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Dynamic simulation and analysis of daylighting factors for gymnasiums in mid-latitude China

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ABSTRACT

Energy-conscious design of gymnasium daylighting can contribute to significant energy savings and improve users' playing environment. The purpose of this research is to assess the relative impact of 22 different design factors on interior daylighting effects, and to formulate design recommendations for gymnasiums in mid-latitude area of China. Each factor with very high impact: dates, latitude, window position, glazing transmittance, building height, building depth and window area were simulated under the constraints of gymnasium illumination and illumination uniformity. The window area, which has the direct relationship with daylighting, is considered as the evaluation standard for the daylighting performance of other influence factors. A complex interdependence among these daylighting factors was found. By considering daylighting and energy-saving in combination, 'Autumnal Equinox' at 16:00 was identified as an appropriate daylighting design date and time. Side windows are not suitable for gymnasium daylighting except in designs where there is no seating. For small gymnasiums with no seats, the lighting performance of side-windows is most influenced by glazing transmittance, building height and depth. For all sizes of gymnasium skylights, the influential factors are glazing transmittance and building height. A simplified formula was obtained via linear regression, which enables architects to quickly calculate the required window area during the preliminary design phase.

1. Introduction

Daylighting is an effective means to create a pleasant visual environment in gymnasium buildings. Gymnasium is a unique type of public building, due to its large scale, capacity and daylighting requirements, which present specific design challenges for visual comfort and energy consumption. Therefore, adequate daylighting of the interior space is necessary in order to achieve a high-quality light environment and to maximize the energy efficiency. Artificial lighting is one of the major uses of electricity in many public buildings, accounting for about 20–30% of the total building energy load [1]. Although electrical lighting brings many benefits to mankind, it also consumes a great deal of energy, and causes serious environmental pollution. Therefore, maximizing the use of natural light can achieve significant energy savings.

Many studies have examined the daylighting factors of buildings with the goal of comfortable lighting environment and energy saving. The former researches revealed that window location, window area, glazing transmittance, building size are the daylighting factors with very high impact.

When architects are engaged in daylighting design, the first consideration is the location of windows. Luo et al. indicated that with the same window area, the daylight factor of skylight was better than side-window, but the lighting uniformity was worse. For large-span buildings, a mixed lighting method combining side-window and skylight was more appropriate [2]. Vartiainen et al. researched side-window lighting of an office building and concluded that the vertical location of windows was more important than the shape. Furthermore, windows should be close to the working surface; the preferred horizontal location was the center of the façade [3]. Perez and Capeluto indicated that for large-span buildings, the interior daylighting effect was increased with higher window position [4]. Kim and Chung investigated the skylight daylighting of museums and found that the daylighting effect of a sawtooth skylight was better than a spire arrangement [5].

Vartiainen et al. concluded that window area was the most important factor for daylighting [3]. Studies by Bodart and Herde [6], Krarti et al. [7], Li and Tsang [1] found that interior daylighting effect was maximized with the greatest ratio of window-to-wall area. Perez and Capeluto simulated an education building in a hot–wet area, and concluded that the ratio of window-to-wall area should

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not exceed 12% in the north–south direction and 10% for the east–west direction [4]. Li examined gymnasium daylighting in a severe cold region, and found that illumination and illumination uniformity showed a linear increase with increased ratio of window-to-wall area [8]. Wang et al. found that increasing the ratio of window-to-wall area can increase the daylight factor of bright-field region, but the growth of dark-field region was limited [9].

Bodart and Herde analyzed the role of glazing transmittance for daylighting in a classroom, and found that higher glazing transmittance was related to lower energy consumption for artificial lighting, but this did not show a linear relationship [6]. Li and Tsang simulated the daylighting of two Hong Kong buildings, and demonstrated that, compared with ordinary single-layer glass and tinted glass, Low-E double glazing was more suitable for Hong Kong's daylighting, due to its lower glazing transmittance, reducing incoming light and heat [1]. Perez and Capeluto simulated daylighting glazing transmittance of an education building in a hot–wet area, and indicated that, at all orientations, Low-E was the most effective in reducing cooling energy consumption and increasing the lighting effects, followed by green glazing and double glazing [4]. A study by Jian Yao and Neng Zhu in Nanjing city showed that the illumination of thermotropic double-glazed windows was better than double glazed windows and tinted double-glazed windows [10].

