Title	Generating robust algorithms for energy efficient lighting as a performance aspect of the building operational energy optimisation framework
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Publication Date	2016-08-29
Publication Information	Ganguly, T, Hajdukiewicz, M, Keane, M, Goggins, J (2016) Generating robust algorithms for energy efficient lighting as a performance aspect of the building operational energy optimisation framework Civil Engineering Research in Ireland Conference (CERI 2016) Galway, Ireland, 29/08/2016-30/08/2016
Publisher	NUI Galway
Link to publisher's version	http://doi.org/10.13025/S8H01H
Item record	http://hdl.handle.net/10379/6233
DOI	http://dx.doi.org/10.13025/S8H01H

Generating robust algorithms for energy efficient lighting as a performance aspect of the building operational energy optimisation framework

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ABSTRACT: This paper presents a part of the ongoing research in the nZEB-Retrofit project in the National University of Ireland, Galway. This research aims to optimise residential building performance by enhancing the key performance metrics of certain performance aspects. In this paper, one of these aspects (lighting) has been discussed, algorithms developed and tested on the living room of a semi-detached dwelling in Dublin. The main objective of the paper is to formulate algorithms to: 1) calculate the power required to illuminate a space up to standard CIBSE design maintenance, 2) calculate the energy consumption and costs per year for lighting that space, and 3) determine power loss and potential energy savings from lighting. For this purpose, key performance indicators (KPIs) that would facilitate the optimisation process have been selected from several national and international standards and guides. The key findings of this paper are that (1) the difference between the provided power of the light to the required power significantly affects the energy costs, and this should be a key consideration in the selection of light source and (2) the output effectiveness of a lighting source is largely dependent on various factors like lamp lumen depreciation (LLD), luminaire dirt depreciation (LDD) and optical and thermal losses. It is inversely related to energy consumption.

KEY WORDS: BIM, scenario modelling, building optimisation, national standards and guides, energy simulation.

1 BACKGROUND

This work is based on the scenario modelling framework developed by O'Donnell et al. [1]. This method used reproducible transformation leverage formulae to generate specific grades of information useful for building managers to understand. The usefulness of this method lies in the fact that a variety of performance aspects can be analysed to formulate data from different sources such as measured building data, predicted data from simulation model or utility provider data from dynamic tariffs. The class diagram representation of the scenario modelling method is given in Figure 1. In different scenarios, specific aspects are considered (see aspect list in Table 1) in building objects (zones/ spaces). They have specific objectives, which are driven by metrics. Once the datum sources for these metrics are quantified, the results are formulated. Each metric definition contains only one formula that may access raw data from any number (denoted as N) of predefined data streams.

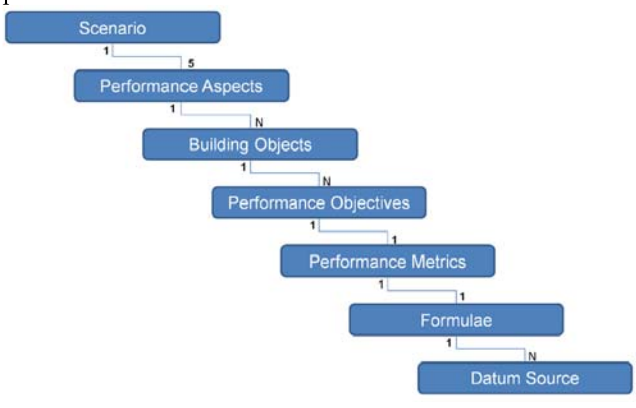

Figure 1 - Class diagram representation of the scenario-modelling method [1]

This mechanism helps in the comparison of measured and simulated data. O'Donnell et al. [1] have presented some hypothetical and real life examples in their work, such as reduction of zone temperature, evaluation of system heating performance and comparing indoor comfort and energy consumption. Each scenario deals with some performance aspects whose objectives involve enhancement of certain metrics. This is achieved by comparing measured and simulated data sources, which in turn facilitate the development of algorithms.

