



Ergonomic rationalization of lighting in the working environment. Part I.: Proposal of rationalization algorithm for lighting redesign

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ABSTRACT

This article describes the creation of an ergonomic rationalization algorithm and its subsequent verification in the creation of the redesign of the working environment lighting in conjunction with the tools of the digital enterprise. The rationalization algorithm consists of 15 sequences, whose accuracy is subsequently verified on a practical example of a built digital twins in the Dialux Evo 6.1 simulation tool. To build a digital twin were used a series of practical measurements of artificial lighting in the production hall. In conclusion, the article compares the current state with the newly proposed solution after the application of rationalization algorithm. In each of the observed points, there was an increase in light intensity compared to the original solution. The increase of artificial lighting on individual planes ranged from 420 lx to 668 lx. The conclusion of the article provides the main benefits for the scientific area and for practice.

1. Introduction

Contemporary knowledge and technologies are capable of creating a better work environment, for example by rationalizing it, which then ensures more appropriate working conditions. Mass digitization is the concept of creating an integrated PC system, which consists of models, simulations, analyses, 3D visualizations. These tools help each other to create new, faster solutions that save production companies besides time a lot of financial resources. At present, several authors deal with the issue of lighting the work environment. In their research, they focus on the proposal and optimization of lighting systems, compares individual versions of available software for modelling and assessing lighting, evaluate energy efficiency, and so on (Hu, 2017; Na et al., 2016; Mangkuto, 2016; Meshkova and Budak, 2013; Domingues dos Santos et al., 2013; Li et al., 2012; Salata et al., 2015; Avci and Memikoğlu, 2017; Sanchez et al., 2015; Ekren et al., 2007). No rationalization algorithm for the redesign of lighting in manufacturing enterprises was found in the overview of previous studies. However, it is this contribution that provides a general rationalization algorithm that, can be applied in different production and nonproduction enterprises.

2. Material and method

The Dialux Evo 6.1 simulation tool was used to verify the rationalization algorithm design. Selection of the simulation tool was made on the basis of a comparison of the three available software. Individual software has been compared from the point of view of several criteria. These criteria are listed in the following table (Table 1).

From the comparison of the simulation tools, it follows that the most accessible and the most comprehensive tool for assessing lighting is the freeware simulation light-technical programme Dialux Evo 6.1. This simulation tool provides to a regular user a simple working environment that does not need to be controlled through a hierarchical tree as in other cases. An important positive point is a possibility of creating a simulation model in one user environment for artificial, daytime and combined lighting, without the need for study of additional modules. This software is tailored to design, visualize and calculate lighting in individual rooms, floors, buildings and exteriors. To create artificial lighting this software uses catalogues of luminaire from different manufacturers that are either available online or on specific websites, or the user installs them as an active plug-in. The programme Dialux Evo 6.1 with its light-technical calculations is a suitable tool for creating and assessing different types of objects.

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Table 1

Criteria for selecting the most appropriate software.

Criterion	Specification	Dialux Evo 6.1	Relux Pro	Building Design
Products	Type of packages	Comprehensive package for all types of illumination	Relux CAD ReluxEnergy Relux Tunel ReluxOffer	Wils WDLS Sunlis
Create your own light database	Quick access to the most used luminaires	yes	yes	no
Compliance with the standard EN 12464-1	Equivalent STN EN 12464-1	yes	yes	yes
Import of objects from external files	Support of 3ds format	yes	yes	yes
Modelling multiple types of lighting at the same time	Modelling in one user environment	yes	yes	no
The graphical design of simulation - visualization	View results in 2D and 3D versions	yes	yes	yes
Multiple choices to interpret the results	Illuminance view	yes	yes	yes
	Summarize the results in one transparent spreadsheet	yes	no	yes
	Warning to achieve the minimum required values	yes	no	yes
Export of results	Export of results to Adobe Reader	yes	yes	yes

**Fig. 1.** Current state of illumination in the manufacturing hall.

Individual models from which the subsequent rationalization was carried out were compiled based on input measurements made in machine engineering company manufactures (Fig. 1). The company is oriented to piece production, producing various types of aluminium forms which it subsequently supplies to various companies in the electrotechnical industry and also its production focuses on customizing its own forms. In addition to these activities, the company is involved as well as the production of measuring instruments for automotive and shaped milling in the area of general mechanical engineering.

To create the original model, which was then rationalized in synergy with the rationalization algorithm an objective assessment of the light climate was realized at the workplace (direct lighting measurement), and based on this measurement current state models were created.

Direct measurement and assessment of lighting in the production hall were carried out according to the STN EN 12464-1 Light and lighting. Lighting of workplaces. Part 1: Indoor workplaces (N 12464-1 Light and, 1246) and ČSN 36 0011-3 Lighting measurement in areas – Part 3: Measurement of artificial indoor lighting (ČSN 36 0011-3) in December at 5:45 a.m. (an artificial indoor lighting measurement). The measurement was performed using the Roline RO-1332 digital lux meter with a resolution of 0.1 lx, a measurement speed of 2.5 measured for second and repeatability of 2% and accuracy classes of 3%, 0.5% (Fig. 2).

