A Generative Design Approach to Improving the Environmental Performance of Educational Buildings in Hot Arid Climates. (Assiut National University as a Case Study)

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TECHNICAL ARTICLE

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ABSTRACT

The architectural design process is complex, involving diverse objectives that may be contradictory, and on which orientation exerts significant influence. The artificial intelligence application, Generative Design facilitates solving multi-objective design dilemmas through the creation and evaluation of numerous design alternatives. However, its exploration in educational buildings in hot arid climates remains limited. Given the impact of spaces' function distribution, this study aims to optimize it in the typical plans of educational buildings. Employing a multi-objective design approach to enhance environmental performance. The study is conducted and evaluated in national universities in Egypt as a case study, specifically in Assiut City.

The results revealed that the optimum design for a certain objective has not equated to optimal performance for other goals, highlighting an inherent contradiction between them. Among 26,334 possible alternatives for spaces' function distribution, the difference between the optimal scenario and the least favourable one is significant for the parameters related to study spaces: natural daylighting, and visual comfort, ranging from 10% to 24%, besides around 1% difference for parameters related to the whole building, including energy consumption, thermal comfort, and carbon emission.

This research offers a framework applicable to various building types. Additionally, it encourages decision-makers to adopt a no-cost sustainable design approach.

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LIST OF SYMBOLS

AI	**A**rtificial **I**ntelligence
BIM	**B**uilding **I**nformation **M**odeling
EUI	The total **E**nergy **U**se **I**ntensity
GA	**Gl**are **A**utonomy
UDI	**U**seful **D**aylight **I**lluminance
CEI	**C**arbon **E**mission **I**ntensity
EPW	**E**nergy**P**lus **W**eather Format
HypE	**Hyp**ervolume-Based **E**volutionary Optimization
SPEA	**S**trength **P**areto **E**volutionary **A**lgorithm
W-S courtyard case	**W**estern **S**outh Courtyard (Case 1)
E-N courtyard case	**E**astern **N**orth Courtyard (Case 2)

INTRODUCTION

The architectural design process has always been complicated as it deals with many different objectives that may contradict sophisticated design goals. Furthermore, the environmental performance of buildings is one of the main objectives worldwide since the world is suffering from climate change and a shortage of energy resources. Operation of buildings accounts for 30% of global final energy consumption, besides 26% of energy-related emissions according to the International Energy Agency, which added that "Yet the sector needs more rapid change to get on track with net zero emissions by the 2050 scenario." (International Energy Agency, 2023). Knowing that location climate and orientation have a significant effect on the performance of the building (Khidmat et al., 2022 a) and (J. Zhang et al., 2021), the orientation of spaces should be taken into consideration, as there is always an ideal orientation according to each climate zone for each function. However, in developing countries, due to economic issues, they always use typical plans with different functions facing different directions. Therefore, studying the configuration of spaces in the plan is essential to getting the optimum performance for the building since each space has its own requirements.

Designing a sustainable building is gaining more focus from everyone related to the construction industry. Therefore, there are many certifications and rating systems for buildings to be sustainable or green buildings. They all set indicators for the environmental performance of buildings, which has been studied by (Fowler & Rauch, 2006) showing that there are six main domains for building evaluation. By comparing the weight of each, Energy efficiency and Indoor environment quality have gained higher values (average of 25% and 20% respectively). While (Chandratilake & Dias, 2013) have summarized the aspects of each domain, energy efficiency includes energy usage, building envelope performance, lighting efficiency, greenhouse gas emissions, and renewable energy. Indoor environment quality includes occupant health and safety, thermal comfort, daylight, acoustic and noise control, visual quality, and indoor air quality. Moreover, educational buildings need to meet their specific multi-disciplinary performance criteria since the design of educational buildings affects the comfort of students, influencing their outcomes (Tanner, 2009). In these terms and since the significance of the environmental performance of buildings, (Park et al., 2020) have aimed to improve thermal comfort in educational buildings, while (Bian et al., 2023) and (Kong et al., 2022) have focused on visual comfort and view clarity in classrooms. Moreover, (Barbhuiya & Barbhuiya, 2013) have taken insight into the energy efficiency and occupants' thermal comfort in the educational buildings in the United Kingdom. (Sekki et al., 2015) have studied the energy efficiency of educational buildings in Finland. In addition, (Aboulnaga & Moustafa, 2016) have worked on enhancing energy performance and mitigating carbon emissions of educational buildings in hot arid climates. Numerous studies have examined different aspects of improving the environmental performance of educational buildings. These aspects include energy usage and greenhouse gas emissions, which fall under the domain of energy efficiency. Additionally, considerations have been made for the indoor environmental quality domain, through thermal comfort, daylight, and visual quality aspects. However, these studies have primarily focused on enhancing only one or at most two parameters. However, it is important to note that there is a hypothesis that these parameters can conflict with each other and that improving one may have adverse effects on others. Therefore, there is still a significant gap in comprehensively studying all these environmental parameters as a multi-objective study, which necessitates further in-depth research.

On the other hand, integrating artificial intelligence into the architectural design process is considered an opportunity to solve this multi-objective design dilemma. Generative design is counted as a sort of integration of AI in architecture, which entails a collaboration between human creativity and technology. Humans input the goals and constraints of the design problem, and the computer task with the automatic generation, evaluation, and evolution is to produce thousands of high-performing solutions and choose the optimum one (Autodesk, 2023). Moreover, generative design has been studied on different building elements, for instance, (Khidmat et al., 2022 c) studied the building form of a residential two-story wooden building and its effect on solar radiation on both the site and the building itself. (Fathy et al., 2021) and (Queiroz et al., 2021) studied facade design in terms of daylighting and thermal performance. (Khidmat et al., 2022 a) and (Khidmat et

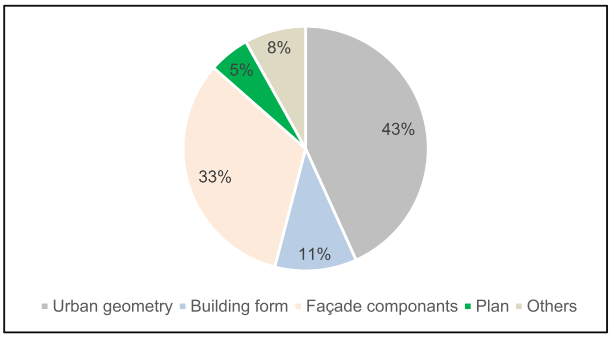


Chart 1 Generative Design Optimization Literature Ratios.

al., 2022 b) addressed different shading systems and their effect on natural daylighting, besides view and cooling energy respectively. Furthermore, related to generative design on the plan, (J. Zhang et al., 2021) have used Rhino®, Grasshopper®, and Python for the design of typical floor plans of residential buildings according to design standards, functionality, and energy consumption to gain optimum solutions. While (Rohrmann & Vilgertshofer, 2019) have used Revit®, Dynamo©, and Refinery© software for the design of an office building's typical floor plans, taking into consideration factors like footprint, facade area, form factor, rentable area, meeting area, and circulation. However, there is still a gap in this area and generative design on the level of the plan needs more exploration, especially in terms of the environmental performance of buildings. According to the analyzed literature, only 5% of the studies focus on this level as shown in Chart 1. These studies investigate functionality and energy objectives only. Furthermore, none have studied it from a retrofitting point of view.

Based on the conducted literature review, the study attempts to fill the mentioned gaps by comprehensively examining different environmental performance factors collectively in a multi-objective study at the level of horizontal plans. It contributes to proposing a simulation-based optimal spaces' function distribution aiming for an improvement in energy usage, greenhouse gas emissions, thermal comfort, daylight, and visual quality of educational buildings. The study is conducted on the Egyptian National Universitys' typical first-floor plan in the two most common building orientations on the campus in Assiut city, to find out the optimum distribution of educational spaces and offices in the plan and to get the optimum designs under these different conditions.

METHODOLOGY

The work is mainly a performance-based simulation that focuses on energy consumption, carbon emissions, natural daylighting, visual comfort, and thermal comfort. To achieve the study objectives, First, a double-track analytical study is conducted, one on a typical National university in Egypt to get a suitable case study, and the other on educational buildings to determine the space's function and environmental performance requirements, on which climate and location have a significant effect. Secondly, a parametric model is created for the case study typical educational building unit. Using Revit® (Rohrmann & Vilgertshofer, 2019) and Rhino.Inside®. Revit plugin to merge Python and Grasshopper into the modelling and simulation process. Thirdly, a multi-objective simulation study is conducted using Ladybug©, Honeybee©, and Octopus© plugins (Queiroz et al., 2021) and (Shahbazi et al., 2019), according to environmental performance criteria, examining hundreds of different generated design options to get the optimum one for different orientations. Finally, from the analysis of the results, a framework for the plan design of educational buildings in different climates is developed, which helps decision-makers apply a sustainable design approach to educational projects. The methodology is summarized in Figure 1.

