Enhancement of the Energy Performance of an Existing Building Using a Parametric Approach

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Abstract: According to the European Union, buildings account for 40% of overall energy use and 36% of CO_2 emissions, with existing energy-inefficient buildings the main source of losses. Efforts to enhance the thermal comfortability of users in buildings can result in overheating if not appropriately designed, which in turn could lead to health issues as well as continual emission of greenhouse gases. To provide further insights into this dilemma and contribute to improving energy-efficient building designs, we undertake a new modeling technique encompassing a complete analysis of the existing building 3D model as well as solar radiation behavior on buildings. The technique involves 3D building information modeling (3D BIM) that is reconstructed using computer-aided design (CAD). Ladybug and Honeybee plugins for Grasshopper for Rhino are then used to evaluate environmental and building performance using the energy plus weather (EPW) file of Wuhan city, China, as a case study. An assessment of 'with' and 'without' built architectural surroundings contexts is also carried out in relation to summer and winter solstices. An overall change of approximately 29.56% is observed between 'with' and 'without' surrounding contexts, which suggests that both have a significant influence on the solar potential of individual buildings. Investigation of internal and external thermal energy consumption behaviors in relation to building comfort lead us to suggest an optimized smart solution which is validated using our case study site in Wuhan. Our findings suggest that the building energy lifespan can be increased while reducing environmental consequences if an estimated 50% of monthly energy savings are made. The findings of this study provide useful insights for decision-makers, engineers, and designers of energy-efficient buildings. **DOI: 10.1061/JLEED9.EYENG-4546.** *© 2022 American Society of Civil Engineers.*

Author keywords: 3D building information modeling (3D BIM); 3D Rhino; Solar and building energy; Smart solution; Renewable energy; Energy-efficient buildings.

Introduction

Renewable energy plays a significant role in the enhancement of building energy performances (Dong et al. 2018), and to help achieve the standard of near-to-zero energy building (nZEB) design efficiency for all building constructions (Rey-Hernández et al. 2020). The World Green Building Council (WGBC) states that all new buildings must run with zero-carbon emissions by the end of 2050 to help limit global temperature rises to acceptable levels (Zhang et al. 2021). When deciding whether to create net-zero energy-efficient buildings, inter-related technical, economic, and environmental issues should be considered (Papadopoulos et al. 2017), which justifies the use of multi-criteria decision analysis techniques for net-zero energy building designs. In the context of global warming, existing buildings are consuming 40% of the total energy with 36% of CO_2 emissions (Yan et al. 2021). With the rapid growth of solar energy, the United Nations (UN) are encouraging researchers to develop techniques that reduce consumption and that promote more efficient building design resources and increased adoption of sustainable buildings (Omer and Noguchi 2020).

Sustainable buildings are defined as high-quality energy-efficient buildings that last longer and cost less to maintain and operate (Dwaikat and Ali 2016). Minimizing the negative impacts on the surrounding environment and protecting human health are the main advantages of sustainable buildings (Balaban and de Oliveira 2017). According to Esen et al. (2017) and Zhou and El-Gohary (2018), solar energy for building applications is the main source of achieving sustainable buildings. Solar radiation is often converted to enable the internal needs of a given building to be met, including electricity and water heating (Al-Naghi et al. 2020; Jamar et al. 2016; Zhang et al. 2021). Improving building thermal energy efficiency is vital (Esen and Yuksel 2013; Safari et al. 2017) but poses significant challenges (Zheng et al. 2019). According to the Chartered Institution of Building Services Engineers (CIBSE), overheating can hurt the productivity of the indoor

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working environment, and there is a danger of heat stress (Mohajeri et al. 2016), which can cause health issues for building inhabitants. Solar radiation absorbed on the outer surfaces of walls, roofs, and windows is partially transferred inside the building and should be accounted for and minimized from the early design stages (Fernandez et al. 2017; Park et al. 2020). However, this is difficult to achieve in existing energy-inefficient buildings.

This study sets out to develop parametric solutions to reduce building energy loss while improving the thermal comfortability of buildings. The objectives are framed using a case study in Wuhan city, China, with specific contributions including: (1) development of a workflow to convert computer-aided design (CAD) files to a 3D building information model (3D BIM), (2) evaluation of the impact of site context on building total solar radiation gain that can drastically affect building performance, (3) assessment of internal and external thermal energy consumption behaviors, and (4) provision of parametric solutions to improve thermal comfortability using solar radiation gain modeled in the Grasshopper Ladybug software. Results are presented as statistical metrics in tables as figures as well as infographic images.

A preplan 3D modeling with the integration of solar energy and installation of devices is required to enhance existing building performance (Moldovan et al. 2017; Dall et al. 2020). The 3D model of the existing buildings comes from different sources, like CAD, different scanners, drafted drawings, or other BIM technologies (Akanbi et al. 2022). The aim is to convert 3D BIM to 3D Rhino for future simulation processes that conserve solar energy in a different form and to enhance existing building performance (Chokor and El Asmar 2017), which is an important aspect of this study.

Without an assessment of site contexts like roads, neighbor buildings, and topography, the goal cannot be achieved (Desthieux et al. 2018). To make a building thermally comfortable and to enhance its performance, a detailed assessment of solar radiation on buildings is subsequently fundamental for accurate measurement (Gottschall et al. 2017; Ehsan et al. 2018) and energy prediction for future smart buildings construction and technologies (Tushar et al. 2021). In this case, individual buildings play an important role in making a human-friendly environment; therefore, it needs more concentration (Yan et al. 2021).

The impact of solar radiation on an existing building with and without surrounding contexts has been studied by validating real-time ground data with digital data (Ehsan et al. 2018). For this purpose, the study performs an environmental analysis of incident solar radiation (ISR) using a Grasshoppers platform for external and internal analysis of the building (Foroughi 2018). Based on the study findings and by highlighting the impact of solar radiation on existing buildings, some smart solutions have been discovered and suggested for thermally unsustainable existing buildings that can help to generate maximum solar energy preservations (Zhou and El-Gohary 2018). It should be noted that 3D techniques play a crucial role in making thermal energy consumption down, especially in existing buildings (Papadopoulos et al. 2017; Saretta et al. 2019). By using 3D technology, we can make the strategy to alter the form of the existing buildings for the best response to the environmental conditions (Al-Naghi et al. 2020).

Related Work

One of the most abundant energy sources on earth is solar energy (Chukwu et al. 2019; Sahlol et al. 2021). It is a source of renewable energy that can supply sufficient power for building needs (Esen et al. 2007). Previous research reveals that existing buildings and new construction of buildings play a significant role in greenhouse gas emissions and associated climate change (Langnel and Amegavi 2020; Majeed et al. 2021; Nugroho et al. 2022). This is because heavy materials used in buildings store large amounts of energy in the form of solar radiation that is then returned to the surroundings in the form of warmer air (Feng et al. 2016; Nugroho et al. 2022). The ISR strikes the exterior of the building (e.g., exterior brick walls, concrete tiles), and as a result of overheating due to increased temperatures inside of the building (Yan et al. 2021), air conditioning and other cooling mechanisms are required to keep the indoor workplace comfortable for users, thereby shifting the peak demand for energy use. Warmer temperatures due to rising global temperatures (Shahsavari and Akbari 2018; Waqas et al. 2021) raise the energy demand for cooling in the summer while decreasing the need for heating in the winter (Yan et al. 2021).

To improve efficiency while maintaining the structure of existing buildings (Haruna et al. 2021), BIM and sustainable designs play a significant role (GhaffarianHoseini et al. 2017). For example, BIM technology has helped to relieve thermal energy usage (Najjar et al. 2019), suggesting that the use of BIM technologies with appropriate software tools in different scenarios (e.g., Kim et al. 2015) provides much improved thermal energy consumption (e.g., Asl et al. 2015).

The era of 3D digital technology provides significant opportunities in the building research and construction sectors (Beyhan and Selçuk 2017). For example, technologies such as 3D BIM (Kota et al. 2014), Revit, 3D geographical information sciences (3DGIS), and 3D Rhino (Xu et al. 2014; Aksamija 2018; Machete et al. 2018) enable key insights into developing new energy-efficient building designs. The Grasshopper suite of plugin tools provides one of the most commonly used platforms among designers. This platform has several benefits that are currently unavailable in other environmental design plugins (Al-Naghi et al. 2020). Using Grasshopper provides a 3D modeling interface that simplifies the analytical process and automates expedited computations, thereby delivering easy-to-understand graphical displays. Grasshopper's parametric platform enables designers to investigate the direct connection between environmental data and design production through graphic data outputs that are strongly linked with building geometry. On the other hand, traditional approaches to assessing buildings through 2D drawings and photographs were time-consuming (Al-Naghi et al. 2020). This is further hindered by the sparsity in modern weather stations of appropriate geospatial coverage (Biagini et al. 2016; Sanhudo et al. 2018).

To date, many studies have been conducted to identify appropriate solutions that can overcome issues regarding the impact of ISR on buildings (Santos et al. 2017; Lima et al. 2019). A 3D model with a high level of detail (LOD) is highly desired with the built surrounding context to efficiently assess spatial changes in ISR that reach the roofs and façades (Biljecki et al. 2017; Wu et al. 2021). According to Sakin and Kiroglu (2017), 3D simulation techniques increase the overall building energy efficiency and reduce running costs.

