International Research Journal of Engineering and Technology (IRJET) e-ISSN: 2395-0056
Volume: 05 Issue: 07 | July 2018 www.irjet.net p-ISSN: 2395-0072

A SCHEME FOR OPTIMAL PLACEMENT OF LIGHT SENSORS FOR ILLUMINATION CONTROL

Elvis Twumasi[1], Emmanuel Asuming Frimpong[2]

[1,2]*Department of Electrical and Electronic Engineering, Kwame Nkrumah University of Science and Technology, Kumasi, Ghana*

---***---

Abstract - *The optimal placement of light sensors is critical for effective lighting control. In this paper, a technique for optimally placing light sensors in a room is presented. The design (or input) data used by the technique comprises room dimension, number of bulbs and their coordinate positions, polar data of bulbs, and the number of light sensors to be installed. Coordinate points are obtained for the room and the total illumination at each point determined. The k-medoid algorithm is employed to cluster the coordinate points based on the number of light sensors to be installed. The average illumination for each cluster is then computed. The coordinate point for each calculated average illumination becomes the optimal sensor location in that cluster. The technique was tested by both field measurements and the application of design data. The results obtained show that the proposed technique has a high degree of accuracy.*

***Key Words*: Lighting, Lighting control, Light sensor, Optimal placement**

1. INTRODUCTION

To address the challenges associated with the high rise in energy demand, several strategies have been put in place. One of such strategies is demand-side management (DSM). DSM is a leading strategy employed to reduce energy demand [1]. Effective activities under DSM include (a) promotion of high efficiency building practices, (b) use of energy-efficient products, (c) shifting of non-critical usage of electricity from peak periods to off-peak periods, (d) institution of programmes that provide limited utility control of customer equipment such as air conditioners, (e) promotion of energy efficiency awareness among consumers and (f) installation of energy management devices [2]-[6]. Behaviour-based approaches such as (c) and (e) can be implemented without capital investment. However, behavior-based strategies alone cannot offer the needed energy savings, hence the need for the installation of energy management devices [7].

The deployment of energy management devices, including devices for lighting control, has yielded appreciable savings [1]. Many intelligent lighting control systems have been developed to reduce wastage in the provision of lighting, particularly, in schools [8]. However, several problems remain unsolved in lighting control. For example, it is difficult to provide the desired illumination to an arbitrary location in an installation area [9]. Additionally, there is difficulty in determining the optimal location of light sensors to ensure effective coverage, for optimum lighting control [10]. With regards to optimal location of lights sensors, there is presently no published research paper that outlines a clear generalized approach to solving this problem. For example, whereas lighting designers discourage the positioning of light sensors inside skylight or in direct light from the fixtures, they do not indicate how the optimal position for light sensors can be determined [11].

This work proposes a solution to the challenge of optimal placement of light sensors. A technique for the realization of optimal location of light sensors is presented to aid designers and installers. The proposed technique places light sensors at points of average illumination within a zone or area. The use of the point of average illumination is supported by the fact that per the Charted Institute of Building Services (CIBSE) code for lighting [12], the quality of lighting in a work area is determined by the average illumination in the area. For the proposed technique, the average illumination and its corresponding coordinate point (i.e. where a light sensor should be installed) is determined by first obtaining coordinate points for the entire room and then determining the total illumination at each point due to each installed light bulb. The coordinate points are then zoned depending on the number of light sensors to be deployed. For each zone, the average illumination is then determined, and its corresponding point used as the optimal sensor location.

The rest of the paper is organized as follows: Section 2 discusses the theoretical concepts employed while Section 3 presents the methodology used by the proposed technique. The approach used to test the proposed scheme is presented in Section 4. Test results are presented and discussed in Section 5 and conclusions drawn presented in Section 6.

2. THEORETICAL CONCEPTS USED

The scheme combines the inverse square law and Lambert's cosine law. These laws were used for illumination calculations. The k-medoids clustering algorithm was also utilized to cluster coordinate points. The sub-sections that follow explain these theoretical principles.

2.1 Inverse square law

The inverse square law states that the illumination, *E*, of a surface is inversely proportional to the square of the distance, *d*, between a light source and a light surface provided that the distance between the surface and the source is sufficiently large so that the source can be regarded as a point source [13]. Mathematically,

$$E \propto \frac{1}{d^2} \, . \tag{1}$$

2.2 Lambert's cosine law

According to the Lambert's cosine law, the illumination, *E*, at a surface varies proportionally to the cosine of the angle, φ , between the normal to the surface and the direction of the incident light [13]. Mathematically,

$$E \propto \cos\varphi \, . \tag{2}$$

Combining the inverse square law (1) and the Lambert's cosine law (2) yields

$$E \propto \frac{1}{d^2}\cos\varphi = \frac{I_V}{d^2}\cos\varphi \tag{3}$$

where I_V is the luminous intensity of the source.