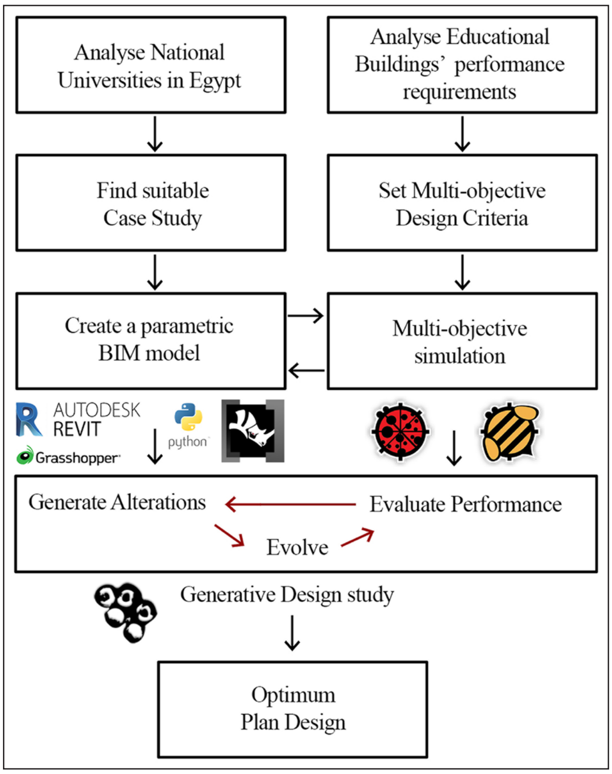


Figure 1 The Study Framework.

CASE STUDY: A TYPICAL NATIONAL UNIVERSITY IN EGYPT

Although the strategy of building national projects with typical shapes (plans and facades) may save costs in the short term, it causes extra operating costs in the long term, in the form of energy for cooling or heating besides lighting, due to the different orientations.

There are numerous educational building prototypes in Egypt. However, in recent years, the government has initiated the establishment of a national educational project comprising a series of national universities (Official Journal of Egypt, 2022) Some of these universities have already been constructed, while others are still in the planning or construction phases. The typical building design employed in this project follows site boundaries, with orientations that do not adequately consider space requirements. The study places particular emphasis on this project due to its recent implementation and widespread coverage across the country.

National universities in Egypt were selected for this study due to their representative nature across all cities, with the potential for a significant impact on the entire country if improvements are implemented. As of the study's commencement, construction has been completed in Assiut, Helwan, Beni Swif, Ismailia, Benha, and Zagazig, as indicated in Figure 2. The project utilizes two typical buildings: a square-shaped administration building with a dome and an educational U-shaped building. The research specifically focuses on the educational building unit.

Egypt's climate according to the Koppen Climate Classification subtype is mostly hot arid Climate "BWH". Assiut location has been chosen for the study, focusing on two different dominant orientations, as shown in Figure 2, Case 1; Western South (W-S) courtyard, and Case 2; Eastern North (E-N) courtyard. The effect of building orientation on the environmental performance of the campus will be evaluated.

EDUCATIONAL BUILDINGS DESIGN CRITERIA

Educational buildings play a crucial role in community development, and educational spaces must adhere to standardized multi-disciplinary performance criteria to maintain a stimulating and productive environment for students. These criteria encompass functional requirements, representing our variables, and its data is estimated from the case study. Additionally, environmental performance requirements are derived from previous literature and serve as our objectives, or evaluation parameters.

FUNCTION REQUIREMENTS

By analysing the case study, the educational building plans of national universities in Egypt shown in Figure 3, the spaces' functions can be classified into three categories:

1. Educational spaces: such as classrooms, laboratories, and lecture halls.
2. Offices: for administration and staff.
3. Services: that compromise stairs, elevators, W.C.s, and cafeterias as service cores for the building.

The location of stairs and elevators has remained unaltered to conform to the building codes of Egypt. Furthermore, the research aims to improve its practicality by serving as a potential retrofitting plan for existing educational structures and a redesign strategy for those yet to be built. This is achieved by identifying an optimal typical plan that distributes various functions across all

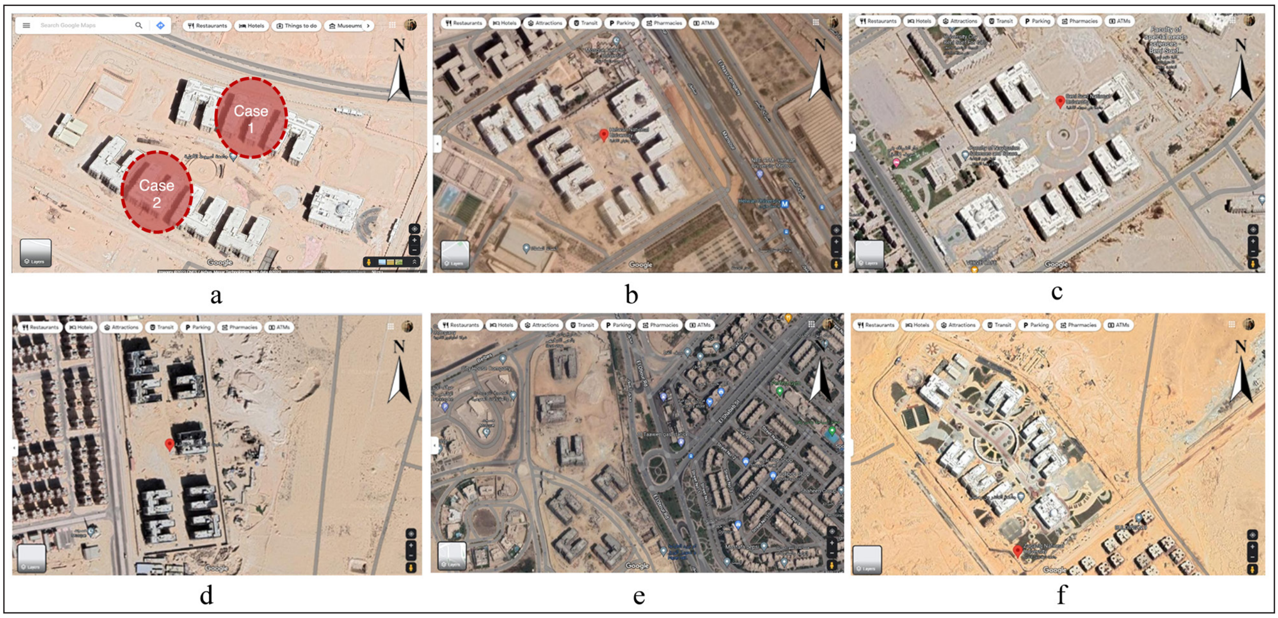


Figure 2 Masterplan of National Universities in different cities in Egypt. **a)** Assiut city (27°16'28.47"N, 31°16'30.15"E), **b)** Helwan city (29°52'12.71"N, 31°19'1.34"E), **c)** Beni Swif city (29°2'3.00"N, 31°7'19.21"E), **d)** Ismailia city (30°35'9.38"N, 32°21'15.96"E), **e)** Benha city (30°14'46.46"N, 31°27'24.10"E), **f)** Zagazig city (30°14'32.76"N, 31°42'5.57"E).

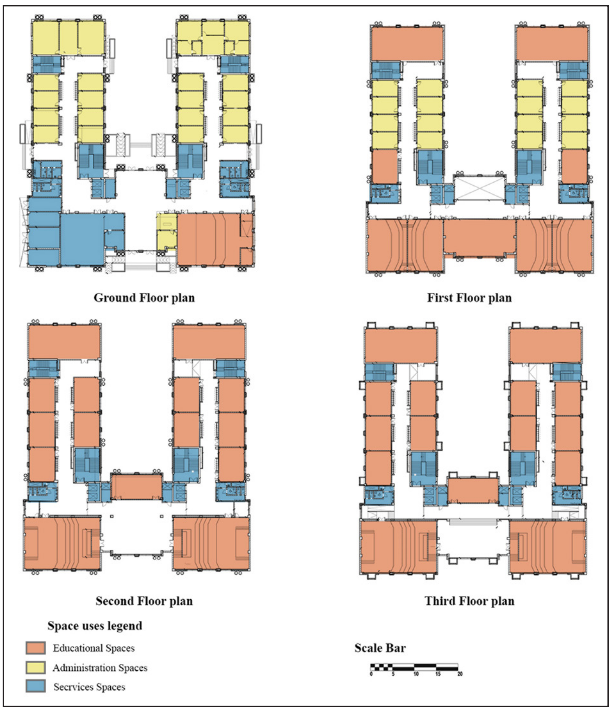


Figure 3 Educational typical building floor plans of National Universities in Egypt.

levels to maximize the utilization of different orientations, following the concept of a multi-function floor. This contrasts with the current approach of somehow a single-function floor, which concentrates administrative spaces on the ground and first floors only, leaving the second and third floors with only educational spaces facing various orientations. The entire building has undergone comprehensive calculations of areas and ratios, revealing that, aside from services, educational spaces constitute approximately 77%, while administration and staff offices make up around 23%.

