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Design optimisation for window size, orientation, and wall reflectance with regard to various daylight metrics and lighting energy demand: A case study of buildings in the tropics

Rizki A. Mangkuto *, Mardliyahtur Rohmah, Anindya Dian Asri

Laboratory of Building Physics and Acoustics, Engineering Physics Research Group, Institut Teknologi Bandung, Jl. Ganesha 10, Labtek VI, Bandung 40132, Indonesia

HIGHLIGHTS

- Influence of WWR, wall reflectance, and window orientation on daylight metrics in the tropics.
- A simple multi-objective optimisation approach was proposed by pairing the results.
- Optimum solutions in all Pareto frontiers were filtered against the criteria and were ranked.
- Three optimum solutions were found, all with south window orientation.
- The approach enables to observe inter-relationship between the performance indicators.

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ABSTRACT

Design optimisation problems of window size and façade orientation in buildings have been investigated many times, with regard to energy and comfort criteria. To indicate daylight availability in indoor spaces, a number of daylight metrics have been proposed, but those metrics are not always fully accounted in the optimisation process. Also, most studies were conducted for locations with high latitude, where the sun is located most of the time either at the south or at the north part of the sky hemisphere, which is not the case in the tropics. Therefore, this article presents a simulation study to investigate the influence of window-to-wall ratio (WWR), wall reflectance, and window orientation on various daylight metrics and lighting energy demand in simple buildings located in the tropical climate. A simple approach for the multi-objective optimisation was proposed by classifying the results in six pairs of two different performance indicators. Solutions in all Pareto frontiers were filtered against the defined target criteria, and were accepted into the optimum solution space if they belong to at least 4 out of 6 Pareto frontiers, and were ranked either in the order of their mean distance to the utopia points, or in the order of number of times they belong to a Pareto frontier. Three optimum solutions are found, all of which belong to four Pareto frontiers. The most optimum solution with the least mean distance to the utopia points is the combination of WWR 30%, wall reflectance of 0.8, and south orientation. The proposed approach enables one to observe the inter-relationship between the involved performance indicators, while providing a possibility to visualise the boundaries of the solution space.

1. Introduction

Windows are regarded as one of the most important building components, and are acknowledged for their positive influence on the health and well-being of building occupants. Moreover, windows play an important role not only in providing daylight and view [1–4], but also in shaping the overall energy demand in buildings [5–10]. In the design phase, contradictions often occur when trying to maximise daylight penetration and view, which usually translates to applying large windows, while trying to minimise energy consumption, which usually translates to applying small windows.

The problems can be even more complex, knowing that perception of comfort is heavily dependent on numerous aspects and parameters, which can also have a conflicting nature among themselves. These conflicting objectives commonly require a multi-objective optimisation approach [11–14].

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* Corresponding author. Tel.: +62 22 2504424; fax: +62 22 2506281.
E-mail address: armanto@tf.itb.ac.id (R.A. Mangkuto).

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The investigation to find the optimum window configuration and its impact on the energy performance of the building has been conducted by many researchers since long time ago (e.g. [15–17]). An optimum window-to-wall ratio (WWR) is believed to be able in yielding significant energy savings for heating, cooling and lighting demand in buildings. Later on, the influence of the material of the fenestration [18–20] and the integration of active elements such as photovoltaic panels [21–27] has been investigated as well. Over the broad and extensive results, it is noticed that as more efficient technologies are employed in buildings, the influence of WWR on the building energy performance tends to become lower [28].

However, several issues in the topic of WWR study are yet to be addressed. Two of them are the use of appropriate metrics for indicating daylight performance in the interior spaces, and the specific application for buildings in tropical region. These two issues are discussed in this article.

1.1. Daylight metrics

In some of the aforementioned references, artificial lighting energy consumption was not evaluated. Meanwhile, it is realised that integration and better use of daylight is important in achieving energy savings [29], and the optimisation of window size should consider both energy consumption and visual acceptance criteria [30].

To indicate the availability of daylight in interior spaces, a number of metrics have been proposed, ranging from the established daylight factor (DF) [31,32], to the emerging climate-based daylight metrics such as the daylight autonomy (DA) [33] and useful daylight illuminance (UDI) [34,35]. The DF is now seen as a 'static' metric, since it is insensitive to climate variation. The DA and UDI are 'dynamic' in a sense that they take into account the variation of sky conditions over the year, which highly depends on the local climate type. Moreover, both DA and UDI respectively also require a defined minimum and a range of acceptable illuminance values.

