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Building Daylight Simulation Analysis Based on Ladybug + Honeybee Parametric Approach: A Case Study of Gando Primary School

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Abstract: The Gando Primary School project faces several challenges like extreme environmental constraints, resource scarcity, and design requirements. These challenges include the hot climate of Burkina Faso, economic underdevelopment, building material scarcity, and lack of electrical resources. To implement an architectural design for the classrooms that accommodates these difficulties, especially in the absence of an electrical system, architect Francis Kéré employed various passive design strategies that can provide shelter from the rain and heat while achieving essential lighting levels and ventilation. This paper used Gando Primary School as the research object and utilized the parametric tools of Ladybug + Honeybee (L + H) to conduct numerical simulations and evaluations of the building's daylighting, glare analysis, and indoor thermal comfort. The aim of this study is to investigate the application of passive design strategies in energy conservation under extreme environmental conditions, propose a parametric energy-saving evaluation strategy with L + H, and explore energy-saving design ideas in economically underdeveloped Third World countries.

Keywords: Gando Primary School; Parametric; Passive energy conservation; Ladybug + Honeybee

1. L + H parametric research methods and theoretical foundations

African architect Diébédo Francis Kéré, winner of the 44th Pritzker Prize in 2022, is renowned for his impactful work in Burkina Faso, a landlocked country in West Africa that has harsh climate and limited resources [1]. The Gando Primary School project in Burkina Faso showcases Kéré's ability to consider local climate and construction constraints [2]. This paper examines the daylighting and energy-saving effects of the Gando Primary School using the parametric tools Ladybug + Honeybee (L + H), in order to establish a comprehensive architectural energy-saving optimization mechanism.

1.1. Introduction to L + H tools

Ladybug and Honeybee (L + H) tools form a comprehensive architectural system, with separate computational cores and additional toolsets. Ladybug supports meteorological data processing, offering an interactive interface through Grasshopper for bioclimatic charts and passive design strategies. It provides solar path, wind speed, and other data visualizations. Honeybee integrates EnergyPlus, Radiance, Daysim, and Butterfly for building energy consumption, light environment, and ventilation simulations respectively [2]. L + H tools support performance analysis throughout the design cycle, as shown in **Table 1**.

Table 1. L + H Parametric tool function summary

Tool	Function	Performance analysis	Computing core
Ladybug	Environmental analysis Climate meteorological analysis data visualization	Climate Data Map Sun path Wind speed and direction Shadow simulation Enthalpy chart Adaptive Comfort Chart etc.	Python
Honeybee	Energy consumption simulation Sunshine simulation Adaptive computing	Calculation of thermal comfort Annual Solar Analysis Glare analysis Visualize energy balance etc.	EnergyPlus Radiance Daysim OpenStudio Python

2. Gando primary school parametric building daylighting evaluation strategy construction

2.1. Meteorological data extraction

The meteorological data EPW file used in this study came from the TMYx dataset, which is a typical meteorological file obtained from the ISD (U.S. National Oceanic and Atmospheric Administration's Integrated Surface Database) and provides hourly data for 2021 using the TMY/ISO 15927-4:2005 method. The individual annual ISD files were created using the general principles of the IWEC (International Weather for Energy Calculations) typical meteorological year published in 2001. The resulting files have been peer-reviewed by relevant parties. ERA5 data is a comprehensive, satellite-based global grid solar radiation dataset provided by Oikolab, with reliable and valid data sources. Ladybug tools can extract hourly temperature, humidity, wind speed, and solar radiation intensity data from EPW files for the region.

Gando Primary School is located in Poussoaka County, under the jurisdiction of Bourgou Province in the Central East Region of Burkina Faso. Meteorological data for this region is not available, thus meteorological data from Ouagadougou, the capital of Burkina Faso, which is geographically close and has similar climatic characteristics was used instead.

2.2. Daylight design strategy analysis

The acquired EPW meteorological data file was imported into Ladybug Tools, and quantitative analysis of the region's climatic and meteorological conditions was performed by setting relevant field parameters at the Ladybug battery port. At this stage, multi-dimensional energy-saving strategies can be formulated based on the local average annual meteorological conditions. The building's passive energy-saving design strategy can be adjusted in real-time according to changes in the climate timeline.