2 RESEARCH APPROACH

The approach taken is that which yields the greatest benefits for homeowners. Given the large number of owner occupied houses in Ireland, a mechanism of fulfilling the needs of the owners/ occupants is significant. The selection of the aspects has been made based on the literature review and it is possible to quantify these aspects into performance objectives with definitive performance metrics that will have a two-fold function – 1) achieving significant energy savings and enhancing Building Energy Performance (BEP), 2) influencing the decision of homeowners by demonstrating visible energy savings and aesthetic upgradation. Table 1 presents the performance aspects that have been selected for this research and their corresponding sources. This list is non-exhaustive nor final, being open for further editions. In this paper, only the performance aspect 'Lighting' has been analysed in detail, and studies on the other performance aspects will be the consequent parts of the research.

Table 1- Performance aspect selected for this research and corresponding sources

No.	Performance aspect	Source
1	Lighting	[2]–[9]
2	Visualisation	[10][11]
3	Interior comfort conditions	[2], [12]–[14]
4	Building acoustics	[15], [16]
5	Renovation scheduling	[17], [18]
6	Sustainability (LCA)	[10], [16], [19], [20]
7	Legislation	[2], [21], [22]
8	Health and safety	[23]–[25]
9	Retrofitting costs and payback	[10], [26]
10	Pro-environmental attitude (human	[27], [28]

Building systems are complex. Most, if not all, of the performance aspects are linked in a certain way. Performance of one aspect more often than not, affects the performance of the other. Figure 2 presents an interdependency diagram, depicting the relationship between the performance aspects of a built environment.

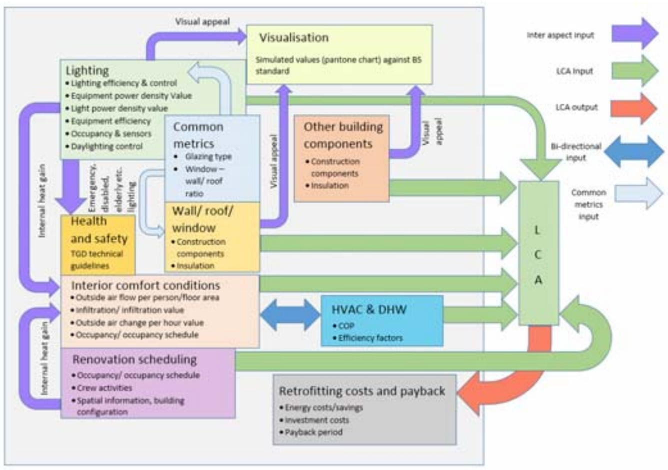

Figure 2 - Performance interdependency diagram

The diagram is under development and will be revised with further ongoing research. Some salient features of the diagram are given below:

- Lighting and wall/ roofs/ windows have common metrics (glazing type and window - wall/roof ratio) that drive the performance of these aspects.
- The lighting of the room generates internal heat gain, and there is also heat gain from the occupants as well, which affects the internal comfort conditions of the space indirectly.
- The characteristics of lighting and building components such walls, roofs, windows, doors indirectly affect the visual properties of the building.
- Interior comfort conditions depend directly on certain performance metrics with indirect inputs from wall/ roof/ window features and other building components.
- Renovation scheduling is directly dependent on the occupancy schedule of the tenants/ homeowners and the renovation crew as well as spatial info and building configuration.
- Life cycle assessment of a building can only be possible with information from lighting conditions, building components, interior environment, HVAC and DHW and renovation scheduling.
- An accurate life cycle assessment helps retrofitting cost and payback analysis, which directly depends on performance metrics – energy cost/ savings, investment costs and payback period.

