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Article

Modeling the Role of Courtyards with Clusters of Buildings in Enhancing Sustainable Housing Designs

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Abstract: As urbanization increases, buildings require greater amounts of energy for heating and cooling, thereby necessitating the search for effective solutions. The courtyard is often considered a viable option; however, the limited availability and high cost of land resulting from rapid urbanization hinder its widespread use. Consequently, a courtyard with a cluster of buildings is proposed as a feasible solution to address land scarcity. Nonetheless, further investigation is required to effectively integrate this solution into neighborhood urban planning. This study examines the influence of three variables—courtyard orientation, courtyard size, and the arrangement of buildings around the courtyard—on the provision of cooling and heating for buildings. The research focuses on 216 experimental scenarios simulated using Revit software, which excels in its ability to accurately interpret input data and conduct real-time analysis depending on the variables of the building design. The results were recorded for the facades and ground, and the shaded area was computed for each scenario; following these measurements, the shadow areas on both the facade and ground were converted into percentages. The testing involved a group of buildings surrounding courtyards of four different shapes (square, rectangle, triangle, and circle). This approach aimed to identify the most efficient design for implementation in neighborhood planning contexts. The findings indicate that the shape of the courtyard significantly impacts cooling and heating of buildings. Specifically, the square courtyard is unsuitable for countries with Mediterranean climates, such as Jordan, as it can reduce shade coverage by 30%, leading to higher temperatures. Conversely, employing a rectangular courtyard results in a higher proportion of shadows compared to other shapes. The study further demonstrates the influence of the examined variables on the efficacy of the courtyard in cooling and heating of buildings.

Keywords: cluster of buildings; sustainable housing designs; simulation; courtyard; Jordan

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1. Introduction

Thermal comfort plays a crucial part in human existence, considering that individuals spend the majority of their time in indoor settings [1]. However, the thermal comfort of urban residents is increasingly affected by the impacts of climate change, making living conditions more challenging [2]. Additionally, the emergence of the urban heat island (UHI) phenomenon has posed a significant challenge. High temperatures in urban areas compromise human well-being [3,4] and negatively impact the environment, for example, by increasing energy consumption for summer cooling of buildings [5,6]. This is a critical issue, as climate change is the foremost challenge of the 21st century. The construction sector significantly contributes to this problem, with buildings consuming 34% of the world's energy, surpassing the energy consumption of both the industry and transportation sectors [7].

Some research focuses on enhancing inside comfort by adjusting artificial materials such as glass [8] and radiant cooling floors [9]. Additionally, several factors that might influence thermal comfort in interior spaces have been also found, including CO_2 levels, temperature, ventilation rates, room size, occupant density, and occupancy rates [10]. However, in recent years, particularly over the past decade, there has been growing interest in passive design for heating and ventilation as part of a trend toward sustainable architecture to minimize energy consumption in buildings [11]. Passive cooling strategies refer to environmentally friendly methods that effectively lower indoor temperatures with minimal or no use of electrical power [12]. The courtyard is gaining importance as an effective passive cooling strategy due to its longstanding history and proven ability to create a comfortable atmosphere during the summer [13]. Several studies have investigated the impact of courtyards on cooling energy consumption in buildings. Diz-Mellado et al. [14] found that the design of courtyards in buildings, along with their function as a central space within buildings, significantly impacts the energy required for cooling. Therefore, it is essential to assess their energy requirements. Similarly, Diz-Mellado et al. [15] discovered that courtyards function successfully as a highly effective passive cooling system while also improving energy efficiency by up to 20.5%. Soflaei et al. [7] demonstrated that design variations in courtyards significantly impact the amount of shading. According to Turhan et al. [1], a very pessimistic mood state results in a 7.4% increase in the feeling of heat compared to a neutral mood state. Consequently, very pessimistic and extremely positive situations may impact one's sense of warmth by increasing the feeling of heat. Furthermore, Diz-Mellado et al. [16] highlighted the ability of courtyards to reduce health risks associated with extreme temperatures.

In Jordan, buildings account for the highest percentage of electrical energy consumption, with heating and cooling accounting for about 60% of the energy use in buildings [17]. Consequently, Jordan has initiated more research into the passive cooling of residential buildings through the implementation of courtyards [18–20]. However, providing courtyards for individual residences poses challenges due to high costs and limited land availability. As a solution, urban planning strategies that facilitate the organization of residential structures in a courtyard-centric manner remain feasible. In this context, Fahmy et al. [21] confirmed the necessity of guiding housing neighborhood development in Jordan to promote clustered housing arrangements with courtyards. According to Krier and Rowe [22], grouping houses around a courtyard allows high levels of control over the inner space created, making this spatial housing model well suited for residential use.

The geometry of courtyards is defined in existing literature by considering the aspect ratio [14]. For a cluster of buildings, a courtyard is geometrically defined as an open space partially or completely enclosed on all four sides [23]. However, limited studies have examined the effects of integrating a courtyard into a cluster of buildings. Zhang [24] found that employing a square courtyard among a cluster of buildings could improve warmth in cold places such as Canada. Other studies have only briefly highlighted variables that might influence climate modification within a courtyard with a cluster of buildings. According to Sun [25], a rectangular shape offers superior shade and sun protection compared to a square shape, making it more suitable for sun exposure. Al-Qeeq [26] argued that the arrangement of buildings around a courtyard is crucial in enhancing shade, with buildings along the shorter side providing better shade coverage than those along the longer side.

Courtyards can come in various shapes. Krier and Rowe [22] state that spatial forms and their derivatives can be divided into three main groups: the square, the rectangle, the circle, and the triangle. The orientation of courtyards, especially rectangular ones, can vary. Ntefeh et al. [27] noted two orientations for rectangles: 90 degrees, with the long axis from south to north, and 180 degrees, with the long axis from east to west. Kheirabadi et al. [28] confirmed these orientations and added a third—45 degrees clockwise or counterclockwise (as shown in Figure 1). Taleghani et al. [29] further emphasized that courtyards might present in four distinct spatial orientations: NS, EW, NE-SW, and SE-NW.

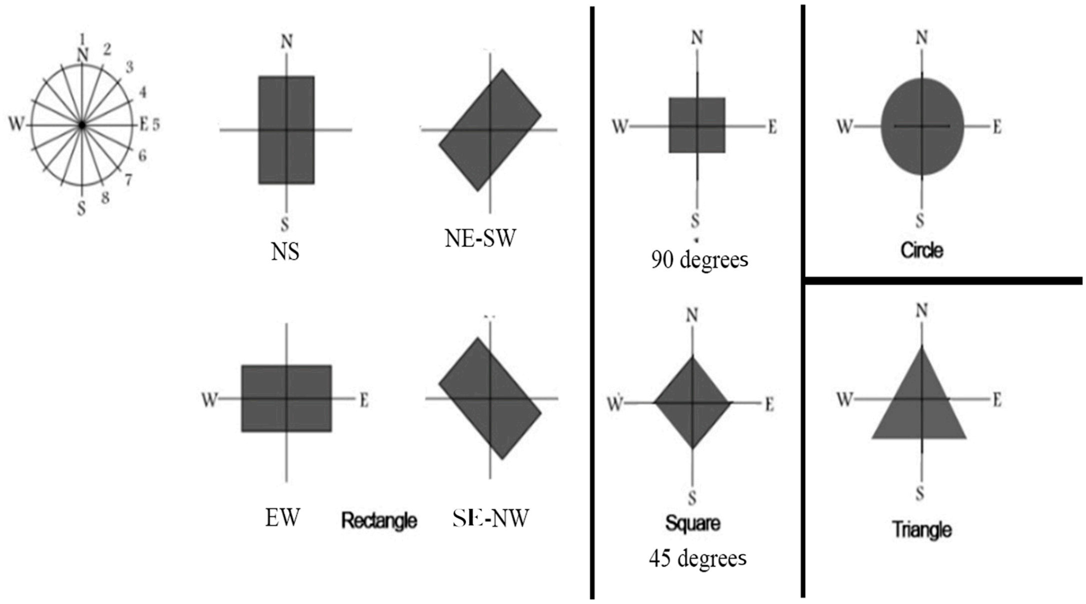


Figure 1. The characteristics of the orientations of courtyards [28]. Modified by the author.

When surrounded by buildings, the minimum and maximum sizes of a courtyard may vary. Gehl [30] provided the maximum and minimum area for courtyards used in housing: 700–1000 sqm, with a minimum length of 20–25 m and a maximum length of 70–100 m. For the smallest size, a rectangular shape should have a 1:2 ratio, while Gehl [30] recommends a 1:1.5 ratio for the largest size [22,27]. According to Al-Qeeq [26], the arrangement of buildings, including the orientation of their facades along the long or short side, can be found in courtyards. In this context, Fahmy et al. [31] confirmed that the arrangement of buildings impacts thermal performance.

The process of shadow calculation is essential for analyzing the impact of courtyard variables on cooling and heating [26]. Calculating shadow dynamics for critical days and hours of the year can be accomplished using specialized software. Several computer programs enable the design of shadows based on latitude, day, and hour for any given year [32,33]. Researchers have employed various programs to measure shadows, including Ecotect, which is no longer available [34]. However, other programs such as AutoCAD, Revit, and 3ds Max are still widely used for shade measurements [35,36].

Given the increasing pressure on land, incorporating a courtyard surrounded by a group of structures has been suggested to mitigate the energy consumption associated with heating and cooling. However, there is a dearth of studies on this subject, hindering its practical implementation in Jordan. The relevance of this research lies in its investigation of the impact of a courtyard within a cluster of buildings on the distribution of shaded and sunny regions. This study examines the influence of three variables: courtyard orientation, courtyard size, and the arrangement of buildings around the courtyard. It focuses on four different courtyard shapes in multi-floor housing areas: rectangle, triangle, circle, and square. The impact of these variables is analyzed at three specific times of day: 8 a.m., 1 p.m., and 6 p.m., during both summer and winter seasons.

In light of the growing interest in incorporating courtyards into clusters of housing to achieve urban sustainability, this study contributes to the development of an inclusive model that measures the impact of courtyard shape, orientation, and size on the amount of shade. This model is not only applicable in Jordan but can also be implemented worldwide, assisting designers globally in selecting the optimum shape and design.

2. Materials and Methods

In this study, a quantitative method was employed using Revit to achieve the primary research objective, as illustrated in the research design (Figure 2). Autodesk Revit is a cloud-based program that utilizes Autodesk Green Structure Studio to provide an energy simulation service. It is designed to help sustainable design and streamline the analysis process for any building [37]. Revit is a highly advanced and capable program that excels in its ability to accurately interpret input data and conduct real-time analysis depending on the variables of the building design. Autodesk Revit 2023 software accurately determines the precise position of the sun relative to the structure at any given moment and from any specified location. It is an interactive depiction. However, that starts to provide dynamic information. Moreover, technical advancements may ultimately result in an unlimited array of reliable images that may be used to replicate research findings, beyond the restricted graphics offered by existing applications [38]. Using Revit software, a person can make a 3D model and determine the shadow path based on the geographical situation of the building. At different times of the day, the shadow shapes move around. The problem with this program is that the prospective user needs to be trained and know a great deal about it [39]. Revit implementation provides quantitative data about the percentage of shading. These data can be used to carry out a quantitative study comparing various cases.

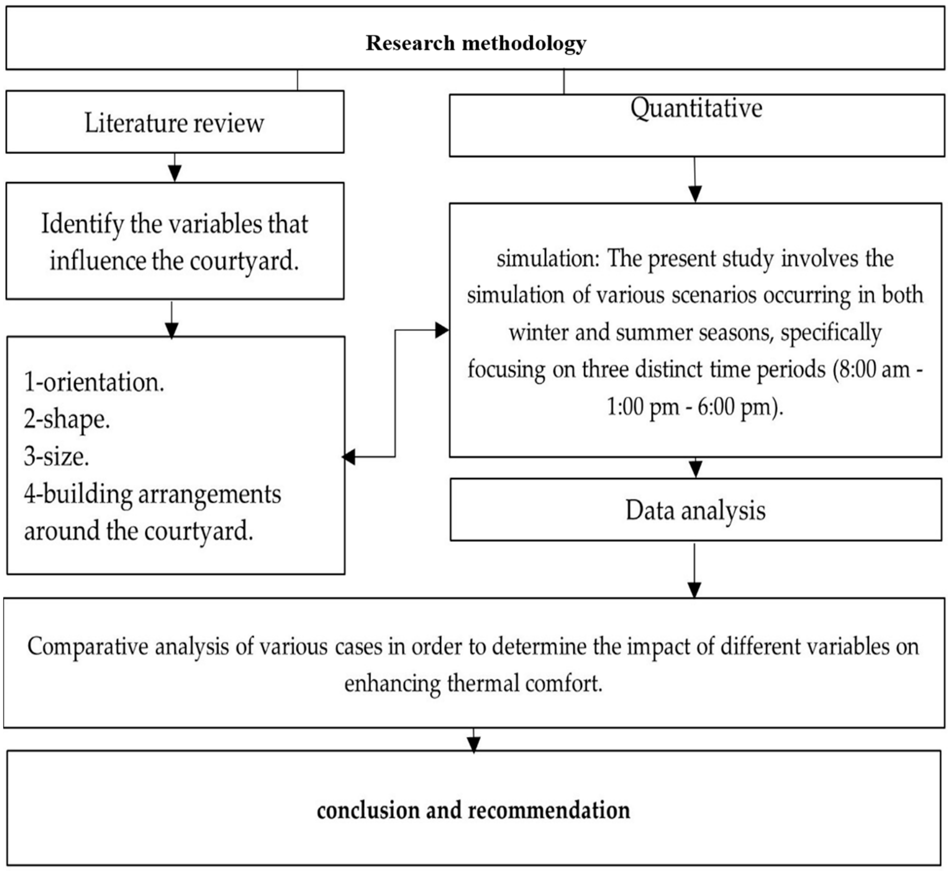


Figure 2. Research methodology.

To assess the impact of various variables on the courtyard, a shade analysis was conducted following these steps:

Location Specification: Detailed location information was provided, using the following coordinates for Jordan: latitude 31.951568603515 and longitude 35.923961639404. The weather station used was 1257552. Jordan has a diverse variety of climates, including a Mediterranean climate and a desert environment. The study case's coordinates fit with a Mediterranean climate [40].

Date and Time Determination:

The dates of the study were set for the winter solstice (21 December) and the summer solstice (21 June).

The hours selected for analysis were 8:00 a.m., 1:00 p.m., and 6:00 p.m. to study all sun incidence angles on the building.

