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Energy and reliability optimization of a system that combines daylighting and artificial sources. A case study carried out in academic buildings

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HIGHLIGHTS

- Integration of natural and artificial lighting is examined in a classroom.
- Simulation of a LED lighting plant characterized by a control logic system.
- Visual comfort is guaranteed while meeting the regulations EN 12464-1.
- The aim is the energy efficiency and economic advantage with respect to the reliability.
- A significant increase of energy efficiency and MTBF (Mean Time Between Failure) is reported.

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ABSTRACT

The necessity to reduce energy requirements of lighting systems should bring among engineers a more mature and conscious vision while planning and this means that their main goals should be the visual comfort and a decrease in energy and maintenance costs. Therefore this paper examines the case study of a classroom located in the Faculty of Engineering of Sapienza University in Rome and, to evaluate the possibility to combine natural and artificial light, it focuses on the realization of a new lighting system. This new solution is formed by LED sources and control systems able to modulate the power absorbed by every single lamp (to adapt, according to the hour and day, to the conditions of the natural light). In order to meet the EN 12464-1, the process of incorporating natural and artificial light must occur while guaranteeing both the minimum levels expected for the average illuminance E_m [lx] and the uniformity coefficient (E_{min}/E_m) and this is the reason why a simultaneous exertion of artificial lights and a variable shielding system of glass surfaces activated through a motorized electronic control unit is required. Thanks to the software DIALux Evo 5.1 a 3D model of the classroom was reproduced and validated in order to simulate the combination of natural and artificial lighting and to verify if the results complied with the regulations. This was followed by an analysis concerning: the reliability of the system (through the examination of the MTBF – Mean Time Between Failure) and energetic and economic aspects (through the software ecoCALC 4.5.4). The novelty of this study is represented by the fact that in order to obtain the highest results in each of the three fields examined, it is possible to avoid the exertion of those negative feedback control-type systems (requiring high installation and maintenance costs due to sensor devices), thanks to pre-programmed logic control systems based on the data obtained with the simulations by prediction softwares. In this case study the solution suggested, while using a pre-programmed control logic, presents a MTBF of 1205 h (about twice of a negative feedback system solution) with payback periods that justify the higher costs presented by the electronic characterizing the control logic system with respect to traditional plant solutions.

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1. Introduction

The optimization of the energy consumptions produced by lighting systems in indoor environments is a very important issue for those engineers working in this field and it is a matter which interests the entire scientific community. Many studies concerning this problem have been published [1–3]. Nowadays indoor environments represent the core of everyday life activities and in order to have comforting environments high amounts of energy are necessary [4]. Without considering the residential sector, global consumption of non-domestic buildings in Europe is of 11% and this percentage increases in USA up to 18%.

Other studies [5,6] show that the lighting system only affects 50% of the general energy requirements in buildings used as offices, 20–30% in hospitals, 15% in factories, and 10–15% in schools. Such percentages provide important information concerning the weight of lighting systems on the energy expense in places where people usually spend their time [7]. The United States report that about 31% of the overall academic electrical consumptions is provoked by lighting systems [8,9]. In Europe about half of the electrical consumptions in academic buildings (that is 17% of all non-residential buildings) is due to the illumination [10–12].

Therefore energy managers are asked to give precise answers concerning both the reduction of energy consumptions and the effective economic advantage of choices concerning the planning and management aspects [13]. At the same time it is important to meet the energy saving (EN 15193 [14] for its assessment) parameter and the current technical regulation in the lighting field (EN 12464-1 [15] in particular) which gives precise standards to the lighting systems according to how the environments that must be lit will be used, hence their visual task.

This article examines the problem of a proper lighting in academic environments through a multi-objective optimization that wants to take into consideration the regulations concerning the visual comfort and at the same time meet the need to reduce the energy requirements and the necessity to have a building which is economically sustainable thanks to a minimum, though proper, maintenance.

1.1. Classrooms

To be more specific, academic buildings, in the public sector, are an example of environment where high lighting levels must be guaranteed for many hours during the day in accordance with the parameters set by the current regulation, without forgetting the optimization of the energy management, an important issue for the community [16,17]. The proper exertion of natural light can integrate, energetically speaking, the lighting demand in academic buildings where people tend to stay mostly during the daytime. Moreover the exertion of natural light is also vital for a proper perception of colors [18] and therefore it is an important aspect for the visual comfort.

Unfortunately the geometry and the orientation of the spaces used as classrooms or libraries and glass surfaces are not organized to facilitate a proper exertion of sunlight during school schedule [19]. Natural light varies deeply during the day and according to the season with respect to the apparent position of the sun in the sky vault. Most of the time the architecture of academic buildings focuses more on other factors rather than the optimization of the space for a visual comfort. Such issue has only been studied during the last decade and not every academic building has been constructed recently [16].

Planning hybrid lighting systems which exploit properly the benefits of natural light (for what concerns visual comfort [20], human wellbeing [21,22] and energy saving) and combining them with artificial lighting systems is more complicated than planning systems formed by artificial sources only. The main problems are caused by the high variability over time of the natural radiation [23,24] (which in some intervals during the day and year is too high, thus it must be shielded through systems able to mutate their geometrical configuration) and by the combination, thanks to the superposition effects principle, of natural light with artificial light in order to have a proper illuminance uniformity in indoor environments [25–27].

1.2. Integration and optimization methods concerning natural and artificial light

The advancement in technologies that rationalize the exertion of electrical energy for the illuminance has the goal to reduce energy costs [28,29]. Hence according to the changes made to the European regulation 2010/31/UE about energy savings in buildings, which determined the recast of the regulations package EPBD (Energy Performance of Buildings Directive) [30], it must be examined accurately which of these techniques can actually be considered the best strategy to adopt.

The best results can be achieved through an accurate planning of the architectural characteristics of the buildings in order to optimize the exertion of natural light as a primary source of daylighting, but this is possible when the planning of academic buildings is from scratch [31,32]. An accurate analysis of the methods for the integration of natural light/artificial light can also concern existing buildings, where the system optimization [33] may be a benefit for a proper energy management of the problem [34,35], observing the lighting standards set by the current regulations [15,36].

If the choice is a plant solutions able to observe the current regulations with respect to certain lighting performances in classrooms (with areas subject to a comforting visual task for the readers characterized by a good uniformity of the illuminance to prevent fatigue), without exceeding the energy consumptions of artificial lighting systems (that in order to have uniform areas subject to natural light, coming from glass surfaces, which usually exceed the minimum level required, must provide high lighting levels in some spaces thus achieving an uniform illuminance), the only solution is represented by systems with a variable control logic based on the hour of the day and the season of the year [37,38].

However, these systems must be able to modify the flux of artificial light sources, and control the shade projected by the shielding systems with a variable geometry to mitigate the excessive natural light, right in the middle of the day, coming from glass surfaces [39,40]. As a matter of fact the literature reports previous scientific studies describing lighting systems which aspire to have energy savings [41] by both performing a luminous modulation with new generation lamps or fluorescent lamps equipped with dimmable electronic ballast [42–45] and providing automatized systems with control variable shielding systems [46–51,31]. These systems require electric systems equipped with a set of sensitive photometric sensors in the range of the visible spectrum; for what concerns the control optimization, some distributed control systems were suggested [52,53].

2. Systems and control logic

To combine natural and artificial light, the system requires shields with variable geometry which are programmed to respond properly to outdoor conditions [54–56] and lighting systems which, beside presenting highly energy efficient light sources [57], can guarantee a proper and uniform light. As a matter of fact the level of light near the windows is usually higher than in the rest of the environment (especially if the dimensions of the space