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Performative driven form finding in the early design stage

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Abstract

One of the most crucial factors architects should consider in building energy performance design is the energy consumption of residential buildings, particularly in megacities such as Cairo. Oxman classifies that a five-paradigmatic design model can help architects generate building forms. In this study, the authors aimed to develop a form-driven design framework based on a generative design model based on shape grammar that allows architects to generate building forms based on rules, which generate the building through variables that act as genes in the fitness function. The results indicate a significant framework that can help architects select the optimum building form that saves energy by enhancing daylight penetration and thermal and cooling loads on a building. Furthermore, after optimizing radiation and cooling load metrics, the form generated significant block and balcony arrangements, enhancing the shading in the eastern, western, and southern facades. In addition, the northern façade has been developed without block projections or balconies. Finally, the optimum window-to-wall ratio generated to balance spatial daylight autonomy (SDA) and annual sunlight exposure (ASE) lighting metrics for the north facade is 60% and for the southern, western, and eastern facades 10%.

Keywords: Form finding, Shape grammar, Environmental parameters, Building performance simulation, Evolutionary optimization algorithms

Introduction

Megacities all over the world consume resources and energy. Worldwide, building operations accounted for 27% of all energy sector emissions and 30% of the world's energy consumption in 2021 [15]; Cairo has an estimated population of over ten million. Furthermore, its population continuously grows with the demand for energy and resources. In addition to climate change issues, these factors put much pressure on architects to design buildings with low-energy consumption [31]. In all parts of the world, the combined facilities and building construction sectors are responsible for 30% of total global energy consumption; moreover, they take the lead with approximately 25% of greenhouse emissions [32], according to the last report presented by the Egyptian Ministry of Electricity and Renewable Energy. Furthermore, the energy consumed by the residential sector was approximately 40% of the total energy consumption in 2019–2020 [7].

Therefore, energy-efficient residential buildings are highly recommended to meet this growing energy demand.

Adopting the design of building envelopes and generating their forms are two significant decisions that affect energy consumption [9]. Moreover, a well-designed building form provides an energy-saving and comfortable environment [32].

The design process for responsive building forms is frequently complicated due to their shape's spatial and functional sensitivity [31]. However, a building's design can allow or prevent the surrounding environment from affecting the energy balance of the building [8].

In addition, the rate of architectural change has been linked to rapid urbanization; however, additional achievements in energy savings remain to be achieved. Recently, most residents have been dissatisfied with their living environment because it lacks in natural aspects to meet human needs [33], especially in developed countries. However, the architectural design process has evolved because of the generation of new tools. The conventional design was based on users' needs, preferences, and priorities; therefore, it was not necessarily adaptable to the surrounding environment. Generative design techniques and evolutionary methods enable architects to find more alternatives with different possible solutions by integrating many parameters and metrics, which may be environmental, social, or functional, to find the optimal solution [6].

During the first half of the twentieth century, a new generation of design tools was launched that helped architects simplify the complexity of architectural design, especially when combined with a performative design parameter among various variables. For example, shape grammar is a powerful tool for form generation, precisely the initial shapes provided by multiple previous researchers. For design development, findings are placed into a genetic algorithm allowing designers to optimize design alternatives through a list of environmental metrics achieving proper review [34].

Although establishing generative design through the use of shape grammar is a well-thought-out approach, it has been the subject of previous research to analyze and generate designs. Building forms that mimic environmental building performance are still difficult to create. Therefore, there is a gap in the generation of building structures that respond to the environment in the early design stages [45].

Therefore, this research aims to generate a methodology to develop performative residential building forms based on daylighting and thermal performance metrics. First, find the optimum solutions for these forms using shape grammar rules by addition and subtraction through an evolutionary genetic algorithm combined with computational tools to obtain multiple design explorations.

Literature review

Designing is complex and challenging, yet it is an ability that an architect must learn and develop. Meanwhile, the architecture form generation method has been modified to address this issue. The form has traditionally been regarded as a generation of trial-and-error geometrical transformation techniques based on the architect's vision for meeting the requirements of users and contextual elements [22].

Engineers and architects have recently transformed the tools they use to develop buildings. Designers are now integrating the power of technology to explore the world beyond the limitations imposed by traditional design methodologies, influenced by advances in 3D modeling, material science, and automated production [2].

Oxman has divided digital design models into five paradigmatic classes, beginning with computer-aided design, the model element without generation memory, and then an approach that switches from form making to form finding called "formation design models." The availability of computer mechanisms for structured generating processes distinguishes the third generative paradigm model of digital design. The fourth model is the performative design, which exists when a digital simulation of external forces drives a form based on environmental parameters. The last is the algorithmic form creation of an integrated compound model. Formation-based design can be considered performance based, incorporating performance simulation, generative, and formative methods [21]. Furthermore, this research will focus on the integrated model for the genetic generation of building forms with the integration of the design of environmental performance.

Computer-aided design

Computer-aided design programs are switched from form creation to form discovery, and architectural techniques are shifted from fixed design to process design. However, computer-aided design is considered the only graphical representation of a digital product, unlike the formation model that remembers the history of form creation, so this will move to the next design model that evolved from form making to form finding.

Formation model

In the architectural field, parametric design was first introduced in the early 1990s, parallel to the evolution of digital design software. Its ability to reconstruct and change models based on multiple factors distinguishes it. Compared to traditional design methods, parametric design uses mathematical variables to solve complicated geometrical problems and produce advanced design models in an automated process [22]. Additionally, changes to the architectural model based on user decisions and contextual design information are time- and effort-consuming in the traditional sense [31], as models frequently require a complete redesign or critical components are constantly edited. On the contrary, parametric design allows rapid iteration by changing parametric values related to aspects of the geometrical model built on mathematical sliders that automatically adjust model geometry properties such as height, width, and number of floors [16].

Generative design

In architecture, generative design is applied in various ways. According to Singh and Gu ([28]), five commonly used generative design techniques in architecture have been described: shape grammar (SG), L systems, cellular automata, genetic algorithms, and swarm intelligence. This research will focus on shape grammar and genetic algorithms as critical components of a new product analysis and design tool generation [26].

Shape grammar

Stiny and Gips invented the shape grammar design model in 1972, a powerful computational formalization for shape generation. They have been studied for more than 40 years in various areas of design generation, starting from product design, architecture, and engineering [14]. Recently, they have been used to generate forms based on computer design systems [25].

Shape grammar is used in many fields to generate or analyze forms. For example, in the early 1990s, it was used in architectural education to teach students how to apply grammar languages in form generation at MIT, Harvard, Lille, and UCLA universities. Moreover, during the 1980s and 1990s, shape grammar tools were supposed to analyze Wright's work and the home design of Taiwanese and Japanese restaurants [13].

Multiple definitions are proposed for the shape grammar design model. For example, it was defined as a set of rules that transform the initial shape, generating new forms to help designers and decision-makers develop alternatives. A design generating or analysis tool for an existing design was also mentioned. Shape grammar has also been described as "a relation between elements," since the proposed approach is based on addition, subtraction, or replacement via shape rules [28]. What distinguishes the shape grammar process is that it is based on algorithms that can be fitted to the engineering process to obtain the optimum form.

