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Performance-based Evaluation of Courtyard Design in China's Cold-Winter Hot-Summer Climate Regions

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Abstract: A courtyard is a traditional and popular construction feature found in China's urban buildings. This case study evaluates the performance of the traditional courtyard design of the Jiangnan Museum, located in Jiangsu Province. In the evaluation, the spatial layout of courtyards is adjusted, the aspect ratio is changed, and an ecological buffer space is created. To model and evaluate the performance of the courtyard design, this study applied the CFD software PHOENICS for wind environment simulation, and EnergyPlus-based software DesignBuilder for energy simulation. Results show that a good combination of courtyard layout and aspect ratio can improve the use of natural ventilation by increasing free cooling during hot summer and reducing cold wind in winter. The results also show that ecological buffer areas of a courtyard can reduce cooling loads in summer by approximately 19.6% and heating loads in winter by approximately 22.3%. The study provides insights into the optimal design of a courtyard to maximize its benefit in regulating the microclimate both during winter and summer.

Keywords: courtyard design; ecological effect; layout; aspect ratio; ecological buffer area

1. Introduction

In traditional Chinese architectural design, construction typologies associated with human needs—including shelter, work, and rest—were structured around an open space, usually called a courtyard. The courtyard is an ancient concept, where interior spaces are distributed around a central, open space. Courtyards are still used today around the world, taking advantage of local climate characteristics. They remain a traditional building component in Asia, the Middle East, South America, and Mediterranean countries [1–5]. Jang and Ham [6] conducted a study of courtyard-type apartments in South Korea, reviewing the layout, access, and number of the courtyard story. Han, et al. studied the courtyard-integrated ecological system in China and its important economic-environmental benefit [7]. Sun [8] investigated the traditional courtyard space and studied the impacts of natural elements such as light, water, and soil on the traditional dwellings in southern Anhui Province and Jiangsu, Zhejiang and Fujian provinces. Courtyards have contributed to improved micro-climates, creating comfortable interior spaces. Several researchers have shown that courtyards can have significant impacts on the thermal comfort and performance in buildings [9,10]. Ghaffarianhoseini et al. analyzed the thermal characteristics of unshaded courtyards in the hot and

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humid climates of Malaysia with ENVI-met software [11]. Adi et al. studied different natural ventilation approaches in eight student rooms in a residential college building with an internal courtyard arrangement [12]. In the Dariya Dwellings, part of a United Nations experimental project in Saudi Arabia, Fathy applied the traditional internal courtyard model to create an area protected from the dry and hot climate, making use of shades to provide architectural cooling [13]. Taleghani et al. studied heat in urban courtyard microclimates in the Netherlands, providing evidence of their promise as strategies for cooling cities [14]. Jara et al. studied the thermal microclimate by characterizing the air temperature drop in courtyards through monitoring campaign [15]. Martinelli presented a numerical analysis of the thermal comfort of courtyards in Italian climate zones and considered the effects of height/width proportions, finding results that can have a stabilizing effect on thermal comfort for both winter and summer seasons [16]. Micallef et al. [17] researched the influence of courtyard height on the cross-ventilation of a room abating a courtyard building. Mousli and Semprini conducted a case study in Damascus to analyze thermal performances of traditional houses in hot, arid climates in the area [18]. Fernandez et al. identified and proposed a geographic information system (GIS)-based exploration of relationship between aspect ratio of inner courtyards, porosity of urban fabric and climatic factors [19].

Courtyard spaces can provide climatic protection and building buffer areas that can regulate local microclimates and passively reduce building energy consumption [20–25]. For example, Muhaisen and Gadi analyzed the effect of courtyard proportions on solar heat gain and energy requirements in the temperate climate of Rome [26]. Vaisman and Horvat analyzed the influence of internal courtyards on energy load and hours of illuminance in row houses in Toronto, Canada, to develop performance and design information [27]. Yasa and Ok [28] evaluated the effects of courtyard building shapes on solar heat gain and energy efficiency in various climate regions. Al-Masri et al. [1] simulated the environmental performance of courtyard-type housing in midrise buildings for an environmental assessment by analyzing the energy cost and daylight, considering materials of the courtyard in hot-arid climate. Zhu [29,30] and Liu [31] researched the ecological strategy of traditional dwellings (e.g., simulating indoor thermal environments in traditional civil dwellings during summer in Anhui Province and a study of the wind movement in traditional quadrangle courtyards. In addition, Xu and Luo [32] studied passive cooling techniques in traditional civil dwellings and conducted qualitative and quantitative evaluations of the wind and thermal environment in traditional civil dwellings, using ecological simulation software. Yang also conducted a simulation-based analysis of a courtyard in Beijing, analyzing courtyard surface temperature distribution, to develop effective methods for mitigating or managing the micro-heat-island effect [33]. Sadafi et al. [34] evaluated the thermal effects of internal courtyards in a tropical terrace house by computational simulation [35–37].

Current studies generally focus on filed measurements and simulation-based analysis for existing courtyards by considering passive ventilation, thermal comfort, and energy saving. Previous studies of the ecological effects of courtyards use the simulation analysis of traditional Chinese courtyards and lack sufficient consideration on how to build a desirable micro-climate environment for newly planned and designed courtyard buildings. More insight and guidance are needed to regulate and control different factors that influence the thermo-environment of courtyards in the design phase [38–40]. This study uses the design phase of Jiangnan Museum as a case study. According to the original design parameters, this study proposes an improved design considering the courtyard layout, the aspect ratio, and the ecological buffer area. The PHOENICS software for wind environment simulation and the EnergyPlus-based software DesignBuilder for energy consumption simulation are employed based on the physical parameters of courtyards.

This study:

(1) Proposes courtyard design strategies in terms of layout, aspect ratio, and ecological buffer areas in China’s cold-winter hot-summer climate region.

(2) Evaluates the impact of proposed design on the outdoor and indoor ventilation, thermal comfort, and energy efficiency of courtyards.

(3) Provides insights for courtyard design considering local climate, courtyard geometry, and micro-ecological impact.

2. Method for Courtyard Design Optimization

2.1. Research Framework

China spans a variety of geographic latitudes. Courtyard design must take into account, and respond to, various natural and cultural environments and local conditions and climates [41]. Upon those, this study applied a methodological framework consisting of field investigation, design parameters selection, simulation models, and results evaluation of design alternatives, which is shown in Fig. 1. In field investigation, this study gave an overview of weather conditions, typical forms of the courtyard in Southern Jiangsu Province, and case study information of Jiangnan Furniture Museum. Secondly, based on an initial design of courtyard, this study proposed improved design strategies with consideration of layout, aspect ratio, and an ecological buffer area. In the simulation process, two typical software, EnergyPlus-based DesignBuilder for energy use and PHOENICS for building wind environment simulation, were applied in typical summer and winter seasons to compare field wind speed, and the impact of ecological buffer area on room natural temperature and energy use. Finally, recommendations were made with some design strategies for the design phase of future courtyards.

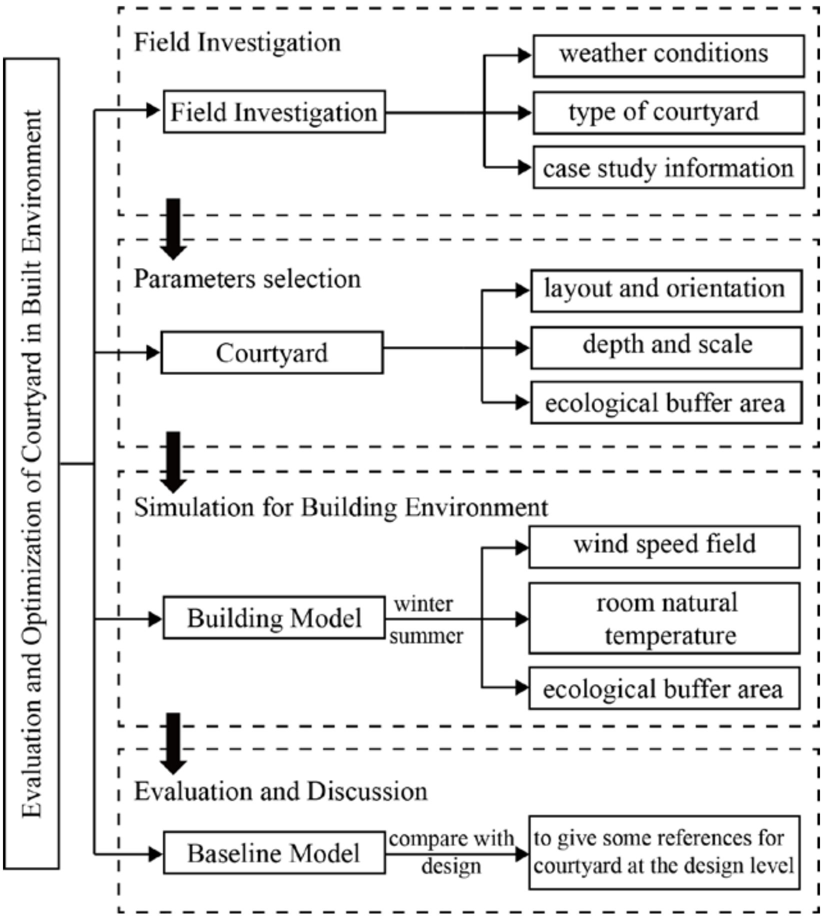


Fig 1. Overview of research approach and workflow of this study.

