Optimizing Lighting Energy Savings in Public Buildings through Maximal Use of Daylight

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Abstract: The current research represents a new approach for lighting energy consumption optimization and automation of indoor lighting systems. The basic idea is to minimize the electrical energy consumption of the lighting system by effectively using the natural light. The approach proposed uses genetic algorithm as an optimization tool for the lighting control strategy. Further reduction of the energy consumption for lighting and improvement of the system's performance is realized by utilizing experimental results for daylight coefficient's values for rooms with west and east geographical exposure, thus reducing the number of sensors needed for correct operation of the system.

1. Introduction

Buildings consume up to 40% of total end-use energy in the European Union [1]. Lighting accounts for 14% of the primary energy use in public buildings and therefor holds a greatest potential for energy savings among all the electrical systems, except the space heating. Although a great percent of the energy savings can be achieved through daylight harvesting, load shedding, scheduling, etc., modern lighting control technologies are still considered too expensive for public buildings, because of the big retrofitting costs [2]. The emergence of wireless sensor network technologies promises an economic lighting system by replacing the costly wiring with wireless devices. Not only the installation of photosensors and occupancy sensors benefit by wireless sensor network technologies, but also light switches or dimmers may be wirelessly enabled to form actuator networks for more sophisticated lighting control [6].

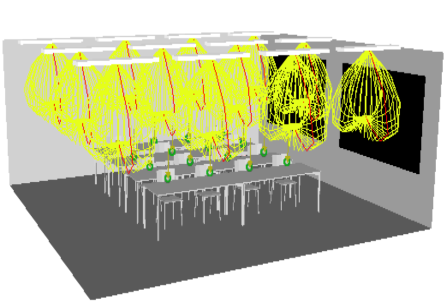
Energy savings and efficiency are some of the most important design considerations for contemporary lighting systems of public buildings. For achieving energy savings it is important considering an appropriate lighting control system. The most efficient lighting control systems are those that use the maximum possible amount of daylight and only complete it with artificial electrical lighting, whenever the illuminance levels on the working plane become lower than the norm [4]. This lighting control strategy is called daylight harvesting. A well designed daylight harvesting system guarantees a preset light level on the work plane at all times and has an impact on human productivity [5]. The artificial light only starts to dim or switch the fixtures off (on) when the norm light level is exceeded by the overall amount of light (artificial + daylight). There are a lot of lighting control strategies existing, but the most widely employed are switching and dimming lighting controls. Each of these control methods have its advantages and drawbacks and its efficiency depends on a lot of factors, but mainly on the geographical coordinates of the place where it will be used, the architecture of the building and the availability of natural light.

2. Approach and considerations

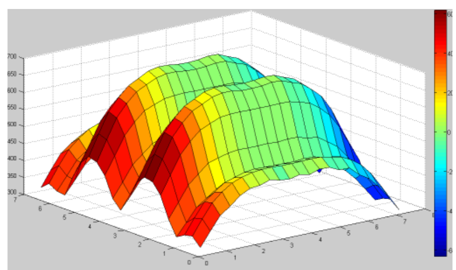
The illuminance on the work planes in public buildings results from the combined light contribution of multiple overhead luminaires. The European standard for indoor lighting

EN-12464 gives the norm values of the necessary illuminance on the work planes according to the visual tasks being performed [3]. This research is targeted in developing an algorithm for intelligent lighting control system for public buildings with the following objective: minimize the overall lighting energy usage without compromising the norms given by the standard for indoor lighting. The control algorithm formulated considers lighting control as a linear programming problem and is based on genetic algorithm. The algorithm uses experimental data for daylight coefficients obtained for public buildings in Bulgaria. The two basic control strategies taken in consideration in the optimization algorithm are automatic switching of the lighting fixtures and individual dimming of the light sources.