Analyses, explanations of design, and the creation of new thematically similar strategies have all been carried out with the help of shape grammar. This research focuses on applying shape grammar to the analysis of residential buildings and the production of forms. Therefore, all studies previously selected are residential and have been used to analyze or generate building forms (Fig. 1).

Many researchers have used shape grammar rules to analyze existing building designs. For example, Hasani has reread the form of courtyards in 100 houses in Kashan city, using shape grammar (SG) to develop a decision tree based on specific rules that guide the design process for building new homes. First, the study indicates the spatial relationships between the components of the residential houses, since the decision tree was started with a point at which it was converted to a court. Then, based on the number of rooms and the spatial relationships between them, many designs were generated using a specialized algorithm [13].

Additionally, applying shape grammar principles to 44 vernacular buildings in Mazandaran in northern Iran [42] invested in the characteristics of vernacular housing and devised an efficient procedure to generate vernacular houses at the exact location. The generation process began with placing the living room as the primary space in vernacular buildings. Then, it progressed to the additional rules of other rooms in the composition of the plan. Similarly, Wang, Zhao, Fan, Yang, and Zhao ([39]) provided a shape grammar-based method to analyze the design vocabularies of 56 villages in Shandong

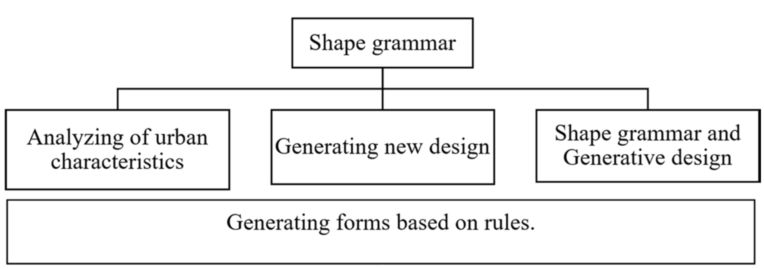


Fig. 1 Shape grammar used in architecture

province, situated on the North China Plain, through a field survey and produce new solutions to a rural housing problem. They discovered that shape grammar could successfully address the issue of matching customized mass housing designs with various user demands, and AbdulRaheem and Abdul Wahab Rayis ([1]) used shape grammar. Furthermore, Tari and Abdolhoseini ([33]) designed a new model to develop the shape pattern of houses using shape grammar, which produced a decision tree based on the concept of existing houses of the Pahlavi era.

Additionally, Schnier and Gero ([26]) established an evolutionary approach with shape grammar rules after analyzing 11 prairie houses, so 34 rules were based on developing two-dimensional functional housing plan zones. Similarly Park and Economou ([23]) were used to investigate the shape grammar rules of the courthouse designed by Mies van der Rohe. The study indicates five types of functional spaces and generative shape rules to generate new shapes. Additionally, Toussi ([34]) used genetic algorithms and shape grammar to analyze the primary characteristics and spatial functional element relationships of 30 historical houses in Kashan, Iran, before beginning to generate new building forms based on shape grammar exploring rules and generative evolutionary design. This engagement provides an effective way to analyze and develop new techniques that respect the traditional method and evolve a new one.

Aydin and Lo ([5]) used this idea to apply a participatory approach through gamification techniques to generate new homes in Kashgar's vernacular architecture. Gamification is a method of shaping grammar applications to create a master plan for single-family homes that meets the needs of the community and meets energy efficiency requirements. Form generation from scratch is another approach to applying shape grammar rules [18]. To do this, students can produce different alternatives utilizing the shape grammar design model model, which will then be assessed by rules viable with the requirements for tenability and energy efficiency. Furthermore, Upasani, Shekhawat, and Sachdeva [37] ideally suited an automated generation of rectangular dwelling floor plans based on dimensional constraints and room relationships in proportion, in which shape grammar rules occur.

Additionally, Shekhawat, Upasani, Bisht, and Jain ([27]) developed a new software called GPLAN to optimize the floor plan dimensions design based on shape grammar rules, which can generate alternatives for boundary floor plan rectangular layout adjacencies through platforms used by designers.

Shape grammar was also introduced in applying energy performance-generated design to optimize the building envelope in the early design stage. It presented a study integrating shape grammar with energy simulation to support decision-making in the early-stage design phase of the building envelope within the guidance of energy performance simulations to obtain multiple alternatives through energy simulation (cooling/heating) calculations. The new tools generated in the last decade are Rhinoceros and Grasshopper programs, which are considered algorithm-based tools that can produce forms according to geometric rules. Andino and Chien ([4]) presents the role of the Grasshopper program in the shape of grammar applications.

A design tool that combines shape grammar with a genetic algorithm to produce multiple design solutions to a given problem and find the best one is one of the most significant applications of shape grammar in the design process [6]). Additionally, this tool generates alternatives to meet specific energy metrics. Using specific guidelines and metrics, this tool has been tested on residential buildings that are thought to improve shapes.

Previous research has shown that shape grammar is valuable for analyzing and producing two- and three-dimensional forms. Moreover, multiple alternatives are generated, particularly when combined with the evolutionary genetic algorithm technique, which speeds up the design process, generates conditions based on specific metrics, speeds up the design process, and causes conditions based on specific metrics. The most critical metrics that can be adopted in designing housing units are daylighting accessibility and enhancing building thermal loads. Therefore, this project will focus on producing residential building forms using shape grammar and genetic algorithms through specified daylighting metrics and thermal energy performance to create optimal building forms that are more comfortable for users while consuming less energy.

Table 1 investigates and compares the previous research projects that used shape grammar rules to analyze or generate house designs. The researchers used shape parameters and rules to establish the relation between the spatial position of rooms, room proportions (width, length, and height), courtyard position, and floor plan shape. The most practiced rules were addition and subtraction, and after analyses and obtaining the form rules, the process will be changed to develop new forms based on the analyzed one to be capable of the same context, especially in the vernacular context. Therefore, each study will generate a framework for architects to make a simple design decision when designing a new house following the rules of the existing one. The tools used ranged from mathematical calculations and computer support; researchers used programming languages such as MATLAB and Python to code the shape grammar rules to generate building forms with specific proportions of a room.

Performative design One of the most critical roles in the performance design model is to generate the form of the building based on its energy performance in the early design stage [46]. Zhang's works used a parametric performative approach to develop a Chinese residential building based on three primary components: the spatial relationship between residential building components, the energy simulation of the schematic design, and the generation and evaluation of new design ideas. The methods used in this work were to generate multiple alternatives for Chinese residents. Users first started to select the building orientation, room area, functions, etc. The second step was to determine the optimal building design using the simulation of energy consumption. Finally, the final building form and the schematic floor plan were automatically generated.

Furthermore, to minimize energy consumption, Feng, Luo, Gao, Abbas, Xu, and Pouramini ([11]) used different tools to optimize the form of residential buildings. The manta ray algorithm optimizer and energy simulator RIUSKA have been used to find the optimal building form through specific parameters such as floor area, window type, orientation, and building shape. The benchmark is the cost of the life cycle and the electrical energy used, and it was found that rectangular- and trapezoid-shaped buildings have the lowest life cycle costs.