In the production hall measuring $26.035 \times 17,500 \times 8.000$ mm, three measuring points were placed. The first measuring point was placed close to the Hermle machine, the other was located close to the machine MCV 750 Sprint and third close to the 5-axis CNC machine

DMU 340 P. For every measuring point 9 measurements were made at a height of 0.85 m from the floor - three in the vertical position, three in the horizontal position and three close to the auxiliary table. Deployment of individual measuring points is shown in the following figure (Fig. 3).

Measurement of artificial lighting was performed at given measuring points. Measuring results are shown in the following table (Table 2).

Based on individual measurements and their graphical interpretations (Figs. 4–6), it is clear that in none of the measuring points, according to STN EN 12464-1 Light and lighting. Lighting of workplaces. Part 1: Indoor workplaces (N 12464-1 Light and, 1246) the required light intensity (500 lx) has not been reached and therefore it is necessary to rationalize lighting at the workplace. Based on these measurements and technical drawing documentation, simulation models were constructed in the simulation tool Dialux Evo 6.1 - creating a digital twin of the current state. This model was necessary to build up due to its subsequent rationalization. The calculation areas for each area of the working environment were determined on the basis of measurement points determined directly at real measurements in the production hall in height of 0.85 m. Specific values were generated based on the definition of the working environment - industrial and craft activity - metal processing and other treatments of metal, rough and medium machining. The simulation tool for generating individual results has lighting requirements according to standards EN 12464-1, DIN V18599, CIE 097–2005.

The model of the production hall (Fig. 7) below also shows the calculation areas, that have been defined in the program according to the measurement points determined in real-time measurement in practice. From the individual computational areas, the average value of each of the computational areas considered into final comparison. A model calculation is performed for artificial lighting.

After the creation of the lighting system of the production hall, simulation of artificial lighting was carried out, the results which are presented in a numerical form in the following table (Table 3) and graphically by displaying the course of isophote process in the following figure (Fig. 8).

After creating a digital twin of real state artificial light intensity, the results clearly confirm the measured values in practice and thus the model is created correctly.

A summary of the real measurements and the results obtained through the assembled digital twin is shown in the following table (Table 4) and graph (Fig. 9).

When working with simulation models, the tolerance of the values obtained by the simulation and the values obtained from the real



Fig. 2. Direct measurement of lighting (left) and Roline RO – 1332 - digital lux meter (right).

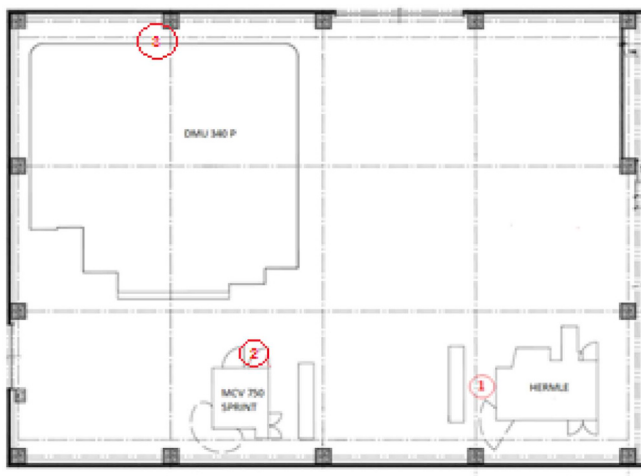


Fig. 3. Scheme of measurement point distribution.

Table 2

Measurement results (in situ).

Measuring point	No. of measurement	E_{iz} [lx]	E_{iv} [lx]	E_{ip} [lx]
1	1	115.4	160.7	167.8
	2	115.3	161.3	169.8
	3	115.8	160.9	170.9
2	1	105.2	170.1	183.4
	2	105.1	170.3	184.7
	3	105.2	170.1	185.6
3	1	88.9	151.1	101.0
	2	89.2	150.9	101.2
	3	90.2	151.2	101.1

E_{iz} – light intensity at a given point “i” measured in the vertical position [lx].

E_{iv} – light intensity at a given point “i” measured in the horizontal position [lx].

E_{ip} – light intensity at a given point “i” measured in auxiliary table [lx].

measurements is 15% (Vangimalla et al., 2011). Due to this fact and the above results it can be stated that the assembled digital twin models are correct. Confirmation of the accuracy of the digital twin model allows subsequent rationalization based on the algorithm below.

2.1. Rationalization algorithm for redesigning of working environment lighting

The main rationalization algorithm consists of 15 basic parts – sequences (Fig. 10). The individual sequences can be divided into two basic phases. The first phase - the selection phase of the most suitable simulation software available, consists of 9 basic phases, in which an important part is the decision block, which determines the suitability of selecting the simulation tool for further needs and completing the redesign. In this phase, the next algorithm is also included in level 6 describing the sequence of work with simulation models. The second phase of the main rationalization algorithm - the redesigned software application phase – is a sequence of a number from 10 to 15. This phase is focused on the application of selected software, which was determined based on the sequences of the first phase. The overall view of the main rationalization algorithm is shown in the following figure, which shows the detailed characteristics of its individual steps.

Side Algorithm I - The design of the rationalization algorithm for simulation models is provided in the second part of the article: Rationalization of working environment lighting. Part II: Design of a rationalization algorithm for simulation models.

