BULLETIN OF THE POLISH ACADEMY OF SCIENCES
TECHNICAL SCIENCES, Vol. 72(3), 2024, Article number: e149233
DOI: 10.24425/bpasts.2024.149233

POWER SYSTEMS AND POWER ELECTRONICS

Analysis of the general index of modelling in interior lighting

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Abstract. Directionality of light and modelling effects impact lighting quality in interiors. Modelling effects depend on the photometric characteristics of luminaires and their layout but also interior size and reflectance. This research aims to evaluate lighting design limitations and the characteristics of the impact of interior and luminaires on modelling effects, as well as elaborate a prediction method of modelling effects in interior lighting. The general index of modelling was used for the analysis of modelling effects in interiors. The implementation of the research objectives was based on simulation and statistical analysis. 432 situations, varied interior size, and reflectance, the lighting class, luminaire downward luminous intensity distribution, and layout were considered. The results show that achieving the required range of the general index of modelling in interior lighting is substantially limited. The general index of modelling is impacted the most by the layout of luminaires. The elaborated multiple linear regression models can have a practical use for interior lighting design and analysis in terms of obtaining the required range of the general index of modelling.

Keywords: electric lighting; interior lighting; directionality of light, modelling; regression.

1. INTRODUCTION

Electric lighting is currently a key point in debates on sustainable development, and thus the rational use of electricity. This is since 19% of global electricity usage is spent on public lighting [1]. Electric lighting is commonly used in public and private spaces to meet various human needs [2].

Creating a good interior luminous environment involves the desired effect on the human body and psyche. Appropriate lighting enables the effective and comfortable performance of visual tasks [3, 4] and the proper circadian rhythms operation [5, 6]. The illumination method can also affect the perception of the interior and objects [7, 8] and the subjective impression, emotion, mood, and behaviour of users [9–11].

Verification of any lighting solution in terms of creating a good luminous environment in interiors conducted at the design or implementation stage is based on the verification of the criteria contained in lighting standards, e.g., [12] or guides. Requirements for interior lighting are determined based on parameters characterizing the luminous environment and criteria values of these parameters, whose fulfilment guarantees the occurrence of the expected human needs.

The analysis of lighting conditions in interiors is based on the exploration of quite extensive and interrelated aspects, regarding the quantity of light, the spectral distribution of light, and spatial distribution of light, including glare and directionality of light [13]. The aspect that we have analysed in detail is the directionality of light and the related modelling effects in general interior lighting.

Obtained desired modelling in interiors depends to a considerable extent on the illumination method of the analysed object: the number, luminous intensity distribution, and layout of luminaires [14]. It also depends on the characteristics of the interior and objects in the space. When the object is illuminated by one luminaire with a narrow light distribution, from a specific direction, we implement directional lighting, which usually leads to strong modelling. When the object is illuminated by many luminaires from different directions, or by luminaire(s) with a wide light distribution, we implement diffuse lighting, which usually leads to soft modelling.

In general, too directional or too diffuse lighting is not recommended as interior lighting in workplaces. Ensuring an appropriate balance between directional and diffuse lighting facilitates eliminating undesirable effects, such as strong shadows in the case of excessively directional lighting or a monotonous luminous environment in the case of excessively diffuse lighting [15, 16].

Research on the directionality of light in interiors and the related modelling effects has a long history. In his work, Gershun pointed out that "the required illumination on a working surface was not an adequate criterion, since the illumination of a working surface is not a universal measure of the lighting" [17]. He noticed the need to consider the "magnitude of the illumination and correct coordination of general and local illumination, to the direction of the light, and shadows" [17]. Waldram [18] proposed definitions of basic concepts related to the issues of light directionality in interiors, such as modelling, modelling index, modelling pattern, cast shadow pattern, structure pattern, and texture pattern. He presented modelling indices, as well as methods and apparatus for the systematic study of modelling and shadow. Hewitt *et al.* [15, 16] concluded that the assessment of modelling should be based on the analysis of the horizontal-

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Manuscript submitted 2023-10-13, revised 2024-02-06, initially accepted for publication 2024-02-20, published in May 2024.