Nevertheless, not all of those daylight metrics are accounted in the optimisation process, i.e. researchers normally choose a metric that is considered more suitable to indicate the daylighting performance, rather than evaluate all metrics and observe their inter-relationship. Some researchers prefer using DA (e.g. [30,36]) as daylighting performance indicator, since most national standards prescribe minimum (rather than a range of minimum and maximum) illuminance values for task-specific activities. Some prefer using UDI (e.g. [37,38]), considering the risk of visual discomfort, which is normally characterised with an upper threshold of illuminance or luminance values. There are also a few researchers who prefer using only daylight uniformity ratios (e.g. [39]).

While the choice of using UDI seems fair and efficient for the optimisation purpose, the investigation of Reinhart et al. [40,41], which links the perception of daylit areas according to building occupants and simulations of daylight metrics, has shown that the DA can better predict the perceived daylight condition in interior spaces, as compared to other daylight metrics. This suggests further investigation on the particular topic of choosing the most appropriate daylight metrics, which for now is still very much an open-ended question. Having known that, it is therefore necessary to include DA and UDI, as well as DF and uniformity ratios in the optimisation process, to observe their inter-relationship and how they are affected by the input variables.

1.2. Daylighting in tropics

Secondly, it is noticed that most studies on window optimisation were conducted for locations with high latitude (beyond 23.5°N and 23.5°S), particularly North America and Europe (e.g. [20,28,30,36–38]). In those regions, the sun's apparent position is mostly at the south part of the sky hemisphere, since the geographical locations are in the northern hemisphere, giving an intuitive knowledge on which façade orientation receiving the most sunlight.

In the tropical region, particularly in locations nearby the equator (approximately in latitudes 10°N–10°S), for a part of the year, the sun's apparent position is slightly at the north part of the sky hemisphere, while for the rest of the year it is at the south part of the sky. Sunshine duration is relatively longer than that in the non-tropical climates. Seasonal variation is low, but the presence of wet and dry seasons, referring to periods with high and low precipitation, is observed. The context is therefore somewhat unique and different, compared to cases in high latitude regions.

Review and analysis of daylighting systems for buildings in the tropics are available [42–46], so are information on solar radiation, sky luminance, and other related data for the tropics [47–51]. Few studies on the influence of building envelopes on ventilation and thermal comfort in Singapore and Indonesia [52,53] and on incident solar radiation in Malaysia [54] are also available. Lifetime performance of innovative technologies such like semi-transparent building integrated PV systems in Singapore has been discussed [55]. Nevertheless, in general, window optimisation studies dedicated for locations in the tropics are still relatively rare, and therefore can be further explored.

1.3. Aim and objectives

The aim of this study is to demonstrate the importance of daylight criteria consideration in optimising the design of window size, orientation, and wall reflectance. A large number of daylight metrics have been proposed by many researchers, but these metrics are not always fully accounted in the optimisation process. Meanwhile, these various metrics can also interact with each other, in a sense that the inter-relationship between them should be also observed and understood.

The objectives are to obtain the most influential design parameters, for which sensitivity analysis was performed; and to find the most optimum solutions, for which a simple approach is proposed by ranking the solutions on the Pareto frontiers that satisfy the defined criteria. For the case study, a location in the tropical region is chosen, since most studies on window optimisation were conducted for locations with high latitude. The context of tropical regions is somewhat unique and different compared to cases in high latitude regions.

Section 2.1 describes the relevant settings of simulation that was employed to generate the results. Section 2.2 describes the assessment method by giving the performance indicators, sensitivity analysis, and multi-objective optimisation procedure. The results are given and discussed in Section 3, while Section 4 presents the conclusion of the article.

2. Method

2.1. Settings

The space observed in this study is an office room, based on the IEA Task 27 reference office [56], having internal dimensions of L 5.4 m × W 3.5 m × H 2.7 m (Fig. 1). Reflectance values of the ceiling and the floor were respectively 0.85 and 0.20, according to the IEA Task 27. The window was assumed to consist of a single glazing with typical visible transmittance of 0.88. No shadings, furniture, and other accessories were associated with the space. The workplane area is divided into two zones of equal size. In the centre of each zone, a calculation point is defined.