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Optimizing the View Percentage, Daylight Autonomy, Sunlight Exposure, and Energy Use: Data-Driven-Based Approach for Maximum Space Utilization in Residential Building Stock in Hot Climates

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Abstract: This paper introduces a comprehensive methodology for creating diverse layout generation configurations, aiming to address limitations in existing building optimization studies that rely on simplistic hypothetical buildings. This study's objective was to achieve an optimal balance between minimizing the energy use intensity (EUI) in kWh/m^2, maximizing the views percentages to the outdoor (VPO), achieving spatial daylight autonomy (sDA), and minimizing annual sunlight exposure (ASE). To ensure the accuracy and reliability of the simulation, the research included calibration and validation processes using the Ladybug and Honeybee plugins, integrated into the Grasshopper platform. These processes involved comparing the model's performance against an existing real-world case. Through more than 1500 iterations, the study extracted three multi-regression equations that enabled the calculation of EUI in kWh/m^2. These equations demonstrated the significant influence of the window-to-wall ratio (WWR) and space proportions (SP) on the EUI. By utilizing these multi-regression equations, we were able to fine-tune the design process, pinpoint the optimal configurations, and make informed decisions to minimize energy consumption and enhance the sustainability of residential buildings in hot arid climates. The findings indicated that 61% of the variability in energy consumption can be attributed to changes in the WWR, as highlighted in the first equation. Meanwhile, the second equation suggested that around 27% of the variability in energy consumption can be explained by alterations in space proportions, indicating a moderate correlation. Lastly, the third equation indicated that approximately 89% of the variability in energy consumption was associated with changes in the SP and WWR, pointing to a strong correlation between SP, WWR, and energy consumption. The proposed method is flexible to include new objectives and variables in future applications.

Keywords: multi-objective optimization (MOO); views percentages to the outdoor (VPO); spatial daylight autonomy (sDA); annual sun exposure (ASE); space configuration and façade design

1. Introduction

The growth of energy scarcity worldwide can be attributed to several factors, including increasing energy costs, global economic issues, and the impacts of global warming and climate change. These factors have significant consequences for individuals and communities, particularly those who have recently gained access to energy but are unable to afford its costs. As a result, approximately 75 million people around the world are currently facing energy poverty. Energy scarcity proscribes individuals of essential services such as cooking, heating, and cooling in their homes and access to subsidies that contribute to their overall well-being and societal development [1–3].

The main causes of high energy consumption in building spaces are using outdated air conditioning equipment for heating and/or cooling purposes and inadequate maintenance. Inefficient appliances and lighting fixtures also contribute to increased energy consumption. Another significant factor is the lack of thermal insulation in buildings, which leads to excessive heat gain or loss. Additionally, high levels of infiltration through openings in the building envelope can result in energy inefficiencies. It is important to note that behavioral and cultural factors within society can also play a role in contributing to high energy loads [4–9].

Buildings have a significant impact on energy consumption and greenhouse gas emissions. In 2021, buildings accounted for approximately 30% of total final energy consumption and 15% of greenhouse gas emissions. Within the construction sector, there has been a steady growth of 0.5% per year in emissions since 2010. According to the World Energy Outlook (WEO) 2022, the building sector is projected to experience a 20% increase in floor area by 2030. Notably, this growth is primarily anticipated in developing countries, accounting for 80% of the overall expansion [10–13]. The residential sector consumes more than half of Egypt's buildings' energy consumption [14,15]. The residential sector has become the focus of recent research, especially in Egypt [16]. Recent trending research topics varied between urban and building scales [17,18]. Addressing energy efficiency, optimizing building designs, and implementing sustainable practices are crucial steps toward reducing the energy consumption and environmental footprint of the building sector in the face of this projected growth.

The COVID-19 epidemic has increased the time that people spend in buildings to conceal themselves. As a result, having a view of the outdoors has become more vital for maintaining mental well-being [19]. It is critical to consider the view as an objective as early as possible during design because considerations such as space configuration and façade design can substantially impact the quality of the view [20]. Nevertheless, earlier research has only taken into consideration the view of the outdoors when changing the façade design, and it has not been integrated into the multi-objective optimization (MOO) of the building form for energy performance. Moreover, lighting design is frequently outsourced to outside experts late in the design process [21].

Natural daylight is a crucial element essential for creating a comfortable living environment, ensuring residents experience adequate visual and psychological comfort. Furthermore, its optimal presence in terms of quantity and intensity can contribute to the reduction of reliance on non-renewable energy sources, thereby promoting enhanced energy conservation [22–24]. The building envelope plays a vital role in distributing light within indoor spaces [25]. Additionally, the intensity of daylight may vary based on factors such as climatic conditions, earth rotations, sky cover, and seasonal changes [26–28]. Energy efficiency can be improved through the implementation of daylighting technology and efficient lighting systems. This includes the use of high-reflectance materials on walls, ceilings, floors, and furniture [29,30]. In residential buildings, the design and glazing of windows play a crucial role in enhancing both visual comfort and energy efficiency. Numerous studies and research endeavors have been conducted to assess the performance of window areas, taking into account various parameters such as the type, material, and orientation to achieve optimal visual and thermal comfort [31–33]. Various strategies have been proposed to optimize the window-to-wall ratio (WWR) and the selection of glazing, aiming to enable buildings to attain Annual Sunlight Exposure (ASE) and Spatial Daylight Autonomy (sDA) metrics [34]. Following extensive investigations, researchers have determined acceptable values for the window-to-wall ratio (WWR) and width-to-depth ratio, considering specific orientations and climatic conditions [35]. Researchers have explored the impact of technologies such as light shelves and translucent materials on dynamic daylight measurements, assessing their influence on light uniformity and energy efficiency [36,37]. Additionally, innovative materials such as ceramic louvers and customized designs have been investigated for their potential to enhance Usable Daylight Illuminance (UDI) and reduce energy consumption. Furthermore, studies on the implementation of kinetic shading systems have been conducted to improve interior daylight efficiency, visual comfort, and overall energy consumption [38–41].

This paper proposes a computational method that performs a multi-objective optimization of the layout unit and envelope for energy, daylighting, and views performance. This research uses a real validated residential case study in the hot climate of Cairo to validate the applicability of the proposed method.

2. Multi-Objective Evolutionary Algorithms

Building Performance Optimization (BPO) is being widely accepted in advanced simulation technology and algorithms. It is used to optimize and develop multiple aspects of building morphology and characteristics [42–44]. Building Performance Optimization (BPO) is the method for enhancing a building's design to obtain optimum performance while reducing budgets. To do this, BPO determines a set of design parameters from a predefined range of mutually constrained values. Depending on the specific performance goal, the BPO aims to either decrease or increase the value of building performance. In addition, to conserve energy consumption, BPO will seek out the optimal arrangement of design characteristics such as insulation, ventilation, and lighting.

On the other hand, BPO can also address indoor air quality by seeking an optimal combination of design elements such as air filtration, ventilation systems, and material selection. This approach ensures that the building provides the best possible air quality for its occupants. Multi-objective optimization is a key strategy in BPO, as it aims to find a balance between different performance objectives. By considering multiple objectives simultaneously, such as energy efficiency, indoor air quality, thermal comfort, and cost-effectiveness, BPO can help maximize a building's capabilities while maintaining a harmonious equilibrium among these objectives. Overall, BPO leverages advanced simulation tools and algorithms to optimize building performance, considering various factors such as energy consumption, indoor air quality, and budget constraints [45]. By utilizing this approach, designers can create more sustainable and efficient buildings that meet the diverse needs of occupants while minimizing their environmental impact [46–48].

Indeed, multi-objective optimization has gained significant attention in the field of building design over the past few decades [49]. This approach involves considering multiple parameters simultaneously during the simulation and optimization process, allowing for a more comprehensive and holistic assessment of building designs [50]. Parametric modeling tools have been increasingly utilized to facilitate this optimization process, particularly in the early stages of building architecture design. These tools enable architects and designers to explore and manipulate various design parameters, such as building form, orientation, shading devices, material properties, and energy systems, flexibly and efficiently.

By integrating parametric modeling tools with simulation software, architects can evaluate the performance of different design alternatives and explore trade-offs between conflicting objectives. These objectives may include energy efficiency, thermal comfort, daylighting, indoor air quality, and other sustainability metrics. Multi-objective optimization techniques help identify design solutions that achieve a balance among these objectives, leading to more sustainable and high-performing buildings. The use of parametric modeling tools not only enhances the design process but also allows for the exploration of more complex and advanced design tasks related to building performance [51].

The genetic algorithm (GA) is a computational optimization technique inspired by the principles of natural selection and evolution in biology. GAs mimic the process of biological evolution to solve complex engineering problems by generating diverse solutions and iteratively refining them over generations.

Genetic algorithms (GAs) can be integrated with the EnergyPlus engine for building energy simulations. EnergyPlus, developed and managed by the U.S. Department of Energy's (DOE) Building Technologies Office (BTO) and the National Renewable Energy Laboratory (NREL), is a widely used software tool for simulating and analyzing the energy performance of buildings. Depending on the specific implementation, GAs can be integrated with EnergyPlus in diverse ways. One approach is to write scripts or code that interface with EnergyPlus and utilize GAs to optimize building designs or parameters. Another option is to utilize software platforms or interfaces that provide a visual programming environment and pre-built components for building energy simulations. For example, tools such as Grasshopper, which is often used with Rhinoceros, can incorporate EnergyPlus as a simulation engine within their canvas.

Table 1 showcases more than 50 research studies that have tackled the simultaneous resolution and optimization of multiple parameters. These studies focused on either the building form only, the building envelope only, or both types of dynamic parameters in addition to other types such as heating energy sources. Notably, many of these studies concentrated on hypothetical case studies, lacking real-world scenarios and contextual information. On the other hand, the selected case studies are simple hypothetical forms with a limited number of thermal zones, neglecting considerations for space adjacency and heat transfer between zones [52–54]. Nevertheless, the primary focus of these investigations was to examine the influence of indoor thermal comfort, energy reduction in buildings, and their broader impact on the environment. Furthermore, these studies aimed to assess their effects on building occupants and the mitigation of non-renewable resource consumption.

Table 1. Previous research on the same topic of study.

