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Impact of Courtyard Concept on Energy Efficiency and Home Privacy in Saudi Arabia

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Abstract: The aim of this research is to develop an architectural style commensurate with the requirements of residential buildings in the hot and dry climate of Najran. The courtyard concept is one of the most important passive design strategies most in tune with the desert climate. The courtyard concept also meets the sociocultural requirements of the region. The success of this strategy can be verified by selecting a typical residential unit (villa) and assessing its indoor environmental conditions and energy performance. The villa can then be redesigned with the same functional and spatial determinants while creating a courtyard at the heart of the new villa configuration. To determine the level of improvement resulting from the proposed solution, the energy consumption per square meter is measured, and the results are compared with the DesignBuilder simulation program. The results indicate that with the proposed design focused mainly on the courtyard and some passive design strategies, the total energy consumption is reduced by 32.80% compared to the base case. The research concludes with a set of recommendations related to opportunities to improve the quality of the indoor environment and reduce cooling energy demand, in addition to achieving privacy for occupants and meeting the sociocultural requirements in the context of preserving Islamic values.

Keywords: courtyard; energy efficiency; simulation; Saudi Arabia; residential buildings

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1. Introduction

The courtyard is one of the most important sustainable environmental solutions for residential buildings in desert climate, where high diurnal temperature variation occurs [1–3]. Courtyards serve as collectors of cool air at night and a source of shade in the daytime [4,5], providing a healthy, comfortable environment for building users and maintaining a reduction in energy consumption in residential buildings [6,7]. On the other hand, courtyards provide complete visual privacy for occupants of residential buildings and represent an architectural alternative to metal barriers often installed by residents on the fencing wall of buildings (Figure 1), which are among the visual pollutants that most distort the beauty of buildings and cities alike [3,8]. A courtyard is an open space surrounded by walls located inside or outside of building and overlooked by windows. Courtyards are used as an architectural element in the design of buildings to regulate heat and light inside rooms and provide ventilation [9].

Figure 1. Metal barrier boundary walls on housed in Najran.

During the last decade, Saudi Arabia became one of the fastest-growing urban countries in the Middle East [10]. Through its Vision 2030 plan, the government has adopted policies to increase the rate of homeownership among citizens, including a policy of providing interest-free housing loans [11]. The launch of the housing program in 2018 rapidly increased the demand for housing units. According to the Housing Program report [12], the proportion of homeownership among Saudi families increased from 47% in 2016 to more than 60% in 2020. The Housing Program continues its efforts to increase the proportion of homeownership among Saudi families to 70% by 2030.

Official statistics provided by GAStat [13] indicate that the size of housing units in the Kingdom of Saudi Arabia (KSA) residential building stock exceeds 5,466,910 units across various categories, as illustrated in Figure 2. Moreover, 25% of housing units are villas. The building sector accounts for as much as 23% of the total energy consumption in Saudi Arabia and more than 75% of the total electricity consumption in the country, with an annual growth rate of about 7% [14]. A breakdown of the annual electricity consumption shows that residential, commercial, government, and industrial buildings account for 49.5%, 15.4%, 13%, and 18.8% of total energy consumption, respectively, although this figure does not exceed 29–30% globally, as shown in Figure 3 [15]. As shown in Figure 2, the building sector accounts for a maximum of 67% of the total electricity consumption in the Southern Operating District, where present study was carried out [14]. The majority of new building designs in the KSA are developed to meet the client's requirements without significant concern for the climate and with no intention to conserve energy [16]. During the last few decades, the construction industry has undoubtedly disregarded climate as a design determinant in the building envelope design process, resulting in buildings with poor thermal performance and becoming increasingly dependent on artificial approaches and consuming large amounts of electrical energy to provide a comfortable thermal environment [17]. Therefore, HVAC systems consume about 70% of the total electrical energy produced in the country [18,19] There is an urgent need to solve the problem of energy consumption in residential buildings with an environmentally sustainable solutions. The concept of courtyards, which were once an integral part of the Islamic culture, influences residential buildings in hot and arid climates.

Figure 2. Distribution of KSA residential buildings.

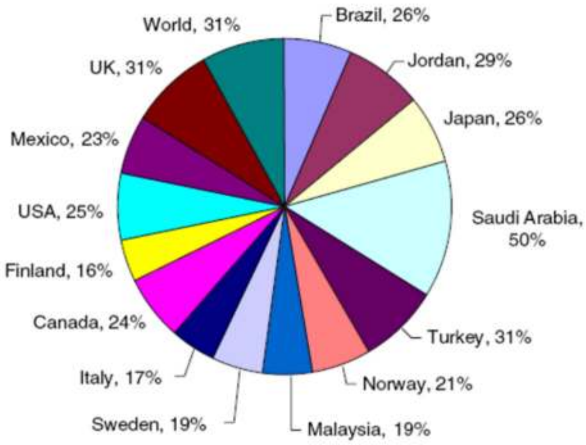

Figure 3. Worldwide distribution of residential buildings.