2.2. Field Investigation

Jiangnan Furniture Museum, designed by Academician Jianguo Wang of Southeast University, is a large building complex located in Yixing, a city famous for its history and culture in southern Jiangsu Province. Southern Jiangsu Province features crisscrossed rivers and lakes, a large population, and relatively high building density with relatively little land. The museum is located to the west of Qiansu Marsh, and is blessed with flat terrain, a graceful environment, and a superior geo-location and traffic location. The total planned construction area of the Jiangnan Furniture Museum complex is about 84,470 m². Its eastern side contains the main body of the museum—a site area of about 57, 802 m² including the Furniture Museum, Red Stoneware Museum, Sundry Exhibition Hall, and the Expert Buildings. Its western side is used for supportive commercial facilities, covering an area of about 26, 668 m². Fig. 2 shows the layout of the Jiangnan Furniture Museum complex and the Expert Buildings. T black dotted area is the research scope of this study.

Field investigation and data collection for the building project provided an initial understanding of its geo-location, cultural condition, natural endowment, and physical parameters related to the local courtyard design (e.g., local temperature, humidity, wind direction, solar radiation, and other climatic parameters). Southern Jiangsu Province is a typical area, hot in summer and cold in winter. Summer daytime temperatures range from 30℃-35℃ with temperature highs of 37℃-39℃, occasionally up to 40℃, and a winter temperature range of -10℃-5℃. The dominant wind directions in winter and summer are different: a north wind in winter and a southeast wind in summer. Reducing heat in summer and retaining heat in winter are key goals for local building design [42]. In regions with a cold winter and a hot summer, courtyard design against summer and winter should take into consideration conditions of extreme hot and cold seasons together, and it is possible to propose a courtyard design solution which is comfortable and energy-efficient both in winter and summer by reasonably settling building ventilation and courtyard distribution. Therefore, hot-summer and cold-winter climate characteristics should be considered first of all on the thermal environment and energy efficiency of traditional courtyards in southern Jiangsu Province [38].

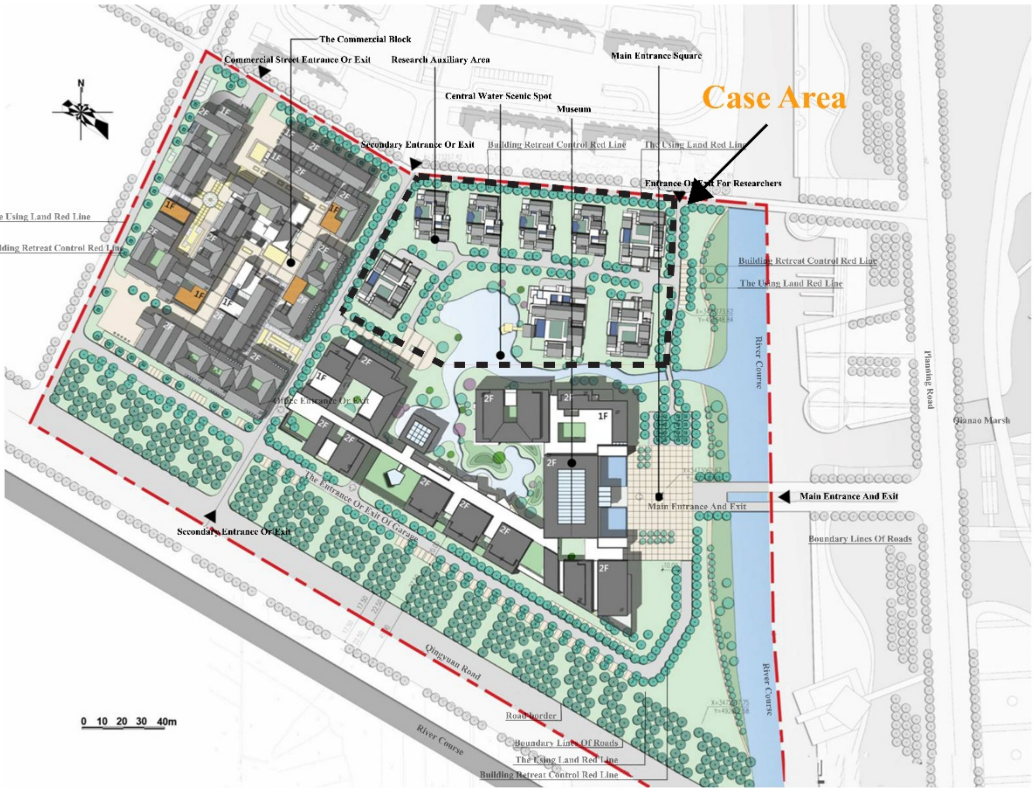


Fig 2. The layout of Jiangnan Furniture Museum complex and Expert Building area (black dotted line).

2.3. Courtyard Design Optimization

Courtyard layout influences building heat gain from solar radiation, and a natural ventilation system incorporating the courtyard area influences the convective heat transfer in residential areas [43]. However, most designers put more emphasis on the visual effect of peripheral landscapes and the layout of spaces with different functions, with little attention to ventilation in courtyard buildings and how to improve the thermal environment of courtyards. To fill this research gap, this study used the Expert Building area of Jiangnan Furniture Museum as a case study—a typical model of the "two halls and one courtyard" design type, to demonstrate, through numerical simulations, the performance-based evaluation of courtyard design integrating the ecological effects. In southern Jiangsu Province, the northern wind is piercingly cold in winter while it is hot and humid in summer. In addition, it is extremely hot and humid in the Plum Rain Season. Natural ventilation can remove the residual heat and moisture from buildings in hot seasons and improve the comfort of dwelling spaces. The active wind field can bring in the fresh air and help to discharge indoor air, thus promoting human physical and mental health.

Therefore, the courtyards should consider such natural conditions and make full use of passive ventilation and natural lighting to meet the daily use requirement of buildings as well as reduce the heating, ventilation, and air conditioning systems' energy consumption. In this study, research on the traditional Chinese quadrangle dwellings prototype is applied. During modeling, the central yard of a quadrangle dwelling was placed on one side, its backyard removed into a reverse setting with a three-section compound. Next, a small-scale courtyard space was added, to enrich the form of courtyard space. Third, rich spatial layers were built in connection with the landscape view and with the use of the grey and white walls.

Scheme generation and evaluation were conducted using the simple ecological principle of the traditional courtyards to regulate the micro-climate. Impact analyses were also conducted to determine the effects of spatial layout and courtyard aspect ratio on wind environment and the impacts of the ecological buffer space on the thermal environment of courtyards.

2.3.1. Adjusting Spatial Layout of Courtyards

Orientation has a direct impact on the ecological effect of courtyard buildings. A reasonable spatial layout of a courtyard can control solar heat. Moreover, the natural ventilation system of a courtyard controls convective heat transfer. Designers tend to put emphasis on the layout between the peripheral landscape environment and the plane function of courtyards, but pay little attention to their ventilation effect. Ecological effects of courtyard layout have not yet been systematically studied [1,44].

This study attempts to adjust courtyard orientation of the Expert Building Area of the Jiangnan Furniture Museum, to ascertain the ecological effect of its spatial layout. As shown in Fig 3, in the initial design, the entire courtyard opening of the Expert Building faces west; enclosure strength on the northwestern corner is not high. In the improved design, the courtyard is opened toward the southeast to maximize ventilation in summer using wind pressure—and it closes access toward the northwest to avoid cold winter wind currents. In further refinements, to meet other basic requirements, the courtyard opening is adjusted to face the east, and the enclosure degree on the northwestern corner is increased, which improves the courtyard wind environment compared with the initial design.

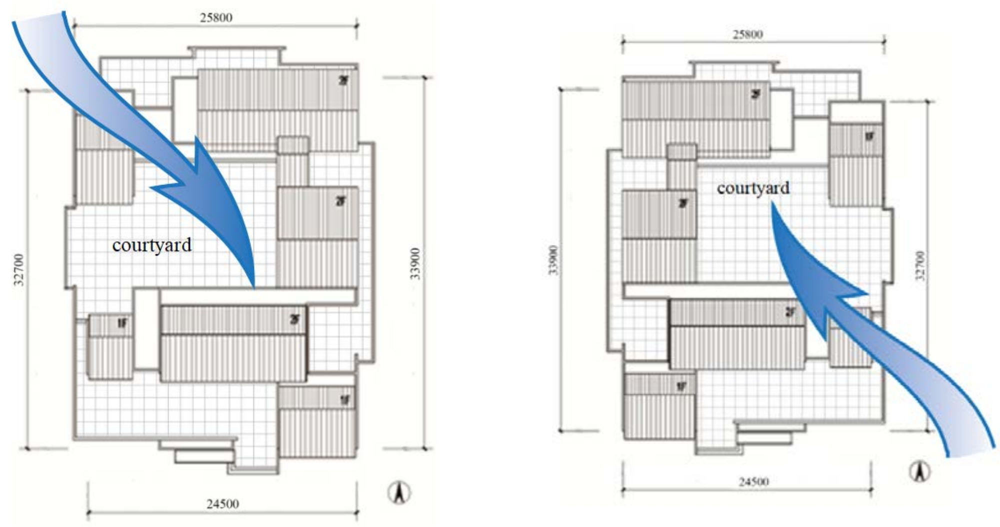


Fig 3. Courtyard's spatial layout: initial design (left), improved design (right).

2.3.2. Adjusting Aspect Ratio of Courtyards

Residential buildings in southern Jiangsu Province are generally very tall, and have narrow patios on the backside with a large height-to-width ratio. This kind of design can use two types of forms:

1) A combination of two courtyards: the southern bigger one and the northern smaller one—in transitional seasons, wind flows toward the rear patio through the narrow corridor and the house due to wind pressure in the horizontal direction

2) A type of layout with a larger height-width ratio, which can increase the "chimney effect" in the rear patio and increasing ventilation.