Reference	Typology	Case Study	Site	Simulation Tool	Dynamic Parameters	Objectives
[21]	O	HB	Cairo, London, and Chicago.	Rhinoceros Grasshopper Ladybug + Honeybee Octopus	lattice incubates boxes form generation method	Energy efficiency in addition to daylitghting and views to the outdoor in the second and third parts
[55]	O	HB	Cairo, Aswan, and Alexandria	Rhinoceros Grasshopper Ladybug + Honeybee Octopus	Optimized building form and envelope of a three floor open plan	Thermal energy performance and daylighting
[56]	O	HB	Atlanta, Miami, and Chicago.	Rhinoceros Grasshopper Ladybug + Honeybee Octopus	Building form (including roof shape) and envelope	Energy performance Daylighting
[57]	RMF	HB	Budapest, Hungary.	Rhinoceros Grasshopper Ladybug + Honeybee Octopus python	Form, materials, and envelope in addition to heating energy source.	Six common life-cycle assessment metrics such as acidification potential, stratospheric ozone depletion
[58]	O	HB	Shanghai, Beijing, and Shenzhen.	Rhinoceros Grasshopper Galapagos DIVA.	Form and envelope of two building forms	Energy performance
[59]	R	HB	Three cities in the USA	GA optimizer GENE_ARCH DOE-2	Form (including roof shape) and envelope parameters such as dimensions of the rooms and the window size.	Daylight Energy performance

Table 1. *Cont.*

Reference	Typology	Case Study	Site	Simulation Tool	Dynamic Parameters	Objectives
[53]	U	HB	Philadelphia	Energy plus Matlab M file	Manipulating a single-zone box to generate complex forms	Energy performance
[54]	U	HB	Three different climates (hot, cold, and temperate)	Energy plus Matlab M file	Manipulating a single-zone box to generate complex forms	Energy performance
[60]	O	HB	Cairo	Rhinoceros Grasshopper Ladybug + Honeybee Octopus Python	Building form and orientation of four new proposed form genetion methods including polygons, pixels, letters, and round families.	Thermal energy performance
[50]	O	HB	Cairo, London, and Chicago.	Rhinoceros Grasshopper Ladybug + Honeybee Octopus	Building form and orientation	Thermal energy performance
[48]	RMF	HB	Singapore	Rhino + grasshop-per/Ladybug + Honeybee	2 shapes, orientation + 16 variables	Daylight performance, energy efficiency, and thermal comfort
[61]	RMF	HB	Yazd, Tehran, Tabriz, Rasht, Bandar Abbas, Iran	EnergyPlus	4 variables	Payback period and the predicted percentage dissatisfied
[62]	I	HB	Kjevik, Norway	IDA ICE	17 variables	Energy consumption and thermal comfort
[63]	O	HB	Qingdao, China	EnergyPlus	Orientation + 27 variables	Carbon emissions, discomfort hours, and global cost
[64]	I	RB	Guangzhou, China	Grasshopper	Orientation + 29 variables	Energy, thermal comfort, and daylighting
[65]	I	HB	Nanjing, China	EnergyPlus	22 variables	Daylighting, thermal comfort, energy savings, and economy
[66]	I	RB	Tianjin, China	EnergyPlus	13 variables	Improve energy efficiency and thermal comfort
[67]	I	RB	Wuhan, China	DesignBuilder, EnergyPlus	6 variables	Energy consumption and indoor thermal comfort
[68]	RSF	HB	Serbia	DesignBuilder, EnergyPlus	7 variables	Improve energy efficiency and thermal comfort
[69]	RSF	HB	Marrakech, Morocco	TRNSYS	7 variables	Improve thermal comfort and energy performance

Table 1. *Cont.*

Reference	Typology	Case Study	Site	Simulation Tool	Dynamic Parameters	Objectives
[70]	RMF	HB	Agadir, Tangier, Fez, Ifrane, Marrakech and Errachidia, Morroco	TRNSYS	Orientation + 8 variables	LCC, energy saving, and thermal comfort
[71]	RSF	HB	Darwin, Alice Springs, Brisbane, Perth, Sydney, Mildura, Melbourne, and Hobart, Australia	TRNSYS and Daysim	9 variables	Thermal discomfort hours, unsatisfied daylight hours, and LCC
[72]	–	HB	Boston, MA, USA	EnergyPlus	Orientation + 4 variables	Energy consumption for annual heating, cooling, and electric lighting
[73]	RMF	RB	Osmaniye and Erzurum, Turkey	EnergyPlus	Orientation + 7 variables	Thermal energy and investment cost
[11]	RMF	RB	Hanzhong, Chengdu, Wuhan, Changsha, Xinyang, Yichang, Chongqing, Shaoguan, China	EnergyPlus	Orientation + 13 variables	EUI for heating and cooling, thermal discomfort cooking rate, and LCC
[74]	RSF	HB	Bento Gonçalves, Santa Maria, and Florianopólis, Brazil	EnergyPlus	4 variables	Energy demand and thermal discomfort
[75]	RSF	HB	Chapecó, Brazil	EnergyPlus + Archsim	Window orientation + 12 variables	Degrees of hours of cooling and heating
[76]	RMF	HB	South Korea	TRNSYS	12 variables	Building energy demand, LCA, and LCC
[57]	RMF	HB	Budapest, Hungary	Rhinoceros 3D Grasshopper EnergyPlus	Number of floors, building width + 12 variables	Embodied and operational impact
[77]	RMF	HB	Roma, Italy	EnergyPlus	11 variables	Investment cost, energy cost, energy Demand, and CO_2 emissions
[78]	RMF	HB	19 different cities	EnergyPlus	11 variables	CO_2 emission, annual energy costs, and energy retrofit costs.

Table 1. *Cont.*

Reference	Typology	Case Study	Site	Simulation Tool	Dynamic Parameters	Objectives
[79]	O	HB	Hohhot, Tianjin, Shanghai, Guangzhou, China	DesignBuilder	Orientation + 9 variables	Heating, cooling, lighting energy consumption, and discomfort hours
[80]		HB	Curitiba, Brazil	EnergyPlus	Orientation + 6 variables	Degrees of hours of cooling and heating
[81]	RMF	HB	Roma, Italy	EnergyPlus	(Phase I): Shape, shape proportion, orientation + 5 variables	Total energy demand, heating and cooling demand
[82]	O	HB	Athens, Greece	Rhino and Grasshopper software via the plugins Honeybee and Ladybug EnergyPlus	4 shapes + 4 orientations + 5 variables	Energy demand, energy production, and adaptive thermal comfort
[83]	RMF	HB	Stockholm, Sweden	Grasshopper, EnergyPlus, Honeybee,	Rectangular, H, U, L, T, and cross shapes, orientation + 10 variables	Embodied and operational energy
[84]	RSF	HB	Singapore	EnergyPlus	Phase I: Orientation + 8 variables—Phase II: 4 variables	Phase I: thermal discomfort rate and daylighting ineffective time. Phase II: LCC and energy consumption
[85]	RMF	HB	Palermo, Naples, Florence, and Milan, Italy	EnergyPlus	Orientation + 15 variables	Primary energy consumption, energy-related global cost, and discomfort hours
[85]	RSF	HB	Naples, Italy, and Athens, Greece	EnergyPlus	9 variables	Global cost and primary energy consumption
[86]	RMF	HB	Hong Kong, China	EnergyPlus	Orientation + 10 variables	Heating, cooling, and lighting demand
[87]	RSF	HB	Québec, Canada		39 variables	LCC, greenhouse gases emissions, and the thermal discomfort
[85]	O	HB	Milan, Italy	EnergyPlus	Orientation + 53 variables	Primary energy consumption, global cost, and CO_2-eq emissions
[9]		HB	Curitiba, Florianópolis, Campo Grande, and Belém, Brazil	EnergyPlus	Shape of a module (array), orientation + 6 variables	Energy consumption and constructive cost

Table 1. *Cont.*

Reference	Typology	Case Study	Site	Simulation Tool	Dynamic Parameters	Objectives
[88]	RSF	HB	Curitiba, Santa Maria and Florianopólis, Brazil	EnergyPlus	4 variables	Heating demand and degree-hours of cooling
[43]	O	HB	Beijing, Shangai, and Guangzhou, China	Radiance + DesignBuilder	Rectangle, L-shaped, H-shaped, U-shaped, cross, T-shaped and trapezoidal + 11 variables	Building proportion, daylight, and energy consumption
[89]	RMF	HB	Embrun, La Rochelle, Nice, Nancy and Limoges, France. Beirut, Qartaba, Zahle, Cedars, Lebanon	TRNSYS	14 variables	Thermal and electrical demands, and LCC
[90]	RMF	HB	Shanghai, China	EnergyPlus	Orientation + 19 variables	Comfort Time Ratio and energy demand
[91]	RMF	HB	Hong Kong, Guangzhou, China. Taipei, Taiwan. Bangkok, Thailand. Singapore.	EnergyPlus	Orientation + 6 variables	Lighting and cooling energy consumption
[92]	RMF	HB	Hong Kong, China	EnergyPlus	Orientation + 9 variables	Lighting energy and cooling energy
[93]	RSF	HB	Paraná, Argentina	EnergyPlus	Orientation + 6 variables	The comfort of naturally ventilated rooms and energy consumption in air-conditioned rooms
[94]	RSF	HB	Viçosa, Brazil	Rhino + Grasshopper + Archsim + EnergyPlus	8 variables	Degrees of hours of cooling and heating and cost
[95]	O	HB	Naples, Italy	EnergyPlus	Orientation + 47 variables	Energy consumption, thermal discomfort hours, and the global cost of energy
[96]	I	HB	Benevento, Italy	EnergyPlus	10 variables	St1: discomfort hours, heating and cooling demands St2: investment cost, primary energy consumption, and LCC

RMF: Residential multifamily; RSF: Residential single-family; R: Residential; O: Office building; I: Institutional building. RB: Real building; HB: Hypothetical building; U: Unknown.

In addition to the aforementioned study, Khalil et al. [21] conducted a study among these researchers, focusing on the analysis of an office building. Their approach involved employing a multi-objective evaluation to optimize various factors, including the quality of outdoor views, energy use intensity (EUI), and daylight intensity.

3. Research Aim and Contribution

This paper presents a comprehensive method for generating diverse forms of varying complexity for a standard middle-income apartment in Egypt, utilizing architect-friendly tools. The main aim of this research was to address the limitations in existing building optimization studies, which often rely on simplistic hypothetical buildings [52]. These studies typically focus on a single thermal zone while neglecting considerations such as space design, configuration, and occupant behavior. The second objective of this study was to identify the optimal trade-off between minimizing EUI kWh/m^2, maximizing the views percentages to the outdoor (VPO), maximizing spatial daylight autonomy (sDA), and minimizing annual sunlight exposure (ASE). These parameters are utilized to enhance outdoor views for regularly occupied spaces, encompassing at least 75% of the total plan area to meet the views percentages to the outdoor (VPO) requirement. The sDA metric is employed to assess whether the space receives adequate daylight on the work plane during standard operating hours, aiming for a minimum of 300 Lux for over 50% of the occupancy period. Lastly, ASE is employed to identify surfaces that receive excessive direct sunlight, leading to visual discomfort (glare). ASE measures the percentage of the work plane that exceeds the 1000 Lux threshold for more than 250 occupied hours per year.

One of the authors of this paper has already developed comprehensive framework algorithms for measuring the energy use intensity (EUI). The findings were compared to an existing real case study, and the level of skewness was evaluated, validated, and calibrated. Attia's research, which focused on energy performance and sustainable design in buildings across various locations in Egypt, served as the basis for the comparative analysis [42]. Attia and his team conducted thorough physical surveys and inspections of the buildings, collecting detailed information on various aspects, including space proportions, construction materials, building operations, and HVAC systems. The surveys were designed to ensure comprehensiveness and reliability, incorporating interviews with building operators and occupants to gather additional information and feedback. The analyst responsible for the study modeled Attia's input data in a way that facilitated the replication of the method and the attainment of comparable results by other analysts.

