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The impact of room and luminaire characteristics on general lighting in interiors

P. PRACKI*

Faculty of Electrical Engineering, Electrical Power Engineering Institute Lighting Technology Division,
Warsaw University of Technology, ul. Koszykowa 75, 00-662 Warsaw, Poland

Abstract. General lighting is the most common way of illuminating interiors and the source of electricity consumption in buildings. This fact forces the search for lighting solutions effective both for people and the environment. In this study the impact of room and luminaire characteristics on general lighting conditions and energy efficiency in interiors is considered. In rooms of different sizes and reflectances, seventeen luminaire types with various light distributions were arranged in uniform layouts. The levels of average illuminance, uniformity and normalised power density related to two horizontal working planes were calculated. The impact of working plane reduction, room index and reflectances, lighting class and luminous intensity distribution of luminaire on the considered parameters was investigated. The use of the reduced working plane resulted in the increase in the average illuminance (7.7% on average), uniformity (33% on average) and normalised power density (23% on average). The impact of the room index and lighting class on the average illuminance and normalised power density was significant while the impact of the luminaire luminous intensity distribution and room reflectances was low. The normalised power density levels of the general electric lighting in interiors, with luminaire luminous efficacy of 100 lm/W, are in the following range: 1.08–3.42 W/m² per 100 lx. Based on these results a normalised power density level of 2 W/m² per 100 lx is recommended for designing and assessing the new general electric lighting systems in buildings.

Key words: lighting technology, interior lighting, energy efficiency.

1. Introduction

Our society depends on energy and this dependence increases each year [1]. There are two main reasons behind the increase in the demand for energy: the increase of the world population and energy consumption per capita. The first reason is quite obvious and the second one is associated with increasing globalization and industrialization. It is also connected with the increase of wealth and standard of leaving, and growing availability of products and services which use energy.

World energy consumption exceeds the level of 500 quadrillion Btu today and it is estimated that the level from the end of the 20th century will be doubled in 2040 [1]. It is also expected that in 2040 the share of energy consumption in non-OECD countries would be much bigger than in OECD countries. Electricity is an important part of the total energy consumption and in 2014 the electricity consumption accounted for 18.1% of the total energy consumption [2].

Energy consumed in the buildings sector accounts for 20.1% of the total delivered energy consumed worldwide [1]. Considering the three end-use sectors: building, industrial and transportation, building sector became the biggest energy consumer in the end of the 20th century and today it uses about 40% of total energy consumed [1]. The growth of energy consumption in buildings is expected to continue in the long term. Moreover, the electricity consumption is the largest part of the total energy consumption in buildings [3].

The electricity consumption for lighting purposes in buildings represents a significant share of the total electricity consumption. Based on 2003 data from US DOE's EIA, lighting accounts for 30%, 39% and 42% of total electricity consumption in education, office and health care buildings respectively [4] and represents the largest share of total electricity consumption in these building types. Lighting in buildings creates the luminous environment and is the important source of electricity consumption and thus its use should be effective for both people and the environment.

2. Lighting and energy efficiency in interiors

Interior lighting in buildings is provided by daylight, electric light or their combination. Design and implementation of the electric lighting system often have to assume its use as the only light source in interiors. This is due to a shorter day in winter and limited access to daylight in large parts of interiors in buildings. For this reason, the analysis of the electric lighting is the starting point for looking into the energy efficiency and the topic under consideration in this paper.

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*e-mail: piotr.pracki@ien.pw.edu.pl

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General lighting is the most common way of illuminating interiors in public buildings [5–7]. Its implementation consists of an even layout of luminaires, usually on the ceiling, and leads to generating the uniform illumination of working plane and meeting the requirements for average maintained illuminance and uniformity of lighting. Regardless of this expected uniform working plane illumination, general lighting has to fulfil a number of other lighting requirements. They include average illuminance and uniformity on ceiling and walls, average cylindrical illuminance and uniformity, modelling index, glare level, colour of light and colour rendering [4, 8].

The analysis of lighting solutions in interiors is currently going beyond the considerations of creating the luminous environment and studying its impact on people through the visual system. They should be analysed in terms of circadian [9], psychological [10] and environmental [11] impact, also taking into account its functionality and all limitations related to energy and cost [12]. The analysis of relations between the applied system and the obtained lighting and energy effect is one of the most interesting issues in the interior [13], road [14] and outdoor lighting [15]. This paper focuses on the analysis of general lighting for interiors as far as power of the system and working plane illumination are concerned.

Basically, obtaining the energy-efficient lighting results from the principle of reducing the energy consumption for lighting while meeting the quantitative and qualitative lighting requirements. It is worth mentioning that this idea of energy-efficient lighting is the part of a wider context of high-quality lighting [16], currently called human centric lighting [17, 18]. It is also worth mentioning that the energy-efficient lighting needs to be friendly for both the environment and society.

The topic of energy efficiency of interior lighting in buildings covers a number of issues. They concern such matters as analysing and evaluating the lighting energy efficiency [19–21], designing and developing the energy-efficient lighting equipment [22–24] and implementing the energy-efficient solutions [25–27] that meet the requirements for the luminous environment quality [28]. The 21st century has brought more interest in the issues of lighting energy efficiency at a large scale including various approaches towards evaluating and implementing the energy-efficient solutions [29–31].

The lighting energy efficiency is determined by a large number of factors related to lighting requirements (including the average maintained illuminance level on the working plane), room features (including the size and reflectances in the room), applied luminaires (including the luminous efficacy of luminaire, lighting class and luminous intensity distribution) and their layout. As many factors affect lighting conditions and energy efficiency in interiors, to determine a degree of their impact on the lighting parameters, power and energy is an interesting research problem. Moreover, there are not many studies conducted in this area.