As shown in **Figure 1**, Ladybug Tools was used to generate the region's annual average dry bulb temperature chart. The region experienced high temperatures throughout the year, with March–June having the most concentrated high temperatures, with highest daily temperatures reaching above 42°C. As shown in **Figure 2**, Ladybug Tools was also used to generate the region's annual average relative humidity chart, the visualization showed that the region has a rainy season between June–October. In response to this unique climate, Kéré designed a massive overhanging tin roof and thick stone foundation for Gando Primary School; the tin roof absorbs solar radiation, shields sunlight, and prevents external heat from entering; the stone foundation prevents rainwater from flooding the interior and effectively protects the clay brick walls from rainwater erosion. In this way, the impact of extreme weather can be mitigated while ensuring the safety and stability of the building.

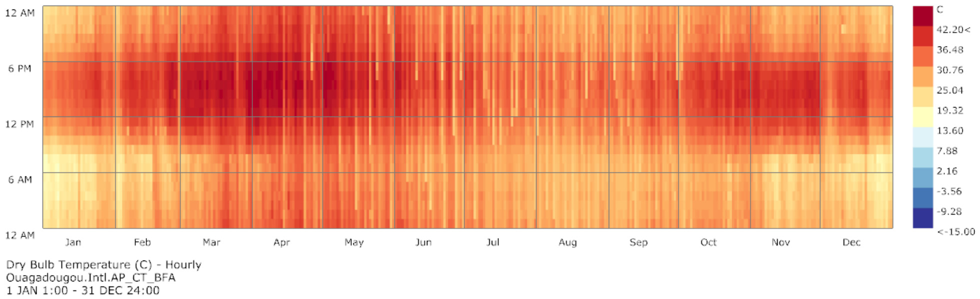

Figure 1. Annual average dry bulb temperature – hourly (drawn by the author)

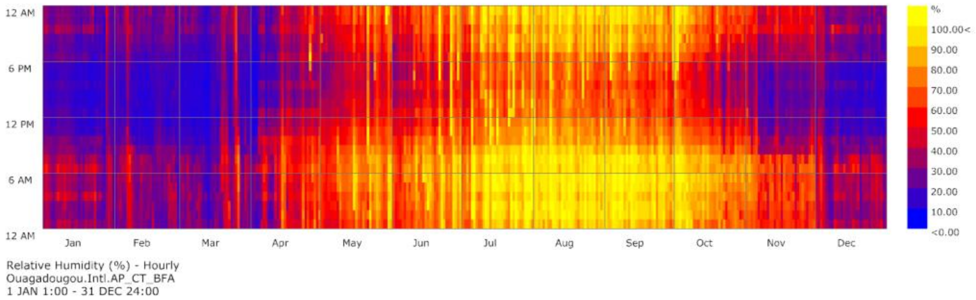

Figure 2. Annual Average Relative Humidity Chart – hourly (drawn by the author)

2.3. Building daylighting evaluation indicators based on L + H

Since there are no relevant standards for daylighting design of campus buildings in the country and region where the Gando Primary School project is located, the parameter settings and relevant standards in this simulation are based on the national standards of China, with the “Architectural Daylighting Design Standard” (GB50033-2013) as the relevant evaluation standard. The focus of this paper is to analyze and explore the effects of building daylighting under parametric simulation. Due to the constraints of the COVID–19 pandemic during the experimental period, on-site measurements could not be conducted, thus the study does not delve into the specifics of building construction and only the critical values of the lighting coefficient under the parametric model were considered.

(1) Indoor illuminance

Indoor illuminance is generally defined as the luminous flux per unit area passing through a work plane indoors, which indicates the extent to which fixed work planes, such as desks, are illuminated by light. Although it cannot directly reflect the perception of the human eye, it can objectively quantify the brightness on the work plane, thus making it a commonly used indicator for evaluating indoor light environment quality. In the “Architectural Daylighting Design Standard” (GB50033-2013), the standard value of natural light for primary school classrooms is 450lx [3].

(2) Daylight Glare Probability (DGP)

Daylight Glare Probability (DGP) is a robust glare metric standard used to evaluate the probability of glare in buildings from windows, and it is considered the most accurate glare model for human eye perception. DGP values represent the probability of sunlight entering through windows and causing glare interference to indoor occupants, with effective values ranging from 0.2 to 0.8. Intuitively, when DGP = 0.2, it indicates that 20% of people feel glare interference in that environment. The value is calculated using equation (1):

$$DGP = 5.87 \times 10^{-5} E_v + 9.18 \times 10^{-2} \log\left(1 + \sum_i \frac{L_{s,i}^2 \omega_{s,i}}{E_v^{1.87} P_i^2}\right) + 0.16 \tag{1}$$

where E_v represents the vertical illuminance of the eye, L_s is the brightness of the glare source, ω is the solid angle of the glare source, and P_i is the Guth position index.