ENVIRONMENTAL PERFORMANCE REQUIREMENTS

To enhance the environmental performance of the educational building the study focuses on the following aspects:

Energy usage

Energy usage includes cooling, heating, lighting, equipment, and others. The study takes total energy consumption as an indicator of the environmental performance of the building in the form of the total end-use intensity (EUI) (Pilechiha et al., 2020). EUI is the sum of all electricity, fuel, district heating, cooling, etc. divided by the gross floor area (including both conditioned and unconditioned spaces). The value is in kWh/m^2. This objective is studied for the whole building.

Greenhouse gas emissions

To study the environmental effect of each design option, the study calculates the total annual carbon emission intensity (CEI) for 2030 (Y. Zhang et al., 2022) CEI is the sum of all operational carbon emissions divided by the gross floor area. Units are kg CO_2/m^2. This objective is studied for the whole building.

Thermal comfort

Thermal comfort has been examined as the Total Comfort hours percentage parameter (Cheng et al., 2020) which is the percentage of the data on the psychrometric chart that is inside a comfort polygon. The criteria for the comfort polygon set were between 22°c and 27°c for operative temperature (Carlucci & Pagliano, 2012) and between 40 and 60 percent for the relative humidity to minimize adverse health effects (Arundel et al., 1986). This objective is studied for the whole building.

Daylight

One of the most accurate indicators of the environmental performance of buildings in terms of natural daylighting is Useful Daylight Illuminance (UDI). UDI is a daylight metric that describes how useful the illuminance levels are inside a room annually, (Nabil & Mardaljevic, 2006) have introduced UDI as a new method for assessing natural daylighting in buildings. Unlike traditional methods that only provide an overall daylight level, UDI provides detailed information on the levels of daylight illumination throughout the year, considering both useful levels and excessive levels that can cause discomfort and unwanted solar gain. Their article compares UDI with other methods such as daylight autonomy and daylight factor for evaluating daylight provision in different design variants of a building. The results show that UDI offers a more comprehensive assessment of daylight conditions and can be a valuable tool for designing buildings with optimal levels of daylighting. This objective is studied for educational spaces only.

Visual comfort

To investigate the level of visual comfort, the study relied on Glare Autonomy (GA) (Shirzadnia et al., 2023), to find out the annual level of the students' visual comfort in the studying spaces. GA is the percentage of occupied hours falling within a given range of daylight glare probability values, within the range of human visual comfort, for each measured point on the interior working surface throughout the year. In other words, GA is the percentage of time without glare. This objective is studied in educational spaces only.

MODEL GENERATION

The study's methodology primarily employs simulations, using software to develop models and conduct a multi-objective performance analysis to attain the optimal design that fulfils the design objectives.

SOFTWARE

Building Information Modeling (BIM) tools are widely used by architects generally and especially in generative design since they are powerful in integrating building information into the process. Revit® is the most common BIM tool used in generative design studies reviewed. (Vahdatikhaki et al., 2022), (Fathy et al., 2021) and (Filippo et al., 2021) have used Revit®, Dynamo©, and Refinery© software as tools for generative design. However, Rhino® and Grasshopper® are the most used generative design tools due to the availability of simulation plugins like Ladybug©, Honeybee©, and others. (Khidmat et al., 2020), (Queiroz et al., 2021) and (Shahbazi et al., 2019) have used Grasshopper®, Ladybug©, Honeybee©, Radiance®, and Octopus© software. On the other hand, a programming language like Python can help complete some tasks that may not be available in the visual programming tool and create an algorithm for evaluating some objectives. (J. Zhang et al., 2021) have used Python as a helping tool besides Rhino® and Grasshopper®. Thus, this research will merge all tools to benefit from each in its powerful areas. Using the plugin, Rhino.Inside®.Revit merges Rhino® and Grasshopper® in the process, besides using Python scripts inside Grasshopper® to help solve different problems. Figure 4 shows the generative design process through the study and the software used.

MODEL CREATION

The process starts with creating a digital model which takes three steps to be ready for the simulation, starting with the building model, then converting it to a parametric model that changes according to required variables, and ending by changing it into an energy model that is ready for simulation.

The main aim has been to make the script applicable in many cases; therefore, the focus is to find a way to model the building and make the procedures read any building regardless of its shape or even the number of spaces. So, the idea is to make a relationship between the building model and the procedures to query the changeable spaces and then convert them to the required new functions.

Building model

Firstly, the typical educational four-story building is modelled in Revit® as shown in Figure 5, The building comprises twenty-one changeable spaces on the first floor. As shown in Figure 6, the spaces are all named rooms to make them easily queried by the script in the next step, except for the corridor and service core, which will not be changed. The study has committed to keeping areas around twenty-five square meters multipliers, so

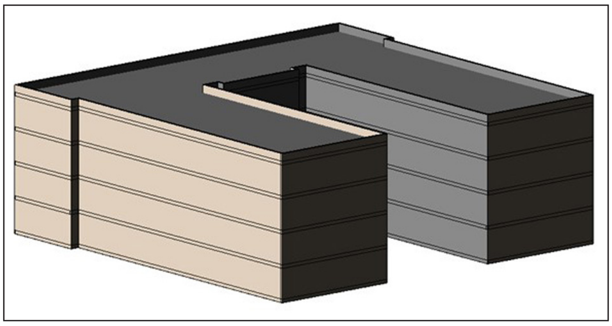


Figure 5 3D model in Revit®.

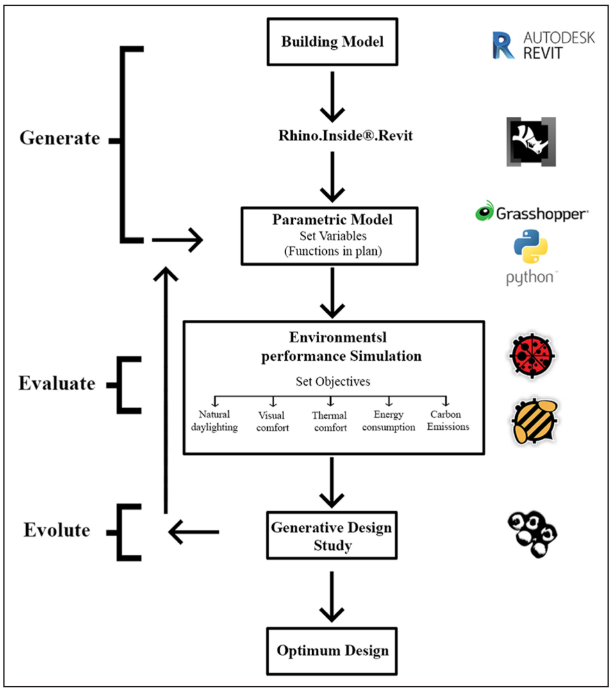


Figure 4 Generative design procedure.

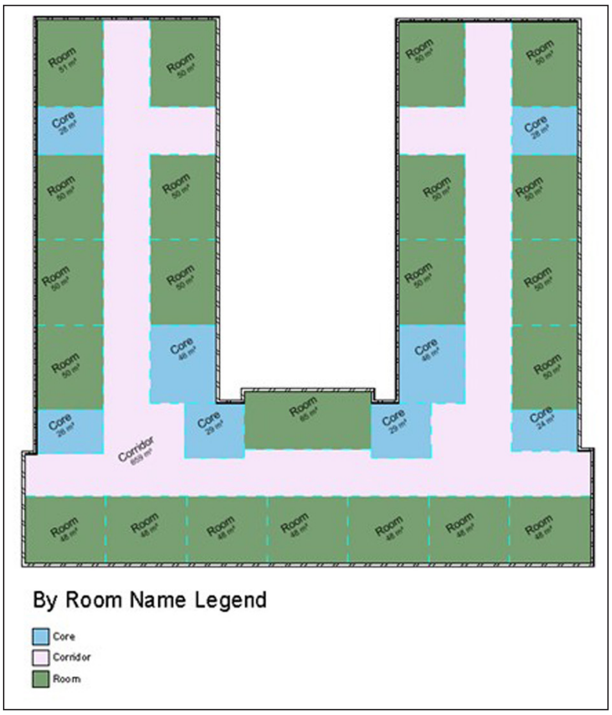


Figure 6 Typical First-floor plan.

the plan has been divided into spaces of fifty square meters, which makes it easy to modify for different uses. It can be used as a classroom, divided into two offices, or two units merged to form a laboratory.

The study is done on the first-floor plan, while the other floors will be used as a simulation environment context. The gross floor area of the plan is 2015 m², with 915 m² dedicated to corridors and services, and the remaining 1100 m² allocated for the rooms that are the subject of study.

Parametric model

In the case study, the functions are categorized into two different uses, educational spaces (classes and laboratories), and offices. Using the plugin, Rhino.Inside®. Revit, the script is written in Grasshopper®, starting by querying the rooms, and then changing the uses using a Python script as shown in Figure A 1.

While writing the script, there has been a problem in getting all possible permutations without any repetitions, since the script at the beginning has not understood that “class” and “class” are the same. Thus, Python has solved this problem also. The Python script has been written to change 77 percent of the spaces into educational spaces “class” and the remaining into administration and staff offices “office”, as shown in Figure 7. It also calculated all possible permutations that could be examined by the study after removing all permutations, they reached 26,334 design options.