Makaremi and her colleagues reported their research in two papers [32, 33]. The tests were of an analytical nature and verified by the measurements in the real room. They were conducted for one small room (3.35 m long, 3.10 m wide, 2.75 m high) and concerned the assessment of the impact of the selected room and luminaire characteristics on the values of average illuminance and uniformity on the working plane, UGR and the lighting power.

In the paper [32] the impact of reflectances of the ceiling, walls and floor on the values of average illuminance and uniformity on the working plane as well as the UGR was analysed. The room was illuminated with one fluorescent luminaire (36 W and 3350 lm). The impact of the increase in reflectances on the growth in average illuminance and uniformity as well as on the reduction in UGR was observed. The significance of the impact of the ceiling, wall and floor reflectances on the changes in the analysed lighting parameters was assessed. It was noticed that the reflectances of the walls had the highest total impact on the analysed lighting parameters. However, the reflectances of the floor had the lowest total impact on the analysed lighting parameters.

In the paper [33] the impact of three sets of interior reflectances, five types of luminaires, their number and suspension height on the values of uniformity on the working plane, the UGR and the installed lighting power in the same small room was analysed. In this study the LED luminaires with luminous efficacy of 110 lm/W were used. Consequently, a significant impact of reflectances on the analysed parameters and power was confirmed. The research demonstrated that the type of luminaire (lighting class) was the most important factor influencing the lighting parameters and power. Additionally, when applying the direct lighting, uniformity of 0.6 or higher was not obtained. The suspension height and number of luminaires had a significant impact on the uniformity level for the direct lighting.

Following the studies discussed above, the results presented in this paper develop the findings [21–33] and concern the evaluation of the impact of the parameters characterising the room and luminaires on the level of average illuminance, uniformity and normalised power density related to the working plane in interiors. Due to the currently widespread use of LED systems, the conducted studies also verify energy targets for the newly designed and implemented lighting systems. The application of the reduced working plane for the calculation of illuminance distribution and assessment of the lighting power is also an important issue discussed in this paper.

The objectives of this research are to:

- determine the levels of average illuminance, uniformity and normalised power density of general lighting related to two working planes for various interiors and lighting systems;
- assess the impact of using the reduced working plane on the change of average illuminance, uniformity and normalised power density of general lighting in interiors;

- assess the impact of changes in parameters characterising the interiors and lighting systems on the change of average illuminance, uniformity and normalised power density of general lighting.

3. Methodology

The conducted research is based on the calculations of the average illuminance and uniformity as well as the normalised power density on the working planes in the interiors. For the purpose of this research, the calculations were made for a big number of lighting scenarios taking into account the use of general electric lighting as the only interior lighting system. For this reason, the calculations were made on the horizontal working plane stretched between the walls – the total working plane, as well as on the smaller horizontal working plane – the reduced working plane. The DIALux software, which is a verified tool [34] applied to analyse the electric lighting in interiors, e.g. [32, 33, 35–37], was used in this study. It was necessary to make a number of assumptions regarding the luminaires and rooms.

3.1. Luminaires. The luminaire light distributions representing the direct lighting (Class I), semi-direct lighting (Class II), direct-indirect lighting (Class III), semi-indirect lighting (Class IV) and indirect lighting (Class V) were analysed in order to consider the influence of photometric characteristics of luminaires on the average illuminance, uniformity and lighting power. Additionally, for the lower hemisphere four different luminous intensity distributions were analysed, from Class I to Class IV.

It was decided to analyse the luminaires with theoretical, rotationally symmetrical luminous intensity distributions as representative for a wide range of light distributions. It was assumed that a wide light distribution would represent a distribution compliant with the cosine function (LID 1). The narrower distributions would also represent the cosine function but in the second (LID 2), third (LID 3) and fourth (LID 4) power respectively. In the upper hemisphere, it was assumed that the luminaires would perform the cosine distribution. In this way 17 reference light distributions of luminaires were created. It was assumed that the luminaires would emit a luminous flux with a lower or upper surface of the area of 0.36 m^2 (the luminous surface of luminaire was a square with a side of 0.60 m). The calculations of lighting parameters in the interiors were made for a luminous flux of the luminaire equal to 5000 lm and power of 50 W (the luminous efficacy 100 lm/W). The luminaire luminous intensity distributions with their markings are shown in Fig. 1.

3.2. Rooms and luminaire layouts. In order to consider the impact of the room size on the analysed parameters it was also necessary to make some assumptions which allowed the author to select the various room sizes where the reference luminaire layouts were implemented. The following assumptions were made:

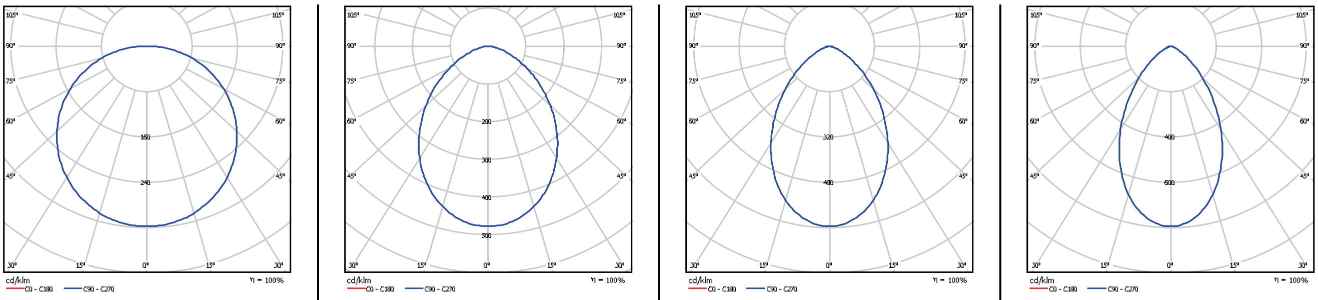
- empty cubical rooms with a base of rectangle and length-to-width ratio of 2 were analysed;
- the room heights were: 2.75 m for the direct lighting luminaires (located directly on the ceiling) and 3.25 m for the other luminaires (suspended from the ceiling at 0.5 m);
- the horizontal working plane was located at the height of 0.75 m over the floor;
- the spacing between the centre-to-centre of adjacent luminaires was constant and equal to 3 m, and the distances between the centres of the outermost luminaires from the nearest wall were also constant, equal to 1.5 m.