Xia and Li ([40]) designed and evaluated the optimum residential urban morphology to improve access to sunlight and energy consumption. The main parameters used were

Table 1 Shape grammar investigation of previous studies

Authors	Aim	Algorithm objective	Tools	Building type	Methods	Parameters/variables
Schnier & Gero ([26])	An evolving system that modifies the form of the building	Fitness function evolved genes	The grammar is handmade	House	Analyze the new design The rules are divided into 24 steps to create different layouts	■ Fireplace ■ The shape of the floor plan ■ Grid ■ Adding comers and porches ■ Functional zones ■ Third dimension ■ Roof ■ Services place
Smyth & Edmonds ([30])	Computer support using shape grammar to help the designer in the early-stage design	-	Computer support	Early-stage design	Set of design rules	Spatial arrangements
Chouchoulas & Day ([6])	Shape grammar ideas are linked to a genetic algorithm to provide a tool for design exploration	Genetic algorithm	Linking shape grammar concepts to a genetic algorithm to provide a tool that can be used for design exploration	Early-stage design	Shape grammar rules to reach the final form, genetic algorithm	■ Rotation mirror ■ Reflection core position ■ The number of apartments, area, and volume ■ Height and footprint
Trescak et al. ([36])	Introduce a new tool based on shape grammar called the shape grammar interpreter	Automatic generation Algorithm	SGI shape grammar interpreter in JAVA	2D shapes	An optimized sub shape detection algorithm	■ Shape grammar rules ■ Rectangle room ■ Rotation ■ Random ■ Point position ■ Shape transformation
Ruiz-Montiel et al. ([25])	Developing two-dimensional single-family dwelling plan designs	Simulated annealing Genetic algorithm	Dynamic programming Algorithms	2D plan A single-family house	Set of rules	■ Relationships between spaces ■ Housing program ■ Bathroom ■ Kitchen ■ Distributor ■ Non-personalized space

Table 1 (continued)

Authors	Aim	Algorithm objective	Tools	Building type	Methods	Parameters/variables
Granadeiro et al. ([12])	Proposes a framework to help design decisions on the geometry of the building envelope in terms of its impact on energy performance	Parametric design system	Generative design encoding systems	Early design stages	■ Formulating transformation rules as equations and variables ■ Energy simulation	Design principles ■ Building width ■ Building length ■ Total floor area ■ Second-floor area ■ Living area ■ Service area porch ■ External surface ■ Roof ■ Window areas ■ Heating ■ Cooling
Andino & Chien ([4])	Shape grammar has been used to capture Garifuna's design architecture	Parametric design	Rhinoceros/Grasshopper software	Vernacular architecture	Geometric rules	Building ■ Width and height ■ Positioning of columns ■ Beam positioning parameter ■ Windows and wall panel position
Aydin et al. ([5])	Showing a participative design process that uses gamification techniques to motivate strong participation	Optimization algorithm	3D puzzle	Kashgar's vernacular architecture Mass-production housing	**Gamification**: the strategy of shaped grammar	■ Void ■ Circulation ■ Cubes position
Park & Economou ([23])	A generative description of Mies van der Rohe's courthouse language is presented as a shaped grammar	Generative description	Applying shape grammar rules	Analysis	Set of rules	Spatial relations ■ Courtrooms ■ Circulation networks ■ Vertical cores ■ Office spaces ■ Support spaces

Table 1 (continued)

Authors	Aim	Algorithm objective	Tools	Building type	Methods	Parameters/variables
AbdulRaheem & Abdulwahab Rayis ([1])	A parametric shape grammar of traditional SUAKIN houses is presented	Generative design	Parametric tools	Residential plan spatial arrangement	Restoration of a modern SUAKIN architectural style is based on knowledge and understanding of the formal composition of the old SUAKIN style	Spatial relations Height-width area ■ Diwan ■ Harim entrance ■ DHLIS ■ Courtyard ■ Stairs ■ Room ■ Entrance ■ Kitchen ■ Toilet ■ Circulation
Prakash et al. [24]	Let the shape grammar helps designers and educators overcome the organic aspect of creativity by making learning visible and tangible	Mathematical computations	Blocks are physically manipulated	Explanatory and generative in use 3D	Educational approach through shaping grammar rules	■ Orthogonal grid ■ Joining shapes ■ Replacement ■ Addition
Hasani et al. ([13])	Generate a decision tree based on rules that directs the design process for constructing new residences	Rules and algorithms-	Mathematical calculation	The traditional architectural style of the Qajar home 2D	Analyze approximately 100 residences in Kashan city from the Qajar era to assess the existence of open, semiopen, and closed areas. Then, the shape grammar is applied to generate various designs based on these relations	The shape and styles of the courts ■ Courtyard ■ An IWAN partially closed space ■ Distance from the closed room ■ Spatial relationships within homes

Table 1 (continued)

Authors	Aim	Algorithm objective	Tools	Building type	Methods	Parameters/variables
Toussi ([34])	Examine the conventional structures and design new ones around them, resulting in a hybrid generative evolutionary technique to solve the problem	Genetic algorithm optimization	MATLAB	Kashan's traditional houses	Shape grammar method and genetic algorithm for studying historical houses	■ Position of entrance ■ Courtyard ■ Main bedroom ■ Secondary room ■ IWAN
Mandow et al. ([18])	Explain how to create sketches of compact single-family homes that meet the requirements of habitability while being energy efficient	Generative grammar	Computation	Small single-family house	Experimental results	■ Energy simulation ■ Spatial relation ■ Outside spaces ■ Cooking ■ Storage ■ Laundry ■ Specialized space ■ Openings position
Upasani et al. ([37])	A method for creating rectangle floor plans automatically while adjusting dimensional limitations and adjacency relations	Automated generation	A software based on MATLAB	Floor plan layout	An algorithmic approach for room proportional and adjacency	■ Rectangular arrangement ■ Room ratio ■ Min width ■ Min height
Yousefniapasha et al. ([42])	Analyze and generate the layout and characteristics of vernacular homes and application of grammatical rules	Mathematical rules	Rule addition	Vernacular housing	Living room was first placed as the primary area in vernacular structures, followed by adding other rooms to the plan composition	■ Spatial relation ■ Living room location ■ Room ■ Kitchen ■ Front porch ■ Guest room

Table 1 (continued)

Authors	Aim	Algorithm objective	Tools	Building type	Methods	Parameters/variables
Shekhawat et al. ([27])	Graph theoretical and optimization approaches are used to create dimensioned floor plan layouts by introducing GPLAN software	Automated generation	GPLAN software Python	Floor plan layout	Python was used to implement GPLAN Optimize room dimensions	■ An adjacency of spatial relation ■ Rooms ■ Area ■ Height ■ proportions
Lee et al. ([17])	A descriptive shape grammar develops a statistical approach to measuring and guiding grammatical applications	Mathematical algorithm	Computational design	Residential building	Shape grammar rules to identify spatial relation	■ Spatial relation ■ Room unit ■ Core unit ■ Hall unit ■ Entrance ■ Height
Wang et al. ([39])	Introduce a shape grammar-based strategy for analyzing 56 villages in Shandong's design vocabulary	Mathematical calculation	Computational design	Analysis of rural housing in China	Analysis of room ratio through shape grammar	■ Spatial relation ■ Courtyard ■ Living space ■ Bathroom ■ Bedroom ■ Storeroom

the plot area ratio, building density, type, and height. Ladybug and honeybee simulated each iteration to optimize these variables to calculate solar radiation access and energy consumption. Similarly, Yi and Kim ([41]) introduced an agent-based geometric control system that helps designers find the optimal shape and position of the building to enhance the hours of solar access.