In general, the concept of courtyards was introduced in traditional architecture as a response to the prevailing climatic conditions as an ideal solution to provide thermal comfort and regulate natural lighting in residential buildings [20,21]. Therefore, prevailing local climatic conditions were the foremost factor behind the design of courtyard houses. However, the influence of the cultural, social, and religious requirements of the occupants plays a crucial role and must be integrated into building designs. For hundreds of years, the presence of central courtyards in traditional housing designs gave architects the freedom to address the cultural, social, and religious requirements of the occupants. Central courtyards also give architects and building engineers the freedom to incorporate bioclimatic features necessary in hot and dry climates to regulate the indoor thermal environment within the scope of traditional architecture [22]. A review of published literature revealed various qualitative advantages of a central courtyard in traditional architecture in hot and dry climates, although with little mention of the quantitative aspects of courtyards. To overcome this knowledge gap, the present study was conducted with an objective of investigating courtyard buildings as a sustainable design approach for modern single-family housing developments in Najran, KSA. We also explored the implications of courtyards as an architectural element to improve the indoor thermal environment, reduce energy consumption, and satisfy the sociocultural and privacy requirements of the occupants of such traditional residential buildings.

2. Literature Review

The concept of courtyards is one of the oldest housing styles and is common in many civilizations and geographies. Courtyards were have been implemented in vernacular buildings in parts of Asia, the Middle East, South America, and Mediterranean countries [6,22,23]. Courtyards are considered one of the most famous sustainable environmental solutions in traditional architecture to overcome climatic constraints. Studies have indicated that the courtyard concept is be energy-efficient in many climates, specifically in hot–dry and hot–humid climates [24–27]. Literature studies on the performance of courtyards have mainly dealt with natural ventilation, the relationship between the sun and shaded spaces, and the geometric composition of courtyard elements [7].

In their study Muhaisen and Gadi [28] focused on the impact of solar heat gain on the energy demand of courtyard buildings with varying proportions in Rome, Italy. A computer simulation tool, Integrated Environmental Solutions–Virtual Environment (IES-VE) was used to investigate the use of light colours for the external surfaces, as well as shading devices to improving the thermal characteristics of the building envelope components. The results showed that deeper courtyard forms were most effective in reducing the cooling load in summer and the heating load in winter. In addition, it was found that self-shaded courtyards reduce the cooling demand in summer by 4%; however, in winter, self-shaded courtyards increase the heating load by 12%.

Sadafi et al. [29] examined the thermal performance of terrace housing in Malaysia by exploiting an internal courtyard through field measurements and simulation. Results from field measurements were used to develop a baseline model for the computational experiment. Subsequently, the impact of an internal courtyard on thermal performance was investigated using ECOTECT software. The simulation results showed that including an internal courtyard in terrace housing improves natural ventilation and thermal comfort in spaces with openings to the outside environment. In addition, courtyards can improve the thermal conditions of the surrounding spaces, providing sufficient and efficient openings with shading devices that are suitably incorporated. An experimental and statistical study [30] investigated the effect of a ventilated interior courtyard on the thermal performance of a house in the hot–arid climate of Riyadh, KSA. The results confirmed that courtyard integration, along with cross-ventilation, provides a significant cooling enhancement to interior spaces and reduces energy consumption.

A study carried out by Al-Masri and Abu-Higleh [6] evaluated the environmental impact and energy savings associated with integration of a courtyard into a house in hot–humid weather conditions in Dubai, UAE. Simulations were carried out using the IES-VE simulation tool. By comparing the annual energy consumption of two buildings with the same physical characteristics, one with a courtyard and the other without, it was found that the building with an integrated courtyard consumed 6.9% less energy than the conventional building. Aldawoud [26] investigated the energy performance of varied heights, glazing types, and sizes of glazed windows in a courtyard under varying climate conditions using an energy simulation program, DOE2.1E. The results showed that energy performance of courtyard buildings differed depending on the climate, showing significantly enhanced energy performance in hot–dry and hot–humid climates. Another study [27] evaluated the performance of courtyards in providing thermally comfortable outdoor spaces according to different design configurations and scenarios in the hot–humid climate of Malaysia using the Environment for Visualizing Images (ENVI-met) simulation tool. The results show that well-designed courtyard parameters, such as height ratio, an abundance in the amount of vegetation and orientation, and an acceptable level of thermal comfort, can be achieved during the entire daytime.

On the other hand, many studies conducted in the Saudi residential sector have investigated the impact of varied passive design strategies independent of the integration of such strategies in courtyard houses [10,16,31–34]. The results of these studies showed considerable opportunities to reduce energy consumption and improve thermal performance in an extremely hot climate. Despite courtyards being well-known as a microclimatic modifier to provide indoor thermal comfort, few studies have specifically focused on applying the courtyard concept to new Saudi villas to improve energy efficiency. Therefore, with this study, we aim to fill this gap by proposing a new residential housing design with an integrated courtyard concept and evaluate the impact of applying the Saudi Building Code for energy efficiency requirements (BSC-602) in the hot–arid climate of the KSA.