The author utilized a genetic algorithm, using Ladybug and Honeybee V1.5.1 plugins which are both supported by Grasshopper, to calculate the EUI for the highest month observed during the simulations for the entire year. August has the maximum EUI due to the operation of HVAC units in multiple spaces and the additional time spent operating them. The entire study is confined to this month since it is recognized as the worst month in terms of energy use when compared to other months.

When optimizing building performance to reduce energy consumption, it is possible to unintentionally compromise the view of the outdoors and the quality of adequate natural daylight, which are highly valued by building occupants. The view of the outdoors is an indoor environmental parameter that can influence mental and physiological health [19,47]. Gordon has emphasized and proved the importance of having an adequate view of the outdoors, especially in office buildings with high occupancy density and extended working hours. Therefore, it is essential for architects and engineers to strike a balance between energy performance and user well-being when designing buildings, and to investigate techniques for optimizing energy performance without sacrificing the benefits of natural daylight and views of the outdoors [97].

4. Materials and Methods

The residential buildings' thermal loads and energy use intensity (EUI) calculations were performed using the EnergyPlus engine (version 9.0.1); this engine is free and open source, and its results are considered reliable. To facilitate these calculations, Rhino Version 6, a widely used modeling software in the architecture and design industry, was employed. The modeling process was enhanced by integrating Rhino with Grasshopper, a visual programming plugin, which is free. Ladybug and Honeybee, two free downloadable plugins integrated within Grasshopper, expanded the modeling process's capabilities. They enabled climate analysis, weather data visualization, and energy modeling and simulation. By combining these components and leveraging the EnergyPlus engine (version 9.0.1), comprehensive assessments of thermal and energy performance were carried out.

This article focuses on the application of multi-objective optimization (MOO) to a real case study involving a residential building situated in Cairo, Egypt. This case study is distinct because it was not initially solved during the design phase, neglecting various factors that could have contributed to reducing energy consumption. One of these factors involves protrusions, where the building's bays can be extended by 1, 2, or 3 m. Simultaneously, the aim is to maximize outdoor space views by increasing the window-to-wall ratio (WWR) while considering the impact of daylight studies. The integration of all these parameters is essential to achieve an optimized solution. The selected case study represents a prototype residential building that is typically replicated throughout the country without considering the specific climatic conditions of each region. By employing multi-objective optimization, the article aims to address these limitations and identify strategies for reducing energy consumption in residential buildings while considering the integration of various design parameters.

5. Description of Case Studies

According to the Ministry of Health and Housing, it is mandated to provide comprehensive care and hospitality services to citizens. This responsibility is part of the government's duty to ensure the well-being and comfort of the Egyptian population. As a rule of the Ministry of Health and Housing, providing full care and hospitality for citizens and a hospitable space for Egyptians is a part of their duty as a government. In response to the rapid increase in population within a short period, the Ministry of Health and Housing has made efforts to meet the housing requirements. To facilitate quick implementation on-site, they have adopted a standardized housing prototype. However, it is important to note that these prototypes are often implemented without adequate consideration for environmental aspects. For instance, the same prototype may be used regardless of whether the housing site is located in a hot and dry or hot and humid region, disregarding the varying weather conditions present throughout Egypt. This lack of consideration for environmental factors raises concerns about the long-term sustainability and suitability of housing solutions in different climatic zones.

The chosen prototype was for a "Dar Misr Project" that was selected as a case study due to the availability of detailed architectural drawings and building specifications, as well as the opportunity to influence future development phases. As a major housing development of over 30,000 units constructed [98], with governmental plans for over 150,000 units in total being targeted [99], the Dar Misr Project provides a substantial project to analyze and optimize techniques for improving energy efficiency in hot arid climates. Although actual energy consumption data are unavailable, the comprehensive set of CAD drawings, material specifications, and equipment schedules enables accurate modeling and simulation of energy performance for the existing structures. Additionally, there is potential value in understanding how energy efficiency can be designed into future phases of this massive development by applying genetic programming to model energy optimizations. The technique can reveal insights into conserving energy that could inform sustainability goals for the remaining growth of the Dar Misr Project and large-scale projects in Egypt and similar hot, arid regions.

The prototype being utilized was designed as a single unit that is mirrored and flipped for the fourth dimension in a five-floor building. This prototype is depicted below in Figure 1. This means that the same unit design is repeated and arranged in a mirrored and flipped manner across each floor. The attached drawing plan and photos of the building provide visual documentation of this prototype's implementation. The unit's layout includes two bedrooms, one master bedroom, a spacious salon, a water closet, and a kitchen. The average areas for these spaces are approximately 12 m^2, 16 m^2, 30 m^2, and 20 m^2, respectively. This standardized unit serves as the basis for the housing solution being implemented on-site.

Figure 1. An architectural plan for the examined prototype and photographs showcasing the constructed prototype within its current surroundings.

In this study, parametric modeling was employed to explore and optimize the design of spaces that have limitations in terms of their ability to extend towards the south and east directions due to the surrounding neighboring buildings. The focus of the modeling was on manipulating two key parameters: the room's proportions in the X and Y dimensions and the window-to-wall ratio (WWR) for the same rooms, as depicted in Figure 2 below.

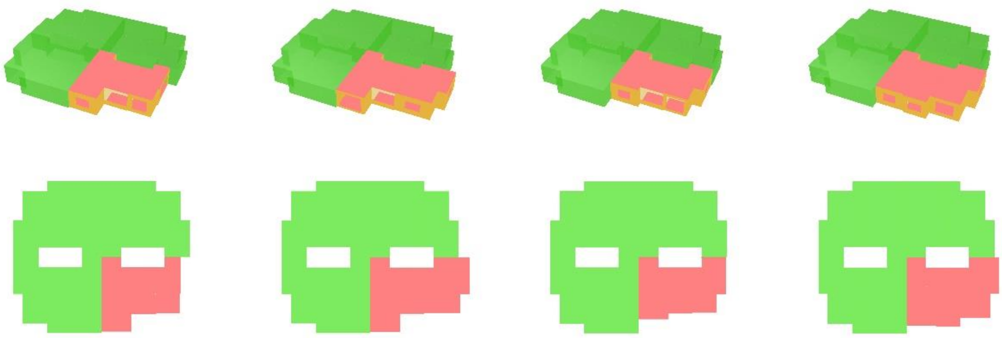

Figure 2. The variations of the room's proportions and WWR.

By varying the room's proportions and WWR, this study aimed to assess their combined impact on several performance metrics, including the energy use intensity (EUI), views percentages to the outdoor (VPO), annual sun exposure (ASE), and spatial daylight autonomy (SDa). These metrics serve as indicators for energy consumption, visual comfort, and daylight availability within spaces.

This study analyzed the effects of different room proportions and WWRs on the energy use intensity (EUI), considering how variations in these parameters can influence the heating, cooling, and lighting requirements. Additionally, views percentages to the outdoor (VPOs) were assessed to evaluate the amount of visual connection to the outdoors and its impact on occupant comfort and well-being. Furthermore, this study examined annual sun exposure (ASE) and spatial daylight autonomy (sDA) as metrics for daylighting analysis. By considering these metrics and their relationships, the study aimed to find optimal room proportions and WWRs that balance energy efficiency, visual comfort, and daylighting performance within the given constraints imposed by the neighboring buildings.

6. Objectives, Variables, Energy Sources and Climate Context

This study's objective was to balance between minimizing both EUI and ASE and maximizing the VPO while achieving an adequate sDA; these objectives are presented in Table 2. This will ensure that the optimum solution will adhere to energy consumption issues through EUI and ASE and comply with the user's requirements whether they are related to functionality, such as sDA, or satisfaction, such as VPO. This study's design variables are presented in Table 2, where the quantification method and values of space proportions and WWR are shown. These variables were selected to cope with the possibilities of changing based on the case study's contextual limitations. Both the space proportions and WWR were examined simultaneously using the Octopus plugin, as mentioned earlier. This allowed for a comprehensive analysis of the interactions between these parameters. As a result, a large matrix of more than thousands of iterations was generated to explore the various combinations of space proportions and WWRs. This analysis's objective was to identify the combination of space proportions and WWR that leads to the lowest energy use intensity (EUI) value. By examining these parameters together and conducting extensive iterations, this research aimed to optimize the design and achieve the most energy-efficient outcomes for the residential building under study. Furthermore, the energy sources that were considered while minimizing the EUI are presented in Table 2.

Table 2. The quantification methods and values of the case study objectives, variables, and energy sources. OV: original value.

	Objective/Variable/Energy Source	Units	Quantification Method	Quantification Values
Objective	EUI	kWh/m^2	Minimize	-
	ASE	%	Minimize	-
	sDA	%	Maximize	-
	VPO	%	Maximize	-
Space proportions	Living Room oriented towards the south direction	m	A ratio from the original dimension of each side of the space	X, Y (OV) = 3.85 0.8 (80%) = 3.08 0.9 = 3.465 1.1 = 4.235 1.2 = 4.62
	Master Bedroom oriented towards the east direction	m	A ratio from the original dimension of each side of the space	X, Y = 3.55 0.8 = 2.84 0.9 = 3.195 1.1 = 3.905 1.2 = 4.26

Table 2. *Cont.*

	Objective/Variable/Energy Source	Units	Quantification Method	Quantification Values
Space proportions	Bedroom oriented towards the east direction	m	A ratio from the original dimension of each side of the space	X, Y = 3.55 0.8 = 2.84 0.9 = 3.195 1.1 = 3.905 1.2 = 4.26
	Bedroom oriented towards the south direction	m	A ratio from the original dimension of each side of the space	X, Y = 4.15 0.8 = 3.32 0.9 = 3.735 1.1 = 4.565 1.2 = 4.98
	Salon oriented towards the south direction	m	A ratio from the original dimension of each side of the space	X, Y = 5.5 0.8 = 4.40 0.9 = 4.95 1.1 = 6.05 1.2 = 6.6
Window Wall Ratio	Living Room oriented towards the south direction	%	Window ratio compared to wall area	0.24 (24%) 0.48 0.72
	Bedroom oriented towards the east direction	%	Window ratio compared to wall area	0.15 0.3 0.45
	Bedroom oriented towards the south direction	%	Window ratio compared to wall area	0.18 0.36 0.54
	Salon oriented towards the south direction	%	Window ratio compared to wall area	0.2 0.4 0.6
Energy Sources	Cooling	kWh/m^2	Minimize	-
	Interior Light	kWh/m^2	Minimize	-
	Electric Equipment		Minimize	-
	Residential HVAC Fans	kWh/m^2	Minimize	-

The weather file used for the analysis of the residential building was obtained from a one-building website that regularly updates its weather files. Multiple weather stations were used to ensure a higher level of accuracy in representing the existing weather conditions. Figure 3 below illustrates the dry bulb temperature and relative humidity. The attached figure clearly shows that the weather during the summer is extremely hot, with temperatures peaking at 43 °C and averaging around 30 °C. Conversely, in the winter, the weather becomes very cold, with nighttime temperatures dropping to 7 °C during the coldest periods. Interestingly, the relative humidity exhibits an inverse relationship with temperature. As the temperature increases, the relative humidity decreases, and vice versa. The relative humidity reaches its peak during winter when solar radiation is minimal.