In addition, Amr and Youssef ([43]) applied the performative optimization process to increase the surfaces exposed to solar radiation to enhance the use of photovoltaic cells for energy generation. In this case, the shape grammar rules have been integrated to change the building form based on the addition and subtraction of the shapes. Each generation has been examined by the DOE-2 engine and compared with the base case to obtain better solar exposure for building integrated photovoltaic cells. In addition, some research is based on the performative optimization of the components of the building form to improve energy consumption and is supposed to find the optimum sustainable residential building design that balances energy consumption and daylight penetration. In this study, the parameters used were to change the construction materials of the building wall, the window material, and the depth and count. The Octopus plug-in engine chose the optimum spatial daylighting autonomy (SDA) and energy use intensity (EUI) metrics design.

Furthermore, Vukadinović, Radosavljević, Đorđević, Protić, and Petrović ([38]) tried to find the most passive solar component that affects heating, cooling, and energy consumption through the parameters of the WWR architecture, window material, wall construction, and shading. Moreover, NSGA-II examined this idea, a nondominant genetic algorithm tool. The results indicate that the WWR has the most significant influence on energy consumption among all parameters of the building elements.

Table 2 demonstrates the popularity of the genetic algorithm optimization method, as it generates genes to find the best solution to fit the objective function, which was based on building performance metrics such as energy consumption, energy use intensity (EUI), daylighting, and spatial daylighting autonomy (SDA), which parametric programs can provide in the simulation process.

The research projects presented merged parameters such as shape length, width, and height and add parameters that affect energy consumption, such as building orientation, location, azimuth, degree, and construction materials (*U*-value & window types).

Most of the programs used in the previous studies are Rhinoceros and Grasshoppers, which can integrate plugins in different areas. Moreover, most of these software programs are open sources of energy, ladybug, and honeybee programs. They are based on verified engine OpenStudio, which is based on EnergyPlus for energy simulation and radiance for lighting simulation. Therefore, these programs can merge the parameters for geometrical building form generation, and the objective metrics and the optimal solution can be found through optimization.

Methods

In various Egyptian cities, the government promotes Sakan Masr middle-class prototypes with the same shape. Therefore, the researchers were interested in creating these buildings in various regions with less energy consumption. This method can offer a flexible housing unit in shape for mass production housing, which can be used

Table 2 Investigate the performance design of previous studies

Authors	Aim	Methods	Software	Building type	Region/location	Parameters		Performance objective	Results
(Zhang et al. [46]	Find the optimal form of a residential building with less energy consumption	Performative genetic algorithm	Parametric/optimizer ■ Rhinoceros/Grasshopper and Python Energy simulator ■ Ladybug & honeybee	Residential buildings Early design stage	Beijing, China	Core ■ Location ■ Shape Room ■ Orientation ■ Width ■ Height ■ Function window ■ Orientation ■ WWR	■ Width ■ Height ■ Area to space area Circulation ■ Shape ■ Length ■ *U*-value ■ Schedule	■ Cooling ■ Heating ■ Total	The ideal design plan is from 1595 automatically created schemes with the lowest cooling and heating hand. As a result, it has a total load of 15.8% lower than the worst scenario and 4.2% lower than the original scenario
(Feng et al. ([11])	Find the optimal form of a residential building with less energy consumption and less life cycle cost	Optimization	Optimizer ■ Manta-Ray Energy simulator ■ RIUSKA	Residential buildings	■ El Centro ■ California ■ Fort Wayne Indiana ■ Orlando, Florida ■ California	Building shape ■ Wall and roof insulation ■ Orientation ■ Azimuth (degree) ■ Ceiling insulation ■ Thermal mass ■ Wall construction insulation ■ Infiltration • Glazing type • Type of windows		■ Life cycle cost ■ Electric consumption	A building with rectangular and trapezoid forms has the lowest life cycle cost

Table 2 (continued)

Authors	Aim	Methods	Software	Building type	Region/location	Parameters	Performance objective	Results
(Xia & Li ([40])	Design and evaluate the optimal residential urban form through energy consumption and access to solar radiation.	Morphology and performance of the optimized generated	Parametric/optimizer ■ Rhinoceros/Grasshopper and Python Energy simulator ■ Ladybug & honeybee	Urban residential block	Hangzhou in China	■ Plot ratio Building ■ Density ■ Type ■ Height	■ Solar radiation ■ Energy consumption	Access to solar radiation is much more responsive to changes in morphology than energy consumption The number and location of building blocks are responsible for the changes in morphological characteristics among lower energy consumption and higher solar radiation access
(Vukadinović et al. ([38])	Determine which parameter has the most significant impact on heating and cooling energy consumption and thermal comfort	Multiobjective optimization	Optimizer NSGA-II Energy simulator Design builder	Residential Buildings	Serbia	■ WWR ■ Window material. ■ Wall Construction ■ Shading	■ Cooling ■ Heating ■ Total	The window-to-wall ratio is the component of the passive solar architecture that significantly impacts energy efficiency
(Youssef et al. ([43])	Get the optimal building form for maximizing photovoltaic cell integration	Optimization	Optimizer ■ GenOpt Energy simulator ■ DOE-2 ■ Autodesk ECOTECT	Commercial building	Cairo, Egypt	■ Orientation. ■ Shape direction ■ Shape addition ■ Shape subtraction	■ Pv power ■ Pv cost ■ Energy Consumption	When photovoltaic cells are integrated, the improvement in energy consumption ranges from 1.8 to 12.5 percent

Table 2 (continued)

Authors	Aim	Methods	Software	Building type	Region/location	Parameters	Performance objective	Results
(Toutou et al. ([35])	Optimize residential building envelope elements through specific parameters to enhance lighting and energy consumption	Performative genetic algorithm	Parametric ■ Rhinoceros/Grasshopper and Python Optimizer ■ Octopus plug-in Energy simulator ■ Ladybug & honeybee	Residential buildings Five storey	Cairo, Egypt	■ WWR ■ Window material ■ Wall construction ■ Shading depth ■ Shading width ■ Shading count	■ Daylighting ■ SDA300/50%) ■ Energy consumption ■ EUI	It resulted in the creation of more than 300 generations. The SDA value was discovered to be 84.11, approximately 10% higher than the base case design, and the EUI was 166.01 kWh/m^2, which was reduced to approximately 3.5%
(Yi & Kim ([41])	Proposes a new method for optimizing a building's direct sunlight access	Genetic algorithm optimization	Parametric ■ Rhinoceros/Grasshopper Optimizer ■ Galapagos simulator ■ Ladybug	Tall residential building	Korea	Building ■ Location ■ Rotation ■ Twist factor ■ Geometry factor	■ During hours of direct sunlight ■ Solar hours are less than 2 h	Introduce an agent-based geometric control that relocates the building position in a specific area to minimize solar hour access