3. Study Methodology

Several methods have been used in similar research studies, including modelling, experimental field measurements, and surveying. However, the technique used most often in recent studies is computer simulation. Computer-based simulation technology can enable testing of conceptual systems in an empirical venue and answer questions about how physical environments can enhance some aspects of thermal comfort [35–37]. In this research, three methods were adopted to evaluate the significance of integrating the courtyard concept in combination with isolation of the building envelope components according to the Saudi Code requirements for energy efficiency in hot–arid climates. We began by conducting an extensive literature review, followed by field measurements and a redesign of a BC, including the courtyard. The final stage was simulation. A schematic representation of the applied methodology is shown in Figure 4. The methodology is explained in detail hereafter.

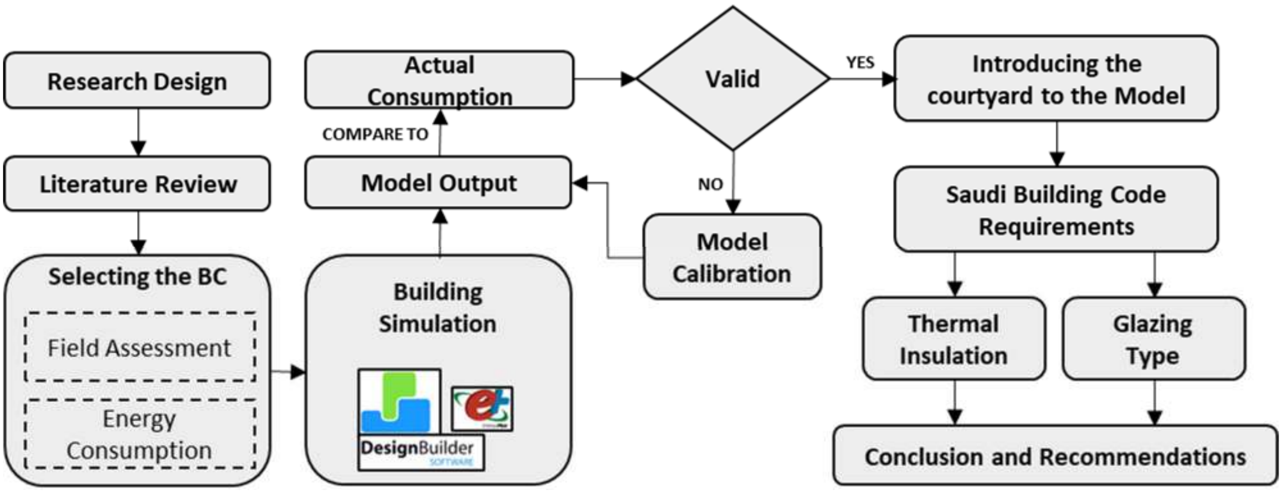

Figure 4. Schematic summary of the research methodology.

3.1. Building Characteristics

The selected case study is a residential building or "villa" located in the Khalidiya district, Najran. It was chosen to reflects the prevailing style of traditional villas constructed and widely preferred by Saudi families in Najran. A field visit was carried out to the residential building to conduct measurements related to the building's thermal performance and to assess the internal environment by measuring air temperature and relative humidity using an Extech RHT20 datalogger. Structural characteristics of the building envelope, occupant activities, equipment power density, lighting density, setpoint temperatures, and operation schedule of the HVAC systems were recorded. Monthly electrical energy consumption data for a whole year (2019) were also collected. Figure 5 shows the location of the investigated villa. Figures 6–9 illustrate the floor plan and main elevations of the selected villa. The material and construction characteristics of the building are summarized in Table 1. The occupancy, lighting, HVAC, and equipment schedules are shown in Table 2. During the site visit, we found that the building was not thermally insulated. Moreover, the villa is oriented to maximize the usage of available land, without consideration of the environmental design.

Figure 5. Site map of the case study villa, Najran.

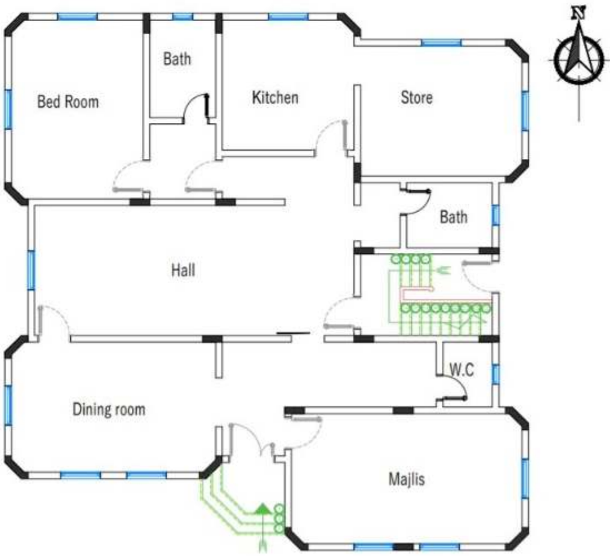

Figure 6. Ground floor of BC.