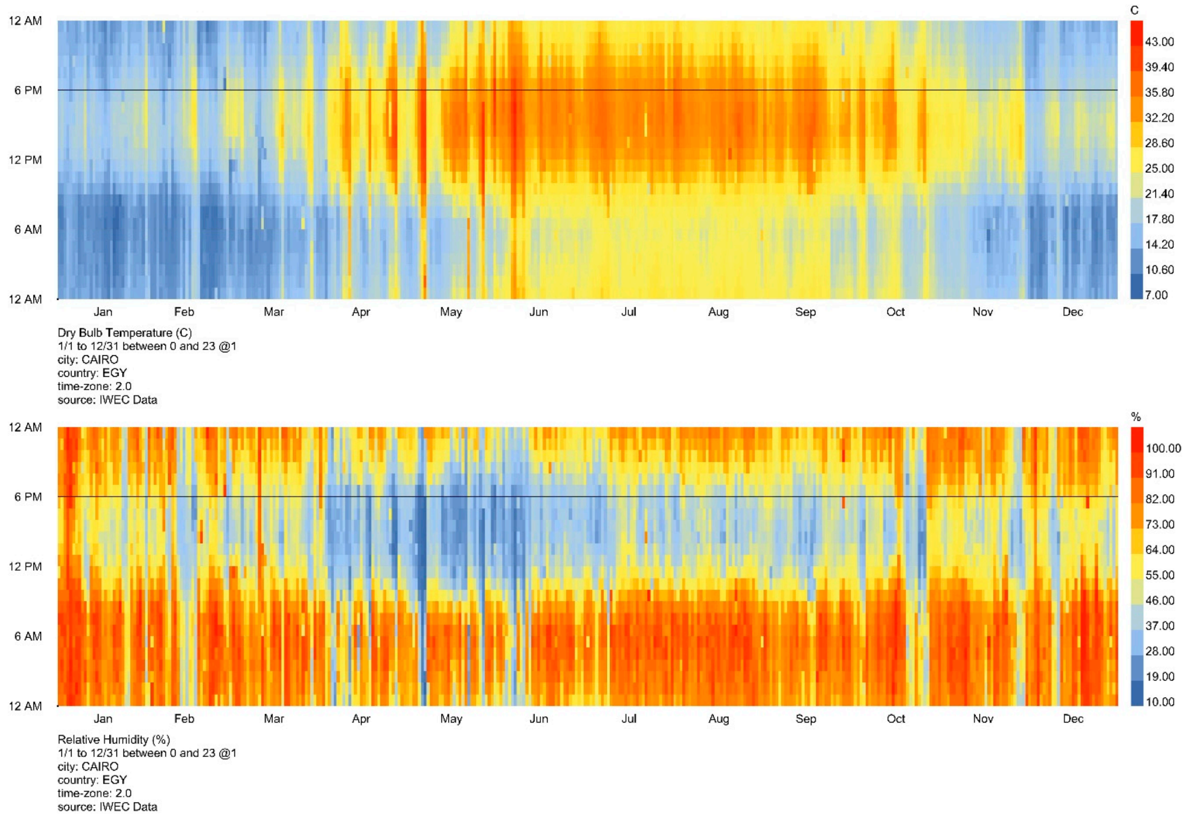

Figure 3. Charts displaying the variations in dry bulb temperature in Celsius and relative humidity as a percentage.

7. Modeling and Settings for Simulation and Optimization

The buildings were modeled using Rhinoceros V.6 and the simulation setups were conducted in EnergyPlus with a simulation timestep of four simulations per hour. This research aimed to bridge the gap by implementing optimization techniques on buildings with multiple floors and various parameters, as discussed in the literature review. An example of this is the incorporation of shading between floors, such as the shading effect of the first floor on the ground floor. This shading helps in reducing energy consumption by mitigating the thermal loads transferred to the lower floors. In the following section, the settings and data inputs for the model will be introduced, where all the simulations were integrated with the model to achieve the research objectives.

The optimization process was performed on a laptop equipped with an Intel Core i7-H series processor running at 2.4 GHz, with 16 GB of RAM, and a 64-bit Windows 11 operating system.

8. Internal Loads

The spaces within the building were defined and characterized individually, without any merging between them. Each zone was defined based on occupancy, lighting, and appliance schedules that apply throughout the entire year. The building itself was occupied 24 h a day, 365 days a year, with an occupancy level consistently set at 100%. The input data for the occupation schedule and the EUI measurements are provided in Table 3 below. All the input data provided comply with the Egyptian national code for energy. Furthermore, the data for each space are presented in Table 4.

Table 3. The occupation schedule and the EUI measurements in kWh/m^2.

Months		January	February	March	April	May	June	July	August	September	October	November	December
Seasons		Fall	Spring				Summer				Fall		
AC Condition: On/Off		NO AC operated	NO AC operated	NO AC operated	NO AC operated	NO AC operated	2 AC units operated/1 bedroom & Living room	3 AC units operated/2 bedrooms & Living room	3 AC units operated/2 bedrooms & Living room	4 AC units operated/2 bedrooms & Living room	NO AC operated	NO AC operated	NO AC operated
EUI Breakdown	Cooling	0	0	0	0	0	1.07	2.297	2.48	2.323	0	0	0
	Interior Light	0.209	0.209	0.209	0.209	0.209	0.287	0.287	0.287	0.287	0.287	0.209	0.209
	Electric Equipment	1.07	1.07	1.07	1.07	1.07	1.122	1.148	1.148	1.148	1.148	1.07	1.07
	Residential HVAC Fans	0	0	0	0	0	0.052	0.104	0.104	0.104	0	0	0
Total EUI in kWh/m^2/y		1.28	1.28	1.28	1.28	1.28	2.53	3.83	4.02	3.86	1.43	1.28	1.279

Table 4. The data for each space, individually.

Condition	Space Definition	Area	Number of Occupants	Interior Light	Electric Equipment	Schedule
AC spaces	Living room	14 m^2	3 persons	17 watts × 2 lamps	37 watts	During the summer season, both zones of the residential unit are heavily occupied and require air conditioning, resulting in higher energy consumption for cooling. However, during the fall and spring seasons, there is no need for air conditioning, and the energy consumption for appliances and lighting is reduced by half for bedrooms, while the living room is found to be used more frequently than the bedrooms, which also contributed to differences in energy consumption during the whole year.
	Master bedroom, bedroom, and living room	34 m^2	3 persons	13 watts × 3 lamps	45 watts	

Table 4. *Cont.*

Condition	Space Definition	Area	Number of Occupants	Interior Light	Electric Equipment	Schedule
Non-AC spaces	Salon, corridor, entrance lobby, and toilets	53 m^2	3 persons	9 watts × 4 lamps	15 watts	These areas have consistent energy consumption levels throughout the year with little to no significant variation.
	Kitchen	12 m^2	2 persons	9 watts × 1 lamps	550 watts	It is important to note that equipment such as the refrigerator is often operated without rest throughout the whole year, while the equipment and lamps are primarily used during the cooking process.

9. Constructive Parameters

The selected materials used in the project's construction comply with the local energy efficiency code and ASHRAE 90.1-2009 standards [100]. The resistance characteristics of the opaque envelope (exterior walls, interior walls, and ceiling) have two different values: 1.732 m^2·K/W and 1.66 m^2·K/W. Regarding the translucent envelope, the windows feature single glazing with a thickness of 3 mm. They have a solar heat gain coefficient of 0.5 and a thermal transmittance (U-value) of 6.25 W/m^2·K.

10. Natural Ventilation Versus Cooling and Heating Demands

The building is equipped with a mechanical ventilation system for both cooling and heating purposes. Natural ventilation is not implemented in the building design. However, a small value for infiltration was considered during the simulation to account for any leakage resulting from construction and finishing issues. The infiltration rate used in the simulation was approximately 0.000227 m^3/s per m^2, which represents a minimal amount of air leakage.

The HVAC system utilized in the simulation was the VAV air-cooled chiller with a central air-source heat pump reheat routine in the EnergyPlus software. This HVAC template zone represents an air conditioning system with a coefficient of performance (COP) equal to 1. The setpoints for the HVAC system were set at 21 °C for heating and 27 °C for cooling, ensuring comfortable indoor conditions for the occupants.

11. Research Framework

Figure 4 depicts the working framework developed for the study, focusing on the impact of the window-to-wall ratio (WWR) and changes in space proportions (X and Y dimensions) on the energy use intensity (EUI), views percentages to the outdoor (VPO), annual sun exposure (ASE), and spatial daylight autonomy (sDA). The framework consists of three phases.

Parametric Model Generation: The first phase involved generating a parametric model using Grasshopper scripting. The model identifies each zone based on its functionality and scheduling for the users' utility within the specific space. This step includes defining the spatial layout, room proportions, and other architectural elements.

Identification of Influencing Parameters: As depicted in the second phase, this study identified the parameters that can influence the outcomes of EUI, VPO, ASE, and SDa. These parameters may include the WWR and room proportions in the X and Y dimensions. It is crucial to understand and define the key parameters that significantly impact the performance metrics under investigation.

Simulation and Optimization: The third phase involved using the Octopus plugin, a tool for connecting and optimizing parameters within Grasshopper. The plugin facilitates running selective simulations with different parameter combinations and ratios. The simulations are performed iteratively until the desired goals or objectives are achieved.

The optimization engine works continuously, exploring different parameter settings and evaluating their impact on the performance metrics of interest.

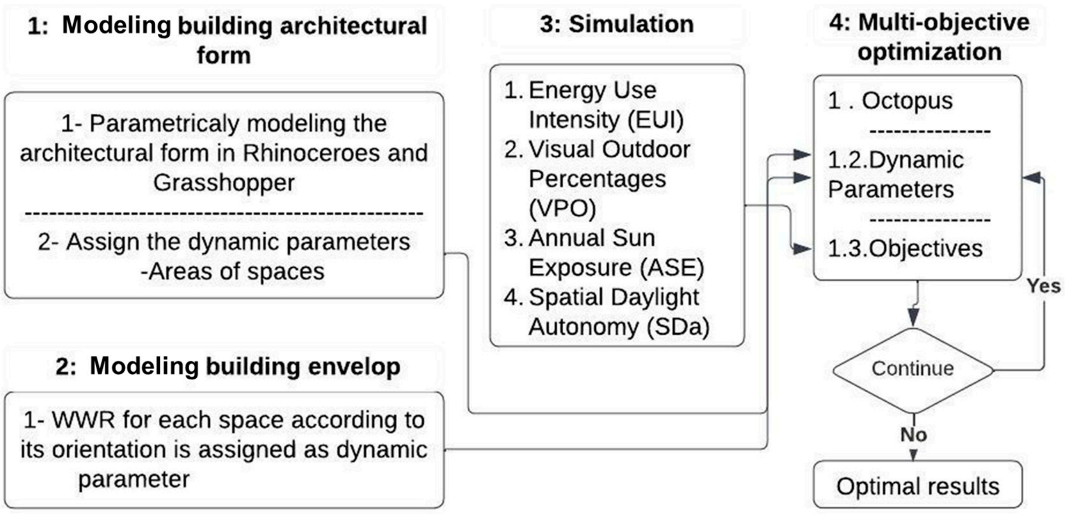

Figure 4. The research framework.

