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Optimising Energy Efficiency and Daylighting Performance for Designing Vernacular Architecture—A Case Study of Rawshan

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Abstract: Building optimisation techniques provide a rigorous framework for exploring new optimal design solutions. In this study, a genetic algorithm (GA) was used to investigate the energy efficiency of a vernacular architectural element (Rawshan) in Saudi Arabia. Two objectives were optimised using a GA simulation enhanced: energy consumption optimisation and useful daylight illuminance (UDI) optimisation. A calibrated simulation model of a typical house in Saudi Arabia was used in the study. Several metrics, such as light interference from shadows or other windows, were considered to indicate the importance of the Rawshan. Computational studies were performed using different climatic conditions, and the results were compared with and without a Rawshan element using the weather data of Mecca, Jeddah, Riyadh, and Al-Baha. In this study, the blind thicknesses on the front and sides of the Rawshan were used as optimisation variables. The results showed that using a GA with energy consumption as an objective can reduce energy consumption. One of the methods proposed in the paper can reduce energy consumption by 3.6%, 3.6%, and 16.6% for Mecca, Riyadh, and Al-Baha, respectively. The single-objective optimisation method demonstrated that Rawshan provided sufficient UDI in four cities: Mecca, Jeddah, Riyadh, and Al-Baha. The research provided optimised values for Rawshan blind thicknesses on the front and lateral sides under different optimisation constraints. The results showed that using Rawshans in modern building architecture can reduce energy consumption and improve useful daylight illuminance.

Keywords: Rawshan; vernacular architecture; evolutionary optimisation; genetic algorithms; energy efficiency; energy consumption; daylight; single-objective

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1. Introduction

The vernacular architecture of a community demonstrates how to build comfortable living environments using only renewable and natural resources. Amos Rapoport mentioned in his book that vernacular design is born out of the need to design for the surrounding environment [1]. Thus, with the help of local wisdom and knowledge, traditional buildings were built to house and protect people from natural elements, while also meeting environmental needs and cultural preferences [2].

Daylighting is a significant method for enhancing the energy efficiency of residential buildings. It serves as a viable alternative to artificial lighting, as it constitutes an efficient form of renewable energy in residential buildings [3]. Natural daylight in residential buildings enhances the quality of life and well-being of occupants. Edwards and Torcellini [4] reviewed and summarised the effects of natural light on building occupants. Their findings indicated that daylighting correlated with enhanced efficiency, diminished absenteeism, elevated mood, reduced fatigue, and less eyestrain. Phillips [5] asserted that the energy consumed by artificial lighting constitutes a substantial fraction of energy usage in buildings, and it is believed that minimising artificial lighting will lower carbon dioxide emissions; thus, this will contribute to the reduction of greenhouse gases and significantly impact the mitigation of global warming.

During the last two decades, inefficient building energy usage has led to unsustainable fossil fuel consumption and pollution. In total, global building energy usage accounts for about 70% of sulphur oxides and 50% of the CO_2 emissions into the atmosphere [6]. About 40% of the global energy produced is used in the building sector [7]; thus, energy consumption in domestic buildings has become a topic of interest for many academic researchers. According to the Ministry of Water and Electricity of Saudi Arabia, domestic buildings use over 51% of electrical energy output within the country [8]. Reducing energy demand would help to reduce CO_2 emissions and redistribute electrical energy for other purposes. As energy prices, shortages, and blackouts increase, as well as the growing concerns for pollution, resource depletion, environmental degradation, and climate change, building design professionals have dramatically increased their awareness of the environmental impacts of building engineering [9]. Many factors cause high energy consumption in domestic buildings [10]. To address this problem, vernacular architecture elements, such as a Rawshan, may be considered as an effective element for saving energy. The Rawshan is one such vernacular architectural element that embodies Arab-Islamic values. Historically, Rawshans were used in older Middle Eastern cities, particularly in the western region of Saudi Arabia [11–13]. Given that Rawshans comprise three-sided boxes, they provide resting areas for one person reclining at full-length. In terms of the indoor environment, Rawshans can assist in cooling and humidifying residences. When exposed to air currents, the wood of a Rawshan absorbs, retains and releases water, and after this wood is warmed by sunlight, it releases any retained humidity [14]. As Alelwani Ahmad [15] addressed in their survey findings, the energy efficiency and daylight criteria are considered by a majority of participants and decision-makers when the Rawshan will be revived. The goal of the modern architect is no longer to simply create an aesthetically pleasing building. Vernacular architectural elements must be environmentally responsive for efficient future designs [16].

2. Literature Review

Building performance simulation (BPS) has been developed since the mid-1970s to imitate reality [17] and enhance conventional manual methods to analyse and optimise the energy performance and daylighting of buildings. In the building performance simulation (BPS), the term 'optimisation' does not necessarily mean finding the globally optimal solutions to a problem since it may be unfeasible due to the nature of the problem [18] or the simulation program itself [19]. It is generally accepted among the simulation-based optimisation community that this term indicates an automated process that is entirely based on numerical simulation and mathematical optimisation [20]. In most cases, this process is automated in a conventional building optimisation study by combining a building simulation system with an 'engine' optimisation, which may be one or more optimisation algorithms or strategies [20].

The method used to implement goal-oriented design is the application of a search and optimisation technique, genetic algorithms (GA), borrowed from the field of artificial intelligence. Genetic algorithms are efficient methods of general-purpose stochastic optimisation inspired by the Darwinian evolution of a reproductive population, crossing mutations in a competitive system in which the fittest survives [21]. Genetic algorithms (GAs) are based on the process of natural selection (i.e., survival of the fittest) and have three evolution operators: reproduction, crossover, and mutation [22].

According to the number of objective functions, optimisation problems can be classified into single-objective and multi-objective optimisation. Usually, single-objective optimisation aims at finding one global optimum solution, while multi-objective optimisation aims at a set of global Pareto Front solutions. The literature review of this study will cover single and multi-objective optimisation techniques. Caldas [23] applied a system, the GENE_ARCH system, which is an evolution-based generative design system that uses adaptation to create sustainable architectural solutions and energy efficient. He chose a standard GA for single optimisation or a Pareto GA for multi-criteria optimisations to optimise lighting and energy in a generative system that can be integrated with a specific design aesthetic intent.

Many researchers have studied a variety of simulation-based optimisation methods with a focus on the energy efficiency of buildings [24,25], sufficient daylight [26–28], and thermal comfort [29], to optimise their overall performances for cooling, heating, and lighting. Others have used either the multi-objective [30,31] or single-objective methods [32,33], via Octopus or Galapagos, respectively.

The revival of vernacular architecture has successfully addressed environmental and socio-cultural issues by using integrated solutions at both urban and building levels to preserve occupants' thermal comfort, visual comfort, and social integration while also maintaining architectural identity. The integrative role of the traditionally used architectural element (i.e., the Rawshan) has contributed to the creation of a sustainable built-up environment, which in turn inspired some contemporary architects to mimic them or interpret and develop them differently, leading to the emergence of a global contemplation since the beginning of the 21st century. In addition, Fathy [14] defines the Rawshan with five values or criteria: (1) passage of light; (2) control of airflow; (3) reduction of temperature; (4) privacy; and (5) increased humidity. He enclosed the functions of Rawshan within these five criteria, such that they must all exist whenever the Rawshan is constructed. This research considers these criteria in addition to other values, including energy efficiency. This chapter will concentrate on comparing the general values of Rawshan with the values of the product design within the initial context of practice. A triangulation of all inventoried vernacular architectural elements and practice-based values is much needed in the theoretical literature. Furthermore, it is crucial to pinpoint the areas that require improvement in the optimised Rawshan, with the aim of revitalising and preserving its unique character, all while pursuing energy efficiency. Figure 1 shows the contributions of the vernacular architectural elements according to Fathy's criteria. In accordance with design values, many scholars have used a variety of values, such as social, aesthetic, and environmental values, as well as energy efficiency.

The social value is the most significant, as it plays an important role in Muslim houses. The Middle Eastern form of Islamic culture imposes strict segregation between males and females; as such, women are required to maintain modesty and privacy from unrelated males. This Islamic tradition has been reflected in the form, structure, and function of domestic and public spaces in order to allow female occupants to experience outdoor life without being observed. The Rawshan is a true reflection of this tradition and has enjoyed secular importance in the region's domestic architecture. This criterion has been investigated by many scholars in the same field [14,34–41]. However, other researchers, such as Samuels [42], have overlooked the social aspects in their research on a new screen of the Rawshan (Mashrabiyyah). Evidence of the aesthetic value of the Rawshan or Mashrabiyyah design has been shown in multiple studies [38,43–46]. A Hedjazi house, which was built in the western region of Saudi Arabia without the Rawshan, is described as a large block provided with extensive fenestration [35]. In other words, without the ornament of Rawshan, it looks deprived of its architectural values [47]. Thus, nowadays, a Rawshan is considered by modern architects to be an old legacy. Based on this, we can conclude that the Rawshan industry has grown and flourished artistically more than functionally.

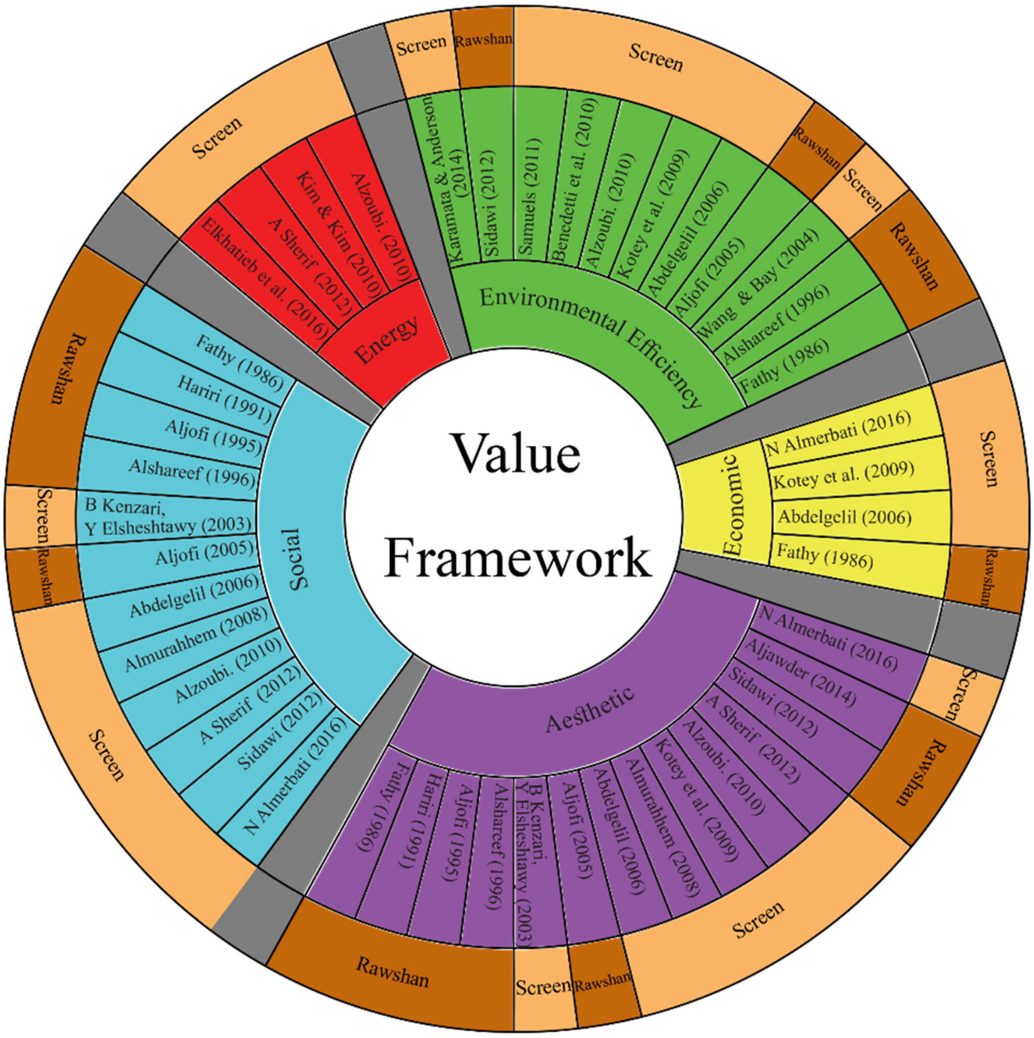


Figure 1. Rawshan's values in the literature review (by authors).

The environmental value of the Rawshan is one of the most discussed perspectives by researchers and scholars in the field. In the literature review of this paper, two criteria were particularly investigated: daylight and thermal comfort. As these aspects have been included in a variety of scientific quantitative measurement instruments, most researchers have successfully validated the environmental values of the Rawshan [35,47]. Moreover, Aljofi [48] confirmed that his critical assessment of Rawshan thermal output, with its capacity as a natural ventilation source, should always be pursued in order to produce environmentally sensitive screens. On the other hand, Gelil M and Badawy [49] prevented the revival of Rawshan screens (Mashrabiyyah) in countries such as Egypt due to air pollution. Nevertheless, the ventilation value is still one of the defects of the Rawshan in the western region of Saudi Arabia (Hedjaz). This is one of the major reasons for it being rejected. Karamata [50] proposed a flexible design of a Rawshan screen (Mashrabiyyah) that maximises diffusing sunlight and provides a view to the outside while minimising solar gains. He utilised an experimental method and a software-based theoretical method to validate experimental results [50]. Although many researchers in different disciplines have verified this approach, its validity should still be considered when producing Mashrabiyyah in new contexts.