Some studies conducted at the city scale demonstrate the significance of solar energy evaluation. However, most of these studies analyzed the roof geometries only due to the lack of 3D spatial data for entire buildings as well as high computational needs (Araya-Muñoz et al. 2014; Catita et al. 2014; Gautam et al. 2015). These limitations can result in insufficient and inaccurate solar energy evaluations of buildings, ultimately misrepresenting their energy demands. More recently, several pioneering studies conducted on individual buildings appear to provide adequate assessments (Kota et al. 2014; Yi 2014; de Sousa Freitas et al. 2020; Alammar et al. 2021; Tabadkani et al. 2021; Nugroho et al. 2022). However, these studies are limited to the indoor environment and to early design

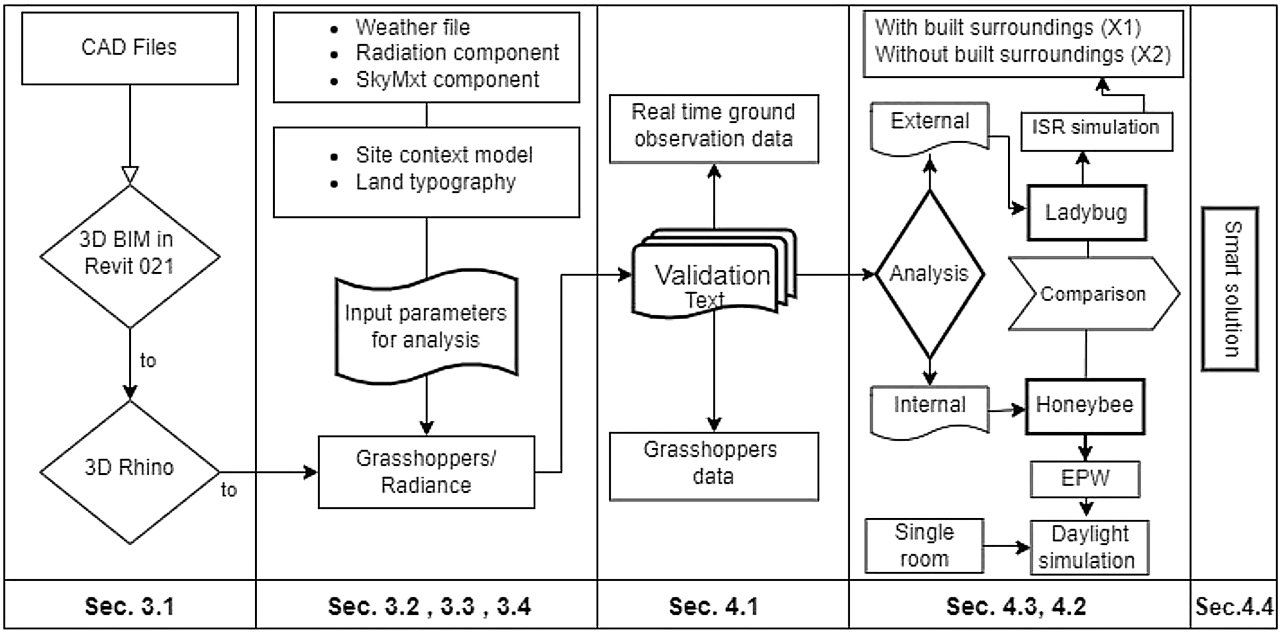

Fig. 1. Proposed methodology overview.

constructions of individual buildings. The study conducted by Machete et al. (2018) suggests that the accurate analysis of ISR behavior on buildings should be mandatory and are only enabled through 3D models with accurate building geometries.

In light of the presented discussion, the influence of new evaluation techniques presents an effective solution to enhance existing building performance (Huovila et al. 2019). However, this research gives different perspectives, such as the use of 3D Rhino in Grasshoppers, Ladybugs, and Honeybees, with extensive performance analyses of reconstructed BIM models from 2D CAD. Real-time assessments of thermal radiation falling on buildings, sun angle with seasonal and daily fluctuations, and shadows cast effects by surrounding context have been undertaken (with consideration of summer and winter solstices). Recently Peronato et al. (2017), Costanzo et al. (2018), and de Sousa Freitas et al. (2020) have used Ladybug, Honeybee, and Rhino, respectively, which were linked to Grasshoppers for such studies. Due to its robust outcomes and less computational efforts, this platform has attained more attraction from the scientific community in recent times. According to de Sousa Freitas et al. (2020), Grasshopper/Ladybug is the optimum approach for solar analysis because of its high degree of compatibility, which allows for quick solar energy analyses and visual simulations with a reasonable level of accuracy and time investment.

Methodology

Wuhan is the capital of Hubei province located in the middle of the Yangtze River at 29°58′–31°22′ and 113°41′–115°05′ north latitude and east longitude, respectively. Usually, Wuhan has very hot summers, with a mean maximum temperature of 39.9°C. The rapid growth of many built-up areas and urban buildings has been witnessed in the city. Thus, planning of building and design strategies are required to ensure a suitable environment in the main city and surrounding areas.

In this research, we analyze solar radiation to evaluate the existing performance and efficiency of a selected building in Wuhan. The 3D BIM model covers all surrounding characteristics of the building with the capacity to support solar energy systems that are sensitive to interfering with solar access to the building envelope. Mapping of solar radiation patterns and assessing the individual and relative effects of contributing elements are carried out to quantify the effects. The proposed methodology in this study involves four major steps represented in Fig. 1 and are detailed in four main sections: (1) Reconstruction of a 3D BIM model from 2D CAD and development of a Grasshoppers algorithm framework, (2) Validation of real-time ground observations with digital data, (3) Evaluation of the external and internal solar radiation effects, and (4) Assessment of the potential solution to enhance the performance of the building based on the results. These steps are explained in detail in the following sections.

Reconstruction of a 3D BIM Model

A 3D building model comprising attribute information on building scale and geometric features was reconstructed from CAD files using Revit 2021. CAD files were collected from a six-story building, specifically, the Engineering Laboratory Building of the University of Geosciences, Wuhan, China (Fig. 2). This building has multiple CAD files comprising dimensions, text labels, and geometrics. The conversion process was divided into two main steps. The first step involves data preparation and cleaning of the CAD files. In the second step, a reconstruction of the 3D BIM model is carried out. the building walls, slabs, columns, floor, roofs, doors, and windows are reconstructed in the 3D model to assess the impact of thermal radiation behavior inside the building (Fig. 2).

BIM to Autodesk Revit 3D Rhino

To perform the multiple Grasshoppers analyses, the BIM file of the investigated building blocks was imported into 3D Rhino and all of the scale parameters were set. The input parameters included the contour lines, height points, building footprints, and relevant characteristics (e.g., geographic coordinates, geometry, volume) that were interpolated to create a digital terrain model (DTM). Additional input parameters included roads, street networks, number of building stories, floor-to-floor height, and solid-to-void ratios.

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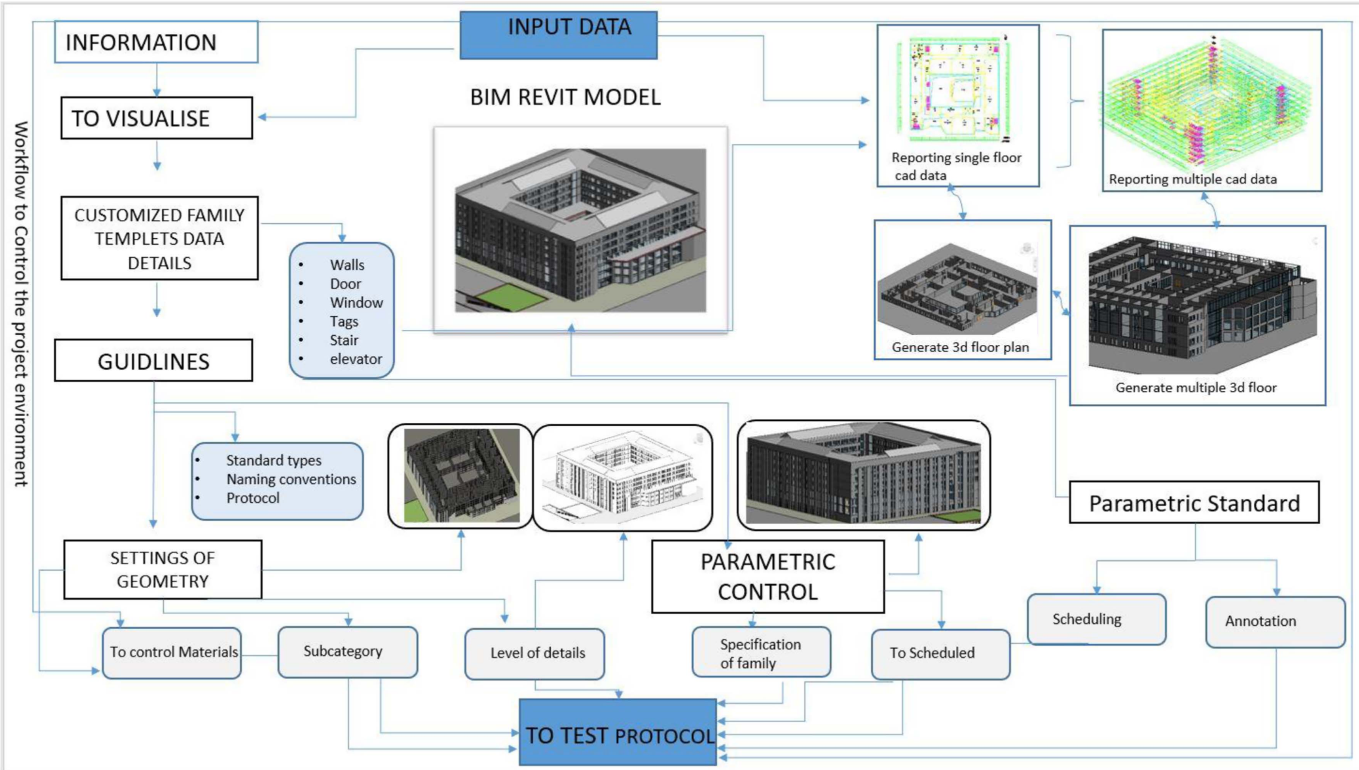

