graphical interpretation of lighting intensity over time

For the creation of a model reflecting the real conditions in the workplace, data were statistically processed, supplemented with calculations of uniformity as another important quantitative lighting factor. To ensure clarity and evaluative capability, data were collected at a frequency of 5 seconds, processed into 10 intervals of time, and subsequently into overall average values.

Table 3. Basic quantifiable indicators of artificial lighting intensity obtained through in-situ measurements

Parameter	Value
Average value of artificial lighting intensity	232.7
Minimum value of artificial lighting intensity	185.8
Maximum value of artificial lighting intensity	294.6
Mean deviation	32.72
Uniformity U1	0.6
Uniformity U2	0.8
Uniformity U3	0.7

Based on measured and mathematically determined parameters, it can be observed that there is a discrepancy between the detected average illumination intensity and the normative requirements. The fundamental requirement for the minimum illumination intensity at the visual task area for the specific type of activity is 500 lux. The uniformity at the visual task area should not be lower than 0.6, meeting the minimum requirement for the workstation.

Subsequently, a model of the visual task area in the production hall was created using Dialux Evo to identify and predict further lighting-technical parameters.

4. Visual Task Area Model Creation of the Production Hall

A model of the work environment focusing on the workstation (Figure 5) in the production hall was constructed according to the dimensional characteristics of the room and the conducted measurements.

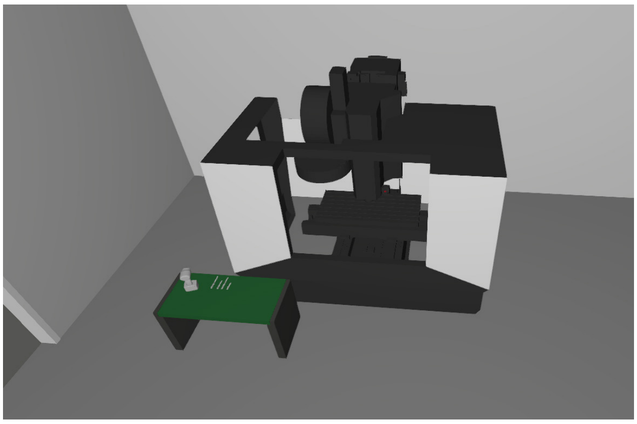
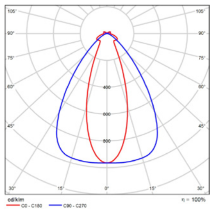


Figure 5. Model of the workstation with the visual task

Since the luminaires installed in the production hall are outdated, it was not feasible to implement the same luminaire into the digital model. Instead, a luminaire from a different manufacturer with similar characteristics, luminous intensity curve, and design was used.

Table 4. Characteristics of the used luminaire

Data specification		Polar LDC
Power [W]	60	
Luminous Flux of lamp [lm]	9 112	
Luminous Flux of luminaire [lm]	9 110	
Luminous efficacy [lm/W]	151.8	
CCT [K]	4 000	
CRI [-]	80	
Beam angle [°]	36 - 74	

In the digital model, an object defining the precise dimensional characteristics of the analysed space with surrounding area delineation was created for the visual task area.

Additionally, a general calculation object was set up to monitor the UGR parameter and a surface result for luminance identification (Figure 6).

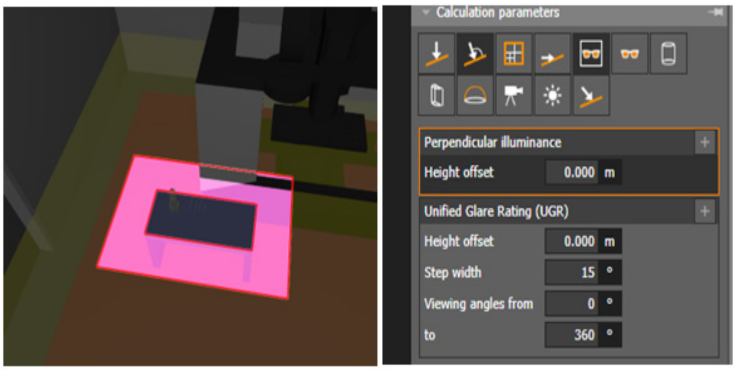


Figure 6. Creation of the visual task area object and selected calculation parameters

The assembled digital model of the assessed visual task area in the production hall was then compared with the real state and supplemented with analysis conducted in a virtual environment.

