Comparison of Different Methods of Distribution Factor Calculation

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***Abstract*—The calculation of utilization factors relies on geometric multipliers to arrive at the distribution factors which give the fraction of the source flux arrives directly at each room surface. There are a number of possible assumptions that can be used to derive geometric multipliers each resulting in different values. This paper explores these differences and estimates the potential differences in utilisation values that may be expected. The key finding is the method in CIE 52 may no longer be appropriate.**

***Index Terms*--Utilization factor, distribution factor, geometric multiplier**

I. Introduction

The standard method of utilisation factor calculation is being reviewed by CIE TC 3-48 and as part of that work the method used to determine the distribution factors (DFs) has been studied. Distribution factors are used to describe how much light falls onto each of the room's surfaces directly from the luminaires. The first step in calculating the DFs is assessing the direct flux reaching the floor (DFF) formula (1) gives this calculation.

$$DFF = GML1 \times FCL1 + GML2 \times FCL2 + GML3 \times FCL3 + GML4 \times FCL4 \qquad (1)$$

Where:

GML1 to *GML4* are the 4 geometric multipliers calculated according to the formulae in CIE 40 [1]

FCL1 to *FCL4* are the cumulative fluxes for the luminaire for the zones 0 to 41.4° (*FCL1*), 0 to 60.0° (*FCL2*), 0 to 75.5° (*FCL3*) and 0 to 90.0° (*FCL2*).

When the luminaires are mounted to the ceiling the distribution factors may be calculated with the formulae (2) below.

$$\begin{aligned} DF(F) &= \frac{DFL}{1000} \\ DF(W) &= DLOR - DF(F) \\ DF(C) &= ULOR \end{aligned} \qquad (2)$$

Where:

DF(F), DF(W) and DF(C) and the distribution factors to the floor, walls and ceiling respectively

DLOR is the downward light output ratio of the luminaire and ULOR is the upward light output ratio

When suspended luminaires are employed the system becomes slightly more complex with added calculation to determine how much of the upward flux reaches the ceiling and how much flux goes to the upper walls.

Once the DFs are know then the utilisation factors to the floor may be calculated using the formula (3)

$$UF(F) = DF(F) \times TF(F,F) = DF(W) \times TF(W,F) + DF(F) \times TF(C,F) \qquad (3)$$

Where

UF(F) is the utilisation factor on the floor

TF(F,F), *TF(W,F)* and *TF(C,F)* are the transfer factors to the floor from the floor, walls and ceiling respectively.

This process is again slightly more complex if suspended luminaires are used. The basic method for deriving the transfer factors is given in CIE 40[1] however the method has been further developed by Raynham & Bean [2].

Thus utilisation factors can easily be calculated, however, there are a number different approaches to the calculation of the geometric multipliers. This paper will study the differences between the method used in CIE 52 [3] and the CEN method of calculation [4].

II. Underlying Assumptions

Whilst the basic principals of calculating geometric multipliers are set out in CIE 40 [1] the variation between different methods arise because there is less agreement on the number of luminaires and their arrangement within a room. In CIE 52 the number of luminaires used in a room is purely a function of room size with the number being given in Table 1

Room Index (K)	No. in length	No. across
0.6	2	1
0.8	2	2
1	3	2
1.25	3	3
1.5	4	3
2	4	4
2.5	5	4
3	6	4
4	8	5
5	10	6

Table 1 the luminaire numbers from section10.3.6 of CIE 52

In the CEN standard it does not spell out exactly how the geometric are derived, however it does provide different GM values for different luminaire spacing to height ratios (SHRs). Checking the values given in the CEN standard against the basic calculation in CIE 40 it is clear that the GMs for a low SHR luminaire would seem to be based on more luminaires being in the room that for a high SHR luminaire. This is illustrated below