Energy model

At this stage, the script changes the model into an energy model in Rhino® to be ready for the simulation step, first by changing it to be readable volumes in Rhino® as shown in Figure A 2, then converting it to a Honeybee© energy model as shown in Figure A 3.

For the simulation, each function has a different schedule and program; this is scripted as shown in Figure A 4 and assigned to each space as shown in Figure A 5. Finally, the energy model is shown in Figure 8.

PERFORMANCE-BASED MULTI-OBJECTIVE SIMULATION

After setting the parametric model according to the variables, which are the different functions to be distributed on the plan, the criteria to achieve through running a performance-based multi-objective simulation have been set to be examined.

SIMULATION OBJECTIVES

The study aims to enhance the environmental performance of educational buildings by achieving the following targets:

- Minimizing the amount of total Energy Use Intensity (EUI). Through a script written by Honeybee©, as shown in Figure A 6.

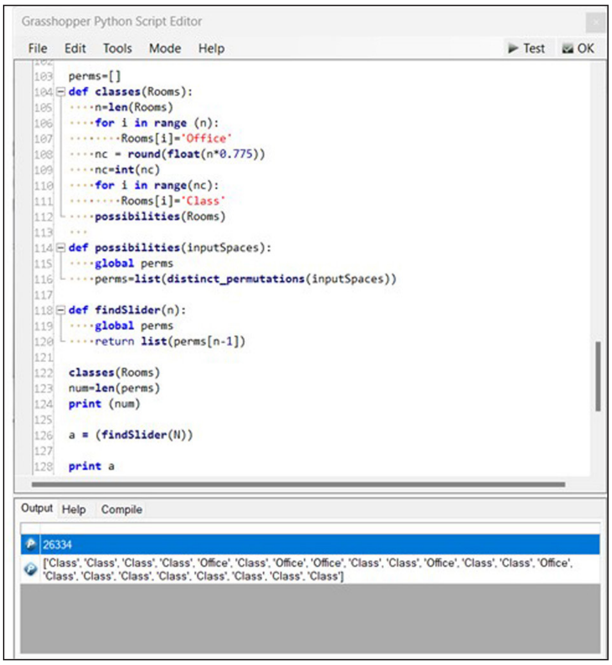


Figure 7 Python Script for changing the functions of the rooms without reparations.

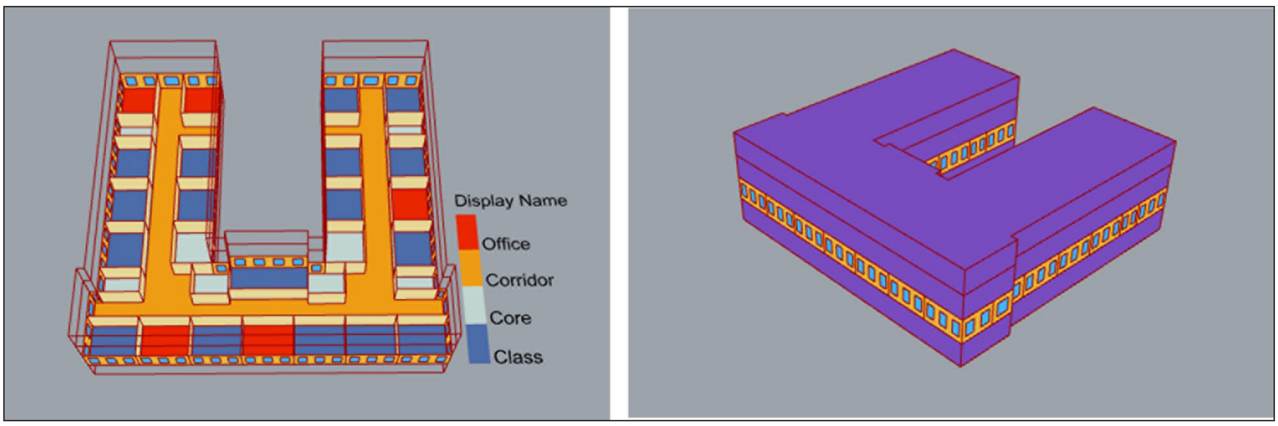


Figure 8 Energy Model in Rhino®.

- Minimizing the amount of carbon emission intensity (CEI) for 2030. Through a Honeybee© component, as shown in Figure A 7.
- Maximizing the percentage of total thermal comfort. Through the Total Comfort parameter in Ladybug©, as shown in Figure A 8.
- Maximizing the percentage of Useful Daylight Illuminance (UDI). Through a sensor grid created for educational spaces using Honeybee©, as shown in Figure A 9.
- Maximizing percentage of Glare Autonomy (GA). Through a sensor grid created for educational spaces using Honeybee©, as shown in Figure A 9.

These targets will be the outputs of the generative design study that will help in the evaluation and evolution of the design options.

GENERATIVE DESIGN OPTIMIZATION ALGORITHM

The study utilizes Octopus© for multi-objective optimization, a plugin in Grasshopper®. Octopus© utilizes two different algorithms for optimization SPEA-2 (Strength Pareto Evolutionary Algorithm) and HypE (Hypervolume-Based Evolutionary Optimization). The study uses the HypE algorithm because it is faster and more effective than others (Johannes Bader & Eckart Zitzler, 2008). Mainly genetic algorithms for generative design are composed of three stages; Generate, Evaluate and Evolute as shown in Figure 4. The initial phase of the algorithm involves the generation of a collection of designs that constitute the initial 'generation'. Various strategies can be employed by genetic algorithms to generate these initial designs. Nevertheless, the prevailing approach typically involves randomly selecting designs from the design options. In the present scenario, a population size of 150 designs is utilized. Next, in the Evaluation stage, the algorithm proceeds to determine which of the initial designs will be utilized in generating the subsequent generation. Various methods can be employed for this purpose, but the overarching objective is to ensure that superior designs have a greater likelihood of being chosen. This ensures that effective strategies discovered in the initial generation are carried forward into the succeeding ones. The process of selection and crossover guarantees that a majority of the advantageous designs from each generation are incorporated into subsequent generations. However, relying solely on these methods can result in a suboptimal solution, as the best solution may remain elusive if none of the designs in the first generation possess the potential for it. Similar to natural processes, a mechanism is required to introduce new information randomly into the gene pool. This is accomplished through the implementation of a 'mutation' operator, which randomly alters the inputs (to a small extent) before they are introduced into the next generation, this represents the third stage of Evolution. In this study, the probability of mutation is set at 0.2, while the mutation rate is 0.9, and the crossover rate is 0.8. By repeatedly applying these operators over a sequence of 10 generations, the algorithm eventually converges towards the correct solution. All settings applied in the Octopus© interface are shown in Figure A 10.

The optimization of the Octopus© plugin primarily depends on minimizing values. However, there are specific objectives that necessitate maximization. To overcome this challenge, these objectives are multiplied by a negative one (Value x -1). By applying this technique, the desired results can be achieved.

Generative Design Study

Octopus© software is utilized in the generative design study to identify the most suitable design that offers the highest level of environmental performance from a range of potential solutions. Out of 26,334 possible alternatives, the study investigates 1500 designs in the form of 10 generations, each consisting of approximately 150 solutions. This number of generated solutions is considered adequate in comparison to all the potential alternatives, as it allows for the attainment of an almost optimum solution. However, it is important to acknowledge the possibility that there may exist marginally superior options that necessitate additional generations and, consequently, more simulation time. To address this, an extended simulation has been conducted for case 1, involving the examination of 35 generations. Nevertheless, the disparities between the new solutions obtained through this extended simulation are insignificant. From an alternative perspective, the Optimum Design appeared in Generation number 5 and 6 for Cases 1 and 2 respectively, suggesting that a total of 10 generations may be satisfactory in yielding precise outcomes. Figure 9 represents the full Grasshopper© script written for the study, representing all previous stages.

Verification

To verify our generative design algorithm, the study has analyzed two different orientations (J. Zhang et al., 2021), using their EnergyPlus Weather format (EPW) files (EnergyPlus, 2023). The angles in Case 1 and Case 2 are 200° and 32°, respectively. The results revealed that each case has its unique optimum spaces' function distribution, as discussed in the following section.