Fig. 2. Procedure to build a 3D BIM model by using Revit 2021.

For the ISR analysis with and without built surrounding contexts, the 3D-built surrounding environment plays a major role (Machete et al. 2018). Thus, we created neighborhood-building contexts and associated DTM using the SketchUp software and then imported the output file with the same scale settings used for the BIM in 3D Rhino. This enables a volumetric demonstration of the building blocks to be obtained through the extrusion of the building polygons. A gridded output was then obtained by dividing all of the surfaces into panels. The procedure of importing the building blocks with surrounding context in Rhino and subsequent conversion of the BIM to 3D Rhino is shown in Fig. 3.

Rhino to Grasshoppers

Rhino to Grasshoppers is a user-friendly programming language that works within the Rhinoceros 3D CAD application (Yi 2014; Kensek 2015). Multiple parameters were configured in Grasshopper to perform the multiple solar energy analyses. These included ISR for solar calculation, and required characteristics such as geometry, volume, mass, and height of the building. Additional input parameters used included the energy plus weather (EPW) data, radiation component, SkyMxt component, site context model, and land typography.

EPW is a text file (EPW file) containing real-time daily observations of temperature/solar radiation at various elevations which profile a particular climate zone's annual weather conditions (https://www.Ladybug.tools/epwmap/). The EPW file is crucial for performing the solar energy analysis and its enhancement in building efficiency and works with a sky description program for simulation called Gendaylit (Kota et al. 2014). The SkyMxt uses the EPW file to generate a description for annual daylighting analysis. The EPW file enabled analysis of the building and surrounding context through a script in the solar energy analysis (Lupato and Manzan 2019). This was aided by the Ladybug plugin that enabled access to the Grasshoppers suite (Eltaweel and Yuehong 2017).

Radiance is a state-of-the-art backward ray tracer that uses a mixture of stochastic and deterministic ray-tracing techniques (Reinhart and Herkel 2000; Jakica 2018) and represents the radiant flux emitted, reflected, transmitted, and received by our target building and the surrounding context. Through this component, we analyzed the ISR from different angles with different intensities.

The SkyMxt component specifies the radiation values from each patch of the sky. It first locates the EPW file of Wuhan city and then merges the direct and diffuse radiation parameters to get accurate real-time values of the specific region of Wuhan. This is a necessary step before doing solar energy analysis with the Rhino 3D model. The SkyMxt component can be used for a specific period such as an hour, month, or longer (Gomaa et al. 2021). Through this component, we established a winter and summer solstices matrix (SkyMxt) for the study region in Wuhan city and for a particular analysis period (i.e., December 21, 2020 7:00, 12:00, and 17:00 h) and (July 21, 2021 7:00, 12:00, and 17:00 h). This step calculates the radiation falling on a building and surrounding context, in addition to representing outdoor spaces such as parks or water areas, where radiation affects thermal comfort and/or vegetation growth.

To capture the surrounding condition of an existing building, the site context model was defined as an input parameter (e.g., Machete et al. 2018). This provides information on the different radiation levels relative to building heights, types of buildings, and the position of parks and water bodies. It also quantifies the effect of the surrounding context on the building in terms of hurdles in the solar radiation and its impacts.

The solar energy analysis was performed with plain topographic surfaces and surfaces with different elevation levels (Guo et al. 2020), as solar radiation has different intensities of temperature on different levels of land. Hence, land topography is used as a key component in enhancing the sustainability of the building.

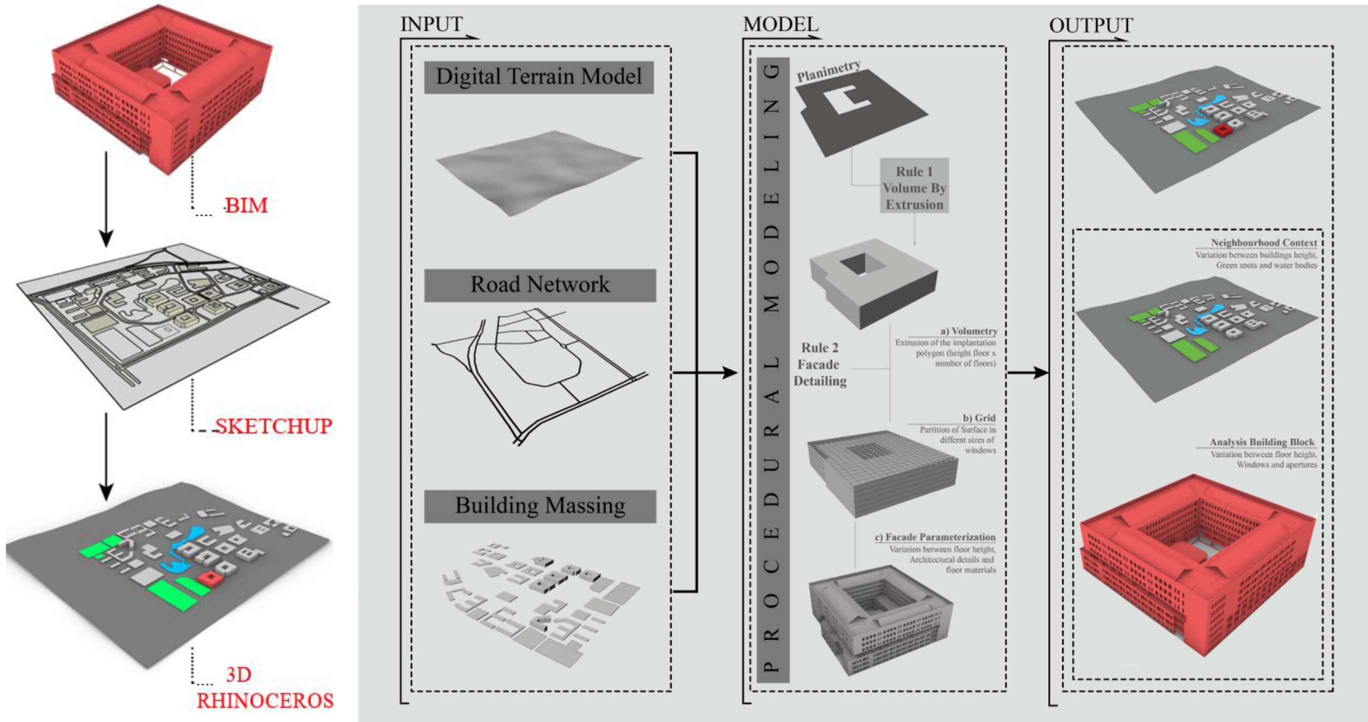

Fig. 3. Working principle of converting BIM to 3D Rhino (Autodesk Revit to Rhino).

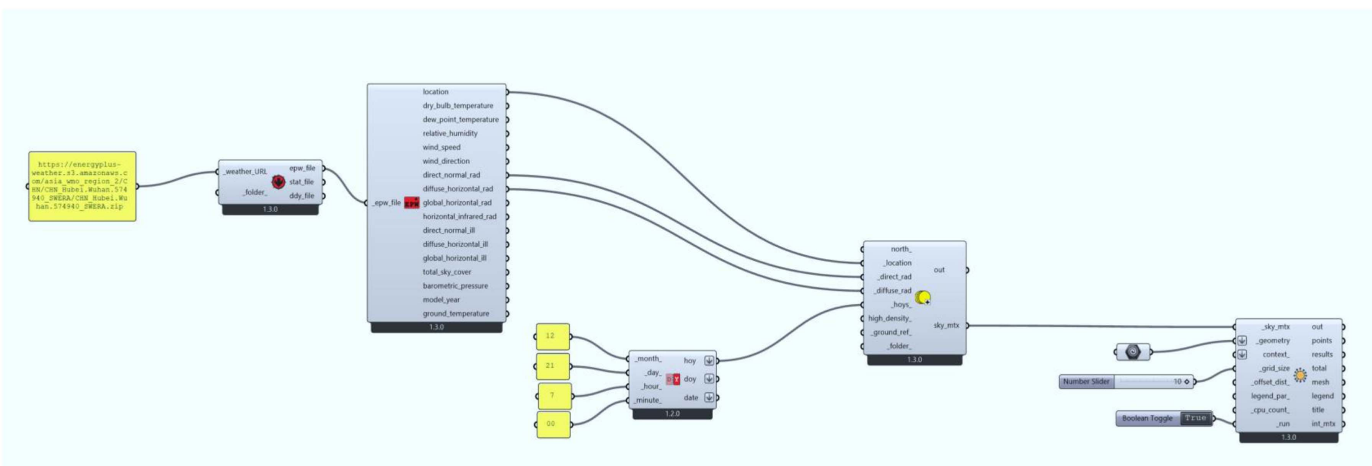

Fig. 4. Principle to develop a Grasshoppers algorithm framework for external analysis.