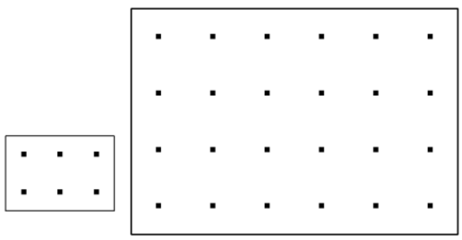

Figure 1

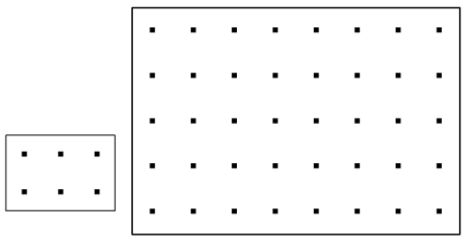

Figure 2

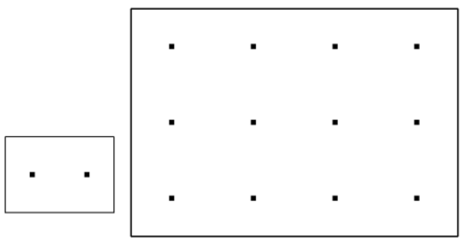

Figure 3

These figures show the nominal disposition of luminaires in a small room K = 1 and a larger room K = 3. Figure 1 shows the luminaire layout from CIE 52. Figure 2 shows the layout for the CEN standard with a SHR of 1. Figure 3 is the CEN layout for SHR 2.

These changes in layout result in different geometric multipliers.

	K = 1			**K=3**		
	CIE 52	CEN		CIE 52	CEN	
		SHR = 1	SHR = 2		SHR = 1	SHR = 2
GML1	0.636	0.636	0.459	0.282	0.258	0.192
GML2	0.121	0.121	0.588	0.118	0.118	0.100
GML3	0.088	0.088	-0.032	0.562	0.563	0.658
GML4	-0.015	-0.015	0.009	0.016	0.016	0.067

Table 2 Geometric multipliers from CIE 52 and the CEN method

III. Assessment of the Impact of Different GMs on the Calculated Values of UF

To explore the consequences of these different GMs for the UF tables generated it is necessary to do the utilization factor calculations using the GMs from both the CIE 52 and CEN methods. A range of light distributions was needed for the testing so the 10 light distributions of the British Zonal (BZ) system were adopted for this study. These distributions are described in detail in Raynham [5]. The BZ distributions are defined by the mathematical functions given in table 3 and figure 4 gives the polar curves for some of them.

BZ Number	Function	Normalisation Factor	SHR Max
1	$\cos^4\gamma$	795.61	1.255
2	$\cos^3\gamma$	636.52	1.405
3	$\cos^2\gamma$	477.42	1.624
4	$\cos^{1.5}\gamma$	397.86	1.779
5	$\cos\gamma$	318.36	1.989
6	$1+\cos\gamma$	106.11	2.381
7	$2+\cos\gamma$	63.66	2.512
8	1	159.15	2.767
9	$1+\sin\gamma$	89.14	3.184
10	$\sin\gamma$	202.65	1.584

Table 3 The function, normalization factor and SHR for each of the BZ distributions

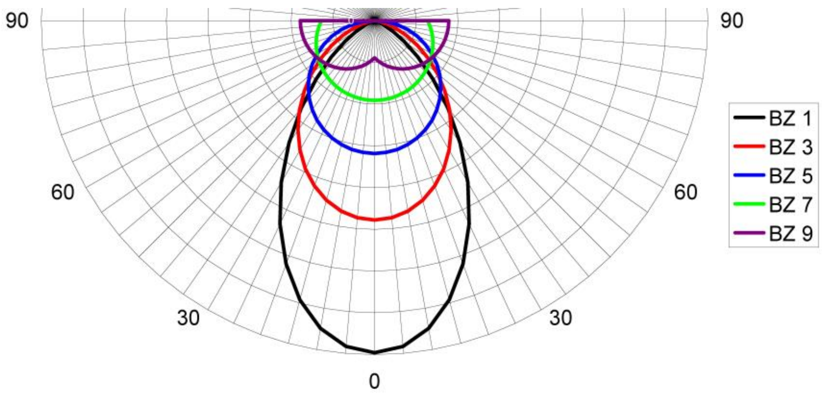

Figure 4 A polar plot of some of the BZ distributions

A set of UF tables was calculated for each BZ distribution by both the CIE 52 and CEN methods.

IV. Results

It was found that in all cases that the CEN method gave higher UF values than the method from CIE 52. Table shows the average and maximum differences between the two methods.