to-average vertical illuminance ratio at a reference point. The average vertical illuminance was represented by the cylindrical illuminance, measured with the elaborated apparatus. The results of subjective assessments showed that both too-strong and too-soft modelling were rated lower than moderate modelling. Hewitt's results are the basis for the assessment of the modelling effects, adopted in the current standard for interior lighting [12]. Lynes *et al*. [19] developed the idea of using scalar and vector illumination. The vector illumination indicated the directional qualities of the lighting. The ratio of vector to scalar illumination served as a modelling index in interiors. Cuttle, in one of his first works [20], developed the concept of the pattern of light (lighting patterns) and proposed an assessment of the flow of light according to the vector to scalar illuminance ratio. In the next paper [21] he described the concept of cubic illumination and the method of calculations and measurements, and also proposed this form of specification as the basis of a system of applied photometry. He developed his ideas in subsequent works [e.g., [22–25]. Bean [26, 27] used the already used concepts of scalar and cylindrical illumination, and also studied the possibilities of using semi-cylindrical illuminance where a single direction of view was considered. He concluded that the vector to cylindrical illuminance ratio was marginally better than the vector to scalar illuminance ratio for controlling the modelling effects in interiors.

In conclusion, various appraisals have been applied to evaluate the modelling effects in interior lighting. Currently, two indices are used in practice most often: the cylindrical to horizontal illuminance ratio (index of modelling for overhead lighting installations) and the vector to scalar illuminance ratio (General Index of Modelling: MCU). Our paper focuses on the analysis of the MCU index.

The main objectives of our research concerned:

- the assessment of design limitations in general interior lighting, resulting from the application of the MCU index requirement for the modelling effects verification,
- the assessment of the room, luminaires and their layouts impact on the level of the MCU index,
- the development of a multiple linear regression model for the MCU index prediction on the ground of the room, luminaires, and their layouts, in general interior lighting.

2. METHOD

The assessment of the modelling effect, based on the distribution of the MCU index, was performed on the need to avoid both too-directional and too-diffuse lighting in interiors in order to achieve a pleasant appearance for human faces in informal communication. The expected effect, "moderately weak", occurs at the MCU index value equal to 1.5. In practice, it is acceptable to obtain slightly softer and slightly stronger effects. The preferred MCU index value should be then in the range of 1.2–1.8 [25]. This requirement was adopted to assess the modelling effect in our work.

The research covered a simulation part, consisting of calculations in the DIALux 4.13 verified program [28], of 432 lighting situations and an analytical part, with the use of the R software for statistical computing and graphics. General lighting systems were selected for interior illumination.

First, for each situation, the illuminance distribution on the task area (the area stretched between the walls in the analysed interior) was calculated. Then, the MCU index distribution on the reference area (also stretched between the walls of the analysed interior but located at a different height over the floor than the task area) was calculated. The work considered the influence of independent variables: room index RI, reflectance of the main interior surfaces RO, luminaire lighting class CL, luminaire downward luminous intensity distribution LID and luminaire spacing-to-height ratio SH (the ratio of the distance between luminaires S to the mounting height H), on the dependent variable: MCU index.

To consider different general interior lighting situations, the following assumptions were made:

- The room size was determined based on the RI index: 1.5 (relatively small rooms), 3.0 (moderate rooms), and 4.5 (relatively large rooms).
- The room reflective properties were determined based on the RO reflectance: 752 (0.7 for the ceiling, 0.5 for the walls, 0.2 for the floor), 753 (0.7 for the ceiling, 0.5 for the walls, 0.3 for the floor), and 772 (0.7 for the ceiling, 0.7 for walls, 0.2 for floor).
- The luminaire properties were determined based on the CL lighting class (CIE, N4 index): I (direct lighting), II (semi-direct lighting), III (direct-indirect lighting), and IV (semi-indirect lighting).
- The luminaire properties were also determined based on the LID downward luminous intensity distribution (CIE, N1 index): 1 (widest distribution), 2 (wide distribution), 3 (narrow distribution), and 4 (the narrowest distribution).
- The luminaire layouts were determined based on the SH ratio: 0.5 (relatively small distance between luminaires in relation to mounting height), 1.0 (moderate distance between luminaires in relation to mounting height), and 1.5 (relatively large distance between luminaires in relation to mounting height).