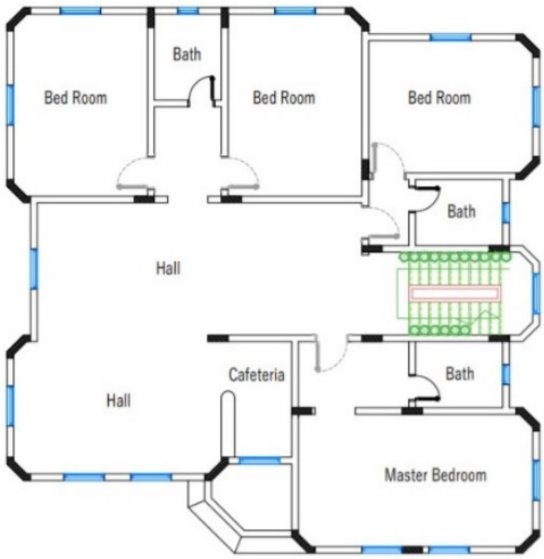

Figure 7. First floor of BC.

Figure 8. Southern elevation.

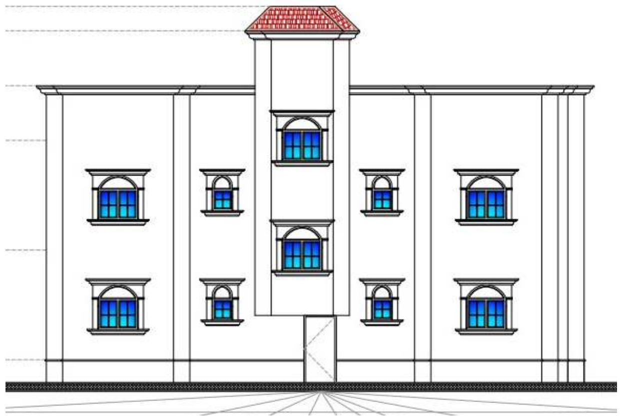

Figure 9. Eastern elevation.

Table 1. Building construction specifications and systems characteristics of the case study villa.

Characteristic	Description
Date of construction	2002
Land area	500 m^2
Gross floor area	479 m^2
Gross wall area	207.70 m^2
Total building height	6.60 m
Glazing area	34.8 m^2
Type of glass (U value = 5.894 W/m^2 K)	Single clear 0.006 m
Overall WWR	10%
External walls from outside to inside (U-value = 1.619 W/m^2 K)	0.02 m plaster with paint 0.20 m concrete block 0.02 m plaster with paint (light)
Internal partition	0.15 m thick plaster (light) 0.20 m thick concrete blocks 0.15 m thick plaster (light)
Roof from outside to inside (U-value = 3.644 W/m^2 K)	0.02 m terrazzo tiles 0.02 cement mortar 0.05–0.080 m sand for roof levelling 0.15 m reinforced concrete 0.02 m plaster with paint (light)
Ceilings	0.01 m ceramic tiles 0.02 mortar/Plaster 0.15 m reinforced concrete 0.02 m plaster with paint (light)
Ground floor	0.01 m ceramic tiles 0.02 mortar/Plaster 0.04 m membrane (moisture insulation) 0.10 m light reinforced concrete 0.15 m base-course stone
Number of occupants	7
Type of HVAC system	DX air-cooled (window unit)
Lighting power	3.0 kW (lower level), 2.0 kW (upper level)

Table 2. Occupancy schedules and analysis considerations.

Characteristics	Description	
Number of occupants	7	
Occupancy schedule	Living room	Bedrooms
Sunday–Thursday	3 pm–11 pm	11 pm–7 am
Friday–Saturday	9 am–4 pm	12 pm–9 am
Lighting power	3.0 kW (lower level), 2.0 kW (upper level)	
Lighting schedule	Corresponds to occupancy, except bedrooms, where a nominal lighting load of 10% was applied	
Equipment load (TV/VCR, PC)	118 W for bedrooms, 150 W for living/dining room	
Equipment schedule	Corresponds to occupancy, except bedrooms, where a nominal equipment load of 10% was applied	
Type of HVAC system	DX air-cooled (window unit)	
Air conditioning schedule	Corresponds to occupancy schedule	
Temperature-set point for cooling	24 °C	
Infiltration rate	0.6 air changes per hour	
Period of cooling analysis	9 months (February–October)	

3.2. Climate Conditions of Najran

Najran is located in the southwestern part of the Kingdom of Saudi Arabia, near the Yemeni border. The city is located at the intersection of 17°29″ 30 N and 44°70″ 56 E, at 1310 m above sea level. Najran is characterized by a semidesert climate. Many months have 0 mm of precipitation. The largest amount of rain falls in April, with an average of 75 mm. The hottest month of the year is July, with an average temperature of 33.2 °C. The lowest average temperature of the year occurs in January. The average monthly climate characteristics of Najran city are presented in Table 3.

Table 3. Climate characteristics of Najran.