Develop Grasshoppers Algorithm Framework

A Grasshoppers script was developed to perform the ISR analysis for the external envelope of the building, The script was generated using Ladybug and was applied to building blocks and the built surrounding context. The major component in the script is the EPW file for Wuhan city. The analysis was performed by setting specific period parameters (summer and winter solstices), as these represent the longest and shortest days of the year, respectively (Machete et al. 2018; Sharma et al. 2021). Sky parameters were then configured based on the sky matrix we developed. The ISR component was then implemented by inputting the out-building block and surrounding context with a grid parameter configured that helps in visualizing the results (Figs. 4 and 5).

A single room was chosen for the interior daylight simulation using a Honeybee script. The simulation incorporated the building material characteristics of reflectance and roughness of glass, concrete, and brick.

Results and Discussions

Validation of Real-Time Digital Observation

A sample experiment was carried out to validate the real-time digital observations and evaluate the approach and findings. This included a survey of field measurements conducted during various periods of the day (i.e., December 21, 6:00–17:00 h; Table 1) to

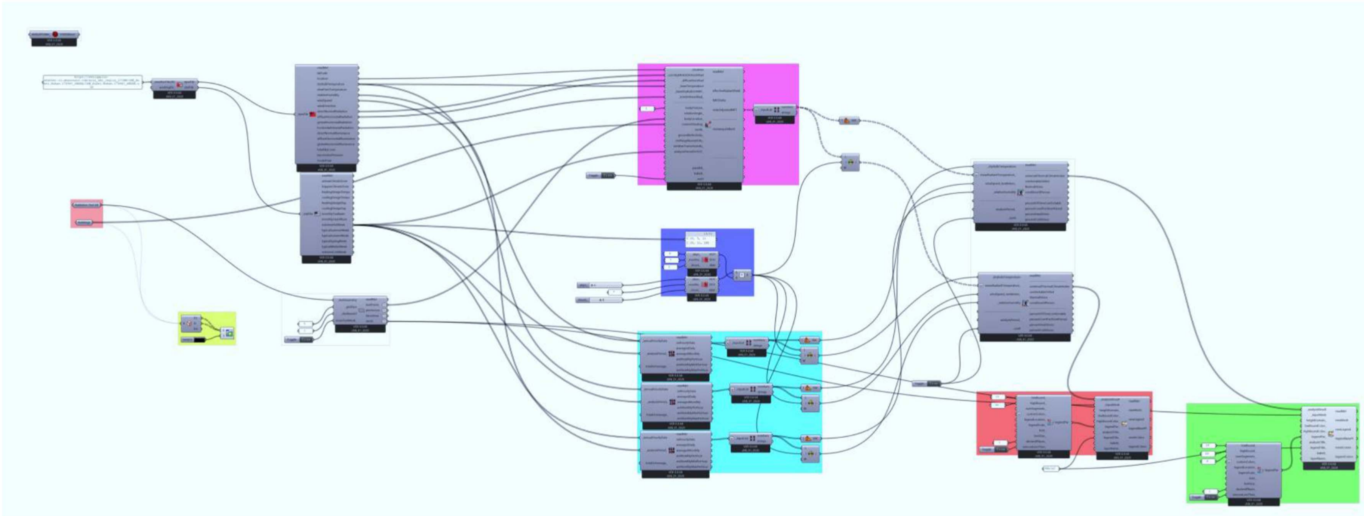

Fig. 5. Principle to develop a Grasshoppers algorithm framework for internal analysis.

Table 1. Showing the real-time observations on December 21, 2021 at various time periods to validate the ground data with digital data (Temperature in ℃)

Time (min: s)	Real-time observations	Grasshopper observations	Error	% Error	% Accuracy
06:00 h	1.89	2.65	0.40	40.21	59.79
07:00 h	15.92	16.11	0.012	1.19	98.81
08:00 h	17.06	18.38	0.08	7.74	92.30
09:00 h	19.14	19.9	0.10	3.97	96.03
10:00 h	21.61	22.17	0.03	2.59	97.41
11:00 h	22.74	23.69	0.04	4.18	95.82
12:00 h	24.07	24.64	0.02	2.37	97.63
13:00 h	24.83	25.21	0.02	1.53	98.47
14:00 h	25.4	25.97	0.02	2.24	97.76
15:00 h	22.93	23.88	0.04	4.14	95.86
16:00 h	17.43	20.85	0.20	19.62	80.39
17:00 h	8.53	11.75	0.40	37.75	62.25
				Accuracy	89.38%

measure the ground observations using a temperature-sensing device. The exact time was set to take real-time analysis of the building interior using Honeybee Grasshoppers and exterior observations using Ladybug Grasshopper. This step used the EPW file of Wuhan city by configuring all input parameters and running the script to produce temperature values in degrees Celsius (℃) (Fig. 6).

All interior and exterior temperature readings were arranged to determine the difference between real and digital measurements and to assess accuracy. The percentage difference between real and digital measurements was calculated for each hour of the day. The error in hourly variations at 6 h (morning) was close to 40%, indicating that at 6 h (morning) there is either no or very little solar radiation. Between 7 and 15 h, maximum solar radiation received by the building is observed. A correlation of 89.38% accuracy in the overall comparison of the surveyed and actual real-time temperature is observed, validating the real-time digital and the surveyed data from Grasshopper. The slight changes between the values are explained by the clear sky model assumptions in Grasshopper compared with the actual site. Fig. 6 shows the solar radiation gain result from Grasshopper and real-time digital data recorded with a hygrometer-thermometer. The slight variation between the recorded data and the surveyed values is due to the assumed test points using the Ladybug software with the surveyed data at the actual site. These results suggest that it is not practical to measure the radiation values on-site at the exact point, as assumed by the software.

External Incident Solar Radiation Analysis

With the fast expansion of cities and the goal of lowering primary energy consumption and ISR, assessing solar access for an individual building or an entire city has become a major challenge. To deal with these challenges, ISR has great importance from individual buildings to entire cities. It demonstrates the capacity to cope with complex shadow patterns created by terrain and the built surroundings. As a result, the amount of solar radiation intercepted by built surfaces reduces, affecting the building's solar potential. Currently, Grasshopper algorithms provide a suitable framework for creating and testing comprehensive solar radiation models due to their capacity to show and manipulate spatial and geographic data. To analyze the external solar radiation analysis, the summer (July 21) and winter (December 21) solstices were considered for observations.

Impacts and Analysis

A university campus building was chosen as the topic of study to explore how the surrounding context affects the solar radiation potential of the building envelope. In terms of their influence on solar radiation of surfaces and the resultant quality of findings, two main criteria were investigated: (1) the area of context; and (2) the importance of built and without built surroundings. The solar potential data are produced for each scenario and compared to one another to assess the combined and individual effects of the components that make up these scenarios. Furthermore, solar maps were generated on the surfaces of buildings, i.e., east, west, north, south, and rooftop, to observe the irradiance distribution on the building, using the functionalities and 3D visualization capabilities of the utilized Grasshopper Ladybug tool.

