Journal of
Engineering Sciences
Faculty of Engineering
Assiut University

مجلة
العلوم الهندسية
كلية الهندسة
جامعة أسيوط

journal homepage: http://jesaun.journals.ekb.eg

Cooling Load Reduction in Courtyard Houses: Examining the Role of Courtyard Configuration in a Hot, Arid Climate

Received 28 June 2024; Revised 16 September 2024; Accepted 16 September 2024

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Keywords
Courtyard, Energy Efficiency, Orientation, Plan Aspect Ratio, Simulation.

Abstract: The hot, arid climate of the Qassim region in Saudi Arabia poses significant challenges for energy-efficient building design, especially in terms of passive cooling strategies. Courtyards, a traditional architectural element, offer potential for improving thermal performance in such climates. However, the impact of courtyard plan aspect ratio and orientation on energy consumption in semi-detached houses remains understudied. This research addresses this gap by investigating the thermal behavior of U-shaped courtyards in arid climates through IES<VE> simulations. The study aims to assess the influence of different courtyard shapes (square and rectangular) and orientations (north, east, west, and south) on cooling loads in adjacent spaces. Two semi-detached house configurations, each featuring either a square or rectangular U-shaped courtyard, were modeled and analyzed. The findings indicate that square courtyards perform better than rectangular ones, reducing cooling loads during summer months. South-facing courtyards exhibited the highest energy consumption due to prolonged solar exposure, while west-facing courtyards had the lowest cooling loads. Furthermore, the results show that the internal zoning of rooms adjacent to the courtyard should be strategically planned based on thermal performance, as specific zones experienced varying cooling demands depending on courtyard shape and orientation. In conclusion, optimizing courtyard design, including plan aspect ratio and orientation, can significantly enhance energy efficiency and thermal comfort in arid climates. These insights provide architects with practical guidelines for designing more sustainable and energy-efficient courtyard houses. Future research could explore the integration of social and environmental aspects, as well as the impact of natural light on adjacent spaces.

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https://doi.org/10.21608/jesaun.2024.299960.1346

1. Introduction

The Qassim region in Saudi Arabia has a hot, arid climate during the summer season, and for most of the year, the outdoor temperature is above 40°C (Fig. 1) [1][2], thus, requiring careful consideration of building design to maximize energy efficiency. A desert climate has two extremes of arid weather conditions, hot during summer and cold during winter. This makes passive design strategies quite challenging. The Qassim region is located in the middle of the desert area of Saudi Arabia and architects and designers have highlighted the difficulty of developing a passive design in this area. Buildings often develop overheating as a result of solar radiation penetrating through the building's envelope. To address this issue, numerous design elements can be considered during the initial stages of building design to adopt a passive approach for reducing cooling or heating loads. Among these design elements, courtyards hold great potential for enhancing energy efficiency in a wide range of climates, including hot, arid regions.

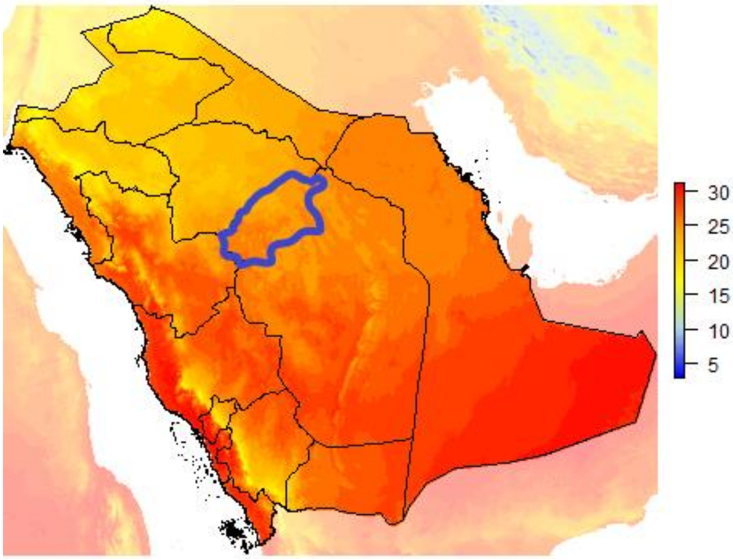

Fig 1. The average annual temperature of Saudi Arabia and the Qassim region (with blue border) adapted from [3].