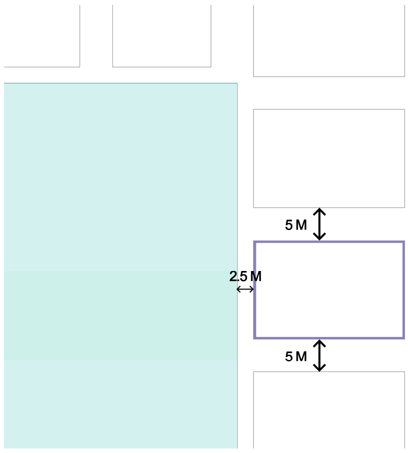
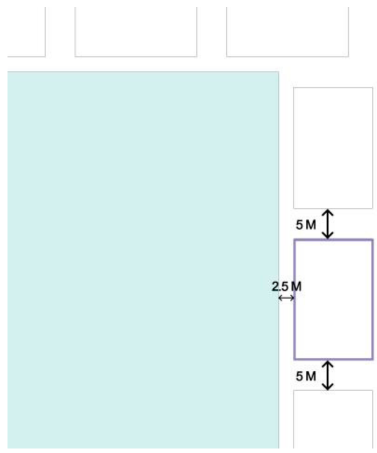
Variable Identification:

The four main variables studied were the shape, orientation, size (maximum and minimum), and building arrangement around the courtyard.

Four courtyard shapes were evaluated: square, rectangle, triangle, and circle. Each shape had different orientations. For the square, two orientations were analyzed (90 and 45 degrees), and for the rectangle, four orientations were considered (NS, EW, NE-SW, SE-NW). Figure 2 displays the orientation of the different courtyard shapes.

Regarding building arrangements, two potential configurations were examined: buildings arranged with either the long facade or the short facade facing the courtyard, as shown in Table 1. For each scenario, two courtyard sizes were selected: the smallest size, 800 square meters, and the largest size, 7000 square meters.

Table 1. Building types.

	
Type 1 building's front is the short side	Type 2 building's front is the long side

Simulation of Courtyard Conditions

The third step involved simulating the conditions using Revit. A total of 216 conditions were simulated, meticulously recording visual representations of the facades and ground and computing the shaded area for each scenario. Following these measurements, the shadow areas on both the facades and the ground were converted into percentages by dividing the shadow area by the total surface area.

The study had two steps, both of which were contingent upon the shading ratios present on both the buildings and the ground.

During the first phase, a comprehensive analysis was conducted, first between each pair of forms and then among all the forms, to determine which of the different situations might provide the greatest degree of shading for both the buildings and the ground. Comparisons between examples were made by evaluating the shading percentage derived from Revit.

In the second step, an analysis was conducted to find the variables that have the most significant influence on enhancing shading or lighting. This analysis involved dividing the cases depending on the variables for each form and calculating the average value of each variable. They were examined using quantitative methods to determine whether one had a more significant influence than the others on buildings.

3. Analysis of Building Shapes and Variables

The variables derived from the literature review, including shape, orientation, courtyard size, and building arrangement around the courtyard, were analyzed at three different times of day (8 a.m., 1 p.m., and 6 p.m.) in Jordan. This analysis was conducted to determine the effect of these variables at different times of the day in both summer and winter.

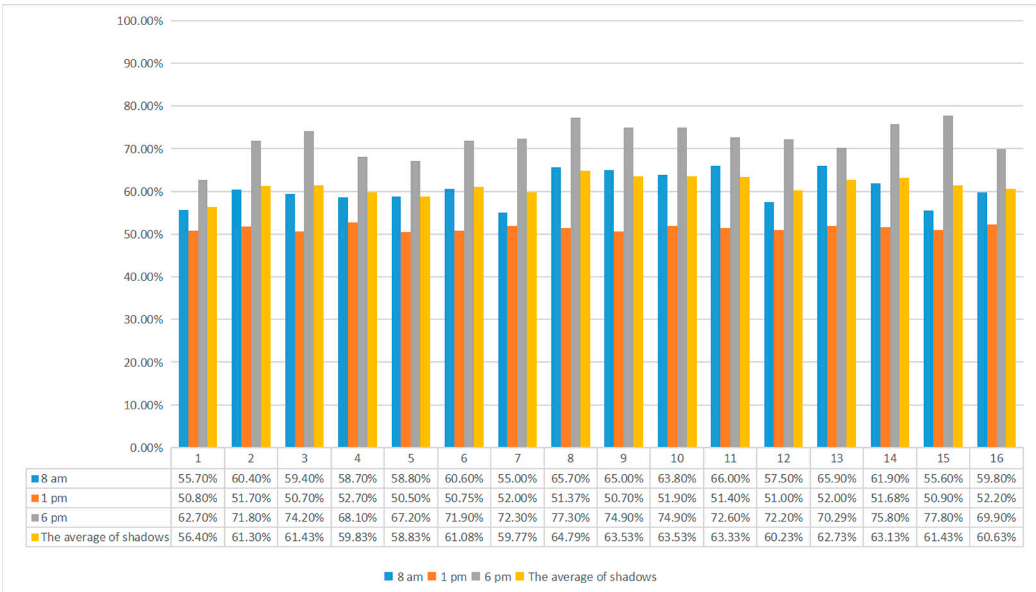
3.1. Rectangular Shape

Sixteen courtyards were simulated: eight with the minimum courtyard size and eight with the maximum courtyard size. Each size included two different building arrangements around the courtyard: each building's front was on either its long side (Type 2) or its short side (Type 1), as indicated in Table 1. All courtyards were simulated with four different orientations—90 degrees from north to south, 180 degrees from east to west, 45 degrees from southeast to northwest, and 45 degrees from southwest to northeast—at 8 a.m., 1 p.m., and 6 p.m., in both summer and winter.

3.1.1. Shade on Building Facades

Summer Conditions:

8 a.m.: The optimum condition for the greatest sun exposure on the building facades at 8 a.m. is when the maximum courtyard size is used, oriented north to south with each building's front on its long side (Type 2). Conversely, the greatest amount of shade at 8 a.m. is achieved with the minimum courtyard size, oriented southwest to northeast with each building's front on its short side (Type 1) (Figure 3).



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
8 am	55.70%	60.40%	59.40%	58.70%	58.80%	60.60%	55.00%	65.70%	65.00%	63.80%	66.00%	57.50%	65.90%	61.90%	55.60%	59.80%
1 pm	50.80%	51.70%	50.70%	52.70%	50.50%	50.75%	52.00%	51.37%	50.70%	51.90%	51.40%	51.00%	52.00%	51.68%	50.90%	52.20%
6 pm	62.70%	71.80%	74.20%	68.10%	67.20%	71.90%	72.30%	77.30%	74.90%	74.90%	72.60%	72.20%	70.29%	75.80%	77.80%	69.90%
The average of shadows	56.40%	61.30%	61.43%	59.83%	58.83%	61.08%	59.77%	64.79%	63.53%	63.53%	63.33%	60.23%	62.73%	63.13%	61.43%	60.63%

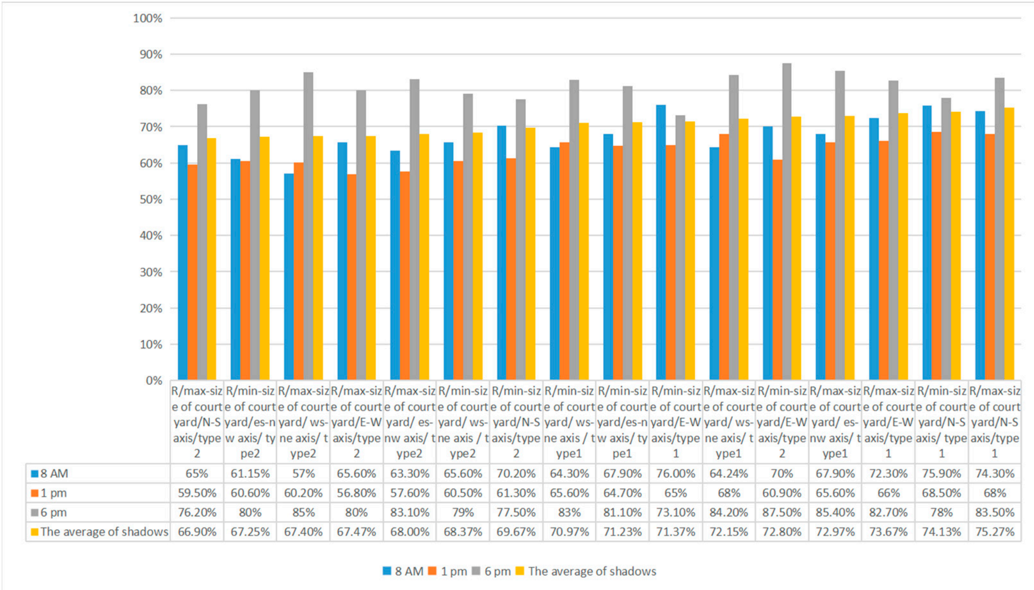
Figure 3. Percentage of shadow coverage on building facades during summer.

1 p.m.: At 1 p.m., the optimum condition for the greatest sun exposure is with the maximum courtyard size, oriented southeast to northwest with each building's front on its long side (Type 2) (Figure 3). The greatest shade is achieved with the minimum courtyard size, oriented west to east with each building's front on its long side (Type 2) (Figure 3).

6 p.m.: The greatest sun exposure at 6 p.m. is achieved with the maximum courtyard size, oriented north to south with each building's front on its long side (Type 2) (Figure 3). The greatest shade is achieved with the minimum courtyard size, oriented north to south with each building's front on its short side (Type 1) (Figure 3).

Winter Conditions:

8 a.m.: The optimum condition for the greatest sun exposure at 8 a.m. in winter differs only in the orientation of the long axis (southwest to northeast at 45 degrees). The greatest shade is achieved with the long axis oriented west to east (Figure 4).



	R/max-size of courtyard/N-S axis/type 2	R/min-size of courtyard/es-nw axis/ type2	R/max-size of courtyard/ ws-ne axis/ type2	R/max-size of courtyard/E-W axis/type 2	R/max-size of courtyard/ es-nw axis/ type2	R/min-size of courtyard/ ws-ne axis / type2	R/min-size of courtyard/N-S axis/type 2	R/min-size of courtyard/ ws-ne axis / type1	R/min-size of courtyard/es-nw axis/ type1	R/min-size of courtyard/E-W axis/type 1	R/max-size of courtyard/ ws-ne axis/ type1	R/min-size of courtyard/E-W axis/type 2	R/max-size of courtyard/ es-nw axis/ type1	R/max-size of courtyard/E-W axis/type 1	R/min-size of courtyard/N-S axis/ type 1	R/max-size of courtyard/N-S axis/type 1
8 AM	65%	61.15%	57%	65.60%	63.30%	65.60%	70.20%	64.30%	67.90%	76.00%	64.24%	70%	67.90%	72.30%	75.90%	74.30%
1 pm	59.50%	60.60%	60.20%	56.80%	57.60%	60.50%	61.30%	65.60%	64.70%	65%	68%	60.90%	65.60%	66%	68.50%	68%
6 pm	76.20%	80%	85%	80%	83.10%	79%	77.50%	83%	81.10%	73.10%	84.20%	87.50%	85.40%	82.70%	78%	83.50%
The average of shadows	66.90%	67.25%	67.40%	67.47%	68.00%	68.37%	69.67%	70.97%	71.23%	71.37%	72.15%	72.80%	72.97%	73.67%	74.13%	75.27%

Figure 4. Percentage of shadow coverage on building facades during winter.

1 p.m.: At 1 p.m. in winter, the optimum condition for sun exposure is with the long axis oriented west to east. The greatest shade is achieved with the long axis oriented south to north with each building's front on its short side (Type 1) (Figure 4).

6 p.m.: The optimum condition for sun exposure at 6 p.m. in winter is with the long axis oriented east to west. The greatest shade is achieved with the long axis oriented north to south with each building's front on its short side (Type 1) (Figure 4).

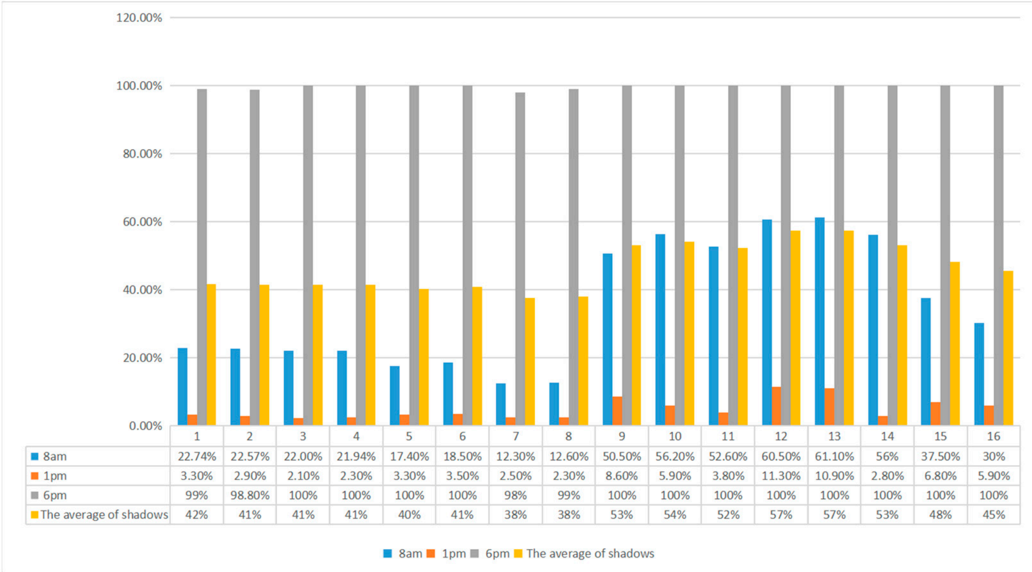
Overall Daily Conditions:

During both summer and winter, the optimum condition for the greatest sun exposure throughout the day is achieved with the maximum courtyard size, oriented north to south with each building's front on its long side (Type 2) (Figures 3 and 4). The greatest amount of shade in summer is achieved with the minimum courtyard size, oriented southwest to northeast with each building's front on its short side (Type 1) (Figure 4). In winter, the greatest shade is achieved with the maximum courtyard size, oriented north to south with each building's front on its short side (Type 1) (Figure 4).