These assumptions determined the size of five rooms characterized by the room index (RI) ranging from 1 (the smallest room) to 5 (the largest room) respectively. In each room the reference luminaire layout was implemented, as shown in Fig. 2.

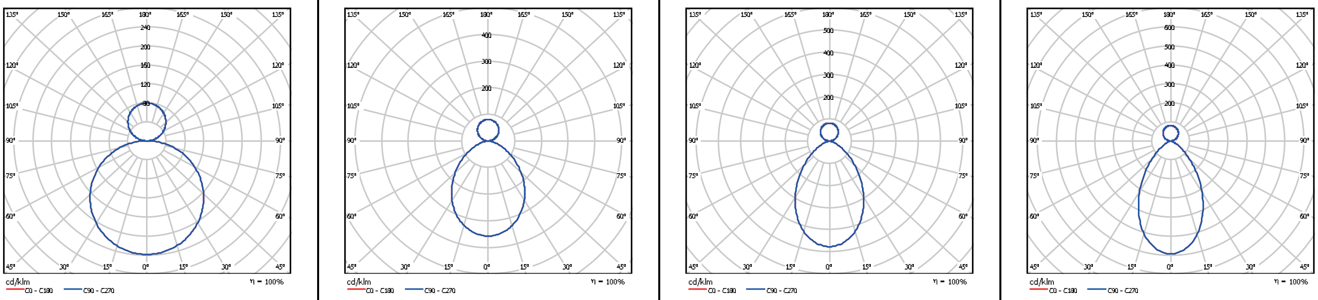
For each room, the reference reflectances were assumed: 0.7 for the ceiling, 0.5 for the walls and 0.2 for the floor (designation 752). The maintenance factor of 0.8 was also assumed for the calculations.

3.3. Calculations. In most cases of general lighting in the public buildings, a working plane is located at the height of workplaces (e.g. desks, school benches, stands in labs, etc.) and stretched between the walls of the room – the total working plane. If there are no workplaces next to the walls, it is accepted to skip the 0.5 m wide strip from the walls [28]. This means that the calculations of illuminance distribution are made on the reduced working plane. The calculations were made for each lighting scenario on such two reference planes located 0.75 m over the floor.

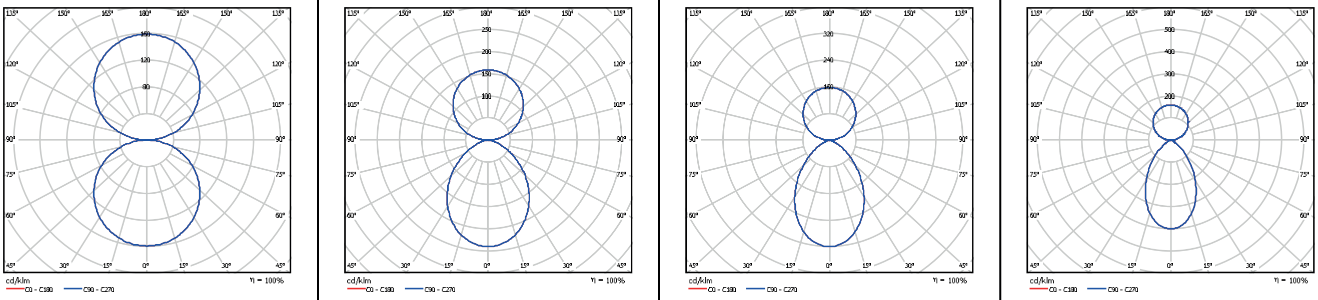
The grid density for the calculation of illuminance distribution on each working plane was determined on the basis given in the standard [28]. The odd number of calculation points in each row was assumed, also according to the standard [28] recommendation. For rooms 1, 2 and 3 calculation grids correspond exactly to these recommendations. For rooms 4 and 5, more points were taken to keep the principle, the bigger the room the more calculation points. Consequently, the following calculation grids were used for the total working planes: room 1: 15×7 points, room 2: 19×9 points, room 3: 23×11 points, room 4: 27×13 points, room 5: 31×15 points. To calculate the illuminance distributions on the reduced working plane, the following calculation grids were applied: room 1: 11×5 points, room 2: 15×7 points, room 3: 19×9 points, room 4: 23×11 points, room 5: 27×13 points. Based on the illuminance distribution results, the average illuminance ET and uniformity UT on the total working plane and the average illuminance ER and uniformity UR on the reduced working plane were calculated. The normalised power density values PT and PR referring to these working planes were also calculated.



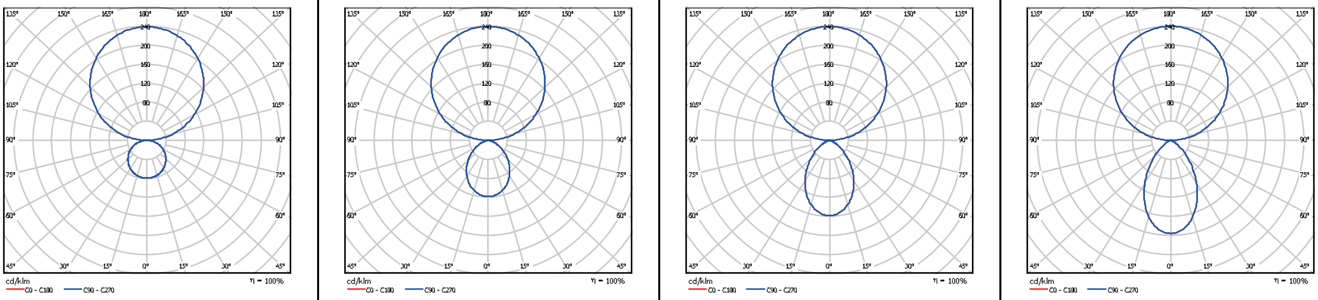
Class I, LID 1 Class I, LID 2 Class I, LID 3 Class I, LID 4