In terms of energy efficiency, research has involved the evaluation of a screen of the Rawshan (Mashrabiyyah) without taking into consideration the whole element. Moreover, all scholars recommend using the perforated screen to diffuse sunlight while achieving energy efficiency. Many other studies have focused solely on solar screens and their perforation. Chan and Tzempelikos [51] studied the relationship between solar screens and daylight performance in buildings located in tropical and sub-tropical areas. Sherif, El-Zafarany [52] examined solar screens forming part of a Rawshan, identifying that they could reduce total energy consumption by up to 30% in south and west directions. Kim and Kim [53] compared the energy performance of two types of shading devices, an external shading device and internal Venetian blinds, concluding that the external shading device reduced the need for cooling and heating by 20% and 12%, respectively [53]. When studying movable and fixed shading systems, Francesca and Marco [54] attempted to optimise daylight and energy performance in office zones, identifying that adequate daylight and energy performance was given by fixed shading systems with an inclination angle and overhang. Freewan [55] studied the impact of external shading devices on daylight and the thermal performance of offices located in Jordan, concluding that daylight and visual comfort were improved considerably by external shading devices, while the temperature was decreased. Erell, Kaftan [56] studied the use of daylight for visual comfort and energy conservation in offices within clear-sky areas by evaluating several shading strategies; they concluded that shading blinds achieved the most visual comfort, but required regular adjustment. Shin, Lee [57] attempted to find the optimum position of Venetian blinds in a residential apartment to allow sufficient daylight by changing the slat angle and shading height. Based on their findings, they recommended that the rotation angle and height should be designed to protect windows from low-angle sunlight. Huang, Niu [58] compared interior blinds and overhangs to evaluate the performance of different popular energy-efficient window designs in cooling-dominant climates. The results revealed that overhangs demonstrated improved performance in comparison to interior blinds.

The Rawshan has lost its identity due to many factors, such as a lack of craftsmen bringing about a high cost, a lack of wood, and becoming undesirable because of a lack of revival (see Figures 2 and 3).

New computational tools available to architects and engineers can be used as more than optimisation tools for the architectural forms already in place. The combination of these methods with parametric modelling will result in the successful incorporation of the research into the production of architectural form in the early stages of design. Single-objective optimisation (SOO) methods, which will be discussed in this research, offer a better approach for comprehensively evaluating energy efficiency and adequate daylight performance.

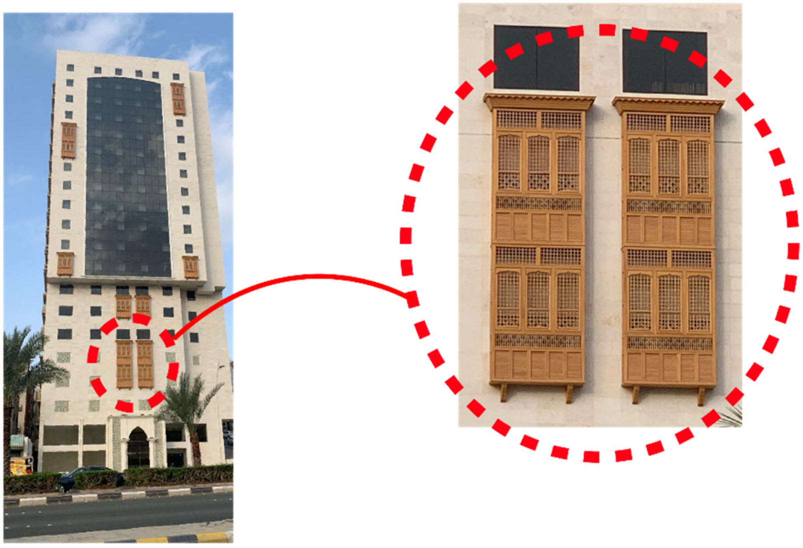


Figure 2. Ornamental Rawshan is constructed on a hotel in Mecca, but loses its projection size (by authors).

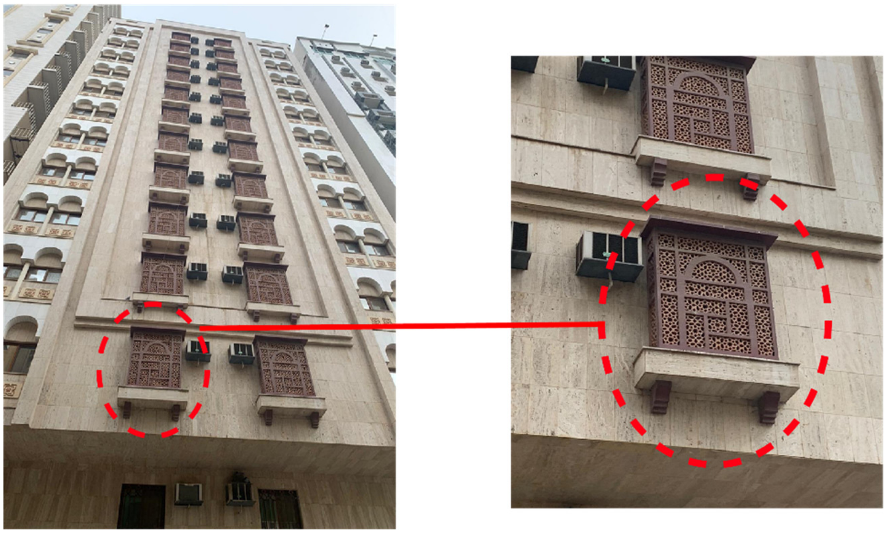


Figure 3. Ornamental Rawshan is constructed on a residential building in Mecca, but loses the appropriate perforation of the Rawshan's blinds (by authors).

3. Methodology

In this study, a software tool was used to investigate the energy consumption and useful daylight illuminance for a modelled room under several simulated climates: Mecca, Jeddah, Riyadh, and Al-Baha (see Figure 4). A wide range of software simulation tools are available to analyse energy consumption and daylight illuminance in buildings (e.g., Revit v2021.1.4, Vasari v1511-1574, DesignBuillder v2.1, Ecotec TRNSYS v18, IES-VE v2012.0.2.0, and Rhinoceros v5/Grasshopper). These tools can analyse and predict patterns of energy consumption in buildings. However, this study needed to investigate complex models, such as a Rawshan. Rhinoceros© [59] has evolved into a robust and reliable tool to model complex geometry with its interface Grasshopper© [60]. To parametrise a Rhino model, Grasshoppers' plug-ins are used, i.e., Ladybug [61], Honeybee [61], and Galapagos [62], for optimising energy and daylighting metrics. Ladybug has a sophisticated energy and daylight performance assessment capability compared to other similar simulation tools.

Figure 4. Saudi Arabia Map Showing the Four Selected Cities.

A case study involved a site visit to Mecca, Saudi Arabia, to design the modelled room and explore the optimal arrangement of a Rawshan's blinds. This actual room's design is then modelled with a standard Rawshan and used for applying climates of three additional cities: Riyadh, Jeddah, and Al-Baha. The methodology involved a standard design of a Rawshan that was configured in previous research by Alelwani, Ahmad [32] and included the relevant properties and materials [32]. This actual home was indicated by the Municipality of Mecca as a 'typical' design. Architectural floor plans, site plans, facade drawings, section drawings, structural drawings, and construction drawings were provided. Other documents supporting the validation of the simulations were 12 months of electricity bills, which were obtained from the Saudi Ministry of Electricity after permission from the homeowner. In addition, interviews were conducted with the homeowner and the building contractor to understand how this property is currently used and what type of construction materials were used.

3.1. Criteria for Case Study Selection

The criteria chosen for selecting the home included window size (opening size) in a living room, the number of windows in a living room, and the dimension of the façade. It was difficult to find homes in Mecca with windows of similar size to a Rawshan. From observations and the site visits, the typical window size for a living room is between 1 m^2 to 1.50 m^2, and the size of a standard Rawshan's opening is 5.7 m^2. Thus, a façade dimension needs to be set such that a Rawshan can be modelled. To ensure that there were no other sources of daylight except through the opening of the Rawshan, the selected room needed to have no more than one window. The majority of Saudi house designs have the living room in the middle of the house with one window facing a shaft as a daylight source. However, during a site visit to the 'typical' house, we found that the living room was on the ground floor and at the front of the house. Thus, the typical house achieves the criteria selections, especially when receiving site visit approval from the Municipality of Mecca Building Permit for the selected home.

Based on the above considerations and criteria, the selected case study is a three-story residential house for a family of five people located in Mecca. Moreover, its living room faces the main façade, is directed toward the east, and can be considered a representative of a typical domestic room, thus being a good fit for the retrofit Rawshan.

3.2. Case Study

Room usage was discussed during the interview with the landlord to establish a user profile that reflects a Saudi Arabian household. Then, the user profile is utilised as an input table for simulations as a fixed profile for the selected four cities. The actual building is in Mecca, and this model was used for the other cities, i.e., Jeddah, Riyadh, and Al-Baha. To determine the weather input, the relevant weather data file (EWP) from the U.S. Department of Energy was utilised [63]. The sky condition in this study for all cities was 'clear sky with sun', which is a typical sky condition in these cities.

The selected case study is a three-story semi-detached villa on the north side of Mecca. Table 1 presents the details of the house. The house includes three floors; the ground-floor plan includes a living room in front, two guest rooms in the back, and a kitchen and dining room with facilities in the middle. The first floor is a private section for the family of the house and should be 70% or less of the total built area, according to the Saudi Building Code (SBC) regulations for houses, which includes two bedrooms, a second living room linked with the main lobby, and a second kitchen. The reason for not selecting the second living room was that it did not meet the Rawshan requirements. The second floor should be 40% or less of the total built area, which consists of one bedroom, a bathroom, and a kitchen linked with a lobby (see Figures 5 and 6).

Table 1. Floor areas with Saudi Building Code requirements.

	Area (m^2)	Percentage of Built Area (%)	Standard Built Area (%)
Ground Floor	357.12	59.52%	60%
First Floor	410.03	68.39%	70%
Second Floor	98.03	37.33%	40%
Land Area	600	-	-

Figure 5. Ground-floor plan, first-floor plan, and second-floor plan (from **left** to **right**).

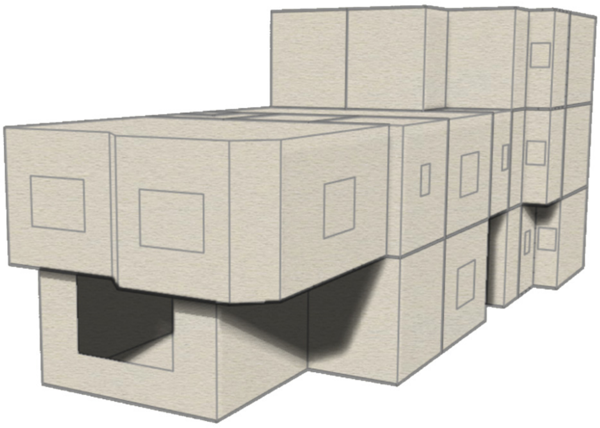


Figure 6. A 3D Schematic of Typical Building Without Rawshan.

The purpose of selecting different cities in different regions is to optimise the retrofit of Rawshan in various climates. The four chosen cities have different climatic conditions: warm to hot temperatures (Mecca), hot and humid climate (Jeddah), hot and arid climate (Riyadh), and high mountainous moderate climate (Al-Baha). Additionally, each city is located at a different sea level according to the database of the Saudi Geological Survey [64], as illustrated in Figure 7.

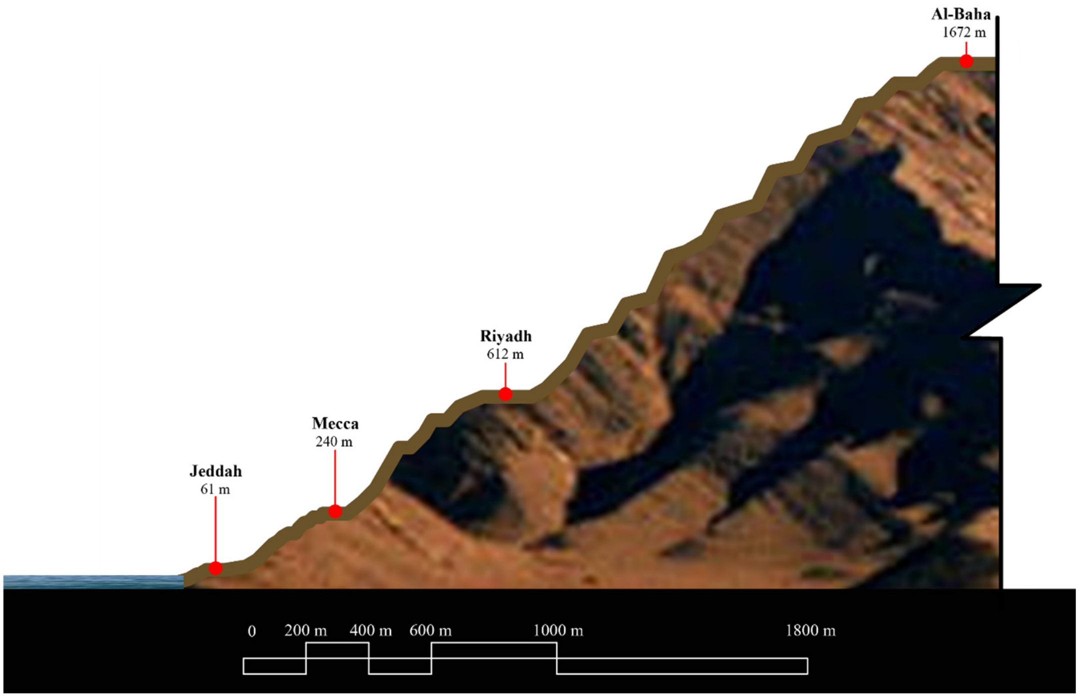


Figure 7. Imaginary section showing the variety of elevations of the Four cities of Saudi (by authors).