3.1.2. Shade on the Courtyard Ground

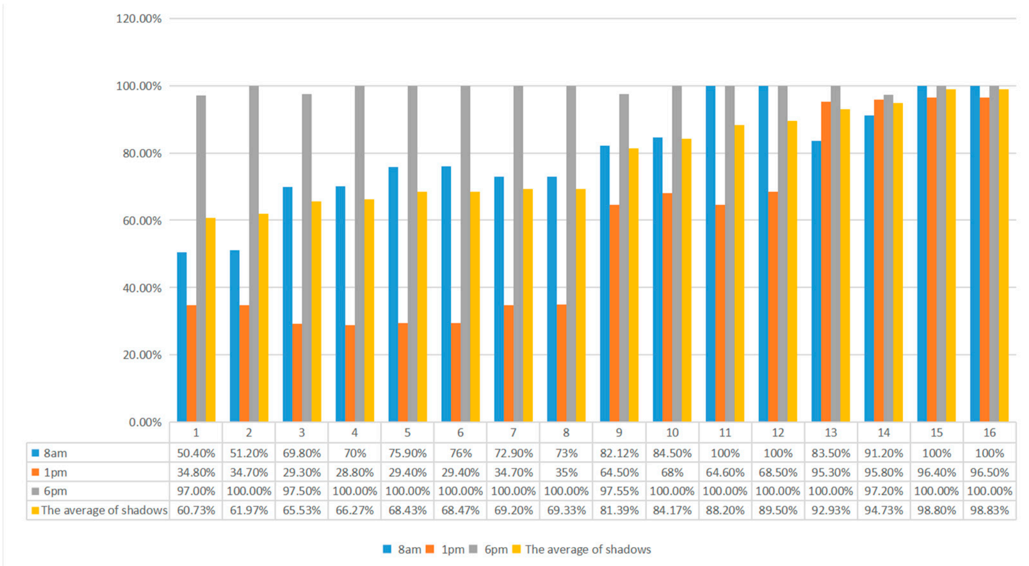
According to Figure 5, the optimum conditions for maximum sun exposure on the courtyard ground at 8 a.m. in summer occur when the maximum courtyard size is used, with its long axis oriented from east to west and each building's front on its short side (Type 1). In winter, the optimum condition for sun exposure at the same time involves the same courtyard size, but with the long axis oriented from southeast to northwest and each building's front on its long side (Type 2) (Figure 6). For the greatest amount of shade on the courtyard ground at 8 a.m. in summer, the minimum courtyard size should be used, with its long axis oriented from southeast to northwest and each building's front on its short side (Type 1) (Figure 5). In winter, the optimum conditions differ in terms of axis orientation, which is from north to south and from east to west (types 1 and 2) (Figure 6).

At 1 p.m. in summer, the optimum conditions for maximum sun exposure on the courtyard ground occur when the maximum courtyard size is used, with its long axis oriented from southeast to northwest and each building's front on its long side (Type 2) (Figure 5). In winter, the optimum condition at 1 p.m. has a slight variation, with each building's front on its short side (Type 1) (Figure 6). For the greatest amount of shade at 1 p.m. in summer, the minimum courtyard size should be used, with its long axis oriented from south to north and each building's front on its short side (Type 1) (Figure 5). In winter, the optimum conditions for shade at 1 p.m. differ only in the long-axis orientation, which should be from east to west (Figure 6).



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
8am	22.74%	22.57%	22.00%	21.94%	17.40%	18.50%	12.30%	12.60%	50.50%	56.20%	52.60%	60.50%	61.10%	56%	37.50%	30%
1pm	3.30%	2.90%	2.10%	2.30%	3.30%	3.50%	2.50%	2.30%	8.60%	5.90%	3.80%	11.30%	10.90%	2.80%	6.80%	5.90%
6pm	99%	98.80%	100%	100%	100%	100%	98%	99%	100%	100%	100%	100%	100%	100%	100%	100%
The average of shadows	42%	41%	41%	41%	40%	41%	38%	38%	53%	54%	52%	57%	57%	53%	48%	45%

Figure 5. Percentage of shadow coverage on ground surfaces during summer.



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
8am	50.40%	51.20%	69.80%	70%	75.90%	76%	72.90%	73%	82.12%	84.50%	100%	100%	83.50%	91.20%	100%	100%
1pm	34.80%	34.70%	29.30%	28.80%	29.40%	29.40%	34.70%	35%	64.50%	68%	64.60%	68.50%	95.30%	95.80%	96.40%	96.50%
6pm	97.00%	100.00%	97.50%	100.00%	100.00%	100.00%	100.00%	100.00%	97.55%	100.00%	100.00%	100.00%	100.00%	97.20%	100.00%	100.00%
The average of shadows	60.73%	61.97%	65.53%	66.27%	68.43%	68.47%	69.20%	69.33%	81.39%	84.17%	88.20%	89.50%	92.93%	94.73%	98.80%	98.83%

Figure 6. Percentage of shadow coverage on ground surfaces during winter.

At 6 p.m. in summer, the optimum conditions for sun exposure on the courtyard ground are achieved with the maximum courtyard size, with its long axis oriented from east to west and each building's front on its short side (Type 1) (Figure 5). In winter, the optimum conditions involve the same courtyard size, but with the long axis oriented from southeast to northwest and each building's front on its long side (Type 2) (Figure 6). Notably, there are multiple optimum conditions for achieving maximum shade on the courtyard ground at 6 p.m. in both summer and winter using both minimum and maximum courtyard sizes (types 1 and 2) as shown in Figures 5 and 6.

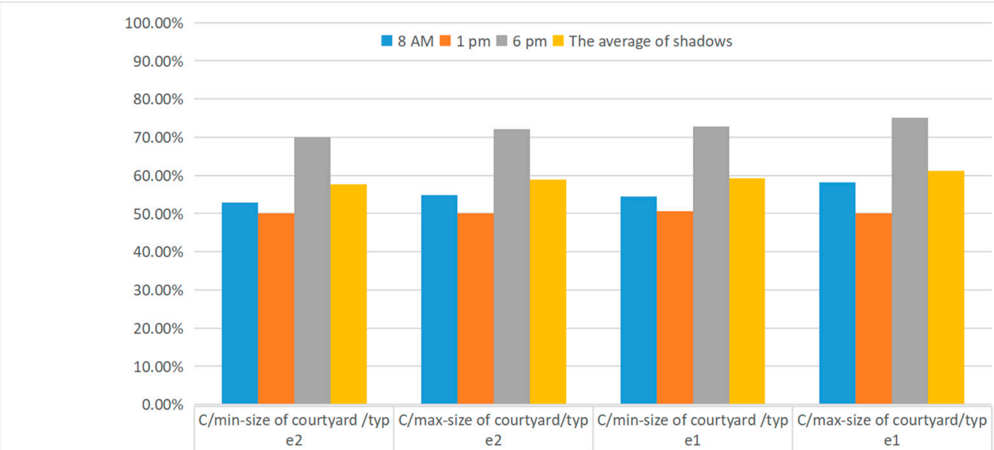
Overall, the optimum conditions for maximum sun exposure on the courtyard ground in summer occur when the maximum courtyard size is used, with its long axis oriented from east to west and each building's front on its short side (Type 1) (Figure 5). In winter, the optimum conditions for sun exposure involve the same courtyard size, but with the long axis oriented from southeast to northwest and each building's front on its long side (Type 2) (Figure 6). For maximum shade on the courtyard ground in summer, the minimum courtyard size should be used, with its long axis oriented from southeast to northwest and each building's front on its short side (Type 1) (Figure 5). In winter, the optimum conditions for maximum shade differ only in the long-axis orientation, which should be from east to west (Figure 6).

3.2. Circle Shape

Four distinct courtyards were simulated, categorized into two groups based on size: minimum and maximum courtyard dimensions. Each size category included two variations in the arrangement of buildings surrounding the courtyard: buildings oriented with their front on its long side (Type 2) and buildings oriented with their front on its short side (Type 1). Simulations were conducted at three different times of the day—8:00 a.m., 1:00 p.m., and 6:00 p.m.—during both the summer and winter seasons.

3.2.1. Shade on the Building Facades

Figures 7 and 8 illustrate that the optimal conditions for maximum sun exposure on building facades at 8:00 a.m., 1:00 p.m., and 6:00 p.m. during both summer and winter occur when the courtyard size is minimized, and the building fronts are on the long side (Type 2). Conversely, the optimal conditions for maximum shade on building facades at 8:00 a.m. and 6:00 p.m. in summer, as well as at 1:00 p.m. and 6:00 p.m. in winter, are achieved when the courtyard size is maximized, and the building fronts are on the short side (Type 1). However, at 1:00 p.m. in summer and at 8:00 a.m. in winter, the optimal conditions for maximum shade on building facades are observed with the minimum courtyard size and building fronts on the short side (Type 1). Additionally, the optimal conditions for the greatest sun exposure on building facades in both summer and winter are consistently found with the minimum courtyard size and building fronts on the long side (Type 2), while the greatest amount of shade is achieved with the maximum courtyard size and building fronts on the short side (Type 1).



	C/min-size of courtyard /type2	C/max-size of courtyard/type2	C/min-size of courtyard /type1	C/max-size of courtyard/type1
8 AM	52.80%	54.75%	54.40%	58.10%
1 pm	50.00%	50.00%	50.50%	50.10%
6 pm	70%	72%	72.80%	75%
The average of shadows	57.60%	58.92%	59.23%	61.07%

Figure 7. Proportions of shadow coverage on building facades during the summer.

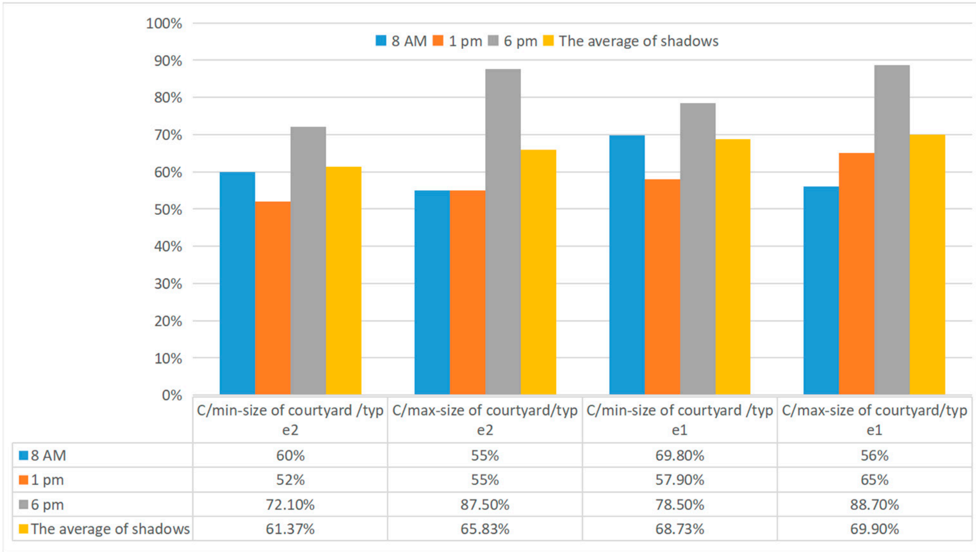


Figure 8. Percentages of shadow coverage on building facades during the winter season.

3.2.2. Shade on the Courtyard Ground

The greatest amount of shade at this time is achieved with the maximum courtyard size and building fronts on the short side (Type 1) (Figure 9). At 1:00 p.m. in summer, optimal sunlight exposure is found with the maximum courtyard size and building fronts on the short side (Type 2), whereas the greatest shade is observed with the minimum courtyard size and building fronts on the short side (Type 1) (Figure 10). For 6:00 p.m. in summer, the optimal conditions for maximum sunlight exposure are with the minimum courtyard size and building fronts on the long side (Type 2), while the greatest shade is achieved with the minimum courtyard size and building fronts on the short side (Type 1) (Figure 9). Conversely, Optimal conditions for the greatest exposure to sunlight on the courtyard ground at 8:00 a.m. during summer occur when the minimum courtyard size is utilized and the building fronts are on the long side (Type 2) (Figure 11).

In winter, the optimal conditions for maximum sunlight exposure on the courtyard ground at 8:00 a.m., 1:00 p.m., and 6:00 p.m. are achieved with the maximum courtyard size and building fronts on the long side (Type 2) (Figure 10). Conversely, the greatest amount of shade at these times is observed with the minimum courtyard size and building fronts on the short side (Type 1) (Figure 10).

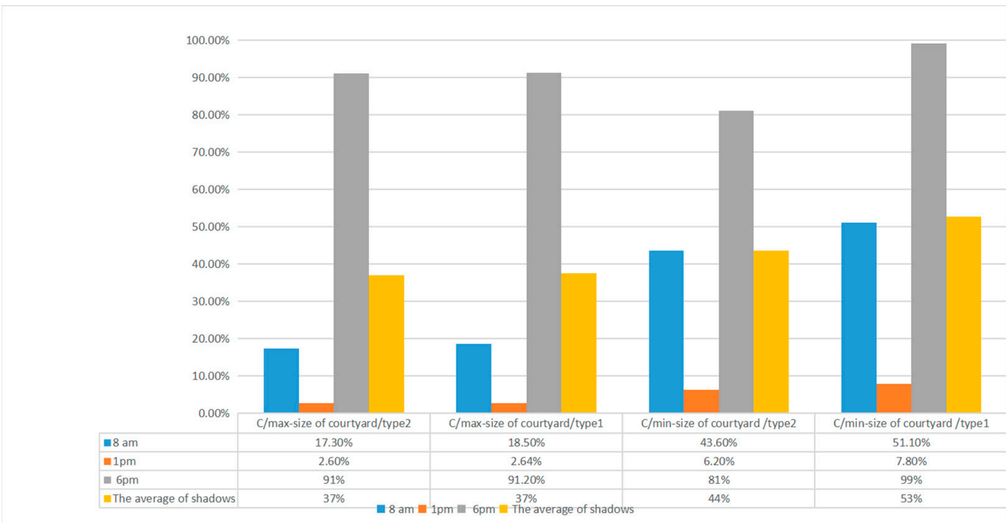


Figure 9. Percentages of shadow coverage on the ground during the summer season.

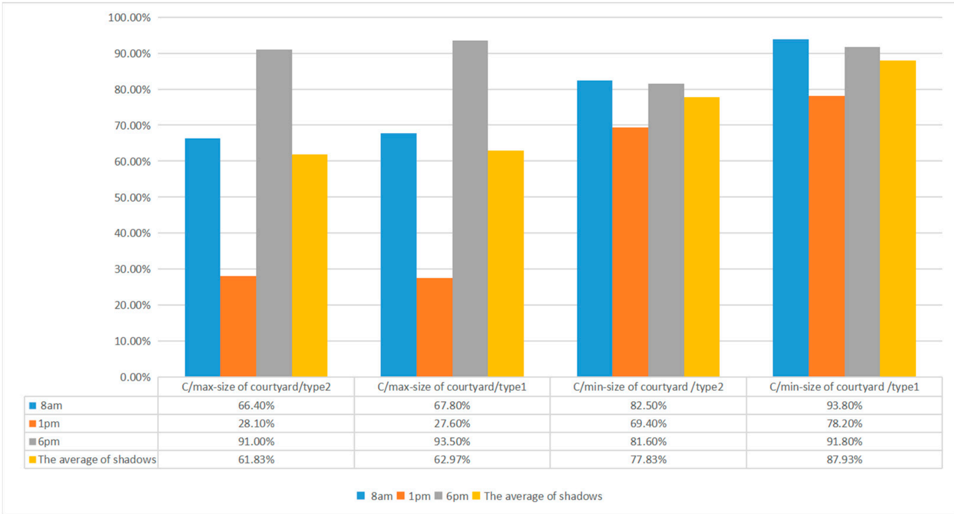


Figure 10. Percentages of shadow coverage on the ground during the winter season.