- After the design of the whole model and setting of the calculation parameters, it is possible to proceed to the realization of the simulations in the selected light-technical tools. The simulations of each type of illumination take place at different time intervals, ranging from a few minutes to hours. This time interval is dependent on the software, hardware, complexity of the model, the quantity of the evaluated parameters as well as the type of rated lighting.
- By completing the simulations, the required light-technical results are generated in the individual simulation tools, such as light intensity, daylighting factor, etc. These results are then compared with real measurements that have been realized in practice. In this comparison of simulated and practically measured values, the so-called tolerance of the difference between simulated and real values. The limit value of this tolerance or deviation Δ is up to a maximum of 15% (Vangimalla et al., 2011). In this decision block it is necessary to determine on the basis of tolerance - tolerance deviation, or simulated values within given limits. If the values achieved are unsatisfactory, then it is necessary to return to step 5

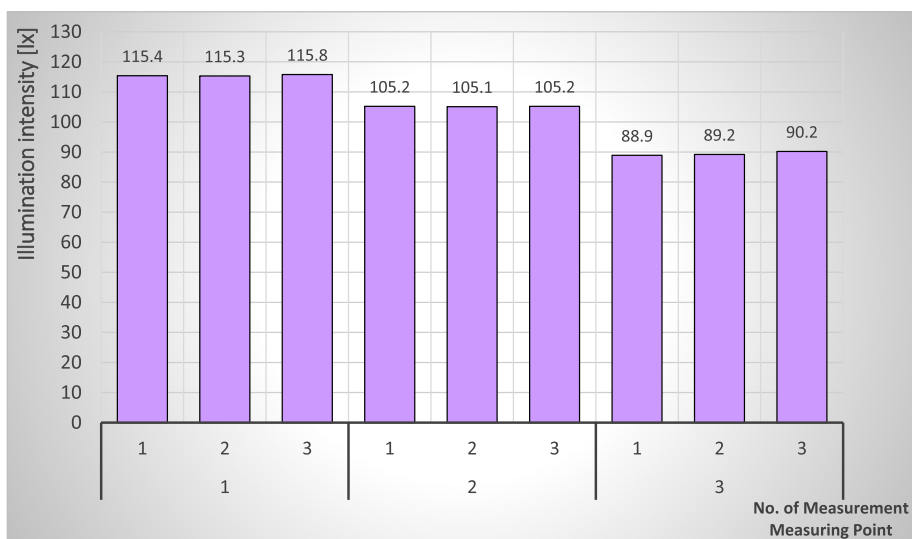


Fig. 4. Light intensity at a given point “i” measured in the vertical position.

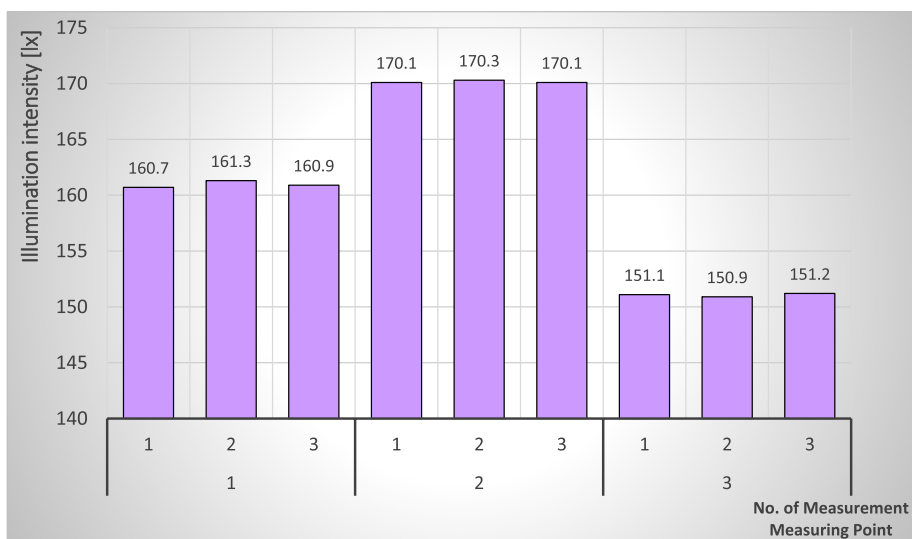


Fig. 5. Light intensity at a given point “i” measured in the horizontal position.

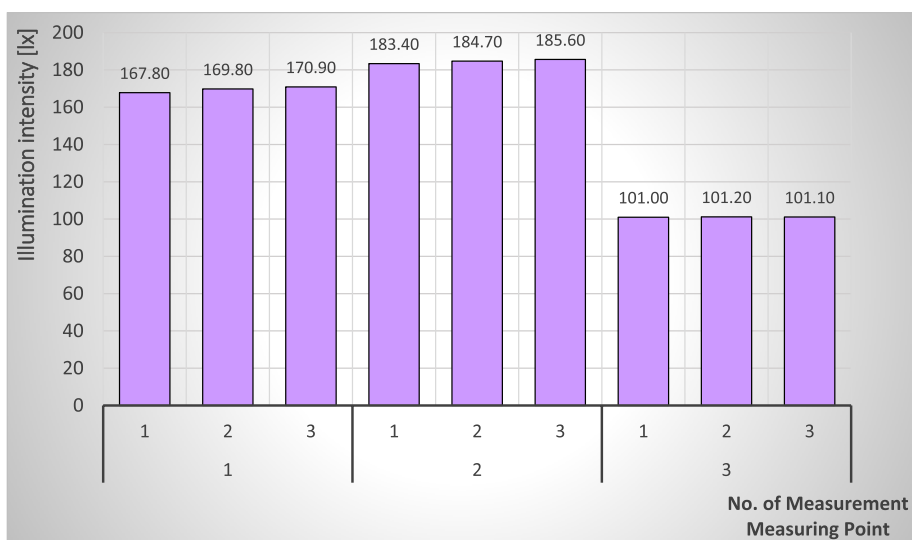


Fig. 6. Light intensity at a given point “i” measured in the auxiliary table.