Courtyards offer several advantages in terms of energy saving. By strategically integrating courtyards into building designs, solar heat gain can be controlled and mitigated. The open space of a courtyard acts as a buffer zone, creating a microclimate that helps regulate temperatures within the surrounding areas. The layout and orientation of the courtyard, along with the design of its surrounding walls and shading elements, contribute to the reduction of solar heat gain and the promotion of natural ventilation. This passive approach harnesses the power of natural elements to minimize the need for mechanical cooling systems, resulting in energy savings and a more sustainable built environment. Courtyard houses, characterized by a central open space surrounded by residential quarters, have been a prominent and enduring housing design across diverse cultures and climates. As seen in Fig 2, traditional courtyard dwellings can be found in regions ranging from the Far East to the Mediterranean [4]. They have played a significant role in shaping the built environment and providing habitable spaces in hot and warm climates throughout history [5].

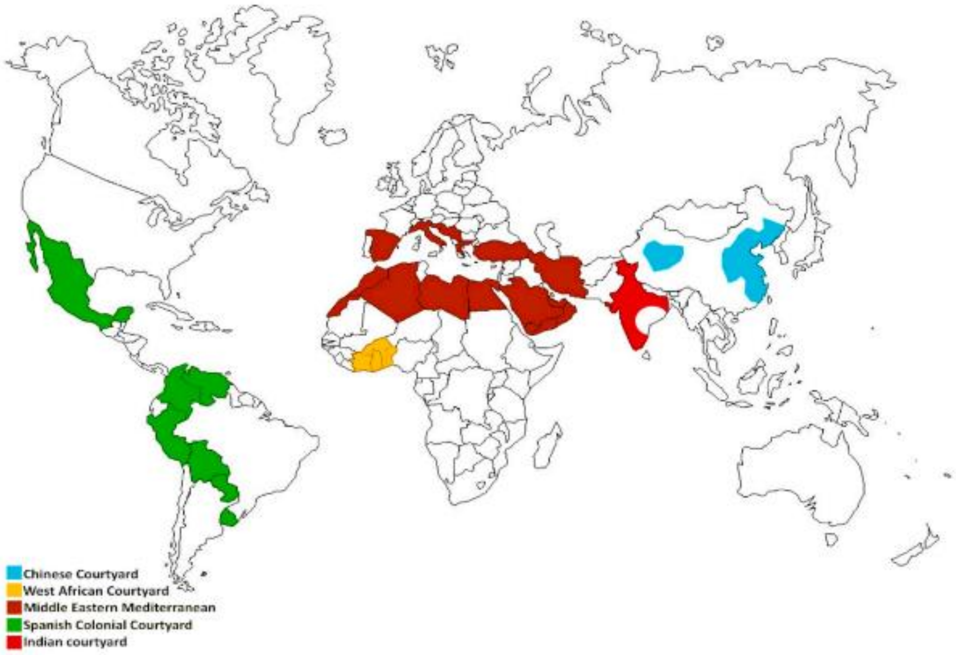

Fig 2. Global presence of courtyard houses [4].

Proper utilization of space and orientation of the courtyard are crucial elements in ensuring privacy and energy efficiency in design. Considering the traditional Saudi house, the concept of a courtyard was widely embraced as it effectively met their social and religious requirements, particularly the need for privacy. The courtyard layout also provided environmental advantages; hence, incorporating environmental sustainability into the design of Saudi houses is essential, as exemplified in the design of the courtyard. In Fig 3, which portrays an old neighborhood in Riyadh, it is evident that every house featured a courtyard. It is preferable for the courtyard to be inward-facing rather than facing the main street. In traditional housing designs, privacy is achieved through various features such as tall roofs, strategic arrangement of doors and entries, and window placement.

Fig 3: Courtyard house as main element space in an old neighborhood in Riyadh [6].