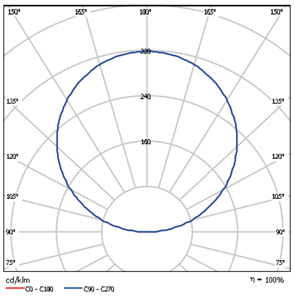
Class II, LID 1 Class II, LID 2 Class II, LID 3 Class II, LID 4



Class III, LID 1 Class III, LID 2 Class III, LID 3 Class III, LID 4



Class IV, LID 1 Class IV, LID 2 Class IV, LID 3 Class IV, LID 4



Class V

Fig. 1. Characteristics of the luminaires for the study

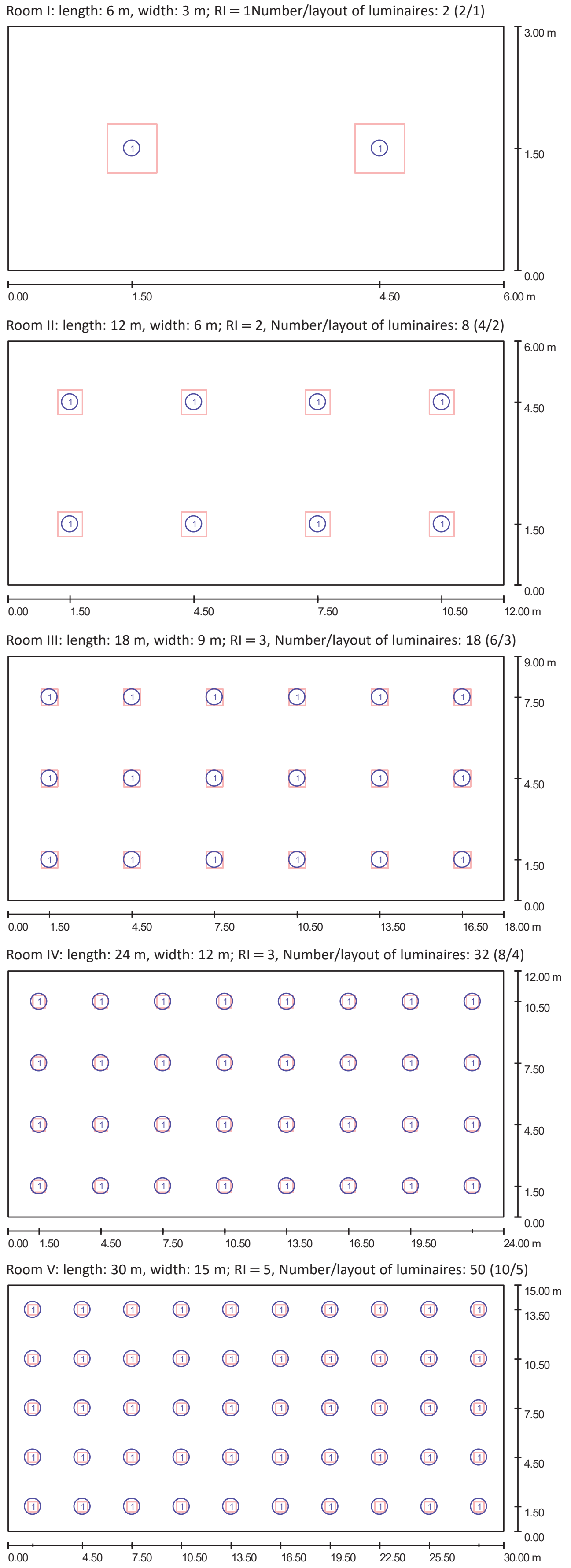


Fig. 2. Floor view of the rooms and luminaire layouts for the study

4. Results and analysis

4.1. Impact of working plane reduction. The maximum level of average illuminance (508 lx) was obtained on the reduced working plane for the direct lighting (Class I) with luminaires of the narrowest luminous intensity distribution (LID 4) in the largest room (RI = 5) – the scenario I45 grey bar. All levels of average illuminance in Fig. 3 are presented as percentages of this maximum level. The uniformities and the normalised power densities are given in absolute values in each case. The calculation results are presented in Fig. 3 for the average illuminances ET and ER, in Fig. 4 for the uniformities UT and UR and in Fig. 5 for the normalised power densities PT and PR. The black bars represent the results for the total working plane and the grey bars for the reduced working plane.

Applying the reduced working plane for the calculations resulted in the increase of the average illuminance by 7.7% on average. The highest growths in average illuminance from 14% to 25%, occurred in the smallest rooms (the highest reduction of illuminated area in relation to the whole floor), regardless of the lighting class and luminaire luminous intensity distribution. In the rooms with RI = 2 the growths in average illuminance oscillated from 5.5% to 13%. The lowest increases in average illuminance were observed in the large rooms (RI: 3, 4 or 5) and they ranged from 3.1% to 6.3%. The working plane reduction influenced quite significantly the growth in average illuminance in the smallest rooms with RI = 1 and in some cases in the rooms with RI = 2.

Applying the reduced working plane for the calculations resulted in the increase of the uniformity by 33% on average. The highest growth in uniformity exceeded the level of 50%, and the increases above 40% were recorded for 33 in 85 analysed cases. Only in two cases, in the largest rooms, this growth did not exceed 10%. The working plane reduction influenced significantly the growth in uniformity of lighting.