Throughout this framework, it was important to consider research limitations and constraints. These limitations may include maintaining the existing building conditions, using consistent construction materials, respecting height restrictions imposed by neighboring structures, and any other relevant constraints. Adhering to these limitations ensured that the study remains applicable and relevant to the real-world context.

12. Research Working Flow

In this study, the simulation of daylight performance, energy efficiency, and visual outdoor comfort was conducted using the open-source tools Ladybug 1.5.1 and Honeybee 1.5.1. These tools were utilized within the Grasshopper platform to write and run the simulations. The EnergyPlus engine and the Radiance engine were employed by these tools to accurately simulate the energy function and daylight performance, respectively.

In the research workflow, as depicted in Figure 5 (an appendix has been included to provide a more detailed and clearer representation of the workflow, featuring a larger scale with readable commands), the simulation was focused on a specific month, August. This selection was because August typically experiences the highest dry bulb temperature compared to other months. The research working flow was divided into fifteen consequential items, starting with the parametric model until it reached the results recorded. The first phase focused on form generation, employing Grasshopper algorithms to model the residential apartment. This involved altering the proportions of spaces by successively increasing them in both the X and Y dimensions. In the second phase, space names were defined, and the window-to-wall ratio (WWR) was specified for each space. Additionally, it was determined whether each space is air-conditioned or not. The third phase was dedicated to an essential factor, depicting the space usage schedule. This included determining the amount of wattage usage per meter for each space and establishing the duration of usage for each space. These initial phases laid the foundation for the research study, encompassing generating the parametric model, defining the characteristics of each space, and establishing the usage patterns and energy requirements. They provided the groundwork for further analysis and optimization in subsequent phases of the research workflow.

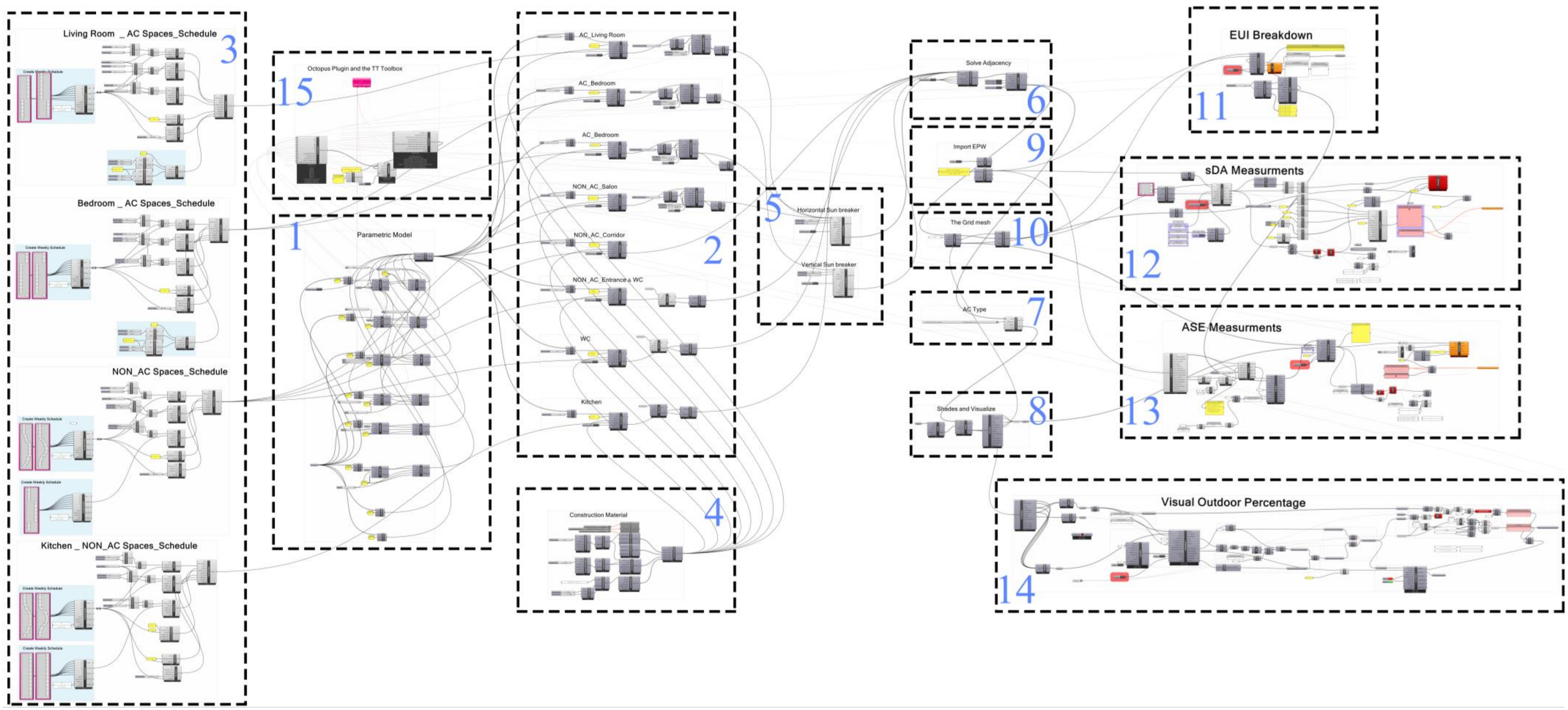

Figure 5. A comprehensive working flow for studying the EUI, VPO, ASE, and SDa.

The fourth step involved defining the specifications of the building construction materials for both opaque and semi-transparent elements. Each element's material properties were specified accordingly. In the fifth phase, the presence of sun breakers was considered, although the researcher neglected their inclusion in this study to match the existing conditions. This means that the design did not incorporate any sun breakers. The sixth step focused on defining the correlation with adjacent spaces. In this case, the correlation was defined as adiabatic, allowing for heat and cooling transfer between spaces. Phase seven addressed the HVAC (Heating, Ventilation, and Air Conditioning) system type, specifically "Residential AC with no heat," as identified based on the LB and HB. The eighth step involved defining the borders with neighboring spaces and outlining the boundaries and interfaces between the apartment and its adjacent areas. In the ninth step, the EnergyPlus Weather file for the selected zone was specified. This file provided the necessary weather data for the simulation and analysis. The mesh grid size was defined in the tenth step. This grid measures 0.5 m above the floor in the interior space of the apartment. The mesh grid was connected to various measurement tools, including EUI measurement, a script written for VPO, and daylight studies, as part of steps eleven to fourteen. These steps contributed to further refining the research parameters and setting up the necessary conditions for analysis and evaluation in subsequent stages of the workflow. In the final step, step fifteen, this research incorporated an iteration engine tool to facilitate the optimization process. This tool is specifically characterized by the Octopus plugin. The Octopus plugin randomly selects values from attached sliders that control the space proportions and window-to-wall ratio (WWR). By utilizing this tool, this research study explored different combinations of space proportions and WWR to achieve the desired outcomes. To record and analyze the results, this research utilized TTToolbox [101]. TTToolbox is a Grasshopper plugin developed by Thornton Tomasetti, CORE studio [101], which allows for the easy export of results in Excel format, enabling further analysis and interpretation of the obtained data. By employing the iteration engine tool and leveraging the capabilities of Octopus and TTToolbox, this research study could efficiently explore and evaluate a wide range of design iterations, providing valuable insights into the impact of different space proportions and WWR on the desired metrics and objectives.

13. Results and Discussion

Extracting three multi-regression equations out of 1693 iterations using the Octopus plugin was a significant achievement of the research. These equations play a crucial role in identifying how the space proportions (SPs) and window-to-wall ratio (WWR) can impact the energy use intensity (EUI) in terms of kilowatt-hours per square meter kWh/m^2. The multi-regression equations provide a quantitative understanding of the relationship between the examined parameters and the resulting EUI values. By analyzing the coefficients and statistical significance of the variables in these equations, the researchers could discern the relative influence of space proportions and WWR on the energy performance of the residential building. These equations serve as valuable tools for predicting and optimizing EUI based on different combinations of SPs (space proportions) and WWR (window-to-wall ratio). They provide insights into the design strategies and interventions that can lead to more energy-efficient outcomes in the specific context of the study. By leveraging these multi-regression equations, the research can further refine the design process, identify optimal configurations, and make informed decisions to minimize energy consumption and enhance the sustainability of residential buildings in hot arid climates.

13.1. First Scenario

The provided Equation (1) represents the correlation between the window-to-wall ratio (WWR) and energy consumption for the four spaces with varying ratios. To evaluate the strength of this correlation, this research conducted a regression analysis and examined the regression statistics. The R-squared value, which measures the proportion of the variation in energy consumption explained by the WWR, was found to be 61%. This indicates that approximately 61% of the variability in energy consumption can be attributed to changes in the WWR. Moreover, the *p*-values were examined to determine the statistical significance of the spaces' parameters in the equation. A *p*-value less than 0.05 indicates that the parameters (spaces) are statistically significant in predicting energy consumption. In this scenario, if all the spaces' parameters had *p*-values less than 0.05, it would indicate that each space's contribution to energy consumption is statistically significant in the regression model. The combination of R-square and *p*-values provides a comprehensive understanding of the correlation strength and the individual significance of the spaces' parameters in the regression model, offering valuable insights into the relationship between the window-to-wall ratio and energy consumption for the different spaces under consideration.

$$EUI = 3.34 + 0.47 \times \mathrm{WWR}_{LS} + 2 \times \mathrm{WWR}_{ME} + 0.76 \times \mathrm{WWR}_{CS} + 0.07 \times \mathrm{WWR}_{SS} \quad (1)$$

where:

- EUI is the energy use intensity in kWh/m^2.
- WWR_{LS} is the window-to-wall ratio for the Living Room oriented towards the south.
- WWR_{ME} is the window-to-wall ratio for the Master Bedroom oriented towards the east.
- WWR_{CS} is the window-to-wall ratio for Corner Bedroom oriented towards the south.
- WWR_{SS} is the window-to-wall ratio for the Salon oriented towards the south.

13.2. Second Scenario

Equation (2) represents the correlation between the changing space proportions (SPs) and energy consumption for the four spaces while the window-to-wall ratio (WWR) was constant with no variations. This equation explores how altering the space proportions of the four spaces impacts energy consumption.

Based on the regression analysis conducted by the researcher, the R-squared value of 27% suggests that approximately 27% of the variability in energy consumption could be explained by changes in space proportions. This indicates a moderate correlation between the space proportions and energy consumption. While the R-squared value was not as high as desired, it still suggests that the space proportions have some influence on energy consumption in the studied residential building. Regarding the *p*-values, values less than 0.05 were found for all the spaces except the Master Bedroom, which is oriented and shifted towards the east. This indicates that the parameters of most individual spaces had a statistically significant contribution to energy consumption in the regression model. This suggests that variations in the space proportions of these rooms can lead to significant changes in energy consumption. However, the Master Bedroom, which is oriented and shifted towards the east, may not have a statistically significant impact on energy consumption according to the *p*-value.

$$EUI = 5.66 + 0.18 \times SP_{LS} - 0.11 \times SP_{CE} + 0.22 \times SP_{CS} - 1.41 \times SP_{SS} \quad (2)$$

where:

- SP_{LS} is the space proportion for the Living Room oriented and shifted towards the south.
- SP_{ME} is the space proportion for the Master Bedroom oriented and shifted towards the east.
- SP_{CE} is the space proportion for the Corner Bedroom oriented and shifted towards the east.
- SP_{CS} is the space proportion for the Corner Bedroom oriented and shifted towards the south.
- SP_{SS} is the space proportion for the Salon oriented and shifted towards the south.

