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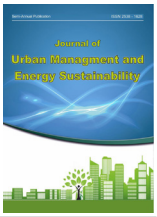

CASE STUDY RESEARCH PAPER

Investigation of factors influencing the natural ventilation pattern of traditional Houses emphasis on the orientation of the central courtyard

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ABSTRACT

The central courtyard, a defining feature of traditional Iranian architecture, plays a crucial role in environmental adaptation by enhancing natural ventilation in surrounding spaces. Its design integrates various physical configurations that facilitate airflow and temperature regulation, making it particularly effective in hot and arid climates. The methodology of this research is designed to comprehensively examine the natural ventilation performance of central courtyards in traditional Iranian houses. This study examines the physical structure of courtyards in Yazd's traditional houses, analyzing how their architectural elements interact with wind dynamics. The methodology integrates experimental strategies, simulations, and case studies to analyze the relationship between the physical characteristics of courtyards and their airflow dynamics. Through a mixed-method approach combining experimental measurements, computational simulations, and case studies, this research explores the correlation between courtyard orientation and ventilation efficiency. The findings show that variations in wind direction can significantly amplify wind speed, often tripling its velocity. However, when the courtyard's main axis aligns tangentially with the prevailing wind direction, unexpected reductions in wind speed occur due to altered aerodynamic behavior. These insights underscore the importance of strategic courtyard design in maximizing passive cooling and airflow efficiency in traditional architecture, contributing to more sustainable urban planning in similar climatic regions. Results show that by refining traditional courtyard designs based on a deeper understanding of airflow behavior, architects can improve passive cooling strategies and overall environmental performance. Future research should examine additional architectural variables, including courtyard height-to-width ratios and surface materials, to further advance sustainable design methodologies.

Running Title: The natural ventilation pattern of traditional houses emphasizes the orientation of the central courtyard

NUMBER OF REFERENCES	NUMBER OF FIGURES	NUMBER OF TABLES
29	20	05

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INTRODUCTION

In recent decades, significant research has been conducted in the field of climate-responsive architecture, emphasizing the utilization of renewable energy resources. Architects have made substantial progress in integrating these sustainable solutions into building designs. Indigenous Iranian architecture, recognized as one of the most successful architectural traditions globally, has historically addressed environmental challenges through innovative and intelligent methods, achieving a harmonious relationship with its surrounding nature. Despite this legacy, many modern homes have shifted toward reliance on air conditioning systems, largely due to a lack of trust in the effectiveness of natural ventilation (Kokh-Nielsen, 2016; Jeong et al., 2021). This shift has resulted in the widespread adoption of mechanical cooling systems as the preferred choice. However, historical evidence suggests that more balanced and sustainable approaches to ventilation were practiced in the past (Energy Information Administration, 1996). Natural ventilation remains a viable and efficient alternative for reducing energy consumption in buildings, while maintaining thermal comfort (Burgess, 1995). For instance, buildings with natural ventilation systems can reduce energy costs by approximately 40% compared to those with air conditioning. This principle was a focal point for traditional Iranian architects (Rahaspar and Azamati, 2021). Preserving and enhancing environmental harmony has always been a central concern of Iranian architecture. Architects have addressed these challenges through various innovative solutions, such as constructing tall walls, utilizing the insulating properties of natural materials like adobe, and designing elements like domes, wind catchers, and central courtyards (Molanayi and Soleimani, 2015). These strategies exemplify the sophistication and ingenuity inherent in traditional Iranian design, offering valuable lessons for sustainable modern architecture. Similarly, the use of natural airflow is considered a tool for enhancing climatic comfort in Iranian architecture (Moghiman and Moradi, 2001). The city of Yazd has many traditional houses that are designed according to its climate, with a central courtyard serving as a space for providing light, ventilation, suitable air, and creating internal connections for the houses (Soltanzadeh, 2000). Central courtyards have a wide variety and have taken various shapes in different climates. The orientation of these courtyards is mostly variable, and despite their visual similarities, there is no exact proportion and degree between them based on the pattern of air circulation inside the courtyard. Therefore, the question raised here is: What relationship should exist between the orientation of the central courtyard so that the airflow inside these courtyards is desirable at different levels, and what are the optimal dimensions of it? Therefore, finding the appropriate orientation for natural and desirable ventilation is also the subject of this research.