It has been suggested that for office buildings, the temperature ranges for comfort depend on geography and culture according to CIBSE (Rupp et al. 2022). The air conditioning of the building should be 21℃–23℃ in winter and 22℃–24℃ in summer. Temperature values higher than CIBSE standard values will influence the sustainability of the building and its life span. Hence, the

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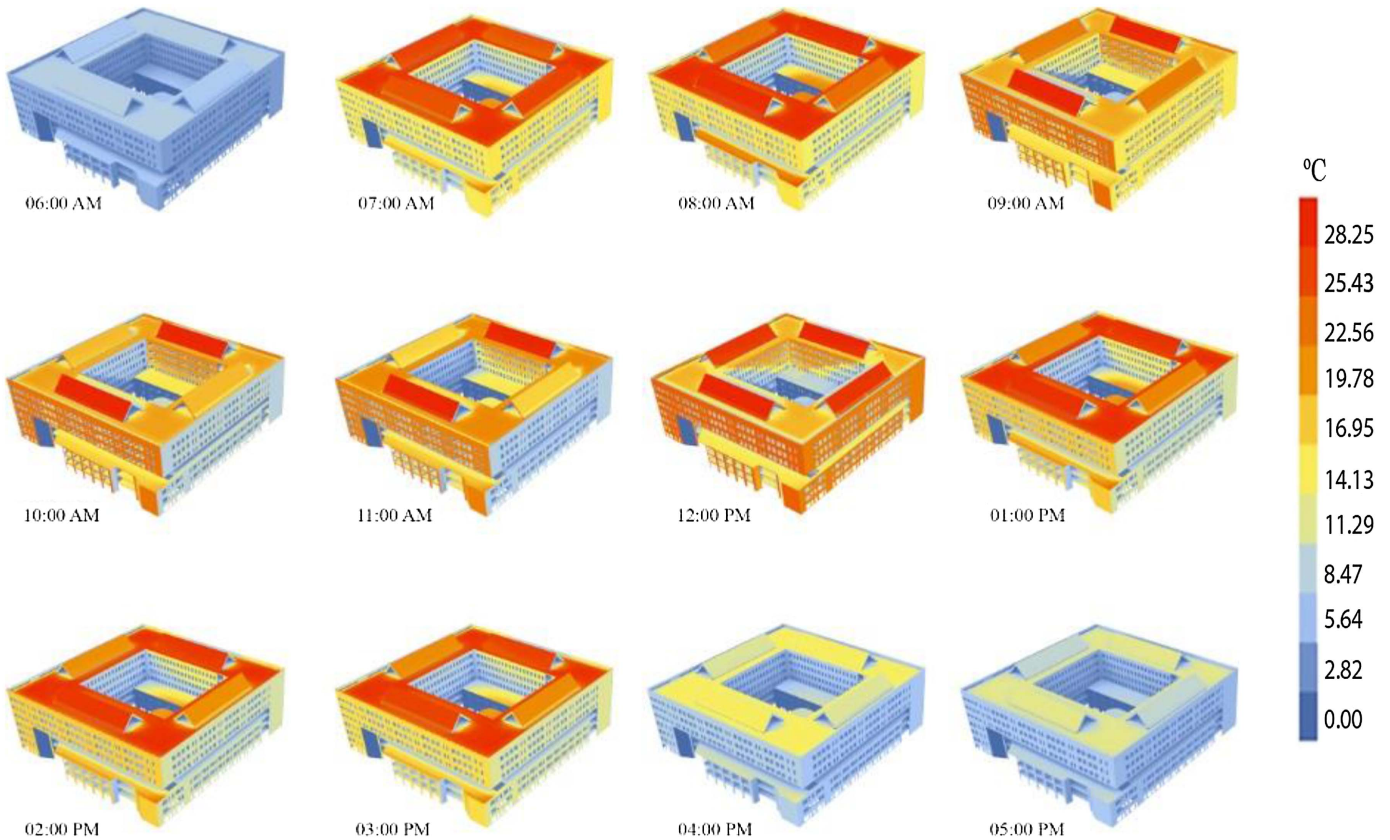


Fig. 6. Showing the real-time observations on December 21, 2021 at various time periods to validate the ground data with digital data.

impacts of built and without built surrounding scenarios under the CIBSE protocols were investigated in this study.

Analysis with Build Surroundings Context (X1). Fig. 7 represents the ISR analysis of the studied building envelope with neighborhood context (X1). The radiation that strikes each side of the building was calculated taking into account the built surrounding context. On 21 June, the maximum temperature rose to 37℃, and on 21 December, rose to 25℃. As previously indicated, the optimum temperature for a building is 23℃ in the winter and 24℃ in the summer. These results are not consistent with the values suggested by CIBSE for the summer and winter solstices. That is, for both solstices, the building shows slightly higher values of temperature than the CIBSE standards, which could have negative impacts on the sustainability of the target building. To overcome this issue, an optimized solution is required to enhance the building's performance.

Analysis without Build Surroundings Context (X2). The ISR analysis results without a build surrounding context (X2) at multiple hours of the day in summer (21 June) and winter (21 December) solstices show the maximum and minimum intensity of solar radiation on the north, south, east, west, and rooftop associated with the computing time for the ISR analysis (Table 2 and Fig. 8). The peak values are higher during the summer solstice and then decrease by a factor of 3.5 times during the winter solstice. It is worth mentioning that throughout the winter and summer solstices, the rooftop and south façades receive the most solar radiation. In light of the presented results, rooftops are the favored area for solar installations. In some cases, façades could also be decent alternatives despite having less time in direct sunlight and are consistent with similar results by Alammar et al. (2021). The building rooftop and south and west façades face maximum direct sun rays (Figs. 8 and 9). Here, the x-axis represents the north, south, east, and west of the building including the rooftop, with the y-axis representing the intensity of solar radiation in ℃. Results of the external analysis of the building block with computing periods, i.e., 07:00, 12:00, and 17:00 h, show that at 12:00 h, in summer, the building rooftop received sun rays up to 31.46℃, while the south, west, and east faced up to 20.47℃, 15.35℃, and 12.89℃, respectively. In winter, the distance of the sun from the earth decreases, and the angle of the sun with the earth changes from 66.7° to 19.8°, indicating that in winter, the temperature rises to 17.62℃. This suggests that the temperature order changes to the rooftop, east, south, west, and north by cogitating the intensity of solar radiation.

Fig. 10 shows the comparative results of built (X1) and without built surrounding contexts (X2) exposure to the intensity of solar radiation in summer (June 21) and winter (December 21) at different hours of the day. Here, the percentage of each scenario is estimated and compared with the actual reduction in the solar radiation temperature. The results indicate that at 07:00 h there is a 20% decrease in temperature after placing the neighborhood buildings. At 12:00 h, there is a 22.9% decrease and at 17:00 h there is a 45.79% decrease. Overall, in the case of built surroundings during the selected periods of summer and winter solstices, a cumulative 29.56% decrease has been found in the direct sunlight that strikes the target building compared to without built surroundings. This decrease in sunlight can be attributed to the neighborhood buildings since they shield incoming direct sun rays. As a result, the temperature decreases due to a certain height and distance from an individual building owing to a large amount of direct solar radiation striking the surrounding buildings, which reduces most of the solar energy, subsequently striking the target building blocks in the form of diffuse light.

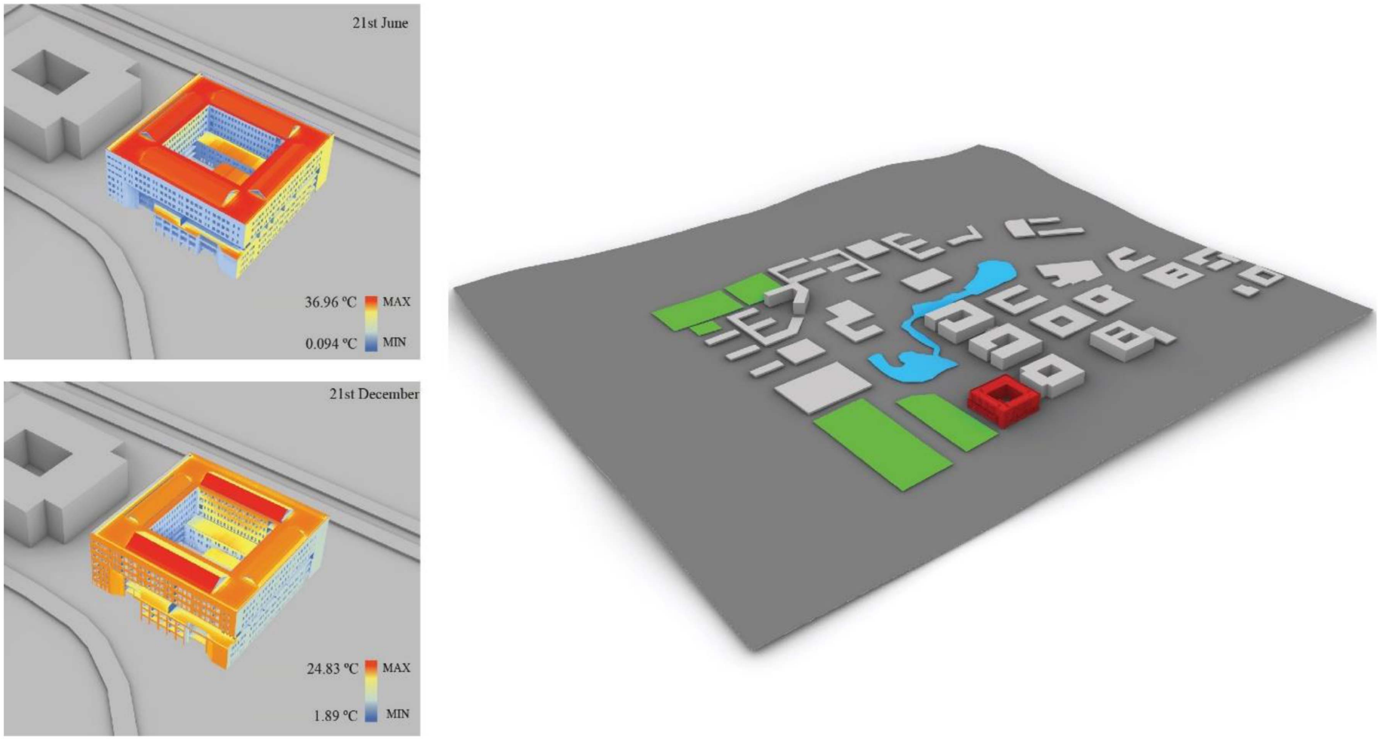


Fig. 7. Analysis with build surroundings context (X1) in summer (21st June) and winter (21st December) solstices.