	Average Difference	Maximum Difference
BZ1	2.6%	6.4%
BZ2	2.4%	6.0%
BZ3	4.9%	12.1%
BZ4	5.5%	15.6%

	Average Difference	Maximum Difference
BZ5	5.2%	14.7%
BZ6	5.9%	15.6%
BZ7	5.7%	15.1%
BZ8	5.3%	14.1%
BZ9	4.9%	12.9%
BZ10	1.8%	5.2%

Table 4 The average and maximum differences in the UFs calculated by the two methods

As expected the differences are greater where there is less inter-reflect light and in smaller rooms where the role of the walls is more important. Table 5 shows the results for BZ6 which is typical of results for BZ4 to BZ8.

Values calculated using CIE 52										
K	Ref(C)	0.8	0.8	0.8	0.7	0.7	0.7	0.5	0.5	0.5
	Ref(W)	0.7	0.5	0.3	0.7	0.5	0.3	0.7	0.5	0.3
	Ref(F)	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
1.00		0.693	0.545	0.442	0.669	0.533	0.436	0.627	0.511	0.425
1.25		0.759	0.618	0.516	0.734	0.604	0.508	0.687	0.577	0.493
1.50		0.809	0.676	0.575	0.782	0.660	0.566	0.733	0.630	0.549
2.00		0.881	0.763	0.669	0.853	0.745	0.658	0.800	0.710	0.636
2.50		0.929	0.824	0.737	0.900	0.804	0.723	0.846	0.766	0.698
3.00		0.964	0.869	0.789	0.934	0.848	0.774	0.879	0.808	0.745
4.00		1.009	0.929	0.859	0.979	0.906	0.842	0.923	0.863	0.809
5.00		1.038	0.969	0.907	1.008	0.945	0.888	0.952	0.900	0.853
Values calculated using CEN										
K	Ref(C)	0.8	0.8	0.8	0.7	0.7	0.7	0.5	0.5	0.5
	Ref(W)	0.7	0.5	0.3	0.7	0.5	0.3	0.7	0.5	0.3
	Ref(F)	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
1.00		0.741	0.608	0.514	0.720	0.596	0.508	0.680	0.574	0.497
1.25		0.806	0.680	0.588	0.783	0.667	0.580	0.739	0.641	0.566
1.50		0.854	0.735	0.645	0.828	0.720	0.636	0.782	0.691	0.619
2.00		0.916	0.811	0.727	0.889	0.793	0.715	0.840	0.760	0.693
2.50		0.953	0.856	0.777	0.925	0.837	0.763	0.873	0.800	0.738
3.00		0.983	0.896	0.822	0.955	0.875	0.807	0.902	0.836	0.779
4.00		1.022	0.948	0.883	0.993	0.926	0.866	0.939	0.883	0.833
5.00		1.046	0.981	0.922	1.016	0.957	0.903	0.962	0.912	0.868
Differences in values (%)										
K	Ref(C)	0.8	0.8	0.8	0.7	0.7	0.7	0.5	0.5	0.5
	Ref(W)	0.7	0.5	0.3	0.7	0.5	0.3	0.7	0.5	0.3
	Ref(F)	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
1.00		6.8%	10.8%	15.0%	7.2%	11.1%	15.2%	8.1%	11.8%	15.6%
1.25		6.0%	9.5%	13.1%	6.5%	9.8%	13.3%	7.3%	10.4%	13.7%
1.50		5.4%	8.4%	11.5%	5.7%	8.6%	11.6%	6.5%	9.2%	12.0%
2.00		3.9%	6.1%	8.3%	4.2%	6.3%	8.4%	4.8%	6.7%	8.7%
2.50		2.5%	3.9%	5.3%	2.7%	4.0%	5.4%	3.1%	4.3%	5.6%
3.00		2.0%	3.1%	4.2%	2.2%	3.2%	4.3%	2.5%	3.5%	4.4%
4.00		1.4%	2.1%	2.8%	1.5%	2.1%	2.8%	1.7%	2.3%	3.0%
5.00		0.8%	1.2%	1.7%	0.9%	1.3%	1.7%	1.0%	1.4%	1.8%

Table 5 The results for BZ6 showing both calculated UF values and the differences between the sets of values. The highlighting shows greatest differences.