Table 2 (continued)

Authors	Aim	Methods	Software	Building type	Region/location	Parameters	Performance objective	Results
(Youssef et al. ([44])	Integrated photovoltaics in buildings, appropriate building form, electricity generation, and economic analysis	Optimization	ECOTECT. Classifying the subsurface of the model based on solar irradiation using the SAM tool to predict PV performance RETScreen "SolVelope" "RADIANCE" "GRIPVS"	Commercial building	Cairo, Egypt	Surface tilt angle Initial building shape PV type	■ Solar exposure rate per cubic meter ■ Solar irradiation	Identifying the best envelope design with the highest solar exposure was the key Findings of cost-efficient photovoltaic systems with optimal envelopes A framework of such an approach to formulating optimal building envelope shapes and the appropriate PV systems for the identified envelopes

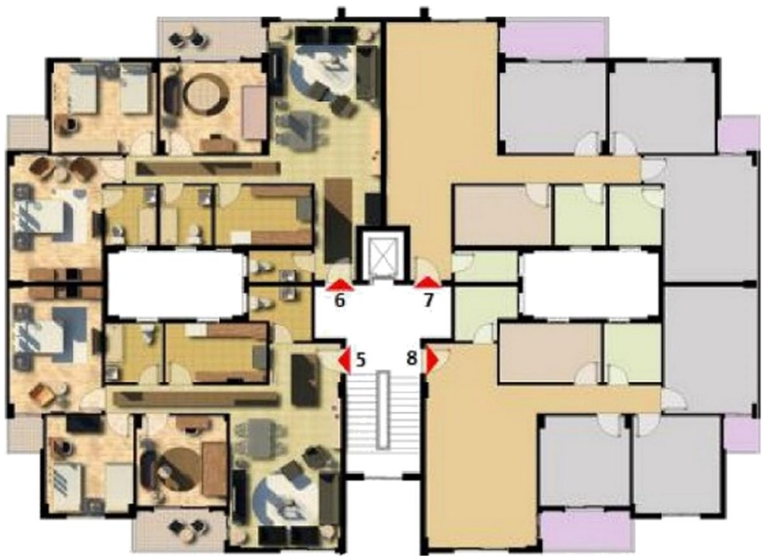


Fig. 2 Sakan Masr architecture plan


Fig. 3 Sakan Masr's perspective

with government programs to produce homes for the middle class and save energy. The case study will focus on the prototype housing project Sakan Masr in Cairo, as shown in Figs. 2, 3, and 4, which illustrate the typical form of the building, the spatial relation between rooms, and a geographical map of the site.

The average area is 115 m^2 per unit. Either single-family or multifamily housing unit design is a highly restricted process. The nature of such limitations varies, from concerns such as the area of each space to adjacency relations [25]. Although the architectural design is a challenging process that progresses from purely conceptual ideas to practical methods, spatial space arrangements, organization, and expected human implications are solved through problem-solving [20]. Based on the configurational theory of space, invisible features of space are deciphered using space syntax to find the accessibility between different house activities, such as living areas, bedrooms,

Fig. 4 Sakan Masr layout (Google Earth)

kitchens, and spacious gardens [29]. This theory provides a methodology that investigates a framework for spatial relations [20].

The house design has been generated by adding specific parameters based on the Egyptian housing code, as shown in Table 3, which represents the minimum requirements for the spatial relation and the range of the used parameters that act as genes for the optimization process.

The design starts with the idea generation process. Then, it transforms these concepts into actual spatial structures, illustrating a link between each space activity and indicating the required space adjacencies between functional house spaces [19]; then, performance metrics will be added to set the fitness function for the simulation.

Building performance metrics

According to the literature review, this study adopts the most reliable and accurate energy, daylighting, and thermal metrics to determine the optimal form of the building based on the benchmarks of these metrics. *Energy use intensity*, or EUI, is one of the primary metrics used as a benchmark for calculating energy usage. EUI is expressed as energy per square foot per year. The total energy consumed by the building in 1 year (measured in kWh) is divided by the total gross floor area. According to standards [10] for multifamily housing, the required EUI is 118.1 kBtu/ft^2.

Daylighting design is critical to building rating systems, such as leadership in energy and environmental design, BREEAM, and certification. For assessment, BREEAM uses daylighting metrics such as spatial daylight autonomy (SDA 300 lx/50% of the annual occupied hours) for at least 55% of the floor area and annual sun exposure (ASE), which measures the percentage of floor area that receives at least 1000 lx for at least 250 occupied hours per year [8]. However, metrics such as ASE and SDA, which do not have an upper illuminance threshold, may be better suited to determine whether a place is well lit for a particular activity.

Table 3 Representing the minimum requirements for the proportional room ratio of the Egyptian housing code

Space	Indicator	Range	Fixed	Variable
Building	Width-length	12 × 12 + 1.2 cantilever		
Volume			√	
Number of rooms				√
Floor area				√
Location	Weather file	Alex, Aswan, Cairo		√
WWR	West	10–100%		√
	North	10–100%		√
	South	10–100%		√
	East	10–100%		√
Room (lobby)	Width-length	1.4 M min		
Room (reception)	Orientation			√
	Area	32 m^2 (18 M^2 min*)	√	
	Width-length	Min 2.7 m*		√
	Height	3 m	√	
Room (bathroom)	Orientation			√
	Area	4 $m^{2'}$	√	
	Width-length	Min 1 m*		√
	Height	3 m	√	
Room (kitchen)	Orientation			√
	Area	6 m^2	√	
	Width-length	Min 1.5 m*		√
	Height	3 m	√	
Room (bedroom)	Orientation			√
	Area	12 M^2 min*, 16 m^2	√	
	Width-length	Min 2.7 m*		√
	Main	3 m	√	
Room (master bedroom)	Orientation			√
	Area	16 m^2 (12 M^2 min*)	√	
	Width-length	Min 2.7 m*		√
	Height	3 m	√	
Room (living)	Orientation			√
	Area	16 m^2	√	
	Width-length	Min 2.7 m*		√
	Height	3 m	√	
Green area	Orientation			√
	Area	16 m^2	√	
	Width-length	Min 2.7 m*		√
	Height	3 m	√	
U-value			√	

Solar heat gain coefficient (SHGC) of 0.60. The building shape coefficient (or shape factor). The ratio between the external surface of a building and its volume.

* Minimum requirements for the Egyptian housing code

Then, to examine the generative component of evolutionary algorithms, evolutionary approaches were adopted to acquire the ideal building form through fitness objectives. Individuals' ability to explain sample designs is measured via genetic optimization, as

Table 4 Selected metrics with their benchmarks

Objective function	Metric	Benchmark
Energy	EUI intensity of energy use	118.1 kBtu/ft^2
Lighting	Spatial daylight autonomy (SDA)	An average SDA of 300.50% is achieved for > 55% of the regularly occupied floor area
		An average SDA of 300.50% is achieved for > 75% of the floor area occupied regularly
	Annual sunlight exposure (ASE)	ASE measures the percentage of floor area that receives at least 1000 lx for at least 250 occupied hours per year
Solar radiation	Solar exposure rate per cubic meter	
	During hours of direct sunlight	Exposure and incident radiation analyses

gene inputs and actuators (building form variables) are operated, and a physics engine simulates them based on predefined evaluations [34] as shown in Table 4.