RESULTS AND DISCUSSION

The graphical representation of the multi-objective optimization conducted across the two distinct scenarios is depicted in Figure 10 providing a perspective and top view of the results. The X-axis

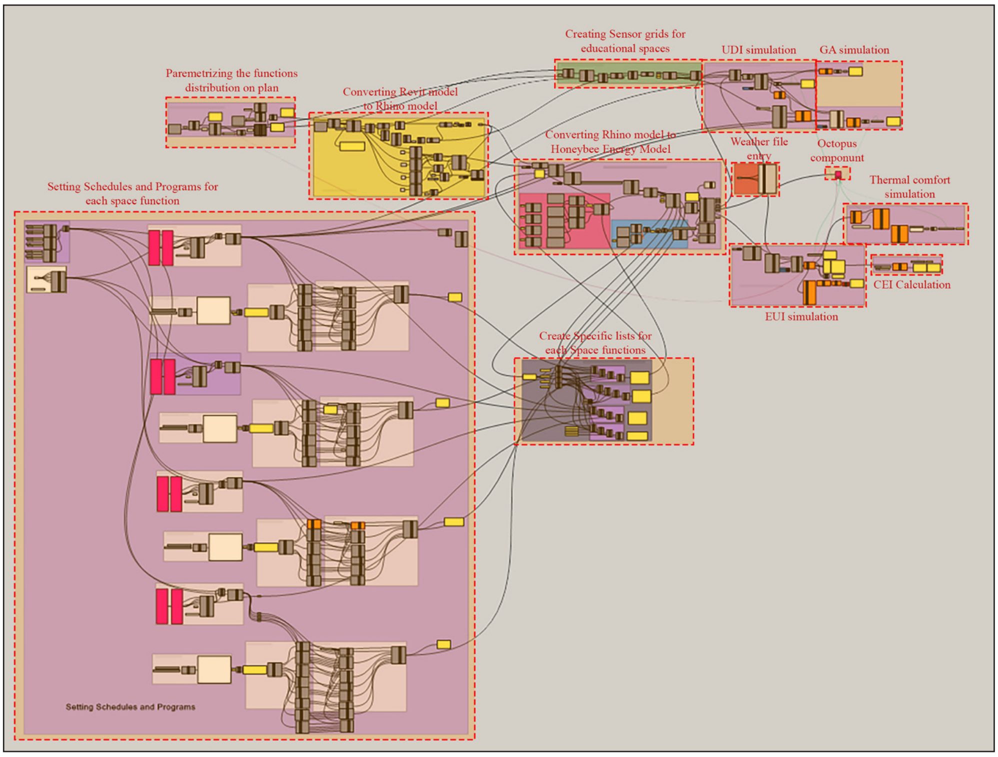


Figure 9 The Grasshopper Script written by the author.

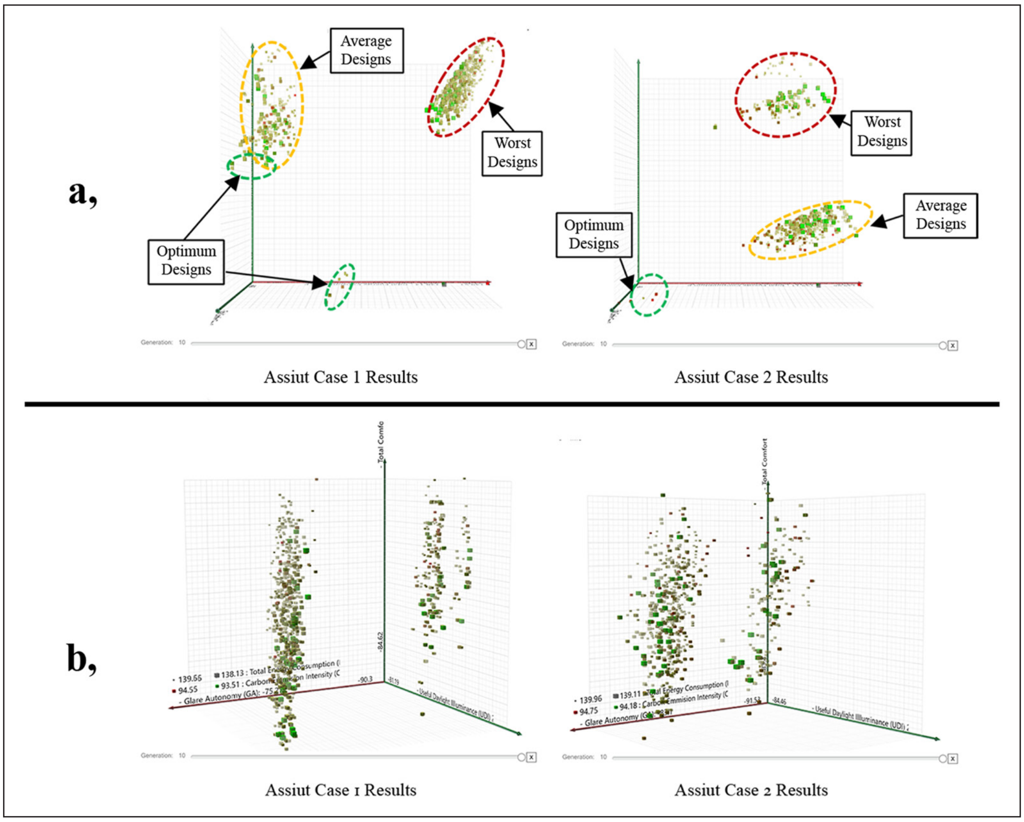


Figure 10 The graphical representation of multi-objective optimization results in the Octopus© interface. **a**, in the Top view. **b**, from a Perspective view.

represents Glare Autonomy (GA), the Y-axis represents Useful Daylight Illuminance (UDI), and the Z-axis represents Total Comfort. Additionally, the size of the data points represents the total Energy Use Intensity (EUI), while the colours represent the Carbon Emission Intensity (CEI). It is important to note that the Octopus© technique relies on minimization, therefore, values closer to the origin indicate optimal designs, while those farther away from the origin indicate unfavourable designs.

When observed from the top view, the relation plotted is between GA and UDI. It can be classified into three distinct clusters for each case. Firstly, the optimum designs cluster, which is located near the origin, represents designs that achieve high levels of performance in GA and UDI. It is very clear in Case 2 that the courtyard opening direction (Eastern north) achieves optimum levels in both GA and UDI in the same design. However, these designs are represented in small and red dots, revealing their adverse effects on EUI and CEI. On the other hand, in the W-S courtyard case, it appears that there is no cluster near the origin revealing that the optimum scenario is to get high UDI or GA values with lower levels of the other. Next, we encounter the subsequent cluster of designs that exhibit average performance. These designs demonstrate elevated levels in one objective but lower levels in the other. In the first scenario, the average design showcases heightened levels of GA, whereas, in the second scenario, it exhibits elevated levels of UDI. This observation suggests that the orientation in the first scenario significantly affects GA, while the orientation in the second scenario has the most significant effect on UDI. Finally, the third cluster comprises the least favourable designs in terms of both objectives. On the other hand, by taking an insight into the perspective view, taking Total Comfort (represented in the Z-axis) into consideration, it seems that the clusters near the origin in both cases are raised in the Z-axis, stating that optimum designs in terms of GA and UDI have low levels of thermal comfort.

Next, the results have been gathered and analysed in tables, aiming to identify the best and worst design alterations.

The courtyard opening in Case 1 is located on the western-southern side, slightly closer to the south. While in Case 2, the opening is on the eastern-northern side. The results in Table 1 indicate a substantial difference between the best and worst designs in GA and UDI, at approximately 20% and 13%, respectively for the W-S Courtyard case, and at around 10% and 24% for the E-N courtyard case. However, there is no significant difference in Total Comfort, CEI, or EUI, as they all remain within 1%. Nevertheless, these low percentages compensate for a reduction of 2.085 and 1.155 Tons of CO_2 emissions per floor in the W-S courtyard case and E-N courtyard case respectively, besides 3082 and 1707 kWh for each floor. From an alternative standpoint, the W-S courtyard case is regarded as superior to the E-N courtyard case when considering factors such as EUI, CEI and Total Comfort. Nevertheless, it exhibits diminished levels of UDI and GA.

Comparing the optimization results with that of the base case, there is a significant enhancement for the W-S Courtyard case in terms of GA and UDI at about 18.39% and 10.54% respectively. For the E-N courtyard case, the maximum possible enhancement is 9.12% and 6.31% respectively. This is because it already has relatively high levels of GA and UDI at 83.88% and 79.44% compared to 76.27% and 73.45% for the W-S Courtyard case. For both

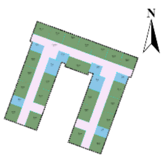
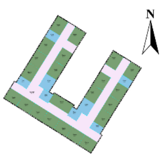
	ORIENTATION	ATTRIBUTES	OPTIMUM VALUE	WORST VALUE	DIFFERENCE PERCENTAGE	DIFFERENCE VALUE	BASE CASE VALUE	MAXIMUM ENHANCEMENT PERCENTAGE
Case 1 W-S courtyard case		Glare Autonomy	90.30 %	75.26 %	19.99 %	15.04 %	76.27%	18.39%
		Useful Daylight Illuminance	81.19 %	71.86 %	12.98 %	9.33%	73.45%	10.54%
		Total Comfort time	84.63 %	83.85 %	0.93 %	0.78%	84.35%	0.33%
		Carbon emission intensity	93.51 $kgCO_2/m^2$	94.55 $kgCO_2/m^2$	1.09 %	2085 $kgCO_2$	94.25 $kgCO_2/m^2$	0.78%
		Total Energy Consumption	138.13 kWh/m^2	139.66 kWh/m^2	1.10 %	3082 kWh	139.21 kWh/m^2	0.78%
Case 2 E-N courtyard case		Glare Autonomy	91.53 %	83.08 %	10.16 %	8.44 %	83.88%	9.12%
		Useful Daylight Illuminance	84.46 %	67.90 %	24.38 %	16.55 %	79.44%	6.31%
		Total Comfort Time	83.40 %	82.67 %	0.88 %	0.72 %	83.12%	0.33%
		Carbon emission intensity	94.18 $kgCO_2/m^2$	94.75 $kgCO_2/m^2$	0.60 %	1155 $kgCO_2$	94.79 $kgCO_2/m^2$	0.64%
		Total Energy Consumption	139.11 kWh/m^2	139.96 kWh/m^2	0.61 %	1707 kWh	140.01	0.64%

Table 1 Cases 1 and 2 general results and differences.

cases, the highest achieved improvement in EUI, CEI and Total Comfort is less than 1%.