In finding the illumination of a bulb, the polar data of the bulb needs to be taken into consideration because, in practice, the luminous intensity is not uniform because of the shape of lamps. Therefore, luminaire manufacturers provide the luminous intensity data as either polar curve or polar table showing how the luminous intensity varies with direction (angle) along the surface of a cone which has its apex at the source. A curve fitting approach is therefore used to obtain luminous intensities for angles not given in manufactures' polar tables.

2.3 K-medoids clustering algorithm

K-medoids algorithm is a partitional clustering algorithm which is slightly modified from the K-means algorithm. A medoid is the object of a cluster, whose average dissimilarity to all the objects in the cluster is minimal. The algorithm outputs a set of clusters from a data set containing multiple objects [14]. It can be implemented using the MATLAB software.

The basic idea of this algorithm is to first compute k representative objects which are known as medoids. After finding the set of medoids, each object of the data set is assigned to the nearest medoid. That is, object *a* is put into cluster ***A***, when medoid m_a is nearer than any other medoid. The k-medoids algorithm works as follows [14]:

(i) *k* random points are selected as the medoids from the given data points of the data set.

(ii) It then associates each data point to the closest medoid by using a distance metric such as the Manhattan distance.

(iii) For each pair of non-selected object and selected object, the total swapping cost is calculated.

(iv) If the total swapping cost is found to be less than zero, the selected object is replaced by the non-selected object and steps (ii) and (iii) are repeated until there is no change of the medoids.

3. SCHEME FOR OPTIMAL LIGHT SENSOR PLACEMENT

Figure 1 shows a flowchart of the technique for optimal placement of light sensors. The input (or design) data requirement for the scheme comprises the following:

(i) dimension of the room, namely, length, width and height,
(ii) number of bulbs to be used,
(iii) polar data of bulbs,
(iv) coordinate point for each bulb, and
(v) number of light sensors to be placed.

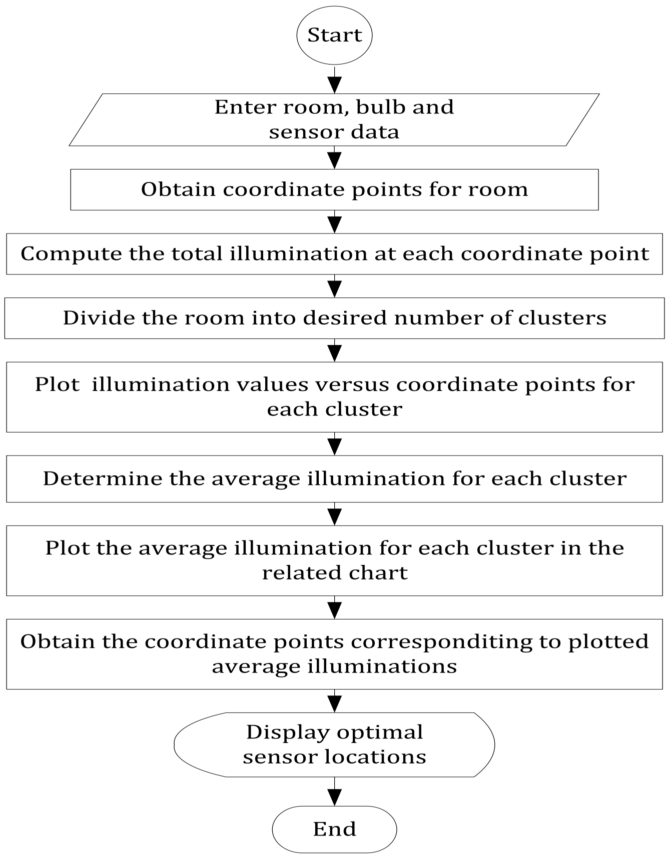

Fig -1: Proposed light sensor placement scheme

A detailed description of the operation of the scheme is provided as follows:

(i) At the start of the algorithm, the design data is entered.
(ii) Based on the dimension of the room, the room is divided into one-meter square grids. Where the room's dimension is not an integer value, it is rounded to the nearest integer. The 1m by 1m grid is generated as follows:

The length, n-meters of the room is partitioned at 1m intervals to obtain a set of lengths $\boldsymbol{A}$ as

$$\boldsymbol{A} = \{1, 2, 3, \ldots, n\} \tag{4}$$

The width, m-meters of the room is also partitioned at 1m intervals to obtain set $\boldsymbol{B}$ as

$$\boldsymbol{B} = \{1, 2, 3, \ldots, m\} \tag{5}$$

The set of coordinate points, $\boldsymbol{G}$, is constructed by obtaining the Cartesian product of sets $\boldsymbol{A}$ and $\boldsymbol{B}$. Set $\boldsymbol{G}$ is given as

$$\boldsymbol{G} = \boldsymbol{A} \times \boldsymbol{B}. \tag{6}$$

(iii) The illumination, E_{Gxyb}, at each coordinate point (G_x, G_y) of set $\boldsymbol{G}$ due to each bulb b is determined using (10). Figure 2 is provided to afford a better comprehension of the mathematical manupulations that preceeded (10). In figure 2, I_{Vb} is the luminous intensity of bulb b, (b_x, b_y) is the coordinate position of bulb, projected to the work area, h is the ceiling height (considered the same as height of bulb), (G_x, G_y) is the coordinate position of the point whose illumination is to be determined, D_{Gxyb} is the horizontal distance between points (b_x, b_y) and (G_x, G_y), and d_{Gxyb} is the distance between actual bulb position on ceiling and (G_x, G_y).

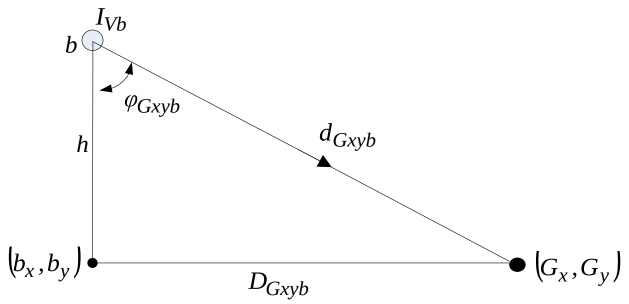

Fig -2: Graphical view to aid application of used illumantion laws

In applying (10), the horizontal distance, D_{Gxyb}, is first computed using (7).

$$D_{Gxyb} = \sqrt{(b_x - G_x)^2 + (b_y - G_y)^2} \tag{7}$$

Hence,

$$d_{Gxyb} = \sqrt{h^2 + D_{Gxyb}^{\,2}} \tag{8}$$

After d_{Gxyb} is determined, $\cos\varphi_{Gxyb}$ is also obtained using (9).

$$\cos\varphi_{Gxyb} = \frac{h}{d_{Gxyb}} \tag{9}$$

Finally, the illuminance of each coordinate point due to each bulb, E_{Gxyb}, is found using (10).

$$E_{Gxyb} = \frac{I_{Vb}}{d_{Gxyb}^{\,2}} \cos\varphi_{Gxyb} \tag{10}$$

where I_{Vb} is the luminous intensity of each bulb b.

(iv) The total illumination at each grid point, E_{Gxy}, due to the contribution of all bulbs is calculated using (11) where B is the number of bulbs.

$$E_{Gxy} = \sum_{b=1}^{B} E_{Gxyb} \tag{11}$$

(v) The coordinate points are groupd into K clusters (or zones) based on the number of light sensors, S, to be deployed, using the k-medoids clustering algorithm. Here, the number of clusters is made equal to the number of light sensors to be installed (i.e. K=S)
(vi) The average illumination for each cluster is determined. The average illumination of the kth cluster, $E_{avg,k}$, is given as

$$E_{avg,k} = \frac{1}{N} \sum_{n=1}^{N} E_{Gxy,n} \tag{12}$$

where $E_{Gxy,n}$ is the illumination E_{Gxy} at the nth coordinate point in the cluster.
(vii) All coordinate points (G_x, G_y) are plotted against their correspoing illumination values, E_{Gxy} (obtained in step (iv)), based on the clusters formed in step (v).
(viii) The average illumination values obtained in step (vi) are also plotted in the related charts in step (vii) and the corresponding coordinate points determined.
(ix) The coordinate points obtained in step (viii) are the optimal locations for the light sensors.