The room taken in consideration in the current research is a laboratory, located on the third floor of the Electrotechnical Faculty of the Technical University of Sofia, Bulgaria. The floor area of the laboratory is 52 m^2, and its height is 2.8m. There are two windows with a total area of 14m^2 facing west (for enhanced results the same geometry is taken in consideration with windows facing east). The walls and the ceiling are white; the work plane is light gray. The corresponding reflectance coefficients of the surfaces are 70%, 50%, 30%. New design of the lighting system in the room is considered with 12 electric lighting fixtures to provide electrical lighting. Each fixture is provided with one fluorescent lamp, T5, 35W and electronic ballast – figure 1a. Figure 1b gives the overall illuminance that the electrical lighting system provides in the test laboratory.



(a)



(b)

Fig. 1 Lighting system configuration (lighting fixtures and luminous intensity curves) of the test room (a). Illuminance provided by the electrical lighting system (b)

Sixteen working places are taken in consideration – figure 3 [10]. The daylighting coefficients are considered the same along the work places situated at the same distance from the window and their values decrease in a direction perpendicular to the windows. The daylight coefficients remain the same, no matter of the atmospheric conditions outside the room. They change with the season and geographical exposure of the windows of premises and have different values in the morning and in the evening. The daylight coefficients give the correlation between the inside and outside illuminance and once calculated, they can be used to get the values of the illuminance on work planes indoors, while only the outside natural illuminance is measured – figure 4.

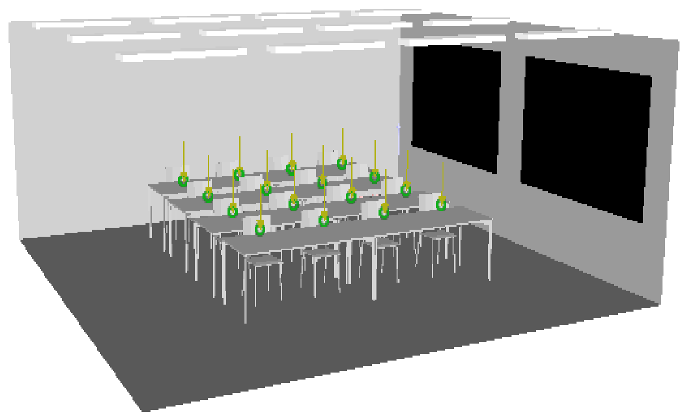


Fig. 3 Configuration of the control points on the working plane taken in consideration.

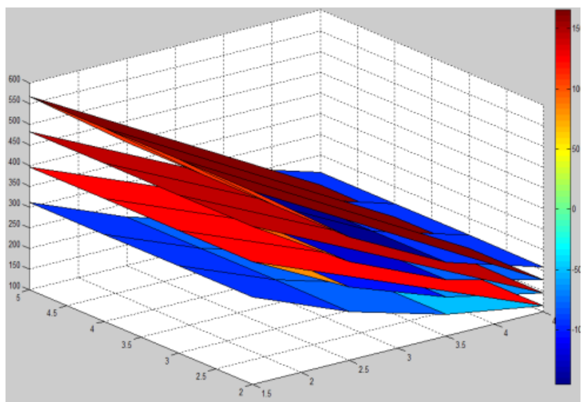


Fig. 4 Illuminance on the work planes taken in consideration, calculated by means of daylight coefficients.

3. Formulation of the daylighting control and optimization problem

The electrical lighting fixtures are operated to maintain constant illuminance level of 500lx on the work plane in 16 control points where the desks are situated. The illuminance output required from the electrical lighting system is determined by taking the difference between the norm value of the illuminance for the task performed and the calculated daylight illuminance for the time of the day reviewed. Thus the illuminance level required by the artificial lighting is given by the equation:

$$E_{AL} = E_N - DC \cdot E_{DO} \qquad (1)$$

where,

- E_N is a vector representing the desired illuminance level on the working plane;
- DC is the matrix for the daylight coefficients;
- E_{DO} is the outside illuminance level (calculated from statistical calendars).

The overall lighting in a space is considered a linear combination of the light contributions of each of the luminaires.