	January	February	March	April	May	June	July	August	September	October	November	December
Average Air Temperature (°C)	18.5	21	26.4	24	29.5	31.5	33.2	30.5	30	22.5	20.5	21.5
Average Wind Speed (m/s)	43	28	30	51	21	14	19	22	18	17	31	35
Average Relative Humidity (%)	5.1	5	0	75.4	0	0	8.5	35.5	0	0	1.5	0
Average Global GHI (Wh/m^2)	229	268	285	294	317	322	295	300	294	285	246	222
Average Rainfall	7.4	7.4	9.3	11.1	7.4	7.4	11.1	9.3	7.4	5.6	5.6	5.6

3.3. Thermal Modelling Tool: Designbuilder

Many well-documented energy simulation programs have been used in the past. DesignBuilder simulation tool has been used extensively, owing to its combination of accuracy and user-friendly design. DesignBuilder provides advanced modelling tools with an easy-to-use interface. This enables the whole design team to use the same software to develop comfortable and energy-efficient building designs from concept through to completion. In essence, DesignBuilder is a commercially available software package with a three-dimensional interface that provides dynamic and comprehensive energy simulation for buildings. The simulation is based on 'real' hourly weather data and takes into consideration both solar gain through windows, as well as heat conduction and convection between zones of different temperatures [38,39]. The accuracy of the DesignBuilder software has been validated using the BESTest (Building Energy Simulation TEST) procedure originally developed by the International Energy Agency. The BESTest is a comparative set of tests that are regarded by the American Department of Energy and the international community as a reputable basis for evaluating the capabilities of building energy simulation programs [40]. DesignBuilder has been successfully used as a simulation tool in many published works [16,41–43]. Thus, DesignBuilder 6.1.0.6 was chosen to carry out this research due to its accuracy and capabilities.

Infiltration rate is one of the most important factors to predict the energy performance of buildings. Uncontrolled outdoor air enters buildings via doors, windows, or building envelope cracks caused by pressure differences [44]. Air infiltrating buildings has a considerable impact on energy performance, depending on climatic conditions of and factors such as the age of the building, method of construction, and the building type [45]. The infiltration rate is measured by air changes per hour (ACH). This means that the estimation of model infiltrations has a significant effect on building energy performance. Due to the limited availability of measurement equipment, we could not measure the rate of inflation for the case study houses. However, Saudi Arabian residences generally have moderate rates of inflation, varying between 0.65 and 0.90 ACH in traditional houses and between 0.55 and 0.90 ACH in modern apartments and villas [46]. Based on the previously mentioned study, it was assumed that the villa has fixed infiltration rates of 0.7 ACH in DesignBuilder models.

4. Results and Discussion

4.1. Energy Consumption Profile of the Base Case Building

The energy consumption in the residential villa was analyzed by collecting the monthly electronic invoices corresponding to each month to identify the periods of highest and lowest energy consumption, as well as the building's energy use intensity (EUI) in kWh/m^2/year. Figure 10 shows the monthly energy consumption of the building for the year 2019. The rate of energy consumption is strongly related to the environmental and climatic conditions of the city, as demonstrated by the maximum consumption recorded in the summer months, with an increase of approximately fourfold between September and January. The total energy consumption of the villa is 72,659 kWh/year, or 146.2 kWh/m^2/year.

The total energy consumption of the modelled villa without a courtyard concept is 70,241.2 kWh/year, or 141.3 kWh/m^2/year. The gap between measured and simulation results shows good agreement, with relative errors of approximately 3.3%. That means that the templates of the building construction characteristics, occupant activities, equipment power density, setpoint temperatures, and operation schedule of the HVAC and lighting systems are ready to be applied to the proposed design of the villa with a courtyard concept.

4.2. Proposed Building Description with Courtyard-Based Concept

The BC villa was redesigned on the same land. For the design concept, we assumed that all architectural spaces required by the owner must be included. On the other hand, some new spaces in line with the current lifestyle of the average Saudi family were also included, such as a maid room, while maintaining almost the same gross area. The design proposal area is 502 m^2, whereas the current BC villa is 497 m^2 and constructed on the same 500 m^2 plot of land of. The only difference between the two cases is the addition of a courtyard in the proposed case. To evaluate the effect of the courtyard, all structural and operational characteristics in the existing building were retained in the proposed building, such as the type of building materials and thickness of the building envelope components, the type and size of the glazing, the operating pattern of electrical appliances, lighting and HVAC systems, the occupancy schedule of the users, etc. Figures 11–16 show a full architectural drawing of the proposed case.