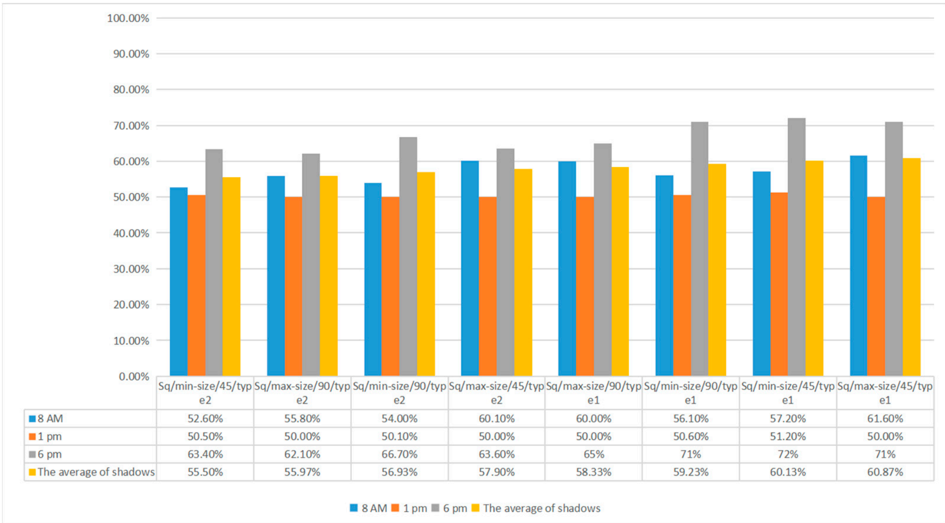


Figure 11. Percentages of shadow coverage on building facades during the summer season.

In summary, the optimal conditions for maximum sunlight exposure on the courtyard ground, both in summer and winter, are achieved with the maximum courtyard size and building fronts on the long side (Type 2). For maximum shade, the optimal conditions involve the minimum courtyard size and building fronts on the short side (Type 1) (Figures 9 and 10).

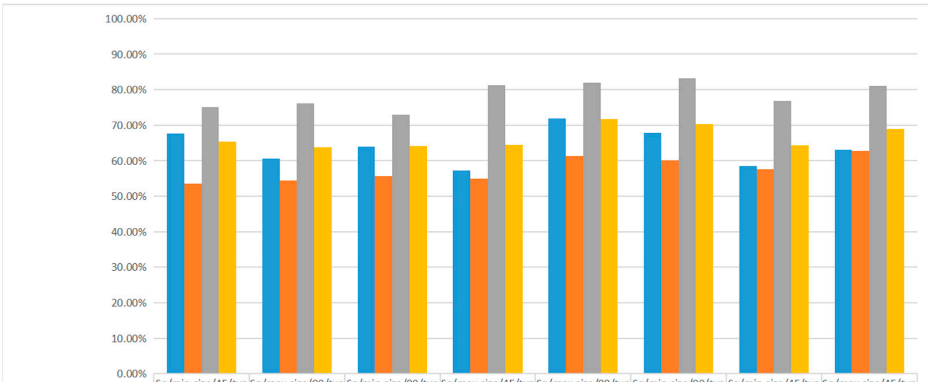
3.3. Square Shape

Eight courtyards were simulated, comprising four with the minimum courtyard size and four with the maximum courtyard size. Each size category included two distinct arrangements for buildings surrounding the courtyard: buildings oriented with their front on its long side (Type 2) and buildings oriented with their front on its short side (Type 1). Additionally, each courtyard configuration was simulated with two different orientations, 90 degrees and 45 degrees, at 8:00 a.m., 1:00 p.m., and 6:00 p.m. during both summer and winter seasons.

3.3.1. Shade on the Building Facades

In summer, as depicted in Figure 11, the optimal conditions for maximum sun exposure on the building facades at 8:00 a.m. occur when the minimum courtyard size is used with a 45-degree orientation and each building's front faces the long side (Type 2). Conversely, the greatest amount of shade at 8:00 a.m. is achieved when the maximum courtyard size is used with a 45-degree orientation and each building's front faces the short side (Type 1). At 1:00 p.m., optimal sun exposure conditions are found with the maximum courtyard size at 45- and 90-degree orientations and each building's front facing the short and long sides, respectively (Type 1 and Type 2). The greatest shade at 1:00 p.m. is observed with the minimum courtyard size on a 45-degree orientation and each building's front on its short side (Type 1). At 6:00 p.m., the optimal conditions for sun exposure are with the maximum courtyard size on a 90-degree orientation and each building's front on its long side (Type 2), while the greatest shade is achieved with the minimum courtyard size on a 45-degree orientation and each building's front on its short side (Type 1) (Figure 11).

In winter, Figure 12 indicates that the optimal conditions for maximum sun exposure on the building facades at 8:00 a.m. are with the maximum courtyard size on a 45-degree orientation and each building's front on its long side (Type 2). The greatest shade at 8:00 a.m. occurs with the maximum courtyard size on a 90-degree orientation and each building's front on its short side (Type 1). At 1:00 p.m., optimal sun exposure conditions are with the minimum courtyard size on a 45-degree orientation and each building's front on its long side (Type 2), whereas the greatest shade is achieved with the maximum courtyard size on a 45-degree orientation and each building's front on its short side (Type 1). At 6:00 p.m., the optimal conditions for sun exposure are with the minimum courtyard size on a 90-degree orientation and each building's front on its long side (Type 2), while the greatest shade is observed with the minimum courtyard size on a 90-degree orientation and each building's front on its short side (Type 1) (Figure 12).



	Sq/min-size/45/type2	Sq/max-size/90/type2	Sq/min-size/90/type2	Sq/max-size/45/type2	Sq/max-size/90/type1	Sq/min-size/90/type1	Sq/min-size/45/type1	Sq/max-size/45/type1
8 AM	67.60%	60.60%	64%	57.30%	71.80%	67.80%	58.40%	63.10%
1 pm	53.50%	54.40%	55.60%	55%	61.30%	60.10%	57.50%	62.70%
6 pm	75%	76.10%	73%	81.20%	82%	83.20%	76.80%	81%
The average of shadows	65.37%	63.70%	64.20%	64.50%	71.70%	70.37%	64.23%	68.93%

Figure 12. Percentages of shadow coverage on building facades during the winter season.

Overall, the optimal conditions for maximum sun exposure on the building facades are achieved with the minimum courtyard size on a 45-degree orientation and each building's front on its long side (Type 2). The greatest shade is observed with the maximum courtyard size on a 45-degree orientation and each building's front on its short side (Type 1) (Figure 11). In winter, the optimal conditions for maximum sun exposure are with the maximum courtyard size on a 90-degree orientation and each building's front on its long side (Type 2), while the greatest shade occurs with the maximum courtyard size on a 90-degree orientation and each building's front on its short side (Type 1) (Figure 12).

3.3.2. Shade on the Courtyard Ground

In summer, as illustrated in Figure 13, the optimal conditions for maximum sun exposure on the courtyard ground at 8:00 a.m. and 1:00 p.m. occur when the maximum courtyard size is oriented on a 90-degree axis with each building's front on its long side

(Type 2). Conversely, the optimal conditions for the greatest amount of shade on the courtyard ground at 8:00 a.m. are when the minimum courtyard size is oriented on a 45-degree axis with each building's front on its long side (Type 2). Additionally, at 6:00 p.m., the optimal conditions for sun exposure are achieved with the minimum courtyard size on a 45-degree axis and each building's front on its long side (Type 2), while the greatest shade is observed under the same courtyard size and orientation with each building's front on its short side (Type 1).

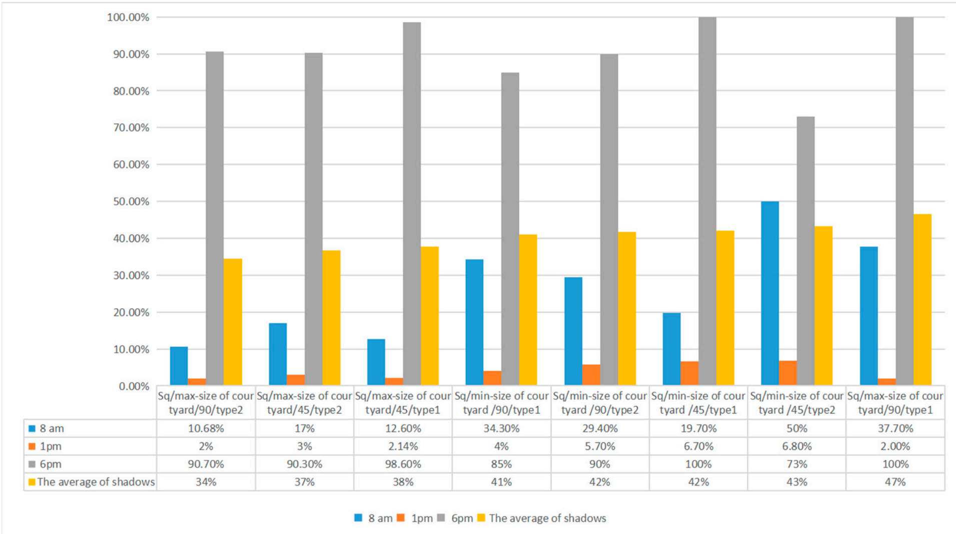


Figure 13. Percentages of shadow coverage on the ground during the summer season.

In winter, according to Figure 14, the optimal conditions for maximum sun exposure on the courtyard ground at 8:00 a.m. and 6:00 p.m. are found with the minimum courtyard size on a 90-degree axis and each building's front on its long side (Type 2). The greatest amount of shade at 8:00 a.m. is achieved when the maximum courtyard size is used on a 90-degree axis with each building's front on its long side (Type 2). At 1:00 p.m., optimal sun exposure conditions are attained with the maximum courtyard size on a 45-degree axis and each building's front on its long side (Type 2), while the greatest shade is observed with the minimum courtyard size on both 45-degree and 90-degree axes with each building's front on its long side (Type 2).

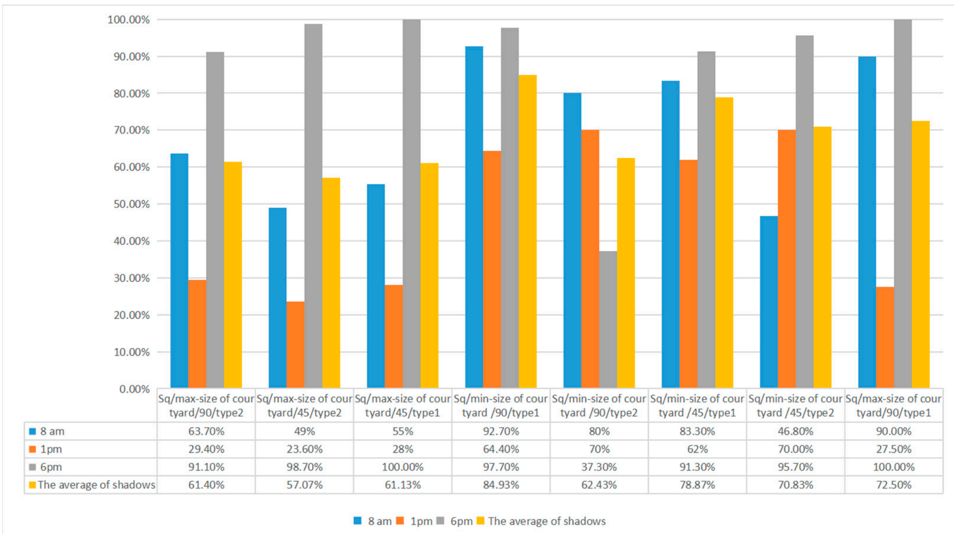


Figure 14. Percentages of shadow coverage on the ground during the winter season.

Overall, the optimal conditions for maximum sun exposure on the courtyard ground are achieved with the maximum courtyard size on a 90-degree axis in summer and a 45-degree axis in winter, with each building's front on its long side (Type 2). The optimal conditions for the greatest amount of shade on the courtyard ground are observed with the minimum courtyard size on a 45-degree axis in summer and a 90-degree axis in winter, with each building's front on its short side (Type 1) (Figures 13 and 14).

3.4. Triangle Shape

Four triangular courtyards were simulated for both summer and winter conditions. Two of these courtyards featured the minimum size, while the other two had the maximum size. Each size category included two different arrangements for buildings surrounding the courtyard: one with each building's front on its long side (Type 2) and the other with each building's front on its short side (Type 1). Simulations were conducted at three different times: 8:00 a.m., 1:00 p.m., and 6:00 p.m.

3.4.1. Shade on the Building Facades

According to Figures 15 and 16, the optimal conditions for maximum sun exposure on building facades at 8:00 a.m. are achieved when the minimum courtyard size is used in summer and the maximum courtyard size in winter, with each building's front on its long side (Type 2) in both cases. The optimal conditions for the greatest amount of shade at 8:00 a.m. occur when the maximum courtyard size is used and each building's front faces the short side (Type 1).

Figures 15 and 16 also indicate that at 1:00 p.m., the optimal conditions for both maximum sun exposure and maximum shade on the building facades remain consistent in summer, with only a slight variance in winter. Additionally, at 6:00 p.m., the optimal conditions for maximum sun exposure are when the maximum courtyard size is used in summer and the minimum size in winter, with each building's front on its long side (Type 2) in both cases. The optimal conditions for the greatest amount of shade at 6:00 p.m. are achieved with the minimum courtyard size and each building's front on its long side (Type 2) in summer, while in winter, the optimal conditions involve the maximum courtyard size and each building's front on its short side (Type 1).