3.2.1. Description of the Room

The selected room is a living room on the ground floor that has a window facing the main entrance (east side), which meets the Rawshan requirements. The dimensions of the base-case living room are 6.18 m × 5.25 m × 3.30 m for length, width, and height, respectively (see Figure 8), and the opening window size is 2.85 m × 2.00 m, or 5.7 m, as illustrated in Table 2. About 26% of the northern wall is 'adiabatic', and the rest is exposed to sunlight. The southern and western walls and ceiling are defined as 'adiabatic'. Moreover, the cantilevers of the first floor were defined as shadows in the context of the model and were located on the north and east sides. The frame structure of the whole building is constructed of reinforced concrete. For the living room, the wall construction materials used are Jordanian stone, cement mortar, Saudi hollow blocks, insulation expended, cement mortar, ½-inch gypsum board, and indoor plaster (see Table 3). The construction of the ground floor consists of 20 cm of concrete slap, insulation expended, sand, cement floor, and ceramic floor tiles (see Table 4).

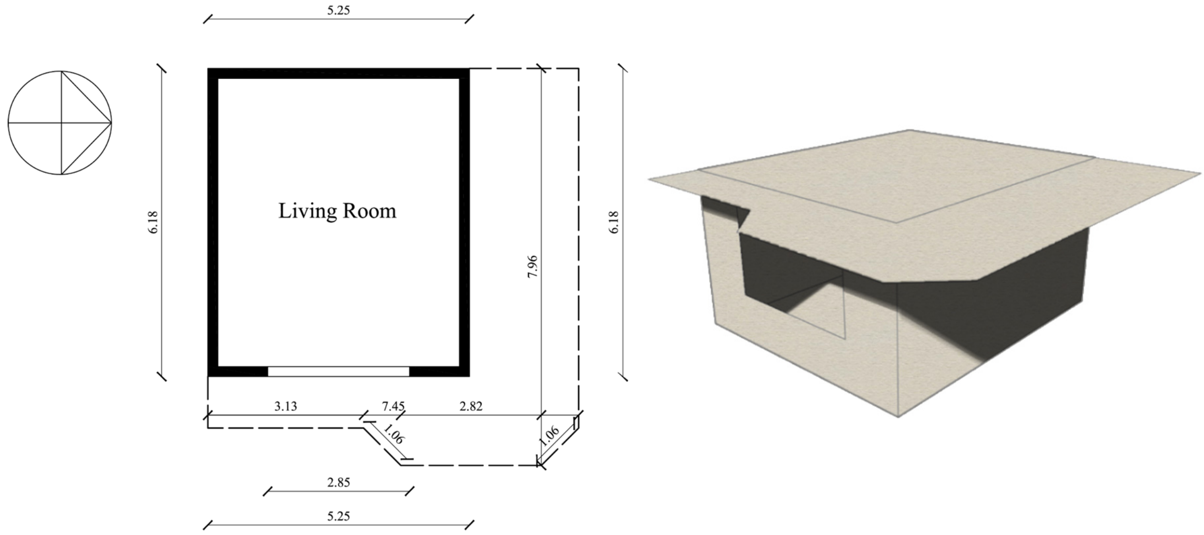


Figure 8. Living Room Plan and 3D Schematic without Rawshan on the **left** hand and Living Room Plan and 3D Schematic without Rawshan on the **right** hand.

Table 2. Simulated Living Room Properties.

Room Area	**32.45 m^2**
Window-to-Wall Ratio WWR	40%
No. of Window	1 (single pane)
Main Window Dimension	2.85 m × 2.00 m
Sill Height	1 m
Glass Transmittance	0.807

Table 3. Study Room Wall Construction and Properties.

Name	**Thickness (m)**	**Conductivity (W/mK)**	**Density (kg/m^3)**	**Specific Heat (J/Kg.K)**	**Thermal Absorptance (Value Range: 0–1)**
Jordanian stone	0.06	1.6	1936	710	0.2
Cement mortar	0.003	0.001	1648	920	0.7
Saudi hollow blocks	0.25	0.2	694	2000	0.2
Insulation	0.06	0.049	265	836	0.9
Gypsum board	0.013	0.17	800	830	0.9
Indoor plaster	0.003	0.02	800	840	0.002

Table 4. Ground Floor Construction and Properties.

Name	**Thickness (m)**	**Conductivity (W/mk)**	**Density (kg/m^3)**	**Specific Heat (J/Kg.K)**	**Thermal Absorptance (Value Range: 0–1)**
Concrete slab	0.20	1.95	2240	900	0.9
Insulation	0.06	0.049	265	836	0.9
Sand	0.05	1.94	2240	980	0.7
Cement floor	0.05	0.184	2100	840	0.7
Ceramic floor tiles	0.01	0.01	3500	840	0.7

The living room was simulated with one window (more details in Section 5) to be compared with the optimised Rawshan that was implemented in the same space (more details in Section 6). The living room that implemented the Rawshan has the same characteristics as the initial simulated living room, except for an opening window without a glazed pane to create a sub-zone between the living room and the Rawshan itself.

3.2.2. Description of the Rawshan

The Rawshan has five exposure sides: a front side, right and left sides, and top and bottom sides (see Figure 9), as discussed in the previous paper by Alelwani, Ahmad [32]. The front side area is 5.7 m^2, the right and left sides areas are 1.94 m^2 each, and the top and bottom sides areas are 2.77 m^2 each. Each vertical side has openings: four openings on the front side with an area of 0.87 m^2, and one opening on the right and left sides with each having an area of 0.33 m^2. Additionally, each opening was covered by a single-pane glaze with a transmittance of 0.81. The thickness of one blind is 0.133 m. The opening percentages of the front side and right/left sides are 61% and 17%, respectively. When completely closed, the Rawshan's blinds cover the pane glaze such that daylight is not allowed to get in. On the other hand, when the blinds are completely opened, the percentages of open areas are 85% and 84% for the front side and left/right sides, respectively, because of the thickness of the blinds (0.02 m), as in Table 5. The material of the Rawshan was defined as wood for simulations, as illustrated in Table 6.

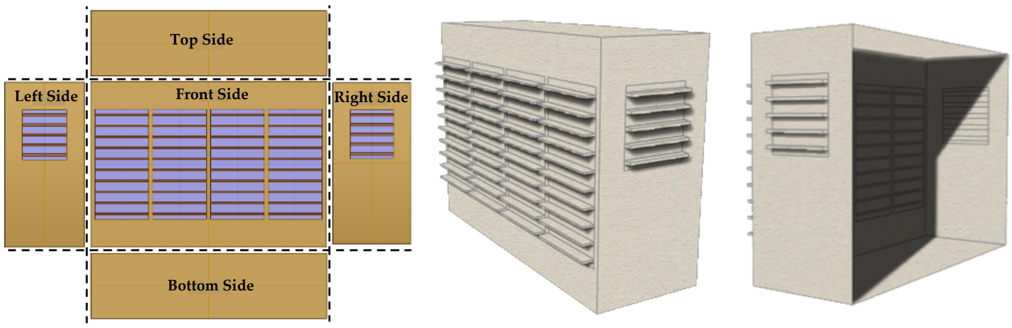


Figure 9. Standard Rawshan Element.

Table 5. Opening Sizes and Rawshan's Blind Dimensions.

	Front Perf. Screens	Right Perf. Screen	Left Perf. Screen
Opening Size	1.33 m × 0.65 m	0.61 m × 0.54 m	0.61 m × 0.54 m
Cell Dim. (width × depth × thickness)	0.65 m × 0.10 m × 0.13 m	0.54 m × 0.07 m × 0.12 m	0.54 m × 0.07 m × 0.12 m

Table 6. Rawshan Properties.

Name	Thickness (m)	Conductivity (W/mk)	Density (kg/m^3)	Specific Heat (J/Kg.K)	Thermal Absorptance (Value Range: 0–1)
Wood	0.3	0.11	544.62	1210	0.9
Plaster	0.003	0.02	800	840	0.002

According to computational capability, Rhinoceros© was used [65], with its interface Grasshopper© [60] and Grasshoppers' plug-ins, i.e., Ladybug [61], and Honeybee [61] for energy and daylighting predictions, respectively. From the building documents, a 3D model was built via Rhino3D, and then using Grasshopper, the energy simulation, daylight simulation, and optimisation were run.

3.3. Calibration of Electricity Bills with Simulation Results

Model calibration plays a significant role in modelling simulation because it saves time, effort and money. From the site visit and documents collected, the authors were able to calibrate the simulation results to electricity data. From the interview with the landlord, the occupant usage data were gathered. Therefore, the electrical equipment is considered as a need for the occupant in case of increasing lights or thermal comfort. Additionally, the home has three individual electricity reading meters, one for each flat. The energy usage collected from electricity bills is illustrated in Table 7. Therefore, to validate the room simulation, the process followed three scenarios: (a) simulate the whole building, (b) simulate the whole floor that has a living room, and (c) simulate the living room individually.

Table 7. Annual Energy Consumption for utility bills for the Case Study Building.

Utility Bill					
First Floor Reading Meter		**Second Floor Reading Meter**		**Third Floor Reading Meter**	
Month-Year	**kWh**	**Month-Year**	**kWh**	**Month-Year**	**kWh**
January 2018	3430	January 2018	3975	January 2018	1438
February 2018	3008	February 2018	3648	February 2018	1172
March 2018	4787	March 2018	5098	March 2018	2107
April 2018	7395	April 2018	9706	April 2018	3399
May 2018	4967	May 2018	7648	May 2018	3043
June 2018	4808	June 2018	6068	June 2018	2923
July 2018	5008	July 2018	6384	July 2018	2872
August 2018	4854	August 2018	6081	August 2018	2756
September 2018	4882	September 2018	6435	September 2018	2678
October 2018	3619	October 2018	7360	October 2018	1980
November 2018	2714	November 2018	6283	November 2018	1802
December 2018	2618	December 2018	4304	December 2018	1630
Total	52,090	Total	72,990	Total	27,800
Total annual energy consumption = 152,880 kWh					

3.3.1. First Scenario: The Whole Building Simulation

The building drawings were used to model the building in the simulations. The total energy consumption (kWh), which includes total cooling, heating, lighting, and electrical usage for the whole year, and the average useful daylight illuminance (%) were output from the simulation. EnergyPlus through Honeybee/Ladybug provides the energy consumption for each room, thus providing an estimate of the living room energy consumption. These simulated results were then compared in Microsoft Trademark and Brand Guidelines, Excel, with the total energy consumption that was listed in the electricity bills.

3.3.2. Second Scenario: The Ground Floor Simulation

The process of the second scenario follows the same steps as 0 without including the above two floors. Additionally, the ground floor was simulated with the living room, and then the simulation was repeated without the living room. The goal is to deduct the living room energy consumption from the ground floor model such that it can be used to validate the living room model in Section 3.3.3.

3.3.3. Third Scenario: The Case Study Room Simulation

Because it is difficult to determine the electricity usage for each individual room based on the electricity bill, it was decided to simulate the case study of the living room alone and then compare it with the previous two scenarios. After modelling the room with the same dimensions and property materials, as well as defining the same walls, ceiling, and floor as the actual room, daylight, and EnergyPlus simulations were run to compare the findings with the results from Sections 3.2.2 and 6. This test case helps to ensure that the result of the total energy consumption for the living room alone is the same as what was predicted in the whole building and ground floor simulations.

4. Simulation Software and Optimisation Tools

To simulate, optimise, and examine the energy consumption and useful daylight illuminance for the case study living room with a computationally installed Rawshan, the Rhinoceros© [65] architectural modelling software was used, with its interface Grasshopper© [60]. To parametrise the Rhino model, Grasshoppers' plug-ins, i.e., Ladybug [61], Honeybee [61], and Galapagos [62], were used to investigate energy, daylighting, and optimised values, respectively [32]. Plug-ins such as Ladybug and Honeybee for Grasshopper can be used to link parametrised geometry with energy and daylight simulation software: EnergyPlus v9.0.1 and RADIANCE v5.2, respectively. This helps to support decision-making during the initial design phases. Galapagos is a Grasshopper plug-in used to perform single-objective evolutionary optimisation with either a genetic algorithm or a simulated-annealing solver.

4.1. Energy and Daylight Simulation Tools and Processes

Using validated simulation engines provides a means of integrating environmental analyses and building design simulations. The energy consumption for the actual living room case was calculated with EnergyPlus engine through Honeybee components. Annual energy consumption for heating, cooling, lighting, and equipment is presented. Climate-based daylight modelling is based on the totality (e.g., sun and sky components) of contiguous daylight data for a certain location for a full year duration [66]. Useful Daylight Illuminance (UDI) was proposed by Nabil and Mardaljevic [66], and it is defined as providing ambient light at the work plane at illuminance levels between 100 lux and 2000 lux. Illuminance levels above 2000 lux lead to heat gains and glare, thereby becoming potential problems. Potential UDI metrics give thresholds using bins (too low, useful, and too high) for certain percentages of the work plane. According to other studies conducted by Nabil and Mardaljevic [67], daylight illuminances in the range of 300 to around 3000 lux were often perceived either as desirable or at least tolerable in large office buildings based on the survey. In addition, it is important to note that many of these surveys were carried out before LCD display panels (which are much less prone to glare than CRT screens) became commonplace. The UDI range is further subdivided into two ranges called UDI supplementary and UDI autonomous. UDI autonomous represents daylight illuminances in the range of 300 to 3000 Lux, where additional artificial lighting will most probably not be necessary. In contrast to office buildings, tasks in the domestic setting are not, of course, largely desk-, and display-screen orientated. For these reasons, it is reasonable to recommend a higher upper limit for UDI in a residential setting than for an office environment [66–69]. This study calculated Useful Daylight Illuminance (UDI100–200), along with the total lighting energy, cooling load, and energy consumption required, to determine the net energy savings when the Rawshan is utilised. Honeybee contains a component that calculates UDI [67,69]. UDI is also used by Ahmad, M., M. Mourshed [7] in their study as an optimisation constraint. Different ranges of UDI are given below:

- UDI is less than 100 lux, which is insufficient to be the only source of illumination.
- UDI between 100 and 2000 is sufficient to be the sole source of illumination or in conjunction with artificial lighting and can be either desirable or at least acceptable.

- UDI over 2000 lux is likely to cause thermal or visual discomfort or both.