3 PERFORMANCE ASPECT - ENERGY EFFICIENT LIGHTING

The scenario-modelling method recognises conventional performance analysis contexts and categorises them as building objects. These building objects can be micro (zone) or macro (building site, building portfolio or simply building). Figure 4 presents the performance aspects of the building energy optimisation framework.

In this paper, only one performance aspect – lighting – has been analysed only. The relationship between the aspects and its performance objectives, metrics, algorithms and measurements have been presented in Table 4. The data sources have been identified and algorithms for artificial lighting of a space have been developed in section 4.

The lighting consideration for a whole building should be done zone or space wise, since the lighting requirement for each zone is different from the other. The performance objective is to optimise lighting, based on certain metrics provided in standard guides and technical documents [2]–[9]. The recommended lighting requirement for a dwelling has been provided by the Chartered Institution of Building Engineers [7], and presented in Table 2. The guide provides standard options in using light sources, energy efficient automatic lighting controls, maintenance, emergency lighting and luminaire types, among other aspects.

Table 2 – The CIBSE recommended lighting levels (developed from [7])

Building zone or space	**Recommended illuminance (lux)**
Entrances	200
Corridors	100 for daytime, 20 for night time
Stairs, stairwells, and lift lobbies	100 on the treads
Bathrooms and toilets	100 for toilets, 150 for bathrooms
Bedroom	100
Living room and kitchens	200
External lighting	10 for pathways and car parks, 20-30 for care homes with transition between interior and exterior areas

4 ALGORITHM DEVELOPMENT FOR ACHIEVING PERFORMANCE OBJECTIVES OF LIGHTING FRAMEWORK

4.1 *Formulae for calculating power (W_{total}) required for lighting as per standard design illuminance (IL)*

The first step of the algorithm development is to find the total power (W_{total}) required to light a space up to the CIBSE recommended illuminance levels [7] shown in Table 2. To do so, it is required to find out the lighting power density (LPD) of the light source, which is the ratio of the room illuminance (IL, measured in lux or lumens/m^2) and the light output effectiveness (OE, measured in lumens/ watt). LPD is the wattage of power required for each square meter of floor space

$$LPD= [IL/OE]\ (W/m^2) \quad (1)$$

Illuminance (IL) here is the lux level to which the lighting needs to be powered (say, 200 lux for the living room and kitchen, obtained from Table 2, which should be catered by both natural and artificial sources). Natural light contribution is described briefly in sub-section 7.1.

Output effectiveness (OE) is product of the luminous efficacy (LE, measured in lumens/ watt) with depreciation factors such as LLD (lamp lumen depreciation), LDD (luminaire dirt depreciation), CU (coefficient of utilisation), TC (thermal coefficient), all measured in percentages.

$$OE = [LE \times CU \times LLD \times LDD]\ (lm/W) \quad (2)$$

Light efficacy (LE) of a lighting source is the ratio of the light output (lm, measured in lumens) and the power (W, measured in watts), given by equation (3).

$$LE= [lm /W]\ (lm/W) \quad (3)$$

The coefficient of utilisation (CU) is a percentage that depends on the fixture used for the light source. It determines the optical efficiency of the secondary optical device, which is the fixture [6]. The LED luminaire design guide [6], developed by CREE Inc., suggests assuming a specific percentage for reflectivity and also the light hitting the reflector cup of the fixture. Equation (4) gives the formula for coefficient of utilisation.

$$CU = [(100\% \times UL) + (RF \times RL)]\ (\%) \quad (4)$$

Where, UL = un-reflected light/ incident light, RF = fixture reflectivity, RL = percentage of light hitting the reflector cup.

For all light sources besides LEDs, LLD is commonly calculated as the ratio of mean to initial lumens, where mean lumens are defined as the output at a certain percentage of rated life, based on the lumen depreciation curve for a specific product [5]. In contrast, when quantity of light is an important design consideration, the IES recommends using an LLD of not greater than 0.70 for LEDs, regardless of the rated lifetime or lumen depreciation characteristics of the product [8]. The default value of LLD for compact fluorescent lamps (CFLs) is given as 0.92 in the IES handbook [8].