A combination of luminaires CLs and LIDs gave 16 luminaire types in total. The luminaires CIE code flux was as follows:

– Luminaire I1 (CLI, LID1), code flux: 44 75 94 100 80;
– Luminaire I2 (CLI, LID2), code flux: 58 88 98 100 80;
– Luminaire I3 (CLI, LID3), code flux: 69 94 100 100 80;
– Luminaire I4 (CLI, LID4), code flux: 77 97 100 100 80;
– Luminaire II1 (CLII, LID1), code flux: 44 75 94 75 80;
– Luminaire II2 (CLII, LID2), code flux: 58 88 98 75 80;
– Luminaire II3 (CLII, LID3), code flux: 69 94 100 75 80;
– Luminaire II4 (CLII, LID4), code flux: 77 97 100 75 80;
– Luminaire III1 (CLIII, LID1), code flux: 44 75 94 50 80;
– Luminaire III2 (CLIII, LID2), code flux: 58 88 98 50 80;
– Luminaire III3 (CLIII, LID3), code flux: 69 94 100 50 80;
– Luminaire III4 (CLIII, LID4), code flux: 77 97 100 50 80;
– Luminaire IV1 (CLIV, LID1), code flux: 44 75 94 25 80;
– Luminaire IV2 (CLIV, LID2), code flux: 58 88 98 25 80;
– Luminaire IV3 (CLIV, LID3), code flux: 69 94 100 25 80;
– Luminaire IV4 (CLIV, LID4), code flux: 77 97 100 25 80.

A combination of rooms RIs and luminaires SHs produced nine outcomes, presented in Table 1.

Table 1
Data of the interiors (L, H, RI), luminaires numbers, and their layouts (N, SH) for the study

L [m]	H [m]	RI [–]	N [–]	SH [–]
9	3	1.5	36 (6/6)	0.5
6	2		9 (3/3)	1.0
6	2		4 (2/2)	1.5
18	3	3.0	144 (12/12)	0.5
12	2		36 (6/6)	1.0
12	2		16 (4/4)	1.5
27	3	4.5	324 (18/18)	0.5
18	2		81 (9/9)	1.0
18	2		36 (6/6)	1.5

In this study, the illuminance distributions on the horizontal task area and reference areas were calculated to determine the following parameters:

- The average illuminance E on the task area
- The minimum and maximum MCU indices on the reference areas

The task area was extended between interior walls at a height of 0.75 m above the floor. The two reference areas were also extended between interior walls and located at 1.2 m above the floor (for sitting position) and 1.6 m above the floor (for standing position).

The starting point in the calculation was to adjust luminaire luminous flux in each situation to keep the E level on the task area equal to 500 lx. For this E level, the distributions of vector and scalar illuminances on the reference areas were calculated. From these distributions, for each situation, the following quantities were calculated:

- The minimum general index of modelling on the reference area at 1.2 m: MCUmin12
- The maximum general index of modelling on the reference area at 1.2 m: MCUmax12
- The minimum general index of modelling on the reference area at 1.6 m: MCUmin16
- The maximum general index of modelling on the reference area at 1.6 m: MCUmax16

The MCU value at the point on the reference area (equation (3)) was calculated on the ground of the vector E_V (equation (1)) and scalar E_S (equation (2)) illuminances, in main directions x, $-x$, y, $-y$, z, $-z$.

$$E_V = \sqrt{\left(Ex - E_{(-x)}\right)^2 + \left(Ey - E_{(-y)}\right)^2 + \left(Ez - E_{(-z)}\right)^2}, \quad (1)$$

$$E_S = \frac{E_V}{4} + \frac{\min\left(Ex, E_{(-x)}\right) + \min\left(Ey, E_{(-y)}\right) + \min\left(Ez, E_{(-z)}\right)}{3}, \quad (2)$$

$$\text{MCU} = \frac{E_V}{E_S}, \quad (3)$$

where:
E_v – the vector illuminance at the point on the reference area,
E_s – the scalar illuminance at the point on the reference area,
E_x, $E_{(-x)}$, E_y, $E_{(-y)}$, E_z, $E_{(-z)}$ – the vertical illuminances at the point on the reference area in the main directions,
MCU – the vector to scalar illuminance at the point on the reference area.