Ghisi and Tinker reported that in order to meet indoor illumination requirements, window area was directly proportional to room size parameters [11]. Ochoa and Capeluto simulated the daylighting of an office near Haifa, and demonstrated that the level of illumination was insufficient when the working location was 7 m from the window. Therefore, the office could be no more than 7 m deep, or the desk could not be more than 7 m from the window [12]. Gon Kim and Jeong Tai Kim analyzed the relationship between the recess depth and illumination in Korea. They found that the depth of a recessed balcony should be less than 3 m in order to ensure that indoor illumination met the required level [13].

Although the literature includes many studies on daylighting, most were conducted on residential, office and educational buildings; the daylighting guidelines for such structures are not applicable to gymnasiums, due to their specialized lighting requirements. This lack of appropriate design guidance for gymnasium structures is considered a major factor in the lack of daylighting features incorporated in gymnasium designs.

This paper focused on gymnasiums in mid-latitude areas of China. The study used a computer model to examine 22 different design factors in terms of their relative impacts on interior daylighting. All factors with very high impact were systematically simulated to determine their influence and interrelation in order to formulate daylighting design recommendations for architects, and to minimize the energy required for artificial lighting.

2. Basic model of gymnasiums

According to the Chinese standard <Design code for sports building JGJ31-2003> [14], gymnasiums can be divided into four categories (small, medium, large and extra-large) according to the number of seats. As there is a wide range of gymnasium sizes, the study formulated 6 ranks of rectangular gymnasiums, intended primarily for basketball; the seating capacity varied by approximately 2000 between each rank. The size of the basketball court met the minimum standard requirement [14]. The building height met the minimum specified in the Chinese standard, and the visual requirement for watching games in <Sports Building Design Manual> [15]. The parameters of each gymnasium are shown in Table 1.

3. Methodology

Mathematical model is used for daylighting factors analyzing and classifying. Compared with its complication and time-consuming, the study used the simulation method, which is more convenient and fast to determine the correlation between each factor affecting gymnasium daylighting.

3.1. Software introduction

DIALux is a computer package for simulating and visualizing lighting in and around architectural environments using the backward radiosity calculation. It is a well-established lighting program, which can help designers to create virtual environments simply and intuitively [16]. DIALux can simulate overcast, clear and average sky conditions. The present study used parameters for overcast sky conditions, representing the most negative scenario for indoor daylighting.

3.2. The design basis of daylighting

A playing court is the core of a gymnasium space, so this paper examined daylighting illumination above the basketball court. According to the Chinese standard <Standard for lighting design and test of sports venues> [17], the lighting level was set at a minimum of 150 lx; the horizontal illumination uniformity U1 (minimum illumination/maximum illumination) was set at a minimum of 0.3; the horizontal illumination uniformity U2 (minimum illumination/average illumination) was set at a minimum of 0.5; illumination was calculated at a height of 1.0 m. The illumination calculation grid was 1 m $\times$ 1 m, so the grid point was set at 28 m $\times$ 15 m, in accordance with the scale of the basketball court.

This study examines the design constraints involved in maintaining appropriate interior illumination level and uniformity. The window area, which has the direct relationship with daylighting, is considered as the evaluation standard for the daylighting performance of other influence factors. Search for the variation regulation and analyze the correlation between the influence factors, illumination and illumination uniformity, in order to provide foundation for architecture design.

3.3. Calculation date and time

Daylighting illumination and illumination uniformity vary according to the date and time. To investigate the annual

Table 1
Parameters of gymnasiums.

Serial number	Classification	Auditorium capacity (seats)	Court scale (length × width, m)	Building scale (length × width × height, m)
G1	Small	No seating	38 × 20	38 × 20 × 12.5
G2	Small	2046	38 × 20	48.8 × 45.7 × 12.5
G3	Medium	4064	44 × 24	61 × 57.9 × 12.5
G4	Medium	5936	44 × 24	61.2 × 72.2 × 15.4
G5	Large	7948	70 × 40	75.6 × 72.9 × 14.7
G6	Extra large	10,040	70 × 40	78.8 × 82.5 × 16.3