To optimize the electrical energy use from the light fixtures it is necessary to minimize the entire lighting output of the system. Each lamp then must be set to provide a specific amount of light to supplement available daylighting in order to maintain the desired illuminance level in all working zones. The optimization problem can be expressed by equation (2) to state that the required additional illuminance output from the electrical lighting should be equal to the desired illuminance level minus the illuminance, received through the natural light:

$$A \,.\, X = E_{AL} = E_N - DC \,.\, E_{DO} \qquad (2)$$

where,

- X is a matrix that provides the illuminance output from the electrical lighting system. The matrix X is m x n, where m is the number of lighting circuits (lamps) in the space;
- A is a n x m matrix that represents the illuminance contribution of the m lighting fixtures to the n working zones;
- E_{AL} is a n x 1 matrix that represents the illuminance required from the electrical lighting system.

The electrical lighting energy use depends on how the electrical inputs for the lamps are adjusted to provide the required illuminance levels. This adjustment in the current case utilizes two strategies – on/off and dimming. It should be noted that when using dimming strategy the relation between the light output of the lighting fixtures and the power consumption of the same fixtures is not linear. Dimming below 10% does not reduce the energy consumption any further, but the color rendering of the light source decreases significantly and efficacy declines. In order to deliver different light outputs for energy savings, it is necessary to enable individual control of each luminaire.

If the number of the working places (control points) is equal to the number of luminaires installed in the room under consideration (n=m), the system of linear equations can be solved and has only one solution. However, when the space has more working zones than electrical lighting circuits (n >m), equation 2 becomes an over-determined system of linear equations and there is no unique solution of the system. In this case an approximate solution is necessary. That is why an n x 1 error vector, E, is introduced as follows:

$$E = E_{AL} - A \,.\, X \qquad (3)$$

This vector E represents the excess illumination for the working zones. To achieve the maximum energy savings, the norm of the excess illumination, E, must be minimized:

$$||E|| = [(E_{AL} - A \,.\, X)^T (E_{AL} - A \,.\, X)]^{1/2} \qquad (4)$$

In the research presented, a minimization method based on the Genetic Algorithm (GA) approach is used to estimate X and consequently the potential electrical lighting energy savings. Specifically, the GA method determines the most efficient operating schedule for electrical lighting lamps and calculates the excess illumination based on the desired illuminance level for the working zones.

4. Genetic algorithm

A genetic algorithm is an explanatory procedure, inspired by evolution that is often able to find near optimal solutions to complex problems [7]. To do this it maintains a set of trial solutions, called individuals, and forces them to evolve towards an acceptable solution. First a representation of possible solutions must be developed. These algorithms encode a potential solution to a specific problem on a simple chromosome-like data structure, and apply recombination operators to these structures in such a way as to preserve critical information. Then, starting with an initial random population and employing survival-of-the-fittest and exploiting old knowledge in the gene pool, each generation‘s ability to solve the problem must improve. Given a clearly defined problem to be solved, a simple GA works as follows [8]:

1. Start with a randomly generated population of n chromosomes (candidate solutions of the problem).
2. Calculate the fitness f(x) of each chromosome x in the population.
3. Repeat the following steps until n offspring have been created:
   - Select a pair of parent chromosomes from the current population, the probability of selection being an increasing function of fitness.
   - With chosen crossover probability cross over the pair to form two offspring.
   - With chosen probability mutate the two offspring.
4. Replace the current population with the new population.
5. Go to step 2.