3. RESULTS AND ANALYSIS

Table 2 summarises the basic descriptive statistics for the MCUmin12, MCUmax12, MCUmin16, and MCUmax16 indices: the minimum (Min), maximum (Max), mean (Mean), standard deviation (SD), median (Med), lower quartile (Q1) and upper quartile (Q3) values.

Table 2
Basic descriptive statistics for the MCUmin12, MCUmax12, MCUmin16, MCUmax16 indices

Stat.	MCUmin12	MCUmax12	MCUmin16	MCUmax16
Min	0.8	1.2	0.07	0.74
Max	1.72	3.19	1.63	3.2
Mean	1.23	1.94	0.93	1.91
SD	0.16	0.49	0.37	0.61
Med	1.22	1.83	1.05	1.74
Q1	1.12	1.51	0.63	1.43
Q3	1.34	2.3	1.2	2.44

It should be observed that a significant part of the MCUmin results is below the lower target of 1.2 and also that a significant part of the MCUmax results is above the upper target of 1.8. The dispersion between the maximum and minimum values extends from 0.49 for MCUmin12 (0.70 for MCUmin16) to 1.29 for MCUmax16 (1.25 for MCUmax12). The variability of SD levels and the difference between Q3 and Q1 have the same trends.

Figure 1 shows histograms for MCUmin12, MCUmax12, MCUmin16, and MCUmax16 indices.

The histograms show that only for 121 lighting situations (29% of all cases), the values of the MCU index at 1.2 m are in the required range of 1.2–1.8. For the MCU index at 1.6 m, the result is even worse, with only 83 situations (19.3% of all cases) meeting the requirement. The overall results are considered in more detail.

Figure 2 shows the distribution of the minimum and maximum MCU indices at 1.2 m and 1.6 m reference area height. A large share of cases outside the required range (1.2–1.8), which in the graph is between black horizontal lines, is noticeable. A greater dispersion of the minimum and maximum values of the MCU indices at 1.6 m height should also be noticed.

For the obtained data, Pearson's correlation coefficients were also calculated and presented in Table 3. Statistically significant correlations (p-value < 0.05) are marked with an asterisk, and those with the strongest correlation are bolded. The strongest correlation exists between the MCU and SH indices. There is