ORIENTATION CASE 1 (WESTERN SOUTH COURTYARD)

In the W-S courtyard Case, the study findings presented in Figure 11, beside Tables A 1 and A 2, reveal the following insights.

Firstly, in terms of GA (Glare Autonomy), the least favourable orientation for educational spaces is primarily the southern side, followed by the western side, as these areas are utilized as offices in the optimal GA design. Conversely, the best orientation is the northern side, followed by the eastern side, particularly those located within the courtyard. These spaces serve as office locations in the worst design scenarios, which hinders the educational spaces from attaining maximum benefits, leading to reducing the visual comfort of students by 20% rather than using them as educational spaces.

Moving on to UDI (Useful Daylight Illuminance), the northern facade, besides the western ones, is considered the most favourable. In the worst designs, these spaces are utilized as offices, thereby limiting the educational spaces' access to the highest amount of useful daylight. On the other hand, the underperforming spaces are predominantly situated on the side facades of the courtyard, with the eastern side being the least favourable, followed by the western one. Utilizing these spaces as offices increases the amount of beneficial natural lighting in educational spaces by 13%.

In terms of Total Comfort, it is recommended to allocate offices on the western facades, whether they are external or within the courtyard while avoiding their placement on the north and east sides. This is

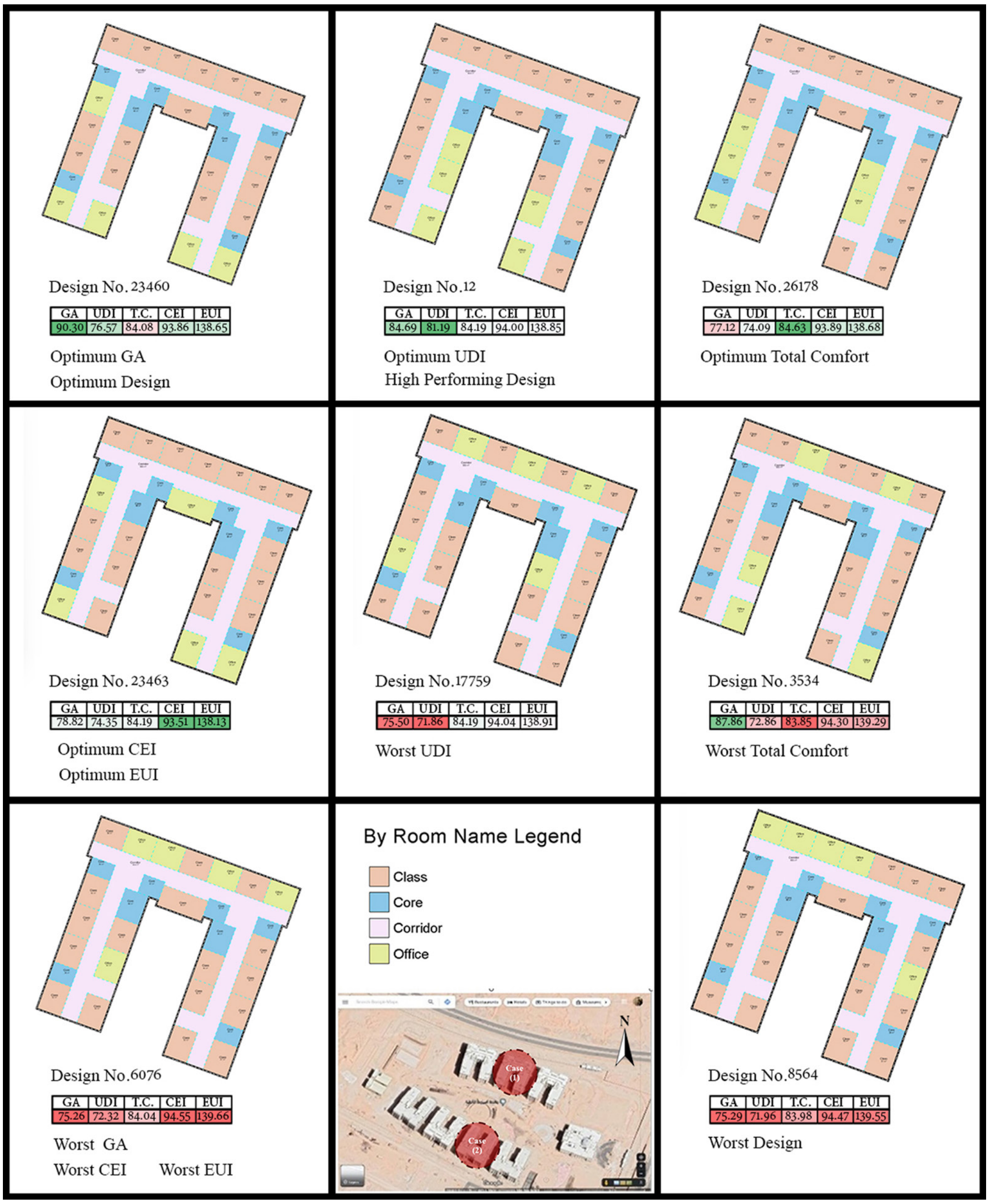


Figure 11 Orientation Case 1 (Western South Courtyard) results summary.

particularly crucial for spaces located on the corners of the building, as they are deemed the most favourable performing areas. It is advisable to utilize these spaces as educational areas that accommodate more occupants and extended operating hours.

Regarding EUI (Energy Use Intensity) and CEI (Carbon Emissions Intensity), the situation is somewhat like Total Comfort. However, there is a difference for spaces situated in the southern corners of the building, whether on the eastern or western facades. These spaces are designated for offices due to their higher energy demands for cooling, attributed to the presence of windows on two facades, one of which faces south. Similarly, the space facing the courtyard opening. Since offices typically have less demanding schedules, energy usage can be reduced by approximately 3000 kWh per floor annually. This reduction in energy usage subsequently leads to a decrease in carbon emissions by 2 tons for each floor per year.

ORIENTATION CASE 2 (EASTERN NORTH COURTYARD)

Based on the findings of E-N courtyard case shown in Figure 12, beside Tables A 3 and A 4, the study reveals the following.

Firstly, for GA, the spaces on the southern façade (especially those in the middle), followed by the eastern facade on the side of the courtyard, perform the worst. However, it is worth noting that the internal spaces on the eastern side façade of the courtyard still maintain average values in GA, as they are common in both the worst and optimum cases. While the highest performing