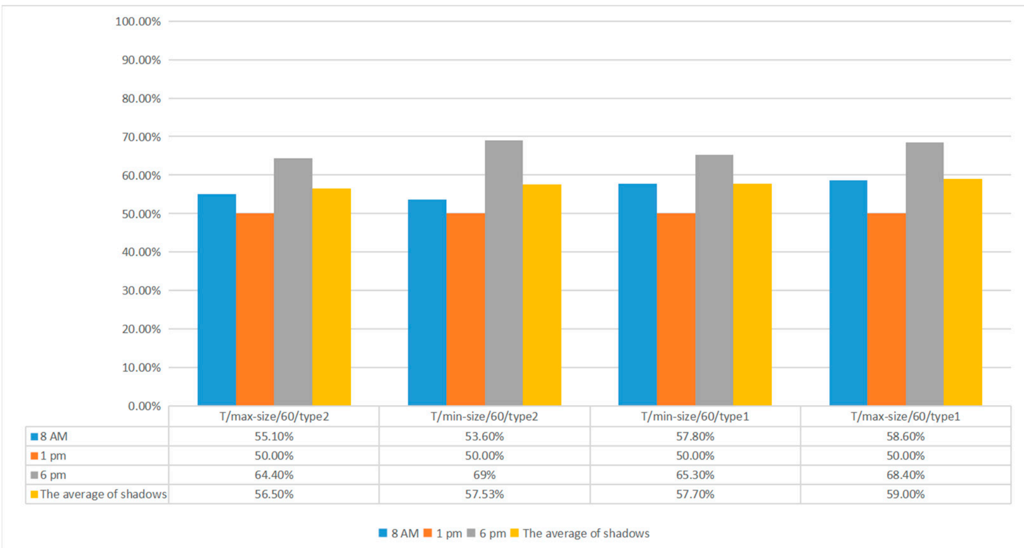


Figure 15. Percentages of shadow coverage on building facades during the summer season.

Furthermore, the overall optimal conditions for maximum sun exposure on building facades are with the maximum courtyard size in summer and the minimum size in winter, with each building's front on its long side (Type 2) in both cases. For the greatest amount of shade on building facades in both summer and winter, the optimal conditions are with the maximum courtyard size and each building’s front on its short side (Type 1) (Figures 15 and 16).

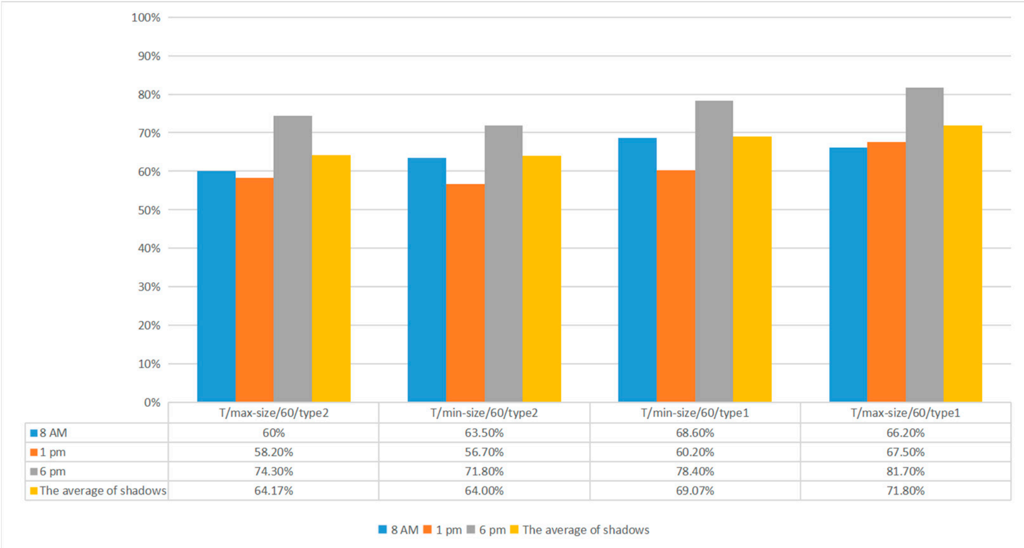


Figure 16. Percentages of shadow coverage on building facades during the winter season.

3.4.2. Shade on the Courtyard Ground

According to Figures 17 and 18, the optimal conditions for maximum sun exposure on the courtyard ground at 8:00 a.m., 1:00 p.m., and 6:00 p.m. during both summer and winter occur when the maximum courtyard size is used and each building’s front faces the short side (Type 1). Conversely, the optimal conditions for the greatest amount of shade on the courtyard ground at these times are achieved when the minimum courtyard size is used and each building’s front faces the long side (Type 2).

Furthermore, the overall optimal conditions for maximum sun exposure on the courtyard ground in both summer and winter are when the maximum courtyard size is used, and each building’s front faces the short side (Type 1). Similarly, the optimal conditions for the greatest amount of shade on the courtyard ground are observed when the minimum courtyard size is used, and each building’s front faces the long side (Type 2) (Figures 17 and 18).

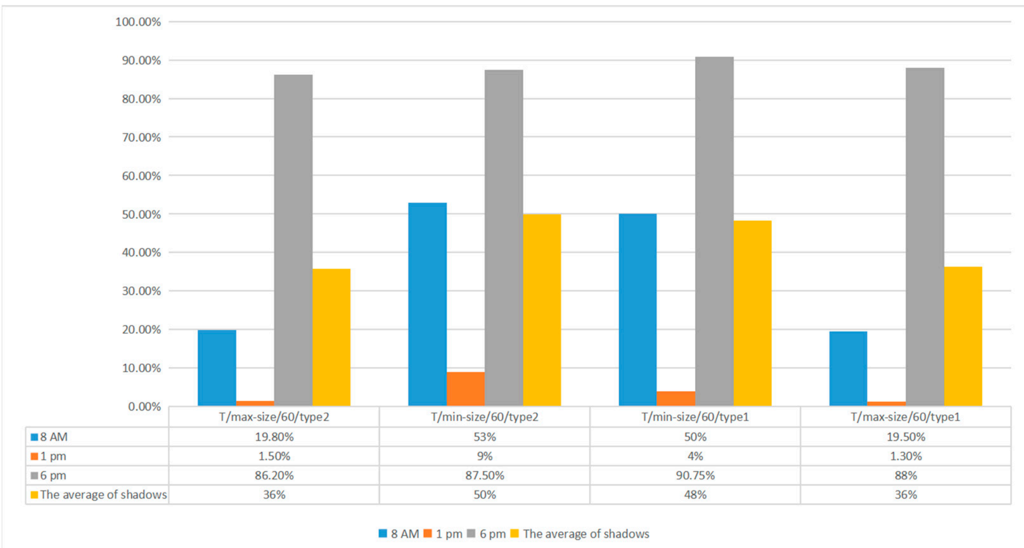


Figure 17. Percentages of shadow coverage on the ground during the summer season.

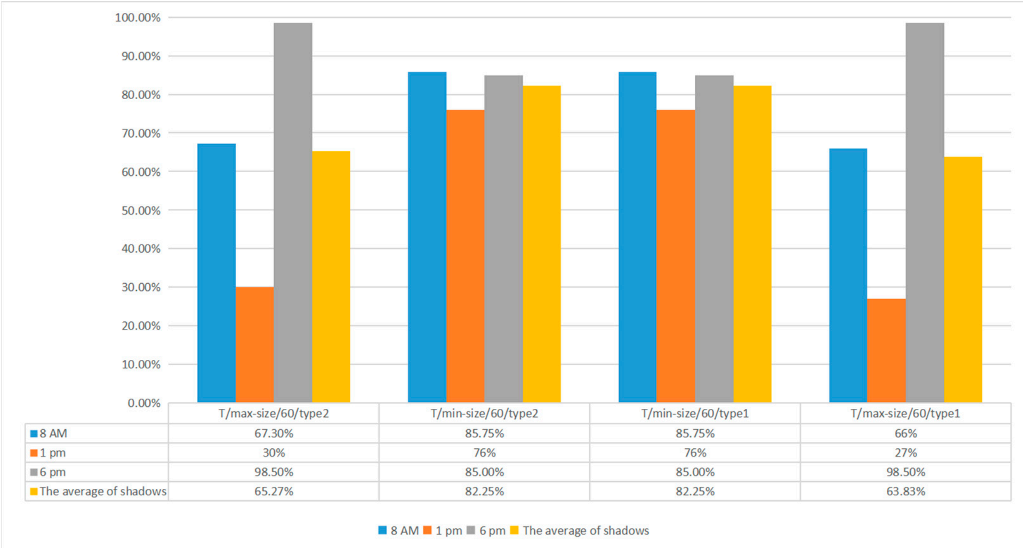


Figure 18. Percentages of shadow coverage on the ground during the winter season.

4. Results

In this section of the study, the results for ground and facade shadow coverage during summer and winter at three different times of day (8:00 a.m., 1:00 p.m., and 6:00 p.m.) for all building configurations were compared to identify the optimal configuration in terms of the greatest and least amount of shadow in both seasons. The findings were as follows:

4.1. Building Facades in Summer and Winter

According to Figures 19 and 20, the optimal conditions for maximum sun exposure on building facades at 8:00 a.m. are achieved with a square-shaped, minimum-sized courtyard on a 45-degree axis (Type 2) in summer or a circular, maximum-sized courtyard (Type 2) in winter. Conversely, the optimal conditions for the greatest amount of shade on building facades in both summer and winter involve a rectangular, maximum-sized courtyard on a southwest–northeast axis (Type 1).

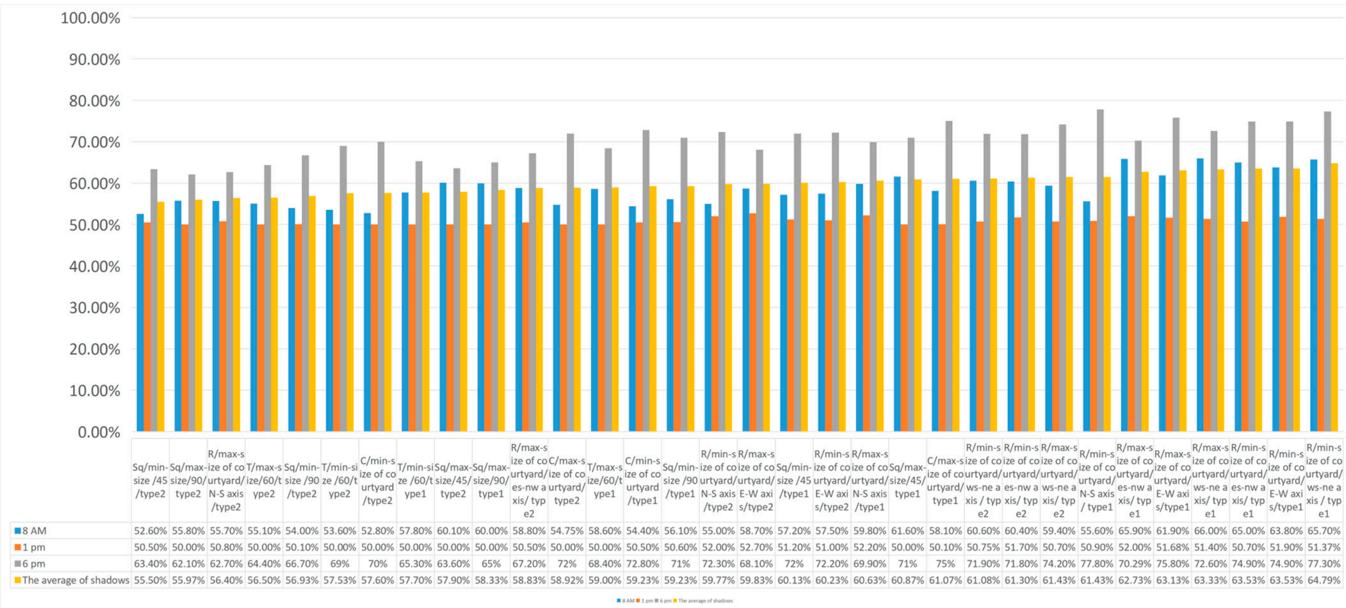
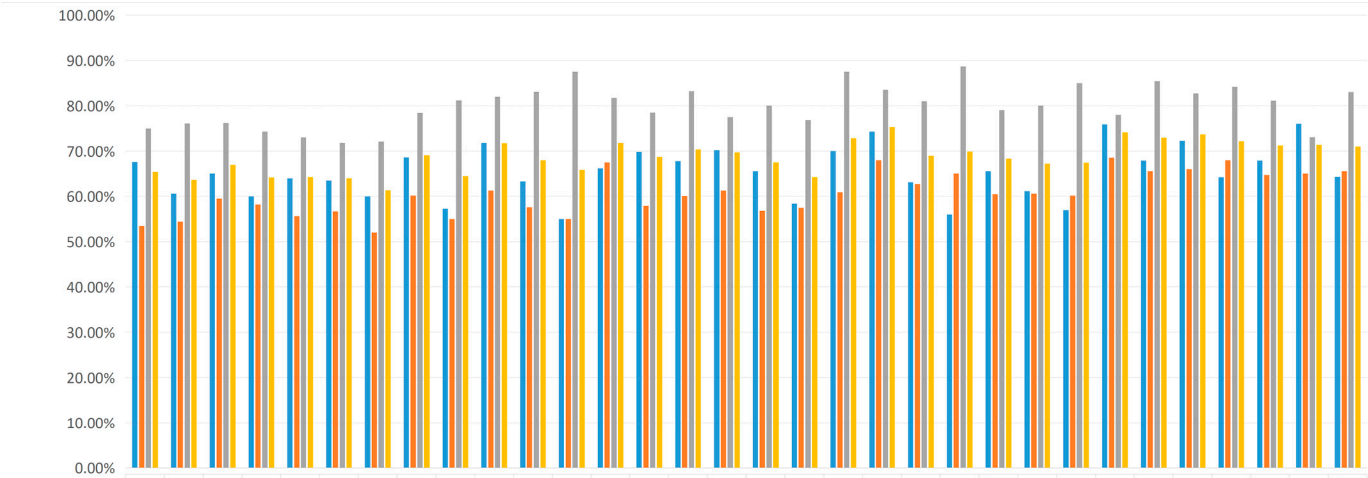


Figure 19. Percentages of shadows in summer for building facades.