The passive daylighting design of Gando Primary School was quantitatively simulated and analyzed from the dimensions of indoor illuminance and daylight glare probability, with the control objective of each link being “and whether the classroom daylighting comfort requirements are met according to relevant standards based on the solar radiation received by the classroom work plane.” The illuminance should meet the minimum value required for teaching activities, glare should be controlled below the acceptable threshold, and the indoor daylight factor should be maintained at an appropriate level.

3. Evaluation of energy-saving effect of Gando Primary School L + H parametric architecture

3.1. Daylight environment simulation

The indoor daylight environment of a Gando Primary School classroom unit was simulated through utilizing the Ladybug and Honeybee collaborative workflow. The .epw format weather file was input into Ladybug, which then connects with Radiance, Daysim, Energyplus, and other plugins on the Grasshopper platform using Honeybee. This bridges the gap between building performance calculation and parametric simulation [4]. The plugin processes input data through algorithms and visualizes simulated data using data charts. The Ladybug and Honeybee versions used were 1.5.0.

Due to a lack of material resources, natural lighting was the only lighting method for Gando Primary School classrooms. Therefore, the indoor illuminance level of natural light inside Gando Primary School classrooms is an essential indicator to measure the lighting comfort level. Illuminance, expressed in lux, is a physical quantity describing the light power from all directions, used to ensure the required intensity of illumination in a space. The illuminance on the desktop surface in the classroom was used as the basis for evaluating the lighting level of the teaching space. According to the “Building Daylighting Design Standard” (GB50033-2013), the standard value of indoor natural illuminance for educational buildings should be 450lx; discomfort may occur if the value is lower or higher than this standard.

A satisfactory lighting condition can be considered if the illuminance satisfaction in the core work area reaches more than 50%. The illuminance satisfaction limit is at 150-300lx.

As shown in **Figure 3**, the Generate Standard CIE Sky in Honeybee was chosen as the sky model for illuminance calculation, where CIE (Critical Illuminance of Exterior) represents the outdoor natural illuminance when indoor artificial lighting needs to be fully turned on. Under this model, parameters can be input to adjust the required illuminance simulation date and time.

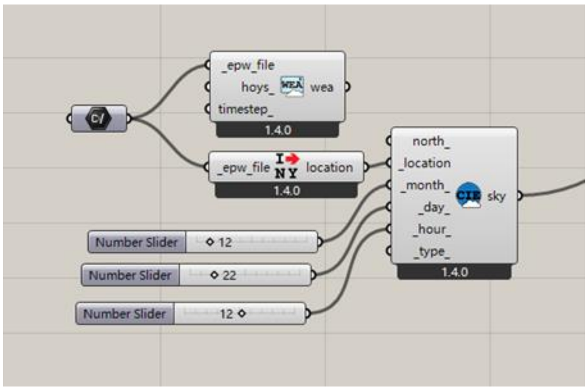

Figure 3. Sky model battery pack (drawn by the author)

3.2. Daylight environment simulation

Using the Average Sky Model (Honeybee_Generate Average sky), real sky measurement data for 8760 hours throughout the year was obtained from Gando Primary School's location, Ouagadougou. The weather data was input into the average sky model in order to calculate the monthly average illuminance by taking the average value of the same time in each month, which resulted in an objective representation of the average indoor illuminance distribution throughout the year (**Figure 4**). High illuminance values were concentrated between 12:00 and 15:00 from November to February, while more evenly distributed around 12:00 in other months. This aligns with the students' class time, achieving lighting standard of more than 450lx for most of the time, demonstrating significant natural lighting potential.

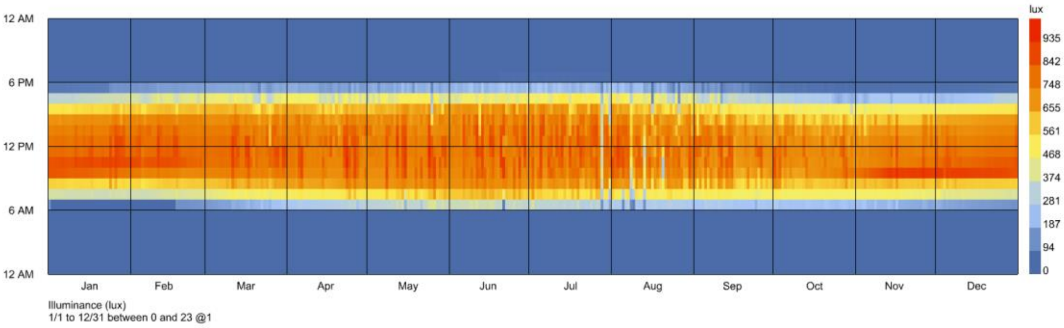

Figure 4. Annual indoor illuminance distribution (drawn by the author)