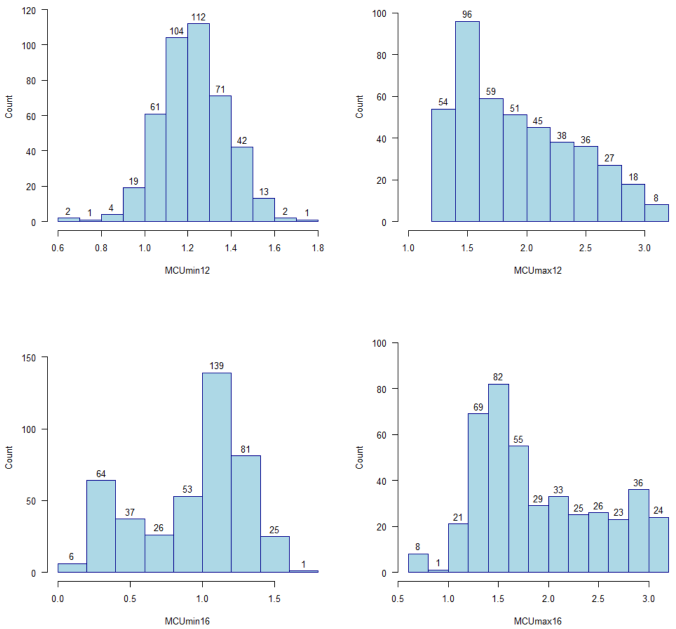

Fig. 1. Histograms for the MCUmin12, MCUmax12, MCUmin16, and MCUmax16 indices

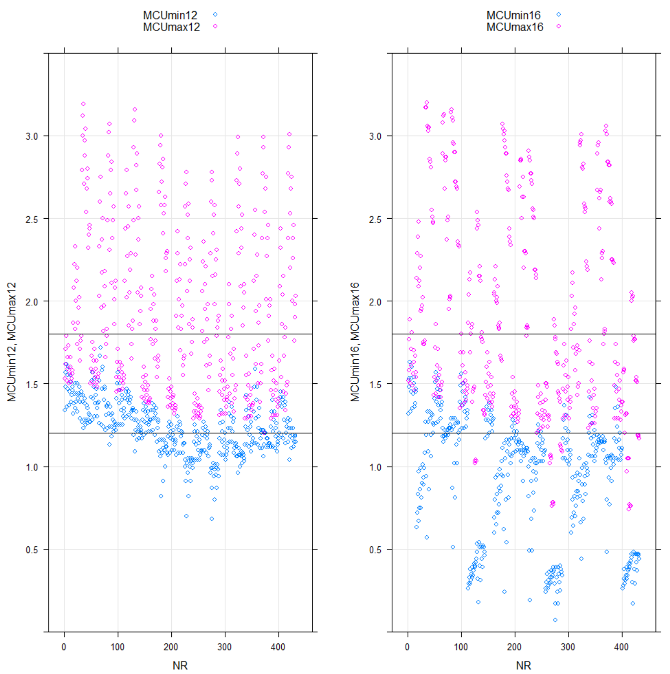

Fig. 2. Distribution of the minimum (blue) and maximum (purple) MCU indices, for reference areas at 1.2 m (left) and 1.6 m (right)

also a moderate correlation between the MCUmin12 index and weighted room reflectance ROA (weighted average of room reflectance, over the surface areas of the ceiling, walls, and floor), as well as between MCUmin16 and RI indices. These relationships were considered in detail.

Figure 3 shows the distributions of the MCUmin12, MCUmax12, MCUmin16, and MCUmax16 indices for data aggregated against SH and RO variables. Horizontal lines mark the limits of the required range (the red line corresponds to the

Table 3
Pearson's correlation coefficients between the variable MCU and variables ROA, RI, SH, N4, and N1

Variable	ROA	RI	SH	N4	N1
MCUmin12	**–0.4214***	–0.1078	–0.3546*	0.1577*	0.2300*
MCUmax12	–0.1519*	–0.0361	**0.7996***	0.3612*	0.2556*
MCUmin16	–0.0677*	**–0.4305***	**–0.5228***	–0.0711	–0.0003
MCUmax16	–0.0249	–0.3964*	**0.6073***	0.3497*	0.0670