4. TESTING OF PROPOSED SCHEME

The scheme was tested using data collected from a case study lecture room at the Kwame Nkrumah University of Science and Technology. The room was divided into 1-meter square grids and the coordinate points noted. The room had no installed light sensors. A decision on the number of light sensors to deploy in a particular room depends on the reach of the light sensors to be deployed and the total room area. For the case study room, the number of sensors to use was chosen to be four. The room was thus divided into 4 zones for illumination measurements and subsequent determination of the optimal location of the four sensors, in accordance with the proposed technique.

The illumination at each coordinate point due to the combined effect of sunshine and bulb illumination was measured using a lux meter. The measurements were carried out at four different time periods. This was done to capture likely changes in illumination due to variations in the intensity of sunlight in the room, which can potentially affect the optimal location of light sensors. The measurements were started at the following times: 9am, 11am, 1pm and 4pm. The measured illumination values were plotted against their corresponding coordinate points. For each of the four zones, an average illumination was computed from the measured illumination values. The computed average illumination values were also plotted. The coordinate points corresponding to the average illuminations were noted as the optimal sensor locations.

The required design data for the case study room was later applied to the proposed technique to evaluate the performance of the technique. The results obtained by utilizing the proposed technique through field measurements and using design data only were then analyzed.

5. RESULTS OBTAINED

To demonstrate the performance of the proposed method, results obtained (i) through field measurements and (ii) by applying design data only, are presented in the sub-sections that follow.

5.1 Results obtained by field measurements

Plotted results for only one section (zone) of the case study room is presented. Summarized results for all other sections are presented later in sub-section 5.3.

Figure 3 shows a plot of measured illumination values versus coordinate points, for measurement period starting at 9am. Here, the average illumination corresponded to coordinate point (2, 1). Figure 4 also shows a plot of measured illumination values versus coordinate points, for measurement period starting at 11am. The average illumination again corresponded to coordinate point (2, 1). A plot of measured illumination values versus coordinate points for measurement period starting at 1pm is shown as figure 5. For this period, the average illumination rather corresponded to coordinate point (2, 4). This variation arose due to the increased intensity of sun light during the period. Furthermore, figure 6 shows a plot for the same variables but for the period starting at 4pm. For this period, the average illumination and hence the point for optimal sensor placement was once more found to be (2, 1).

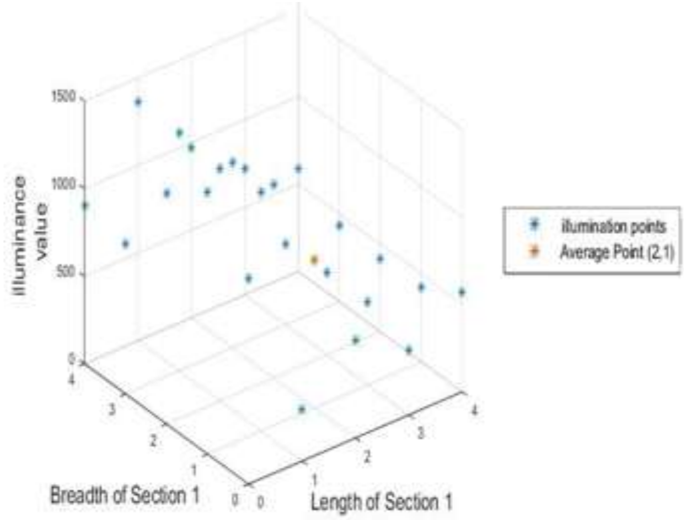

Fig -3: Illumination values and point of average illumination for measurements at 9am

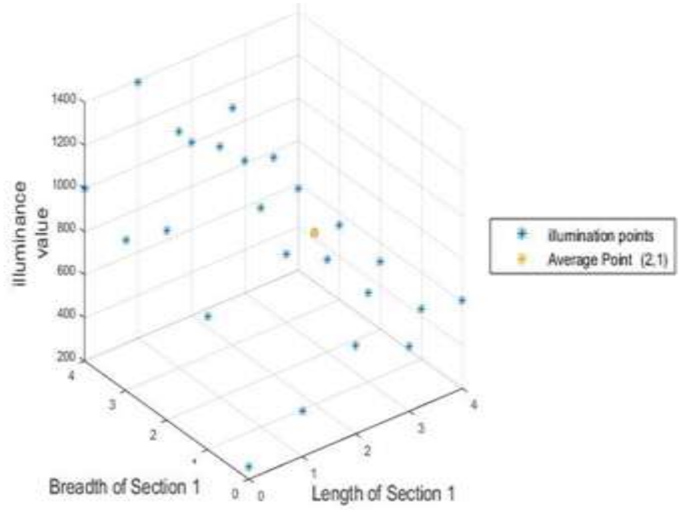

Fig -4: Illumination values and point of average illumination for measurements at 11am

