Designing an integrated daylighting system for deep-plan spaces in Malaysian low-rise buildings

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Abstract
Daylighting technologies have been developed recently to harness solar energy, and eventually, meet the goals of sustainable development. However, the use of natural light in the tropics is challenging. Many factors limit the efficiency of solar energy because of the intensity of solar irradiance and the inconstancy of sky conditions in this region. This research aims to design and evaluate an integrated daylighting system for enclosed spaces without access to daylight from side openings. The proposed system eliminates the requirements for electrical lighting during daytime. The new design combines three components, namely, roof light, dynamic shading, and fiber optic daylighting system, in one integrated platform. The methodology was based on a quantitative approach that used empirical experiments in an actual-sized room. Two stations were set up outside and inside the test cell for data collection. The study used a data acquisition system with nine calibrated sensors to record the performance of the integrated daylighting system. The readings indicated the capability of the system to control natural light from 8:00 to 18:00, even during peak hours. Results showed that the proposed system utilized and boosted the efficiency of the individual components, and the fiber optic daylighting system delivered sufficient level of natural light within the range of 300–680 lx, at an average of 492 lx, with functionality ranging from 44% to 54%. In addition, the skylights were controlled with a dynamic shading system and delivered a maximum reading below 2000 lx during peak times, at an average of 350 lx, with functionality between 46% and 56% under the intermediate sky condition. The integrated daylighting system delivered uniform illuminance when solar irradiance was above 500 W/m².

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1. Introduction
Malaysia is a tropical country located in Southeast Asia with a population of 30.7 million, a gross domestic product growth rate of 4.70%/year, an energy independence of 100%, and total carbon dioxide emissions of 7.30 tCO2/capita (Department of Statistics Malaysia, 2015; Enerdata, 2015). The demand for energy of consumers in Malaysia is increasing steadily. In the residential sector, the number of consumers reached 6,128,224 in 2009 and 6,710,032 in 2014. In the commercial sector, the number of consumers reached 1,224,414 in 2009 and 1,404,501 in 2014. In general, the building sector is one of the highest energy consumers in the world, accounting for 40% of the total energy consumption globally (Lam et al., 2008; Hassan et al., 2014); this percentage comprises nearly 48% of the electricity consumption in Malaysia (Chua and Oh, 2011). These situations directly challenge the plan of Malaysia to become a developed country by 2020 and to fulfill the requirements of the 2015 United Nations Climate Change Conference held in Paris (COP21) by limiting global warming to below 2 °C.

To achieve sustainable development, electricity consumption should be reduced; hence, the 11th Malaysia Plan for 2016–2020 aims to promote the use of green technology in providing electricity products and services (Kolony, 2011). However, statistics have indicated that the cooling and lighting loads in Malaysian buildings will pose the main challenges. Saidur (2005) reported that lighting
in Malaysian office buildings represented approximately 19% of their total energy consumption. Lighting consumption depends on the purpose of the building and the use of daylight (Roshan and Barau, 2016). The energy consumption level depends on the power consumption of lighting systems and the operating periods. The US Department of Energy (2012) indicated that 62% of the residential sector worldwide still uses energy-inefficient lighting systems. Khorsanizadeh et al. (2015) suggested that replacing conventional lighting units with efficient lighting systems in Malaysian buildings could significantly reduce energy use. In addition, they asserted that using lighting technology in certain cases could save energy for up to 50% with minimal or no efficiency loss. The Chartered Institution of Building Services Engineers (CIBSE, 2012) asserted that applying lighting technology could decrease lighting costs by 30–60% and reduce environmental impact. Li et al. (2009) and Hee et al. (2015) indicated that energy consumption level would depend mostly on the building envelope, and particularly, on fenestration. Bellow-Hübe (2001) attributed 20–40% of wasted energy in a building to openings, with the percentage increasing further in tropical countries. Thus, fenestration requires an appropriate design to satisfy the required level and balance of user comfort and energy gain/loss in a building (Li and Lam, 2001; Hee et al., 2015). By 2035, the largest source of carbon dioxide emissions is predicted to be the electricity generation sector (33%), followed by the domestic transport sector (24%), and then the industry sector (21%) (APEC, 2013). Lancashire and Fox (1996) specified that each kW h of energy saved would stop the emission of 680.39 g carbon dioxide, 5.67 g sulfur dioxide, and 2.27 g nitrogen oxide. Annual savings in carbon dioxide emissions through the daylighting approach in buildings were estimated to reach 192 million t in 2000 and 223 million t in 2010 (Burton and Doggart, 2012). McHugh et al. (2004) asserted that the use of daylighting could result in annual savings of 0.015 USD/kWh throughout the lifetime of a building. Therefore, understanding daylighting can save energy, decrease electric lighting costs, and reduce electricity demand during peak seasons.