13.3. Third Scenario

When combining both scenarios and merging all parameters into a single equation, a different result was obtained compared to analyzing each parameter separately. The R-squared value of 89% indicates that approximately 89% of the variability in energy consumption could be attributed to changes in the space proportions (SPs) and window-to-wall ratio (WWR). This suggests a strong correlation between the space proportions, WWR, and energy consumption. In terms of statistical significance, the p-values for most of the spaces (except the Salon) were found to be less than 0.05. This suggests that the relationship between the space proportions, WWR, and energy consumption was statistically significant for most of the spaces. However, further analysis may be required to understand the specific impact and significance of the Salon space.

$$EUI = 4.86 + 0.103 \times SP_{LS} - 0.178 \times SP_{ME} - 0.173 \times SP_{CE} - 0.06 \times SP_{CS} - 1.17 \times SP_{SS} + 0.49 \times \mathrm{WWR}_{LS} + 1.87 \times \mathrm{WWR}_{ME} + 0.7010 \times \mathrm{WWR}_{CS} \quad (3)$$

Table 5 Summarizes the three correlation scenarios and provides an overview of the coefficient of determination (R-squared) value for each scenario.

Table 5. Correlation scenarios summary.

Scenario	Constant Inputs	Variable Inputs	R-squared
First Scenario	Space Proportions (SP)	Window-to-wall ratio (WWR)	0.61
Second Scenario	Window to Wall Ratio (WWR)	Space proportions (SPs)	0.27
Third Scenario	N.A.	(WWR) and (SPs)	0.89

Table 6 provides an overview of the correlations between the Leadership in Energy and Environmental Design (LEED) credit requirements and the space proportions (SPs) and window-to-wall ratio (WWR). It examines how these parameters can potentially affect the attainment of LEED certification. The table indicates that the values of EUI (energy use intensity) in kWh/m^2, whether at their lowest or highest, failed to meet the criteria for the views percentages to the outdoor (VPO) credit. This was due to the requirement of having an unobstructed view of the outdoors through vision glazing for 75% of the regularly occupied floor area, which was not achieved despite an increase in the window area. To fulfill this credit, it would be more beneficial to incorporate a curtain wall system to enhance the window-to-wall ratio (WWR). This suggests that additional adjustments, such as increasing the WWR, may be necessary to achieve the desired level of exposure to the outdoors and natural light. Daylight studies, on the other hand, showed a positive correlation between the increase in window openings and the WWR. As the WWR increases, more natural light can be integrated into the spaces, potentially fulfilling the requirements for daylighting, and achieving LEED credits in this regard.

Table 6. Correlations between (LEED) credit requirements, space proportions (SPs) and window-to-wall ratio (WWR).

Space proportions					**Window-to-wall ratio**				**EUI (kWh/m²)**	**Daylight**				**Visual comfort**	
Living Room	Master Bedroom	The Corner Bedroom Shifted toward the east	The Corner Bedroom Shifted towards the south	Salon, southern orientation	WWR for Living Room	WWR for Master Bedroom, eastern orientation	WWR for Corner Bedroom, southern orientation	WWR for Salon, southern orientation		300 lux for 50% of the Occupied Period	sDA_LEED Status of Your Geometry	ASE_LEED Status of Your Geometry	1000 Lux or More for At Least 250 Occupied Hours per Year	VPO Percentage	VPO (Pass or Fail)
1.1	1.1	1.1	1.2	1.2	0.24	0.15	0.18	0.2	3.674	20.00%	2	1	0.00%	6.70%	2
0.9	1.2	1	1	1	0.48	0.15	0.36	0.6	4.162	47.90%	2	1	0.00%	10.50%	2
0.8	0.8	0.9	0.8	1.1	0.72	0.3	0.36	0.6	4.769	63.90%	1	1	0.00%	14.30%	2
1.2	1.2	0.8	1.2	0.9	0.72	0.45	0.36	0.6	4.978	58.60%	1	1	0.00%	14.70%	2
1.2	0.8	0.9	0.9	0.9	0.72	0.45	0.54	0.4	5.636	59.60%	1	1	0.00%	18%	2

1: Achieves the LEED credit requirements, 2: does not achieve the LEED credit requirements.

14. Study Limitations

The limitations of this study are that the variables were selected to cope with the possibilities of changing based on case study contextual limitations, which generated layout organization options that varied in space proportions and WWR only. For example, the study did not consider changes in the Z direction, local building regulations, or structure system limitations; however, these variables may be included together with other variables in future applications. Moreover, this study focused on energy performance and its related objectives; nevertheless, future studies may include more objectives to develop the proposed method. Furthermore, the study dealt with traditional energy sources. Nonetheless, future studies may include advanced energy sources such as smart systems. Eventually, due to time limitations, this study's analysis was based on 1693 iterations, and more iterations would increase the reliability of the results.

15. Conclusions

This paper introduces a comprehensive approach to generating a wide range of forms with varying complexities for a standard middle-income apartment in Egypt. The main objective of this research was to overcome the limitations found in existing building optimization studies, which frequently utilize simplistic hypothetical buildings. Such studies often concentrate solely on a single thermal zone, disregarding important factors such as space design, configuration, and occupant behavior. The second objective of this study was to determine the optimal balance between minimizing the energy use intensity (EUI) in kWh/m^2, maximizing the views percentages to the outdoor (VPO), achieving spatial daylight autonomy (sDA), and minimizing annual sunlight exposure

(ASE). The research conducted using the Octopus plugin resulted in the extraction of three significant multi-regression equations out of 1693 iterations. These equations played a crucial role in understanding how the space proportions (SPs) and the window-to-wall ratio (WWR) affect the energy use intensity (EUI) measured in kilowatt-hours per square meter (kWh/m^2). By quantifying the relationship between these parameters and the EUI values, the multi-regression equations provided a quantitative understanding of the impact of the SPs and the WWR on energy consumption. These equations serve as valuable tools for predicting and optimizing EUI based on different combinations of SPs and WWRs. The first regression equation illustrated the correlation between WWR and EUI in kWh/m^2, showing a significant relationship between the independent and dependent parameters. Meanwhile, the second equation examined the relationship between SPs and EUI in kWh/m^2. However, the results showed a less significant combination compared to the first equation, especially in the Master Bedroom, where the p-value was more than 0.05, indicating a statistically insignificant contribution to energy consumption in the regression model. The third equation combined the two independent parameters of WWR and SPs with the dependent value of EUI in kWh/m^2. A strong correlation appeared when these two parameters worked together, influencing EUI either positively or negatively. However, for the Salon, the p-value was more than 0.05, suggesting a less significant contribution to energy consumption in the regression model. By leveraging the insights from these equations, the research can refine the design process, identify optimal configurations, and make informed decisions to minimize energy consumption and enhance the sustainability of residential buildings in hot arid climates.

Building Performance Optimization (BPO) for energy consumption is an important area of research, but several challenges need to be addressed. One such challenge is the lack of investigations that consider the entire building with multiple thermal zones, as compared to prior studies that only dealt with one large space. Another challenge is the space configuration and efficiency while generating complex forms. Earlier studies have focused on improving views of the outdoors by adjusting façade manipulation and characteristics, but this does not address the complex relationship between views and energy performance. As a result, views of the outdoors must be considered as an objective in building form optimization for energy performance. To conclude, improving a building's form for energy performance necessitates a multidisciplinary approach that considers various design factors such as thermal comfort, lighting, and ventilation, as well as the occupant's functional and aesthetic needs. Further research is needed to develop new optimization methods and tools that can solve these problems while also allowing architects to construct energy-efficient buildings. Furthermore, it is essential to incorporate additional parameters in the optimization process, such as building orientations, the inclusion of extra shading devices, and considering multi-story buildings rather than restricting the analysis to a single-story building.

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References

1. Bezerra, P.; Cruz, T.; Mazzone, A.; Lucena, A.F.; De Cian, E.; Schaeffer, R. The multidimensionality of energy poverty in Brazil: A historical analysis. *Energy Policy* **2022**, *171*, 113268. [CrossRef]
2. González-Eguino, M. Energy poverty: An overview. *Renew. Sustain. Energy Rev.* **2015**, *47*, 377–385. [CrossRef]
3. Piai, J.C.; Gomes, R.D.M.; Jannuzzi, G.D.M. Integrated resources planning as a tool to address energy poverty in Brazil. *Energy Build.* **2020**, *214*, 109817. [CrossRef]