The two types supplement each other to achieve a better ventilation effect. The superior effect of natural ventilation of traditional courtyards in southern Jiangsu Province is closely related to the aspect ratio of the spatial layout of the courtyards. In the process of courtyard design, the designer tends to emphasize spatial effect and landscape view, but pay little attention to the ventilation effect, so that height-width ratio improvement of courtyards is usually ignored.

This study conducted a simulation analysis of the layout and ratio scale of the front and rear courtyards of the south-to-north house on the northernmost side of the Expert Building Area. The courtyard in front of the house in the initial design has a large depth. Therefore, the ratio scale of the patio behind the house is changed in the improved design, including (1) the depth of the courtyard to the south of the house is increased moderately to facilitate wind-driven ventilation; (2) to the north of the house, the patio is enclosed with a solid wall to enable the thermal pressure to induce the wind. This study tentatively applies the ecological strategy of enclosing the patio behind the house in the improved design, as shown in Fig. 4.

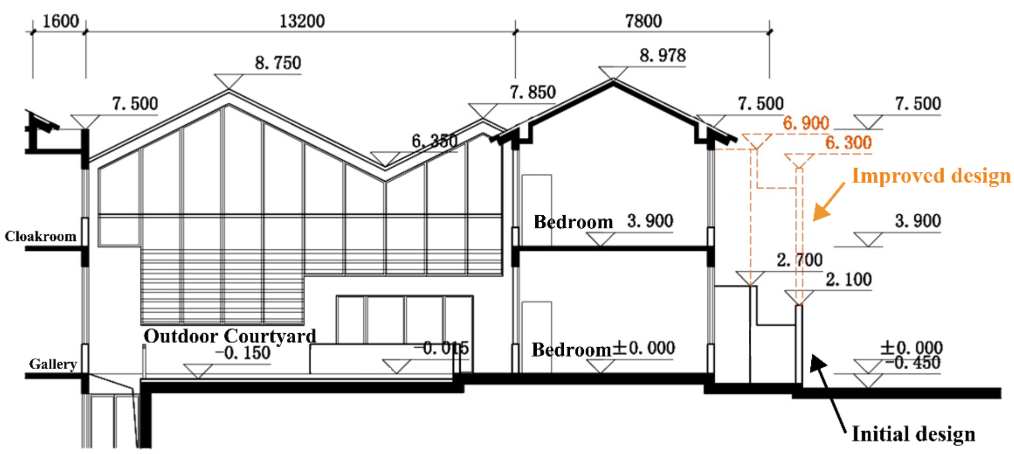


Fig 4. Illustration of the initial design and the improved design.

2.3.3. Adjusting Ecological Buffer Spaces

The micro-climate regulation function of ecological buffer space is that (1) a climatic buffer area with a gradient difference is set up between the building and its surroundings so that the impact of various extreme climatic effects on the indoor environment can be reduced to a certain extent; and (2) the exchange of climatic factors between the outside and the inside of the building can be regulated. This climatic-critical space can not only meet users' various demands of physiological comfort but also promote the adaptability of the human body to climatic changes.

The design of a suitable ecological buffer space is significant in the control of solar radiation. In summer, the ecological buffer space is open to the outdoor environment. Owing to its sheltering effect on solar radiation, the initial indoor air temperature is lower than the outdoor temperature. When outdoor temperature rises, air flow rate will increase due to the thermal convection between the internal and external air, thus, cooling the external wall of the indoor spaces. On the other hand, rooms are connected through the ecological buffer space, so that each indoor space reduces in size and becomes a "shade island;" the indoor area that needs to be conditioned is reduced considerably. In winter, owing to the low solar altitude, sunshine can directly reach the internal and external walls. If the traditional ecological buffer space is improved by closing it with transparent and thermally insulating materials (like double glazing), the solar radiation produces a greenhouse effect. The enclosed ecological buffer space is heated, thus, increasing temperatures of the internal building surfaces and reducing the heating load.

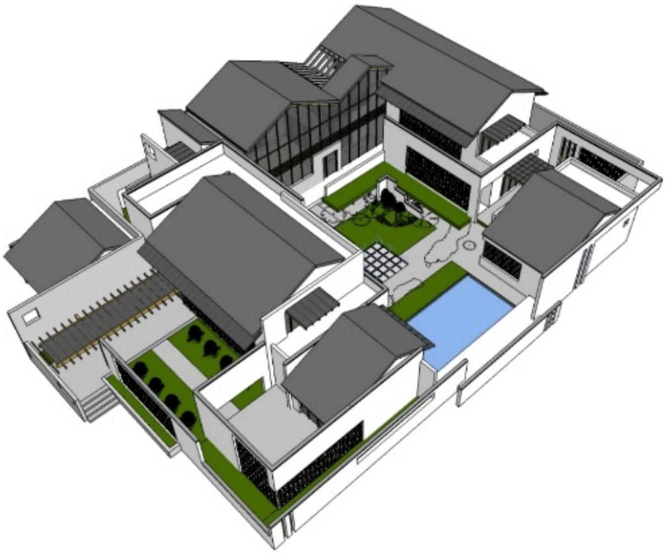
To evaluate the effect of the ecological buffer space, this study considered the effects of its treatment under different circumstances in winter and summer on building energy consumption. The initial design gave little consideration to the micro-climate regulation function of the ecological buffer space of courtyards and lacked a variability consciousness to the boundary treatment of courtyard. Also, the initial design completely mixed the buffer spaces and the indoor spaces, and segmented indoors and outdoors with a glass curtain wall so that the micro-climate regulation function of courtyards could not be used effectively. In the improved design, buffer spaces from the initial design were adjusted, and the boundary was clarified using buffer spaces (i.e., room and corridor, balcony and sunshade terrace on the plane), so that the ecological buffer spaces could have a certain spatial form. Also, a buffer space was added for the south-facing rooms, which is opened in summer and closed in winter, as shown in Fig 5.

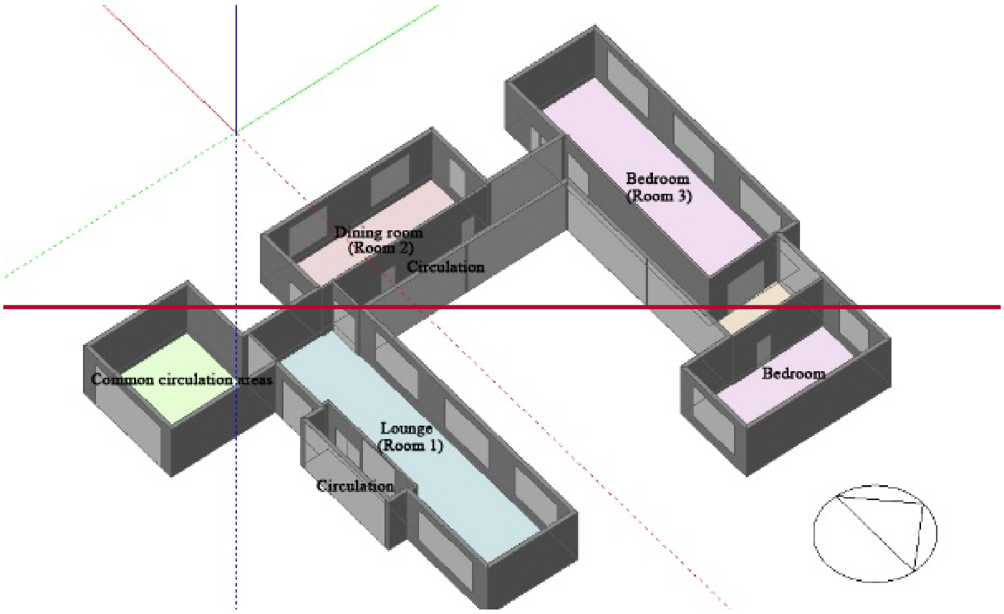
Fig 5. The ecological buffer spaces: initial design (left), improved design (right).

2.4. Details of Simulation Model

To test the performance of the courtyard under the initial and improved designs, this study applied wind environment simulation using the PHOENICS software and the energy consumption simulation using the DesignBuilder software. PHOENICS is a general-purpose commercial CFD code which is applied to steady or unsteady one-, two-, or three-dimensional turbulent or laminar, multi-phase, compressible or incompressible flows. In this study, it was used to simulate wind movement in both the initial design and the improved design to assess the impact of layout and ration scale of the courtyard on the ventilation. DesignBuilder is an advanced modeling tool using EnergyPlus as the calculation engine that provides an easy-to-use interface enabling development and evaluation of comfortable and energy-efficient building designs from the concept through completion. This study used DesignBuilder to simulate the cooling and heating loads with typical weather data for the initial and improved designs of the courtyard.

The Expert Building area of Jiangnan Museum was selected as the "two courtyards and one hall" type layout. Fig. 6 shows the simulation model developed in this study. Table 1 lists the parameters for the simulation models. In the typical weather data, the wind in south regions of the Yangtze River is mainly the southeast direction. The outside wind speed was selected as 3.2 m/s. Two orientations were simulated by locating the courtyard east and west, respectively. In the natural room temperature (free-floating temperature) and energy simulation, this study selected the three bedrooms as the target area and conducted simulations in January (coldest month) and July (hottest month). The simulation step is one hour.