Fig. 7. Visual display of the production hall and computing area 2D (up) 3D (bottom) in the current state.

Table 3

Simulation results of artificial light in the current state.

Calculation area	Monitored factor	Average value [lx]	Min. value [lx]	Max. value [lx]	Uniformity of lighting [-]
Calculation area – Measurement point No. 1	Illumination intensity	169	110	198	0.65
Calculation area – Measurement point No. 2	Illumination intensity	167	10	232	0.06
Calculation area – Measurement point No. 3	Illumination intensity	153	82.3	221	0.54

and repeat the procedure. If the values match, continues to the next step.

9. After determining the appropriate deviations arising between simulations and realistic measurements it is possible to select the most appropriate simulation tool, which will then be used in the redesign - creation of a new digital model of the workplace. The choice is made by comparing the deviations. The most appropriate simulation tool is the tool in which the deviation has the lowest value.
10. By completing all of the previous steps, it is possible to proceed with the redesign – creation of a new digital model of the

workplace in accordance with the procedure given in algorithm I. 11.-12. After the new model is created, a simulation of the required lighting type is carried out to obtain specific light-technical results.

13. In the thirteenth step, the results obtained by the light-technical calculations from the simulation model are compared with the relevant legal requirements (standards) of STN.
14. If the results are not satisfactory, it is necessary to go back to step (10) create a new digital model, modify the model, and then proceed with the simulation.
15. If the results are satisfactory, the whole ergonomic rationalization process using simulation tools can be terminated.



Fig. 8. 3D model of the isophote in the current state (artificial lighting).

Table 4

Comparison of realised measurements with the digital models – current state.

	Measurement point No. 1	Measurement point No. 2	Measurement point No. 3
Average value of real measurement [lx]	160.9	170.1	151.1
Average value of simulation [lx]	169	167	153
Deviation (real measurement/simulation) [%]	5.03	1.82	1.26

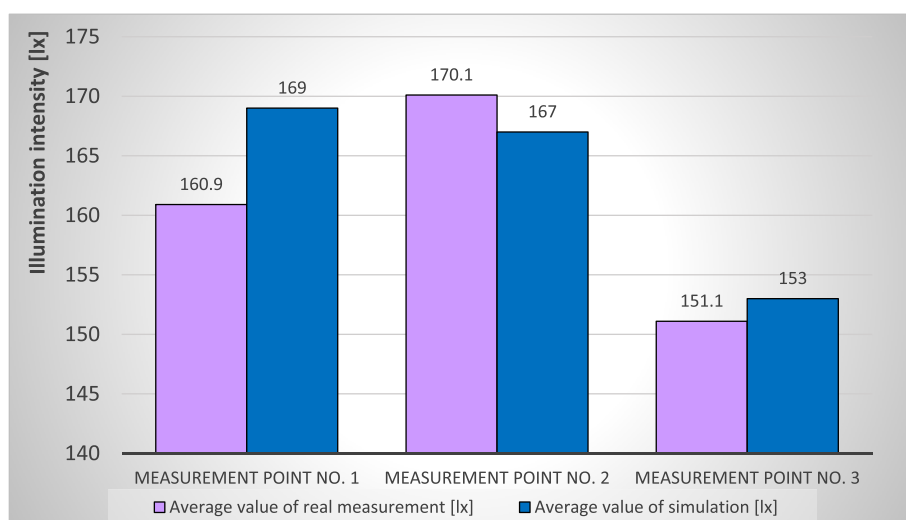


Fig. 9. Comparison of realised measurements with the digital models.

2.2. Practical application of the rationalization algorithm - redesign of the production hall lighting

Based on the phases of the main rationalization algorithm from the previous part of the article, the phase of compiling the new digital model of the workplace was implemented, the redesign phase was applied (step No. 10 in the main rationalization algorithm). Based on the

sequence, the rationalization model was then described and the simulation was performed (step No. 11).

Based on the layout of the production hall, the production machines, equipment and other objects were inserted on prescribed places which are located at the workplace. This has created a comprehensive 3D model of the working environment of the production hall in which new design of artificial lighting will be realized. In the production hall