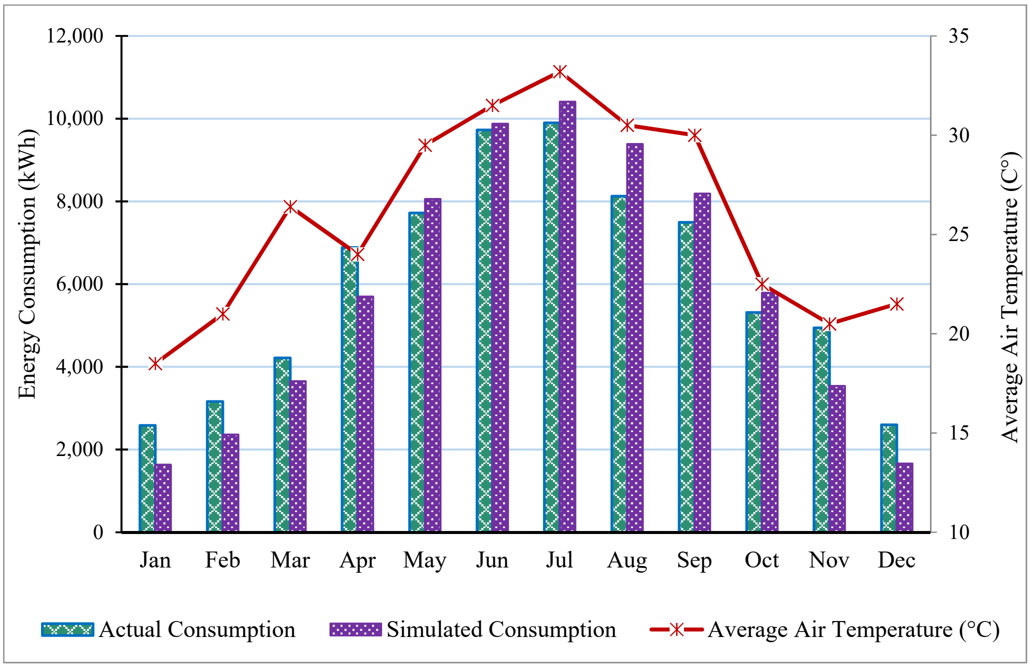

Figure 10. Monthly electricity consumption of the base case and simulated case, along with average ambient temperatures in 2019.

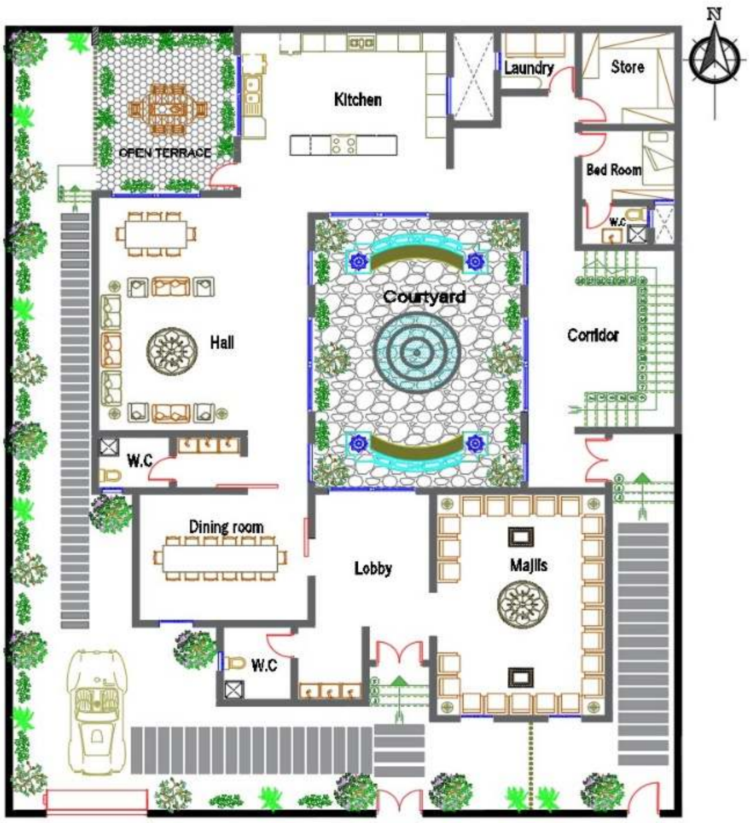

Figure 11. Ground floor of the proposed solution.

Figure 12. First floor of the proposed solution.

Figure 13. North façade.

Figure 14. West facade.

Figure 15. Cross section of courtyard.

Figure 16. First perspective.

4.3. Impact of the Courtyard on Energy Consumption

In this section, a courtyard is incorporated into the building design to provide a buffer zone for indoor temperature regulation. Various forms of courtyards with distinctive features can be implemented to address the particular climatic constraints of a given case [47]. When temperature regulation to enhance thermal comfort is the main objective, features such as self-shading by structures or plantations, openings according to wind direction to enhance natural ventilation, and water bodies are incorporated. It has been found that the optimal courtyard shape is square with slight elongation (3:2) [48]. Figure 17 shows the geometric dimensions of the proposed courtyard.

Figure 17. Geometric dimensions of the courtyard.

The courtyard is surrounded by living rooms and bedrooms arranged with large windows that overlook the courtyard. This arrangement allows cool air to flow through the building to each room in the villa. On days when the interior windows are closed, coolness is maintained inside the rooms. The courtyard is usually planted with trees, flowers, and shrubs to additionally shade the spaces without mechanical cooling systems, providing a comfortable environment through the seasonal use of the courtyard. In this study, the courtyard is in the center of the building, with a total area of 52 m^2. The dimensions of the courtyard are 8.50 m, 6.10 m, and 7.80 m in length, width, and height, respectively. The total outdoor window-to-wall ratio (WWR) is 2.93%. To validate the model, including the courtyard, the energy consumption of the simulated cases (i.e., the simulated BC with and without the courtyard concept) was compared. The annual energy efficiency indices (EEI) were 141.33 and 128.41 kWh/m^2/year for the BC with and without a courtyard, respectively. The annual energy consumption in the villa with a courtyard-based design was reduced by 9.14% relative to the traditional villa BC.