Table 2. The average values of daily global ISR, temperature in °C, and computing time (minutes: seconds)

Days	Time (min: s)	Rooftop (°C)	South (°C)	West (°C)	North (°C)	East (°C)
21 June	07:00 h	14.78	10.23	8.71	7.82	16.11
	12:00 h	31.46	20.47	15.35	6.84	12.89
	17:00 h	17.62	11.37	14.21	6.10	7.91
21 December	07:00 h	12.89	6.44	3.98	2.27	8.53
	12:00 h	17.25	14.78	11.37	2.65	10.23
	17:00 h	8.53	5.11	6.63	2.08	0.94

Internal Incident Solar Radiation Analysis

Since the south-facing side of the building was most exposed to direct ISR, a single room was chosen for additional assessment. For internal ISR, the EPW files were modeled in Grasshopper using the Honeybee plugin. Initially, the room temperature was measured without a window prior to creating grids on the ground floor. By using the component "HoneybeeAnualRadiation," the intensity of the radiation passing through the window was measured as well as how it interacted with the ground floor in terms of increasing temperature. Results show that the radiation rises as it moves toward the window, while it decreases when it strikes the back end of the room (Fig. 11).

Following the previous step, the internal temperature behavior of a single south-facing room was studied. A large glass window to perform the analysis at various times of the day during the summer (June 21) and winter (December 21) solstices. For this analysis, all parameters were included as well as all materials were used to construct the room structure (e.g., concrete and brick roughness parameters, reflective and glass parameters). The internal analysis reveals that ISR enters the room through a high-intensity glass window. In the summer, the scenario for internal temperature rises to 1°C, 39.49°C, and 15.49°C at 07:00, 12:00, and 17:00 h, respectively, and 1°C, 27°C, and 4.46°C at 07:00, 12:00, and 17:00 h in the winter, respectively.

Table 3 shows the internal values of daily global solar irradiation for the summer and winter solstices with the computing time (minutes: seconds). The results show that the internal south side received maximum radiations at 12:00 h. At 12:00 h, the maximum temperature rays entered through the glass windows are 39.42°C in summer and 26.91°C in winter. According to CIBSE standards, the range for the sustainable indoor temperature of a building is 27°C–28°C in summer and 18°C–19°C in winter (Rupp et al. 2022). Our analyzed values are 41.49% and 42% greater than the CIBSE recommended temperature values in summer and winter at 12:00 h. Due to the significant increase in temperature and divergence from the CIBSE standards, the target building in this study is considered unsustainable.

Additionally, a comparative assessment of external and internal analysis shows that solar radiation falling on buildings in the morning at 7:00 h is slightly lower than that of radiation falling at noon h (12:00) and that it decreases in the evening. As previously suggested by Nugroho et al. (2022), stored thermal energy in the building envelope gets released into the atmosphere, resulting in the increase of air temperature. In climate change scenarios, the graphs clearly show a rise in temperature, which should be decreased to ensure optimum future temperatures and to make buildings more environmentally friendly. Since the south-facing side of the building is directly exposed to direct ISR, the continuous rise in temperature will have an impact on the building's lifespan and structure over time. Similarly, the intended building's rooftop is directly exposed to sunlight, which may shorten the building's lifetime and have severe implications for its occupants. To overcome this issue and enhance existing building performance, active cooling solutions could be applied.

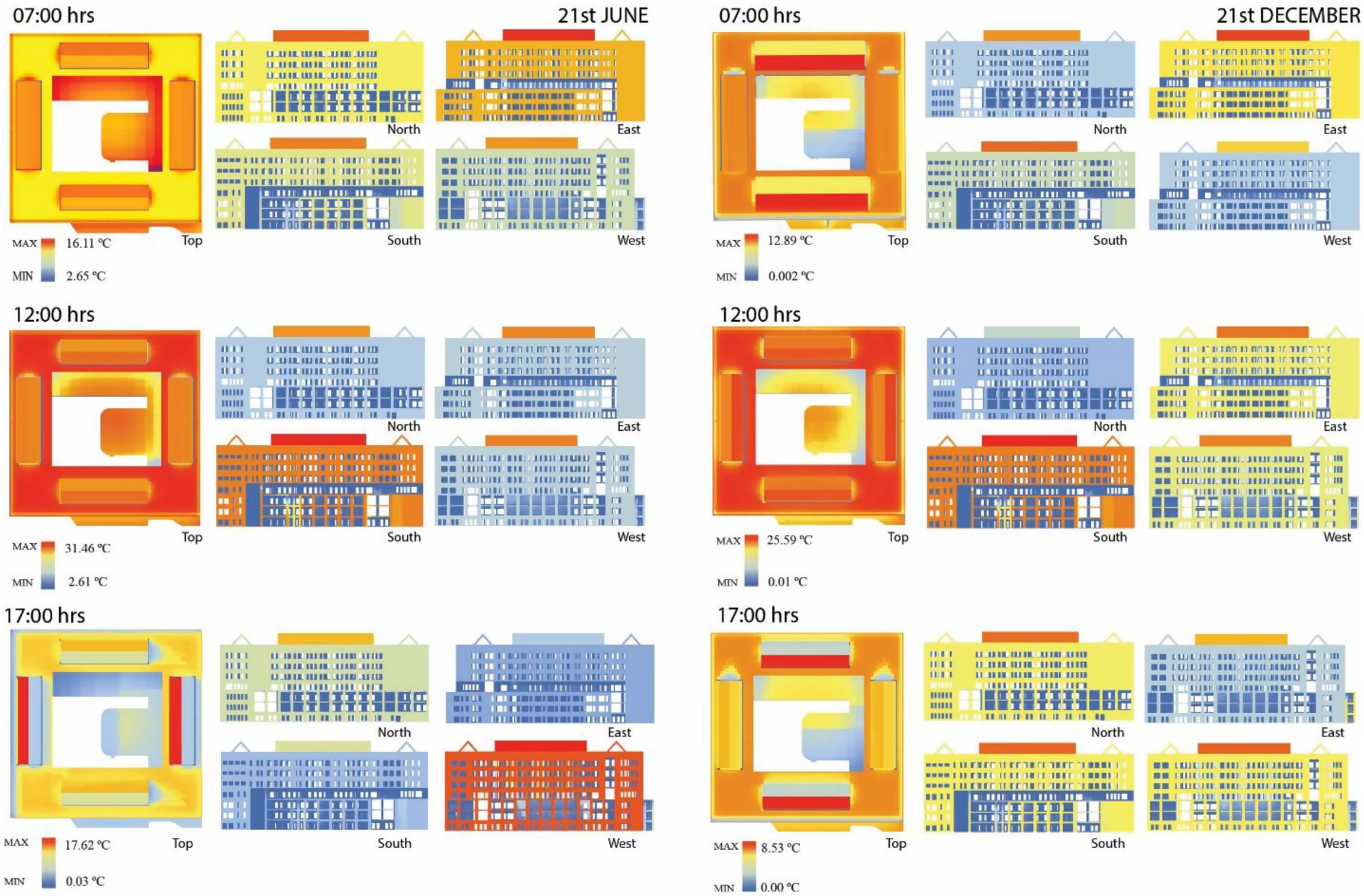


Fig. 8. Analysis without build surroundings context (X2) in summer (21st June) and winter (21st December) solstices.

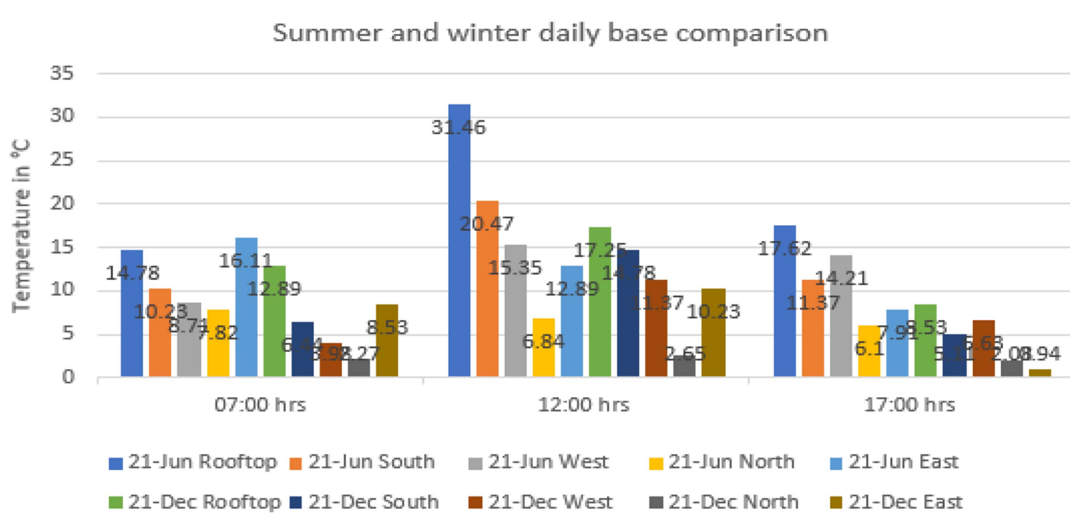


Fig. 9. Graphical representation of summer and winter solstices daily global solar radiation, temperature in °C associated with the computing time (minutes: seconds) for the ISR analysis.