There are different kinds of courtyards, which provide enclosed spaces in buildings, clusters, or cities that ensure privacy, have social benefits, and meet the microclimate requirements of the people [7]. The importance of courtyards arises from their placement in the center of buildings and urban settings, which are considered the focal points of those buildings. Arcades and colonnades are examples of design variations which are used to create shade, which increases both thermal comfort inside the courtyard and visual pleasure. As a result of this integration, the residents not only experience better physical health, but also improved interpersonal relationships, work efficiency, balance between work and life, and quality of life in general [8]. Based on the findings of studies conducted by a number of researchers [9], [10], [11], [12], it can be concluded that a courtyard has a significant impact on thermal, visual, and acoustic design aspects, while also offering a private space for social interaction. Courtyards can be designed and arranged in a way that creates a sense of comfort, shields occupants from external noise, and encourages them to interact with others in order to create an environment that is engaging and relaxing. There is evidence that careful consideration of courtyard design and layout can maximize their potential benefits in terms of both environmental sustainability and human well-being, which can decrease environmental degradation.

The plan aspect ratio of the courtyard plays a significant role in determining the amount of solar radiation received and the areas of shade formed on the facades of the courtyard. This, in turn, strongly influences the energy demand for cooling the house. In a hot, arid climate, it is more important to minimize solar radiation gain during summer than to maximize it during winter. The annual energy demand increases as the length of the courtyard increases. Utilizing computational fluid dynamics, Yasa & Ok [13] analyzed the potential energy savings of seven different types of courtyard forms. The findings revealed that the ideal aspect ratio for courtyards with minimal summer sunshine was (1) in dry, hot, and humid areas, and (3) in cold regions. Additionally, the plan aspect ratio for courtyards with the highest solar energy harvest during winter was (5) in dry, hot, and humid areas, and (3) in cold regions. Based on comfort and energy gain indicators, courtyards with a square aspect ratio were found to be the most suitable choice for all three climatic regions in terms of heat gain.

Previous studies have found that reducing the courtyard plan aspect ratio can result in a higher shading index in dry, hot climates where the aspect ratio is smaller [14]. In view of this, a square courtyard provides better shading than a rectangular courtyard [15]. Additionally, shallow circular courtyards can effectively shade the walls during summer and receive ample sunlight during winter because they have a high perimeter to height (P/H) value. It has been suggested by Hassan & Lee [16] that circular underground courtyards with wind catchers have the advantage of reducing the volume and surface volume ratio while simultaneously identifying and resolving the discrepancy between the plane's orientation and its shape. A similar conclusion was made by Rodríguez-Algeciras et al. [17], who stated that square courtyards are more energy-efficient than rectangular courtyards, where, in comparison to its rectangular counterpart, the square courtyard absorbs less solar radiation. Historically, the orientation of courtyards within buildings mainly depended on the direction of the street adjacent to a building [18]. However, it has been proven that orientation plays an important role in improving the thermal conditions within courtyards [14]. Accordingly, many variables can affect the thermal conditions within a courtyard, including sun direction, wind direction, shading, and solar gain; thus, the parameters described above can be beneficial for optimal orientation of a courtyard [19], [20].

Reviewing related studies on orientation, Berkovic et al. [21] and Meir et al [22] compared rectangular courtyards facing North-South (N-S) and East-West (E-W) respectively. They concluded that courtyards with the central axis-oriented N-S had the highest shading during summer, creating the most thermally comfortable spaces. Similar outcomes were described by [23], [24]. Almhafdy et al. [25] suggested that the orientation of courtyards can significantly affect their microclimatic characteristics. Based on a two-day simulation analysis conducted during the hottest month, it was found that west-facing (W) courtyards exhibited the poorest microclimatic performance, followed by east-facing (E) courtyards, probably because the length of the courtyard coincides with these two directions and aligns with the path of the sun from east to west. Conversely, courtyards oriented towards the north (N) and south (S) experienced lower air temperatures compared to other orientations.
This paper draws attention to a courtyard house and its role as a cooling load mitigator during summer, particularly in the context of hot, arid climates. Many studies have been done on courtyard design; however, numerous aspects still need to be taken into consideration. Consequently, a simulation analysis of a courtyard house in an arid climate was performed in this paper.

2. Methods and tools

The two main methodological approaches used in the paper are described below.

2.1 Modeling Approach

A semi-detached house is selected in Buraydah city, Qassim region; therefore, two semi-detached houses were generated using IES<VE>, one with a square U-shaped courtyard and the other with a rectangular U-shaped courtyard. As illustrated in **Error! Reference source not found.**, both courtyards featured the same indoor area for energy analysis and compression.