Each iteration of this process is called a generation. A GA is typically iterated for anywhere from 50 to 500 or more generations. The entire set of generations is called a run. At the end of a run there are often one or more highly fit chromosomes in the population. Since randomness plays a large role in each run, two runs with different random-number seeds will generally produce different detailed behaviors. A GA provides a number of potential solutions to a given problem and the choice of final solution is left to the user.
For illustration of the genetic algorithm used in the current research, selected results are shown in tables below. A Matlab program has been developed to code the objective function (fitness function) and the Optimization toolbox has been used for the optimization procedure. For results confirmation after running the GA, another run is performed using hybrid function fmincon. The hybrid function is an optimization function that runs after the genetic algorithm terminates in order to improve the value of the fitness function [9]. The hybrid function uses the final point from the genetic algorithm as its initial point. The results obtained have been than simulated in Dialux to confirm that the lighting level needed on the work plane is achieved and the approach chosen is appropriate. The parameters needed for GA initialization are:

- Selection method: Roulette Wheel;
- Crossover: Shuffle;
- Mutation: Adaptive feasible;
- Crossover rate: 0.7;
- Population size:100;

The results of the GA-based optimization as well as electrical lighting use energy savings, obtained by the control strategies used compared to a lighting installation with manual control are discussed below.

On/off artificial lighting control

After obtaining the results from the GA based optimization procedure, an operation schedule for the lighting installation has been developed. Because of the short period of time between the sunrise and the moment when the norm illuminance on the work planes is reached and the fast changing values of the natural illuminance outside, every lighting control scene is considered to last for thirty minutes. Table 1 gives the operation schedule for all of the lighting fixtures considered for a typical sunny day in spring for the room with west geographical exposure. Table 2 shows the results for the same room, but with windows facing east. In tables 1 to 4 “1.00” means the luminaire is on and “0.00” – off.

Table 1. Work schedule of the lighting fixtures for typical sunny day in spring – control strategy on/off switching, orientation of the windows – west.

	Luminaire number											
Time	1	2	3	4	5	6	7	8	9	10	11	12
7:00-7:30	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	1.00	1.00	1.00
7:30-8:00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	1.00	0.00
18:00-18:30	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	1.00	1.00
18:30-19:00	0.00	0.00	0.00	0.00	1.00	0.00	1.00	1.00	0.00	1.00	1.00	1.00

Table 2. Work schedule of the lighting fixtures for typical sunny day in spring – control strategy on/off switching, orientation of the windows – east.

	Luminaire Number											
Time	1	2	3	4	5	6	7	8	9	10	11	12
7:00-7:30	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	1.00	0.00
7:30-8:00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	1.00	0.00
18:00-18:30	0.00	0.00	0.00	0.00	0.00	0.00	1.00	1.00	0.00	0.00	0.00	1.00
18:30-19:00	0.00	0.00	1.00	1.00	1.00	0.00	1.00	1.00	0.00	1.00	1.00	1.00

Figures 5 and 6 show respectively the lighting situation and the illuminance distribution from electrical lighting for the test laboratory with west geographical orientation on a sunny spring day, for period of time from 18:30 to 1900h. The lighting control strategy is on/off.

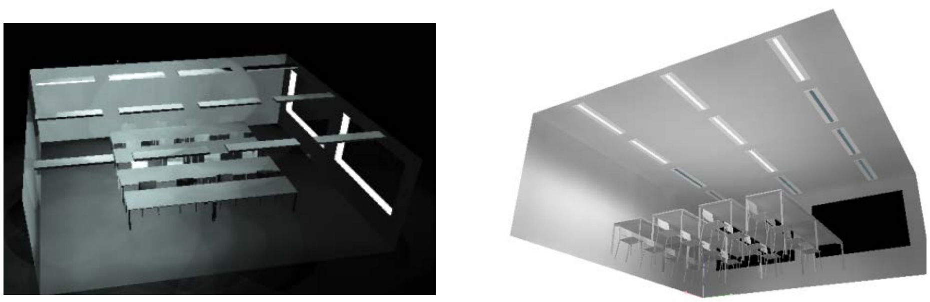


Fig.5 Lighting scene (on/off control) for period of time from 18:30 to 19:00h on a sunny spring day for a room with windows facing west