	Sq/min-size /45/type2	Sq/max-size/90/type2	R/max-size of courtyard/N-S axis/type2	T/max-size/60/type2	Sq/min-size /90/type2	T/min-size /60/type2	C/min-size of courtyard /type2	T/min-size /60/type1
8 AM	67.60%	60.60%	65%	60%	64%	63.50%	60%	68.60%
1 pm	53.50%	54.40%	59.50%	58.20%	55.60%	56.70%	52%	60.20%
6 pm	75%	76.10%	76.20%	74.30%	73%	71.80%	72.10%	78.40%
The average of shadows	65.37%	63.70%	66.90%	64.17%	64.20%	64.00%	61.37%	69.07%

	Sq/max-size/45/type2	Sq/max-size/90/type1	R/max-size of courtyard/ es-nw axis / type2	C/max-size of courtyard/type2	T/max-size/60/type1	C/min-size of courtyard /type1	Sq/min-size /90/type1	R/min-size of courtyard/N-S axis/type2
8 AM	57.30%	71.80%	63.30%	55%	66.20%	69.80%	67.80%	70.20%
1 pm	55%	61.30%	57.60%	55%	67.50%	57.90%	60.10%	61.30%
6 pm	81.20%	82%	83.10%	87.50%	81.70%	78.50%	83.20%	77.50%
The average of shadows	64.50%	71.70%	68.00%	65.83%	71.80%	68.73%	70.37%	69.67%

	R/max-size of courtyard/E-W axis/type2	Sq/min-size /45/type1	R/min-size of courtyard/E-W axis/type2	R/max-size of courtyard/N-S axis/type1	Sq/max-size/45/type1	C/max-size of courtyard/type1	R/min-size of courtyard/ ws-ne axis / type 2	R/min-size of courtyard/es-nw axis / type2
8 AM	65.60%	58.40%	70%	74.30%	63.10%	56%	65.60%	61.15%
1 pm	56.80%	57.50%	60.90%	68%	62.70%	65%	60.50%	60.60%
6 pm	80%	76.80%	87.50%	83.50%	81%	88.70%	79%	80%
The average of shadows	67.47%	64.23%	72.80%	75.27%	68.93%	69.90%	68.37%	67.25%

	R/max-size of courtyard/ ws-ne axis/ type2	R/min-size of courtyard/N-S axis/ type1	R/max-size of courtyard/ es-nw axis / type1	R/max-size of courtyard/E-W axis/type1	R/max-size of courtyard/ ws-ne axis/ type1	R/min-size of courtyard/es-nw axis / type1	R/min-size of courtyard/E-W axis/type1	R/min-size of courtyard/ ws-ne axis / type 1
8 AM	57%	75.90%	67.90%	72.30%	64.24%	67.90%	76.00%	64.30%
1 pm	60.20%	68.50%	65.60%	66%	68%	64.70%	65%	65.60%
6 pm	85%	78%	85.40%	82.70%	84.20%	81.10%	73.10%	83%
The average of shadows	67.40%	74.13%	72.97%	73.67%	72.15%	71.23%	71.37%	70.97%

Figure 20. Percentages of shadows in winter for building facades.

Figures 19 and 20 also indicate that at 1:00 p.m., the optimal conditions for maximum sun exposure on building facades in both summer and winter are with a circular, minimum-sized courtyard (Type 2). The greatest amount of shade at this time is achieved with a rectangular, maximum-sized courtyard on an east–west axis (Type 2) in summer or a northeast–southwest axis (Type 1) in winter.

At 6:00 p.m., the optimal conditions for maximum sun exposure on building facades are found with a square-shaped, maximum-sized courtyard on a 90-degree axis (Type 2) in summer and a triangular, minimum-sized courtyard (Type 2) in winter. The optimal conditions for the greatest amount of shade on building facades at this time in both summer and winter are with a rectangular, minimum-sized courtyard on a north–south axis (Type 1).

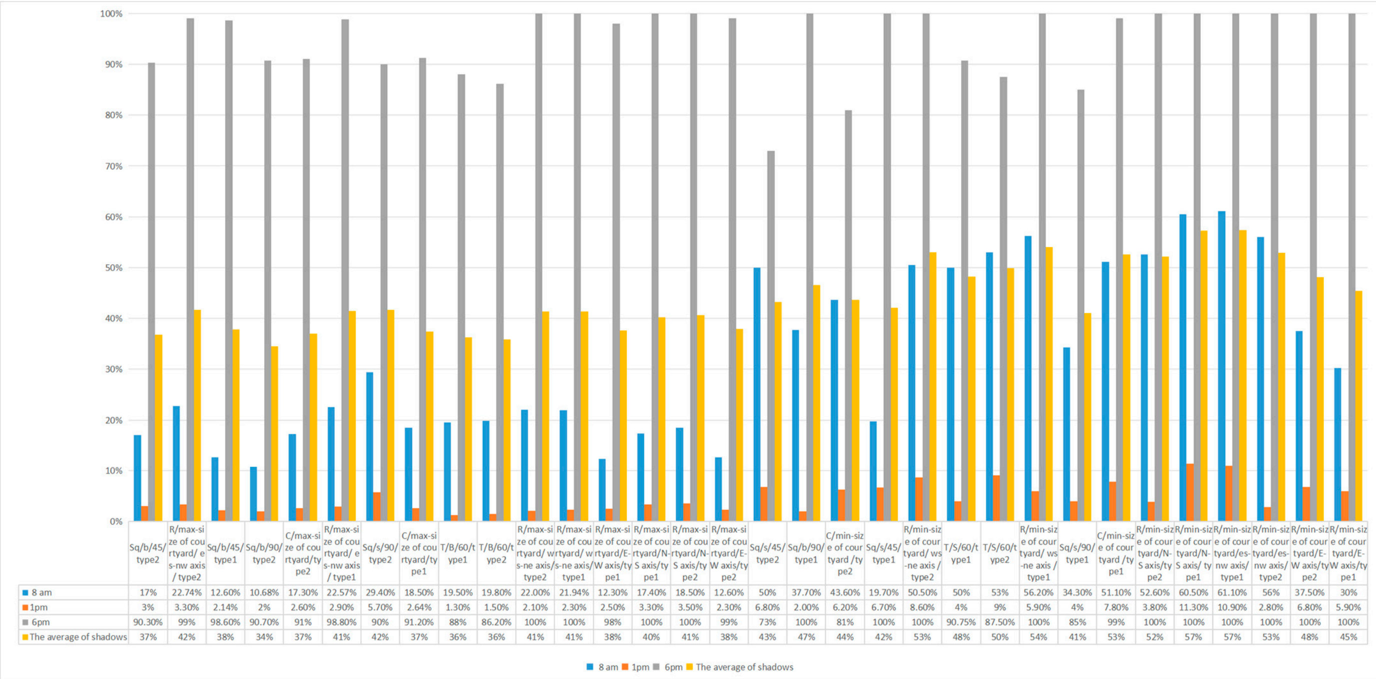
4.2. Courtyard Ground in Summer and Winter

According to Figures 21 and 22, the optimal conditions for maximum sun exposure on the courtyard ground at 8:00 a.m. in summer are with a square-shaped, maximum-sized courtyard on a 90-degree axis (Type 2), while in winter, the optimal conditions are with a square-shaped, minimum-sized courtyard on a 45-degree axis (Type 2). Conversely, the optimal conditions for the greatest amount of shade on the courtyard ground in both summer and winter are with a rectangular, minimum-sized courtyard on a southeast–northwest axis (Type 1) (Figures 21 and 22).

At 1:00 p.m., Figures 22 and 23 indicate that the optimal conditions for maximum sun exposure on the courtyard ground in both summer and winter are with square-shaped, maximum-sized courtyards (Type 1). The greatest amount of shade at this time is achieved with a rectangular, minimum-sized courtyard on a north–south axis (Type 1) in summer, while in winter, the optimal conditions differ only in terms of the long-axis orientation from southeast to northwest (Figures 21 and 22).

At 6:00 p.m., the optimal conditions for maximum sun exposure on the courtyard ground are achieved with a square-shaped, minimum-sized courtyard on a 45-degree axis (Type 2) in summer, and on a 90-degree axis (Type 2) in winter (Figures 21 and 22). Additionally, the optimal conditions for the greatest amount of shade on the courtyard ground in both summer and winter are with rectangular, minimum-sized courtyards on a north–south axis (Type 1) (Figures 21 and 22).

The study's findings include recommendations for optimizing sun exposure and shade, with conditions arranged from the most to the least sun exposure. The results highlight the advantages derived from the shape of the courtyard throughout the day. The findings propose methods to enhance sun and shade conditions for both the facades and the ground in summer and winter, as illustrated in Figures 23 and 24. Consequently, Figures 23 and 24 offer a comprehensive understanding of the conditions necessary for selecting the optimal configuration for both summer and winter.



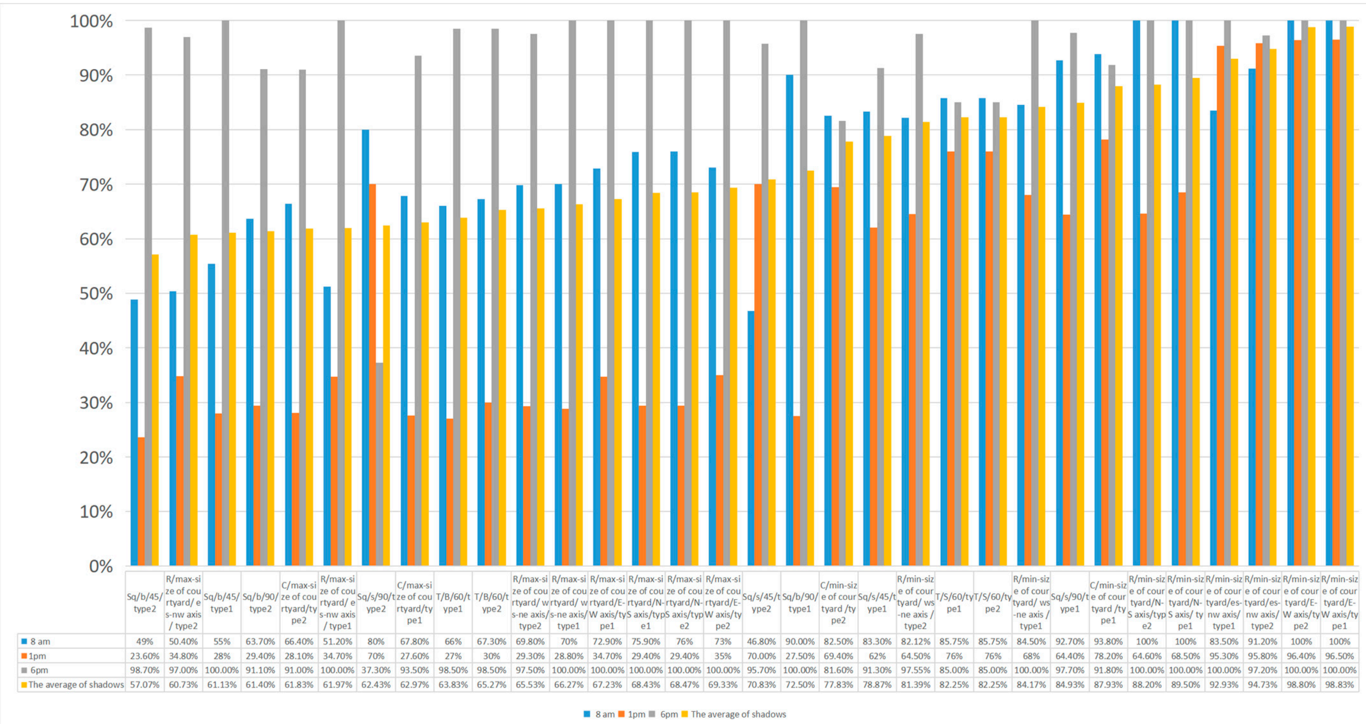
	Sq/b/45/type2	R/max-size of courtyard/es-nw axis/type2	Sq/b/45/type1	Sq/b/90/type2	C/max-size of courtyard/type2	R/max-size of courtyard/es-nw axis/type1	Sq/s/90/type2	C/max-size of courtyard/type1
8 am	17%	22.74%	12.60%	10.68%	17.30%	22.57%	29.40%	18.50%
1pm	3%	3.30%	2.14%	2%	2.60%	2.90%	5.70%	2.64%
6pm	90.30%	99%	98.60%	90.70%	91%	98.80%	90%	91.20%
The average of shadows	37%	42%	38%	34%	37%	41%	42%	37%

	T/B/60/type1	T/B/60/type2	R/max-size of courtyard/ws-ne axis/type2	R/max-size of courtyard/ws-ne axis/type1	R/max-size of courtyard/E-W axis/type1	R/max-size of courtyard/N-S axis/type1	R/max-size of courtyard/N-S axis/type2	R/max-size of courtyard/E-W axis/type2
8 am	19.50%	19.80%	22.00%	21.94%	12.30%	17.40%	18.50%	12.60%
1pm	1.30%	1.50%	2.10%	2.30%	2.50%	3.30%	3.50%	2.30%
6pm	88%	86.20%	100%	100%	98%	100%	100%	99%
The average of shadows	36%	36%	41%	41%	38%	40%	41%	38%

	Sq/s/45/type2	Sq/b/90/type1	C/min-size of courtyard /type2	Sq/s/45/type1	R/min-size of courtyard/ ws-ne axis / type2	T/S/60/type1	T/S/60/type2	R/min-size of courtyard/ ws-ne axis / type1
8 am	50%	37.70%	43.60%	19.70%	50.50%	50%	53%	56.20%
1pm	6.80%	2.00%	6.20%	6.70%	8.60%	4%	9%	5.90%
6pm	73%	100%	81%	100%	100%	90.75%	87.50%	100%
The average of shadows	43%	47%	44%	42%	53%	48%	50%	54%

	Sq/s/90/type1	C/min-size of courtyard /type1	R/min-size of courtyard/N-S axis/type2	R/min-size of courtyard/N-S axis/ type1	R/min-size of courtyard/es-nw axis/ type1	R/min-size of courtyard/es-nw axis/ type2	R/min-size of courtyard/E-W axis/type2	R/min-size of courtyard/E-W axis/type1
8 am	34.30%	51.10%	52.60%	60.50%	61.10%	56%	37.50%	30%
1pm	4%	7.80%	3.80%	11.30%	10.90%	2.80%	6.80%	5.90%
6pm	85%	99%	100%	100%	100%	100%	100%	100%
The average of shadows	41%	53%	52%	57%	57%	53%	48%	45%

Figure 21. Percentages of shadows in summer for ground.