Bedroom
(Room 3)
Dining room
(Room 2)
Circulation
Common circulation areas
Bedroom
Lounge
(Room 1)
Circulation

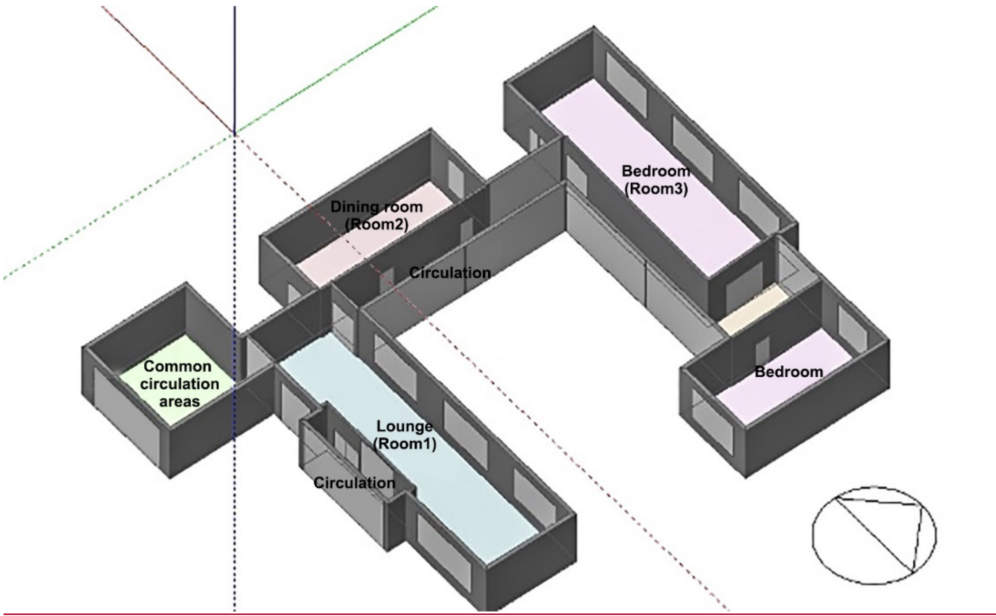

Bedroom
(Room3)
Dining room
(Room2)
Circulation
Common
circulation
areas
Bedroom
Lounge
(Room1)
Circulation

Fig. 6. The simulation model of the courtyard building.

Table 1. Simulation parameters settings.

Basic physical information	
Total area and volume	798.58 m^2 and 3467.052 m^3
Room 1	Lounge room, 19.90 x 7.00 x 3.90 (m)
Room 2	Dining room, 11.20 x 4.30 x 3.90 (m)
Room 3	Bedroom, 16.60 x 5.80 x 3.90 (m)
Weather condition	Typical outside weather condition
Pressure	Standard pressure (101.3kPa)
Wind Profile simulation settings in PHOENICS	
Grid	150 (X) x 180 (Y) x 50 (Z)
Turbulence model	k-ε model standard model
Residuals of convergence	Continuity, momentum, turbulent kinetic 10-4 Energy turbulent dissipation rate 10-6
Number of simulation iterations	10000
Energy simulation settings in DesignBuilder	
Simulation period	Winter: January 1 to 31; summer: July 1 to 31
Simulation step	1 hour
Type of air conditioning	Split-type air-conditioners
Occupancy for room	0.0167 person/m^2
Occupancy schedule	DesignBuilder default schedule for room type
Thermal setting	Summer: 26 ℃ Winter: 22℃
Ventilation	ASHRAE Standard 62, 0.0038 m^3/(s·person)
Shape coefficient of building	＞0.4
Thermal inertia index (D)	＞2.5
Window-wall ratio	North: 0.4; South: 0.45
Heat transfer coefficient W/(m^2·K)	Window: 2.5 Wall: 1 Roof: 0.6
Window shading coefficient	0.4

3. Results of performance evaluation

3.1. Results of Adjusting Spatial Layout of Courtyard

During the simulation, it was indicated that the southeastern wind with a southward deflection degree of 19° is the dominating wind in summer and the northwestern wind with a northward deflection degree of 15° is the dominating wind in winter in the region to the south of the Yangtze River. During the simulation calculation, the height of 1.2 m was selected to describe wind profiles. The direction of summer monsoon was selected as the southeastern wind, with a wind speed of 3.2m/s; the direction of winter monsoon was selected as the northwestern wind, with a wind speed of 3.1m/s, and selected the urban area of cities as the underlying surface. Under the same conditions of parameter calculation, PHOENICS was used to simulate the outdoor state of wind environment. Fig. 7 and 8 show wind simulation results.

Fig 7 show that, in the initial design, the building is enclosed in the southeast direction of the windward side in summer, and the entire courtyard is in the large wind shade area, shaded by the enclosed building. The average wind speed in the courtyard is about 0.5m/s. In the improved design, the entire layout of the courtyard building is low in the southeast and high in the northwest. The courtyard faces east; the summer monsoon directly blows into the courtyard from the southeast direction, inducing cross ventilation. In the improved design, the wind speed at the opening can reach 1.75m/s, which shows a speed comfortable for occupants.

Next, the impact of the courtyard layout on the wind field in winter was considered. As inferred from Fig. 8, in the initial design, the building on the windward side in winter is low and does not have a high degree of enclosure. The highest wind speed at the opening can reach 2m/s. The average wind speed in the courtyard is 0.75 to 1 m/s, a speed that occupants will feel and may be uncomfortable in winter. In winter, the cold current blows from the northwest to the courtyard building. The degree of the enclosure on the northwestern corner is high, and that corner becomes the wind screen of the courtyard. Average wind speed in the courtyard is about 0.25 to 0.5m/s, conducive to the thermal insulation and energy saving of the courtyard building.

Wind environment simulations of the initial design and the improved design in winter and summer show that the courtyard orients to the southeast and is closed to the northwest. This information can help to guide other designs of courtyards in the region to the south of the Yangtze River.

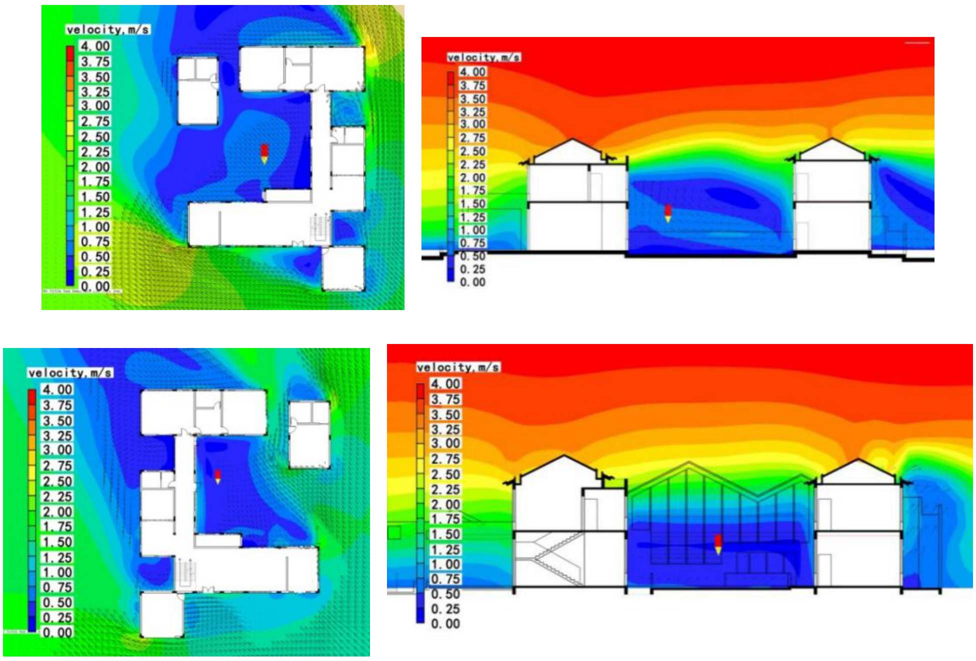
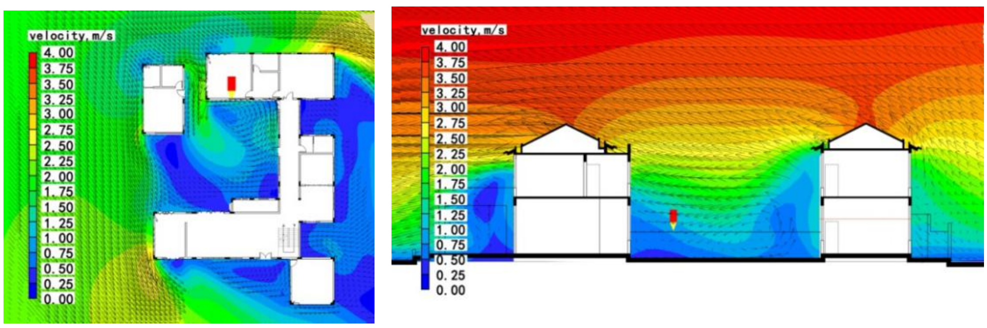


Fig 7. The sectional plan of the wind speed contour of the courtyard in summer under the initial design (top) and improved design (below).



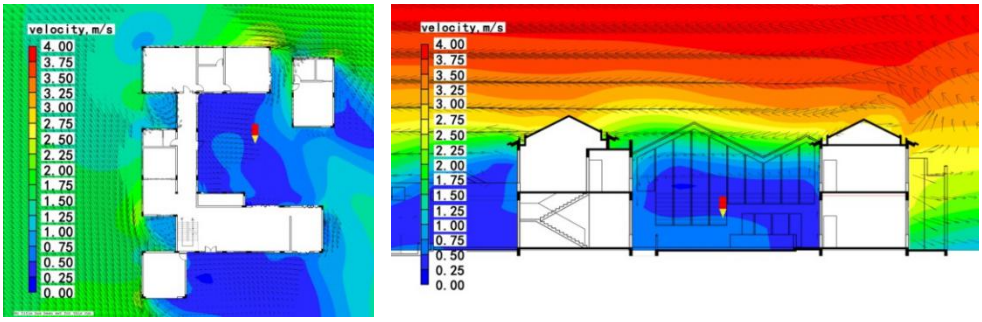


Fig 8. The sectional plan of the wind speed contour of the courtyard in winter under the initial design (top) and improved design (below).

