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Integrative algorithm to optimize skylights considering fully impacts of daylight on energy

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ABSTRACT

In this paper we propose an algorithm to find optimal design of skylight for a one-storey office building while saving source energy consumption. The algorithm simultaneously couples daylighting with energy performance and compares different ratios of skylight to floor area based on both lighting and HVAC loads. Our method integrates different simulation tools with numeric optimization and exhaustive search to find the optimal ratio. More specifically we implemented EnergyPlus as a thermal engine and Radiance as a daylight engine, both of which are embedded in Ladybug and Honeybee. As Ladybug and Honeybee is a plugin for Grasshopper, we developed the algorithm in Grasshopper environment. We used Python and Grasshopper to integrate different simulation tools and implemented two methods of numeric optimization (gradient descent) and exhaustive search (parametric analysis) in order to validate the final result. After applying the proposed algorithm for a small office building in San Francisco, both methods coincide that the optimal skylight to floor ratio is 5.5–6% while decreasing the energy demand by 19%. The experiments show that the energy efficiency only occurs for skylight ratios of 3–14%. In addition, we used sDA and UDI metrics to analyze daylighting performance of each parametric scenario. We infer that only a specific range of skylight ratios that are energy efficient (5–10%) provide adequate daylight and avoid glare. The integrative process and optimization method proposed in this paper enable designers to find a robust energy efficient skylight design.

1. Introduction

Nowadays building industry has entered an era with a view toward minimizing an environmental footprint; however, toplights as energy efficient alternatives are often ignored in this industry. Statistics show that despite the potential of daylighting only approximately 2–5% of commercial building floor space currently has sufficient skylight area [1]. Lawrence and Roth discussed that there have been some unavoidable cautions such as roof leakage, direct solar radiation, heat gain and heat lost that make designers reluctant to apply toplights [1]. While today's technological advancement can mitigate the risk of the roof leakage, it is necessary to train practitioners how to install toplights and educate them how toplights as daylighting strategies impact electrical lighting loads and overall energy consumption of a building. To assess the overall energy consumption including heating, cooling and lighting, an integrative approach is needed. There has been an increasing effort to improve tools' capabilities by coupling them to examine the impact of daylight on electrical lighting loads as well as heating and cooling loads [2–4]. In addition to the necessity of integration between different tools, the exhaustive process of parametric analysis makes it challenging to find robust design solutions. To boost the application of toplights, we facilitate the process of integration and parametric analysis by developing an algorithm to optimize Skylight Floor area Ratio (SFR) for a one-storey office building while enhancing total energy performance.

Despite the stagnant practice, implementation of toplights improves the quality of life and the environment. A body of literature has been dedicated to show daylighting boosts quality of life via positive impacts on health, well-being and moods, as well as reduction of fatigue [1,5,6]. A separate area of knowledge investigates the quantitative side of toplighting that includes its ability to replace electrical lighting and decrease energy consumption as well as CO_2 emissions. These findings are significant because electrical lighting loads account for 20.5% of source energy for commercial buildings while the commercial building sector contributes to 19% of total energy consumption in the U.S. [7]. Preliminary studies show that electrical lighting loads can be reduced by 20–77% if good daylighting practices are implemented [8–16]. As a result, any question addressing the dilemma of daylighting

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design in the building sector plays a crucial role in saving energy in the U.S.

Toplights as energy efficient strategies can be used in both renovations and new designs because a one-storey building is a common practice in the U.S. Although toplights can be installed on the top floor of multi-storey buildings, they are an essential daylighting strategy for one-storey buildings. According to the Environmental Information Administration (EIA) in 2003, one-storey buildings make up 67% of commercial buildings (non-mall) in the U.S. [7]. In addition, six percent of all commercial buildings in the U.S. are vacant of which 67% are one-storey [7]. This giant sector of buildings presents a significant market that can take advantage of toplighting strategies, which eventually bring quality of life and save energy. Hence, toplights have the potential to save energy consumption in the American commercial building sector.

Considering the potential role of toplights in saving energy, the objective of this paper is to propose an algorithm that is able to optimize Skylight Floor area Ratio with regard to energy performance. In this paper the proposed algorithm uses different simulation tools and optimizes results of those simulations. Here, we used Python language within Grasshopper for writing scripts to attain daylighting results from Ladybug and Honeybee and deliver them to EnergyPlus software for energy simulations. To assess daylighting performance, we applied horizontal illuminance [lux] as a daylighting metric. Apart from integrating daylighting and energy tools, we implemented Python to script an optimization method of gradient descent to find an optimal SFR. Then, by a parametric analysis we simulated all possible SFRs and compared them with regard to total source energy consumption. The parametric analysis was used in order to verify the result of optimization method. We examined both methods on a case study which is a small office building in San Francisco. Then, we evaluated the optimal SFR against other SFRs in regard to its energy and daylighting performances.