Optimized Smart Solution to Enhance the Sustainability of Building

Energy performance throughout the building life cycle is an essential sustainable building design aim. To enhance the sustainability of the building, an optimized smart solution has been implemented in the building by applying a parametric kinetic façade (Fig. 12). Kinetic façades are window systems that use customized sets of multiple-glazed modules to adjust the intensity of solar radiation in a building (Luo et al. 2017). These include several subtypes, such as façades with active shading systems, double façades, and integrated façades. The parametric kinetic façade effectively reduces the intensity of sunlight entering through the glass during the

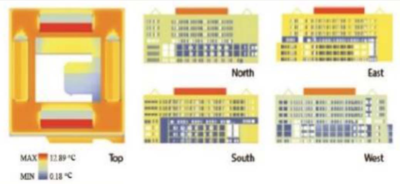
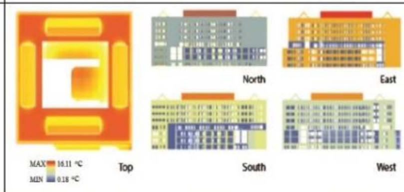
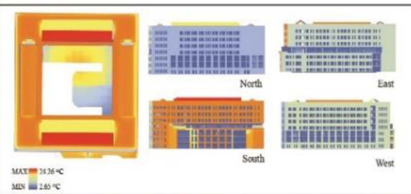
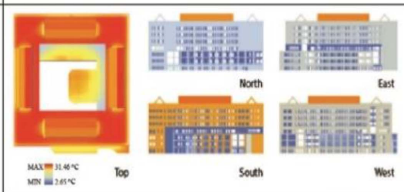
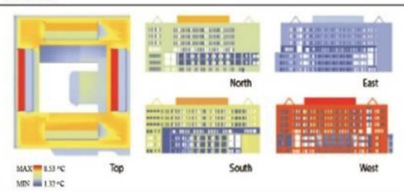
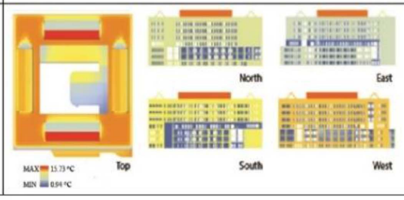
Time	Results With Build Context	With Context In °C	Results Withoud Build Context	Without Context °C	Without Context / With Context (%)	100 - Actual %
07:00 hrs		12.89		16.11	80%	20%
12:00 hrs		24.26		31.46	77.10%	22.90%
17:00 hrs		8.53		15.73	54.21%	45.79%
					Average%	29.56%

Fig. 10. Comparing results of build surrounding (X1) and without build surrounding context (X2).

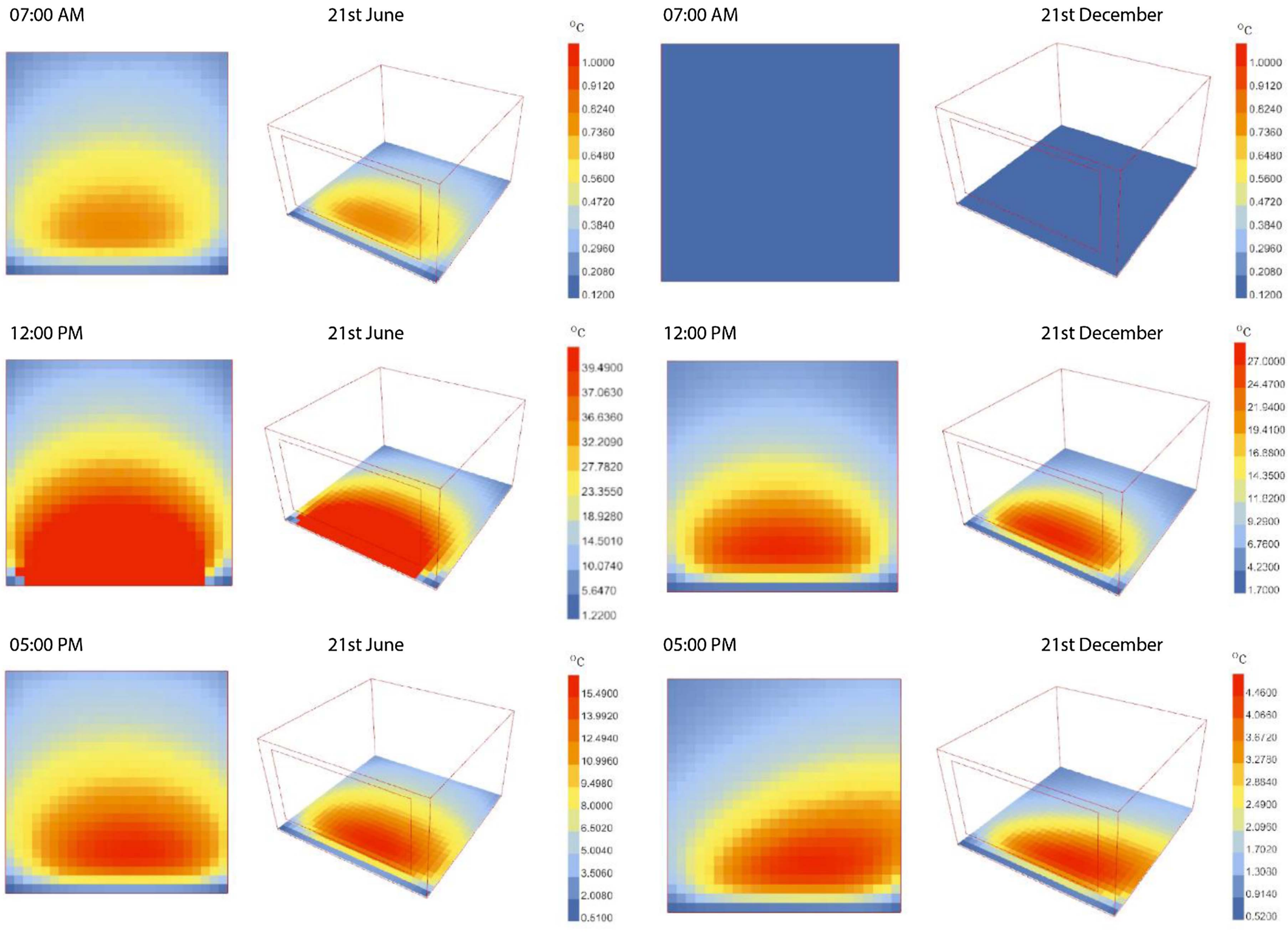


Fig. 11. Internal ISR analysis in summer (21st June) and winter (21st December) solstices.

summer months, as well as discharges surplus heat from solar radiation to the outside. As a result, the indoor environment does not heat up, providing ideal working conditions. External shades and roller blinds, as well as electrochromic shading glass, can be used to minimize light. However, in the summer, their primary purpose is to provide the best possible thermal insulation to the interior, using far less energy from the air conditioning system to provide a comfortable climate for the users. In the winter, it acts in reverse and results in decreased heating costs and energy demand.

Parametric modeling using the Grasshopper software and environmental analysis tools (i.e., Ladybug and Honeybee) indicates that for optimization application of parametric kinetic façade, a parametric design influences the geometric dimensions that are linked to the panel's material that determines the geometry (shape, position, and incoming radiation). To ensure the system's autonomy, semitransparent photovoltaic modules have been employed as the panel's material. The approach is used with a fixed glazing façade window-to-wall ratio. The parametric kinetic façade permits parameterized manipulation of geometry to regulate solar radiation from the sun with various performance criteria. The simulation tools (Ladybug and Radiance) identified potential options for performance evaluation of design variations in terms of solar radiation exposure and its energy utilization. Different types of motion of triangular units move in different ways depending on how the sun transitions throughout the day and year.

Table 3. The average value of daily global solar radiation, the temperature (°C), and related computing time (minutes: seconds)

Days	Time (min: s)	South (°C max)	South (°C min)
21 June	07:00 h	01.00	00.12
	12:00 h	39.49	01.22
	17:00 h	15.49	00.51
21 December	07:00 h	01.00	00.00
	12:00 h	27.00	01.70
	17:00 h	04.46	00.52

Opening variation is the first type of motion that alters by regulating sun radiation levels in response to weather conditions. For the whole façade's panel material, the semitransparent photovoltaic module was used to assess the direct solar radiation impact on the south side of the building. The creation of algorithmic modeling tools for architects and engineers, such as Grasshopper for Rhino, resulted from the advancement of computing in the mathematical process. To improve the energy efficiency of the building, the parametric design offers innovative building envelopes that are more adaptable and interactive by actively responding to the current weather conditions. In this study, the parametric kinetic façade functions and variables are used on the south side of the building, in response to the surroundings to see how they work when the building envelope is exposed to solar radiation.