In most scenarios of direct and semi-direct lighting while using the total working plane for the calculations, the uniformity levels were between 0.4 and 0.6. Applying the reduced working plane gave the uniformity higher than 0.6 in all cases. What is more, for many cases the uniformity was higher than 0.8.

Applying the reduced working plane for the calculations resulted in the increase of the normalised power density by 23% on average. The highest growths in normalised power density, from 44% to 59%, occurred in the smallest rooms regardless of the lighting class and luminaire luminous intensity distribution. In the rooms with RI = 2, the growths in normalised power density ranged from 16% to 24%. In the larger rooms the increases oscillated between 5.8% and 16%. The working plane reduction also influenced significantly the growth in normalised power density.

More detailed analyses were conducted to study the influence of room index, lighting class and luminous intensity distribution of luminaire.

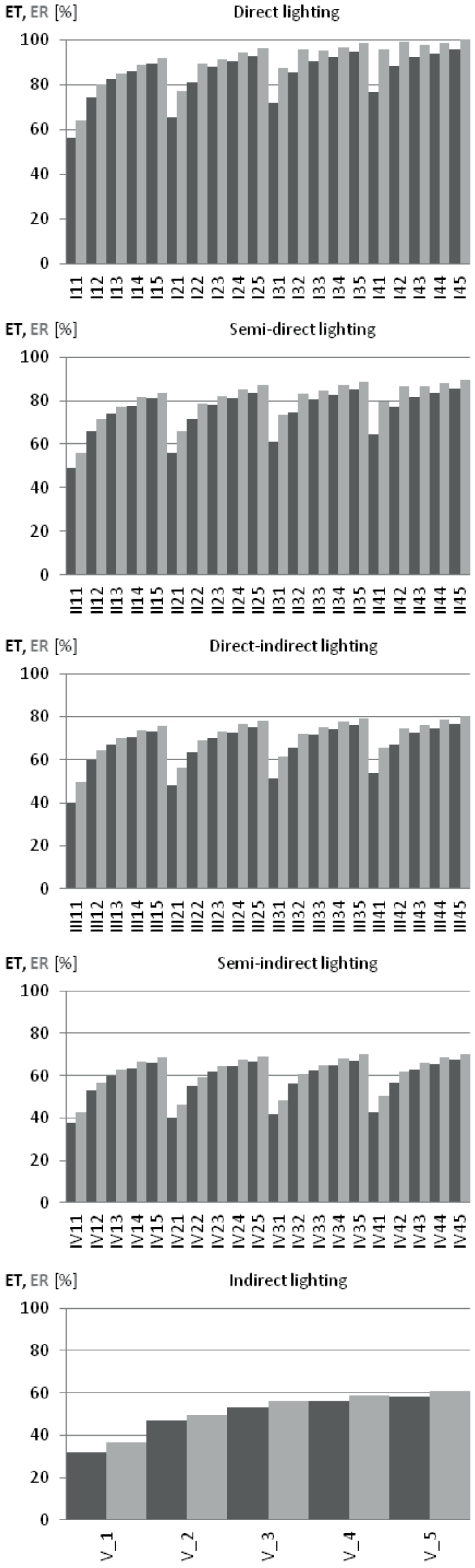


Fig. 3. Average illuminances on the total ET and reduced ER working planes

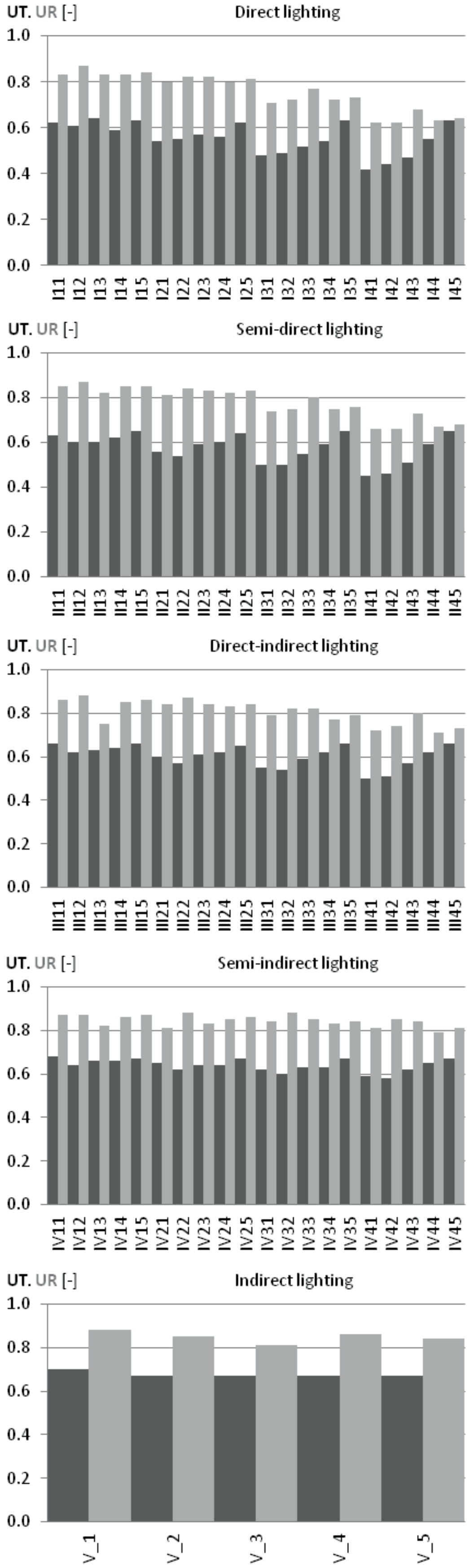


Fig. 4. Uniformities on the total UT and reduced UR working planes

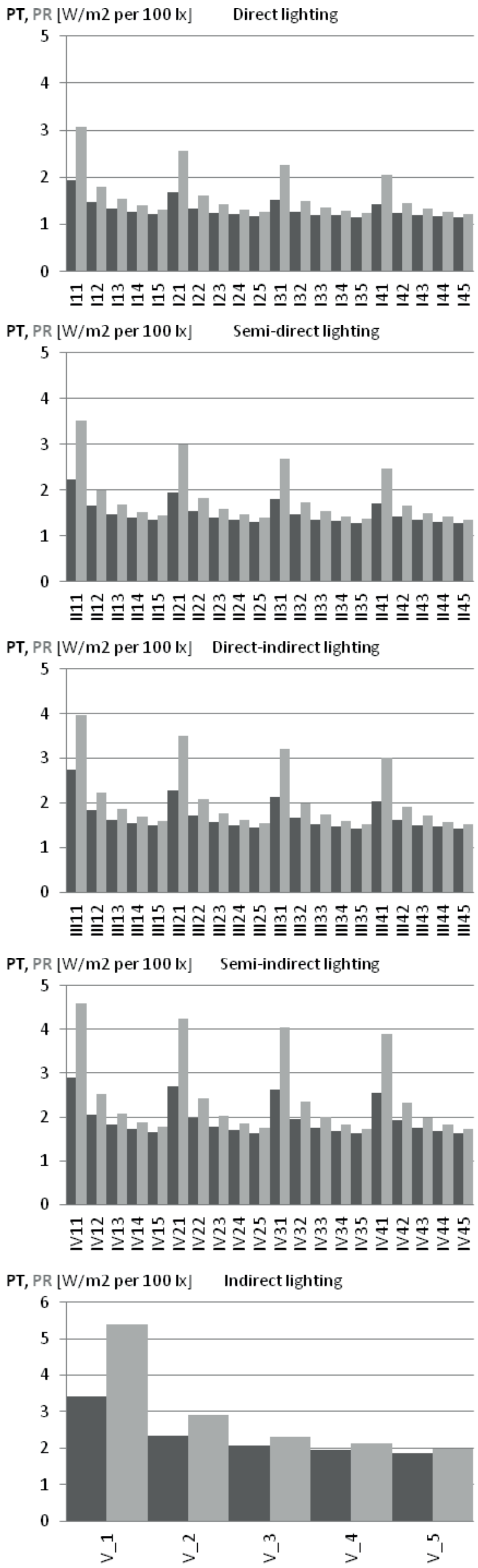


Fig. 5. Normalised power densities related to the total PT and reduced PR working planes

4.2. Impact of room index. Table 1 presents the list of the minimum, maximum and average values on both the total and reduced working planes as well as the standard deviations (SD) and coefficients of variation (CV) of average values for the analysed parameters in interiors with different room index.

Table 1
Variation of average illuminance, uniformity and normalised power density for each room index in the interiors with reflectances 752

RI	Par.	MIN	MAX	AV	SD	CV
1	ET	162	389	265	64	24
	ER	185	485	316	83	26
	UT	0.42	0.70	0.57	0.08	14
	UR	0.62	0.88	0.79	0.08	9.5
	PT	1.43	3.43	2.22	0.55	25
	PR	2.06	5.41	3.38	0.90	27
2	ET	238	450	341	61	18
	ER	251	503	374	72	19
	UT	0.44	0.67	0.56	0.07	12
	UR	0.62	0.88	0.81	0.08	10