5. Results

For the possibility of utilizing combined lighting assessment, it was necessary to first analyze and compare the values obtained from measurements conducted at the visual task area within the production hall with values resulting from simulation (Figure 7).

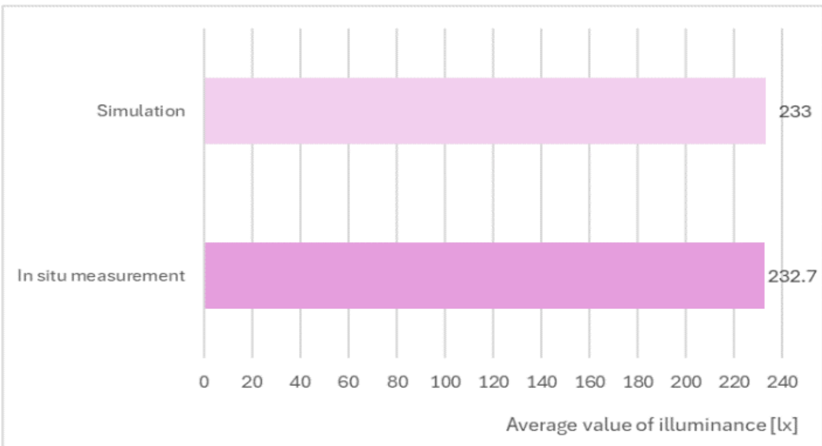


Figure 7. Illuminance of the in situ measurement and simulation

Based on the interpreted data above, the assembled digital model of the workplace in the production hall can be considered suitable for conducting combined analysis, as the rounded average illumination values are identical. When comparing the uniformity of illumination at the visual task area, identity can be observed in two out of three types of uniformity (U2, U3), while uniformity U1 shows a measured deviation of 0.1 from the simulated value.

However, since the achieved values of all uniformity types meet normative requirements both in real and virtual environments, this 0.1 deviation can be accepted. In the simulation analysis, parameters such as luminance and Unified Glare Rating (UGR) were subsequently monitored in addition to uniformity and illuminance. The simulation results for the analysed visual task area are summarized in the following table.

Table 5. Simulation results for analyzed visual task area

Parameter	Value
Average value of artificial lighting intensity	233
Minimum value of artificial lighting intensity	198
Maximum value of artificial lighting intensity	273
Uniformity U1	0.7
Uniformity U2	0.8
Uniformity U3	0.7
UGR	21.5
Average value of Luminance	5.34
Minimal value of Luminance	3.17
Maximum value of Luminance	6.33

When evaluating the obtained results, norm EN 12464-1:2021 is utilized as the fundamental regulatory standard for the design, analysis, and assessment of indoor lighting.

The analysis of illuminance intensity, based on measured data, graphical interpretation of simulation (Figure 8), and simulation results, demonstrated that the acquired value does not comply with current regulations.