The methodologies and functionalities of interactive kinetic façades are constrained by the practicability to interact and iterate with the output of the computer's produced design. The kinetic façade may provide solutions for more energy-efficient buildings, but they are costly and hard to maintain. Further research is required to investigate the performance of various types of building 'skins' independently, as well as compare them to cost and development feasibility models. Nevertheless, kinetic façades offer a potential solution for the design of a complete system that meets a variety of design demands (Bacha and Bourbia 2016). For example, the

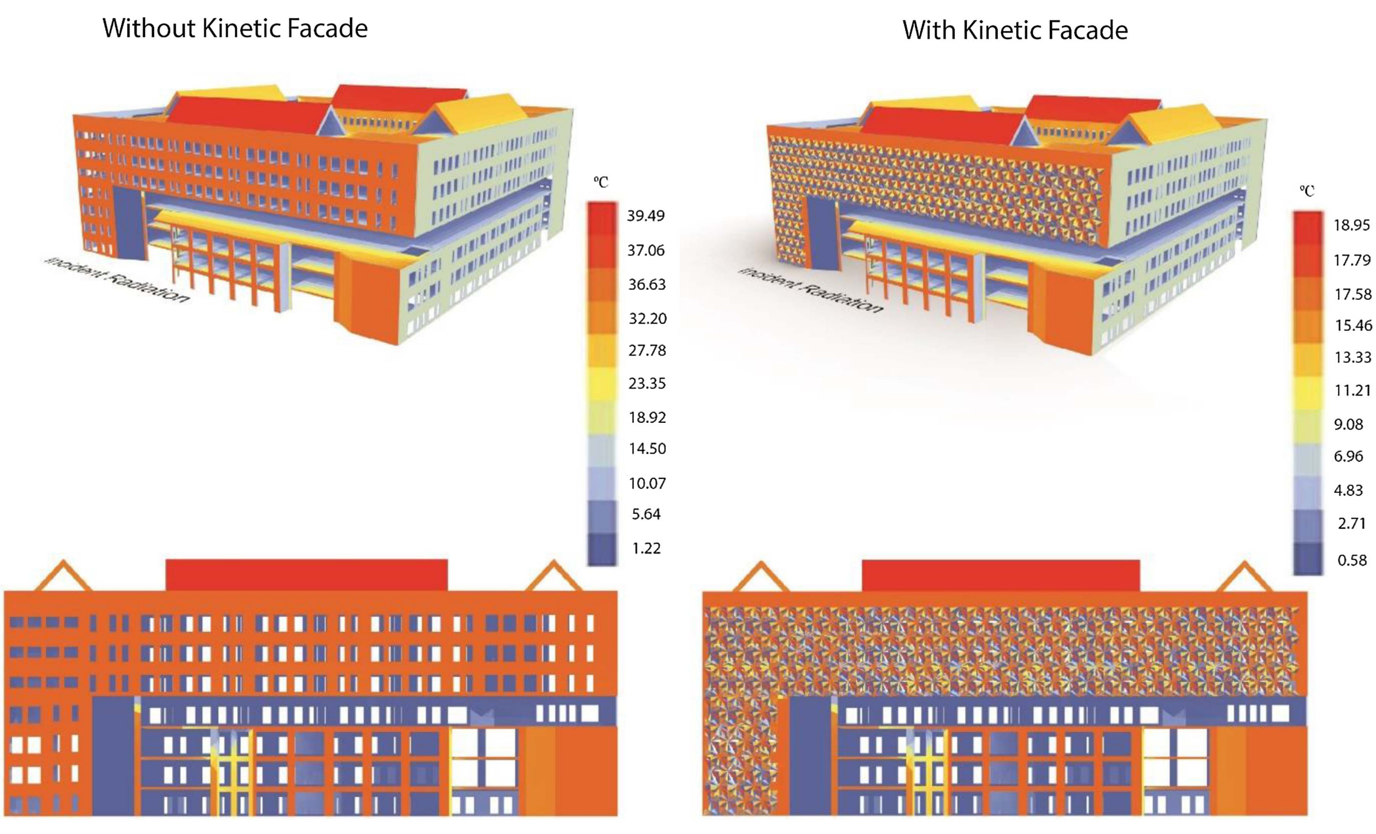


Fig. 12. Implementation of the smart solution having kinetic façades with an active shading system.

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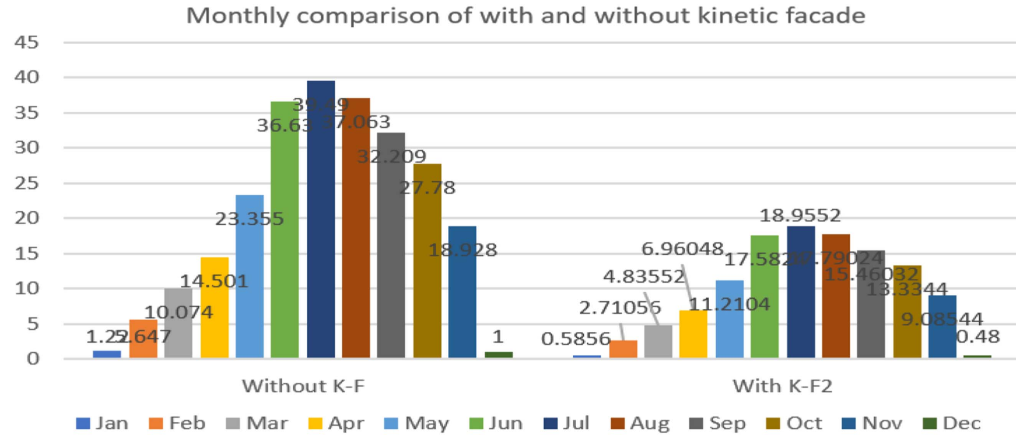

Fig. 13. Graphical representation of a monthly comparison of temperature in oC with and without kinetic façades.

results shown in Fig. 13 indicate that the period of high heat threat starts from February till November, which covers all of the working hours from 8:00 to 17:00 h. The highest temperature warming can be seen during July, August, and June, while the lowest warming trend can be observed during December, January, and February months.

Similarly, the maximum temperature of up to 40°C is marked in July (summer solstice), indicating the month whereby temperature peaks. After applying the kinetic façade system, the studied building received up to 19°C in July (i.e., a reduction of about 52%), demonstrating its significance in developing energy-efficient designs. Furthermore, the system operates independently for each façade as required for work-time protection. As shown in Fig. 12, after installing the kinetic façade system, the overheated area was reduced and the quality of daylight inside the building varied constantly during the day depending on the weather and climate.

Conclusion and Future Work

A new modeling approach was proposed that aimed to develop a 3D model of an existing building by analyzing the building's surroundings. Local weather data collected from real and measured observations were used to analyze the complete building envelope considering single representative days (summer and winter solstices). More extended periods should be considered to analyze solar energy behavior and assess their contribution to meeting the building envelope.

Recent breakthroughs in BIM technology, software, and digital manufacturing have allowed architects to experiment with new building geometries and envelope problems (ISR and surroundings context behavior with building). While solving these difficulties, experts recommend ways to save energy and improve indoor air quality by combining active and passive technological solutions. The future relies on innovative strategies based on flexible solutions for optimizing energy performance since the building envelope has become the focus of creative research and innovation in high-performance buildings.

The influence of the surrounding context on the building envelope in the presence of ISR was evaluated using a 3D model coupled with Grasshoppers tools and in association with six distinct modeling methodologies, X1, X2, internal and external ISR analysis, with and without kinetic façade, over an existing building. In light of the surrounding context, an average difference of 29.56% was recorded between with and without built surroundings. When measuring solar potential, it should be noted that the built environment has a large influence on individual buildings. Lowering the context distance, on the other hand, only conserved energy when the context height was high or mid. As a result, context height might be considered a necessary and prerequisite passive cooling strategy for enhancing interbuilding shadowing effects. 3D technology is the best source for a brighter future and a human-friendly environment according to the results. The analysis does not meet CIBSE standards, and the study building is unsustainable due to a significant spike in temperature. This is hardly unexpected considering that exterior walls carry more heat into the building, affecting thermal comfort. Parametric and quick-finding methods are needed to solve this problem. To improve building efficiency, employ fabrication, shades, louvers, and a kinetic façade on the south side. Reflective coating on the roof could reduce unnecessary heat. The kinetic façade technology reduced energy usage by 52% in the hottest month (July). Our new approach enhanced life cycle energy while lowering environmental consequences, estimating 50% of monthly efficient energy use.

The results offer further insight into this study to establish a tool and connect it to an online cloud platform that appropriately applies this approach and displays real-time energy consumption results with a produced report for each building in any location. Future study might also focus on nearby building materials, façade coatings, and their interaction with solar radiation and its impact on seasonal climate (e.g., wind flow and humidity).

Data Availability Statement

All data, models, and code generated or used during the study appear in the published article.

Acknowledgments

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