3.2. Results of Adjusting Aspect Ratio of Courtyard

Based on different considerations of its northern enclosing walls, in the initial design, the northern enclosing wall of the house is low, and there is no rear patio space, while in the improved design, the northern enclosing wall of the house rises, and there is a rear patio. This study analyzed the impact on the indoor wind environment under different meteorological conditions in the two designs in both winter and summer.

The same climate parameters and simulation software mentioned in Section 3.1 is used to improve the aspect ratio of the courtyard. Evaluation results of the summer monsoon environment from Fig. 9 show that the northern enclosing wall is low, the patio is too low, and the effect of thermal pressure inducing the wind is weak in summer in the initial design. Therefore, the improved design raises the northern enclosing wall, together with the roof eave, forming a rear patio. In summer, the air at the opening of the rear patio rises after being heated and pulls the air from the bottom of the patio upward, so that the thermal effect increases ventilation. In the improved design, the wind speed in the rear patio space ranges from 0.5 to 1.0 m/s, within the human comfort range.

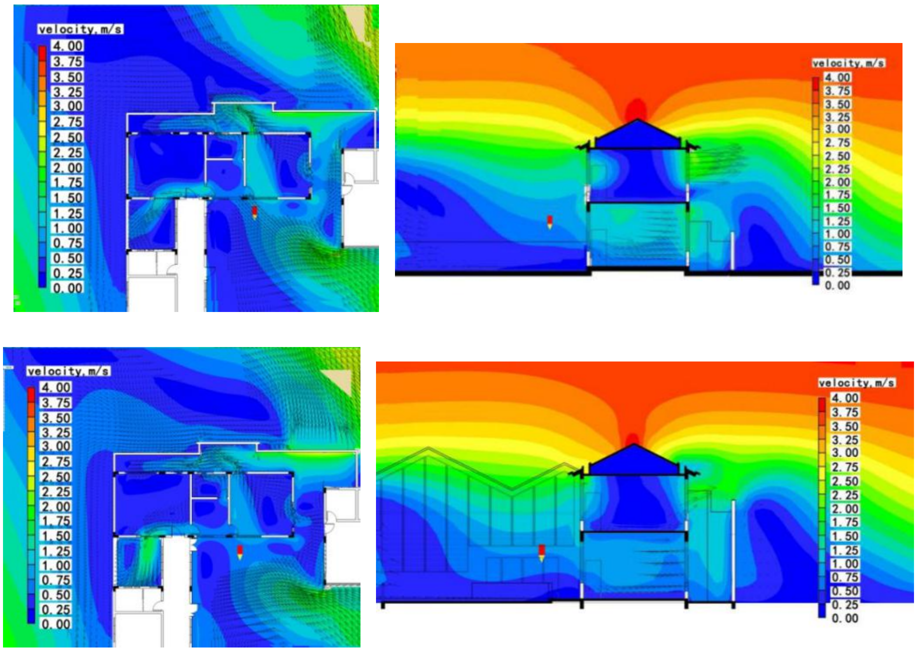


Fig 9. The sectional plan of the wind speed contour in summer under the initial design (top) and improved design (below).

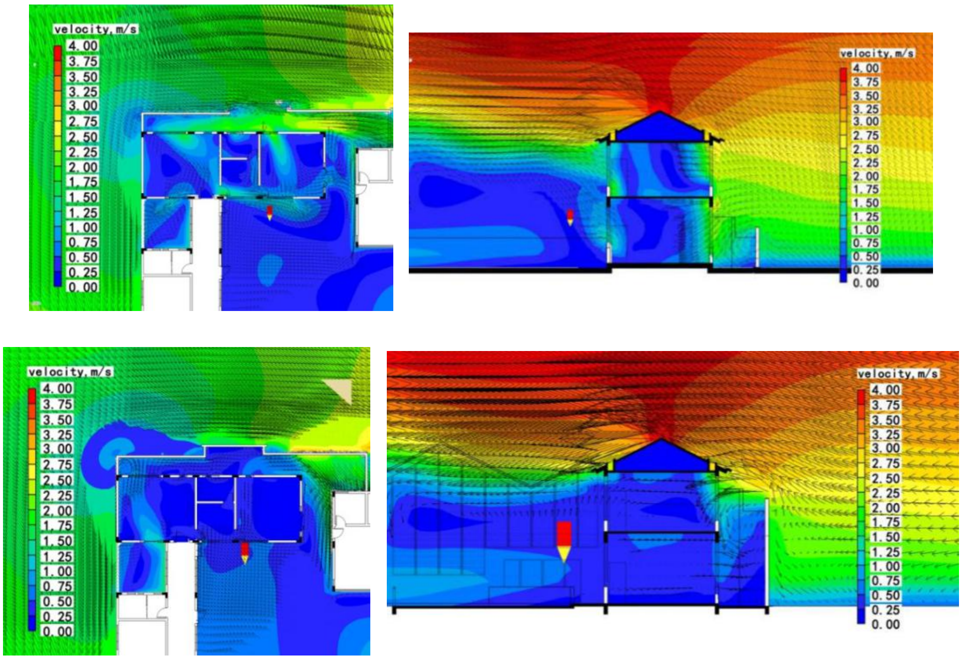


Fig 10. The sectional plan of the wind speed contour in winter under the initial design (top) and improved design (below).

Evaluation results of winter wind environment from Fig. 10 show that the northern enclosing wall is low in the initial design. The wind blows from the northwest to the building in winter, and there is no necessary obstruction on the northern side. This leaves the entire courtyard building vulnerable to the high-speed cold air, which reduces thermal insulation in the residential environment. After the northern enclosing wall is raised and improved, most of the cold wind is obstructed—the indoor wind speed of the building on the northern side declines tremendously in comparison with the wind speed in the initial design, thus ensuring a desirable thermal environment in winter. The comparative analysis of the wind environment in the initial design and the improved design in winter and summer shows that a solid wall to enclose a patio on the northern side of the house increases ventilation due to the interplay of both wind and thermal pressure. In addition, enclosing the patio with a solid wall on the northern side of the house can help to keep cold wind from penetrating indoor spaces in winter.

3.3. Results of Adjusting Ecological Buffer Space of Courtyard

To study the impact of the buffer space on the ecological climate of a courtyard, ~~tenergy consumption in the initial and improved designs were evaluated under different climatic conditions (winter and summer).~~ his study simulated the indoor air temperature of courtyard building without air system to validate natural indoor air temperature under improved and initial designs under different climatic conditions (winter and summer). Also, this study simulated energy consumption in the initial and improved designs were evaluated if air-conditioning systems are applied to eliminate building loads under different climatic conditions (winter and summer). Comparative statistics of the ~~day-by-day~~daily natural average natural temperature and air-conditioning load in the hottest month (July) and the coldest month (January) were ~~reviewed~~ presented for Room 1, Room 2, and Room 3, which are showed in Fig. 11 and 12. Table 2 also summarizes the results of average natural room temperature, peak load, and total load of three rooms in summer and winter from the simulation. ~~.~~In summer, the improved design opens the ecological buffer space wide. As shown in Fig. 11, Room 1 and Room 2 did not consider the ecological buffer effect in the initial design, and the indoor natural temperature in summer is higher than that of the improved design, which conducts opening treatment to the buffer space. In the initial design, Room 1 connects to the corridor space, hallway, and other usable spaces. Its large-area glass curtain wall in the corridor space completely isolates the indoors from the outdoors but creates a large air-conditioning load [45]. In the improved design, the ecological buffer space of courtyard is adjusted to open the corridor space wide. Some buffer spaces are additionally built on the southern side of Room 1 and the effect becomes more obvious after improvements. The results show that at the beginning of the hottest month (from 1st to 9th, July), the outdoor air temperature is relatively low, the temperature results in initial design and improved design are very close. On the remaining days, the improved design can reduce temperature of courtyard around 1 ℃. In winter, the improved design closes all ecological buffer spaces. Fig. 13 shows, when ecological buffer spaces are closed in winter, the air in the buffer spaces would continuously heat up due to solar radiation, with a higher room temperature than that of the practice of partially open buffer spaces in the initial design. For example, the average room temperature in Room 1 in the improved design is 1℃ higher than that in the initial design. As showed in Table 2, results show that the average natural room temperature in Room 1 can be reduced by about 1 ℃ and increased by about 2℃, in summer and winter, respectively; while the average natural room temperature in rooms 2 and 3 can reduce a little compared with the initial design in summer, while in winter the improved design can increase 1.4 and 2.2 ℃ in Room 2 and 3, respectively.[WW1]