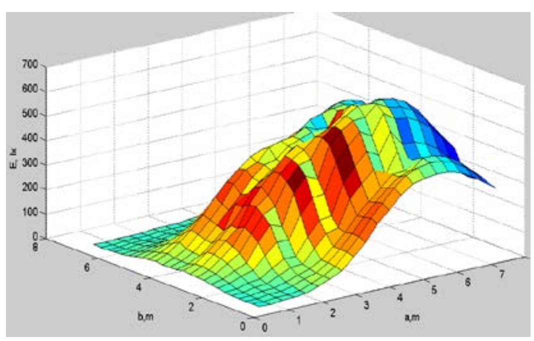


Fig.6 Illuminance distribution (on/off control) for period of time from 18:30 to 19:00h on a sunny spring day for a room with windows facing west

Dimming lighting control strategy

In the case of lighting control strategy with dimming of the light sources the results, obtained for the work schedule of the fixtures is shown in tables 3, 4. Tables 3 and 4 are for sunny spring day, west and east geographical exposure respectively.

Table 3. Work schedule of the lighting fixtures for typical sunny day in spring – control strategy dimming, orientation of the windows – west.

	Luminaire Number											
Time	1	2	3	4	5	6	7	8	9	10	11	12
7:00-7:30	0.00	0.00	0.00	0.00	0.00	0.00	0.23	0.29	0.04	1.00	1.00	0.87
7:30-8:00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.70	0.96	0.26
18:00-18:30	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.07	0.00	0.86	0.91	0.60
18:30-19:00	0.00	0.00	0.00	0.27	0.25	0.25	0.71	0.88	0.20	0.54	0.13	1.00

Table 4. Work schedule of the lighting fixtures for typical sunny day in spring – control strategy dimming, orientation of the windows – east.

	Luminaire Number											
Time	1	2	3	4	5	6	7	8	9	10	11	12
7:00-7:30	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.38	0.55	0.12
17:30-18:00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.71	0.84	0.39
18:00-18:30	0.00	0.00	0.00	0.00	0.00	0.05	0.66	0.76	0.23	0.22	0.00	0.65
18:30-19:00	0.25	0.19	0.32	0.60	0.64	0.34	0.53	0.64	0.24	1.00	0.78	1.00

The lighting situation and illuminance distribution from the artificial lighting for the test laboratory with west geographical orientation on a sunny spring day, for period of time from 18:30 to 19:00h, are shown on figures 5 and 6. These results correspond to the results, shown on figures 5 and 6, but the lighting control strategy in this case is dimming.

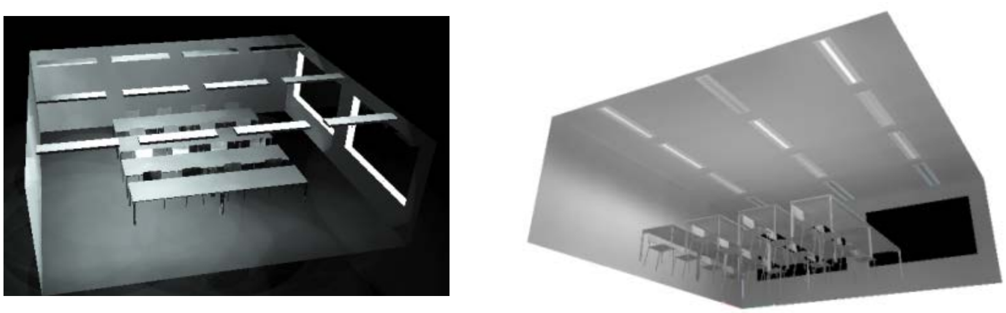


Fig.7 Lighting scene (dimming control) for period of time from 18:30 to 19:00h on a sunny spring day for a room with windows facing west

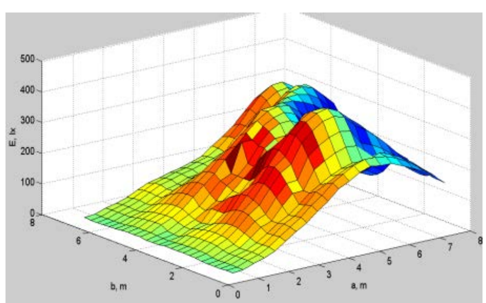


Fig.8 Illuminance distribution (dimming control) for period of time from 18:30 to 19:00h in the morning on a sunny spring day for a room with windows facing west

Table 5 shows the potential lighting energy savings, that can result from using the two considered lighting control strategies based on GA optimization, compared to the case of lighting installation using manual switching.