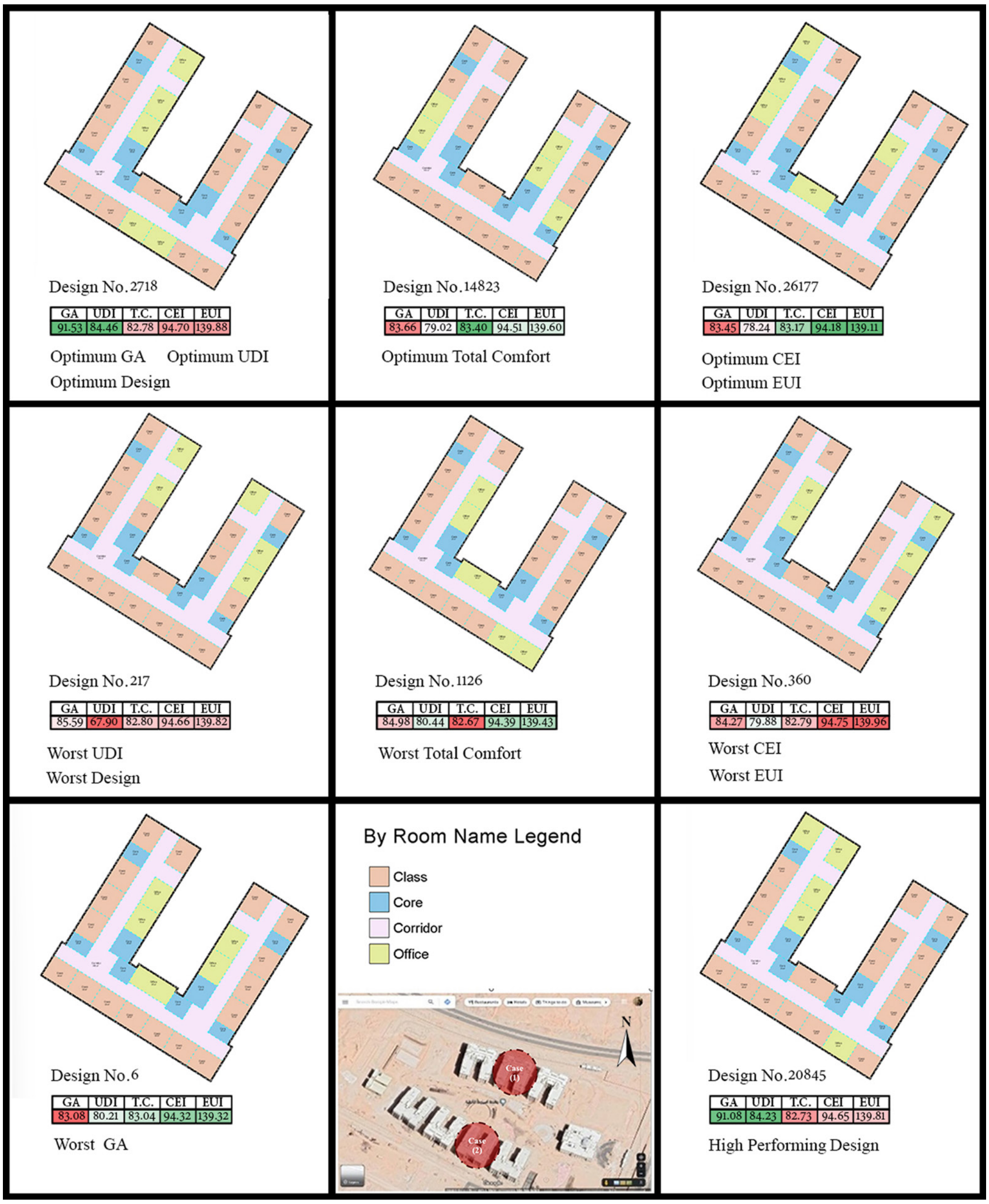


Figure 12 Orientation Case 2 (Eastern North Courtyard) results summary.

spaces are located on the western facades (especially on the side of the courtyard), besides the space facing the courtyard opening. In general, the E-N courtyard case orientation is much better in terms of GA compared to the W-S courtyard case. This is evident as even the worst design in the E-N courtyard case has 83% of the educational space falling within the acceptable range of glare, whereas that in the W-S courtyard case only has 75% of the area within the range of visual comfort.

In terms of UDI, the optimum case is the same with that of GA, the highest performing spaces are located in the western façades beside the space facing the opening of the courtyard. While the worst performing spaces are those in the middle of the southern façade, besides the eastern side façade of the courtyard. The utilization of these spaces as offices resulted in a significant enhancement of 24% in harnessing the advantages of natural daylighting within educational spaces.

In terms of Total Comfort, the spaces in the bottom corner of the southern facade, the space facing the courtyard opening, and the eastern facade of the courtyard perform the best. Conversely, the spaces on the western facades, followed by the external eastern facade (all excluding the spaces on the corner of the building), perform the worst.

Regarding EUI and CEI, the energy consumption is higher for the western facades, whether they are external or facing the courtyard, besides the space facing the opening of the courtyard. On the other hand, the eastern facades require the least amount of energy, resulting in a significant reduction in carbon emissions when used as educational spaces.

Generally, no design can achieve high levels of performance or even average performance in all objectives as a multi-objective performance-based design. Designs that excel in terms of GA and UDI tend to have low levels of Total comfort, EUI, and CEI, and vice versa.

To summarize, in Case 1 (western-south courtyard), there are two approaches to achieving a high-performing design. The first approach, which is the most optimal, involves locating the offices on the southern facade. Alternatively, the second approach suggests placing the offices on the side facades of the courtyard, excluding the space facing the courtyard opening. It is also possible to combine both strategies, as seen in Design 20,353 and 20,362. This particular combination proves to be the most effective one in achieving a high-performing design in orientation Case 2 (eastern-north courtyard). The only difference lies in the importance of restricting the placement of offices on the side facades of the courtyard to the eastern one only. This indicates that the courtyard orientation in Case 1 (western-south) is worse for educational buildings compared to Case 2 (eastern-north), as all the spaces on the courtyard in the W-S courtyard case are underperforming, whereas in the E-N courtyard case, only half of them are. Nevertheless, it appears that there could potentially be another orientation that outperforms both cases. This is particularly significant because although the E-N courtyard case offers improved natural lighting and visual comfort, it faces challenges in terms of thermal comfort and energy consumption.

The previous insights serve as a valuable design guide for single and multi-objective optimization of any building type in hot arid climates, specifically through various Orientations in Egypt as a case study. The analysis conducted through this study has revealed that the optimal distribution of spaces' functions for one objective may contradict that of others. Furthermore, the distribution varies based on the orientation of the building. These findings emphasize the need for further adjustments when utilizing a typical model for projects that cover different locations and are subject to varying site boundary conditions. Such adjustments are necessary to effectively address the climate challenges that the world is currently facing. In this regard, generative design offers a promising approach for achieving multi-objective, performance-based adjustments.

Under similar conditions, these guidelines can be applicable to other building types by prioritizing objectives according to the function of spaces, in the case study, the educational spaces are superior to offices, especially in terms of natural lighting and visual comfort. However, in other building types, the spaces' function distribution would vary depending on their specific requirements.

The results achieved especially for UDI and GA are considered significant compared to other studies considering that the study strategy is costless and does not need any additions to the building like other strategies. For retrofitting, adding shades, photovoltaic cells, or even a coating material is common, while in the design stage, many other possible strategies are applied that also need an extra cost. The study just proposes changing the spaces' function distribution to achieve better environmental performance. (Lakhdari et al., 2021) have studied the optimization of classrooms in hot dry regions and managed to increase the level of UDI to an average of 79.32 %. In addition, have increased the hours within the comfort zone by 4.62%, by adding shades and changing window-to-wall ratio, glazing type, and wall construction materials. The proposed strategy in this study achieves higher values for UDI (81.19% and 84.46% for cases 1 and 2 respectively). However, it is less effective in terms of thermal comfort and energy improvement. This raises the importance of merging other strategies in future studies. From another point of view, (Michael & Heracleous, 2017) have explored the relationship between natural lighting and visual comfort in educational architecture in southern Europe, finding that in their case study, there are proper amounts of lighting levels in the classrooms in different orientations.

However, the increase in lighting contrast and brightness causes glare and visual discomfort, especially in Eastern and Western classrooms, which raises the importance of merging natural daylighting studies with glare analysis. They utilized blinds with variant visible light transmittance, to reduce glare issues by 20% and 25% during the occupancy hours. The proposed strategy in this study achieves 18.39% and 9.12% improvement for cases 1 and 2 respectively without the need for blinds or any other shading system.

CONCLUSION

This study proposes a framework for spaces' function distribution on educational building plans through a multi-objective performance-based simulation, that utilizes Revit® as a BIM tool besides parametric design tools (Grasshopper®) with the aid of a scripting language (Python) and performance simulation plugins (Ladybug© and Honeybee©) to get optimum designs through the Octopus© plugin that benefits from HypE multi-objective algorithm. The written script (tool) can be applied to different building types, under different orientation conditions.

It is evident from the study that the optimal plan design for various environmental objectives can differ significantly depending on orientation. Consequently, employing a typical plan for diverse orientations is inadequate in addressing the current environmental challenges. To tackle this issue, university plans should be designed with the specific location and orientation in mind.

The results indicate that the best design in one objective does not necessarily guarantee the best overall performance. Furthermore, a design may excel in one objective but perform desperately in another. Furthermore, Optimum Spaces' function distribution as a multi-objective differs from that of a single-objective design. It may be more effective to utilize a design that has quite high levels in all objectives instead of achieving the optimum levels in one of them leading to underperformance in others.

The effect of spaces' function distribution is significant on objectives related to educational spaces (classes), such as natural daylighting and visual comfort, The variation in the best and worst design for them is substantial. However, the difference in overall building parameters, including energy consumption, thermal comfort, and carbon emissions, is relatively minimal. This is because the research focuses on the distribution of spaces' functions within the plan, without any alterations to the building itself. Therefore, the number of occupants and occupancy schedules, as seen in office spaces with fewer occupants and shorter occupancy times, are the only factors affecting these parameters. However, it is still an effective no-cost energy-saving technique. Nevertheless, this raises the importance of integrating this strategy with other passive and active techniques that may improve the overall performance of buildings significantly.

In the end, generative design can be an effective solution to multi-objective design dilemmas, as it provides a broader range of design options to explore that cannot be examined by traditional design methods, allowing designers to choose the most suitable design according to their predetermined criteria. The proposed framework encourages decision-makers in developing countries to adopt sustainable design practices in governmental typical model projects rather than relying on them without considering the environment.

DATA ACCESSIBILITY STATEMENT

The authors declare that the data supporting the findings of this study (Grasshopper script and Results tables) are available within the manuscript alongside the attached supplementary file (Appendices). However, if any data files are needed in another format, they are available from the corresponding author upon request.

ADDITIONAL FILE

The additional file for this article can be found as follows:

- **Appendices.** Figures A1–A10 and Tables A1–A4. DOI: https://doi.org/10.5334/fce.236.s1

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COMPETING INTERESTS

The authors have no competing interests to declare.