	Sq/b/45/type2	R/max-size of courtyard/es-nw axis/type2	Sq/b/45/type1	Sq/b/90/type2	C/max-size of courtyard/type2	R/max-size of courtyard/es-nw axis/type1	Sq/s/90/type2	C/max-size of courtyard/type1
8 am	49%	50.40%	55%	63.70%	66.40%	51.20%	80%	67.80%
1pm	23.60%	34.80%	28%	29.40%	28.10%	34.70%	70%	27.60%
6pm	98.70%	97.00%	100.00%	91.10%	91.00%	100.00%	37.30%	93.50%
The average of shadows	57.07%	60.73%	61.13%	61.40%	61.83%	61.97%	62.43%	62.97%

	T/B/60/type1	T/B/60/type2	R/max-size of courtyard/ws-ne axis/type2	R/max-size of courtyard/ws-ne axis/type1	R/max-size of courtyard/E-W axis/type1	R/max-size of courtyard/N-S axis/type1	R/max-size of courtyard/N-S axis/type2	R/max-size of courtyard/E-W axis/type2
8 am	66%	67.30%	69.80%	70%	72.90%	75.90%	76%	73%
1pm	27%	30%	29.30%	28.80%	34.70%	29.40%	29.40%	35%
6pm	98.50%	98.50%	97.50%	100.00%	100.00%	100.00%	100.00%	100.00%
The average of shadows	63.83%	65.27%	65.53%	66.27%	67.23%	68.43%	68.47%	69.33%

	Sq/s/45/type2	Sq/b/90/type1	C/min-size of courtyard /type2	Sq/s/45/type1	R/min-size of courtyard/ ws-ne axis / type2	T/S/60/type1	T/S/60/type2	R/min-size of courtyard/ ws-ne axis / type1
8 am	46.80%	90.00%	82.50%	83.30%	82.12%	85.75%	85.75%	84.50%
1pm	70.00%	27.50%	69.40%	62%	64.50%	76%	76%	68%
6pm	95.70%	100.00%	81.60%	91.30%	97.55%	85.00%	85.00%	100.00%
The average of shadows	70.83%	72.50%	77.83%	78.87%	81.39%	82.25%	82.25%	84.17%

	Sq/s/90/type1	C/min-size of courtyard /type1	R/min-size of courtyard/N-S axis/type2	R/min-size of courtyard/N-S axis/ type1	R/min-size of courtyard/es-nw axis/ type1	R/min-size of courtyard/es-nw axis/ type2	R/min-size of courtyard/E-W axis/type2	R/min-size of courtyard/E-W axis/type1
8 am	92.70%	93.80%	100%	100%	83.50%	91.20%	100%	100%
1pm	64.40%	78.20%	64.60%	68.50%	95.30%	95.80%	96.40%	96.50%
6pm	97.70%	91.80%	100.00%	100.00%	100.00%	97.20%	100.00%	100.00%
The average of shadows	84.93%	87.93%	88.20%	89.50%	92.93%	94.73%	98.80%	98.83%

Figure 22. Percentages of shadows in winter for ground.

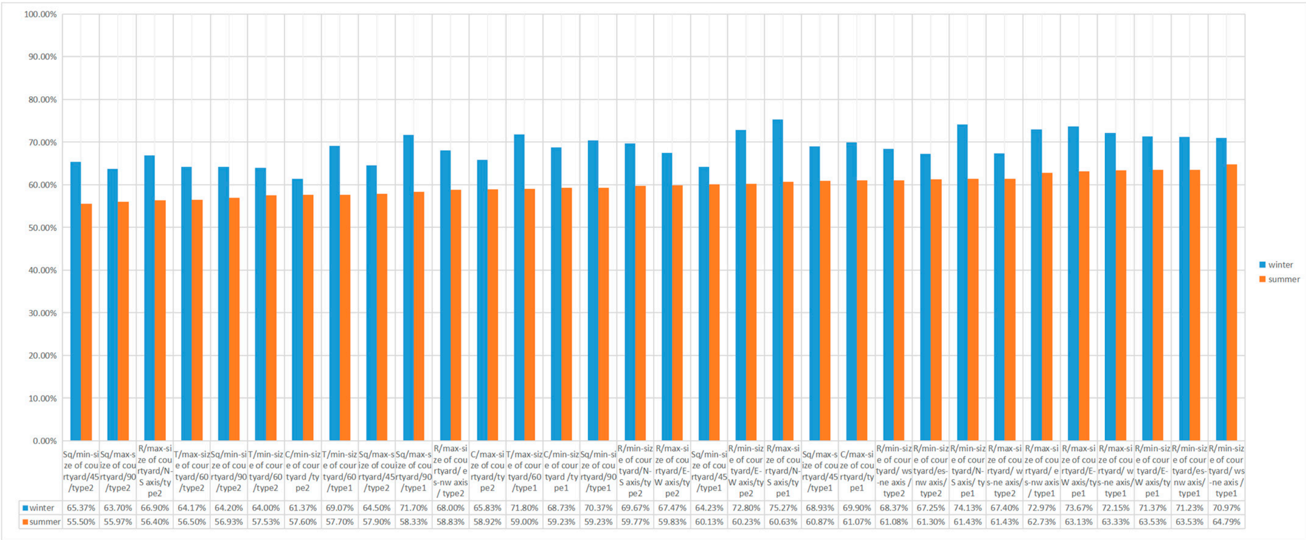


Figure 23. Recommendations to enhance sun exposure, with shadow percentages arranged from highest to lowest sun exposure, for building facades throughout the day in both winter and summer across all courtyard shapes (source: the author, 2022).

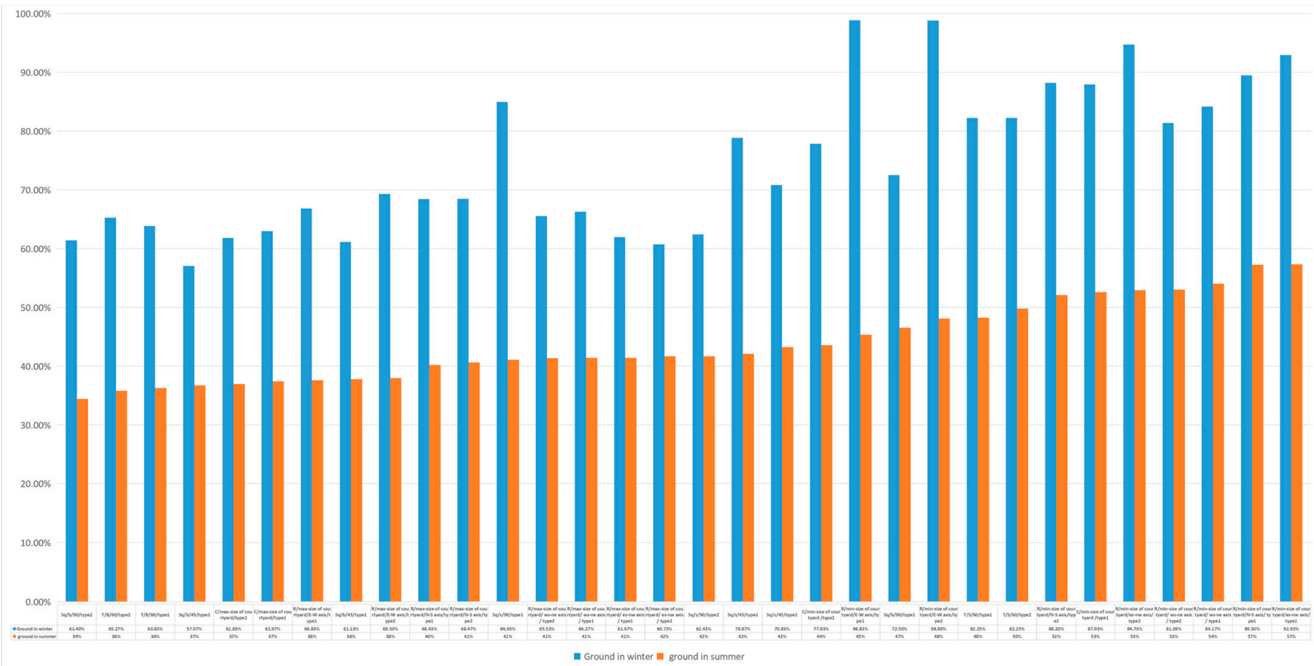


Figure 24. Recommendations to enhance sun exposure, with shadow percentages arranged from highest to lowest sun exposure, for the courtyard ground throughout the day in both winter and summer across all shapes (source: the author, 2022).

5. Discussion

This study examined the influence of the variables of courtyard shape, orientation, size, and building arrangement, analyzed at three different times of the day: 8:00 a.m., 1:00 p.m., and 6:00 p.m.. The aim was to determine their effects at these times in both summer and winter. The findings are summarized as follows:

The average effect of each variable was assessed to determine its impact on sun and shade, represented as a percentage. The outcomes for the three variables affecting each shape are summarized in Figures 25–32.

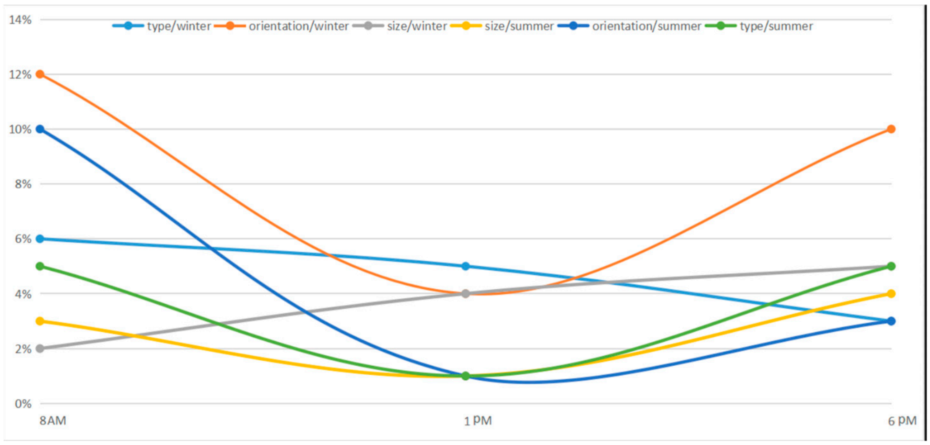


Figure 25. The effect of three variables—orientation, courtyard size, and building arrangement around the courtyard (type)—on facades along rectangular courtyards throughout the day (8:00 a.m., 1:00 p.m., and 6:00 p.m.) during summer and winter (source: the author, 2022).

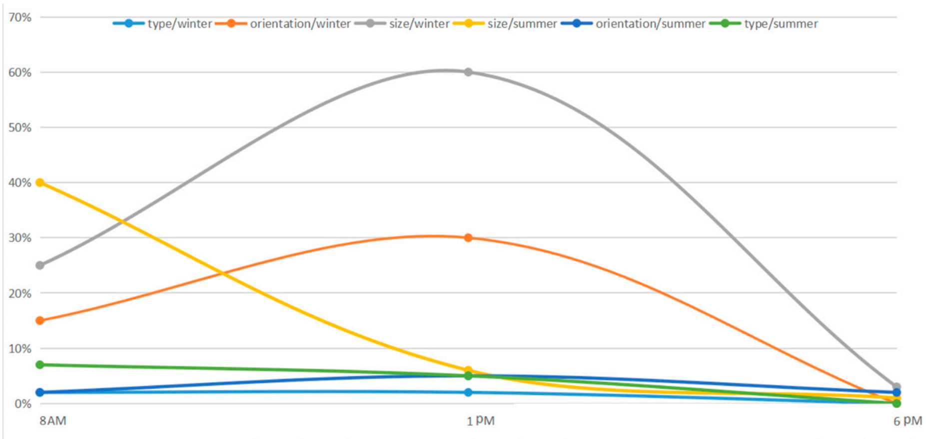


Figure 26. The effect of three variables—orientation, courtyard size, and building arrangement around the courtyard (type)—on facades along rectangular courtyards throughout the day (8:00 a.m., 1:00 p.m., and 6:00 p.m.) during summer and winter (source: the author, 2022).

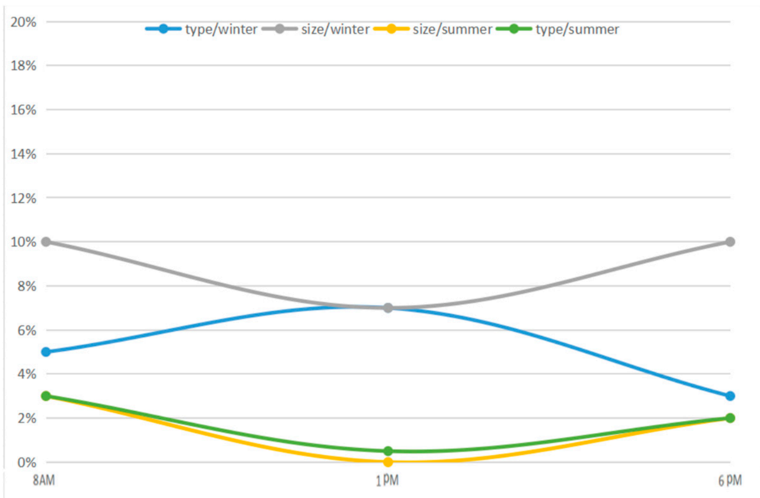


Figure 27. The effect of two variables—courtyard size and building arrangement around the courtyard (type)—on facades along circular courtyards throughout the day (8:00 a.m., 1:00 p.m., and 6:00 p.m.) during summer and winter (source: the author, 2022).

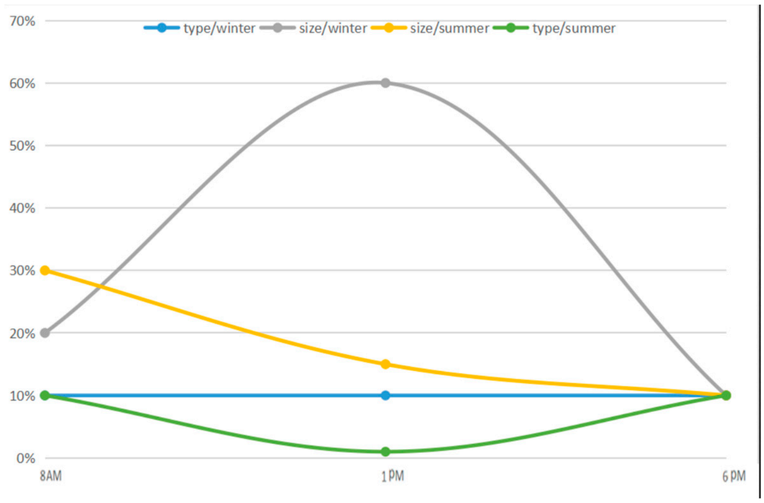


Figure 28. The effect of two variables—courtyard size and building arrangement around the courtyard (type)—on facades along circular courtyards throughout the day (8:00 a.m., 1:00 p.m., and 6:00 p.m.) during summer and winter (source: the author, 2022).