Table 5. Potential lighting energy savings using on/off switching or dimming strategy according to the available daylight levels, compared to manual switching of the lighting system.

Geographical Exposure	Type Day, Season	Energy Savings, On/Off, kWh/day	Energy Savings, Dimming, kWh/day
West	Sunny, Spring	0.61	0.66
East	Sunny, Spring	0.61	0.66
West	Gloomy, Spring	2.10	2.31
East	Gloomy, Spring	2.37	2.66
West	Sunny, Summer	0.35	0.36
East	Sunny, Summer	0.2	0.21
West	Gloomy, Summer	2,02	2,3
East	Gloomy, Summer	1,47	1,8
West	Sunny, Autumn	0,79	0,91
East	Sunny, Autumn	0,57	0,83
West	Gloomy, Autumn	1,91	2,26
East	Gloomy, Autumn	1,88	2,23
West	Sunny, Winter	1,03	1,27
East	Sunny, Winter	0,84	1,00
West	Gloomy, Winter	1,47	2,08
East	Gloomy, Winter	1,23	1,59

Having statistical data about the number of sunny and gloomy day in every season for the climate of Bulgaria, the early energy savings can be calculated and the saved energy in terms of money can be obtained [12]. The value of the energy, saved by employing the two different lighting control strategies can be used for economical appraisal of which system is worth to invest in.

5. Economical Appraisal

The net present value method of economical appraisal is usually used when evaluating the undertaking of a project. Usually, that requires a large outlay of capital in the present moment in exchange of series of positive cash flows in the future [13]. The series of cash flows have to be figured out precisely in order to obtain right appraisal. In the current research, the net present value of the two considered lighting control systems is found through formula (5) in order to analyze which of them is more appropriate for installation in public buildings for the climate and geographical exposure of Bulgaria.

$$NPV = \sum_{t=1}^{T} \frac{C_t}{(1+r)^t} - C_0 \qquad (5)$$

Where: C_0 is the investment value for the lighting system; C_t is the positive cash flow for the year t; r is the discount rate, taken in consideration.

The price of a lighting system including dimmable high frequency ballasts is about 250 Euro, while the price of a system with high frequency ballasts, that do not allow dimming of the light sources is approximately 100 Euro. The current price of the electrical energy in Bulgaria is 0.10 Euro per kWh and the period chosen for return of the investments is 5 years. The positive cash flows are the values of the energy saved through different lighting control. If the discount rate is considered 15% per year and the energy savings obtained in the current research are used, the NPV value of the lighting system using dimming control and the NPV of the on/off switching control system are as follows:

- NPV = -231.7 for the dimming lighting system applied in the room with west geographical exposure;
- NPV= 22 for the on/off control system applied in the room with west geographical exposure;
- NPV = -255.2 for the dimming lighting system applied in the room with east geographical exposure;
- NPV = 4.6 for the on/off control system applied in the room with east geographical exposure.

Positive value of the NPV means that the project can be undertaken, while negative value of NPV means, that the investment should not be made, because the return of the capital cannot be ensured.

6. Conclusions

There is no considerable difference in lighting energy savings obtained by the two control strategies taken in consideration, because the transition between day and night for the climate of Bulgaria is short in terms of time and the norm levels of the illuminance on the work plane are reached fast, especially on sunny days. The results from the economical appraisal conducted confirm that the dimming lighting control systems are still economically unfavorable, which makes the on/off lighting control strategy a preferable choice for public buildings with limited budget.

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