To calculate the open area of the Rawshan's blind perforation for each side, a formula has been established to give the percentage of open area. Because of the symmetry of the Rawshan, the two sides (right and left) have the same equation. The open area percentage is calculated as follows:

$$(\tfrac{1}{2}\,BT \times 2) - (X \times 2)/BT$$

where BT is a blind thickness and X is a blind thickness variable

For right and left sides, $(0.1328 - X \times 2)/0.1325$

For front side, $(0.122X \times 2)/0.122$.

4.2. Optimization Tools and Processes

The optimal combination of values can be identified by applying Darwin's evolutionary theory on development alternatives using genetic algorithm solvers, such as the Galapagos Evolutionary Solver (Plugin for Grasshopper) [62]. After several iterations and removing inadequate options, the result is a pool of optimised design alternatives that satisfy a collection of objective functions. Galapagos is an evolutionary solver and was used in this study to implement and configure a simple genetic algorithm for the optimisation process, which requires the definition of the following three aspects: (1) variables, (2) constraints, and (3) objectives. The selected variable to be optimised is the thickness of the blind (cell dimension), which is on the Z-axis (thickness) with a set between 0.02–0.13 m for the front side of the Rawshan and 0.02–0.12 m for the right and left sides of the Rawshan. Meanwhile, the width (X-axis) and the depth (Y-axis) of a single blind are constraints and remain constant, i.e., 0.65 m and 0.10 m, respectively. Finally, the objective of the optimisation is to either optimise energy consumption [32] or daylight illuminance. Figure 10 represents the Grasshopper's components that were used as a definition to build the model.

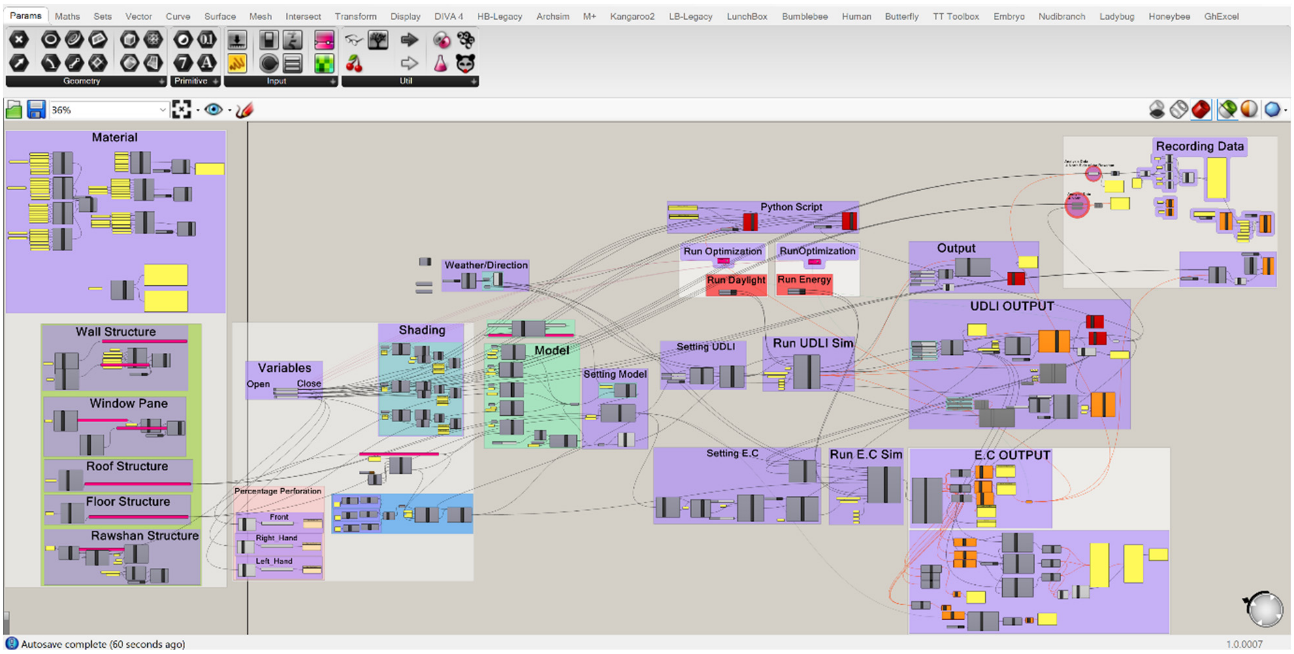


Figure 10. It shows the Grasshopper's components.

5. Analysis and Result of Calibrated a Case Study

As noted above, the energy consumption in the selected house was simulated and analysed using the EnergyPlus engine via Honeybee/Ladybug. The simulations were based on the case study design, the building materials used, the standard EnergyPlus weather data file (EPW), and the example user profile. The results of the simulation provide the energy consumption and daylight illuminance estimates for the house. These results can then be compared with the actual energy consumption, as stated in the utility bills for 2018, to provide precise estimates of accuracy. This process is divided into two main sections: (a) calibration process and (b) simulation of the actual living room in Mecca, Jeddah, Riyadh, and Al-Baha.

5.1. Calibration Process

The calibration process was divided into three scenarios. First, the whole building simulation was calibrated with the actual utility bills of the case study house and the weather data file of Mecca. The analysis showed that the percentage difference between simulation results and the actual utility bills for the annual energy consumption of the whole house was 11%, with the simulation underpredicting the energy usage. Table 8 illustrates a comparison of the total annual electrical energy consumption for the house between the EnergyPlus simulation result and utility bills. Secondly, the simulation results for each floor were computed as shown in Table 9. Summing up the yearly energy consumption of each floor in Table 9, it is possible to reproduce the total predicted energy usage of the building. The third scenario is to run energy and daylight simulations with the living room alone for the four cities and compare them with optimisation results. This will be discussed in the following section.

Table 8. Calibration results.

Month-Year	Utility Bill (kWh)	Simulation Result (kWh)
January 2018	8843	8977.34
February 2018	7828	8440.84
March 2018	11,992	14,363.78
April 2018	20,500	21,749.82
May 2018	15,658	12,826.65
June 2018	13,799	12,618.52
July 2018	14,264	13,033.52
August 2018	13,691	13,365.10
September 2018	13,995	12,953.40
October 2018	12,959	12,763.43
November 2018	10,799	11,472.64
December 2018	8552	10,147.68
Total	152,880	152,712.72

Table 9. Predicted Electricity Usage via Simulation.

First Floor Meter		Second Floor Meter		Third Floor Meter	
Month-Year	kWh	Month-Year	kWh	Month-Year	kWh
January 2018	3384.71	January 2018	4199.12	January 2018	1393.50
February 2018	3159.57	February 2018	3947.22	February 2018	1334.05
March 2018	5400.42	March 2018	6708.95	March 2018	2254.41
April 2018	8000.97	April 2018	10,229.85	April 2018	3519.00
May 2018	4661.16	May 2018	6065.89	May 2018	2099.60
June 2018	4568.58	June 2018	5978.33	June 2018	2071.60
July 2018	4717.19	July 2018	6175.62	July 2018	2140.71
August 2018	4847.70	August 2018	6326.11	August 2018	2191.28

Table 9. *Cont.*

First Floor Meter		Second Floor Meter		Third Floor Meter	
Month-Year	**kWh**	**Month-Year**	**kWh**	**Month-Year**	**kWh**
September 2018	4711.77	September 2018	6125.29	September 2018	2116.34
October 2018	4667.45	October 2018	6028.21	October 2018	2067.77
November 2018	4242.31	November 2018	5402.03	November 2018	1828.30
December 2018	3797.61	December 2018	4763.50	December 2018	1586.57
Total	56,159.45	Total	71,950.12	Total	24,603.15
Total annual energy consumption = 152,712.72 kWh					

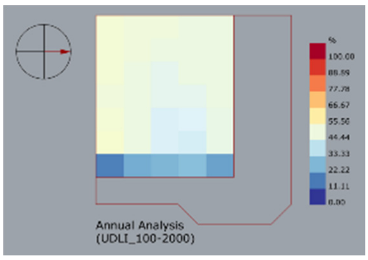
5.2. Actual Living Room Simulation

The purpose of running the simulations four times for the same room, same characteristics, and different weather data was to allow a comparison between the room with and without a Rawshan in various climates. Therefore, the actual living room simulation was divided into four sections according to the four cities: Mecca, Jeddah, Riyadh, and Al-Baha.

5.2.1. Actual Living Room Simulation in Mecca

For the Mecca living room, the results from the energy and daylight simulations showed that the living room consumed 13,931.63 kWh annually with a cooling load of 10,237.85 kWh and artificial light usage of 2968.28 kWh. Electrical equipment used 725.50 kWh, and there is no heating load. Moreover, the room received around 40% of useful daylight illuminance (UDI). This information is illustrated in Table 10. About 74% of the energy consumed was for the cooling load, which may be expected due to the Mecca climate.

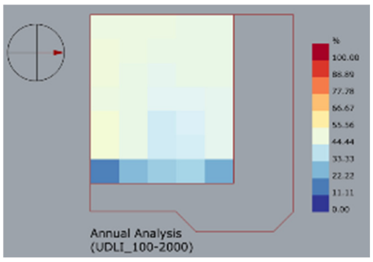
Table 10. Mecca Energy Consumption and UDI Predictions without a Rawshan.

Direction	**Without Rawshan**					
	EnergyPlus				**Radiance**	
	Cooling Load (kWh)	**Total Lights Use (kWh)**	**Total Electrical Equipment Use (kWh)**	**Heating Load (kWh)**	**Average % of UDI 100–2000**	**Preview UDI 100–2000**
East	10,237.85	2968.28	725.50	0	40.1	
	Total Energy Consumption (kWh)					
	13,931.63					

5.2.2. Actual Living Room Simulation in Jeddah

For the Jeddah living room, the results from the energy and daylight simulations showed that the living room consumed 13,879.55 kWh annually, with a cooling load of 10,185.77 kWh and artificial light usage of 2968.28 kWh. Electrical equipment and heating load results were the same as in the Mecca simulation: 725.50 kWh and no heating load, respectively. Moreover, the room in Jeddah received around 40% of useful daylight illuminance (UDI), as illustrated in Table 11. Figure 11 shows that the cooling load consumed the most energy, with about 74% of the total energy usage.

Table 11. Jeddah Energy Consumption and UDI Predictions without a Rawshan.

Direction	Without Rawshan					
	EnergyPlus				Radiance	
	Cooling Load (kWh)	Total Lights Use (kWh)	Total Electrical Equipment Use (kWh)	Heating Load (kWh)	Average % of UDI 100–2000	Preview UDI 100–2000
East	10,185.77	2968.28	725.50	0	40.1	
	Total Energy Consumption (kWh)					
	13,879.55					

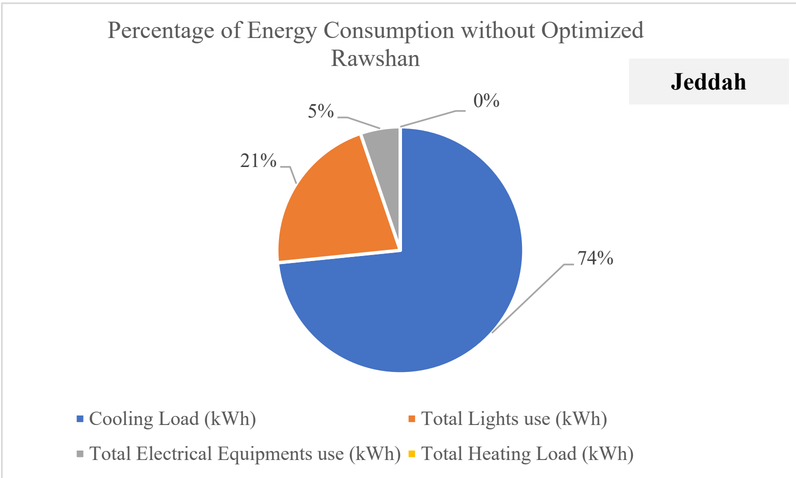


Figure 11. Energy Usage Percentages for Jeddah Climate Simulation.

5.2.3. Actual Living Room Simulation in Riyadh

For the living room in Riyadh, the energy and daylight simulation results showed that the living room consumed 10,405.13 kWh annually, with a cooling load of 6696.32 kWh and artificial light usage of 2983.30 kWh. Electrical equipment and heating load results were the same as in the Mecca simulation: 725.50 kWh and 0 kWh, respectively. Moreover, the room received around 39% of useful daylight illuminance (UDI), as illustrated in Table 12. Figure 12 shows that the cooling load consumed the most energy, with about 64% of the total energy usage.

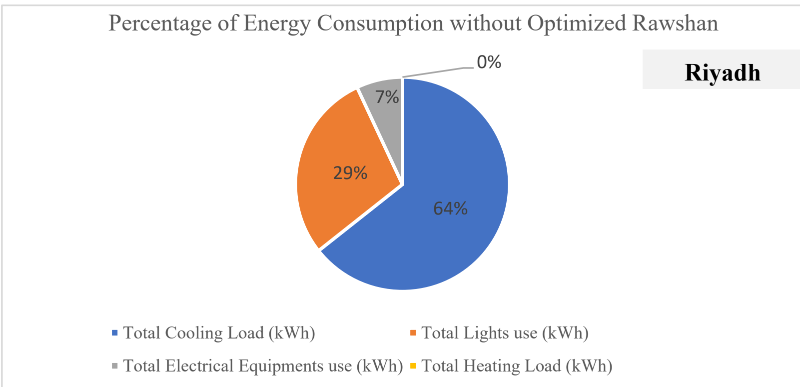
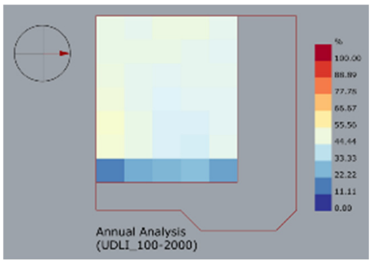


Figure 12. Energy Usage Percentages for Riyadh Climate Simulation.