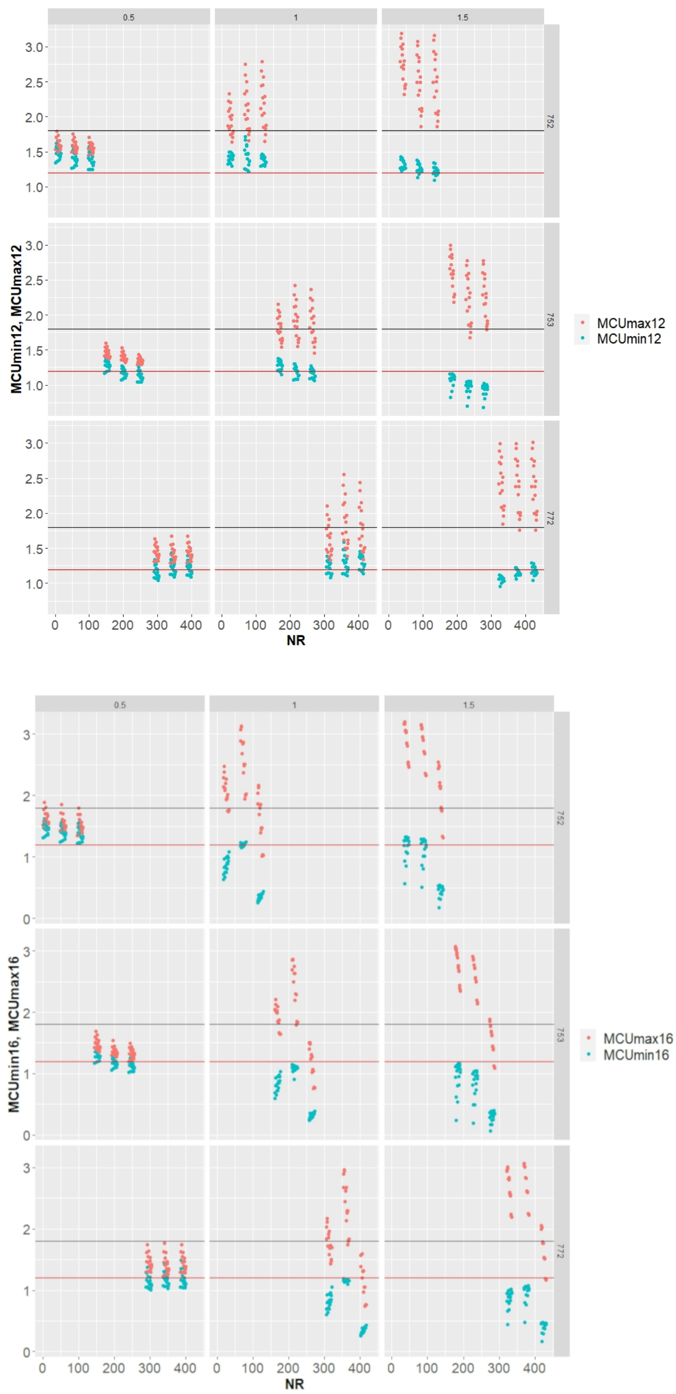

Fig. 3. Distribution of the MCU index against SH and RO

value of 1.2 – lower limit and the black line to the value of 1.8 – upper limit). When analysing the graphs, it should be noted that with the increase of the SH variable, which corresponds to the increase in the distance between the luminaires, there are more difficulties in obtaining the required range of the MCU index for each set of the RO variable. For SH = 1.5, for both analysed heights, almost all considered situations do not meet the requirements for the MCU index. At 1.2 m height, it is more difficult to maintain the maximum than minimum MCU index in the required range. At 1.6 m height, it is the minimum value of the MCU index that is more likely to fall below the lower limit of the required range.

The analysis of Pearson's correlation coefficients also revealed a moderately strong relationship between the MCU16 and RI variables, which is presented in detail in Fig. 4. The data in the graph have been aggregated against the RI variable (from the top RI = 1.5, RI = 3, RI = 4.5, respectively). The least favourable in terms of meeting the required range of the MCU index is RI = 4.5 case, which corresponds to relatively large rooms.

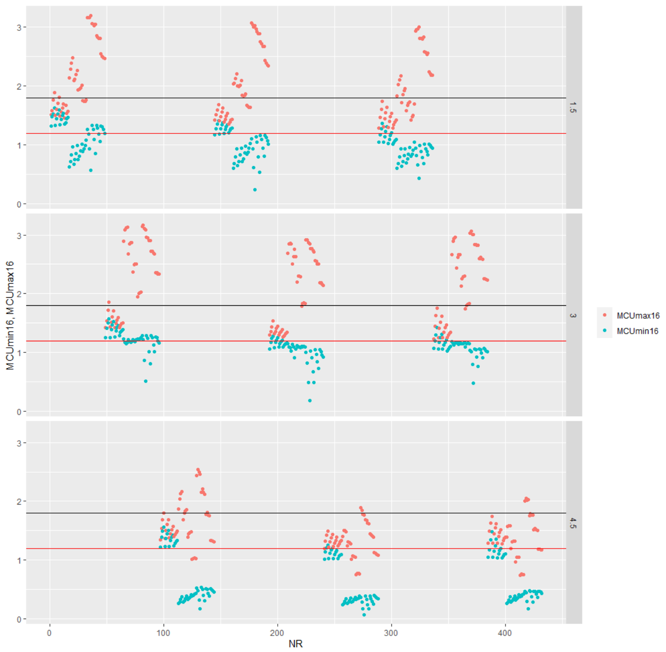

Fig. 4. Distribution of the MCU16 index against RI

To determine the regression equations, the multiple linear regression method was used to quantify the relationships between independent variables and the dependent variable. With the regression equation, one can predict the value of the dependent variable for the values of the independent variables included in the model. In our study, the knowledge of the regression equations allows us to verify the suitability of luminaires and their layouts in terms of creating the desired modelling effect in general interior lighting, already at the stage of developing the lighting concept. The final regression models are presented, for MCUmin12 in Table 4, for MCUmax12 in Table 5, for MCUmin16 in Table 6, and for MCUmax16 in Table 7.