V. DISCUSSION

It is clear from this study that the different calculation methods produce significant differences in the results and for some distributions this is in excess of 5% in average and for particular room and reflectance conditions over 15%. Thus it is necessary to look at the cause of this difference and consider how it relates to actual lighting practice. In CIE 52 the set numbers of luminaires in rooms implies that the luminaires are spaced at a given SHR. Table 6 gives the SHR used in the CIE 52 method. It can be seen that the SHR is quite low, and in most cases below the SHR for the BZ distributions.

Room Index (K)	No. in length	No. across	SHR Length	SHR Width
0.6	2	1	0.78	0.98
0.8	2	2	1.04	0.65
1	3	2	0.87	0.81
1.25	3	3	1.08	0.68
1.5	4	3	0.98	0.81
2	4	4	1.30	0.81
2.5	5	4	1.30	1.02
3	6	4	1.30	1.22
4	8	5	1.30	1.30
5	10	6	1.30	1.35

Table 6 The SHRs implied by CIE 52

The only distributions which come close to these values are BZ1 and BZ2. These two distributions also show only small differences to the between the calculation methods. In figure 7 the full set of differences for BZ 2 is shown

Differences in values (%) For BZ2										
	Ref(C)	0.8	0.8	0.8	0.7	0.7	0.7	0.5	0.5	0.5
Ri	Ref(W)	0.7	0.5	0.3	0.7	0.5	0.3	0.7	0.5	0.3
	Ref(F)	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
0.60		2.7%	3.8%	4.8%	2.8%	3.9%	4.8%	3.0%	4.0%	4.9%
0.80		3.1%	4.5%	5.6%	3.3%	4.6%	5.6%	3.5%	4.7%	5.7%
1.00		3.3%	4.7%	5.8%	3.4%	4.8%	5.9%	3.7%	4.9%	6.0%
1.25		2.9%	4.2%	5.2%	3.1%	4.3%	5.3%	3.4%	4.5%	5.4%
1.50		2.4%	3.5%	4.4%	2.6%	3.6%	4.5%	2.9%	3.8%	4.6%
2.00		1.4%	2.0%	2.6%	1.5%	2.1%	2.6%	1.7%	2.2%	2.7%
2.50		0.4%	0.6%	0.7%	0.4%	0.6%	0.7%	0.5%	0.6%	0.8%
3.00		0.2%	0.3%	0.4%	0.2%	0.3%	0.4%	0.2%	0.3%	0.4%
4.00		0.1%	0.2%	0.2%	0.1%	0.2%	0.2%	0.2%	0.2%	0.2%
5.00		0.1%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%

Table 7 The differences for BZ2 with the highlighting showing the greatest differences

This table 7 shows that room index 2.5 and above the two calculation methods are in good agreement. In these rooms the SHR used by the CIE 52 method (~1.3) is close the nominal 1.25 SHR of the CEN method. It is only in the smaller rooms where the CIE 52 calculation uses a much lower SHR that there is a significant difference in the results.

VI. CONCLUSION

It is now common place for lighting designs to be assessed using computer software. However, utilizations factors are still useful as they provide a quick and easy way to find which luminaires are likely to be most efficient in a given installation and thus their use simplifies the luminaire selection process. The CEN method of calculating the UF takes into account the SHR of the luminaire providing sets of geometric multipliers to cover a range of SHRs. The CIE 52 method does not do this and implicitly assumes SHR values that would be considered low for most modern luminaires. In practice there are great pressures to reduce the number of luminaires used in any given installation so manufacturers strive to produce luminaires with high SHR values which are then installed close to their maximum SHR.

The method in CIE 52 underestimates the performance of luminaires that have been designed to be used at high spacing ratios and thus may be putting such equipment at a commercial disadvantage. For this reason it may be sensible to withdraw CIE 52 and replace it with method that relies on the SHR of the luminaire being evaluated.

[1] CIE 040-1978: Calculations for Interior Lighting: Basic Method.

[2] Raynham P.J. & Bean A. R. Calculation of transfer factors in the European utilization factor method. *Lighting Research and Technology* 38:4 pp 341-357. **2006**

[3] CIE 052-1982: Calculations for Interior Lighting: Applied Method

[4] EN 13032-2:2004 Light and lighting - Measurement and presentation of photometric data of lamps and luminaires - Part 2: Presentation of data for indoor and outdoor work places

[5] Raynham P.J. Room lighting in the absence of a defined visual task and the impact of mean room surface exitance. *Lighting Research and Technology* 48:2 pp 190-204 **2016**