

Application of multi-objective genetic algorithms to interior lighting optimization



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ABSTRACT

The energy consumed by artificial lighting represents a vast amount of total energy consumption of a building. LED luminaires combine many advantages and they are considered a prominent lighting technology. The utilization of miscellaneous optimization methods in lighting control has achieved a variety of benefits, such as energy savings while sustaining illuminance at the required levels. However, there is a lack of methods, which take into account the uniformity of lighting which is a significant factor that should be considered according to the EN 12464. This paper proposes a multi-objective optimization model for artificial lighting control so as to minimize energy consumption and the same time maximize uniformity of lighting while maintaining the illuminance at an appropriate level. Two objective functions have been used, the first is the summation of the dimming levels of the luminaires of an interior space and the second is the coefficient of variation of root mean square error of illuminance which is metric of the uniformity of artificial lighting. Both functions have been formulated as mathematical functions of the dimming levels of the luminaires. Constraints include the required level of illuminance and the luminaires' dimming capabilities. The Non-Dominated Sorting Genetic Algorithm II is used to carry out the optimization. The proposed model has been implemented in an office room and the results demonstrated significant energy savings up to 22%. The proposed approach is flexible and can be applied to all types of interior spaces and is independent of the geometry and configuration of the room.

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1. Introduction

The decrease of energy consumption has been imperative in order to create sustainable buildings for the future. Lighting is energy intensive since the energy consumed for lighting represents a percentage of 25–35% of the total energy consumption of a building [1]. In the European Union the electricity consumed for lighting corresponds to the largest energy consumption percentage in the tertiary sector with 21.57%, namely 164 TWh in 2007 [2].

Several research papers have emphasized the advantages of solid state lighting. A life cycle assessment of two lighting technologies based on compact fluorescent and LED luminaires used for general office lighting has concluded that the LED luminaire has a lower environmental impact mainly due to high energy efficiency in its use [3]. Furthermore, the lifetime of LED luminaires has been highlighted as an indisputable advantage compared to tradi-

tional light sources [4,5]. In particular, LED luminaires have 9–10 times longer lives than fluorescent luminaires [6]. Moreover, LED luminaires provide more flexibility and versatility, regarding the control of their light output than other types of luminaires [7,8]. Thus, it is efficient to combine lighting controls with LED lighting. Conclusively, LED luminaires are considered as a prominent lighting technology for the future [6,9].

Several optimization techniques have been exploited in order to reduce the energy consumption of artificial lighting. Lighting control has been modelled as a linear programming problem so as to accomplish energy efficiency and satisfy occupants' lighting preferences [10]. The same authors used this formulation to integrate daylight exploitation, occupancy control and light level tuning strategies so as to achieve energy savings up to 60% [11]. Linear optimization has been utilized at another research so as to define the appropriate dimming levels of the luminaires and provide uniform lighting in occupied areas [12].

Multi-objective optimization methods have been widely used in lighting control. A multi-objective evolutionary algorithm was developed to design an exterior lighting system which reacts to dif-

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ferent user defined inputs, lighting pole positioning constraints and achieves low energy consumption as well optimum illuminance and uniformity according to standards [13]. A study has combined multi-objective optimization and subjective data obtained from psycho-visual tests to optimize lighting by considering not only energy saving but also visual preferences of the occupants of the room [14]. Some researchers used multi-objective optimization to maximize the accuracy of the illuminance on the work plane and at the same time minimize the power required by the luminaires with the aid of a generalized extremal optimization algorithm [15].

Genetic algorithms have been proven useful in lighting. A genetic algorithm has been employed in order to predict real-time daylight levels in an office, by using external measurements of illuminance [16]. A fitness function that considered light intensity, uniformity, shading effects and costs has been used as input for a genetic algorithm in order to optimize the design of lighting systems for greenhouse facilities [17]. The lighting system of a sports field, was designed through a genetic algorithm by maximizing the product of an illuminance and a uniformity function [18].

Plenty of other optimization methods have been applied in lighting control. Some researchers have utilized a neural network to describe the complex relationship between dimming level and measured illuminance on the task area and proposed an appropriate optimization algorithm for energy efficiency [19]. Moreover, an iterative optimization algorithm, which did not depend on the accurate knowledge of daylight distribution, was used to maximize spatial uniformity and minimize energy consumption in a lighting system that consisted of multiple luminaires, with integrated light and occupancy sensors and a central controller [20]. Another optimization algorithm, which took into account the relationship between the position of luminaires and the light sensors, was used for the design and implementation of an intelligent lighting system and achieved energy savings that ranged from 60 to 80% in an office room [8]. Particle Swarm Optimization has been also employed for energy saving control of luminaires in office lighting [21,22].