	PT	1.24	2.33	1.68	0.30	18
	PR	1.45	2.90	2.02	0.40	20
3	ET	270	468	373	58	16
	ER	286	497	391	61	16
	UT	0.47	0.67	0.59	0.06	9.3
	UR	0.68	0.85	0.80	0.05	5.6
	PT	1.19	2.06	1.53	0.25	16
	PR	1.33	2.31	1.73	0.28	16
4	ET	286	475	387	56	15
	ER	298	500	405	59	15
	UT	0.54	0.67	0.61	0.04	6.2
	UR	0.63	0.86	0.79	0.07	8.9
	PT	1.17	1.94	1.47	0.22	15
	PR	1.27	2.12	1.60	0.24	15
5	ET	297	485	399	57	14
	ER	309	508	415	59	14
	UT	0.62	0.67	0.65	0.02	2.6
	UR	0.64	0.87	0.80	0.07	8.5
	PT	1.15	1.87	1.42	0.21	15
	PR	1.21	1.99	1.52	0.22	15

The increase in room index resulted in increasing the average illuminance and decreasing the normalised power density related to the horizontal working plane. While comparing the results for rooms of neighbouring sizes, the above changes were the highest when comparing the rooms with RI = 1 and RI = 2. The increase in average illuminance was 29% and the decrease in normalised power density was 24%. As for the larger rooms, the influence of room index fell and when comparing the results for the rooms with RI = 4 and RI = 5, the increase in average illuminance and the decrease in normalised power density were at the level of 3%. Comparing the results for the smallest (RI = 1) and largest (RI = 5) rooms, the increase in average illuminance was 51% and the decrease in normalised power density was 36%.

The influence of room index on the uniformity on the horizontal working plane was much lower. The increase in uniformity was only 14% while comparing the results for the smallest (RI = 1) and the largest (RI = 5) rooms.

Analysing the impact of applying the reduced working plane on the calculation results from the room size point of view, the following observations were made:

- the average increase in average illuminance by 19%, 10%, 4.8%, 4.7% and 4.0% in the rooms with RI 1, 2, 3, 4 and 5 respectively,
- the average increase in uniformity by 39%, 45%, 36%, 30% and 23% in the rooms with RI 1, 2, 3, 4 and 5 respectively,
- the average increase in normalised power density by 52%, 20%, 13%, 8.8% and 7.0% in the rooms with RI 1, 2, 3, 4 and 5 respectively.