Tools

The modeling program "Rhinoceros" and its associated parametric scripting tool "Grasshopper," which has many free, open-source plugins and the use of floating sliders and functioning controls for the geometrical shape form and proportional rules, can generate shape grammar geometry. Therefore, it may produce forms based on shape grammar principles, which this work aims to do.

For building performance simulation, lighting performance can be simulated by applying the ladybug-Grasshopper plug-in based on Python scripting and verified by the most well-known radiance lighting engine. In addition, the incident solar facade can determine solar radiation calculations. Moreover, the honeybee plug-in simulates energy based on EnergyPlus by installing an open studio program.

After adding the building parameters as a floating slider, a fitness function is added to generate the performative-driven optimization that maximizes the SDA metric and minimizes the metrics of total radiation, ASE, and EUI.

Shape formation

The initial unit dimension was defined as 4 × 4 × 3 m, which fit with the minimum requirements for the Egyptian housing design code. The case study is a five-story building divided mainly into four apartments per floor. Therefore, the form will be divided into four main parts. Each part consists of a 9-module 4 × 4 grid for each story, and the following rule is to subtract two modules to ensure that each unit has access to sunlight through the addition and subtraction of the other blocks when the form has been generated. See Figs. 5 and 6, which illustrates the form generation rules and script.

The shape grammar rules used can be determined as follows:

- Rule 1: A rectangle with dimensions 12 × 12 generates the building boundary that was divided into nine rectangles, each 4 × 4.
- Rule 2: The rectangles have been moved to generate four floors.

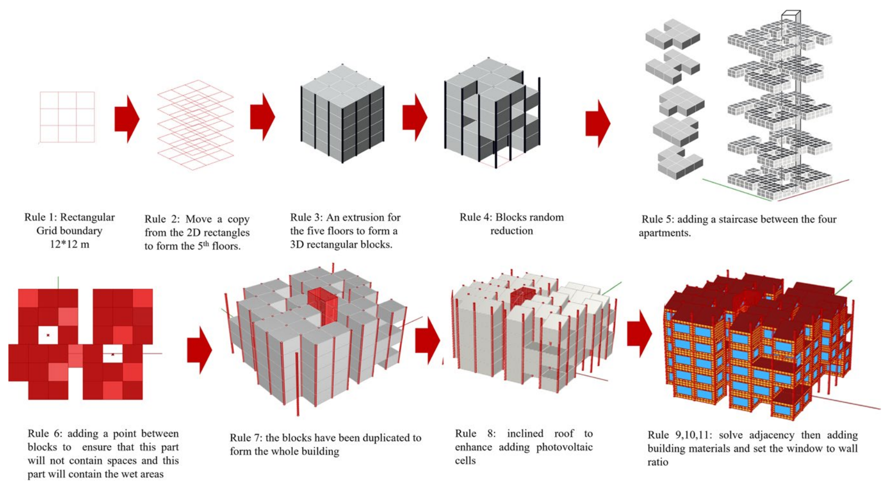


Fig. 5 Rules for form development and shape language

- Rule 3: Rectangular boxes have been extruded so block 1 contains five floors with nine blocks and to ensure daylight penetration and to achieve the area of Sakan Masr units.
- Rule 4: Subtract two blocks from each floor to let the apartment size = 112 m^2 (7 boxes with area 4 × 4 each).
- Rule 5: Add the staircase between the four apartments.
- Rule 6: Add a point in the connection between every two apartments, as the attachment generates blocks without sunlight access. These points develop a void to allow sunlight to enter these parts.
- Rule 7: The blocks have been duplicated to form the whole building.
- Rule 8: The blocks of the fifth floor have been generated with the twisted box to let the roof inclination flexible to add photovoltaic cells.
- Rules 9, 10, and 11 are used to solve the adjacencies between blocks and construct windows in the exposed faces.

Simulation methodology

The first iteration is a random simulation for the base case, the applied weather file of Cairo International Airport (EGY_QH_Cairo.Intl.AP.623660_TMYx.2004-2018.epw).

As examined first, the goal of the optimization is to set a fitness function that merges the optimization of the objective metrics decided to maximize SDA, minimize ASE for daylighting, and minimize the cooling load and total incident radiation.

A powerful PC unit is recommended, as the current hardware did not comply with the standard processing time, which delayed the required results and could delay the entire project. Additionally, each simulation took approximately 5 to 6 days to see the results of the optimization process, and the methodology was changed step by step, as shown in Fig. 7.

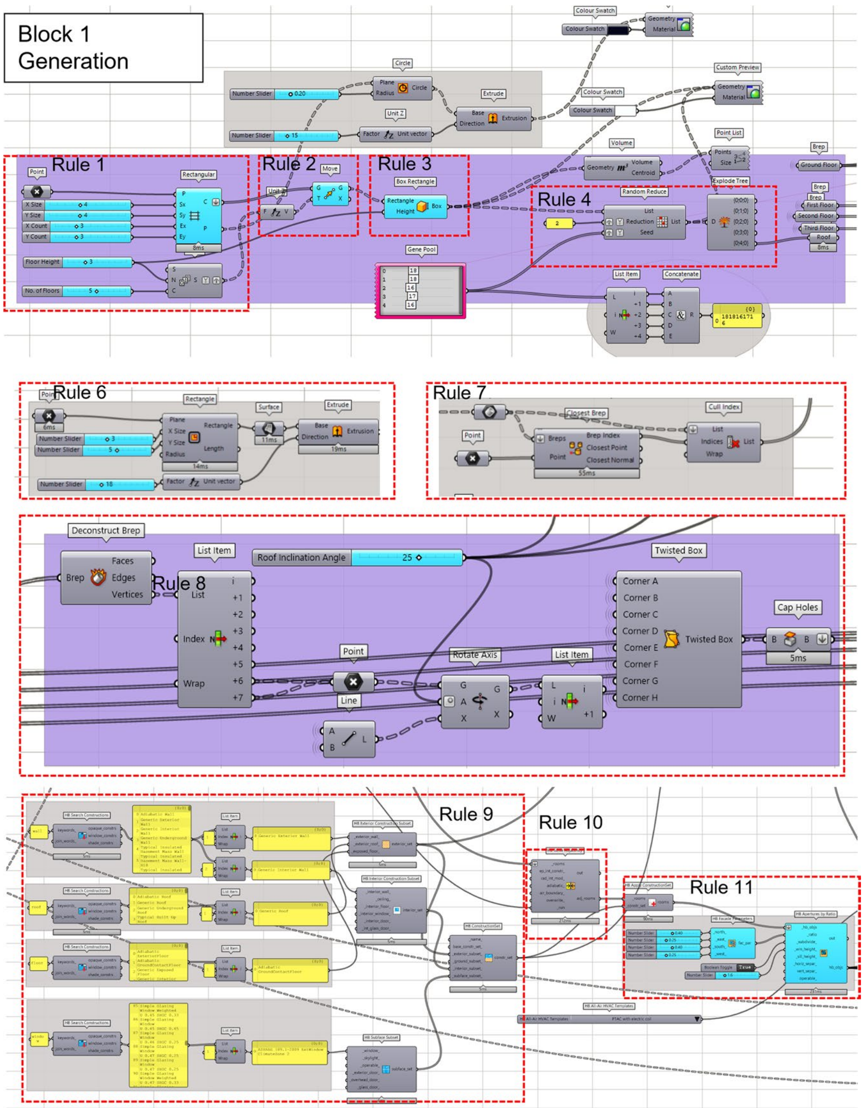


Fig. 6 Introduced Grasshopper script for the shape rules

First, the base-case simulation has a random form but with the selected area for the mentioned metrics. Second, an optimization process was performed on the building unit's arrangements and the balconies' positions to minimize the total incident radiation.