The General Electric (GE) Company, in their product catalogues [29] use typical luminaire dirt depreciation (LDD) values extracted from the IES lighting handbook [8]. Table 3 presents those values, which have been used in the section 7, for analysing the light sources for the selecting the best option of lamps.

Table 3 - Typical luminaire dirt depreciation (LDD) value [29]

Typical luminaire dirt depreciation	Light	Medium	Heavy
Environment (dirt level)	0.94	0.86	0.77
Enclosed fixtures	0.97	0.93	0.88
Enclosed and filtered	0.94	0.84	0.74
Open and ventilated	0.94	0.86	0.77

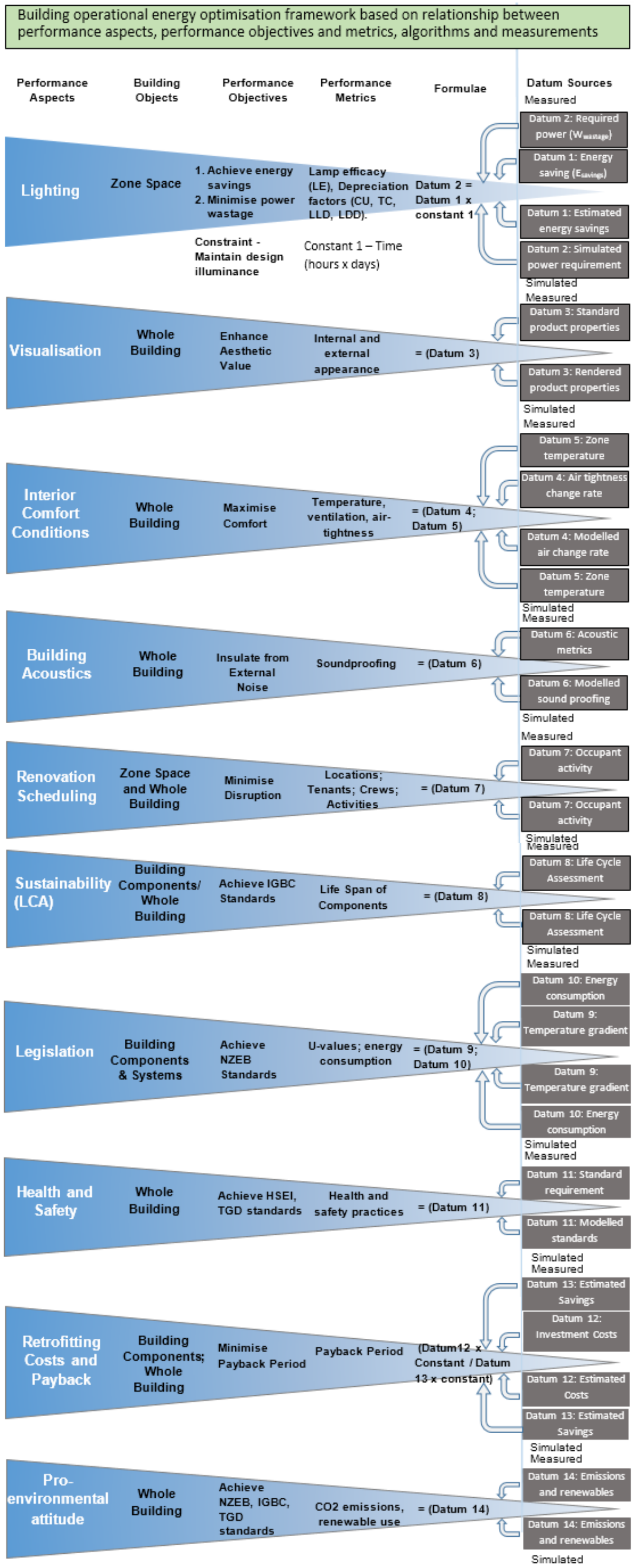

Figure 3- Building operational energy optimisation framework (lighting aspect described in detail in Table 1)