4. Cristino, T.; Neto, A.F.; Wurtz, F.; Delinchant, B. Barriers to the adoption of energy-efficient technologies in the building sector: A survey of Brazil. *Energy Build.* **2021**, *252*, 111452. [CrossRef]
5. Invidiata, A.; Ghisi, E. Impact of climate change on heating and cooling energy demand in houses in Brazil. *Energy Build.* **2016**, *130*, 20–32. [CrossRef]
6. Pacheco, M.; Lamberts, R. Assessment of technical and economical viability for large-scale conversion of single family residential buildings into zero energy buildings in Brazil: Climatic and cultural considerations. *Energy Policy* **2013**, *63*, 716–725. [CrossRef]
7. Triana, M.A.; Lamberts, R.; Sassi, P. Should we consider climate change for Brazilian social housing? Assessment of energy efficiency adaptation measures. *Energy Build.* **2018**, *158*, 1379–1392. [CrossRef]
8. Triana, M.A.; Lamberts, R.; Sassi, P. Sustainable energy performance in Brazilian social housing: A proposal for a Sustainability Index in the energy life cycle considering climate change. *Energy Build.* **2021**, *242*, 110845. [CrossRef]
9. Zemero, B.R.; Tostes, M.E.d.L.; Bezerra, U.H.; Batista, V.d.S.; Carvalho, C.C.M.M. Methodology for Preliminary Design of Buildings Using Multi-Objective Optimization Based on Performance Simulation. *J. Sol. Energy Eng.* **2019**, *141*, 0408011. [CrossRef]
10. Baglivo, C.; Congedo, P.M.; Murrone, G.; Lezzi, D. Long-term predictive energy analysis of a high-performance building in a mediterranean climate under climate change. *Energy* **2022**, *238*, 121641. [CrossRef]
11. Cao, X.; Yao, R.; Ding, C.; Zhou, N.; Yu, W.; Yao, J.; Xiong, J.; Xu, Q.; Pan, L.; Li, B. Energy-quota-based integrated solutions for heating and cooling of residential buildings in the Hot Summer and Cold Winter zone in China. *Energy Build.* **2021**, *236*, 110767. [CrossRef]
12. He, W.; Zhang, L.; Yuan, C. Future air temperature projection in high-density tropical cities based on global climate change and urbanization—A study in Singapore. *Urban Clim.* **2022**, *42*, 101115. [CrossRef]
13. Liu, S.; Kwok, Y.T.; Lau, K.K.-L.; Ouyang, W.; Ng, E. Effectiveness of passive design strategies in responding to future climate change for residential buildings in hot and humid Hong Kong. *Energy Build.* **2020**, *228*, 110469. [CrossRef]
14. The Ministry of Electricity and Renewable Energy. Available online: http://www.moee.gov.eg/english_new/home.aspx (accessed on 30 June 2023).
15. World Bank. World Bank Group—International Development, Poverty, & Sustainability. Available online: https://www.worldbank.org/en/home (accessed on 30 June 2023).
16. Kamel, T. Re-Evaluation of the Egyptian Code of Housing and Energy Consumption with Emphasis on Shading Devices Rotation Angles. *J. Eng. Res.* **2021**, *10*, 38–47. [CrossRef]
17. Kamel, T.M. Integrating a parametric tool in design process to improve the acoustic behavior of the asphalt finishing materials: A case study for housing typologies for low- and middle-income residents. *Noise Mapp.* **2022**, *9*, 157–169. [CrossRef]
18. Eweda, M.M.; Lakousha, M.M. VBA Tool Based on Best Fit Regression Models for the (LUI) Comprehensive System. *J. Eng. Appl. Sci.* **2020**, *67*, 1325–1342.
19. Yeom, S.; Kim, H.; Hong, T.; Park, H.S.; Lee, D.-E. An integrated psychological score for occupants based on their perception and emotional response according to the windows' outdoor view size. *J. Affect. Disord.* **2020**, *180*, 107019. [CrossRef]
20. Kim, J.; Kent, M.; Kral, K.; Dogan, T. Seemo: A new tool for early design window view satisfaction evaluation in residential buildings. *J. Affect. Disord.* **2022**, *214*, 108909. [CrossRef]
21. Khalil, A.; Tolba, O.; Ezzeldin, S. Optimization of an office building form using a lattice incubate boxes method. *Adv. Eng. Inform.* **2023**, *55*, 101847. [CrossRef]
22. Yu, X.; Su, Y. Daylight availability assessment and its potential energy saving estimation—A literature review. *Renew. Sustain. Energy Rev.* **2015**, *52*, 494–503. [CrossRef]
23. Albatayneh, A.; Hindiyeh, M.; AlAmawi, R. Potential of renewable energy in water-energy-food nexus in Jordan. *Energy Nexus* **2022**, *7*, 100140. [CrossRef]
24. Alva, M.; Vlachokostas, A.; Madamopoulos, N. Experimental demonstration and performance evaluation of a complex fenestration system for daylighting and thermal harvesting. *Sol. Energy* **2020**, *197*, 385–395. [CrossRef]
25. Potočnik, J.; Košir, M. Influence of commercial glazing and wall colours on the resulting non-visual daylight conditions of an office. *J. Affect. Disord.* **2020**, *171*, 106627. [CrossRef]
26. Ayoub, M.; Allam, A.S. GeneRT: A Generative Raytracing Tool for the rapid approximation of internal luminous conditions. *J. Build. Eng.* **2021**, *44*, 102711. [CrossRef]
27. Al Haddid, H.; Al-Obaidi, K.M. Examining the impact of urban canyons morphology on outdoor environmental conditions in city centres with a temperate climate. *Energy Nexus* **2022**, *8*, 100159. [CrossRef]
28. Pragati, S.; Priya, R.S.; Pradeepa, C.; Senthil, R. Simulation of the Energy Performance of a Building with Green Roofs and Green Walls in a Tropical Climate. *Sustainability* **2023**, *15*, 2006. [CrossRef]
29. Li, D.H.W.; Wong, S.L.; Tsang, C.L.; Cheung, G.H.W. A study of the daylighting performance and energy use in heavily obstructed residential buildings via computer simulation techniques. *Energy Build.* **2006**, *38*, 1343–1348. [CrossRef]
30. Sun, Y.; Wu, Y.; Wilson, R. Analysis of the daylight performance of a glazing system with Parallel Slat Transparent Insulation Material (PS-TIM). *Energy Build.* **2017**, *139*, 616–633. [CrossRef]
31. Ochoa, C.E.; Aries, M.B.C.; van Loenen, E.J.; Hensen, J.L.M. Considerations on design optimization criteria for windows providing low energy consumption and high visual comfort. *Appl. Energy* **2012**, *95*, 238–245. [CrossRef]

32. Alhagla, K.; Mansour, A.; Elbassuoni, R. Optimizing windows for enhancing daylighting performance and energy saving. *Alex. Eng. J.* **2019**, *58*, 283–290. [CrossRef]
33. Baş, H. Hybrid-model simulations to equilibrate the energy demand and daylight autonomy as a function of window-to-wall ratio and orientation for a perimeter office in Izmir. *Megaron* **2020**, *15*, 537–552. [CrossRef]
34. Kazanasmaz, T.; Grobe, L.O.; Bauer, C.; Krehel, M.; Wittkopf, S. Three approaches to optimize optical properties and size of a South-facing window for spatial Daylight Autonomy. *J. Affect. Disord.* **2016**, *102*, 243–256. [CrossRef]
35. Mangkuto, R.A.; Rohmah, M.; Asri, A.D. Design optimisation for window size, orientation, and wall reflectance with regard to various daylight metrics and lighting energy demand: A case study of buildings in the tropics. *Appl. Energy* **2016**, *164*, 211–219. [CrossRef]
36. Bahdad, A.A.S.; Fadzil, S.F.S.; Taib, N. Optimization of Daylight Performance Based on Controllable Light-Shelf Parameters using Genetic Algorithms in the Tropical Climate of Malaysia. *J. Daylight.* **2020**, *7*, 122–136. [CrossRef]
37. Freewan, A.A.; Al Dalala, J.A. Assessment of daylight performance of Advanced Daylighting Strategies in Large University Classrooms; Case Study Classrooms at JUST. *Alex. Eng. J.* **2020**, *59*, 791–802. [CrossRef]
38. Gutiérrez, R.U.; Du, J.; Ferreira, N.; Ferrero, A.; Sharples, S. Daylight control and performance in office buildings using a novel ceramic louvre system. *J. Affect. Disord.* **2019**, *151*, 54–74. [CrossRef]
39. Khidmat, R.P.; Fukuda, H.; Paramita, B.; Koerniawan, M.D.; Kustiani, K. The optimization of louvers shading devices and room orientation under three different sky conditions. *J. Daylight.* **2022**, *9*, 137–149. [CrossRef]
40. Sorooshnia, E.; Rashidi, M.; Rahnamayiezekavat, P.; Rezaei, F.; Samali, B. Optimum external shading system for counterbalancing glare probability and daylight illuminance in Sydney's residential buildings. *Eng. Constr. Arch. Manag.* **2023**, *30*, 296–320. [CrossRef]
41. Palarino, C.; Piderit, M.B. Optimisation of Passive Solar Design Strategies in Side-Lit Offices: Maximising Daylight Penetration While Reducing the Risk of Glare in Different Chilean Climate Contexts. *J. Daylight.* **2020**, *7*, 107–121. [CrossRef]
42. Attia, S.; Hamdy, M.; O'brien, W.; Carlucci, S. Assessing gaps and needs for integrating building performance optimization tools in net zero energy buildings design. *Energy Build.* **2013**, *60*, 110–124. [CrossRef]
43. Li, Z.; Chen, H.; Lin, B.; Zhu, Y. Fast bidirectional building performance optimization at the early design stage. *Build. Simul.* **2018**, *11*, 647–661. [CrossRef]
44. Lin, B.; Chen, H.; Liu, Y.; He, Q.; Li, Z. A preference-based multi-objective building performance optimization method for early design stage. *Build. Simul.* **2021**, *14*, 477–494. [CrossRef]
45. Khalil, R.; El-Kordy, A.; Sobh, H. Nature-inspired Algorithms as a Part of the Biomimetic Architecture: A Brief Discussion. *Int. J. Sci. Basic App. Res. IJSBAR* **2022**, *62*, 281–287. Available online: https://www.gssrr.org/index.php/JournalOfBasicAndApplied/article/view/13942 (accessed on 14 April 2022).
46. Bre, F.; Roman, N.; Fachinotti, V.D. An efficient metamodel-based method to carry out multi-objective building performance optimizations. *Energy Build.* **2020**, *206*, 109576. [CrossRef]
47. Pilechiha, P.; Mahdavinejad, M.; Pour Rahimian, F.; Carnemolla, P.; Seyedzadeh, S. Multi-objective optimisation framework for designing office windows: Quality of view, daylight and energy efficiency. *Appl. Energy* **2020**, *261*, 114356. [CrossRef]
48. Yan, H.; Yan, K.; Ji, G. Optimization and prediction in the early design stage of office buildings using genetic and XGBoost algorithms. *J. Affect. Disord.* **2022**, *218*, 109081. [CrossRef]
49. Khalil, R.; El-Kordy, A.; Sobh, H. A review for using swarm intelligence in architectural engineering. *Int. J. Arch. Comput.* **2021**, *20*, 254–276. [CrossRef]
50. Khalil, A.; Tolba, O.; Ezzeldin, S. Design Optimization of Open Office Building Form for Thermal Energy Performance using Genetic Algorithm. *Adv. Sci. Technol. Eng. Syst. J.* **2021**, *6*, 254–261. [CrossRef]
51. Touloupaki, E.; Theodosiou, T. Performance Simulation Integrated in Parametric 3D Modeling as a Method for Early Stage Design Optimization—A Review. *Energies* **2017**, *10*, 637. [CrossRef]
52. Zawidzki, M.; Szklarski, J. Multi-objective optimization of the floor plan of a single story family house considering position and orientation. *Adv. Eng. Softw.* **2020**, *141*, 102766. [CrossRef]
53. Yi, Y.K.; Malkawi, A.M. Optimizing building form for energy performance based on hierarchical geometry relation. *Autom. Constr.* **2009**, *18*, 825–833. [CrossRef]
54. Yi, Y.K.; Malkawi, A. Site-specific optimal energy form generation based on hierarchical geometry relation. *Autom. Constr.* **2012**, *26*, 77–91. [CrossRef]
55. Khalil, A. Design Optimization of Building Form and Fenestration for Daylighting and Thermal Energy in Three Variations of the Hot Climate of Egypt. *IBPSA* **2023**, *18*, 3423–3430. Available online: https://publications.ibpsa.org/conference/paper/?id=bs2023_1649 (accessed on 29 December 2023).
56. Fang, Y.; Cho, S. Design optimization of building geometry and fenestration for daylighting and energy performance. *Sol. Energy* **2019**, *191*, 7–18. [CrossRef]
57. Kiss, B.; Szalay, Z. Modular approach to multi-objective environmental optimization of buildings. *Autom. Constr.* **2020**, *111*, 103044. [CrossRef]
58. Lu, S.; Wang, C.; Fan, Y.; Lin, B. Robustness of building energy optimization with uncertainties using deterministic and stochastic methods: Analysis of two forms. *J. Affect. Disord.* **2021**, *205*, 108185. [CrossRef]