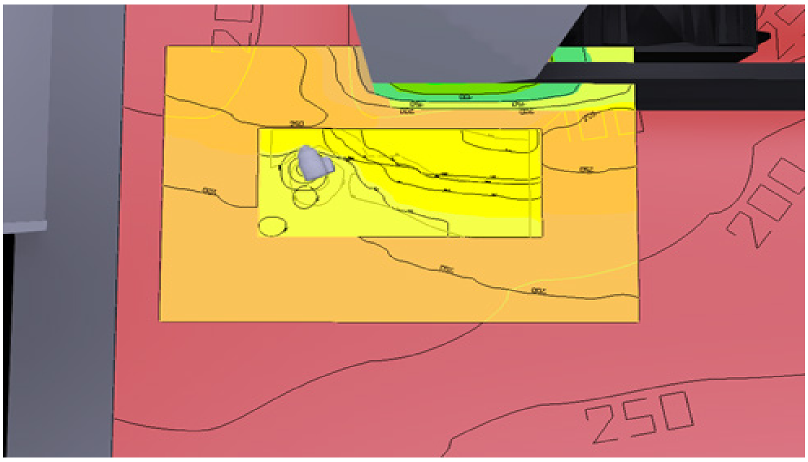


Figure 8. Iso-lux distribution in the visual task area

The illuminance level at the visual task area should ideally exceed 500 lux.

UGR analysis was conducted exclusively using data obtained from simulation.

Based on the results and graphical representation, it was observed that the strongest glare was identified at 300° with a maximum value of 21.5.

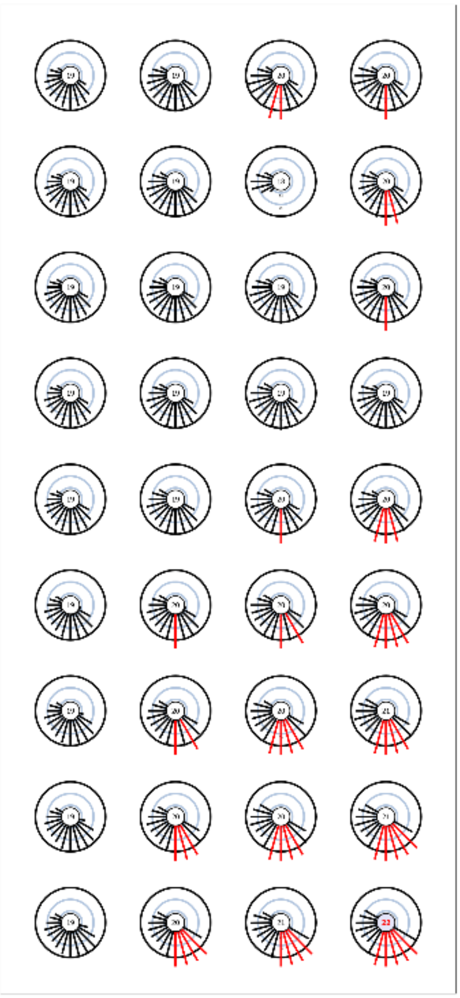


Figure 9. UGR grid in the visual task area

Similarly, an analysis of luminance was performed using simulation data. The average value of this parameter was 5.34, ranging from 3.17 to 6.33 across the visual task area, indicating acceptable values that do not necessitate changes to the shielding angle when designing new luminaires.

6. Conclusion

The combined analysis implementation revealed that certain quantitative lighting-technical parameters are inadequate for the assessed visual task area. Specifically, there is a need to focus on adjusting the illumination intensity, which currently reaches 233 lux, less than half of the required 500 lux. To comprehensively improve lighting intensity at the workplace, it is necessary to replace the lighting system. Based on the conducted combined analysis, the new system should meet the following requirements:

- Distribution and orientation of the lighting system to ensure that reflected light is directed away from the observer's eye.
- Lighting system comprising exclusively direct luminaires directing light towards the work surface.
- Adjustment of the lighting system to a higher correlated colour temperature (CCT).
- To ensure maximum efficiency and sustainability of the lighting system, determine the maintenance factor and develop a maintenance plan for the lighting system.

With this structured and analysed model, a comprehensive rationalization of the lighting system can subsequently be implemented to improve inadequate lighting-technical parameters. The development of design solutions is integral to the workplace redesign and represents a distinct area within the assembly of lighting systems in production halls.

Acknowledgements

This article was supported by research grants VEGA 1/0431/21 "Research of light-technical parameters in production hall using digital ergonomics tools" and KEGA 014TUKE-4/2024 "Innovation of practical education of industrial ergonomics with demand to increase students' adaptability in study program Industrial Management.

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