It has to be mentioned here that a constant ($C_{surface}$) should be taken into consideration to account the surface reflectivity, room surface dirt depreciation, colour and other similar factors. These factors affect the effectiveness of the incident light. For example, a lighter coloured wall would decrease the LPD while dirt on the same would increase it. However, due to lack of datasets, this constant has not been considered in the case study calculations in section 7.

The LPD is the power required to light a square metre of space. So, to find the total power ($W_{total,}$ measured in watts) to light up the whole space, LPD is multiplied with the total floor space (TFA, measured in m^2) it is supposed to light, given by equation (5).

$$W_{total} = [LPD \text{ x } TFA] \text{ (W)} \quad (5)$$

Once the W_{total} is calculated, dividing it by the wattage of the light source (W_{source}) and rounding it up to the nearest whole number gives the number of light sources (N) required:

$$N = W_{total} / W_{source} \quad (6)$$

4.2 *Formulae for calculating energy consumption and costs per annum*

The second step of the algorithm development is to find the energy consumption for power required to light the space. Once the number of light sources are determined, the power delivered to the room can be found out by multiplying N with the power per lamp (W_{source}). The energy consumption for the space for a period of time (E) in kWh is calculated using:

$$E=[N \text{ x } W_{source} \text{ x } 3600 \text{ x } 2.8 \text{ x } 10^{-7} \text{ x hours x days})] \quad (7) \text{ (kWh)}$$

According to the Dwelling Energy Assessment Procedure (DEAP) [2] issued by the Sustainable Energy Authority of Ireland (SEAI), winter months are from October to May (243 days) and summer is June to September (122 days). It is very important that the calculations for energy consumption for a year be done separately for winter and summer months, since the number of hours of lighting will be different. Energy costs for lighting for a given space is given by:

$$C_{year} = [(E_{winter} + E_{Summer}) \text{ x } C_{kWh}] \text{ (€)} \quad (8)$$

where C_{year} = annual energy costs, E_{winter} = energy consumption in winter months, E_{Summer} = energy consumption in summer months, C_{kWh} = cost of electricity per unit of electricity.

4.3 *Formulae for calculating power wastage and potential energy savings from lighting*

The final step of the algorithm development is to calculate power wastage and formulate the potential energy savings per year. The product of N and W_{source} gives the total power of light delivered to the room (W_{prov}). The difference between W_{total} and W_{prov} provides the power wastage for the space (9). So, it is evident that there needs to be a proper selection of light sources, in order to reduce the power wastage.

$$W_{wastage} = [W_{prov} – W_{total}] \text{ (W)} \quad (9)$$

Potential energy savings ($E_{savings}$) per year can then be calculated by the equation (10) . As with the energy consumption (E), the potential energy savings calculation should be done separately for winter and summer months, for greater accuracy.

$$E_{savings}= [W_{wastage} \text{ x} 2.7 \text{ x } 10^{-7} \text{x time] (kWh/year)} \quad (10)$$

5 ASSIGNING ALGORITHMS TO THE BUILDING OPERATIONAL ENERGY OPTIMISATION FRAMEWORK

Table 4 vividly presents of the performance objectives, metrics, formulae and datum sources of the performance aspect – lighting. The objectives of the lighting design are to achieve energy savings, minimise power wastage, while maintaining design lighting illuminance (constraint). The performance metrics on which these goals depend are the lamp efficacy, lamp depreciation factors and surface constant. The performance objectives are attained with the help of equation 10, while the other equations (1-9, 11-13) help construct the main formula. LPD, W_{total}, E, W_{prov}, W_{source} C_{year} are the data sources used ascertaining the formulae. They together make up datum 1 - $W_{wastage}$ and datum 2 - $E_{savings}$. The simulated results for energy savings and lighting power requirement is done in the BIM of the zone space. However, this is outside the scope of the paper, whose objective is algorithm development for measuring data.