As for indoor illumination simulations, winter and summer solstices were selected as measurement dates [5], representing annual indoor illumination values. As shown in **Figure 5**, during winter solstice, natural indoor illuminance exceeding 450lx was mainly concentrated on the Southern side of the classroom, whereas the Northern side complied with control standards. During summer solstice, the area with higher illuminance shifted to the Northern side, whereas the Southern side was slightly above control standards. It is possible that due to this reason, Kéré designed adjustable louver windows for Gando Primary School classrooms, which can block excessive direct sunlight, address excessive illuminance, and dissipate excess indoor heat through convection.

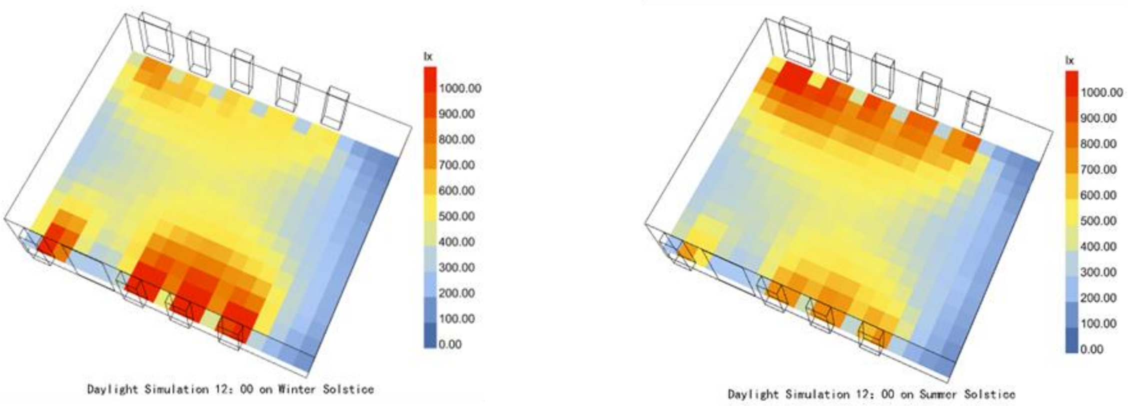

Figure 5. Indoor illuminance at 12:00 on the winter solstice and summer solstice in daylighting simulation (drawn by the author)

3.3. Glare analysis

Due to pandemic limitations, no physical field investigation of Gando Primary School was done. Hence, this study used the "image-free method" to simulate annual Daylight Glare Probability (DGP) and Glare Autonomy (GA) in the school's interior. The "image-free method" does not rely on field images during simulation and is a year-by-year simulation for glare caused by direct sunlight and sky. It depends on normalized coefficients (daylight coefficients) representing flux transfer from simulated sky patches to various observation positions with known direction and solid angle. DGP is calculated under specific sky conditions by applying sky luminance values of each patch, stored in a matrix with one column calculated per hour. The sky matrix contains 8,760 sky vectors per year, including nighttime sky vectors. Calculating daylight coefficients and sky matrix is faster than rendering images for each view under each sky condition with traditional glare calculation methods (e.g., UGR, DGI, CGI, and VCP).

When the DGP is below a threshold (e.g., 0.4), the glare was considered to be within an acceptable range in the space viewing direction. The specific DGP values and their corresponding degrees of glare-free space are shown in **Table 2**.

Table 1. DGP and glare-free space degree correspondence table

DGP	Degree of spatial glare
> 0.45	Unbearable glare
0.4–0.45	Dazzling glare
0.35–0.4	Perceived glare
< 0.35	Imperceptible glare

Given the DGP value vector of all occupied times in the given space viewing direction, we can define GA as the fraction of time without glare in that viewing direction. By setting a target for the maximum number of hours that DGP can exceed the threshold, we can also define the Glare Autonomy of space as the proportion of views in the space that achieve that target. Glare Autonomy provides us with a single value to summarize the degree of glare-free space.