MATERIALS AND METHODS

One of the most important determinants of health is natural ventilation, which provides human comfort by cooling the warm indoor air (Jeong et al., 2021); (Kasmaei, 2012). Utilizing natural energy such as wind energy and its proper direction into architectural spaces to create clean and stable natural air has also been effective in reducing energy consumption (Swan and Ugursal, 2009) (Akbari and Khaghani, 2022). Attention to this important issue in hot and dry regions is one of the most important factors in creating thermal comfort (Hedayat and Ghafari Jabari, 2013). Therefore, by examining studies, it can be stated that significant efforts have been made in the field of ventilation engineering since the late 1930s (Burgess, 1995). The awareness and study of indoor air currents in enclosed environments is worth investigating for three important reasons: 1- Indoor air quality, 2- Thermal comfort, and 3- Building energy consumption (Abdul Hosseini, 2018). Therefore, in order to reduce energy consumption and avoid environmental degradation, the use of natural ventilation methods is also recommended (Hassana, 2007). The energy crisis has

cast a shadow over many human activities and has posed a strong and challenging obstacle to architectural design as one of the key factors in high energy consumption (Wang et al., 2022). Kasmayi (2003) and Soltandoost (2010). With complex research, experts have studied and calculated the dominant wind and the energy required for natural ventilation at a national level, considering wind energy as an important factor for natural ventilation. In the conducted research, researchers have examined the natural ventilation status in educational spaces. (Vassella et al., 2021), (Aguilar et al., 2022), residential spaces, office spaces (Nomura and Hiyama, 2017), high-rise buildings (Omrani et al., 2017) and the geometry of the balcony and windbreak (Jomehzadeh et al, 2020) have discussed and natural ventilation as a factor in maintaining Environment and cost reduction (Hizbaei et al., 2013) and noise reduction in buildings have been preferred over mechanical and forced ventilation. The native architecture of Iran, especially in the hot and dry climate, has presented models and wise solutions from the past in the field of sustainability (Pourmand and Bazisaz, 2005), and has led architects to use the best methods of adapting to the climate. Design is the first line of defense against climatic factors outside the building; climatic design is a response to reduce the energy costs of a building (Abdol Hosseini, 2018), so the courtyard element in traditional Iranian houses can be considered as a successful sustainable design strategy. (Zainlian and Okhovat, 2016). The central courtyard is a uniting element, ordering directions and creating a safe and confidential space (Qabadian, 2011). In general, human thermal comfort conditions are affected by factors such as climate, environment, air temperature, humidity, radiation, and wind speed. that ventilation is an important and determining factor in the formation A space like a courtyard is central in this architecture (Kasmai, 2012), (Sefalai, 2004), (Azarbayjani, 2013), (Moradi et al., 2017). On the other hand, the yard as a connecting factor between the living space and other parts (Sefalai, 2004) can be investigated from two functional and practical aspects (Haeri Mazandarani, 2008). Therefore, it can be said that Iranian architecture can be considered as the product of adapting environmental conditions to lifestyles and culture (Vakilinjad, 2015). In order to carry out and advance related research in the field of energy and especially natural ventilation, the use of Design-builder software is common and welcomed by researchers. The basis of this software is based on climatic conditions, and by means of it, the conditions of ventilation systems and air flow in buildings can be simulated and checked. In their research, Saebi Safa, Heydari and Sulaimanpour (2019) investigated energy wastage using Design-Builder, with the help of which they were able to investigate different wind behaviors in different spaces. Also, Rahai (2013) in research entitled Design Modeling and Analysis addressed the performance of ventilation and heating in the indoor environment and declared the solar chimney in terraced houses as one of the most important factors to increase the performance of natural ventilation and investigated its performance. Rahspar Monfared and Azamati (2014), Safa et al. (2016), Tavakoli, Baghaie and Safari (2014), Moradi et al. (2016), Taban et al. They have studied the effects of effective factors on natural ventilation in a residential building; they have used Design-Builder software in simulation. Based on the research reviewed in the field of natural ventilation, the use of the system has always been of interest to researchers, and in order to investigate natural ventilation, various evaluation methods have been used. According to the background, in the current research, Design-Builder software and validation with field measurement methods have been used. Natural ventilation analysis is used based on the physical components of the central courtyard.