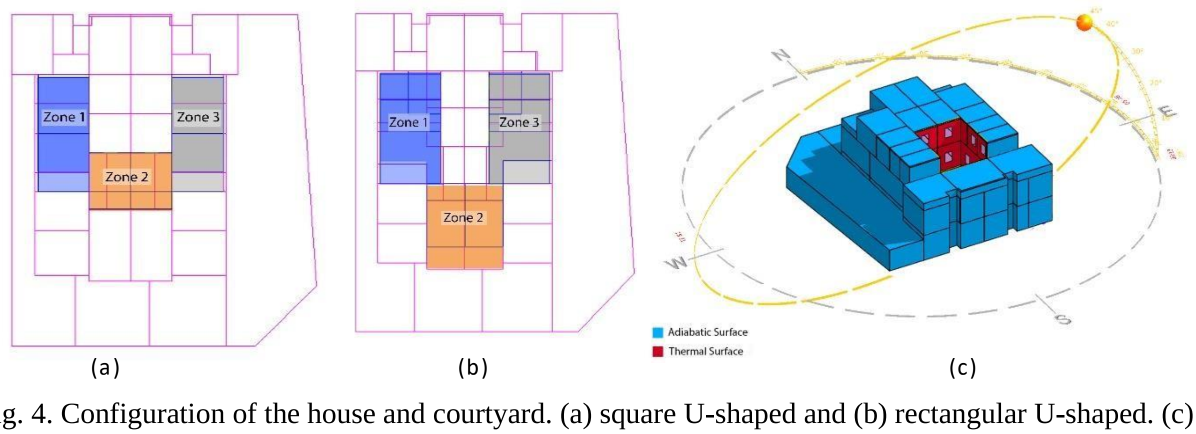

Fig. 4. Configuration of the house and courtyard. (a) square U-shaped and (b) rectangular U-shaped. (c)

Moreover, as shown in Fig 4 (c), all surfaces of the building envelope were considered adiabatic elements except for the courtyard's internal façade. This was consciously set to ensure that the energy consumption (cooling load) results were precise and justifiable. Only spaces facing the courtyard were included in the analysis.

2.2 Analysis

The adjacent zones facing the courtyard directly were investigated using the cooling load needed during the summer months (Table 1).

Table 1. Areas of the zones for each courtyard.

	Square		Rectangle	
	area	volume	area	volume
Zone1	72	245	72	245
Zone2	52	173	52	173
Zone3	72	245	72	245

The results for analysing and comparing the square courtyard with the rectangular were normalized based on MWh/m^2. The results are also given in terms of min, max and the summed total in the graphs.

2.1.1 Plan aspect ratio

In this paper, square and rectangular courtyards were selected for assessment. Although the length and width of the two courtyards are different, the indoor area of the adjacent zones are the same.

2.2.2 Orientation

Orientations of 0, 90,180, and 270 degrees are considered in this study. The courtyard has a U-shape with the open side of the U facing the intended orientation. Moreover, as the energy performance is an indicator of the thermal performance in the internal environment of the zones adjacent to the courtyard, in this simulation, the internal environment was modelled as fully air conditioned at a constant set temperature of 22°C.

3. Findings and Discussion

Error! Reference source not found. presents the overall energy consumption of the cooling load of the two courtyards with combined zones subjected to the energy assessment. The square courtyard recorded a lower energy cooling load compared with the rectangular courtyard during the hottest months (**Error! Reference source not found.**). Moreover, the south orientation of the square courtyard had the highest cooling load because of the longer exposure of the internal façade of the courtyard to the sun's rays during the summer.