In the interiors with higher RI, the values of the analysed parameters were stronger related to a room size which was reflected by the lower values of CV. In case of the average illuminance and normalised power density, this relation was similar in the rooms with RI = 3, 4 and 5. In case of the uniformity this relation was the strongest in the largest room (RI = 5).

4.3. Impact of lighting class. Table 2 presents the list of the minimum, maximum and average values on both the total and reduced working planes as well as SD and CV of average values for the analysed parameters and for different lighting class.

The implementation of a higher lighting class resulted in decreasing the average illuminance and increasing the normalised power density related to the horizontal working plane. These changes are similar while comparing the results for neighbouring classes. The average illuminance fell by minimum 11% and by maximum 15%. The normalised power density went up by minimum 13% and by maximum 21%. When comparing the results for the lowest (direct lighting) and the highest (indirect lighting) classes, the decrease in average illuminance was 41% and the increase in normalised power density was 77%.

The influence of lighting class on uniformity on the horizontal working plane was lower. The growth in uniformity was 21% while comparing the results for the lowest and highest classes.

Analysing the impact of applying the reduced working plane on the calculation results from the lighting class point of view the following observations were made:

- the average increase in average illuminance by 8.2%, 8.2%, 7.4%, 6.5% and 6.0% for classes 1, 2, 3, 4 and 5 respectively,
- the average increase in uniformity by 34%, 37%, 35%, 31% and 25% for classes 1, 2, 3, 4 and 5 respectively,
- the average increase in normalised power density by 22%, 22%, 22%, 25% and 27% for classes 1, 2, 3, 4 and 5 respectively.

The values of average illuminance and normalised power density depended more on the lighting class for direct lighting solutions which was reflected by the lower values of CV. On the contrary, the uniformity depended more on the lighting class for indirect lighting.

Table 2
Variation of average illuminance, uniformity and normalised power density for each lighting class in the interiors with reflectances 752

Class	Par.	MIN	MAX	AV	SD	CV
1	ET	286	485	428	54	13
	ER	326	508	463	46	10
	UT	0.42	0.64	0.56	0.07	12
	UR	0.62	0.87	0.75	0.08	11
	PT	1.15	1.94	1.32	0.20	15
	PR	1.21	3.07	1.61	0.50	31
2	ET	249	435	379	52	14
	ER	285	455	410	43	11
	UT	0.45	0.65	0.57	0.06	11
	UR	0.66	0.87	0.78	0.07	9.0
	PT	1.28	2.23	1.50	0.25	17
	PR	1.35	3.51	1.83	0.61	33
3	ET	202	390	337	53	16
	ER	252	407	362	42	12
	UT	0.50	0.66	0.60	0.05	8.2
	UR	0.71	0.88	0.81	0.05	6.6
	PT	1.43	2.75	1.70	0.35	20
	PR	1.51	3.97	2.08	0.73	35
4	ET	192	342	294	49	17
	ER	218	357	313	43	14
	UT	0.58	0.68	0.64	0.03	4.4
	UR	0.79	0.88	0.84	0.03	3.1
	PT	1.62	2.89	1.96	0.40	21
	PR	1.73	4.59	2.44	0.94	38
5	ET	162	297	251	54	22
	ER	185	309	266	50	19
	UT	0.67	0.70	0.68	0.01	2.0
	UR	0.81	0.88	0.85	0.03	3.1
	PT	1.87	3.43	2.33	0.64	28
	PR	1.99	5.41	2.95	1.42	48

4.4. Impact of luminaire LID. Table 3 presents the list of the minimum, maximum and average values on both the

Table 3
Variation of average illuminance, uniformity and normalised power density for each LID in the interiors with reflectances 752

LID	Par.	MIN	MAX	AV	SD	CV
1	ET	192	453	337	73	22
	ER	218	467	358	66	19
	UT	0.59	0.68	0.64	0.03	3.9
	UR	0.75	0.88	0.85	0.03	3.4
	PT	1.23	2.89	1.74	0.45	26
	PR	1.32	4.59	2.17	0.91	42
2	ET	205	471	357	71	20
	ER	235	489	382	68	18
	UT	0.54	0.67	0.60	0.04	6.7
	UR	0.80	0.88	0.83	0.02	2.6
	PT	1.18	2.71	1.63	0.38	23
	PR	1.26	4.26	2.01	0.78	39
3	ET	212	480	368	71	19
	ER	247	500	398	69	18
	UT	0.48	0.67	0.58	0.06	11
	UR	0.71	0.88	0.78	0.05	6.3
	PT	1.16	2.62	1.57	0.36	23
	PR	1.23	4.05	1.92	0.71	37
4	ET	217	485	376	72	19
	ER	257	508	410	72	18
	UT	0.42	0.67	0.56	0.08	15
	UR	0.62	0.85	0.72	0.08	10
	PT	1.15	2.56	1.54	0.35	22
	PR	1.21	3.89	1.86	0.66	35

total and reduced working planes as well as SD and CV of average values for the analysed parameters and for different luminaire LID.

The use of luminaires with narrower LIDs resulted in increasing the average illuminance and decreasing the normalised power density related to the horizontal working plane. These changes are similar and insignificant when comparing the results of neighbouring LIDs. The average illuminance went up by minimum 2.2% and by maximum 5.9%. The normalised power density fell by minimum 1.9% and by maximum 6.3%. The increase in average illuminance was 12% and the decrease in normalised power density was also 12% only while comparing the results of the widest (LID1) and the narrowest (LID4) LIDs.

The impact of luminaire LID on uniformity on the horizontal working plane was also not significant. The decrease in uniformity was 13% only when comparing the results of the widest and narrowest luminaire LIDs.