Methodology

The methodology of this research is designed to comprehensively examine the natural ventilation performance of central courtyards in traditional Iranian houses. Central courtyards are a defining feature of Iranian architecture,

known for their role in environmental adaptation and creating comfortable living conditions. This study aims to analyze how variations in courtyard orientation affect airflow patterns and ventilation efficiency, using a combination of experimental, simulation, and case study approaches. This research employs a hybrid methodology. The methodology integrates experimental strategies, simulations, and case studies to analyze the relationship between the physical characteristics of courtyards and their airflow dynamics. The hybrid approach ensures a multi-dimensional understanding of both the current ventilation conditions and the impacts of various physical modifications. The measures employed include library studies, field observations, measurements, and computational simulations. These diverse methods allow the research to capture both qualitative and quantitative data, ensuring comprehensive analysis and accurate validation of results. Specifically, the aim of the research is to evaluate how the orientation of the courtyard, as the independent variable, influences the air circulation pattern within the courtyard, the dependent variable. The statistical population includes houses with central courtyards located in Yazd, with two houses, Lariha House and Golestan House, selected as focused case studies. These examples are representative of traditional Iranian architectural practices, making them suitable for in-depth exploration. Data Collection and Field Measurements were conducted over a 30-day period in August to capture airflow patterns and velocity, with measurements taken at three daily intervals—9:00 AM, 12:00 PM, and 3:00 PM—using a 200 Kimo/v device to collect accurate primary data, and observations were recorded regarding the courtyards' physical features, including orientation, dimensions, and material properties. The field data were then used to develop 3D models of the selected courtyards in Design-Builder, enabling detailed analysis of airflow patterns, and the simulations were validated against the experimental measurements to ensure reliability and alignment with the real-world conditions observed during fieldwork. In the intervention through simulations, the orientation of the courtyards was systematically adjusted in the simulation environment to assess its impact on airflow dynamics, with the aim of identifying how changes in the courtyard's main axis relative to prevailing wind directions would affect airflow patterns and wind velocity. In the analysis and comparative study, baseline data from the original courtyard configurations were compared against the simulated scenarios with adjusted orientations, with a detailed analysis focusing on variations in airflow speed and patterns and highlighting significant changes introduced by these interventions.

DISCUSSION AND FINDINGS

The results of this study revealed that adjustments to courtyard orientation could significantly impact airflow performance. In several cases, reorientation led to a tripling of wind speed, demonstrating the potential for optimization in traditional designs. However, specific examples such as the Lariha House and Mud House exhibited unexpected anomalies:

- In the Lariha House, aligning the courtyard's main axis with the wind direction caused a 6% reduction in wind speed (from 1.1 to 1.03 m/s).
- Similarly, in the Mud Houses, an 8% reduction was recorded (from 0.86 to 0.8 m/s), contrary to initial assumptions that such alignment would enhance airflow.

These findings emphasize the complex interplay between environmental factors and architectural design, providing valuable insights for optimizing natural ventilation in hot and arid climates

- Climatic data of the location of the buildings:

In order to model the building in the real state, it requires entering the climatic data, so that the simulation can be done based on the location determination in the best conditions, emphasizing the desired site in terms of location, climatic conditions, urban density, etc. In the first stage, the location of the desired site, which is the city of Yazd, was selected as the location of

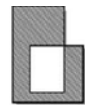
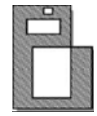
the building, and thus the primary climate data was given as input data for the simulation. Distances of 1 cm are considered, which is standard for urban environments. Then the average wind speed in the city of Yazd in August (according to the reliable global wind finder website, which is introduced as a source in most wind simulation articles) is considered to be 7 meters per second, which in the next step is matched with It has been compared with the wind speed collected in field operations (which was obtained with an average of about 6.3 meters per second) and confirmed in the following (Fig. 1) (Tab. 1)

Considering that the harvests were done in August by the authors, according to the collected information, the prevailing wind direction in Yazd city in August is from the northwest side, which is equivalent to 135 degrees given by the simulation software.