59. Caldas, L. Generation of energy-efficient architecture solutions applying GENE_ARCH: An evolution-based generative design system. *Adv. Eng. Inform.* **2008**, *22*, 59–70. [CrossRef]
60. Khalil, A.; Lila, A.M.H.; Ashraf, N. Optimization and Prediction of Different Building Forms for Thermal Energy Performance in the Hot Climate of Cairo Using Genetic Algorithm and Machine Learning. *Computation* **2023**, *11*, 192. [CrossRef]
61. Bagheri-Esfeh, H.; Dehghan, M.R. Multi-objective optimization of setpoint temperature of thermostats in residential buildings. *Energy Build.* **2022**, *261*, 111955. [CrossRef]
62. Hosamo, H.H.; Tingstveit, M.S.; Nielsen, H.K.; Svennevig, P.R.; Svidt, K. Multiobjective optimization of building energy consumption and thermal comfort based on integrated BIM framework with machine learning-NSGA II. *Energy Build.* **2022**, *277*, 112479. [CrossRef]
63. Chen, R.; Tsay, Y.-S.; Ni, S. An integrated framework for multi-objective optimization of building performance: Carbon emissions, thermal comfort, and global cost. *J. Clean. Prod.* **2022**, *359*, 131978. [CrossRef]
64. Zou, Y.; Lou, S.; Xia, D.; Lun, I.Y.; Yin, J. Multi-objective building design optimization considering the effects of long-term climate change. *J. Build. Eng.* **2021**, *44*, 102904. [CrossRef]
65. Xu, Y.; Zhang, G.; Yan, C.; Wang, G.; Jiang, Y.; Zhao, K. A two-stage multi-objective optimization method for envelope and energy generation systems of primary and secondary school teaching buildings in China. *Build. Environ.* **2021**, *204*, 108142. [CrossRef]
66. Wang, R.; Lu, S.; Feng, W.; Xu, B. Tradeoff between heating energy demand in winter and indoor overheating risk in summer constrained by building standards. *Build. Simul.* **2021**, *14*, 987–1003. [CrossRef]
67. Chen, B.; Liu, Q.; Chen, H.; Wang, L.; Deng, T.; Zhang, L.; Wu, X. Multiobjective optimization of building energy consumption based on BIM-DB and LSSVM-NSGA-II. *J. Clean. Prod.* **2021**, *294*, 126153. [CrossRef]
68. Vukadinović, A.; Radosavljević, J.; Đorđević, A.; Protić, M.; Petrović, N. Multi-objective optimization of energy performance for a detached residential building with a sunspace using the NSGA-II genetic algorithm. *Sol. Energy* **2021**, *224*, 1426–1444. [CrossRef]
69. Chegari, B.; Tabaa, M.; Simeu, E.; Moutaouakkil, F.; Medromi, H. Multi-objective optimization of building energy performance and indoor thermal comfort by combining artificial neural networks and metaheuristic algorithms. *Energy Build.* **2021**, *239*, 110839. [CrossRef]
70. Abdou, N.; El Mghouchi, Y.; Hamdaoui, S.; El Asri, N.; Mouqallid, M. Multi-objective optimization of passive energy efficiency measures for net-zero energy building in Morocco. *J. Affect. Disord.* **2021**, *204*, 108141. [CrossRef]
71. Naji, S.; Aye, L.; Noguchi, M. Multi-objective optimisations of envelope components for a prefabricated house in six climate zones. *Appl. Energy* **2021**, *282*, 116012. [CrossRef]
72. Kahsay, M.T.; Bitsuamlak, G.T.; Tariku, F. Thermal zoning and window optimization framework for high-rise buildings. *Appl. Energy* **2021**, *292*, 116894. [CrossRef]
73. Acar, U.; Kaska, O.; Tokgoz, N. Multi-objective optimization of building envelope components at the preliminary design stage for residential buildings in Turkey. *J. Build. Eng.* **2021**, *42*, 102499. [CrossRef]
74. Vettorazzi, E.; Figueiredo, A.; Rebelo, F.; Vicente, R.; da Cunha, E.G. Optimization of the passive house concept for residential buildings in the South-Brazilian region. *Energy Build.* **2021**, *240*, 110871. [CrossRef]
75. Berleze, A.S.; Brasileiro, A.d.B.H.; Silvoso, M.M. Multi-objective optimization of the geometry of single-family housing to improve thermal performance. *Ambient. Constr.* **2021**, *21*, 41–65. [CrossRef]
76. Jung, Y.; Heo, Y.; Lee, H. Multi-objective optimization of the multi-story residential building with passive design strategy in South Korea. *J. Affect. Disord.* **2021**, *203*, 108061. [CrossRef]
77. Rosso, F.; Ciancio, V.; Dell'Olmo, J.; Salata, F. Multi-objective optimization of building retrofit in the Mediterranean climate by means of genetic algorithm application. *Energy Build.* **2020**, *216*, 109945. [CrossRef]
78. Salata, F.; Ciancio, V.; Dell'Olmo, J.; Golasi, I.; Palusci, O.; Coppi, M. Effects of local conditions on the multi-variable and multi-objective energy optimization of residential buildings using genetic algorithms. *Appl. Energy* **2020**, *260*, 114289. [CrossRef]
79. Zhao, J.; Du, Y. Multi-objective optimization design for windows and shading configuration considering energy consumption and thermal comfort: A case study for office building in different climatic regions of China. *Sol. Energy* **2020**, *206*, 997–1017. [CrossRef]
80. Linczuk, V.C.C.; Bastos, L.E.G. Otimização multiobjetivo orientada ao desempenho térmico para o projeto de edificações de baixo consumo de energia na Região Sul do Brasil. *Ambient. Constr.* **2020**, *20*, 509–529. [CrossRef]
81. Ciardiello, A.; Rosso, F.; Dell'Olmo, J.; Ciancio, V.; Ferrero, M.; Salata, F. Multi-objective approach to the optimization of shape and envelope in building energy design. *Appl. Energy* **2020**, *280*, 115984. [CrossRef]
82. Giouri, E.D.; Tenpierik, M.; Turrin, M. Zero energy potential of a high-rise office building in a Mediterranean climate: Using multi-objective optimization to understand the impact of design decisions towards zero-energy high-rise buildings. *Energy Build.* **2020**, *209*, 109666. [CrossRef]
83. Shadram, F.; Mukkavaara, J. Exploring the effects of several energy efficiency measures on the embodied/operational energy trade-off: A case study of swedish residential buildings. *Energy Build.* **2019**, *183*, 283–296. [CrossRef]
84. Lan, L.; Wood, K.L.; Yuen, C. A holistic design approach for residential net-zero energy buildings: A case study in Singapore. *Sustain. Cities Soc.* **2019**, *50*, 101672. [CrossRef]
85. Ascione, F.; Bianco, N.; Mauro, G.M.; Napolitano, D.F. Building envelope design: Multi-objective optimization to minimize energy consumption, global cost and thermal discomfort. Application to different Italian climatic zones. *Energy* **2019**, *174*, 359–374. [CrossRef]

86. Chen, X.; Huang, J.; Yang, H.; Peng, J. Approaching low-energy high-rise building by integrating passive architectural design with photovoltaic application. *J. Clean. Prod.* **2019**, *220*, 313–330. [CrossRef]
87. Gagnon, R.; Gosselin, L.; Decker, S.A. Performance of a sequential versus holistic building design approach using multi-objective optimization. *J. Build. Eng.* **2019**, *26*, 100883. [CrossRef]
88. Dalbem, R.; da Cunha, E.G.; Vicente, R.; Figueiredo, A.; Oliveira, R.; da Silva, A.C.S.B. Optimisation of a social housing for south of Brazil: From basic performance standard to passive house concept. *Energy* **2019**, *167*, 1278–1296. [CrossRef]
89. Harkouss, F.; Fardoun, F.; Biwole, P.H. Multi-objective optimization methodology for net zero energy buildings. *J. Build. Eng.* **2018**, *16*, 57–71. [CrossRef]
90. Gou, S.; Nik, V.M.; Scartezzini, J.-L.; Zhao, Q.; Li, Z. Passive design optimization of newly-built residential buildings in Shanghai for improving indoor thermal comfort while reducing building energy demand. *Energy Build.* **2018**, *169*, 484–506. [CrossRef]
91. Chen, X.; Yang, H.; Zhang, W. Simulation-based approach to optimize passively designed buildings: A case study on a typical architectural form in hot and humid climates. *Renew. Sustain. Energy Rev.* **2018**, *82*, 1712–1725. [CrossRef]
92. Chen, X.; Yang, H.; Wang, T. Developing a robust assessment system for the passive design approach in the green building rating scheme of Hong Kong. *J. Clean. Prod.* **2017**, *153*, 176–194. [CrossRef]
93. Bre, F.; Fachinotti, V.D. A computational multi-objective optimization method to improve energy efficiency and thermal comfort in dwellings. *Energy Build.* **2017**, *154*, 283–294. [CrossRef]
94. Fonseca, L.P.G.; Nunes, V.D.L.; Santana, L.O.; Carlo, J.C.; Júnior, K.M.L.C. Otimização multiobjetivo das dimensões dos ambientes de uma residência unifamiliar baseada em simulação energética e estrutural. *Ambient. Constr.* **2017**, *17*, 267–288. [CrossRef]
95. Ascione, F.; Bianco, N.; De Stasio, C.; Mauro, G.M.; Vanoli, G.P. CASA, cost-optimal analysis by multi-objective optimisation and artificial neural networks: A new framework for the robust assessment of cost-optimal energy retrofit, feasible for any building. *Energy Build.* **2017**, *146*, 200–219. [CrossRef]
96. Ascione, F.; Bianco, N.; De Masi, R.F.; Mauro, G.M.; Vanoli, G.P. Energy retrofit of educational buildings: Transient energy simulations, model calibration and multi-objective optimization towards nearly zero-energy performance. *Energy Build.* **2017**, *144*, 303–319. [CrossRef]
97. Gordon, W.H.; Sommer, R. Tight Spaces: Hard Architecture and How to Humanize It. *Contemp. Sociol. A J. Rev.* **1975**, *4*, 321. [CrossRef]
98. Adel, R.; Kamel, B.; Amin, A.; El-Feki, S.; Nasreldin, R. Middle-income residential compounds towards resilience through risk management: Experts' point of view. *Ain Shams Eng. J.* **2022**, *13*, 101797. [CrossRef]
99. United Nations Human Settlements Programme. Egypt Housing Profile. 2018. Available online: https://unhabitat.org/sites/default/files/download-manager-files/1525977522wpdm_Egypt%20housing%20EN_HighQ_23-1-2018.pdf (accessed on 30 June 2023).
100. ASHRAE 90.1-2009. Available online: https://www.ashrae.org/technical-resources/bookstore/standard-90-1 (accessed on 30 June 2023).
101. CORE Studio. Available online: https://www.thorntontomasetti.com/core-studio (accessed on 30 June 2023).