AUTHOR CONTRIBUTIONS

All authors contributed to the study's conception and design. Material preparation, data collection and analysis were performed by [Ahmad Mady] and [Hatem Mahmoud]. The Grasshopper script was written by [Ahmad Mady], and the Python Script was written by [Samir Elsagheer] and [Ahmad Mady]. The first draft of the manuscript was written by [Ahmad Mady] and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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REFERENCES

Aboulnaga, M and **Moustafa, M.** 2016. Sustainability of higher educational buildings. *Renewable Energy and Environmental Sustainability*, 1: 28. DOI: https://doi.org/10.1051/rees/2016016

Arundel, AV, Sterling, EM, Biggin, JH and **Sterling, TD.** 1986. Indirect health effects of relative humidity in indoor environments. *Environmental Health Perspectives*, 65: 351–361. DOI: https://doi.org/10.1289/ehp.8665351

Autodesk. 2023. *Generative Design*. https://www.autodesk.com/solutions/generative-design.

Barbhuiya, S and **Barbhuiya, S.** 2013. Thermal comfort and energy consumption in a UK educational building. *Building and Environment*, 68: 1–11. DOI: https://doi.org/10.1016/j.buildenv.2013.06.002

Bian, Y, Chen, Y, Sun, Y, Ma, Y, Yu, D and **Leng, T.** 2023. Simulation of daylight availability, visual comfort and view clarity for a novel window system with switchable blinds in classrooms. *Building and Environment*, 235: 110243. DOI: https://doi.org/10.1016/j.buildenv.2023.110243

Carlucci, S and **Pagliano, L.** 2012. A review of indices for the long-term evaluation of the general thermal comfort conditions in buildings. In *Energy and Buildings*, 53: 194–205. DOI: https://doi.org/10.1016/j.enbuild.2012.06.015

Chandratilake, SR and **Dias, WPS.** 2013. Sustainability rating systems for buildings: Comparisons and correlations. *Energy*, 59: 22–28. DOI: https://doi.org/10.1016/j.energy.2013.07.026

Cheng, J, Zhang, Z and **Peng, C.** 2020. Parametric Modelling and Simulation of an Indoor Temperature Responsive Rotational Shading System Design. DOI: https://doi.org/10.52842/conf.caadria.2020.1.579

EnergyPlus. 2023. *Weather Data files by Country*. https://energyplus.net/weather-region/africa_wmo_region_1/EGY.

Fathy, AG, El-Sayad, Z, Saadallah, D and **Bakr, AF.** 2021. BIMPO: A Generative Parametric Technique for Building Envelope Design. *WIT Transactions on the Built Environment*, 205: 127–138. DOI: https://doi.org/10.2495/BIM210111

Filippo, AD, Lombardi, M, Marongiu, F, Lorusso, A and **Santaniello, D.** 2021. *Generative Design for project optimization*.

Fowler, KM and **Rauch, EM.** 2006. *Sustainable Building Rating Systems Summary*. DOI: https://doi.org/10.2172/926974

International Energy Agency. 2023, July 11. *Buildings Energy*. https://www.iea.org/energy-system/buildings.

Johannes, B and **Eckart, Z.** 2008. *ETH Library HypE An algorithm for fast hypervolume-based many-objective optimization*. DOI: https://doi.org/10.3929/ethz-a-005703480

Khidmat, RP, Fukuda, H, Kustiani, Paramita, B, Qingsong, M, and **Hariyadi, A.** 2022a. Investigation into the daylight performance of expanded-metal shading through parametric design and multi-objective optimisation in Japan. *Journal of Building Engineering*, 51. DOI: https://doi.org/10.1016/j.jobe.2022.104241

Khidmat, RP, Fukuda, H, Paramita, B, Koerniawan, MD and **Kustiani.** 2022b. The optimization of louvers shading devices and room orientation under three different sky conditions. *Journal of Daylighting*, 9(2): 137–149. DOI: https://doi.org/10.15627/jd.2022.11

Khidmat, RP, Fukuda, H, Paramita, B and **Kustiani.** 2022c. Computational approach in investigating surface and site radiation in the early phase of designing two-story wooden house in Orio District, Kitakyushu, Japan. *Journal of Applied Science and Engineering (Taiwan)*, 25(1): 95–108. DOI: https://doi.org/10.6180/jase.202202_25(1).0010

Khidmat, RP, Ulum, MS and **Lestari, ADE.** 2020. Facade Components Optimization of Naturally Ventilated Building in Tropical Climates through Generative Processes. Case study: Sumatera Institute of Technology (ITERA), Lampung, Indonesia. *IOP Conference Series: Earth and Environmental Science*, 537(1). DOI: https://doi.org/10.1088/1755-1315/537/1/012015

Kong, Z, Zhang, R, Ni, J, Ning, P, Kong, X and **Wang, J.** 2022. Towards an integration of visual comfort and lighting impression: A field study within higher educational buildings. *Building and Environment*, 216. DOI: https://doi.org/10.1016/j.buildenv.2022.108989

Lakhdari, K, Sriti, L and **Painter, B.** 2021. Parametric optimization of daylight, thermal and energy performance of middle school classrooms, case of hot and dry regions. In *Building and Environment* (Vol. 204). Elsevier Ltd. DOI: https://doi.org/10.1016/j.buildenv.2021.108173

Michael, A and **Heracleous, C.** 2017. Assessment of natural lighting performance and visual comfort of educational architecture in Southern Europe: The case of typical educational school premises in Cyprus. *Energy and Buildings*, 140: 443–457. DOI: https://doi.org/10.1016/j.enbuild.2016.12.087

Nabil, A and **Mardaljevic, J.** 2006. Useful daylight illuminances: A replacement for daylight factors. *Energy and Buildings*, 38(7): 905–913. DOI: https://doi.org/10.1016/j.enbuild.2006.03.013

Official Journal of Egypt. 2022, September 18. National Universities establishment in Egypt cities. 37. https://issuu.com/youm7/docs/_37_ce90d8a7ae09eb.

Park, JH, Yun, BY, Chang, SJ, Wi, S, Jeon, J and **Kim, S.** 2020. Impact of a passive retrofit shading system on educational building to improve thermal comfort and energy consumption. *Energy and Buildings*, 216. DOI: https://doi.org/10.1016/j.enbuild.2020.109930

Pilechiha, P, Mahdavinejad, M, Pour Rahimian, F, Carnemolla, P and **Seyedzadeh, S.** 2020. Multi-objective optimisation framework for designing office windows: quality of view, daylight and energy efficiency. *Applied Energy*, 261. DOI: https://doi.org/10.1016/j.apenergy.2019.114356

Queiroz, N, Pereira, F and **Oscar Ruttkay Pereira, F.** 2021. *A Faster Multi-Criteria Optimization Model to Parametric Facades for Daylighting and Thermal Performance Methodological approaches for preferences and glare assessments View project Casa Nordeste: Tropical Contemporary Architecture and the 21st Century View project A Faster Multi-Criteria Optimization Model to Parametric Facades for Daylighting and Thermal Performance*. https://www.researchgate.net/publication/355874864.

Rohrmann, J and **Vilgertshofer, S.** 2019. *Design Optimization in Early Project Stages A Generative Design Approach to Project Development*. Technical University of Munich.

Sekki, T, Airaksinen, M and **Saari, A.** 2015. Measured energy consumption of educational buildings in a Finnish city. *Energy and Buildings*, 87: 105–115. DOI: https://doi.org/10.1016/j.enbuild.2014.11.032

Shahbazi, Y, Heydari, M and **Haghparast, F.** 2019. An early-stage design optimization for office buildings' façade providing high-energy performance and daylight. *Indoor and Built Environment*, 28(10): 1350–1367. DOI: https://doi.org/10.1177/1420326X19840761

Shirzadnia, Z, Goharian, A and **Mahdavinejad, M.** 2023. Designerly approach to skylight configuration based on daylight performance; toward a novel optimization process. *Energy and Buildings*, 286. DOI: https://doi.org/10.1016/j.enbuild.2023.112970

Tanner, CK. 2009. Effects of school design on student outcomes. *Journal of Educational Administration*, 47(3): 381–399. DOI: https://doi.org/10.1108/09578230910955809

Vahdatikhaki, F, Salimzadeh, N and **Hammad, A.** 2022. Optimization of PV modules layout on high-rise building skins using a BIM-based generative design approach. *Energy and Buildings*, 258. DOI: https://doi.org/10.1016/j.enbuild.2021.111787

Zhang, J, Liu, N and **Wang, S.** 2021. Generative design and performance optimization of residential buildings based on parametric algorithm. *Energy and Buildings*, 244. DOI: https://doi.org/10.1016/j.enbuild.2021.111033

Zhang, Y, Jiang, X, Cui, C and **Skitmore, M.** 2022. BIM-based approach for the integrated assessment of life cycle carbon emission intensity and life cycle costs. *Building and Environment*, 226. DOI: https://doi.org/10.1016/j.buildenv.2022.109691

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