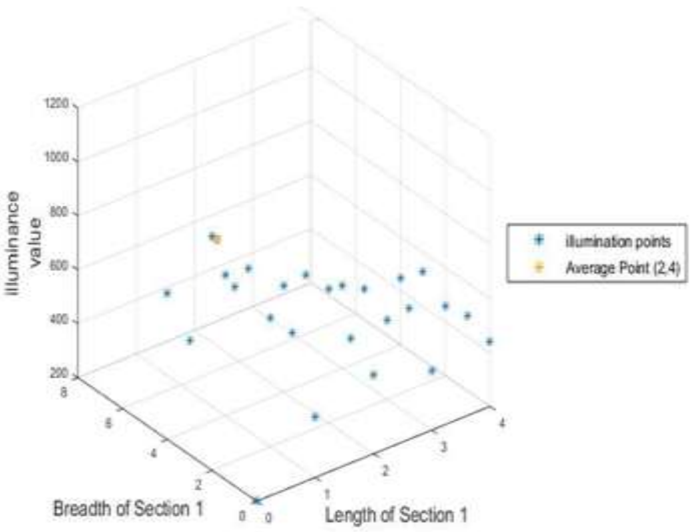

Fig. 5: Illumination values and point of average illumination for measurements at 1pm

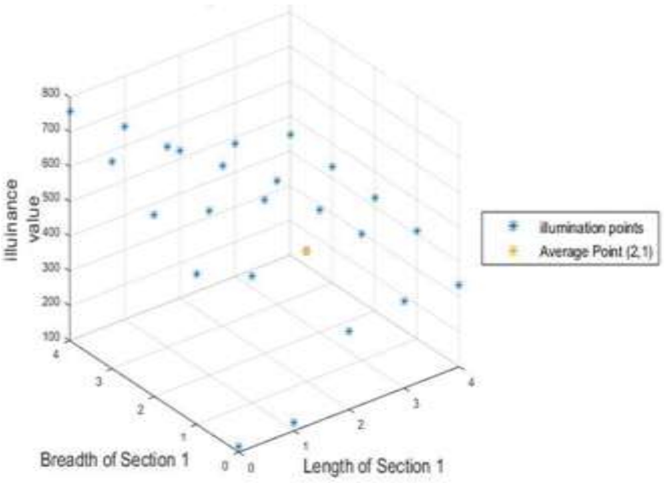

Fig -6: Illumination values and point of average illumination for measurements at 4pm

5.2 Results based on the use of design data only

Figure 7 shows a plot of calculated illumination values at the various coordinate points of section 1, after applying only design data to the proposed technique. The figure also shows the average illumination and hence the optimal position for the light sensor. The calculations were done using the polar data for the bulbs in the room as well as the Fourier curve fitting equation in the MATLAB software. The optimal sensor position was determined to be (2,1).

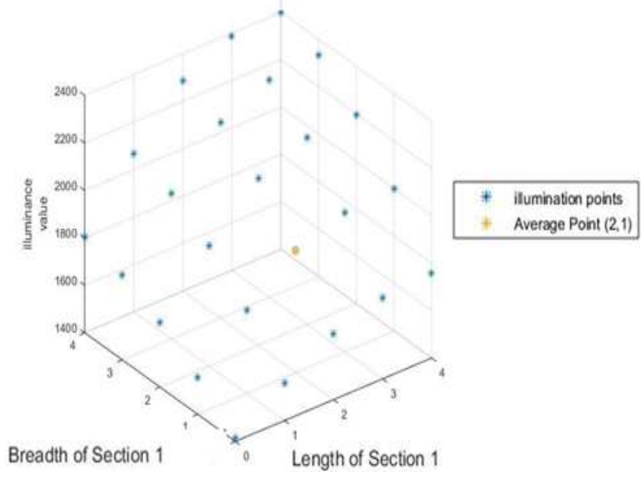

Fig -7: Illumination values and point of average illumination for section 1 using proposed technique

A comparison of optimal sensor locations obtained by field measurements (as shown in figures 3 to 6) and that obtained using only design data show that the proposed technique is accurate. Additionally, the results indicate that bulb and room data alone can be used to determine the point of average illumination and hence the optimal position for light sensors, with appreciable accuracy.