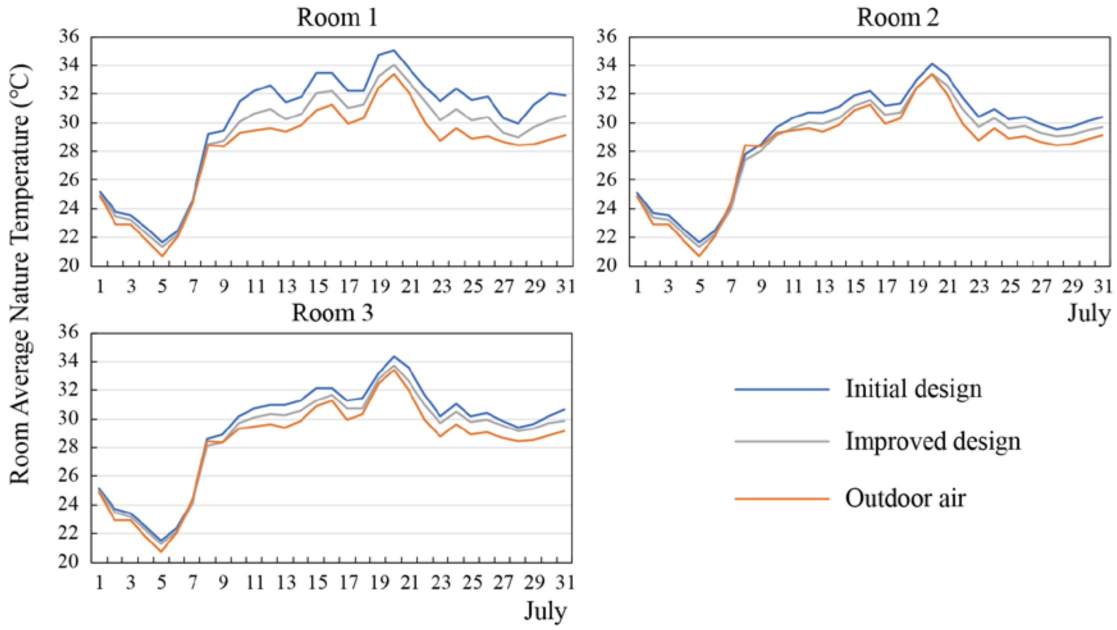


Fig. 11. The average nature temperature results for three rooms in summer for initial design, improved design, and outdoor air.

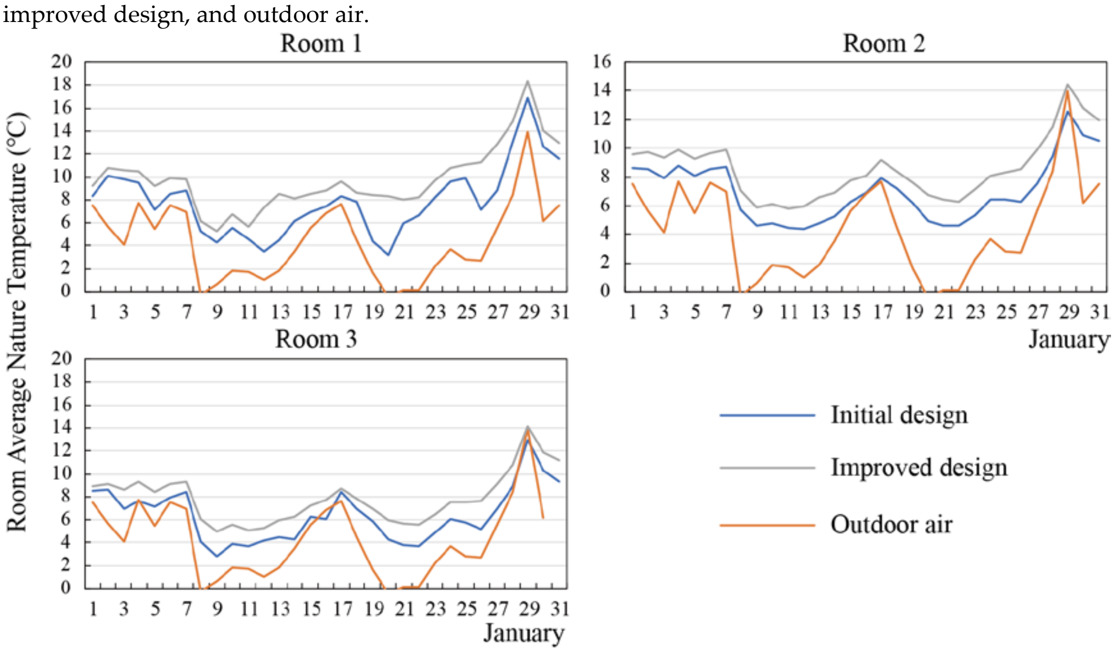


Fig. 12. The average nature temperature results for three rooms in winter for initial design, improved design, and outdoor air.

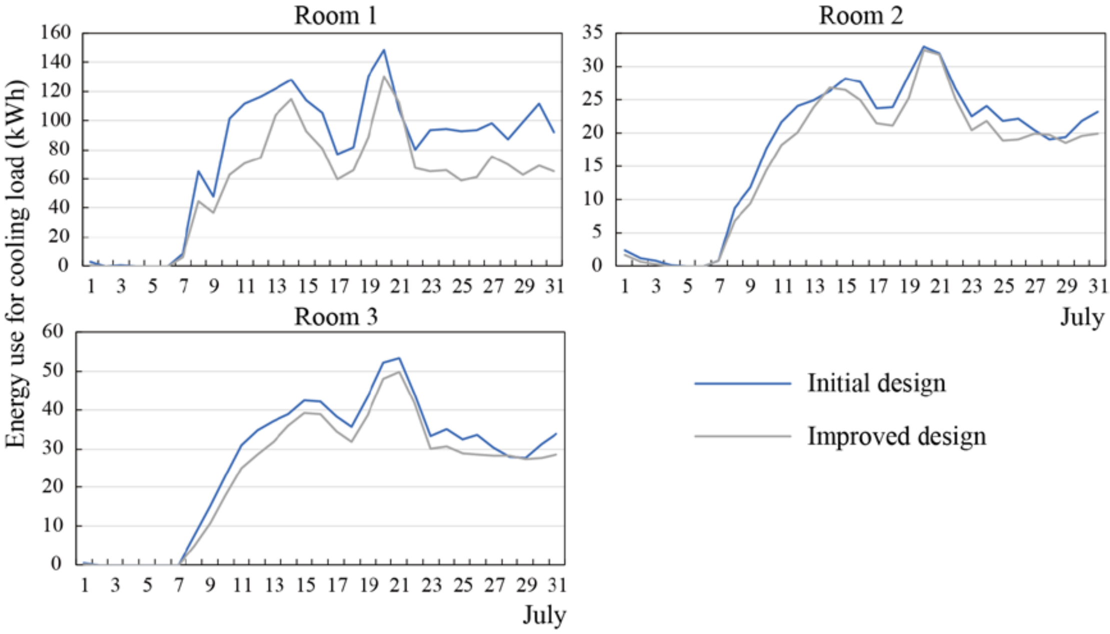


Fig. 13. The energy use for thermal loads in rooms 1, 2, and 3 in summer under initial design and improved design.

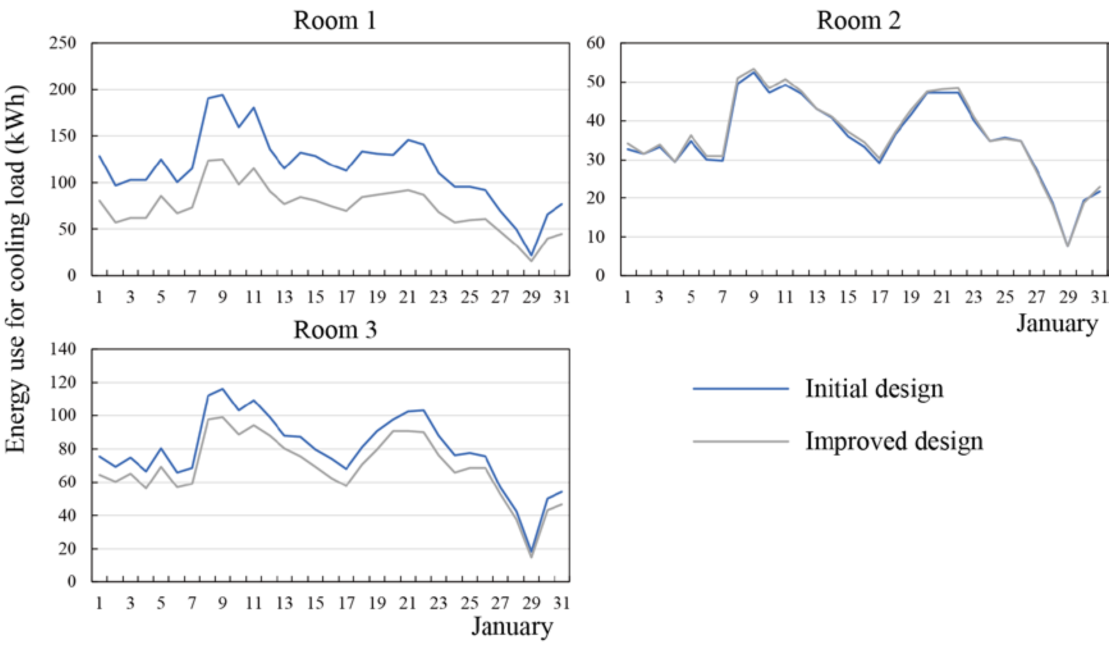


Fig. 14. The energy use for thermal loads in rooms 1, 2, and 3 in winter under initial design and improved design.