Reviewing the current literature it is noticeable that a lot of different methods exist to optimize lighting systems. However, there exist very few methods which take into account not only the level of illuminance but the uniformity of lighting as well. The uniformity of lighting is a significant factor which should be considered in the design of an indoor lighting system. Thus, EN 12464 establish particular standards not only for the levels of illuminance but for uniformity as well [23]. Furthermore, there exist no concrete methods to associate spatial uniformity with the dimming levels of the luminaires. Aim of this paper is to overcome the above mentioned obstacles and present a multi-objective optimization model for interior lighting that fully complies with the EN 12464. Special attention is being paid not only to the illuminance but to the uniformity of lighting as well. Both the illuminance as well as the uniformity have been formulated as mathematical functions of the dimming levels of the luminaires. A multi-objective genetic algorithm is used to calculate the optimum dimming level for each luminaire so as to fulfill the goals of the optimization, namely energy efficiency and at the same time sufficient illuminance and maximum uniformity. The rest of the paper is organized as described below. In Section 2 the formulation of the model is presented, which consists of the documentation of the theoretical background of multi-objective optimization and the mathematical representation of the proposed model. The operation of a multi-objective optimization genetic algorithm, namely the Non Dominated Sorting Genetic Algorithm, is explained in Section 3. In Section 4, a case study is shown, which concerns the application of the proposed optimization approach in an office lighting system. Finally, in Section 5 the results of the case study are documented and in Section 6 the conclusions of this research are presented.

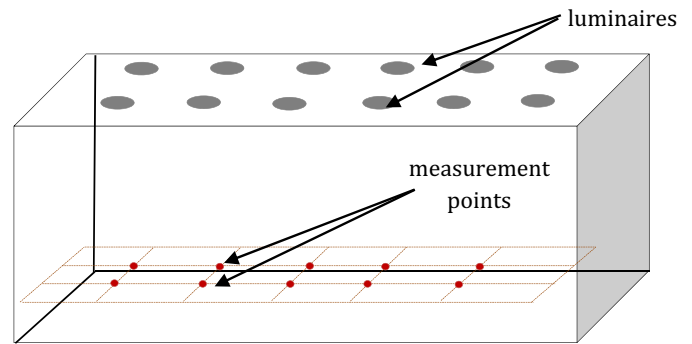


Fig. 1. Visual representation of the proposed approach.

2. Model formulation

2.1. Theoretical background

In real world applications, there exist a lot of problems where the decision maker must take a decision based on multiple and often conflicting criteria or objectives. In contrast to a single optimization problem, where the optimal solution is usually just one, a multi-objective optimization provides the decision maker with a set of solutions that fulfill all conflicting criteria. There exists rarely a single solution that satisfies all criteria or objectives concurrently [24].

The general form of a multi-objective minimization problem is the following one:

$$\begin{aligned} \text{Minf}(\mathbf{x}) &= \min \{f_1(\mathbf{x}), f_2(\mathbf{x}), \dots, f_k(\mathbf{x})\} \\ \mathbf{x} &= \{x_1, x_2, \dots, x_z\} \end{aligned} \quad (1)$$

Subject to: $\mathbf{g}(\mathbf{x}) \geq 0$

$\mathbf{h}(\mathbf{x}) = 0$

$\mathbf{x}^l \leq \mathbf{x} \leq \mathbf{x}^u$ where $\mathbf{f}$ is a vector comprising of k objective functions, $\mathbf{x}$ is a vector comprising of z solutions, $\mathbf{g}$ and $\mathbf{h}$ are vectors corresponding to inequality and equality constraints respectively. Apart from the constraints, lower bounds ($\mathbf{x}^l$) and upper bounds ($\mathbf{x}^u$) can be applied to the solutions of the problem. The solutions of a multi-objective optimization problem are known as the Pareto optimal solutions [24,25].

2.2. Mathematical formulation of multi-objective optimization in interior lighting

The goal of the proposed model is to find the minimum dimming level of the luminaires so as to achieve energy saving as well as to comply with the specifications of EN 12464 regarding illuminance and uniformity in interior lighting. The model exploits the linear relationship which exists between the contribution of each luminaire and the illuminance on the task area. Particularly, an interior space area, which is illuminated by m luminaires, can be discretized into a grid of n measurement points, as shown in Fig. 1. The illuminance at a specific point of the workplane level (E_i), can then be represented as a linear combination of the contribution of each luminaire on that measurement point (c_{ij}) and the corresponding dimming level of that luminaire (d_j) [10,11,22,26]. This model is based on the superposition theory, known from Physics. Representing the illuminance variable as a vector ($\mathbf{E}$) comprising of the values of illuminance on each measurement point, the dimming of the luminaires also as a vector ($\mathbf{d}$) and the contribution of each

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