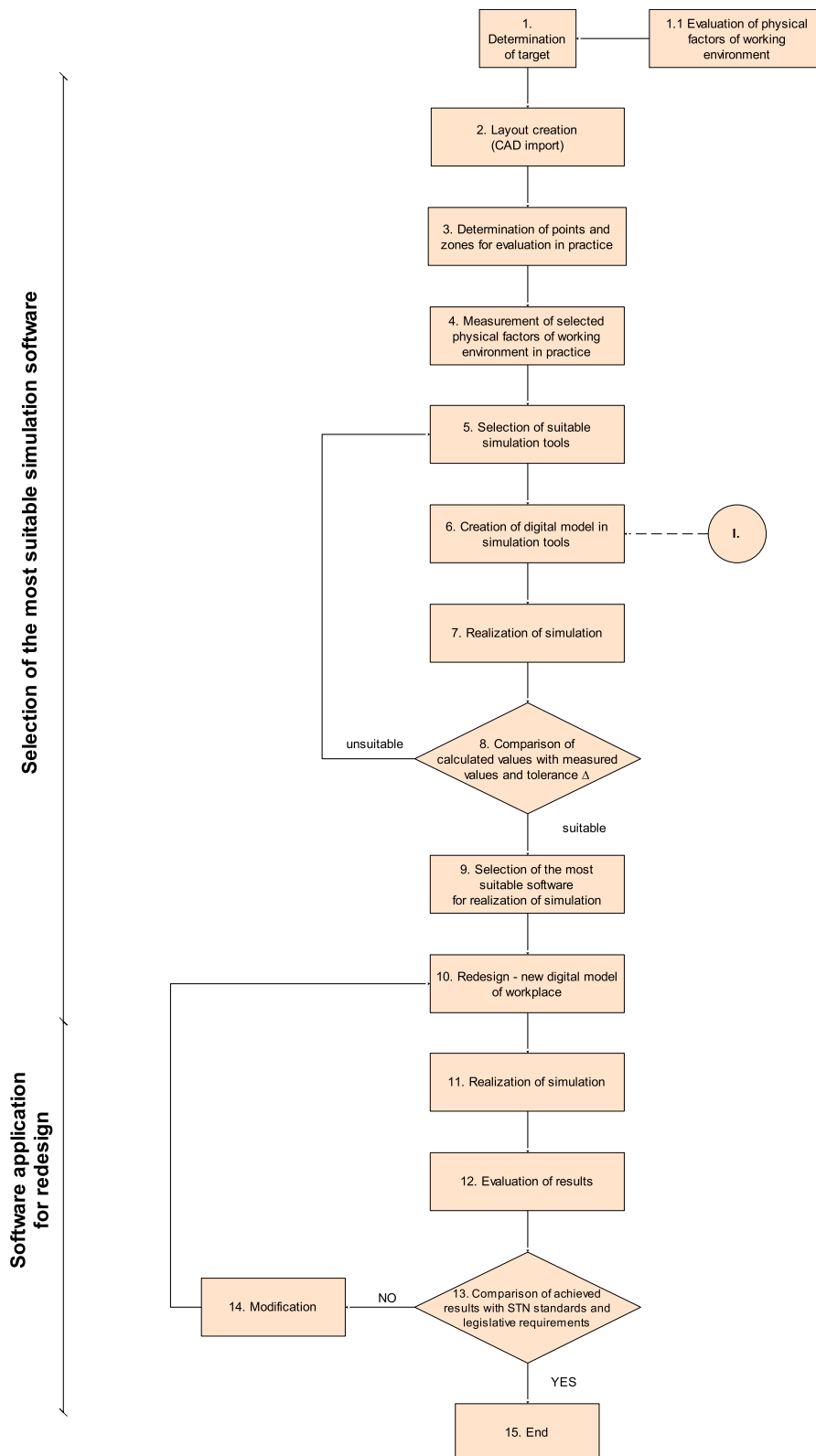


Fig. 10. Rationalization algorithm for redesigning of the working environment lighting.

The sequence of the main rationalization algorithm is the following:

1. Determination of target. One way to determine the physical factor for assessment in practice is also the subjective assessment of the workers concerned. Subjective assessment can be implemented through the survey method; the result of the survey provides information on which physical factors should be considered. Objective assessment is measurement, which points the need for editing redesigning the working environment to achieve acceptable values of the assessed physical factor of the working environment, for instance, lighting.
2. In the second step of the rationalization, it is necessary to compile the current layout of the workplace. If base materials are available at this phase, the basic workplace layout is imported from the appropriate CAD software, and a 3D model is then created through the floor plan. A sophisticated solution is the use of 3D scanning.
3. The third step of the algorithm - the determination of the assessment points and zones in practice consists of the real determination of the measurement points in the considered area. In this area, the basic measurement points and zones are a layout, the selected physical factors of the working environment will be analysed and evaluated in them. Measurement points are determined according to the guidelines given in standards ČSN 36 0011-3 Lighting measurement in areas – Part 3: Measurement of artificial indoor lighting. (ČSN 36 0011-3)
4. By setting basic measurement points in practice, it is possible to proceed to the fourth part of the algorithm - self-measurement of selected physical factors of the working environment. During the measurement itself, it is necessary to follow the procedures according to STN EN 12464-1 and ČSN 36 0011-3 (N 12464-1 Light and, 1246; ČSN 36 0011-3) and to use the calibrated lux meter device.
5. After making the in situ measurements, appropriate simulation tools should be selected. The choice of simulation tools can be realized through market research or practical findings, respectively a personal review of the most appropriate options. In selecting the simulation tool is possible to use a professional table, which is presented in the theoretical part of the thesis.
6. Sixth part of the algorithm - creation a digital model in simulation tools. Based on these rules in the individual light-technical tools will be an identical model. Assuring the build of an identical model for each simulation tool is by creating a CAD version of the layout of the object under consideration. This version is then loaded in each of the selected programs and made into a 3D complex model that includes the necessary building holes, lighting systems etc.

model, there were subsequently defined building openings - two doors and eight windows. The design phase of the new building completes the design of the lighting system. The proposed lighting system consists of the installation of two sets of a luminaire with symmetrical radiation, a number of pieces 12. The technical specification is given in the following table (Table 5). In the case of luminaires with this type of radiation, it is easier to ensure the correct direction of the light beam to

achieve energy savings, as there is no need to choose stronger power lights. From the original layout, the centre line of the luminaires has been removed, since, in the current type of illumination, a medium range of luminaires is not required in terms of intensity. The new luminaires are in the rationalization design placed in the outer row of the original luminaires in the original height of over 7 m.