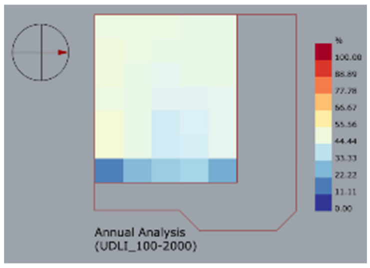
Table 12. Riyadh Energy Consumption and UDI Predictions without a Rawshan.

Direction	**Without Rawshan**					
	EnergyPlus				**Radiance**	
	Cooling Load (kWh)	**Total Lights Use (kWh)**	**Total Electrical Equipment Use (kWh)**	**Heating Load (kWh)**	**Average % of UDI 100–2000**	**Preview UDI 100–2000**
East	6696.32	2983.30	725.50	0	38.9	
	Total Energy Consumption (kWh)					
	10,405.13					

5.2.4. Actual Living Room Simulation in Al-Baha

For the living room in Al-Baha, the energy and daylight simulation results showed that the living room consumed 9331.82 kWh annually, with a cooling load of 5635.42 kWh and artificial light usage of 2970.88 kWh. Electrical equipment used 725.50 kWh, and the heating load was 0.02 kWh. Moreover, the room in Al Baha received around 40% of useful daylight illuminance (UDI), as illustrated in Table 13. Figure 13 shows that the cooling load consumed the most energy, with about 60% of the total energy usage.

Table 13. Al-Baha Energy Consumption and UDI Predictions without a Rawshan.

Direction	**Without Rawshan**					
	EnergyPlus				**Radiance**	
	Cooling Load (kWh)	**Total Lights Use (kWh)**	**Total Electrical Equipment Use (kWh)**	**Heating Load (kWh)**	**Average % of UDI 100–2000**	**Preview UDI 100–2000**
East	5635.42	2970.88	725.50	0.02	40.11	
	Total Energy Consumption (kWh)					
	9331.82					

To summarise Section 5, the simulation results showed that energy consumption changes with changing location, given the same parameters, and living room design. For example, the heating load was non-negligible in Al-Baha because of its location on the upper slopes of the Tihamah Mountain plains. On the other hand, Mecca and Jeddah rooms do not have any heating systems because of the consistently hot climate. In Riyadh city, the heating systems are generally used only in the winter season when the temperatures reach as low as 5.0 °C [70,71]. However, in these results, the simulation found that the heating system was not used in the living room during the year due to the room direction, the city location, and the amount of sunlight that came from the window. Moreover, in the Riyadh room, there is about 1.2% less UDI than in other rooms in the analysed cities.

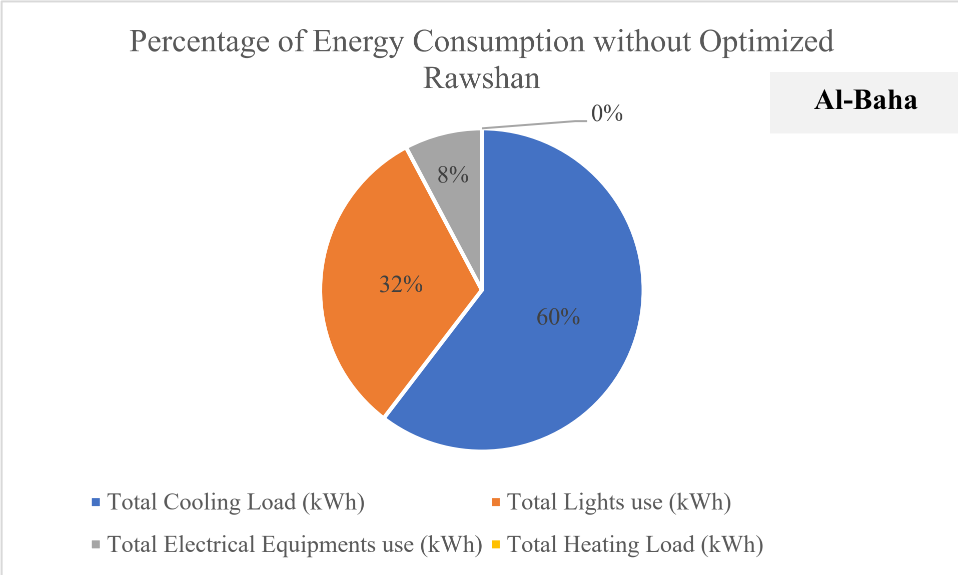


Figure 13. Energy Usage Percentages for Al-Baha Climate Simulation.

6. Optimisation Analysis Results and Discussion

This section examines the parametric design of the vernacular shading device known as Rawshan to improve daylight indoors and reduce energy consumption in an actual living room facing the east in relation to four different climates in Saudi Arabia, as mentioned previously. Thermal comfort has been neglected because the energy simulation engine conflicts with open spaces. This paper aims to examine the optimum aspect of three-sided perforated opening windows on the Rawshan to enhance daylight in the living room and reduce the use of artificial light, thus reducing energy consumption. As in the previous study [32], a virtual room in Saudi Arabia was used to investigate the optimum blind design for reducing electric lighting energy while increasing Useful Daylight Illuminance UDI via Genetic Algorithms (GA).

The optimisation process was run four times, with each run using different climate conditions based on one of four cities. Fifty populations were chosen for each optimisation. Because the solver tool (Galapagos) takes one objective, the optimisation was divided into two processes: (1) energy consumption as an objective and (2) useful daylight illuminance as an objective. Therefore, the fitness was minimised and maximised, in response to each respective objective. Also, the genome (sliders) consists of the thicknesses of the blinds for both processes. GA (Genetic Algorithm) was then used to find the optimum perforation of the blinds' thicknesses in combination with minimum energy consumption and maximum daylight. The analysis was classified into two main sections, with each section divided into sub-sections in reference to each city as follows:

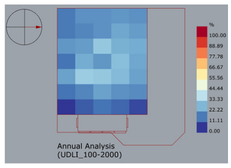
6.1. Energy Consumption as an Objective

The optimisation process needs two types of input: variables and fitness function. The fitness function (objective) is the energy performance metrics calculated by the simulation engine (EnergyPlus). In this process, the fitness function is the maximum value of the performance metric, such as energy consumption. The variables are the thicknesses of the Rawshan's blinds, as explained previously. The constraint is useful in daylight illuminances.

6.1.1. Actual Living Room Optimisation Results in Mecca

The generation reached 65, and the optimum perforation of the three-sided Rawshan was found in two populations: 821 and 3352. The thicknesses of the perforations were 0.01 m, 0.0102 m, and 0.011 m for the north, east, and south sides, respectively, as illustrated in Table 14. These configurations of the Rawshan's blinds consumed 13,432.12 kWh annually with an average UDI of 16%. The opening percentage of the Rawshan blinds was 85% for the front side (east), 84% for the right side (north), and 82% for the left side (south). Moreover, the result showed that 30% more energy was consumed in the summer season, as illustrated in Table A1 and Figure A1.

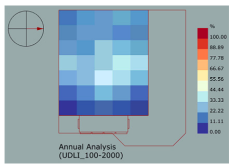
Table 14. Optimisation Results of the Actual Room with Rawshan for Mecca.

Direction	With Rawshan										
	Population No.	Optimum Perforation (Thickness)				Objective				Constraint	
		North	East	South	West	Cooling Load (kWh)	Total Lights Use (kWh)	Total Electrical Equipment Use (kWh)	Heating Load (kWh)	Average % of UDI 100–2000	Preview UDI 100–2000
East	821 and 3352	0.01 m	0.0102 m	0.011 m	X	9125.93	3128.32	1177.88	0	15.57	
						Total Energy Consumption (kWh)					
						13,432.12					

6.1.2. Actual Living Room Optimisation Results in Jeddah

The generation reached 105, and the optimum perforation of the three-sided Rawshan was found in two populations: 2861 and 5402. The thicknesses of the perforations were 0.014 m, 0.01 m, and 0.025 m for the north, east and south sides, respectively, as illustrated in Table 15. These configurations of the Rawshan's blinds consumed 15,872.58 kWh annually with an average UDI of 17%. Comparing the Jeddah room with and without the Rawshan, the energy consumption increased by about 14% with the Rawshan while the average UDI decreased by about 23% without using the Rawshan. The opening percentage of the Rawshan for each side: front side (east) 85%, right side (north) 84%, and left side (south) 82%. Moreover, the result showed that 34% more energy was consumed in the summer, as illustrated in Table A2 and Figure A2.

Table 15. Optimisation Results of the Actual Room with Rawshan for Jeddah.

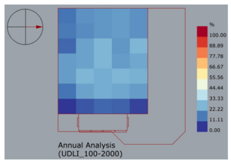
Direction	With Rawshan										
	Population No.	Optimum Perforation (Thickness)				Objective				Constraint	
		North	East	South	West	Cooling Load (kWh)	Total Lights Use (kWh)	Total Electric Use (kWh)	Heating Load (kWh)	Average % of UDI 100–2000	Preview UDI 100–2000
East	2861 and 5402	0.014 m	0.01 m	0.025 m	X	11,561.40	3133.31	1177.88	0	17.03	
						Total Energy Consumption (kWh)					
						15,872.58					

6.1.3. Actual Living Room Optimisation Results in Riyadh

The generation reached 73, and the optimum perforation of the three-sided Rawshan was found in one population: 2600. The thicknesses of the perforations were 0.014 m, 0.01 m and 0.015 m for the north, east, and south sides, respectively, as illustrated in Table 16. These configurations of the Rawshan's blinds consumed 10,025.72 kWh annually with an average UDI of 15%. The opening percentage of the Rawshan for each side: front side (east)

85%, right side (north) 84%, and left side (south) 82%. Moreover, the result showed 41% more energy consumed in the summer season, as illustrated in Table A3 and Figure A3.

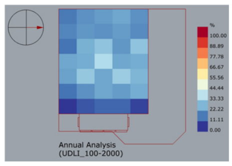
Table 16. Optimisation Results of the Actual Room with Rawshan for Riyadh.

	With Rawshan										
Direction	**Population No.**	**Optimum Perforation (Thickness)**				**Objective**				**Constraint**	
		North	**East**	**South**	**West**	**Cooling Load (kWh)**	**Total Lights Use (kWh)**	**Total Electric Use (kWh)**	**Heating Load (kWh)**	**Average % of UDI 100–2000**	**Preview UDI 100–2000**
East	2600	0.014 m	0.01 m	0.015 m		7060.62	1744.72	1177.88	42.51	15.23	
						Total Energy Consumption (kWh)					
						10,025.72					

6.1.4. Actual Living Room Optimisation Results in Al-Baha

The generation reached 72, and the optimum perforation of the three-sided Rawshan was found in two different populations: 1187 and 3702. The thicknesses of the perforations were 0.015 m, 0.01 m and 0.015 m for the north, east, and south sides, respectively, as illustrated in Table 17. These configurations of the Rawshan's blinds consumed 7779.43 kWh annually with an average UDI of 16%. The opening percentage of the Rawshan for each side: front side (east) 85%, right side (north) 77%, and left side (south) 75%. Moreover, the result showed that 37% of the total energy was consumed in the summer season because Al-Baha has a higher elevation above sea level and its elevation is 1672.1 m. The climate in Al-Baha is a cold, semi-arid climate. Table A4 shows the energy consumption during the four seasons.

Table 17. Optimisation Results of the Actual Room with Rawshan for Al-Baha.

	With Rawshan										
Direction	**Population No.**	**Optimum Perforation (Thickness)**				**Objective**				**Constraint**	
		North	**East**	**South**	**West**	**Cooling Load (kWh)**	**Total Lights Use (kWh)**	**Total Electric Use (kWh)**	**Heating Load (kWh)**	**Average % of UDI 100–2000**	**Preview UDI 100–2000**
East	1187 and 3702	0.015 m	0.01 m	0.015 m		4860.30	1728.66	1177.88	12.59	16.4	
						Total Energy Consumption (kWh)					
						7779.43					

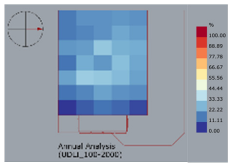
6.2. Useful Daylight Illuminance as an Objective

The optimisation process needs two types of input: variables and fitness function. The fitness function (objective) is the daylight performance metrics calculated by the simulation engine (RADIANCE). In this process, the fitness function is the maximum value of the performance metric, such as Useful Daylight Illuminance (UDI). The variables are the thicknesses of the Rawshan's blinds, as explained previously. The constraint in this method has decreased the value of energy consumption in the modelled room.

6.2.1. Actual Living Room Optimisation Results in Mecca

The generation reached 113, and the optimum perforation of the three-sided Rawshan was found in two populations: 3239 and 5752. The thicknesses of the perforations were 0.026 m, 0.0107 m, and 0.013 m for the north, east, and south sides, respectively, as illustrated in Table 18. These configurations of the Rawshan's blinds consumed 14,626.30 kWh annually with an average UDI of 16%. Moreover, the result showed that 33% of the total energy was consumed in the summer season, as illustrated in Table A5. Additionally, the air conditioner cooling load consumed 80% of the energy.

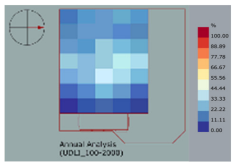
Table 18. Optimisation Results of the Actual Room with Rawshan for Mecca.