2. Literature review

Malaysia is a hot and humid country with a constant climate condition throughout the year. This characteristic creates nearly similar environments for buildings during their life cycle. Studies show that Malaysian buildings are exposed to high levels of solar insolation, which limits and restricts the adoption of passive strategies, particularly daylighting, in low-rise buildings (Al-Obaidi et al., 2014a, 2016a). The highest level of solar intensity ranges from 1750 kW h/m³/year to 1850 kW h/m³/year (Haris, 2010). The majority of sky conditions in Malaysia is intermediate, and cloud cover ranges from 6 oktas to 7 oktas (Shahriar and Mohit, 2006). Zain-Ahmed et al. (2002) divided sky conditions in Malaysia into intermediate (86% of the time) and overcast (14.0%). Lim and Heng (2016) indicated that daylighting studies in the tropics should consider inconsistent cloud formations of intermediate skies. Zain-Ahmed et al. (2002) specified that illuminance level would exceed 80 k lx at noontime in March but would achieve less intensity (60 k lx) in December. Lim et al. (2012) and Al-Obaidi et al. (2014b) exhibited that global illuminance could reach over 110 k lx with more than 1000 W/m² on clear days. Several studies have presented different types of approaches to deliver natural light into deep-plan spaces (Mayhoub, 2014). Nevertheless, the use of toplighting systems in tropical buildings remains challenging, particularly in low-rise buildings (Rahman et al., 2013). A survey conducted on different types of daylighting systems found that the SL system could be extremely useful. However, harnessing SL for low-rise building in this region is difficult and requires complex modification to control the effects of heat gain, light level, and solar intensity in indoor spaces, which can cause thermal and visual discomfort (Chel et al., 2010; Yunus et al., 2011; Al-Obaidi et al., 2014a, 2015a, 2015b). Werring (2009) suggested the fiber optic daylighting system (FODS) as a viable solution. However, the application of FODS was found to be limited in this region because of the inconstancy of sky conditions (Abdul-Rahman and Wang, 2010; Munaaim et al., 2014a, 2014b). Furthermore, studies have shown that shading devices remain under research in this region due to constraints in sunlight quantity, i.e., direct and diffused sunlight (Al-Tamimi and Fadzil, 2011; Lim et al., 2013; Lim and Heng, 2016). Therefore, this section reviews several strategies used in SL systems, FODSs, and daylight control systems (DCSs) to understand their potential for integration.

2.1. Skylight systems (SL)

Skylight is a special fenestration element that delivers a uniform level of illumination over an interior space. However, its performance varies under different sky conditions and solar intensities (McHugh et al., 2004; Al-Obaidi and Rahman, 2016). Al-Obaidi et al. (2014a) conducted a conceptual study to evaluate the behavior of solar radiation in the form of light and heat that fell upon, interacted with, and was emitted from an SL system in a single-storey building. Their study identified a process that classified independent and dependent variables with different natural loads. Several studies were also conducted to identify the optimum SL model. In the US, Lee et al. (1996) introduced a system with four elements: a daylight opening, a lightwell, a reflector array, and a lower diffusing panel. Their study found that the system enhanced light distribution by controlling and reflecting direct sunlight through a prismatic film. In Peru, Beltran (2005) studied different configurations of daylight parameters using various diffusing materials and reflectors in several types of SL systems. The results indicated that using reflectors enhanced the distribution and uniformity of light in spaces. In India, Chel et al. (2010) investigated different types of traditional SL systems in pointed roofs using mathematical models compared with the CIBSE prototype. The results identified different daylight factors and illuminance levels at various vertical levels. In South Korea, Kim and Chung (2011) conducted a study on different types of toplighting systems by implementing 20 scaled prototypes with a lightwell and different reflectance values in indoor elements against currently available SL systems. The study found that a monitor SL could provide effective performance in cutting direct sunlight, whereas a sawtooth SL could exhibit stable performance in light distribution. In Malaysia, Yunus et al. (2011) tested SL systems in different roof shapes, such as flat, structured pyramidal gridded, sawtooth, and pitched roofs. The results showed different findings, such as high angles, complicated roof profiles, east-facing and west-facing surfaces, and the decrease in daylight level to over 50%. In Turkey, Yıldırım et al. (2012) studied five SL systems for roofs, namely, a single-layer one-way roof SL system, a single-layer two-way roof SL system, a sunshade with double layers, a double-layer system without sunshade, and a moving sunshade with double layers. Their research showed that a moving sunshade with double-layer roof system distributed uniform and sustainable lighting under all conditions compared with the other four SL systems. Acosta et al. (2013) analyzed the performance of lightwell SLs under overcast sky conditions. They investigated different variables of SLs, including size, height/width ratio, reflection index,
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