Fig. 13 shows energy use for cooling, which indicates the improved design can reduce the energy use for cooling. Fig 14 shows that enclosing the buffer space in winter can achieve overall energy saving in the courtyard building. ~~Table 2 summarizes the results of average natural room temperature, peak load, and total load of three rooms in summer and winter from the simulation. Results show that the average natural room temperature in Room 1 can be reduced by about 1 ℃ and increased by about 2℃, in summer and winter, respectively; while the average natural room temperature in rooms 2 and 3 can reduce a little compared with the initial design in summer, while in winter the improved design can increase 1.4 and 2.2 ℃ in Room 2 and 3, respectively.~~ Peak cooling load and the total cooling load in summer in Room 1 are reduced by 12.4% and 25.09%, respectively; 35.7% of peak heating load and 36.1% of total heating load can be saved in winter. In Room 2, the improved design saves 1.8% and 8.8% of peak and total cooling load, respectively in summer. However, in winter, the improved design couldn't save energy and has a very similar performance with the initial design. In Room 3, the improved design reduces 6.2% and 10.7% of peak and total cooling load, respectively in summer, and reduces 14.7% and 12.8% of peak and total heating load, respectively in winter, when compared with the initial design. Considering the total performance of the three rooms, the improved courtyard design can save about 19.6% of cooling loads in summer and about 22.3% of heating loads in winter, proving that the improved courtyard design scheme can improve performance and reduce energy use.

400 **Table 2.** Performance results in the three rooms in summer and winter.

		Room 1			Room 2		
		Initial design	Improved design	Reduce/increase	Initial design	Improved design	Reduce/increase
Summer	Average natural room temperature (℃)	35.0	34.0	1	34.1	33.4	0.7
	Peak cooling load (kWh)	148.8	130.3	12.4%	33.1	32.5	1.8%
	Total cooling load (kWh)	2409.8	1805.1	25.09%	558.8	509.6	8.8%
Winter	Average natural room temperature (℃)	3.2	5.2	2	4.4	5.8	1.4
	Peak heating load (kWh)	193.7	124.6	35.7%	52.5	53.3	-1.5%
	Total heating load (kWh)	3600.7	2297.5	36.1%	1107.8	1126.0	-1.6%
		Room 3			Total		
		Initial design	Improved design	Reduce/increase	Initial design	Improved design	Reduce/increase
Summer	Average natural room temperature (℃)	34.3	33.7	0.6	-	-	-
	Peak cooling load (kW)	53.2	49.9	6.2%	-	-	-
	Total cooling load (kW)	823.9	735.4	10.7%	3792.5	3050.1	19.6%
Winter	Average natural room temperature (℃)	2.8	5.0	2.2-	-	-	-
	Peak heating load (kW)	116.2	99.1	14.7%	-	-	-
	Total heating load (kW)	2453.3	2140.4	12.8%	7161.8	5563.9	22.3%

Note: reduce (%) = (initial design – improved design) / initial design

This study compared the different design strategies for different climatic conditions in winter and summer. Looking at both ecological buffer space and energy consumption simulation results for the initial design, it is clear that installing operable glass curtain walls in such buffer spaces as corridor and passage, opening them wide to dissipate heat in summer and close them to preserve heat in winter, and using additional buffer spaces for the south-facing house improves expected performance. In real projects, attention should be paid to the impact of the ecological buffer space of courtyard on energy consumption.

4. Discussion

In the development and evolution of traditional courtyards in southern Jiangsu Province, a series of relatively mature and simple ecological strategies that suit regional features have emerged. However, there are still many issues that arise when bringing this traditional courtyard design element into the modern architectural design. These issues include insufficient mastery of the spatial layout of traditional courtyards and ignorance concerning reasonable applications of ecological buffer spaces. This study focused on suitable strategies to affect and improve courtyard thermal environments. The Expert Building area of Jiangnan Furniture Museum serves as a case study to qualitatively analyze traditional ecological techniques. The environmental simulation software

PHOENICS and the energy simulation software DesignBuilder were used to conduct quantitative analysis.

From the analysis of the wind environment simulation results, the initial design, and the improved design, in winter and summer, several suggestions arise for the design phase:

1) Adjust the spatial layout of courtyards to maximize natural ventilation for free cooling in summer and to prevent/minimize cold wind in winter. Courtyard buildings can be oriented with opening toward the southeast to guide summer wind-pressure-driven ventilation and with closure toward the northwest to avoid cold current in winter
2) Adjust the aspect ratio of the courtyard based on the impact of the depth and height-width ratio of the front and rear courtyard on natural ventilation. The aspect ratio of courtyard can be determined on the basis of other functions. When combining the front and rear courtyard, it is recommended to moderately broaden the depth of the front courtyard and reduce the depth of the rear patio to promote wind-pressure-driven ventilation. Also, it is advised to moderately increase the height of the rear patio to promote the combined ventilation driven by both the wind pressure and thermal pressure. A further suggestion is to moderately increase the height of the enclosing wall on the northern side to form a rear patio, to resist the cold northwestern wind in winter
3) Build the ecological buffer space to consider its micro-climate regulating function and the impact of the opening and closing form of the ecological buffer space on energy use. Adjusting the ecological buffer space of courtyard should also meet other functions. Boundaries between the usable indoor rooms and the corridor can be determined to separate balcony from other buffer spaces. It is recommended to install operable and closeable glass on their lateral side to keep them opened in summer so that the buffer spaces are open wide for sunshade and cooling, while keeping them closed in winter so that the buffer spaces are closed tightly to preserve heat and save energy.

Although three design parameters were evaluated with simulation models in this study, the study has some limitations. Firstly, the case study focuses on the integrative courtyard type in southern Jiangsu Province, while extending results of this study to other courtyard types or other climate regions should take into consideration local culture, climate, courtyard form, etc. Secondly, this study is a preliminary phase of the mono-climatic regional analysis. The study of the ecological strategy of the quadrangle type in northern China, the patio type in southern China, and other types of courtyards which suit different regions need to be studied further. The discussion of the ecological strategy of courtyards focuses on building a suitable residential thermal environment. The impact of the ecological strategy of courtyards on other aspects (e.g., cultural impact) was not discussed in this study. Meanwhile, for thermal comfort validation of courtyard building, future works should take into consideration more variables (e.g. indoor air velocity, mean radiant temperature, humidity of indoor air, metabolic rate, clothing insulation, so on) to assess human comfort inside courtyard buildings [46]. Also, more comfort indices should be further investigated in the future work, such as the impact of courtyard design strategies on building daylighting. [WW2] Thirdly, this study proposed to improve natural ventilation, thermal performance, and energy efficiency of courtyard buildings with the layout, aspect ratio, and ecological buffer space at the design phrase; however, further validation of the simulation results should be conducted when on-site measurements are available.

5. Conclusions

This work studied the traditional courtyards in southern Jiangsu Province based on qualitative analysis of quantitative simulation using the wind environment simulation software PHOENICS and the energy simulation software DesignBuilder. This study proposes three strategies, adjusting the spatial layout of courtyards, the aspect ratio, and building an ecological buffer space. The proposed improved design can increase ventilation in summer—wind speed at the opening can reach 1.75 m/s while keeping the average wind speed from 0.25 to 0.5 m/s to maintain thermal comfort. Further, adjusting the aspect ratio increases natural ventilation driven by thermal pressure in summer, while the northern enclosing wall is raised and improved to resist cold wind in winter. Considering the ecological buffer areas, enclosing the buffer space in winter can achieve the overall energy saving of the courtyard building. Results show that the average natural room temperature in Room 1 can be reduced by about 1 ℃ in summer and increased by about 2 ℃ in winter. The 12.4% of peak cooling load and 25.1% of total cooling load in summer in Room 1 is significantly reduced, and 35.7% of peak heating load and 36.1% of total heating load can be saved in winter. Based on the overall performance in the study's three rooms, results show that the proposed design of a courtyard can save about 19.6% of cooling loads in summer and about 22.3% of heating loads in winter. These findings provide insights into the optimal design of a courtyard to maximize its benefit in regulating the microclimate and saving energy both during winter and summer.

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References

1. Al-Masri, N.; Abu-Hijleh, B. Courtyard housing in midrise buildings: An environmental assessment in hot-arid climate. *Renewable and Sustainable Energy Reviews* **2012**, *16*, 1892–1898, doi:10.1016/J.RSER.2012.01.008.
2. Khan, N.; Su, Y.; Riffat, S. B. A review on wind driven ventilation techniques. *Energy and Buildings* **2008**, *40*, 1586–1604, doi:10.1016/J.ENBUILD.2008.02.015.
3. Kubota, T.; Toe, D. H. C.; Ossen, D. R. Field Investigation of Indoor Thermal Environments in Traditional Chinese Shophouses with Courtyards in Malacca. *Journal of Asian Architecture and Building Engineering* **2014**, *13*, 247–254, doi:10.3130/jaabe.13.247.
4. Soflaei, F.; Shokouhian, M.; Mofidi Shemirani, S. M. Investigation of Iranian traditional courtyard as passive cooling strategy (a field study on BS climate). *International Journal of Sustainable Built Environment* **2016**, *5*, 99–113, doi:10.1016/J.IJSBE.2015.12.001.
5. Berardi, U.; Wang, T. Daylighting in an atrium-type high performance house. *Building and Environment* **2014**, *76*, 92–104, doi:10.1016/J.BUILDENV.2014.02.008.
6. Jang, N.; Ham, S. A study on courtyard apartment types in South Korea from the 1960s to 1970s. *Frontiers of Architectural Research* **2017**, *6*, 149–156, doi:10.1016/j.foar.2017.03.004.
7. Han, B.; Ouyang, Z.; Liu, H.; Cui, Z.; Lu, Z.; Crittenden, J. Courtyard integrated ecological system: An ecological engineering practice in China and its economic-environmental benefit. *Journal of Cleaner Production* **2016**, *133*, 1363–1370, doi:10.1016/j.jclepro.2016.06.061.
8. Sun, P. Courtyard Houses in China: Tradition and Present Werner Blaser. *Journal of the Society of Architectural Historians* **1981**, *40*, 145–145, doi:10.2307/989730.
9. Aldawoud, A. Thermal performance of courtyard buildings. *Energy and Buildings* **2008**, *40*, 906–910, doi:10.1016/J.ENBUILD.2007.07.007.
10. Wang, F.; Liu, Y. Thermal environment of the courtyard style cave dwelling in winter. *Energy and Buildings* **2002**, *34*, 985–1001, doi:10.1016/S0378-7788(01)00145-1.
11. Ghaffarianhoseini, A.; Berardi, U.; Ghaffarianhoseini, A. Thermal performance characteristics of unshaded courtyards in hot and humid climates. *Building and Environment* **2015**, *87*, 154–168, doi:10.1016/j.buildenv.2015.02.001.
12. Jamaludin, A. A.; Hussein, H.; Mohd Ariffin, A. R.; Keumala, N. A study on different natural

ventilation approaches at a residential college building with the internal courtyard arrangement. *Energy and Buildings* **2014**, *72*, 340–352, doi:10.1016/j.enbuild.2013.12.050.