Table 4 – Relationship between performance objectives, performance metrics and algorithms for lighting

Performance objectives	Performance metrics	Formulae	Datum sources
1. Achieve energy savings ($E_{savings}$) 2. Minimise power wastage ($W_{wastage}$) Constraint - Maintain design illuminance (IL)	Lamp efficacy (LE), Lamp depreciation factors (CU, TC, LLD, LDD), Surface constant ($C_{surface}$ - for reflectivity, room surface dirt depreciation, colour and similar)	$E_{savings}$ = [$W_{wastage}$ x 2.7 x 10^{-7} x time] (kWh/ year)	$E_{savings}$ and $W_{wastage}$ which include - LPD, W_{total}, E, $W_{prov,}$ $C_{year,}$ W_{source}

6 ALGORITHM FOR NATURAL LIGHTING

During daylight time, natural light is combined with artificial sources to achieve target illuminance in lux (lumens/m^2). IL, mentioned in the previous sections, is illuminance that should be achieved only by artificial light. So, equation 11 shows the deduction for the part illuminated by natural light (IL_{nat}) is the difference of the total illuminance (IL_{total}) and the IL.

$$IL_{nat} = [IL_{total} – IL] \text{ (lumens/ } m^2) \quad (11)$$

Daylight factor (DF) is the ratio of the light level inside a space, which is IL_{nat}, to the light level outside the structure (IL_{ext}). So, IL_{nat} in terms of DF and light level outside the space (IL_{ext}) is given by:

$$IL_{nat} = [DF \text{ x } IL_{ext}] \text{ (lumens/ } m^2) \quad (12)$$

The daylight reaching any point inside a room is usually made up of three components: sky component (SC), externally reflected component (ERC), internally reflected component (IRC) [6]. If no external obstruction exists, the externally reflected component is omitted. In side-lit rooms, the maximum DF is near the windows, and it is mainly due to the sky component. Daylight factor is used to assess the adequacy of daylight, given by:

$$DF = (A_{win} \text{ x } T \text{ x } \theta)/ (A_{intsurf} \text{ x } ((1-R^2)) \text{ (\%)} \quad (13)$$

where A_{win} = window glazing area in m^2, $A_{intsurf}$ = total area of internal surfaces in m^2, T is the glass transmittance corrected for dirt, θ is visible sky angle in degrees from the centre of the window, R is the average reflectance of area $A_{intsurf}$.

7 APPLYING ALGORITHMS ON A CASE STUDY SPACE

An important part of any research is validation. The algorithms generated in section 4 and 6 have been tested on a case study space. The space is a living room area in a semi-detached house in Dublin. The area of the room is 12.51 sqm and is presently using incandescent lighting sources.

7.1 Contribution of natural lighting to design lux

Using the algorithms from section 6 for natural daylighting, on the case study living room having $A_{intsurf}$ of 60 sqm and glazing area of 1.6 sqm (62% of total window area), natural light incidence angle (θ) of 73°, average reflectance (R) as 0.6 (value given in BS-EN12464-2011 [30]) and transmittance of 0.6 (standard for double glazed glass), the average natural internal illuminance (IL_{nat}) comes to 20 lux. This calculation is done for an overcast day, the outdoor illuminance for 1075 lux [30]. This fraction is deducted from the design lux, and the rest is supplied by the artificial lighting design.

7.2 Selection of case study light sources

8 kinds of light sources (2 CFLs, 4 LEDs and 2 incandescent) have been analysed and tested on the sample area, based on the lighting consideration in table 3. The idea is to test these sources on a smaller space, and then use the same set of algorithms for a larger area or zone-groups.