Direction	Population No.	With Rawshan									
		Optimum Perforation (Thickness)				Constraint				Objective	
		North	East	South	West	Cooling Load (kWh)	Total Lights Use (kWh)	Total Electrical Equipment Use (kWh)	Heating Load (kWh)	Average % of UDI 100–2000	Preview UDI 100–2000
East	3239 and 5752	0.026 m	0.0107 m	0.013 m	X	11,718.85	1729.57	1177.88	0	16.14	
						Total Energy Consumption (kWh)					
						14,626.30					

6.2.2. Actual Living Room Optimisation Results in Jeddah

The generation reached 145, and the optimum perforation of the three-sided Rawshan was found in two populations: 4873 and 7401. The thicknesses of the perforations were 0.018 m, 0.01 m, and 0.01 m for the north, east, and south sides, respectively, as illustrated in Table 19. These configurations of the Rawshan's blinds consumed 15,879.5 kWh annually with an average UDI of 19%. Moreover, the result showed that 34% of the total energy was consumed in the summer season, as illustrated in Table A6. Notably, 73% of energy is used to meet the cooling demand.

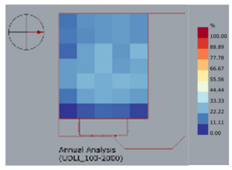
Table 19. Optimisation Results of the Actual Room with Rawshan for Jeddah.

Direction	Population No.	With Rawshan									
		Optimum Perforation (Thickness)				Constraint				Objective	
		North	East	South	West	Cooling Load (kWh)	Total Lights Use (kWh)	Total Electrical Equipment Use (kWh)	Heating Load (kWh)	Average % of UDI 100–2000	Preview UDI 100–2000
East	4873 and 7401	0.018 m	0.01 m	0.01 m	X	11,564.36	3137.26	1177.88	0	18.71	
						Total Energy Consumption (kWh)					
						15,879.50					

6.2.3. Actual Living Room Optimisation Results in Riyadh

The generation reached 73, and the optimum perforation of the three-sided Rawshan was found in two populations: 1069 and 3602. The thicknesses of the perforations were 0.018 m, 0.01 m, and 0.01 m for the north, east, and south sides, respectively, as illustrated in Table 20. These configurations of the Rawshan's blinds consumed 10,032.51 kWh annually with an average UDI of 17%. Moreover, the result showed that 41% of the total energy was consumed in the summer season, as illustrated in Table A7. The air conditioner (cooling load) consumed 70% of the energy, while the heating load increased to 42.5 kWh.

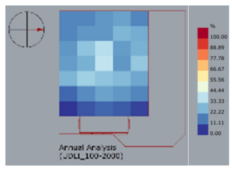
Table 20. Optimisation Results of the Actual Room with Rawshan for Riyadh.

Direction	With Rawshan										
	Population No.	Optimum Perforation (Thickness)				Constraint				Objective	
		North	East	South	West	Cooling Load (kWh)	Total Lights Use (kWh)	Total Electrical Equipment Use (kWh)	Heating Load (kWh)	Average % of UDI 100–2000	Preview UDI 100–2000
East	1069 and 3602	0.018 m	0.01 m	0.01 m	X	7063.45	1748.68	1177.88	42.50	16.7	
						Total Energy Consumption (kWh)					
						10,032.51					

6.2.4. Actual Living Room Optimisation Results in Al-Baha

The generation reached 70, and the optimum perforation of the three-sided Rawshan was found in two populations: 1071 and 3602. The thicknesses of the perforations were 0.01 m, 0.014 m, and 0.015 m for the north, east, and south sides, respectively, as illustrated in Table 21. These configurations of the Rawshan's blinds consumed 9752.11 kWh annually with an average UDI of 17%. Moreover, the result showed that 36% of the total energy consumed was in the summer season, as illustrated in Table A8. Notably, 56% of the energy consumed was by the air conditioner (cooling load), and the heating load was 2.41 kWh.

Table 21. Optimisation Results of the Actual Room with Rawshan for Al-Baha.

Direction	With Rawshan										
	Population No.	Optimum Perforation (Thickness)				Constraint				Objective	
		North	East	South	West	Cooling Load (kWh)	Total Lights Use (kWh)	Total Electrical Equipment Use (kWh)	Heating Load (kWh)	Average % of UDI 100–2000	Preview UDI 100–2000
East	1071 and 3602	0.01 m	0.014 m	0.015 m	X	5435.81	3136.01	1177.88	2.41	16.91	
						Total Energy Consumption (kWh)					
						9752.11					

7. Compare Results

This section will first focus on the breakdown of the energy consumed based on four metrics: total cooling load, total light usage, total electrical equipment use, and total heating load. The energy simulation results of the actual living room without using the Rawshan served as standard indicators to analyse the benefit of the Rawshan. This will show the potential benefit of using an optimised Rawshan for each city: Mecca, Jeddah, Riyadh, and Al-Baha. For example, some of the cities output higher energy consumption due to higher electrical equipment use, which is not related to the Rawshan. Also, the cooling load consumed around 74% for Mecca and Jeddah, 64% for Riyadh, and 60% for Al-Baha. Thus, the cooling load should be less than 74% of the total energy use when the Rawshan is installed in similar climates. Lastly, this section will discuss and compare the two objective methods, energy consumption as an objective and daylight as an objective, for each selected city.

7.1. Mecca

For Mecca, the total energy consumption was reduced in the first method by about 4% when compared to the original living room without a Rawshan. However, in the second method, the energy consumption was increased by 5% when compared to the original living room. Applying the first method (energy consumption as an objective), comparing the living room with and without using the Rawshan, the cooling load is reduced by about 6% when the Rawshan is installed. However, the cooling load increased by about 12% when using the second method (daylight as an objective). Artificial lights are necessary for residential buildings to support the daylight that comes through the windows. In the living room without the Rawshan, the simulation results show that the total light usage was 2% less than with the Rawshan because the first method prevented unwanted daylight. On the other hand, in the second method (daylight as an objective), the lighting energy consumption decreased around 5% compared to the original room, which indicates that more daylight comes through the window, leading to an increase in the cooling load.

As for the heating load, Mecca has warm to hot temperatures, and all residential buildings were designed without heating systems. Therefore, all results in this city for the heating load were zero. Moreover, in the first and second methods, UDI decreased by about 25% and 24%, respectively, compared to the original living room. Tables 22 and 23 illustrate a breakdown of the energy usage and compare the first and second methods, respectively, with the room without the Rawshan. Moreover, they indicate a description of the percentage difference, where the (-) represents a decrease between the two values.

Table 22. Energy Usage Comparison between the First Method (Energy as an Objective) and the Original Living Room (Room without a Rawshan) for Mecca.

	Sim. Results	**Opt. Results (Energy as an Objective)**	**Percent**	**Percentage Difference**
Total Cooling Load (kWh)	10,237.85	9125.93	−10.9	Decreased
Total Lights use (kWh)	2968.28	3128.32	5.4	Increased
Total Electrical Equipment use (kWh)	725.5	1177.88	62.4	Increased
Total Heating Load (kWh)	0	0	0	-

Table 23. Energy Usage Comparison between the Second Method (Daylight as an Objective) and the Original Living Room (Room without a Rawshan) for Mecca.

	Sim. Results	**Opt. Result (Daylight as an Objective)**	**Percent**	**Percentage Difference**
Cooling Load (kWh)	10,237.85	11,718.85	14.5	Increased
Total Lights use (kWh)	2968.28	1729.57	−41.7	Decreased
Total Electrical Equipment use (kWh)	725.5	1177.88	62.4	Increased
Total Heating Load (kWh)	0	0	0	-

7.2. Jeddah

The total energy consumption for the first (energy consumption as an objective) and second (daylight as an objective) methods was higher when compared with the original living room (without Rawshan). For both methods, the total energy consumption and the cooling load increased by about 14% when compared to the original living room.

The simulation results identified that artificial lights in the living room consumed about 21% of the total energy consumption. Comparing the first method results to the original living room, the artificial light usage increased by about 6%. Moreover, a slight increase of 0.1% in light usage was observed in the second method when compared to the first method.

The electrical equipment usage increased by about 62% with the first and second methods when compared with the original room without the Rawshan. While Jeddah has a hot and humid climate, the residential buildings are not constructed with heating systems. Therefore, the simulation and optimisation results for the heating load were zero. Moreover, in the first and second methods, UDI was decreased by about 23% and 22%, respectively, compared to the original living room. Tables 24 and 25 illustrate a breakdown of the energy use and compare the first and second methods, respectively, with the room without the Rawshan.

Table 24. Energy Usage Comparison between the First Method (Energy as an Objective) and the Original Living Room (Room without a Rawshan) for Jeddah.

	Sim. Results	Opt. Results (Energy as an Objective)	Percent	Percentage Difference
Cooling Load (kWh)	10,185.77	11,561.4	13.5	Increased
Total Lights use (kWh)	2968.28	3133.31	5.6	Increased
Total Electrical Equipment use (kWh)	725.5	1177.88	62.4	Increased
Total Heating Load (kWh)	0	0	0	-

Table 25. Energy Usage Comparison between the Second Method (Daylight as an Objective) and the Original Living Room (Room without a Rawshan) for Jeddah.

	Sim. Results	Opt. Result (Daylight as an Objective)	Percent	Percentage Difference
Cooling Load (kWh)	10,185.77	11,564.36	13.5	Increased
Total Lights use (kWh)	2968.28	3137.26	5.6	Increased
Total Electrical Equipment use (kWh)	725.5	1177.88	62.4	Increased
Total Heating Load (kWh)	0	0	0	-

7.3. Riyadh

In Riyadh, the first method reduced the total energy consumption by about 4% compared to the original living room without a Rawshan. Using the second method of optimisation, the total energy consumption was decreased by about 4% when compared to the original living room and was about 0.07% less than the first method result. The optimisation results for the first method (energy consumption as an objective) revealed an increase in the total cooling load of about 5% and a decrease in the total light usage of around 42% with 39% of Useful Daylight Illuminance (UDI) that ranged between 100–2000, comparing to the original room. The electrical equipment use and the heating load increased to 1177.88 kWh and 42.5 kWh, respectively, using the first method. Using the second method (daylight as an objective), the total cooling load and the total lights used were 0.04% and 0.23% higher, respectively, than the first method results.

The electrical equipment use increased using the first and second methods by 62% when compared with the simulation results without the Rawshan. While Riyadh has a hot and arid climate, heating systems should be considered in the building design. Therefore, the simulation result of the original living room had no heating load, and the optimisation results for the first and second methods were 42.51 kWh and 42.5 kWh, respectively. Tables 26 and 27 illustrate a breakdown of the energy use and compare the first and second methods, respectively, with the room without the Rawshan. Moreover, they provide a description of the percentage difference, where the symbol (−) signifies a decrease between two values.

Table 26. Energy Usage Comparison between the First method (Energy as an Objective) and the Original Living Room (Room without a Rawshan) for Riyadh.

	Sim. Results	Opt. Results (Energy as an Objective)	Percent	Percentage Difference
Total Cooling Load (kWh)	6696.32	7060.62	5.4	Increased
Total Lights use (kWh)	2983.3	1744.72	−41.5	Decreased
Total Electrical Equipment use (kWh)	725.5	1177.88	62.4	Increased
Total Heating Load (kWh)	0	42.51	100.0	Increased

Table 27. Energy Usage Comparison between the Second Method (Daylight as an Objective) and the Original Living Room (Room without a Rawshan) for Riyadh.

	Sim. Results	Opt. Result (Daylight as an Objective)	Percent	Percentage Difference
Cooling Load (kWh)	6696.32	7063.45	5.5	Increased
Total Lights use (kWh)	2983.3	1748.68	−41.4	Decreased
Total Electrical Equipment use (kWh)	725.5	1177.88	62.4	Increased
Total Heating Load (kWh)	0	42.5	100.0	Increased

7.4. Al-Baha

For Al-Baha, the total energy consumption was reduced by using the Rawshan in the first method by about 17% when compared to the original living room without the Rawshan. Using the second method of optimisation, the total energy consumption increased about 5% when compared to the original living room. In the first method (energy consumption as an objective), the result revealed about a 14% reduction in the cooling load and a 42% reduction in the total light use when the Rawshan is installed. However, the total cooling load decreased by about 4%, and the total light usage increased by 6% when using the second method (daylight as an objective).

The electrical equipment use increased by 62% in the first and second methods when compared to the simulation results without the Rawshan. While Al-Baha is a mountainous city and has a cold, semi-arid climate, heating systems should be considered in the building design. Therefore, the simulation result of the original living room had a total heating load of 0.02 kWh, and the optimisation results for the heating load for the first and second methods were 12.59 kWh and 2.41 kWh, respectively. Moreover, in the first and second methods, UDI was decreased by about 24% and 23%, respectively, compared to the original living room. Tables 28 and 29 illustrate a breakdown of the energy use and compare the first and second methods, respectively, with the room without the Rawshan. Moreover, they indicate a description of the percentage difference, where the (−) represents a decrease between two values.

Table 28. Energy Usage Comparison between the First Method (Energy as an Objective) and the Original Living Room (Room without a Rawshan) for Al-Baha.

	Sim. Results	Opt. Results (Energy as an Objective)	Percent	Percentage Difference
Total Cooling Load (kWh)	5635.42	4860.3	−13.8	Decreased
Total Lights use (kWh)	2970.88	1728.66	−41.8	Decreased
Total Electrical Equipment use (kWh)	725.5	1177.88	62.4	Increased
Total Heating Load (kWh)	0.02	12.59	99.8	Increased

In summary, the comparison between the two optimised genetic algorithm methods revealed that: (a) the first method of the single-objective optimisation (energy consumption as an objective) achieved a further reduction than the second method (daylight as an objective) in the energy consumption section for all cities except Jeddah. The UDI results were less than those output by the second method (daylight as an objective) except for Mecca, which was the same value in both methods and (b) the second method showed an increase in energy consumption when compared to the living room without a Rawshan for only Mecca and Al-Baha. However, the UDI results were slightly higher (0–2%) than those for the first method, except for Mecca, which stayed the same at 16%. Additionally, all UDI results in both methods achieved the thermal comfort benchmarks [66,67]. Overall, the results indicate that for climates similar to Al-Baha, Riyadh, and Mecca, it is possible to predict energy reduction using a Rawshan design using the first method (energy consumption as an objective). Figure 14 shows the comparison between the optimised and simulated results for the four cities using the first and second methods.