4.4. Impact of Thermal Wall Insulation

Thermal insulation techniques in exterior building walls are among main ways to reduce energy consumption. The focus of the present study was application of thermal insulation layers to external walls. The energy performance was evaluated using the optimum insulation thickness that conforms to Saudi Building Code SBC-602 based on the U value. The code recommends a value of 0.342 W/m^2 K to be used in external insulated walls in the Najran region [49]. According to the literature and by adjusting the outer wall layers, we added an insulating layer (EPS). We first determined the optimum thickness of the thermal insulation using DesignBuilder software to evaluate the most appropriate location of insulation in external walls with an optimum thickness of 0.1 m. The results showed that the total annual energy consumption of the proposed design was 60,721 kWh/year, with a BEI of 120.96 kWh/m^2/year. Therefore, case #2, as shown in Table 4, results in a 14.41% reduction in energy consumption.

4.5. Impact of Thermal Insulation on the Roof

This case focuses on applying thermal insulation layers to the external roof, along with the previously described application of thermal insulation to the external walls. The energy performance was evaluated using the optimum insulation thickness that conforms to Saudi Building Code SBC-602 based on the U value. The code recommends a value of 0.202 W/m^2 K to be used in external insulated walls in the Najran region [49]. According to the literature and by adjusting the outer roof layers, we added extruded polystyrene (XPS) insulation with a thickness of 0.16 m. The results showed that the total annual energy consumption of the proposed design was 55,792.3 kWh/year, with a BEI of 111.14 kWh/m^2/year, representing a decrease of about 21.36%.

4.6. Impact of Window Glazing

The effect of window glazing helps to reduce the penetration of solar energy, resulting in a decrease in temperature, which allows for improved thermal performance of the building envelope. Accordingly, the energy performance was evaluated using a double-glazed layer with an ideal thickness satisfying Saudi Building Code SBC-602 requirements based on the U value. The description of proposed case #4 is shown in Table 4. Saudi Building Code 602 recommends a U value of 2.668 w/m^2 K to be applied in residential window glazing for the Najran region [49]. The results showed that the total annual energy consumption of the proposed design is 62,639.6 kWh/year, with a BEI of 124.78 kWh/m^2/year. Therefore, reduction of 11.71% can be achieved by replacing existing single-glazed clear glass with double-glazed windows.

Table 4. Impact of building envelope modification on energy conservation in the courtyard-based villa design.

Code	Description	Wall Layers (from Outside to Inside)	Roof Layers (from Outside to Inside)	Energy Consumption (kWh/m²/Y)	Energy-Saving Potential (%)
BC	BC model without a courtyard	As in the base case (Table 1) (U value = 1.619 W/m^2 K)	As in the base case (Table 1) (U value = 3.644 W/m^2 K)	**141.33**	**0**
Case #1	BC design with courtyard concept	As in the base case (Table 1) (U value = 1.619 W/m^2 K)	As in the base case (Table 1) (U value = 3.644 W/m^2 K)	**128.41**	**9.14%**
Case #2	BC design with courtyard concept and only walls thermally insulated	0.02 m plaster with paint 0.10 m concrete block 0.10 m EPS (expanded polystyrene) 0.10 m concrete block 0.02 m plaster with paint (light) (U value = 0.321 W/m^2 K)	As in the base case (Table 1) (U value = 3.644 W/m^2 K)	**120.96**	**14.41%**
Case #3	BC design with courtyard concept and roof and walls thermally insulated	0.02 m plaster with paint 0.10 m concrete block 0.10 m EPS (expanded polystyrene) 0.10 m concrete block 0.02 m plaster with paint (light) (U value = 0.321 W/m^2 K)	0.02 m terrazzo tiles 0.02 m cement mortar 0.06 m sand for roof levelling 0.16 m XPS (extruded polystyrene) 0.15 m reinforced concrete 0.02 m plaster with paint (light) (U value = 0.202 W/m^2 K)	**111.14**	**21.36%**
Case #4	BC design with courtyard concept And only windows thermally insulated (U value changed from 5.894 to 2.665 W/m^2 K)	As in the base case (Table 1) (U value = 1.619 W/m^2 K)	As in the base case (Table 1) (U value = 3.644 W/m^2 K)	**124.78**	**11.71%**
Case #5	BC design with courtyard concept and compensation strategies	0.02 m plaster with paint 0.10 m concrete block 0.10 m EPS (expanded polystyrene) 0.10 m concrete block 0.02 m plaster with paint (light) (U value = 0.321 W/m^2 K) Double glazing with a U value of 2.665 W/m^2 K	0.02 m terrazzo tiles 0.02 m cement mortar 0.06 m sand for roof levelling 0.16 m XPS (extruded polystyrene) 0.15 m reinforced concrete 0.02 m plaster with paint (light) (U value = 0.202 W/m^2 K)	**94.97**	**32.80%**

4.7. Impact of Different Strategies

The final set of simulations consists of optimal passive design strategies in one scenario. The main purpose of the combination is to evaluate the improvements in energy consumption of insulated building envelopes with a courtyard-based villa design relative to the base case. The combination case consists of walls and roof insulation, as well as double-glazed windows, according to the SBC-602 energy code, as illustrated in case #5 in Table 4. Figure 18 shows a comparison of monthly energy consumption between the base case and the combined case. Results indicate that a significant reduction in energy consumption of approximately 32.80% is achieved in the combined case. Considering that there are more than 5.5 million houses in the KSA, to enhance energy efficiency and increase the privacy of residents, it is essential to apply a combination of passive design strategies and courtyard concepts, reducing the need for mechanical systems and, therefore, energy demand throughout the country.