Though the exact nature and characteristics of the actual lamps used in the room are unknown, the two types of incandescent sources selected in the analysis should provide a fair idea of the electricity consumption for lighting the spaces up to the required level of 180 (200 - 20) lux. All the bulbs used are samples from the GE lighting sources catalogue [29]. The different light sources selected show varying degree of efficacy. One may question why lamps with different illuminance is chosen. This is simply to analyse which is more efficient – less number of high illuminance sources or more lamps with lesser nominal lumens. The same fixture properties have been taken for all light sources, so as to maintain parity in analysis. It has been assumed that 60% of the light will hit the reflector cup and the reflectivity of the fixture is 85%, as per the CREE technical report [6]. The coefficient of utilisation (CU) then comes to 91% (calculating as per equation (4). Thermal losses are taken as 15%, as per the IES lighting handbook [8], so TC=85%.

7.3 Computation of critical properties of selected light sources

Table 5 presents the light sources and the calculated values of OE, LPD, W_{total}, W_{prov}, N, E, C_{year}. LE is the design luminous efficacy of the sources. The effect of the depreciation factors (CU, TC, LLD, LDD) is quite evident and the OE is approx. 60% for most of the sources. Wprov is the cumulative power provided by N lamps. For instance, the nominal power for CFL 1 provided by the manufacturer is 23. Therefore, 3 lamps are needed to provide more than 56W, which is the requirement of the room. (69-56) = 13W is the excess power. For N lamps, the annual energy consumption is denoted by E and C_{year} is the annual energy costs for lighting the space.

The primary factor that affects energy consumption of a lighting source is the efficacy (LE) of the lamp. Incandescent sources normally have extremely low LEs, and they tend to be relatively costly compared to CFL and LED sources. This is evident from the column representing E and Cyear, for Incandescent 1 and Incandescent 2 lamps.

Table 5 – Computed critical properties of selected light sources

Light source	**LE**	**OE**	**LPD**	$\mathbf{W_{total}}$	$\mathbf{W_{prov}}$	**N**	**E**	$\mathbf{C_{year}}$
	Lm/w	Lm/w	W/m^2	W	W	No.	kWh	(€)
CFL 1	65	40	4.5	56	69	3	218	43
CFL 2	79	49	3.7	46	76	2	240	47
LED 1	77	47	3.8	48	52	4	164	32
LED 2	80	49	3.7	46	49	1	155	30
LED 3	78	48	3.8	47	50	10	157	31
LED 4	60	37	4.9	61	63	14	199	39
Incand-escent 1	9	6	32.7	409	425	15	1344	262
Incand-escent 2	13	8	22.1	277	300	3	949	185

7.4 Findings

Figure 4 shows a relationship graph between the output effectiveness (OE) and the annual lighting energy consumption for the room. Remarkably, though CFL 1 has a lower OE of 40 lumen/ watt, it only consumes 218 kWh in a year. Compared to that, CFL 2 has an OE of 49 lumens/ watt, but it needs 240 kwh/year of electricity to keep the area lighted at the recommended levels. The LED sources show pattern, with slight variance in the (E/OE) ratio. The performance of LED 4 in comparison is slightly worse than its other CFL and LED counterparts. The incandescent lights show extremely poor performance in comparison to the other light sources.

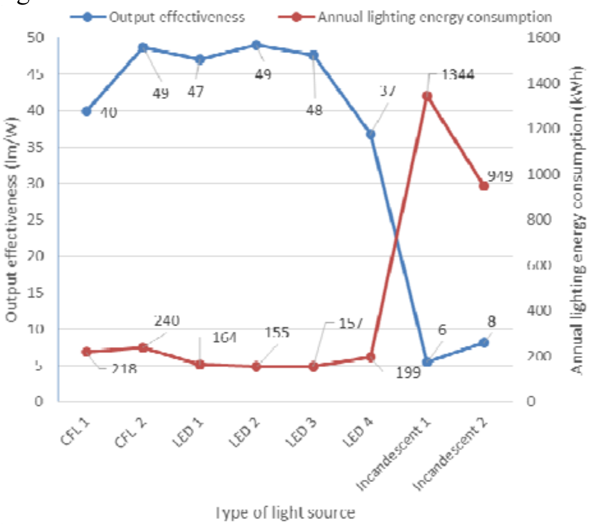

Figure 4 - Effect of output effectiveness (OE) on annual lighting energy consumption (E) of the room.