Analysing the impact of applying the reduced working plane on the calculation results from the luminaire LID point of view the following observations were made:

- the average increase in the average illuminance by 6.2%, 7.0%, 8.2% and 9.0% for the luminaire LID 1, 2, 3 and 4, respectively,
- the average increase in uniformity by 33%, 38%, 35% and 29% for the luminaire LID 1, 2, 3 and 4, respectively,
- the average increase in normalised power density by 25%, 23%, 22% and 21% for the luminaire LID 1, 2, 3 and 4, respectively.

For the narrow light distributions the uniformity was stronger related to the luminaire LID which was reflected by the lower values of CV. In case of the average illuminance and normalised power density this relation was not strong.

4.5. Impact of reflectances. In addition, the calculations for other reflectances (RF) in the rooms were also made. Apart from the previously analysed rooms with reflectances of 0.7 for a ceiling, 0.5 for walls and 0.2 for a floor (designation 752), the rooms with reflectances of 0.7 for a ceiling, 0.5 for walls and 0.3 for a floor (designation 753) and with reflectances of 0.7 for a ceiling, 0.7 for walls and 0.2 for a floor (designation 772) were also analysed.

The average impact of higher reflectances of a floor or walls on the levels of average illuminance, uniformity and normalised power density related to the total working plane and the reduced working plane was evaluated. The influence of using the reduced working plane in the calculations on the analysed parameters was also assessed.

Table 4 presents the list of the minimum, maximum and average values on both the total and reduced working planes

Table 4
Variation of average illuminance, uniformity and normalised power density for all cases in interiors with all reflectances.

RF	Par.	MIN	MAX	AV	SD	CV
752	ET	162	485	353	75	21
	ER	185	508	380	75	20
	UT	0.42	0.70	0.60	0.06	11
	UR	0.62	0.88	0.80	0.07	8.5
	PT	1.15	3.42	1.66	0.44	26
	PR	1.21	5.41	2.05	0.84	41
753	ET	165	517	370	81	22
	ER	188	541	398	81	20
	UT	0.43	0.72	0.60	0.06	10
	UR	0.63	0.88	0.80	0.07	8.0
	PT	1.08	3.37	1.59	0.43	27
	PR	1.14	5.32	1.97	0.84	43
772	ET	203	496	380	68	18
	ER	227	526	407	69	17
	UT	0.46	0.75	0.65	0.07	10
	UR	0.63	0.92	0.83	0.08	9.1
	PT	1.12	2.74	1.52	0.31	21
	PR	1.19	4.41	1.88	0.66	35

as well as SD and CV of average values for the analysed parameters in interiors with different reflectances.

With higher reflectances of a floor (the comparison of results for the rooms with reflectances 752 and 753) the following observations were made:
- the average increase in the average illuminance on the total working plane (reduced working plane) by 4.8% (4.7%),
- no changes in uniformity on the total working plane (reduced working plane),
- the average decrease in normalised power density related to the total working plane (reduced working plane) by 4.2% (3.9%).

With higher reflectances of the walls (the comparison of results for the rooms with reflectances 752 and 772) the following observations were made:
- the average increase in the average illuminance on the total working plane (reduced working plane) by 7.6% (7.1%),
- the average increase in uniformity on the total working plane (reduced working plane) by 8.3% (3.7%),
- the average decrease in normalised power density related to the total working plane (reduced working plane) by 8.4% (8.3%).

The use of a reduced working plane in the calculations resulted in the following points:
- the average increase in the average illuminance by 7.6%, 7.6% and 7.1% for the rooms with reflectances 752, 753 and 772 respectively,
- the average increase in uniformity by 33%, 33% and 28% for the rooms with reflectances 752, 753 and 772 respectively,
- the average increase in normalised power density by 24% for the rooms with all reflectances (752, 753 and 772).

5. Conclusions

The use of the reduced working plane to calculate the illuminance distribution and lighting power in interiors with the general electric lighting results in:
- the average increase in average illuminance level by 7.7%,
- the significant average increase in uniformity level by 33%,
- the significant average increase in normalised power density level by 23%.

The use of the reduced working plane for the lighting calculations in interiors should be clearly indicated in any analysis and design specifications. In case of assessing the lighting energy efficiency, the power and energy demand for lighting purposes should be referred to the surface area of this plane and not to the surface area of the total working plane in the interior.

For the considered variables and their analysed ranges the following issues are noticed:
- significant influence of the change in room index, especially in smaller rooms, on the change in a level of average illuminance and normalised power density,
- significant influence of the change in lighting class on the change in a level of average illuminance and normalised power density,
- much lower influence of the change in room index and in lighting class on the change in uniformity level.

The considered cases also prove that the influence of the change in luminaire luminous intensity distribution on the change of the analysed parameters is low.

The influence of the change in reflectances of the floor from 0.2 to 0.3 or of the walls from 0.5 to 0.7 on the levels of average illuminance, uniformity and normalised power density of the general lighting is low and does not exceed 10%. The normalised power density levels of the general electric lighting for interiors are in the following range: 1.08–3.42 W/m^2 per 100 lx, with luminaire luminous efficacy of 100 lm/W.

Based on the obtained results, a normalised power density level of 2 W/m^2 per 100 lx is proposed as a recommendation when designing and assessing the new general electric lighting systems for interiors. It should be kept in mind that further improvement in luminaire luminous efficacy will result in the simultaneous decrease in the normalised power density level in the near future.

The results obtained for a wide range of room sizes and reflectances, lighting class and luminaire luminous intensity distribution should be used by lighting designers and energy consultants when analysing and implementing the energy-efficient solutions for lighting in interiors.

The research presented in this paper is continued in terms of:
- assessing the impact of room sizes, reflectances, lighting classes, luminaire luminous intensity distributions and luminaire layouts on the quality of the luminous environment and the energy efficiency of lighting solutions in interiors,
- determining the lighting strategies useful while obtaining high quality luminous environment and energy efficiency of lighting in public building interiors.

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