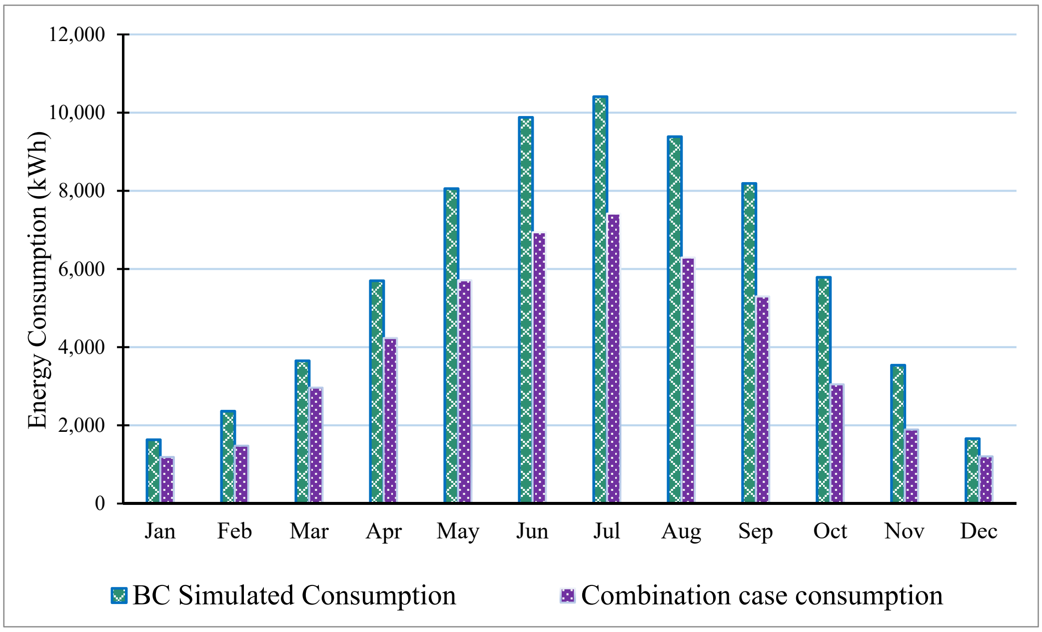

Figure 18. Comparison of the energy consumption of the base case and the combination case.

5. Conclusions

The aim of this project was to investigate the courtyard concept as a sustainable building design approach to provide a comfortable conditions in Saudi villas in Najran. An analytical approach was used to assess the proposed solution with four strategies in terms of building envelope modifications, including changing the building form by adding a courtyard, adding a thermal insulation layer to the roof and walls separately, replacing the window glazing, and integrating all these strategies in a single case. Modifications were selected according to the recommendations of Saudi Building Energy Consumption Code 602. The results of the analysis and simulation showed that the presence of a courtyard in residential buildings has a significant impact on energy consumption. Based on the analyses of the results of this research, the following conclusions and recommendations can be made with respect to energy-efficient design of existing homes, as well as for newly designed or constructed villas under Saudi climate conditions:

- The courtyard plays a major role in providing a suitable environment for the comfort of the users in terms of the environmental conditions and reduction in energy consumption. The courtyard in residential buildings occupies an intermediate position between the elements of the building, with the primary design consideration of providing privacy.
- The proposed villa design satisfies the lifestyle needs of the average Saudi family in terms of functional design of the spaces, provision of privacy, and achieved a reduction in energy consumption of 32.80%. In addition, the proposed solution considers the current and future requirements of Saudi families.
- A building proposal was approved to study four implications of changing some of the building envelope components.
- The proposed configuration with a courtyard concept reduces the area of externally glazed windows so that the building's spaces facilitate illumination and ventilation through large openings towards the courtyard. This reduces the exposure of the

window openings to direct solar radiation. The results showed that the courtyard, with reduced WWR from 10% to 2.93%, results in a 9.14% reduction in energy consumption.

- Adding a thermal insulation layer (expanded polystyrene) to the center of the external walls reduces energy consumption by 14.41%
- Compared to the wall insulation, adding a thermal insulation layer (extruded polystyrene) to the roof significantly reduced annual energy consumption by as much as 21.36%.
- The most common type of glass for windows in residential buildings is single clear 6 mm panes, whereas in the proposed design, double-glazed clear 6 mm/13 mm glass was applied. This alternative results in a reduction of about 11.71% in energy consumption.
- The combination of different passive design strategies used in this research contributes significantly a reduction in annual energy consumption of 32.80%.
- Appropriate design of the building envelope contributes to improvement in the thermal performance of residential buildings. Therefore, appropriate design of the building envelope and proper selection of envelope components are highly recommended.

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