13. Soflaei, F.; Shokouhian, M.; Soflaei, A. Traditional courtyard houses as a model for sustainable design: A case study on BWhs mesoclimate of Iran. *Frontiers of Architectural Research* **2017**, *6*, 329–345, doi:10.1016/J.FOAR.2017.04.004.
14. Taleghani, M.; Tenpierik, M.; van den Dobbelsteen, A.; Sailor, D. J. Heat in courtyards: A validated and calibrated parametric study of heat mitigation strategies for urban courtyards in the Netherlands. *Solar Energy* **2014**, *103*, 108–124, doi:10.1016/j.solener.2014.01.033.
15. Enrique, Á.; Jos, F. Characterizing the Air Temperature Drop in Mediterranean Courtyards from Monitoring Campaigns. **2017**, doi:10.3390/su9081401.
16. Martinelli, L.; Matzarakis, A. Influence of height/width proportions on the thermal comfort of courtyard typology for Italian climate zones. *Sustainable Cities and Society* **2017**, *29*, 97–106, doi:10.1016/j.scs.2016.12.004.
17. Micallef, D.; Buhagiar, V.; Borg, S. P. Cross-ventilation of a room in a courtyard building. *Energy and Buildings* **2016**, *133*, 658–669, doi:10.1016/j.enbuild.2016.09.053.
18. Mousli, K.; Semprini, G. Thermal performances of traditional houses in dry hot arid climate and the effect of natural ventilation on thermal comfort: A case study in Damascus. *Energy Procedia* **2015**, *78*, 2893–2898, doi:10.1016/j.egypro.2015.11.661.
19. Rojas-fern, J.; Gal, C.; Rivera-g, C. Correlations between GIS-Based Urban Building Densification Analysis and Climate Guidelines for Mediterranean Courtyards. **2017**, doi:10.3390/su9122255.
20. Safarzadeh, H.; Bahadori, M. N. Passive cooling effects of courtyards. *Building and Environment* **2005**, *40*, 89–104, doi:10.1016/j.buildenv.2004.04.014.
21. Song, Y.; Li, J.; Wang, J.; Hao, S.; Zhu, N.; Lin, Z. Multi-criteria approach to passive space design in buildings: Impact of courtyard spaces on public buildings in cold climates. *Building and Environment* **2015**, *89*, 295–307, doi:10.1016/j.buildenv.2015.02.025.
22. Rajapaksha, I.; Nagai, H.; Okumiya, M. A ventilated courtyard as a passive cooling strategy in the warm humid tropics. *Renewable Energy* **2003**, *28*, 1755–1778, doi:10.1016/S0960-1481(03)00012-0.
23. Shashua-Bar, L.; Hoffman, M. E. Quantitative evaluation of passive cooling of the UCL microclimate in hot regions in summer, case study: Urban streets and courtyards with trees. *Building and Environment* **2004**, *39*, 1087–1099, doi:10.1016/j.buildenv.2003.11.007.
24. Cantón, M. A.; Ganem, C.; Barea, G.; Llano, J. F. Courtyards as a passive strategy in semi dry areas. Assessment of summer energy and thermal conditions in a refurbished school building. *Renewable Energy* **2014**, *69*, 437–446, doi:10.1016/j.renene.2014.03.065.
25. Aldawoud, A.; Clark, R. Comparative analysis of energy performance between courtyard and atrium in buildings. *Energy and Buildings* **2008**, *40*, 209–214, doi:10.1016/J.ENBUILD.2007.02.017.
26. Muhaisen, A. S.; Gadi, M. B. Effect of courtyard proportions on solar heat gain and energy requirement in the temperate climate of Rome. *Building and Environment* **2006**, *41*, 245–253, doi:10.1016/j.buildenv.2005.01.031.
27. Vaisman, G.; Horvat, M. Influence of internal courtyards on the energy load and hours of illuminance in row houses in Toronto. *Energy Procedia* **2015**, *78*, 1799–1804, doi:10.1016/j.egypro.2015.11.312.
28. Yaşa, E.; Ok, V. Evaluation of the effects of courtyard building shapes on solar heat gains and energy efficiency according to different climatic regions. *Energy and Buildings* **2014**, *73*, 192–199, doi:10.1016/j.enbuild.2013.12.042.
29. Cao, B.; Luo, M.; Li, M.; Zhu, Y. Too cold or too warm? A winter thermal comfort study in different climate zones in China. *Energy and Buildings* **2016**, *133*, 469–477, doi:10.1016/j.enbuild.2016.09.050.

30. Wang, Z.; Zhao, Z.; Lin, B.; Zhu, Y.; Ouyang, Q. Residential heating energy consumption modeling through a bottom-up approach for China's Hot Summer–Cold Winter climatic region. *Energy and Buildings* **2015**, *109*, 65–74, doi:10.1016/j.enbuild.2015.09.057.
31. Liu, J.; Zhu, X.; Yang, L.; Hu, R. Exemplary project of green cave dwellings in Loess Plateau. *Frontiers of Energy and Power Engineering in China* **2010**, *4*, 122–130, doi:10.1007/s11708-010-0005-1.
32. Xu, X.; Luo, F. Analysis and appraisal of the design of traditional courtyards in the South-of-Yangtze Area based on ecological effects. *Architecture & Culture* **2014**, *9*, 79–81.
33. Yang, X.; Li, Y.; Yang, L. Predicting and understanding temporal 3D exterior surface temperature distribution in an ideal courtyard. *Building and Environment* **2012**, *57*, 38–48, doi:10.1016/j.buildenv.2012.03.022.
34. Sadafi, N.; Salleh, E.; Haw, L. C.; Jaafar, Z. Evaluating thermal effects of internal courtyard in a tropical terrace house by computational simulation. *Energy and Buildings* **2011**, *43*, 887–893, doi:10.1016/j.enbuild.2010.12.009.
35. Cannistraro, G.; Cannistraro, M.; Restivo, R. Some observations on the radiative exchanges influence on thermal comfort in rectangular open-space environments. *International Journal of Heat and Technology* **2015**, *33*, 79–84, doi:10.18280/ijht.330213.
36. Cannistraro, G.; Cannistraro, M.; Restivo, R. the Local Media Radiant Temperature for the Calculation of Comfort in Areas Characterized By Radiant Surfaces. *International Journal of Heat and Technology* **2015**, *33*, 115–122, doi:10.18280/ijht.330116.
37. Cannistraro, G.; Cannistraro, M.; Restivo, R. Smart Control of Air Climatization System in Function on the Values of Mean Local Radiant Temperature. *Smart Science* **2015**, *3*, 157–163, doi:10.1080/23080477.2015.11665651.
38. Xu, X. Ecological strategy studies for green urban design based on bio-climatic conditions, Southeast University, 2005.
39. Nasrollahi, N.; Hatami, M.; Khastar, S. R.; Taleghani, M. Numerical evaluation of thermal comfort in traditional courtyards to develop new microclimate design in a hot and dry climate. *Sustainable Cities and Society* **2017**, *35*, 449–467, doi:10.1016/j.scs.2017.08.017.
40. Soflaei, F.; Shokouhian, M.; Abraveshdar, H.; Alipour, A. The impact of courtyard design variants on shading performance in hot- arid climates of Iran. *Energy and Buildings* **2017**, *143*, 71–83, doi:10.1016/j.enbuild.2017.03.027.
41. Xu, X. Research on ecological strategies of urban design based on conditions of bio-climate--taking the example for the urban design in areas marked by cold winter and hot summer. *Urbanism and Architecture* **2006**, *7*, 22–25.
42. *Ministry of Construction of the People's Republic of China, Standards on the Climatic Zoning of Buildings(GB50178 —93)*; China Planning Press: Beijing, 1993;
43. Moosavi, L.; Mahyuddin, N.; Ghafar, N. A. A comparison between atrium and courtyard cooling efficiency in hot tropical climate, implementing different passive cooling strategies. *Journal of Renewable and Sustainable Energy* **2015**, *7*, 043108, doi:10.1063/1.4926760.
44. Taleghani, M.; Tenpierik, M.; Dobbelsteen, A. van den Environmental impact of courtyards—a review and comparison of residential courtyard buildings in different climates. *Journal of Green Building* **2012**, *7*, 113–136, doi:10.3992/jgb.7.2.113.
45. Cannistraro, M.; Castelluccio, M. E.; Germanò, D. New sol-gel deposition technique in the Smart-Windows – Computation of possible applications of Smart-Windows in buildings. *Journal of Building Engineering* **2018**, *19*, 295–301, doi:10.1016/J.JOBE.2018.05.018.
46. D'Ambrosio Alfano, F. R.; Olesen, B. W.; Palella, B. I.; Riccio, G. Thermal comfort: Design and

assessment for energy saving. *Energy and Buildings* **2014**, *81*, 326–336, doi:10.1016/j.enbuild.2014.06.033.

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