Table 29. Energy Usage Comparison between the Second Method (Daylight as an Objective) and the Original Living Room (Room without a Rawshan) for Al-Baha.

	Sim. Results	**Opt. Result (Daylight as an Objective)**	**Percent**	**Percentage Difference**
Cooling Load (kWh)	5635.42	5435.81	−3.5	Decreased
Total Lights use (kWh)	2970.88	3136.01	5.6	Increased
Total Electrical Equipment use (kWh)	725.5	1177.88	62.4	Increased
Total Heating Load (kWh)	0.02	2.41	99.2	Increased

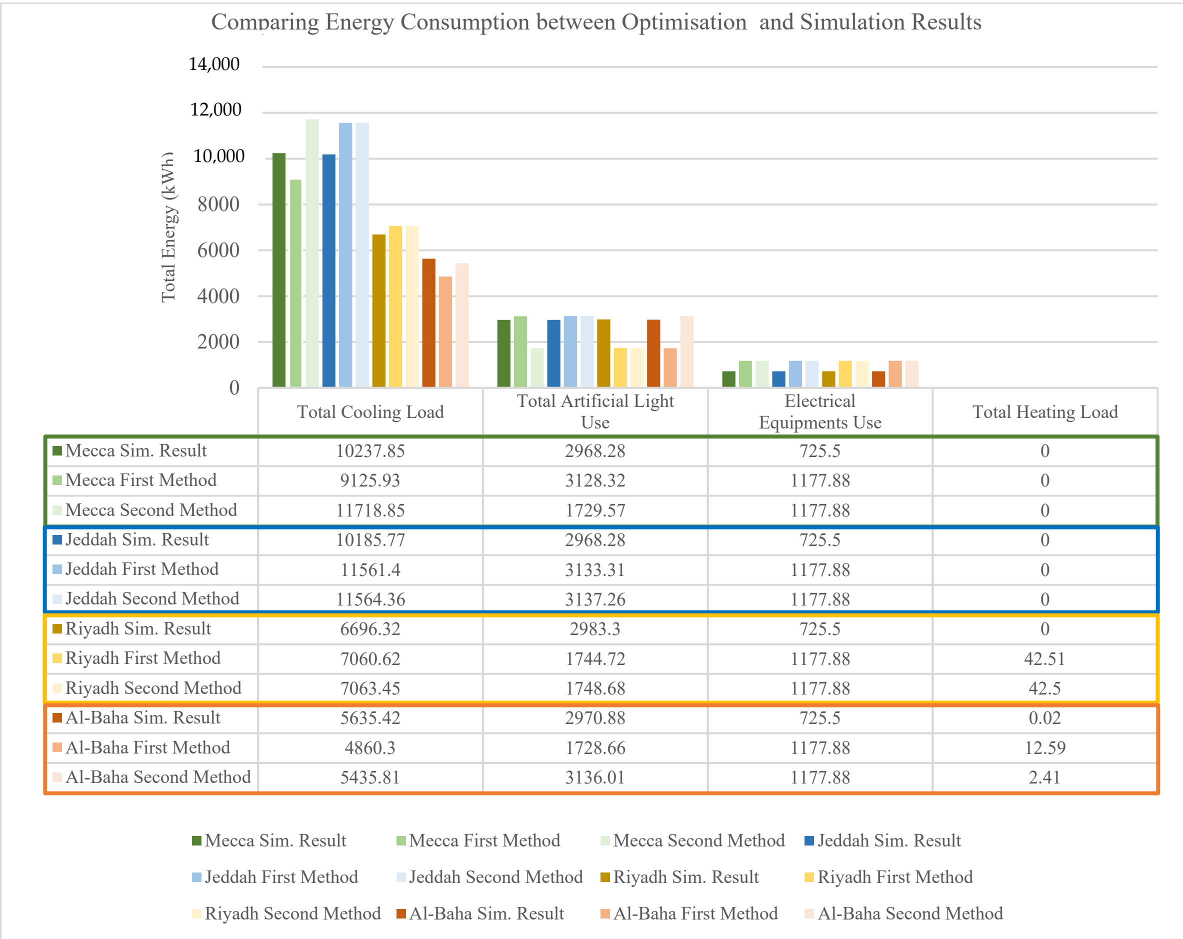


Figure 14. Comparison of Breakdown Energy Consumption between Optimisation and Simulation Results for the Four Cities using the First and Second Method.

8. Conclusions

This study compared simulated calibration results with two optimisation results to investigate the potential for reviving the Rawshan in different climates. This study used single-objective genetic algorithms for two different objectives to demonstrate options for selecting an appropriate method for modern Rawshans and similar elements. The analysis results have shown that the Rawshan vernacular architecture element can both reduce energy consumption and maximise useful daylight illuminance depending on the city's location.

The Rawshan was a realistic model and was optimised under parameters that are representative of a typical Saudi Arabian house design. The cities of Mecca, Jeddah, Riyadh, and Al-Baha were selected as sample climates for this study to test the optimised Rawshan's potential performance under various seasonal conditions and locations. The model was validated using electricity bill data to verify the accuracy of building energy consumption predictions. Using the genetic algorithm tool Rhinoceros with applicable Grasshopper plug-ins, the blind thicknesses on the front and sides of the Rawshan were optimised with respect to total building energy consumption and useful daylight illuminance. The first method (energy consumption as an objective) shows that using Rawshans reduced energy consumption in three cities: Mecca, Riyadh, and Al-Baha. The Rawshans also provided sufficient useful daylight illuminance in four cities: Mecca, Jeddah, Riyadh, and Al-Baha, when compared to rooms without the Rawshan. Moreover, the findings revealed that with Rawshans, a city closer to sea level will show higher energy consumption.

The findings and recommendations in Sections 6 and 7 of this study can offer more insights for reviving the Rawshan vernacular element for both existing and future residential buildings in Mecca, Riyadh, and Al-Baha in order to meet the requirement to reduce energy consumption and decrease CO_2 emissions from buildings.

In reviving the Rawshan vernacular element for a building that faces east in Mecca, use the following perforations of blind thickness: (a) north side 0.01 m; (b) east side 0.0102 m; (c) west side 0.011 m.

For Riyadh, use (a) north side 0.014 m, (b) east side 0.01 m, and (c) west side 0.015 m.

For Al-Baha, use (a) north side 0.015 m, (b) east side 0.01 m, and (c) west side 0.015 m.

It is recommended that architects use the first method (energy consumption as an objective) if optimising with a genetic algorithm via Galapagos. Such optimisation should concentrate on either reducing that objective or should be given another condition.

This study identified that by using a single-objective genetic algorithm, it is possible to investigate the optimised design of the Rawshan when applied in different cities and climates. Possible future work is to provide more comprehensive optimisations that apply to more climates by using a multi-objective genetic algorithm via Rhinoceros and its plug-in Octopus. In addition, utilise the capabilities of cyber-physical systems (CPS) and digital twins (DTs), which can provide real-time predictions about energy efficiency and daylighting performance.

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Appendix A

Table A1. Energy Consumption during Seasons with Optimised Rawshan for Mecca.

Seasons	Energy Consumption (kWh)
Winter	2403.68
Spring	3525.78
Summer	3862.19
Autumn	3188.09

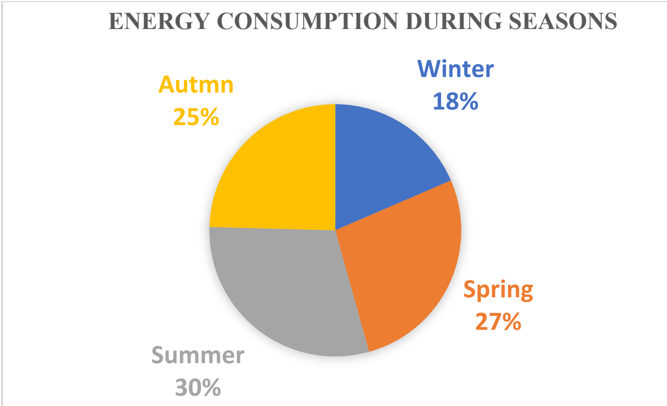

Figure A1. Energy Consumption during Seasons with Optimised Rawshan for Mecca.

Table A2. Energy Consumption during Seasons with Optimised Rawshan for Jeddah.

Seasons	Energy Consumption (kWh)
Winter	2417.80
Spring	4125.28
Summer	5413.60
Autumn	3915.91

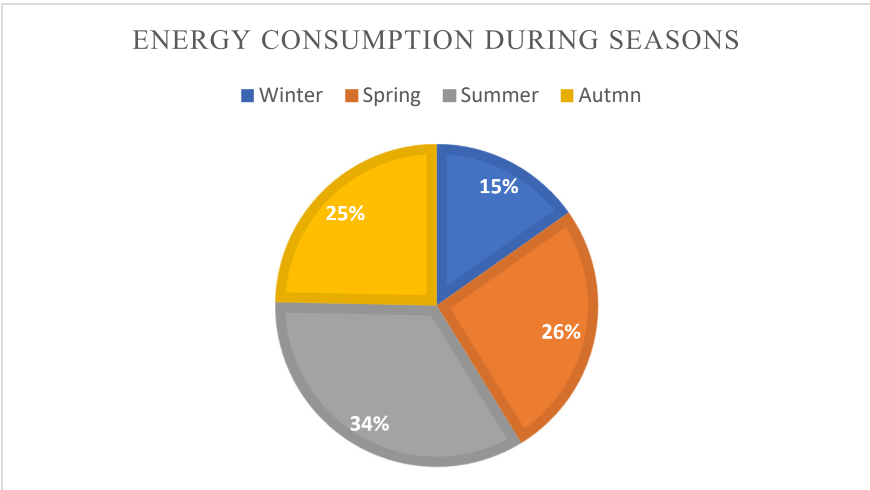

Figure A2. Energy Consumption during Seasons with Optimised Rawshan for Jeddah.

Table A3. Energy Consumption during Seasons with Optimised Rawshan for Riyadh.

Seasons	Energy Consumption (kWh)
Winter	1068.17
Spring	3017.70
Summer	4118.79
Autumn	1821.06

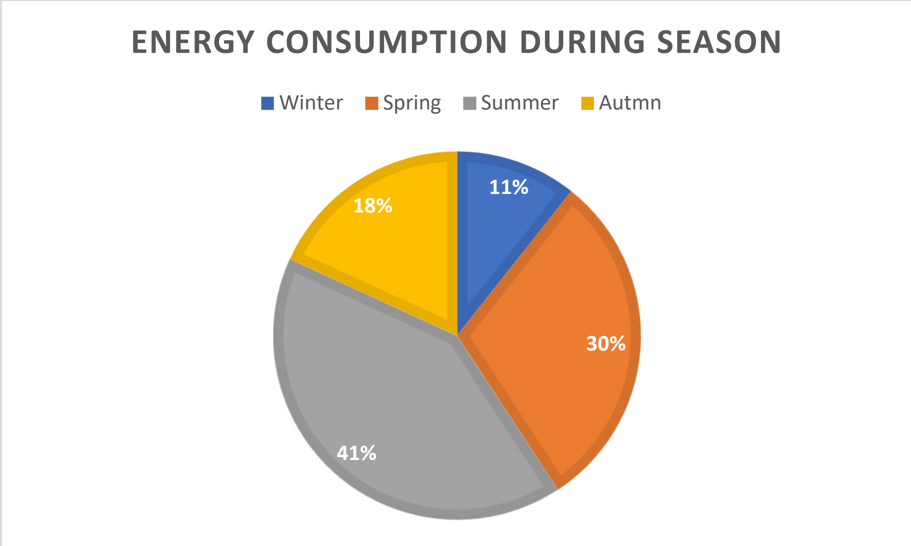

Figure A3. Energy Consumption during Seasons with Optimised Rawshan for Riyadh.

Table A4. Energy Consumption during Seasons with Optimised Rawshan for Al-Baha.

Seasons	Energy Consumption (kWh)
Winter	1085.54
Spring	2224.51
Summer	2866.10
Autumn	1603.29

Table A5. Energy Consumption during Seasons with Rawshan for Mecca.

Seasons	Energy Consumption (kWh)
Winter	2296.88
Spring	4014.08
Summer	4750.13
Autumn	3565.21

Table A6. Energy Consumption during Seasons with Rawshan for Jeddah.

Seasons	Energy Consumption (kWh)
Winter	2419.86
Spring	4125.99
Summer	5414.51
Autumn	3919.15

Table A7. Energy Consumption during Seasons with Rawshan for Riyadh.

Seasons	Energy Consumption (kWh)
Winter	1069.14
Spring	3019.92
Summer	4121.49
Autumn	1821.96

Table A8. Energy Consumption during Seasons with Rawshan for Al-Baha.