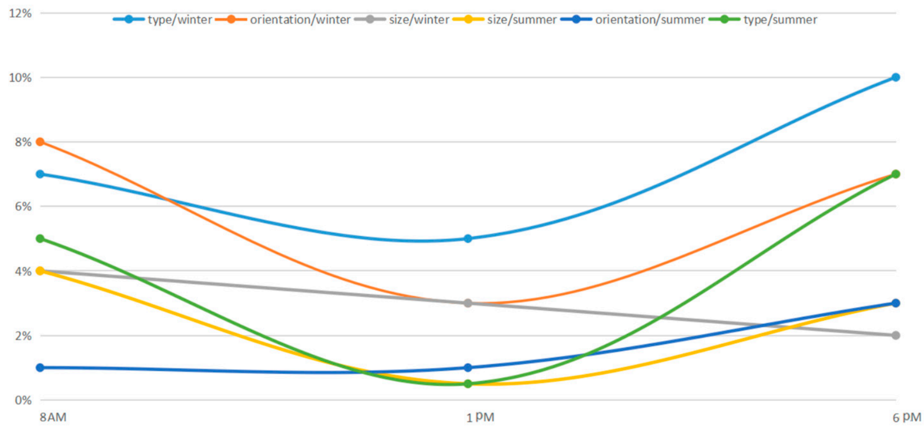


Figure 29. The effect of three variables—orientation, courtyard size, and building arrangement around the courtyard (type)—on facades along square courtyards during the day (8:00 a.m., 1:00 p.m., and 6:00 p.m.), in summer and winter (source: the author, 2022).

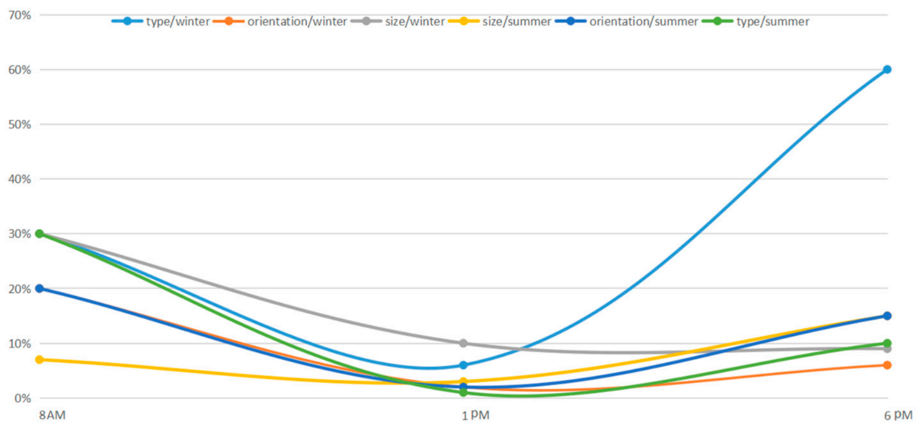


Figure 30. The effect of three variables—orientation, courtyard size, and building arrangement around the courtyard (type)—on the ground in square courtyards during the day (8:00 a.m., 1:00 p.m., and 6:00 p.m.), in summer and winter (source: the author, 2022).

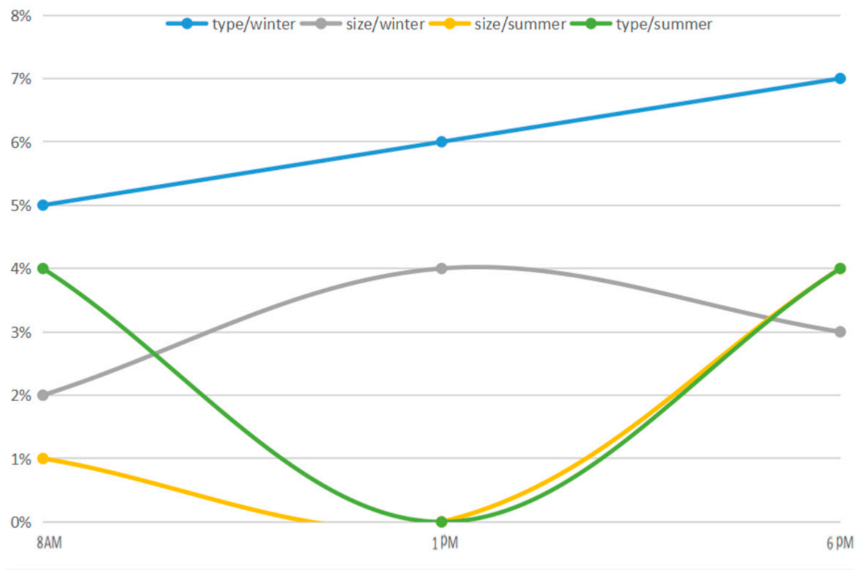


Figure 31. The effect of two variables—courtyard size and building arrangement around the courtyard (type)—on facades along triangular courtyards during the day (8:00 a.m., 1:00 p.m., and 6:00 p.m.), in summer and winter (source: the author, 2022).

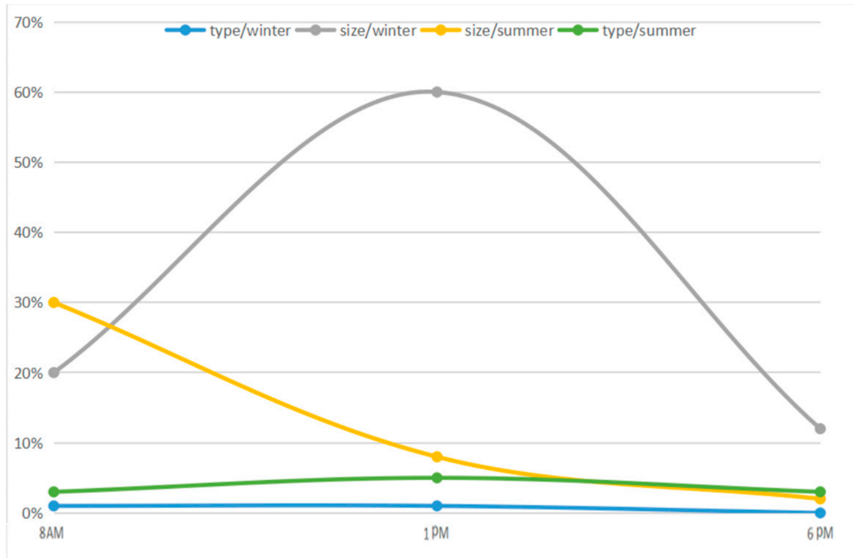


Figure 32. The effect of the two variables—courtyard size and building arrangement around the courtyard (type)—on the ground in triangular courtyards during the day (8:00 a.m., 1:00 p.m., and 6:00 p.m.), in summer and winter (source: the author, 2022).

For rectangular courtyards, the findings indicate that orienting the courtyard at an angle of 180 degrees with the long axis from east to west in summer, and at 45 degrees from southeast to northwest (SE-NW) in winter, enhances sunlight during the day. Shade varies depending on the time of day, with optimal conditions for shade occurring at an angle of 45 degrees SE-NW in summer and 180 degrees with the long axis from east to west in winter. Increasing courtyard size significantly increases the amount of light hitting the ground. For building facades, the optimal orientation for sun exposure is 90 degrees with the long axis from south to north in summer and 45 degrees SE-NW in winter. For shade, a 45-degree orientation in summer and 90 degrees from south to north result in high shade percentages. However, achieving optimal sun exposure in both seasons is challenging because conditions favoring sun exposure in summer are ineffective in winter and vice versa. A 45-degree SE-NW orientation can increase shade in summer and sun exposure in winter. Rectangular shapes yield better sun exposure when the length-to-width ratio is reduced. Overall, arranging buildings with their facades on the longer side (Type 2) improves sun exposure, while arranging them with their facades on the shorter side (Type 1) enhances shading. Orientation is the most influential variable for rectangular courtyards, followed by building arrangement and courtyard size (Figure 25). For ground shading, size is the most influential variable, followed by orientation and building arrangement (Figure 26).

For circular courtyards, arranging buildings with their facades on the longer side (Type 2) improves sun exposure, while facades on the shorter side (Type 1) enhance shading. Increasing courtyard size increases light on the ground. However, for facades, the minimum courtyard size enhances sun exposure in both summer and winter. In circular forms, variables equally affect facades in summer, while courtyard size is the most influential in winter, followed by building arrangement (Figure 27). For ground shading, courtyard size is the most influential variable in both summer and winter, followed by building arrangement (Figure 28).

For square-shaped courtyards, the optimal conditions for sun exposure on building facades in summer occur with the minimum courtyard size on a 45-degree axis, while in winter, a maximum courtyard size on a 90-degree axis is required, with each building's front on the long side (Type 2) for both seasons. For maximum shade on facades, the optimal conditions are a maximum courtyard size on a 45-degree axis in summer and 90 degrees in winter, with each building's front on the short side (Type 1). For sun exposure on the ground, the optimal conditions are a maximum courtyard size on a 90-degree axis in summer and 45 degrees in winter, with each building's front on the long side (Type 2). For maximum shade on the ground, the optimal conditions are a minimum courtyard size on a 45-degree axis in summer and 90 degrees in winter, with each building's front on the short side (Type 1). Arranging buildings on the longer side (Type 2) generally improves light entry to the courtyard and facade, while the shorter side (Type 1) enhances shading. The courtyard size increases light penetration and shading on the ground, but facade results vary. Orientation is the most influential variable for square-shaped facades, followed by building arrangement and courtyard size (Figure 29). For ground shading, orientation remains the most influential, followed by size and building arrangement, with size being less significant compared to other shapes.

These findings offer valuable insights into optimizing sun exposure and shading for various courtyard shapes and configurations, providing a comprehensive understanding of how different variables influence these outcomes.

After a thorough literature review, it became evident that although numerous studies have explored courtyards as part of a single building [7,23,25,41], none have addressed courtyards surrounded by multiple buildings as examined in this study. Moreover, existing research predominantly focuses on square and rectangular courtyard shapes, primarily examining their influence on shade [27]. Fahmy et al. [21] confirmed the prevalence of courtyard design through a comparative analysis of selected performance indicators, encompassing environmental, social, and economic sustainability measures. However, this study did not delve into diverse forms and scenarios of courtyard design. Muhaisen and Gadi [42] acknowledged the integration of various geometric courtyard designs beyond the typical rectangular shape, yet their study focused on shading performance without examining other variables influencing thermal comfort or common shapes such as squares, triangles, and circles.

Sun [23] concluded that rectangular courtyards provide greater shade and sun protection than square courtyards, which are more effective for sun exposure. This study reached similar conclusions but tested additional variables not investigated by Ntefeh et al. [27], such as courtyard orientation and size, and the arrangement of buildings around the courtyard rather than a single block. Additionally, this study examined three time periods during the day, whereas Ntefeh et al. [27] focused solely on 12:00 p.m.. The results indicated that a north–south courtyard orientation increases shade in summer. However, this study found that when there are distances between buildings, the outcomes differ. For facades, a north–south orientation can result in higher sun exposure at noon with a minimum courtyard size (Type 1) or a maximum courtyard size (Type 2). For the ground, a north–south orientation yields greater sun exposure at noon with a minimum courtyard size (Type 2). Unlike Ntefeh et al. [27], this study also tested a 45-degree orientation, revealing that this orientation increases shade in summer and sun exposure in winter for rectangular and square courtyards.

Al-Qeeq [26] found that arranging buildings on the courtyard's short side increases shade compared to the long side. This study corroborates these findings, even when buildings are arranged around the courtyard rather than linearly. Furthermore, it was observed that positioning the front facade on the long side enhances sunlight penetration, except in triangular courtyards. Zhang [24] proposed that for North America and Canada, where increased daylight is desired, rectangular courtyards should be avoided as they increase shade. Prior research had not examined the impact of courtyard size on sun exposure. This study concludes that minimum courtyard size generally increases sun exposure on facades, whereas increasing courtyard size enhances sun exposure on the ground.

Ultimately, selecting a courtyard design that is not compatible with the climate might impact individuals' thermal comfort and hence lead to their displeasure. According to Turhan et al. [1], a sense of displeasure also contributes to thermal comfort negatively and thus impacts individuals' feelings of comfort. Additionally, several studies such as those by Bulut et al. [8], Hu et al. [9], and Arya et al. [10] explored methods to enhance indoor comfort inside the interior setting of buildings. These methods might be considered alongside selecting a well-designed courtyard to achieve optimal thermal comfort.

6. Conclusions

The inclusion of courtyards in housing design is increasingly popular as a means to achieve urban sustainability. However, in certain nations such as Jordan, limited land availability necessitates alternative approaches to courtyard implementation. This study examined courtyards surrounded by clusters of buildings to understand their potential uses. The research investigated the effects, in summer and winter, of three variables (courtyard orientation, size, and building arrangement) for four shapes (rectangular, circular, square, and triangular).

In general, the variables have the following effects during summer and winter: orientation and building arrangement significantly impact facades' sun and shade conditions, while courtyard size is the main influencing variable for ground conditions, except for square shapes. Orientation is the most influential variable for facades, followed by building arrangement and courtyard size. For ground conditions, courtyard size is the primary influence, followed by building arrangement and orientation, except for square shapes (where size and orientation have the greatest effect).

For both ground and facades, arranging buildings with the facade on the longer side (Type 2) improves sun entry, while arranging buildings with the facade on the shorter side (Type 1) increases shade, except for triangular shapes. Increasing courtyard size generally enhances light on the ground but yields different shading results on facades. Countries seeking to improve lighting should use square and triangular courtyards, while those seeking increased shade should use rectangular courtyards. Circular courtyards produce inconsistent results, with facades receiving light and the ground receiving shade unless size is maximized.

To provide shading in summer and improve the climate, Jordan should adopt a rectangular courtyard shape, oriented from south to north, with each building's facade on its shorter side.

7. Limitations and Future Research

This study examined regular shapes to determine their shading effects but did not explore irregular shapes, which should be considered in future research. The large number of simulated conditions made comparisons challenging, potentially introducing minor errors in shaded-area verification. The research was conducted in a warm environment, suggesting that countries with similar climates could benefit from the findings. Cold countries should further examine the findings for validation. Furthermore, during the researchers' investigation, it was discovered that the Revit software enhances the research outcomes. However, the methodologies are still evolving, allowing the possibility of conducting the simulation using different programs that are more specialized in accurately calculating the amounts of light and shadow, since Revit simulations may be slower or less efficient than those of software explicitly designed for simulation purposes.

This study examined humans' thermal comfort but not their thermal sensation. The psychological effects on humans from the courtyard shapes are not discussed in this study. Turhan et al. [1] stated that the mood state plays a role in identifying the level of thermal sensation/comfort in humans. Therefore, further investigation should combine these study findings with the mood state of humans in order to maximize the thermal comfort/sensation of humans.

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