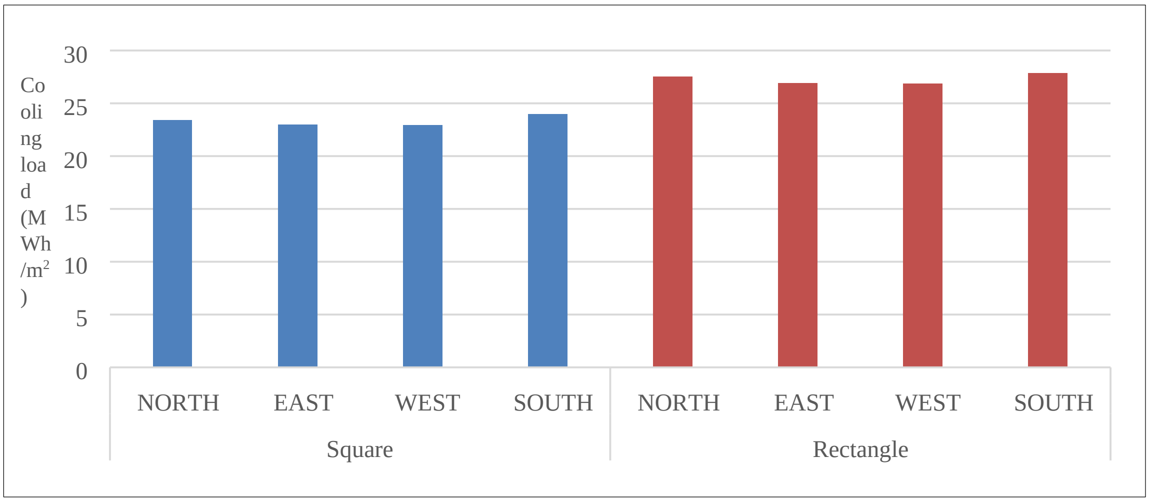

Fig. 5. Simulated overall energy consumption based on the plan aspect ratio and orientation.

As shown in Table 2, the west orientation had the lowest energy cooling load, followed by east, north, and south with both the square and rectangular courtyard configurations. The reason is that the courtyard orientation plays a significant role in the cooling load because of the exposed surfaces of the internal façade of the courtyard. The house courtyard and configuration for zone 2 has the shortest façade compared to zones 1 and 3 (**Error! Reference source not found.**).

Table 2. The overall energy consumption based on the plan aspect ratio and orientation

	Square				**Rectangle**			
Orientation	**North**	**East**	**west**	**South**	**North**	**East**	**west**	**South**
Cooling load (MWh)	23.4137	22.9782 22.9054		23.9884	27.5155	26.903	26.8563	27.876

3.1 Plan aspect ratio

The overall plan aspect ratio and orientation have been explained earlier; however, for a deeper analysis, the investigation in this section was based on the zone areas rather than within the square or rectangular courtyard configuration itself (**Error! Reference source not found.**. 6). Based on the simulation results, it is evident that zone 2 performed the worst in the square courtyard configuration, specifically in the west and east orientations. In the rectangular courtyard, however, zone 2 performed the best, primarily when the courtyard was oriented to the north direction. The explanation for this is that the internal façade of zone 2 in the square courtyard has more extended surface exposed to solar radiation than zone 2 in the rectangular courtyard. Within the square courtyard itself, the exposure to solar radiation was even greater than zone 1 and 3, in the east and west orientation.

For clarification, **Error! Reference source not found.** shows the cooling load in the square and rectangular courtyards with orientation to the north. It is apparent that the square courtyard performed better than the rectangular courtyard with a reduction of 4.1 MWh/m^2. However, when the results were analyzed according to each zone separately for calculating the cooling load (**Error! Reference source not found.**), the rectangular courtyard performed better than the square in zone 2 only, while zone 1 and zone 3 showed less cooling load in the square courtyard with a reduction of 0.027 and 0.028 MWh/m^2, respectively.

Fig. 6. Cooling load comparison based on the zones adjacent to the courtyard after data normalization (MWh/m2)

Fig. 7. Cooling load comparison between square and rectangle when oriented to the north after data normalization (MWh/m2)

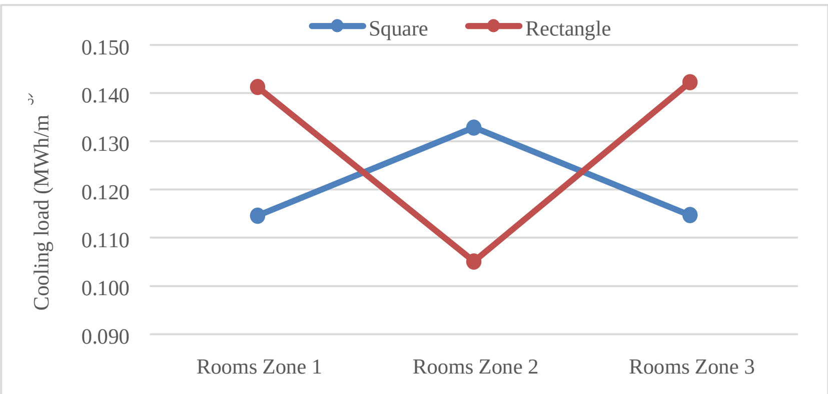

Fig. 8. Cooling load comparison between square and rectangular courtyards according to the zones after data normalization (MWh/m2).