The paper is organized as following: a review of relevant literature is presented in the next section. Section 3 demonstrates the applied simulation tools and an algorithm to integrate those tools with the purpose to reflect impacts of daylighting on total energy performance. Furthermore, in this section we introduce the optimization method in order to discover the most energy efficient SFR. In Section 4, we present a prototype office model to examine the integration algorithm and the proposed optimization method. We apply exhaustive search, parametric analysis, on the case study to verify the proposed SFR by the optimization method. Section 5 compares energy performance of different SFR scenarios by breaking down total energy consumption into electrical lighting, fan, heating and cooling loads. Moreover, those scenarios are compared based on their daylighting performance. Finally, Section 6 summarizes the results of the paper and highlights the outcome that plays a crucial role in optimizing fenestration.

2. Literature review

The importance of toplights mentioned in the previous section has motivated researchers to conduct studies which we subdivide into three major categories: studies of sidelights, individual case studies of toplights as well as initial attempts for optimization of fenestration. While the first category summarizes the studies of sidelights including windows and their impacts on lighting and HVAC loads, the second category reviews toplights and their energy performance. Both of the first and second categories have included integration between daylighting and energy simulation tools for a specific case with a pre-defined location, function and form. The last category has offered methods to optimize fenestration based on energy and daylighting performances. Energy optimization calibrates configurations of fenestration in order to minimize thermal and electrical loads. What follows describes these subdivisions in more detail.

The development of new integrative simulation tools entails studies of sidelights and their impacts on electrical lighting and HVAC loads [17–22,2]. These studies estimated lighting savings in a range of 20–70% [17–19]. Li and Wong used EnergyPlus and its embedded Radiosity lighting tool to evaluate energy performance of the existing building in Hong Kong [20]. If a lighting control system is applied, 25% of electrical lighting consumption can be saved, which is 8.6% of total building energy consumption [20]. This saving is lower if the nearby buildings and their shading were considered [20]. In another study, Li et al. used the same tool to build a regression model and estimate the annual lighting energy for the following variables: Window to Wall Ratio (WWR), light transmittance of the window, the width of overhangs and fines [22]. In addition, Yangi and Nam used a combination of 3D Max 8.0 Radiosity and DOE-2.1 E to predict daylight performance and study an application of on/off lighting control system in energy consumption for an existing office building in Seoul [21]. The result shows that electrical lighting loads can be saved by 32.9%, 31% and 27.5% for WWRs of 100%, 80% and 60% [21]. In a very comprehensive analysis Reinhart and Wienold developed a daylighting dashboard that integrated Ecotect and DesignBuilder simulation tools and analyzed the impact of south facing windows in a Boston climate for an office room [2]. The energy and glare performance were studied in addition to the occupants' behavior. The results of energy performances show that external blinds lower the electric lighting and cooling loads while significantly increasing the heating load [2].

The second category of literature focuses on toplights while they chose different methods, tools, functions and climates for their research. In 2008 the U.S. Department of Energy conducted a report about the energy efficiency of different toplighting configurations in different climates [23]. This report coupled a lighting rendering software tool (Radiance) with building energy simulation software DOE 2.1 E [23]. However, the research had a problematic assumption: they sized the glazing area to meet 2% Daylight Factor (DF), the requirement of LEED [1] at that time (version 2) [23]. DF is an incorrect metric for an annual daylight analysis because it does not take into account different climates, sky conditions, complex geometries of interiors, surrounding objects and orientation of windows [24].

Instead of using DF, other toplight studies have considered horizontal illuminance [lux] as a daylighting metric. In 2012 Motamedi analyzed the energy efficiency of different toplights (sawtooth, skylight and monitor roofs) via IES-VE PRO – an integrative tool of Radiance and Apache – for offices in Austin [8]. She concluded that regarding the site energy a proper toplighting strategy can save electrical lighting up to 70% over the course of a year with smaller impact on heating and cooling loads. This study did not calibrate the shapes of toplights in order to optimize energy efficiency nor did it consider different climates [8]. In 2013 through several publications Ghobad et al. studied monitor-roofs and skylights for offices in climates of Boston, Miami and Charlotte [9,25]. They applied Diva software – an integrative tool of Radiance and EnergyPlus - and defined the illuminance target of 300 lux. Compared to other studies, Ghobad et al. simulated more but still limited cases of toplighting configurations in few climates. In addition, Chen et al. used EnergyPlus and its embedded Radiosity tool to consider the impact of skylights. They also studied different lighting control systems including on/off and dimming systems on energy consumption for an industrial building in Tianjin, China [26]. The result shows that the skylights can decrease the total energy consumption up to 36%

[1] Leadership in Energy and Environmental Design.