Table 4
Final regression model for MCUmin12

$N = 432$	Multiple R-squared:0.4262 Adjusted R-squared:0.4195 F-statistic:63.29 $p < 2.2e\text{-}16$ Residual std. error:0.1192			
	Estimate	Std. Err.	t value	Pr $(>\|t\|)$
Intercept	2.366659	0.102517	23.085	< 2e-16***
ROA	–2.263872	0.180834	–12.519	< 2e-16***
RI	–0.032569	0.004916	–6.625	1.05e-10***
SH	–0.129416	0.014052	–9.210	< 2e-16***
N4	0.079056	0.020524	3.852	0.000135***
N1	0.290008	0.046273	6.267	9.01e-10***

$$MCUmin12 = 2.366659 - 2.263872 \cdot ROA - 0.032569 \cdot RI - 0.129416 \cdot SH + 0.079056 \cdot N4 + 0.290008 \cdot N1$$

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Table 5
Final regression model for MCUmax12

$N = 432$	Multiple R-squared:0.8715 Adjusted R-squared:0.87 F-statistic:577.8 $p < 2.2e\text{-}16$ Residual std. error:0.1779			
	Estimate	Std. Err.	t value	Pr $(>\|t\|)$
Intercept	1.520952	0.153017	9.940	< 2e-16***
ROA	-2.908859	0.269913	-10.777	< 2e-16***
RI	-0.038718	0.007338	-5.276	2.1e-07***
SH	0.973067	0.020974	46.394	< 2e-16***
N4	0.624995	0.030634	20.402	< 2e-16***
N1	1.016603	0.069067	14.719	< 2e-16***

$$MCUmax12 = 1.520952 - 2.908859 \cdot ROA - 0.038718 \cdot RI + 0.973067 \cdot SH + 0.624995 \cdot N4 + 1.016603 \cdot N1$$

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Table 6
Final regression model for MCUmin16

$N = 432$	Multiple R-squared:0.501 Adjusted R-squared:0.4952 F-statistic:85.55 $p < 2.2e\text{-}16$ Residual std. error:0.2632			
	Estimate	Std. Err.	t value	Pr $(>\|t\|)$
Intercept	3.047394	0.226485	13.455	< 2e-16***
ROA	–2.255708	0.399506	–5.646	3e-08***
RI	–0.148821	0.010861	–13.702	< 2e-16***
SH	–0.467703	0.031044	–15.066	< 2e-16***
N4	–0.103096	0.045342	–2.274	0.0235*
N1	–0.000754	0.102228	–0.007	0.9941

$$MCUmin16 = 3.047394 - 2.255708 \cdot ROA - 0.148821 \cdot RI - 0.467703 \cdot SH - 0.103096 \cdot N4 - 0.000754 \cdot N1$$

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Table 7
Final regression model for MCUmax16

$N = 432$	Multiple R-squared:0.6792 Adjusted R-squared:0.6755 F-statistic:180.4 $p < 2.2\text{e-}16$ Residual std. error:0.35			
	Estimate	Std. Err.	t value	Pr (> |t|)
Intercept	2.56777	0.30112	8.527	2.64e-16***
ROA	–3.15220	0.53116	–5.935	6.11e-09***
RI	–0.22481	0.01444	–15.568	< 2e-16***
SH	0.92166	0.04127	22.330	< 2e-16***
N4	0.75528	0.06028	12.529	< 2e-16***
N1	0.33199	0.13592	2.443	0.015*
$MCUmax16 = 2.56777 - 3.15220 \cdot ROA - 0.22481 \cdot RI + 0.92166 \cdot SH + 0.75528 \cdot N4 + 0.33199 \cdot N1$				

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

The R-squared value is an indicator of the quality of the fit of the model to the data (R-squared close to 1.0 indicates that almost all variability of the dependent variable can be explained by the independent variables included in the model) [10]. In our case, we got an Adjusted R-squared of 42%, 87%, 49%, and 68% for MCUmin12, MCUmax12, MCUmin16, and MCUmax16, respectively. The obtained coefficient values for the relevant variables are statistically significant, p-value < 0.01.