Figure 5 is a combination line chart that compares the annual energy costs for lighting of the room to the potential savings of the same. The two lines are far from symmetrical, proving the importance of proper source selection for spaces. The ratio of the power required (W_{total}) to the area of the room (TFA) which gives the LPD (watt/m^2) is extremely important for the selection as well. The combination of powers of different bulb sources should be such that $W_{wastage}$ is minimum. So, though efficacy (LE) is an important criterion for selection of the light sources, the pivotal one is the typology of selection.

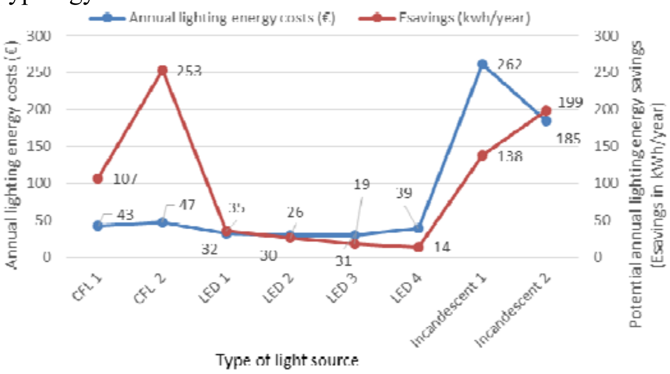

Figure 5 – Comparison of potential energy savings to annual energy lighting costs of the room space

8 LIMITATIONS

There are some limitations in this research:

- Thermal losses for all of the sources are taken as 15%. More research and test results for ascertaining a more accurate thermal coefficient (TC) is required.
- A proper selection of a lamp could only be possible after a thorough life cycle analysis of the sources. The author plans to test the algorithms on the whole house and check for the most feasible solution.
- Factors such as colour rendering and appearance, controls and light distribution will be researched in depth in the future. Such factors affect the visual aspect of the zone space and are intrinsic to energy efficient design of lighting.
- A constant ($C_{surface}$) to take into account the surface reflectivity, room surface dirt depreciation, colour and other similar factors should be considered. These factors affect the effectiveness of the incident light. However, due to lack of datasets, this constant has not been considered in the case study calculations.

9 CONCLUSION AND FUTURE WORK

It is evident from figure 5, that the LPD is an important criterion for the selection of light sources, and in turn for reducing power wastage and increasing energy savings. The greater the difference, the greater the wastage. A good option may be to use a combination of lamps to achieve W_{prov} as close as possible to W_{total}. The aim of the research is to reduce energy consumption, which promotes task lighting, parameters such as light angles, intelligent locations, reflectance and light range are crucial to the installation of the light sources. Although, the efficacy of a lamp is known to be the most important factor for lamp selection, it has to be kept in mind that a more efficient lamp will not necessarily translate into the most energy savings, as evident from the findings. Room size, reflective angles and characteristics of walls and other surfaces, focal points of sources, bends in walls, location of furniture and controls are extremely important for proper space lighting. These factors will be studied in further research and their interdependencies will be identified in similar case studies. To fully implement this framework, the measured value from these algorithms will also be calibrated with the simulated results from the energy calculations of the BIM. The framework will then be tested on other different buildings.

ACKNOWLEDGMENTS

The authors would like to acknowledge the support of SFI through the CDA programme (Grant No. 13/CDA/2200).

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