One of the main reasons for selecting a given type of lighting, except

Table 5
Technical specification of the proposed artificial lighting.

Efficiency [%]	75.82
Lamp flux [lm]	24 640
Lamp power [W]	429
Illumination source	Type
	Halogenated discharge lamp
	Init. Corr. Colour Temperature [K]
	6502

providing the necessary intensity, was to provide the required chromaticity temperature at a level of approximately 6500 K. Recent research (Drahoš and Drahoš, 2008) into the health aspects of lighting at work has also begun, in addition to photometric measurements,

circadian quantities such as index the cyclic effect of Ac. Through the circadian effect is possible to compare the light source. The most suitable solution is to provide Ac 100% - a reference value for the CIE D 65 standard daylight, the chromaticity of which is at 6500 K.

The proposed model contains 5 basic computing areas (Fig. 11). The individual calculation areas - the planes differ only in the definition of the positions - each computing area is located in the working area of the worker in the respective production machine. Measuring graticules are spaced at 8 pixels to 10 pixels in each object.

As can be seen in the following figure (Fig. 12), a digital twin compiled according to practical measurements was supplemented by two new measurement points, taking the practical requirements and the expansion of production.

According to the main rationalization algorithm, an evaluation of the results achieved through simulation (step 12 and 13) was followed (Fig. 13). Table of results of the artificial lighting simulation results of

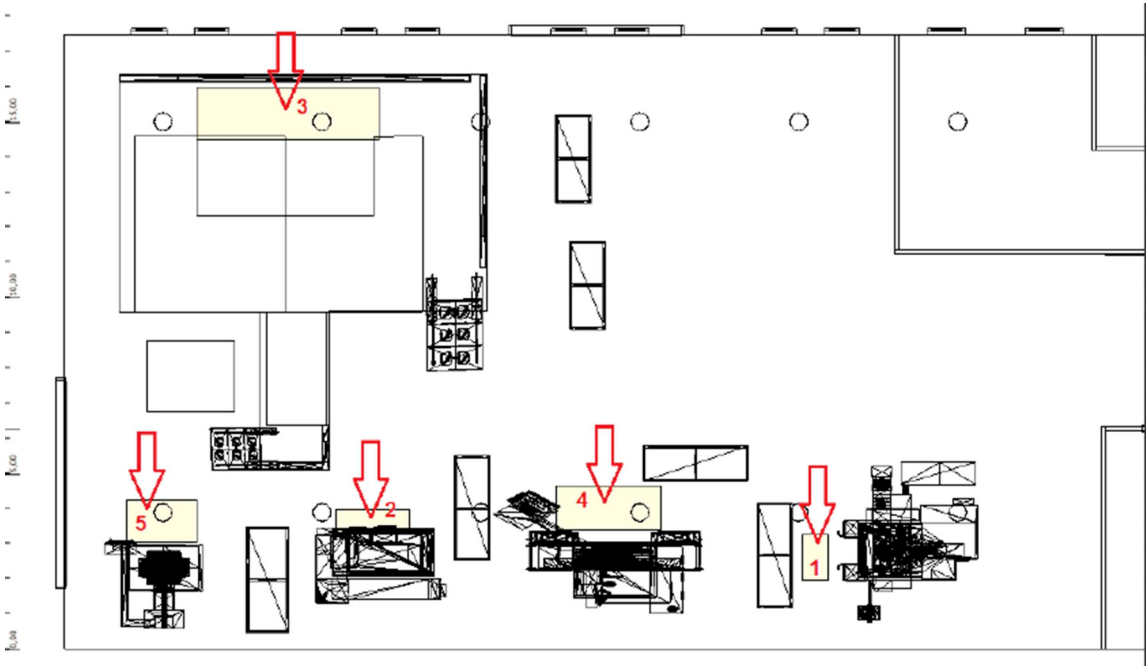


Fig. 11. Scheme of the rationalized model of the production hall with the recognition of the calculations for artificial lighting.

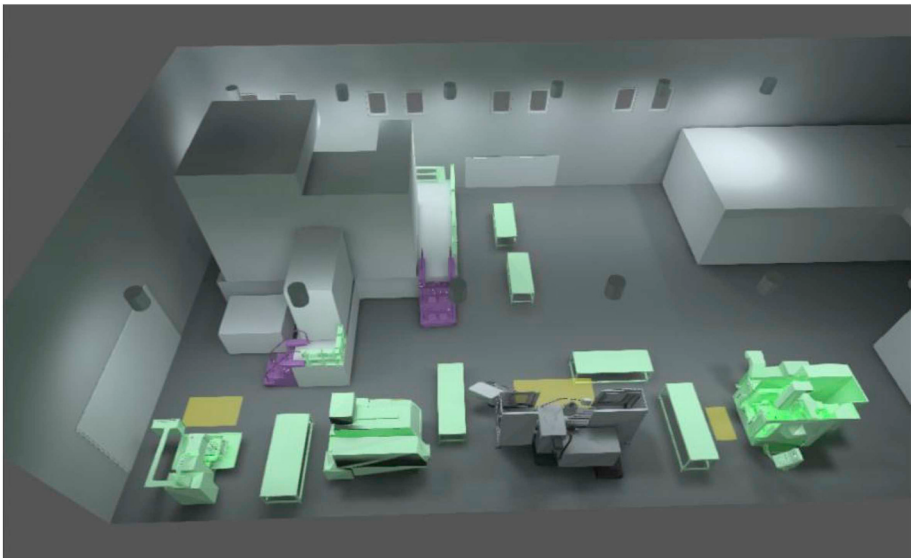


Fig. 12. 3D rationalized model of the artificial lighting layout.