3.2 Orientation

As shown in **Error! Reference source not found.**, the square courtyard acquits better than the rectangular configuration during the summer season. However, the adjacent courtyard rooms should be analyzed separately. This helps architects and designers to identify the best location for a particular function or use of the rooms. For example, zone 1 in the rectangular courtyard performed the worst when the courtyard was oriented to the south. Therefore, spaces like kitchen, bathroom, or storage, which usually do not need much cooling, should be allocated to zone 1. On the other hand, if the rectangular courtyard was oriented to the west, it performed the best, and spaces like the living room, bedrooms, and office should be placed in zone 1. Zone 2 performed best in a north orientation with a rectangular courtyard. It only consumed 0.105 MWh/m^2 during the summer. While in the east and west orientations, it consumed 0.129 MWh/m^2 and 0.128 MWh/m^2, respectively.

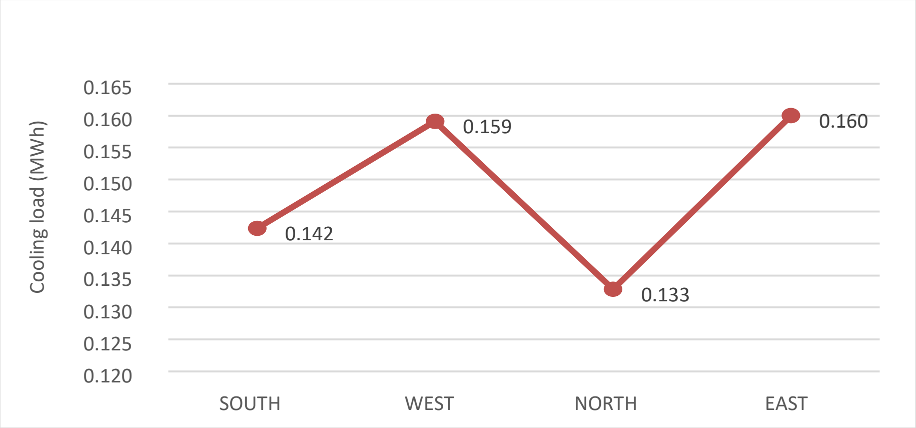

Fig. 9. Cooling load comparison of the different courtyard orientations for zone 2 only and data normalized with (MWh/m2)

As seen in **Error! Reference source not found.**, zone 2 in the square was the best when the courtyard was oriented to the north with a cooling load of 0.133 MWh/m^2 followed by the south orientation with 0.142 MWh/m^2. However, it is still not preferable to assign spaces like the bedroom or living room to zone 2 in this scenario. This is due to the high cooling consumption compared with zones 1 and 3. The internal façade of zone 2 in the square courtyard offers a broader exposure to solar radiation and less shaded areas than zones 1 and 3 and needs more cooling during the summer season.

4. Conclusions

As confirmed by many studies presented in the introduction section, the courtyard has a significant effect on thermal performance and energy consumption in different climates. This paper focuses on a semi-detached house with courtyard located in an arid climate during the summer season. The results showed that the courtyard plan aspect ratio plays an essential role in energy efficiency. The conclusions can be summarized as follows:

- Concerning the overall building in general (regardless of the zoning), a square courtyard performs better than a rectangular one.
- Regarding the zones adjacent to the courtyard (1, 2, and 3), a square courtyard is better than a rectangular courtyard in zones 1 and 3. In contrast, zone 2 shows better energy performance if the courtyard has a rectangular plan aspect ratio.
- In terms of orientation, the overall energy performance of all zones is similar; however, the influence of orientation can be significant if the zoning is taken into consideration.
- Based on the simulation results, the selection of the room function (bedroom, bathroom, or kitchen) should be according to cooling loads, which are determined by the courtyard shape, the plan aspect ratio, and the orientation.

In this study, the courtyard of a semi-detached house was studied. A study on integrating social and environmental aspects could be significant since the courtyard is in the centre of the building. Natural light effects on the adjacent zones could be another challenge worth investigating.

Acknowledgements

The authors express their gratitude to the Department of Architecture and the Deanship of Scientific Research at Qassim University for their support in funding this publication.

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