Another simulation for the entire cooling load and daylighting metrics was generated to compare the base case with the first iteration.

Third, optimizing the window-to-wall ratio allows the fitness function to balance spatial daylighting autonomy and annual sunlight exposure. Then, the simulation for the cooling load and the energy intensity was used to compare the results.

Results and discussion

The results of this research suggest a framework for architects to generate forms through multiple simulations based on the previous one.

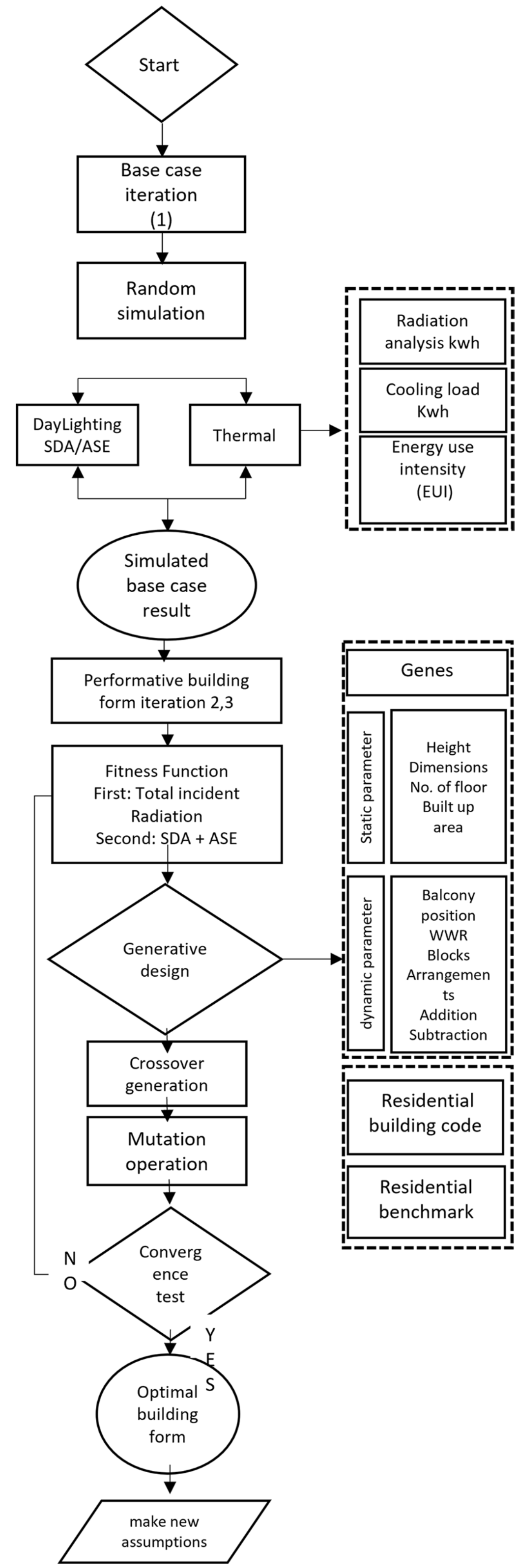


Fig. 7 The simulation methodology

Due to too many different parameters and simulation metrics to balance daylighting and thermal performance, the simulation process took approximately 2 weeks, and there was no output. Therefore, at first, the research suggests optimizing the form through block arrangement and balcony location to reduce the thermal and cooling loads on the building; then, the second phase is optimizing the output form from phase 1 to obtain the best window-to-wall ratio for each orientation. After the optimization process, the results for the building block arrangements are sorted to reduce the total incident radiation upon the building, which has been noticed in the output design. For example, the northern direction has no recess or extrusion in its shape and no balconies, as it has no direct sunlight exposure according to the sun path of Cairo. Instead, the other facades, mainly their shape design for the building blocks, are arranged to increase the shadow on the building surfaces. For example, the western façade block arrangement appears to have more vertically staggered elements to act as vertical shading blocks, and for the southern façade, the balconies' location, and the sorted block form as horizontal shading.

Furthermore, the terraces are rearranged in the eastern, western, and southern exposures to enhance shading on the building blocks, especially when the top block surface is exposed to sunlight, unlike Amr's research project used to increase the surfaces that have high sunlight exposure to add solar panels to produce energy [43]. Therefore, the parameters and selected metrics will change as the target changes. However, this research suggests that shading is improved first, and then, the exposed face to sunlight can be optimized.

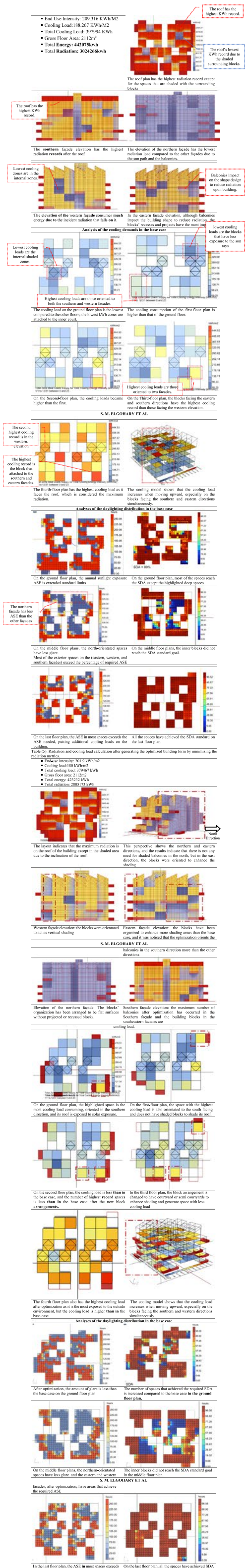
Although the arrangement of building blocks and balconies is essential in designing the form of the building to prevent fewer kWh incident radiation upon the building, the energy savings after optimization are approximately 6% in the whole building per year. However, the building form significantly changes, as shown in Table 5.

Vukadinović, Radosavljević, Đorđević, Protić, and Petrović [38] investigates that WWR has the most significant influence on energy consumption among all parameters of the building element. In this research, the authors added the optimum WWR for each side of the elevation, as in the north direction, the war was recommended to be 60%, and in the rest of the elevations, it was recommended to be 10% to achieve a balance between the SDA and ASE lighting metrics to save energy and penetrate the useful daylight.