Seasons	Energy Consumption (kWh)
Winter	1445.27
Spring	2751.25
Summer	2524.76
Autumn	2030.84

References

1. Rapoport, A. Vernacular Architecture. *Curr. Chall. Environ. Soc. Sci.* **1990**, *24*, 30–45.
2. Asquith, L.; Vellinga, M. *Vernacular Architecture in the 21st Century: Theory, Education and Practice*; Taylor & Francis: Abingdon-on-Thames, UK, 2006.
3. Alelwani, R. *Reviving and Adapting a Vernacular Architectural Element to Promote Low Carbon Homes Using Genetic Algorithms: The Case of Rawshan*; Cardiff University: Cathays, UK, 2021.
4. Edwards, L.; Torcellini, P. *Literature Review of the Effects of Natural Light on Building Occupants*; National Renewable Energy Lab.: Golden, CO, USA, 2002.
5. Phillips, D. *Daylighting: Natural Light in Architecture*; Routledge: London, UK, 2004.
6. Ghiaus, C.; Inard, C. Energy and Environmental Issues of Smart Buildings: A Handbook for Intelligent Building. 2004. Available online: https://citeseerx.ist.psu.edu/document?repid=rep1&type=pdf&doi=7df381661ca10ab8d90459cff0e3ad37afa71f28 (accessed on 26 December 2024).
7. Ahmad, M.W.; Mourshed, M.; Mundow, D.; Sisinni, M.; Rezgui, Y. Building energy metering and environmental monitoring–A state-of-the-art review and directions for future research. *Energy Build.* **2016**, *120*, 85–102. [CrossRef]
8. Arabia, G.A.f.S.i.S. General Authority for Statistics in Saudi Arabia. Available online: https://www.stats.gov.sa/en/statistics-tabs/-/categories/124707?tab=436312&category=124707 (accessed on 4 November 2019).
9. Badr, S. *Towards Low Energy Buildings through Vernacular Architecture of Arab Cities*; Alexandria University: Alexandria, Egypt, 2014.
10. Aldossary, N.A.; Rezgui, Y.; Kwan, A. An investigation into factors influencing domestic energy consumption in an energy subsidized developing economy. *Habitat Int.* **2015**, *47*, 41–51. [CrossRef]
11. Ragette, F. *Traditional Domestic Architecture of the Arab Region*; Edition Axel Menges: Leipzig, Germany, 2003.
12. King, G. *The Traditional Architecture of Saudi Arabia*; IB Tauris (London): London, UK, 1998.
13. Koshak, N.; Gross, M.D. 3D Modelling of historic Makkah. In *CAADRIA Proceedings*; Citeseer: Princeton, NJ, USA, 1998.
14. Fathy, H. *Natural Energy and Vernacular Architecture*; U.S. Department of Energy: Washington, DC, USA, 1986.
15. Alelwani, R.; Ahmad, M.W.; Rezgui, Y. Public Perception of Vernacular Architecture in the Arabian Peninsula: The Case of Rawshan. *Buildings* **2020**, *10*, 151. [CrossRef]
16. Sayigh, A. *Sustainable Vernacular Architecture: How the Past can Enrich the Future*; Springer: Berlin/Heidelberg, Germany, 2019.
17. Clarke, J.A.; Clarke, J.A. *Energy simulation in building design*; Routledge: London, UK, 2001.
18. Banos, R.; Manzano-Agugliaro, F.; Montoya, F.; Gil, C.; Alcayde, A.; Gómez, J. Optimization methods applied to renewable and sustainable energy: A review. *Renew. Sustain. Energy Rev.* **2011**, *15*, 1753–1766. [CrossRef]
19. Wetter, M.; Wright, J. A comparison of deterministic and probabilistic optimization algorithms for nonsmooth simulation-based optimization. *Build. Environ.* **2004**, *39*, 989–999. [CrossRef]
20. Attia, S. *Computational Optimisation for Zero Energy Building Design, Interviews with Twenty Eight International Experts*; Architecture et climat: Paris, France, 2012.
21. Holland, J.H.; Reitman, J.S. Cognitive systems based on adaptive algorithms. In *Pattern-Directed Inference Systems*; Elsevier: Berlin/Heidelberg, Germany, 1978; pp. 313–329.
22. Ahmad, M.W.; Mourshed, M.; Yuce, B.; Rezgui, Y. Computational intelligence techniques for HVAC systems: A review. In *Building Simulation*; Springer: Berlin/Heidelberg, Germany, 2016.
23. 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]
24. Afshari, A.; Nikolopoulou, C.; Martin, M. Life-cycle analysis of building retrofits at the urban scale—A case study in United Arab Emirates. *Sustainability* **2014**, *6*, 453–473. [CrossRef]
25. Ahmad, M.W.; Mouraud, A.; Rezgui, Y.; Mourshed, M. Deep highway networks and tree-based ensemble for predicting short-term building energy consumption. *Energies* **2018**, *11*, 3408. [CrossRef]
26. Katunský, D.; Dolníková, E.; Doroudiani, S. Integrated lighting efficiency analysis in large industrial buildings to enhance indoor environmental quality. *Buildings* **2017**, *7*, 47. [CrossRef]
27. Moazzeni, M.H.; Ghiabaklou, Z. Investigating the influence of light shelf geometry parameters on daylight performance and visual comfort, a case study of educational space in Tehran, Iran. *Buildings* **2016**, *6*, 26. [CrossRef]
28. Ma'bdeh, S.; Al-Khatatbeh, B. Daylighting Retrofit Methods as a Tool for Enhancing Daylight Provision in Existing Educational Spaces—A Case Study. *Buildings* **2019**, *9*, 159. [CrossRef]
29. Escandón, R.; Suárez, R.; Sendra, J.J.; Ascione, F.; Bianco, N.; Mauro, G.M. Predicting the impact of climate change on thermal comfort in a building category: The Case of Linear-type Social Housing Stock in Southern Spain. *Energies* **2019**, *12*, 2238. [CrossRef]
30. Toutou, A.M.Y. Parametric Approach for Multi-Objective Optimization for Daylighting and Energy Consumption in Early Stage Design of Office Tower in New Administrative Capital City of Egypt. *Acad. Res. Community Publ.* **2019**, *3*, 1–13. [CrossRef]

31. Kocabay, S.; Alaçam, S. Algorithm Driven Design: Comparison of Single-Objective and Multi-Objective Genetic Algorithms in the Context of Housing Design. In Proceedings of the 17th Computer-Aided Architectural Design Futures Conference, Istanbul, Turkey, 12–14 July 2017.
32. Alelwani, R.; Ahmad, M.; Rezgui, Y.; Kwan, A. Rawshan: Environmental Impact of a Vernacular Shading Building Element in Hot Humid Climates. In Proceedings of the 2019 IEEE International Conference on Engineering, Technology and Innovation (ICE/ITMC), Valbonne Sophia-Antipolis, France, 17–19 June 2019.
33. Fathy, F.; Sabry, H.; Faggal, A.A. External Versus Internal Solar Screen: Simulation Analysis for Optimal Daylighting and Energy Savings in an Office Space. In Proceedings of the PLEA, Edinburgh, UK, 2–5 July 2017; Volume 16.
34. Fadan, Y.M. *The Development of Contemporary Housing in Saudi Arabia (1950–1983): A Study in Cross-Cultural Influence Under Conditions of Rapid Change*; Massachusetts Institute of Technology: Cambridge, MA, USA, 1983.
35. Hariri, M. Design of Rowshan and its importance to the dwelling. *J. Umm-Al-Qura Univ.* **1992**, *3*, 175–237.
36. Salloum, A. "El Rawashin" of jeddah saudi arabia. In *Passive and Low Energy Architectur*; Elsevier: Amsterdam, The Netherlands, 1983; pp. 245–252.
37. Gelil, N.A. A new mashrabiyya for contemporary Cairo: Integrating traditional latticework from Islamic and Japanese cultures. *J. Asian Archit. Build. Eng.* **2006**, *5*, 37–44. [CrossRef]
38. Aljawder, H.M.H. Residential Window: Daylight vs. Visual Privacy. Ph.D. Thesis, The University of Sydney, Camperdown, Australia, 2014.
39. Almurbati, N.; Headley, D.; Ford, P.; Taki, A. From manual to hybrid, parametric Mashrabiya: Digital workflow for the re-envisioning and conservation of Eastern architectural screens and the engagement of digital tectonics. *Int. J. Architecton. Spat. Environ. Des.* **2016**, *10*, 29–39. [CrossRef]
40. Kenzari, B.; Elsheshtawy, Y. The ambiguous veil: On transparency, the Mashrabiy'ya, and architecture. *J. Archit. Educ.* **2003**, *56*, 17–25. [CrossRef]
41. Tawayha, F.A.; Braganca, L.; Mateus, R. Contribution of the vernacular architecture to the sustainability: A comparative study between the contemporary areas and the old quarter of a Mediterranean City. *Sustainability* **2019**, *11*, 896. [CrossRef]
42. Samuels, W. Performance and Permeability: An investigation of the Mashrabiya for Use Within the Gibson Desert. Doctoral Dissertation, Open Access Te Herenga Waka-Victoria University of Wellington, Wellington, New Zealand, 2011.
43. Almerbati, N. Hybrid heritage: An invistigation into the viability of 3d-printed mashrabiya window screens for bahraini Dwellings. Ph.D. Thesis, De Montfort University, Leicester, UK, 2016.
44. Sidawi, B. A Conceptual Analytic Model of the Vocabulary of the Islamic Architectural Heritage. *Emir. J. Eng. Res.* **2012**, *17*, 47–56.
45. Sherif, A.H.; Sabry, H.M.; Gadelhak, M.I. The impact of changing solar screen rotation angle and its opening aspect ratios on Daylight Availability in residential desert buildings. *Sol. Energy* **2012**, *86*, 3353–3363. [CrossRef]
46. Aljofi, E. Effect of the Rawshan on the Provision of Daylight for Shopping Precincts. Ph.D. Thesis, University of Wales, Cardiff, Wales, 1995.
47. Al-Shareef, F.M. *Natural Light Control in Hadjazi Architecture: An Investigation of the Rowshan Performance by Computer Simulation*; The University of Liverpool: Liverpool, UK, 1996.
48. Aljofi, E. The potentiality of reflected sunlight through Rawshan screens. In Proceedings of the International Conference Passive and Low Energy Cooling for the Built Environment, Santorini, Greece, 19–21 May 2005.
49. Gelil, M.N.A.; Badawy, N.M. Simulated comparative investigation of the daylight and airflow of the conventional Egyptian shutter 'sheesh' and a proposed latticework device 'new mashrabiyya'. *Indoor Built Environ.* **2015**, *24*, 583–596. [CrossRef]
50. Karamata, B. Concept, Design and Performance of a Shape Variable Mashrabiya as a Shading and Daylighting System for Arid Climates. In Proceedings of the 30th PLEA Conference-Sustainable Habitat for Developing Societies, Ahmedabad, India, 16–18 December 2014.
51. Chan, Y.-C.; Tzempelikos, A. Efficient venetian blind control strategies considering daylight utilization and glare protection. *Sol. Energy* **2013**, *98*, 241–254. [CrossRef]
52. Sherif, A.; El-Zafarany, A.; Arafa, R. External perforated window Solar Screens: The effect of screen depth and perforation ratio on energy performance in extreme desert environments. *Energy Build.* **2012**, *52*, 1–10. [CrossRef]
53. Kim, J.T.; Kim, G. Advanced external shading device to maximize visual and view performance. *Indoor Built Environ.* **2010**, *19*, 65–72.
54. Manzan, M.; Clarich, A. FAST energy and daylight optimization of an office with fixed and movable shading devices. *Build. Eng.* **2017**, *113*, 175–184. [CrossRef]
55. Freewan, A.A. Impact of external shading devices on thermal and daylighting performance of offices in hot climate regions. *Sol. Energy* **2014**, *102*, 14–30. [CrossRef]
56. Erell, E.; Kaftan, E.; Garb, Y. Daylighting for visual comfort and energy conservation in offices in sunny regions. In Proceedings of the Passive and Low Energy Architecture Conference, Ahmedabad, India, 16–18 December 2014.

57. Shin, H.Y.; Lee, Y.; Jang, M.; Moon, K.H.; Kim, J.T. Daylighting performance on venetian blind for healthy apartment housing. In Proceedings of the First International Conference on Sustainability and the Future: Future Intermediate Sustainable Cities: A Message to Future Generations, Cairo, Egypt, 23–25 November 2010; Elain Publishing Company: Cairo, Egypt, 2010.
58. Huang, Y.; Niu, J.-l.; Chung, T.-m. Comprehensive analysis on thermal and daylighting performance of glazing and shading designs on office building envelope in cooling-dominant climates. *Appl. Energy* **2014**, *134*, 215–228. [CrossRef]
59. McNeel, R. *Rhinoceros 3D, Version 4.0*; Robert McNeel & Associates: Seattle, WA, USA, 2010.
60. Davidson, S. *Grasshopper-Algorithmic Modeling for Rhino*; Lynnwood: Washington, DC, USA, 2013.
61. Roudsari, M.S.; Pak, M.; Smith, A. Ladybug: A parametric environmental plugin for grasshopper to help designers create an environmentally-conscious design. In Proceedings of the 13th International IBPSA Conference, Lyon, France, 26–28 August 2013.
62. Rutten, D. *Grasshopper & Galapagos*; Robert McNeel & Associates: Seattle, WA, USA, 2007.
63. Energy, U.D.o. EnergyPlus: Whole Building Energy Simulation Program. Available online: https://www.ladybug.tools/epwmap/ (accessed on 10 December 2017).
64. Survey, S.G. Database of Geological Maps. Available online: https://ngd.sgs.gov.sa/en/geological-maps/ (accessed on 1 March 2020).
65. McNeel, R. Rhinoceros 3D. Available online: https://www.rhino3d.com/download/archive/rhino/5/latest/ (accessed on 26 December 2024).
66. Nabil, A.; Mardaljevic, J. Useful daylight illuminances: A replacement for daylight factors. *Energy Build.* **2006**, *38*, 905–913. [CrossRef]
67. Nabil, A.; Mardaljevic, J. Useful daylight illuminance: A new paradigm for assessing daylight in buildings. *Light. Res. Technol.* **2005**, *37*, 41–57. [CrossRef]
68. Mardaljevic, J.; Heschong, L.; Lee, E. Daylight metrics and energy savings. *Light. Res. Technol.* **2009**, *41*, 261–283. [CrossRef]
69. Mardaljevic, J.; Andersen, M.; Roy, N.; Christoffersen, J. Daylighting metrics for residential buildings. In Proceedings of the 27th Session of the CIE, Sun City, South Africa, 9–16 July 2011.
70. Aldossary, N.A.; Rezgui, Y.; Kwan, A. Domestic energy consumption patterns in a hot and arid climate: A multiple-case study analysis. *Renew. Energy* **2014**, *62*, 369–378. [CrossRef]
71. EnergyPlus. US Department of Energy, EnergyPlus, Building Technologies Office (BTO). 2016. Available online: https://energyplus.net/weather (accessed on 10 December 2016).