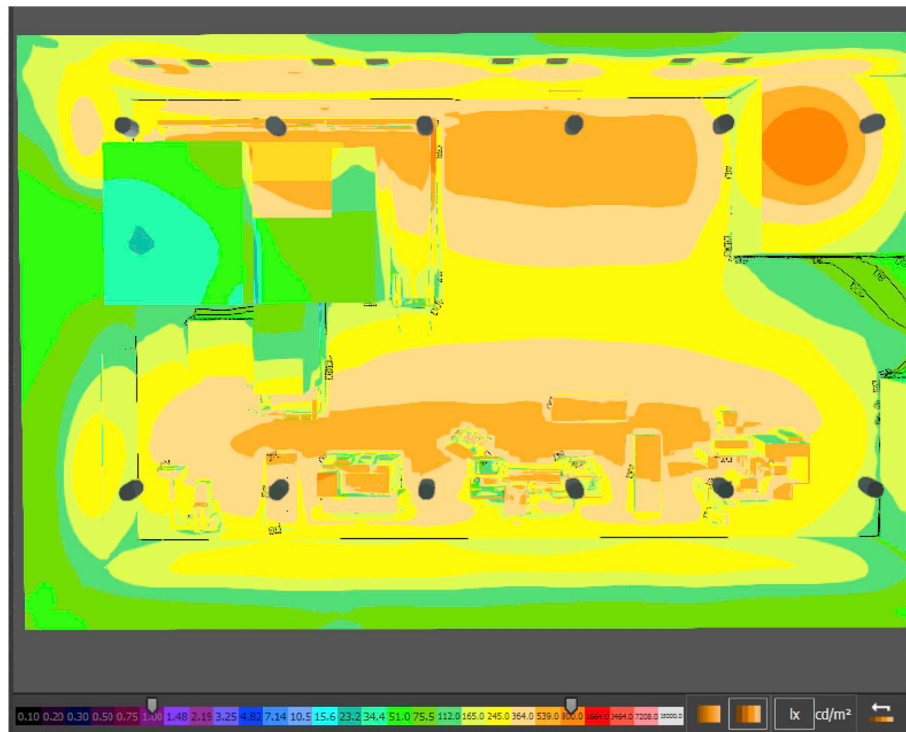


Fig. 13. 3D model of the isophote in the rationalised proposal in the manufacturing hall.

Table 6

Results of simulation of the artificial light intensity of the rationalization proposal.

Calculation area	Monitored factor	Average value [lx]	Min. value [lx]	Max. value [lx]	Uniformity of lighting [-]
Calculation area – Measurement point No. 1	Illumination intensity	589	433	669	0.74
Calculation area – Measurement point No. 2	Illumination intensity	668	651	692	0.97
Calculation area – Measurement point No. 3	Illumination intensity	821	681	928	0.83
Calculation area – Measurement point No. 4	Illumination intensity	685	633	752	0.92
Calculation area – Measurement point No. 5	Illumination intensity	597	532	628	0.89

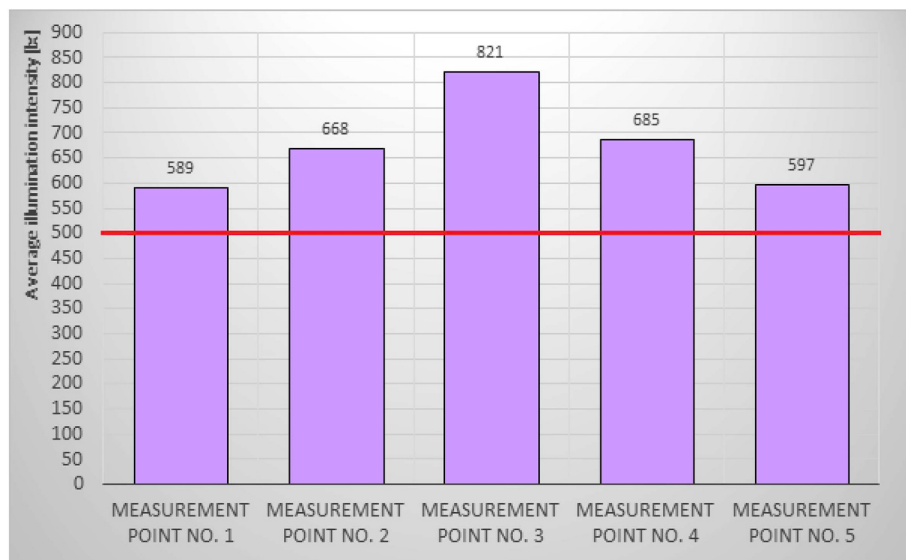


Fig. 14. Graphical evaluation of lighting intensity after the rationalization.

the new proposal below confirms the suitability of the proposed lighting in terms of the parameter under consideration since at all the calculation points the lighting intensity was higher than the value determined by STN EN 12 464-1 (Table 6).