5.3 Further comparison of results obtained by field measurement and application of design data

Table 1 shows optimal sensor positions for all the four sections of the case study room obtained at the various measurement periods. The table also shows the optimal sensor positions obtained when bulb and room data were applied to the proposed optimal sensor placement technique.

For section 2, which was not previously discussed, the opitmal location for the light sensor varied for the various periods of field measurement. This was due to the effect of sun light in that section. When only design data was used, the optimal sensor location was found to be (6,1). This coincided with that for measuremnt period starting at 9am, which is the period of minimal sunshine. The optimal position for the light sensor in section 3, based on field measurements, for the periods starting at 9am and 11am was (2, 6). The optimal sensor location for the remaining periods however varied. For this section, the optimal sensor position when only design data was used was found to be (2, 7), which is the same as that obtained by field measurement starting at 1pm. Lastly, for section 4, the optimal position when design data was used was (6, 7). Here, the position obtained by field measurement was also (6, 7) thrice, and (6, 6) once.

It is noted from Table 1 and the analysis done that the optimal locations outputted by using design data only fairly matches those obtained by field measurement. Future research will look at including sunshine data and building orientation to further improve the accuracy of the technique.

Table -1: Optimal sensor positions by field measurement and by use of design data

Time of measurement	Sensor position (by field measurement)	Sensor position (by use of design data)
Section 1		
9 am	(2,1)	(2,1)
11am	(2,1)	
1pm	(2,4)	
4pm	(2,1)	
Section 2		
9 am	(6,1)	(6,1)
11am	(5,3)	
1pm	(6,3)	
4pm	(6,2)	
Section 3		
9 am	(2,6)	(2,7)
11am	(2,6)	
1pm	(2,7)	
4pm	(2,4)	
Section 4		
9 am	(6,6)	(6,7)
11am	(6,7)	
1pm	(6,7)	
4pm	(6,7)	

CONCLUSION

The proposed technique uniquely combines room and bulb data in a simple way to determine the optimal location of light sensors. It is the first of its kind. The technique eliminates subjectivity in light sensor location. It does not require extensive input data and can be applied to all manner of rooms. It is amenable to coding for easy application. The methodology presented is accurate. The proposed technique will save designers and installers of light sensors a great deal of time and effort.

ACKNOWLEDGMENT

The authors thank the KNUST research fund (KRef) for providing financial support for the work.

REFERENCES

[1] K. Crosby, A. B. Metzger, "Powering down, a toolkit for behaviour-based energy conservation in K-12 schools", U.S. Green Building Council, Inc., 2013.

[2] P. Warren, "Electricity demand-side management: best practice programmes for the UK", Energy and Sustainability IV, vol. 176, pp. 69, 2013.

[3] A. Emeakaroha, C. S. Ang and Y. Yan, "Challenges in improving energy efficiency in a university campus through the application of persuasive technology and smart sensors", Challenges, vol. 3, pp. 290-318, 2012.

[4] Demand-side management. Retrieved from http://www.pacificorp.com/es/dsm.html., 2017.

[5] C. W. Gellings, "The concept of demand-side management for electric utilities", Proceedings of the IEEE, vol. 73, no. 10, 1468-1470, 1985.

[6] E. Twuamsi, E. A. Frimpong, F. Kemausuor, D. O. Appiah and P. Y. Okyere, "Energy efficiency awareness and preparedness among students", Journal of Electrical Engineering, vol. 18, no. 1, pp. 140-146, 2018.

[7] OECD/IEA, Capturing the multiple benefits of energy efficiency, 2014.

[8] A. Radhakrishnan and V. Anand, "Design of an intelligent and efficient light control system", International Journal of Computer Applications Technology and Research, vol. 2, no. 2, pp. 117 - 120, 2013.

[9] S. Attarchi, An intelligent system for energy-efficient lighting and illuminance control in buildings, 2005

[10] ABB i-bus KNX , Constant lighting control, 2015

[11] Lutron, Daylight sensor design and application guide, 2014.

[12] Chartered Institute of Building Services Engineers, Code for lighting, 2002.

[13] A. D. Ryer, Light measurement handbook, International Light, Inc., 1997.

[14] T. Velmurugan & T. Santhanam, Computational complexity between k-means and k-medoids clustering algorithms for normal and uniform distributions of data points, Journal of Computer Science, vol. 6, no. 3, pp. 363-368, 2010.