In each model for the considered MCU dependent variables, all analysed independent variables were included. This guarantees the highest accuracy of prediction. Figure 5 shows the root mean square error (RMSE) value for the dependent variable MCUmin12 depending on the number of independent variables included in the model. This error informs how much the value calculated from the model on average differs from the actual value. It is demonstrated that the smallest RSME occurs when all independent variables are included in the model. The situation is similar for the other MCU-dependent variables.

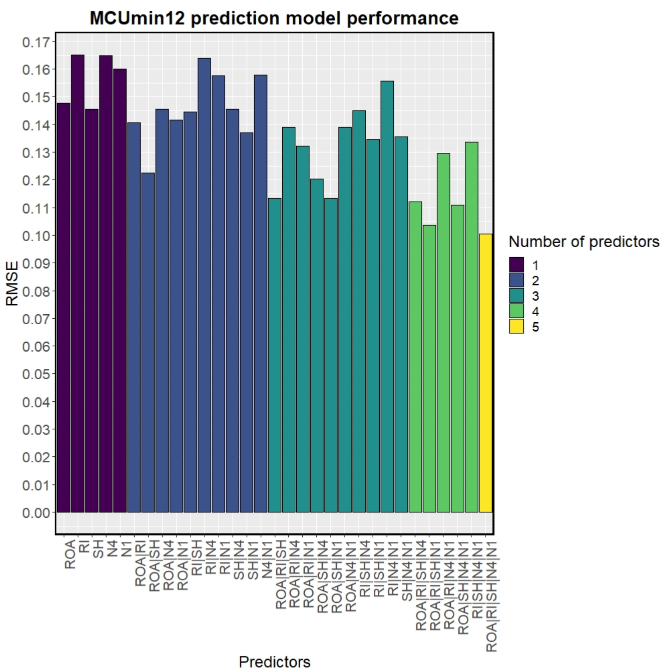

Fig. 5. The RMSE value depending on the number of independent variables in the model

4. CONCLUSIONS

The conducted research showed that obtaining the required distribution of the general index of modelling (MCU) in general interior lighting is significantly limited. The requirements were not met for approximately 70% of the cases for the reference plane at 1.2 m height and for approximately 80% of the cases for the reference plane at 1.6 m height. Such large design limitations are a reason to look for solutions useful in obtaining the desired modelling effect for electric lighting in interiors.

Our research has also demonstrated that the layout of luminaires is a decisive factor in obtaining the desired modelling effect. In practice, this means the need to use more luminaires with lower power, which is not beneficial in terms of the cost of the lighting investment. This is a reason to look for unconventional lighting solutions to achieve the desired modelling effect for electric lighting in interiors.

The linear regression models we developed for MCU indices seem to be a practical solution for predicting the modelling effects for general interior lighting. Such models should be a useful tool for designers and analysts dealing with complex issues in interior lighting.

There is a need to continue research to better understand the possibility of effectively creating modelling effects with general interior lighting. The research conducted by the authors had limitations resulting from the nature of simulation research. The size of the interiors, the combination of the reflectance of the main surface in the interiors, the combination of the layouts of luminaires, and the use of the theoretical luminous intensity of luminaires distributions were limited. The linear regression method was used to predict the MCU indices. Further studies, simulation, measurement verification, and statistical analysis, are aimed at confirming the observed trends, which are of great practical importance in the assessment and design of general interior lighting.

ACKNOWLEDGEMENTS

The work supported by the activities of the Scientific Council for the Discipline "Automation, Electronics, Electrical Engineering and Space Technologies" of the Warsaw University of Technology.

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