The proportion of spaces that exceed 40% DGP within 5% of occupied hours was calculated. Conventional daylight autonomy abbreviates the Glare Autonomy of the 40% DGP threshold to GA40% and the corresponding spatial glare autonomy to sGA40%, 5%, with a target of 5% of occupied time. After L + H simulation calculations, the DGP distribution of Gando Primary School is shown in **Figure 6**, and the GA distribution of classroom units is shown in **Figure 7**.

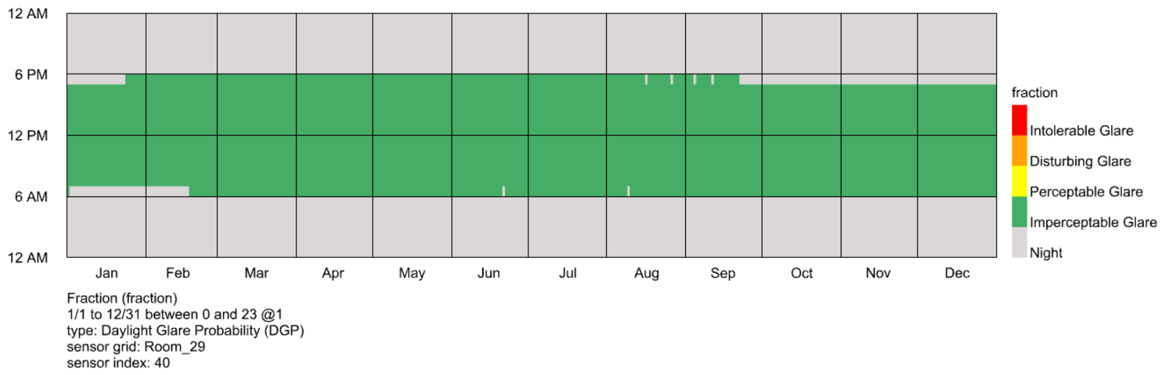

Figure 1. Distribution of daylight glare probability in Gando Primary School (drawn by the author)

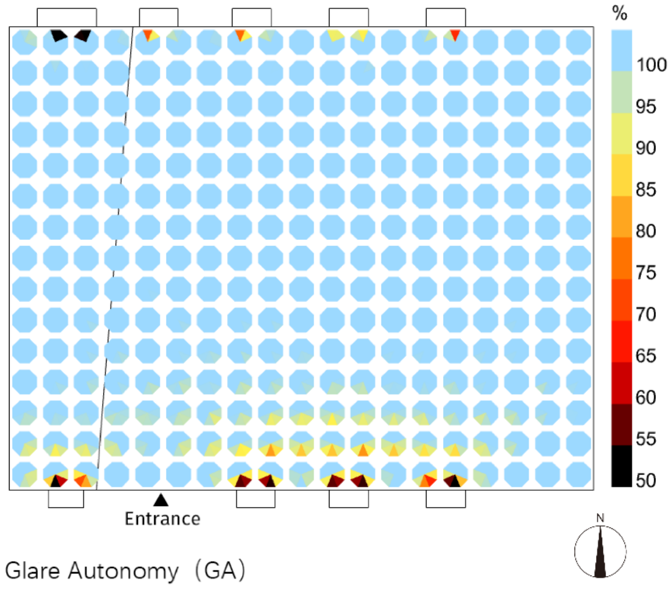

Figure 2. Distribution of glare autonomy in Gando Primary School classroom units (drawn by the author)

4. Evaluation of energy-saving effect of Gando Primary School L + H parametric

The light environment effect of the school’s passive daylighting approach was evaluated for compliance with relevant standards through the light environment simulation analysis of Gando Primary School using the Ladybug + Honeybee toolchain. The simulation and calculation results show that the average indoor illuminance of Gando Primary School meets the daylighting standard of greater than 450lx and can satisfy the usage requirements for most of the year. The indoor planar illuminance distribution is relatively concentrated on the northern side and can meet the usage standards with the help of adjustable louvers. In terms of glare, the probability of glare occurrence in the interiors of Gando Primary School is less than 0.35 throughout the year, which is an imperceptible level of glare. The glare autonomy in most areas of the classroom units is lower than GA40%, indicating that spatial glare can be controlled at a relatively low level with no significant visual discomfort. In summary, the passive daylighting design of Gando Primary School is an effective daylighting strategy with a high level of natural daylighting capability.

Disclosure statement

The author declares no conflict of interest.

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