Additionally, the results can introduce design guidelines for the design of residential buildings in hot arid climates such as Cairo.

- There is no need to add balconies to the northern facade except for the aesthetics of the architect's view or the user's need.
- The western façade design can be consistent with more vertical elements.
- The southern façade needs the projection to be more horizontal.
- Block arrangement and balconies distribution on buildings reduce solar radiation.
- The window-to-wall ratio percentage differs for each facade to balance daylighting penetration and glare. The optimum percentage is 10% for the western, southern, and eastern facades, which is more like the Egyptian energy efficiency in residential buildings, and 60% for the northern direction.

Table 5 Base case results



However, the proposed framework aims to close the knowledge gap between students and architects about analytical techniques. It is to mention that the framework can help decision-makers produce modular housing with less energy consumption. It should be noted that the generated floor plans have some limitations that affect the functionality of the architecture space compared to the Sakan Masr architecture plan; some of them can be solved in the design development stage.

- The first issue, the blocks' random arrangement, was carried out as a rule to generate different 3D forms to test the optimum building form with optimization of thermal and daylighting performance metrics. This makes it a challenge for the early-stage design to design the architecture plan, which can be modified in the next stage of design development, such as if some iteration of generating blocks far from each other's corridors can be added.
- The second issue is the bathroom's plumbing location. Again, it differs that not all the units can be distributed vertically, but two ducts can collect the plumbing and the reservations; screens to hide the plumbing can be added in the design development stage.
- The third issue is the quality of architecture space function; it should be noted that the generated units are in the same area provided by the government, but the footprint is different. As there is a generation of in-between spaces due to the difference in floor outline, this can be developed in the design development stage; its access can be from an apartment or can be shared between every two apartments. Moreover, there is an option to use these spaces as vertical outdoor spaces for users, which was recommended after quarantine.
- The fourth issue, the space syntax, differs from Sakan Masr. Still, most of the spaces are achieved, so the recommended further research will investigate the space syntax with the performative and generative design.

Conclusions

The residential building sector in Egypt consumes approximately 60% of the total energy consumption [3], allowing architects to be responsible for reducing these cooling loads. Therefore, architects should enhance their tools and design methods to generate building forms that consume less energy. Considering these issues, this research aimed to develop a design methodology to improve building energy consumption through form finding. By integrating Oxman design models, one of the generative design models is shape grammar, which depends on rules to generate forms [21]. Research used the characteristics of rules to generate forms based on sliders to act as genes in the fitness function, such as the arrangements of the building blocks and the location of the balconies. As a result, the fitness function optimizes radiation, cooling loads, and daylighting metrics for performance design.

It should be noted that the methodology at first was to optimize the thermal daylighting and cooling metrics simultaneously by applying it at this building scale due to the multiple variables. Nevertheless, no results appeared due to the numerous variables with various metrics simultaneously.

Therefore, the research methodology has been changed step by step. First, the building block arrangement and balconies' locations are optimized to reduce thermal and cooling loads through total radiation metrics. Then, the percentage of WWR is optimized using ASE and SDA daylighting metrics, and the results indicate that in the north façade, the WWR is 60%, and for the southern, western, and eastern facades, the WWR is 10%.

The results present a valuable block arrangement to improve shading, especially in the eastern, western, and southern façades, which is one of the most critical aspects in reducing the cooling load. Additionally, the balconies' arrangement is directed to the southern, eastern, and western facades, not the northern ones.

Finally, the output architecture plan zones can be distributed and furnished with multiple solutions, for example, all wet areas attached to the side elevation or court to be served with infrastructure plumbing fixtures. In addition, a simple modification can be added, such as the highlighted space, to ensure the circulation performance of residences, as shown in Fig. 8. Also, it should be noted that the produced plans have limitations in their designs, as there are generated spaces due to the different outline of each floor; this spaces can be suggested by authors to be used for vertical outdoor spaces for the residence which can be planted, as after the pandemic period the architect should design flexible housing units to be resilient for crisis times and outdoor spaces can be added to the housing prototype standards.

The introduced framework provides a decision-making tool for architects to design buildings with high-energy performance to save energy in residential buildings. Research recommends that the next step is to add renewable energy to produce energy targeting

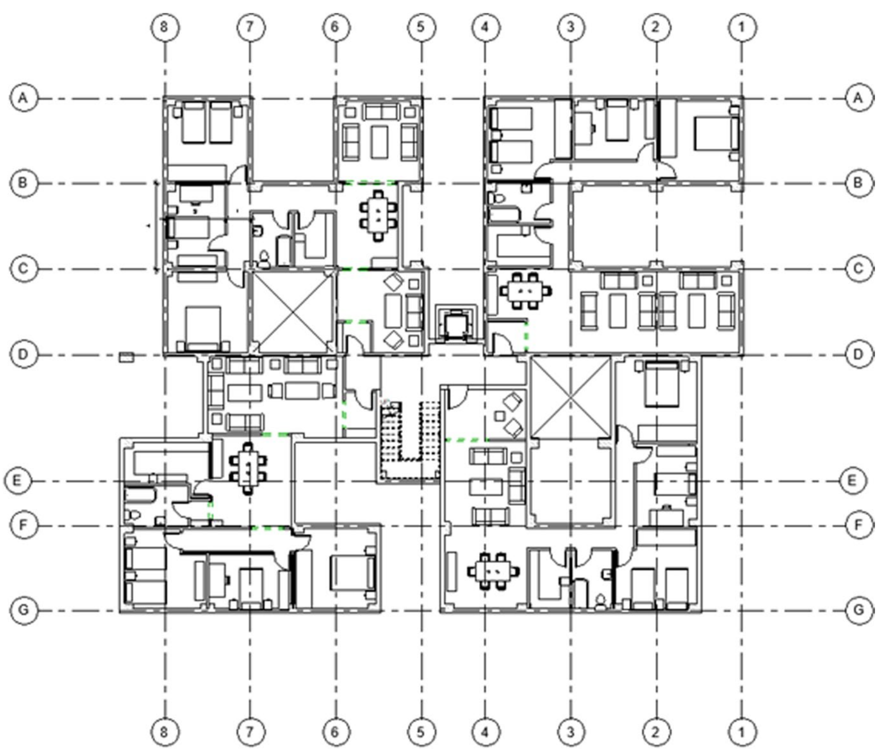


Fig. 8 Illustrates the output architecture plan for level one with zone distributions

net zero energy. Additionally, as the government demonstrates Sakan Masr in different cities in Egypt, another study can be applied to compare the produced forms with different weather files according to the suggested cities and buildings.

Additionally, this framework can be introduced to students and merged into the educational programs/curriculums to make them aware of building performance simulation methods to save energy and decide the optimum building form that saves energy in early-stage design.

Abbreviations

CAD	Computer-aided design
SDA	Spatial daylighting autonomy
Annual ASE	Annual sunlight exposure
EUI	Energy use intensity
SG	Shape grammar
WWR	Window-to-wall ratio

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Authors' contributions
SG analyzed the results and discussion section. AA performed the methods section. RM interpreted the introduction section. Finally, all authors read and approved the final manuscript.

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