According to the STN 12 464-1 standard, the obtained values of lighting in the immediate surrounding area should not be less than 0.7. The results obtained show that the proposed solution can be judged to be correct also in terms of the uniformity of the lighting parameter.

Table 7
Evaluation of the artificial lighting after the application of rationalization proposal.

Monitored factor	Calculation area	Obtained of monitored factors	Required of monitored factors	Deviation of obtained and required values
Average illumination intensity [lx]	Measurement point No. 1	589	500	89
	Measurement point No. 2	668	500	168
	Measurement point No. 3	821	500	321
	Measurement point No. 4	685	500	185
	Measurement point No. 5	597	500	97

Table 8
Evaluation of proposed model before and after the rationalization.

Monitored factor	Measurement area	Value of monitored factors		Differences in values of monitored parameters
		Before rationalization	After rationalization	
Average illumination intensity [lx]	Measurement point No. 1	169	589	420
	Measurement point No. 2	167	668	501
	Measurement point No. 3	153	821	668
Uniformity of lighting [-]	Measurement point No. 1	0.65	0.74	0.09
	Measurement point No. 2	0.06	0.97	0.91
	Measurement point No. 3	0.54	0.83	0.29

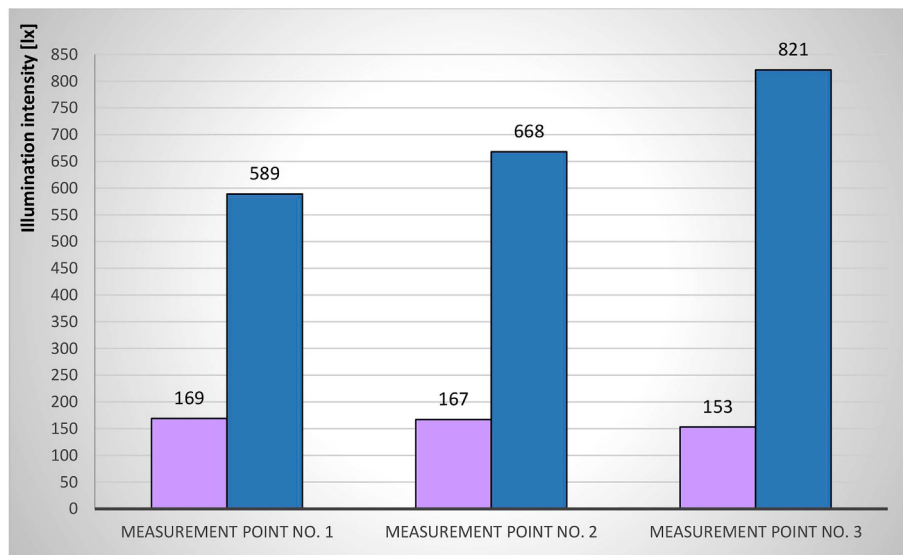


Fig. 15. Evaluation of proposed model before and after the rationalization.

3. Results

It can be stated that not only the desired values have been achieved (Fig. 14), but that their increase over the required values (N 12464-1 Light and, 1246) ranged from 89 to 321 lx based on the average values of the light intensity. Specific values, including an increase in the required values (N 12464-1 Light and, 1246), are given in the following table (Table 7).

Because of the inadequate in situ measurement results, a digital model light illumination was then built up, which was subsequently added. In the given form of the model, redesign of lighting (through a general rationalization algorithm) was performed, which is compared with the passing state (Table 8 and Fig. 15).

4. Conclusion

4.1. Evaluation of the contribution of the rationalization algorithm design for redesign lighting

The redesign is a very important part of industrial management. The manufacturing industry as a whole is heading at an unstoppable speed

for promotion digitization of production, auxiliary and service processes, but also complex digitization of workplaces. The working environment has to be suitable for every worker (Flimel, 2015, 2017; Kočiško et al., 2017; Novák-Marcinčin et al., 2013; Knapčíková, 2012; Čumas et al., 2016; Čep et al., 2010; Dupláková et al., 2016; Suszyński et al., 2012). The article presents one of the options as effective to use digital business tools not only in areas such as production or planning but also in areas of assessing the working environment, namely in the assessment of lighting. On the basis of practical measurements and the creation of a digital twin in the simulation tool, a general rationalization algorithm for redesigned lighting was developed. Based on the research carried out and the creation of the rationalization algorithm, the following benefits were set for the scientific area and practice:

- Enhancement of knowledge in the field of ergonomic computer support
- The general design of the working environment lighting algorithm
- Practical and realistic design of redesign lighting for the working environment of the production hall
- Improvement of working conditions at a particular workplace by security sufficient light intensity

By applying a general rationalization algorithm for redesigning the lighting in the production hall, the average value of artificial lighting intensity has been increased in each of the assessed planes. The increase in artificial lighting on individual planes moved in values ranging from 420 lx to 668 lx with the guarantee of the allowed brilliance of the UGR and required by the uniformity of lighting. This rationalization algorithm is applicable in different production lines and is helpful in re-organizing layouts of production halls, or assessing or modifying lighting.

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