Examining the current status of case examples

The main components of Lariha's House are two large and small courtyards with a series of porches, halls, rooms, and a vestibule. This house is built on a plot of 2379 square meters with an occupied area of 1747 square meters (73%) on one floor (Tab. 2 and 3).

Table 2: The design pattern of the Larry House, source: authors

Building orientation	North-East-South-West
Texture continuity	Dense
Internal Divisions Plan	Central courtyard and package plan
Optimized Translation: Building Occupation on Land	
Relationship between full and empty space	Ivan and the hallway
Distribution of Full and Empty Spaces	

Golshan House has three courtyards, different closed and semi-open spaces, two entrances and several service open spaces. The two eastern and western courtyards and the large courtyards of each central complex are an important part of the House. These two courtyards with a rectangular base are located in the northeast-southwest direction. Golshan House is built on a plot of land with an area of 2160 square meters with an occupied area of 1614 square meters (74%) and on one floor (Tab. 4 and 5).

Table 3: Analysis of the quantitative structure of Lariha House, Source: Authors

	Space Type	Area (square meters)	Compared to the total building
Open space	Main Courtyard	472	19.84%
	Northeast Courtyard	131.5	5.53%
	Small Courtyard	27.72	1.17%
	Total	631.22	26.53%
Gross Domestic Product Close space	Rooms (Ground Floor)	891.78	37.49%
Gross Domestic Product Communication Spaces	Hashti	30.55	1.28%
	Entrances	28	1.18%
	Hallways	459.71	19.32%
	Total	518.26	21.78%
	Total Ground Floor Corridor Areas337.74		14.2%

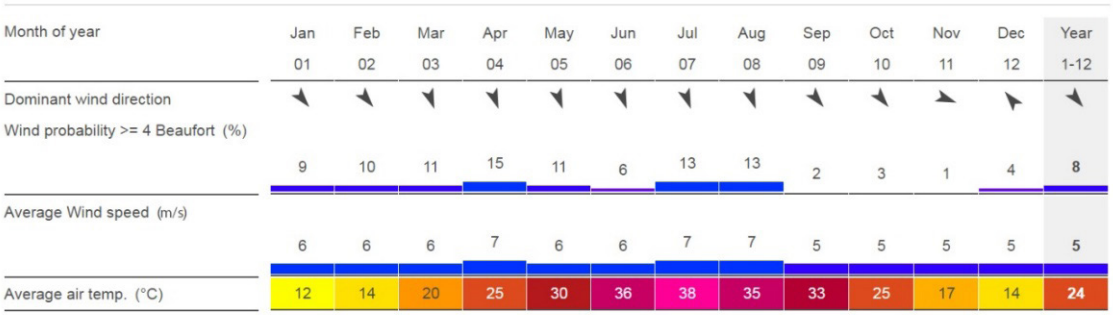


Figure 1: Direction and average wind speed and temperature in different months of the year in Yazd city

Table 1: Distribution of wind direction in different months in Yazd province, source: data of Iran Meteorological Organization.

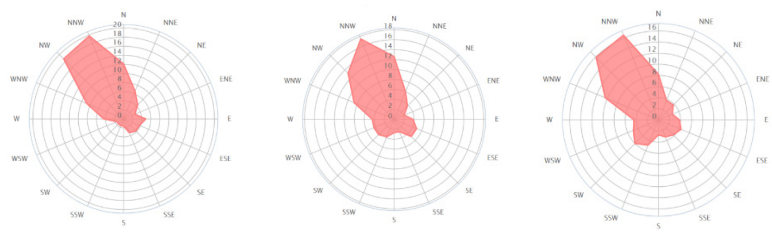
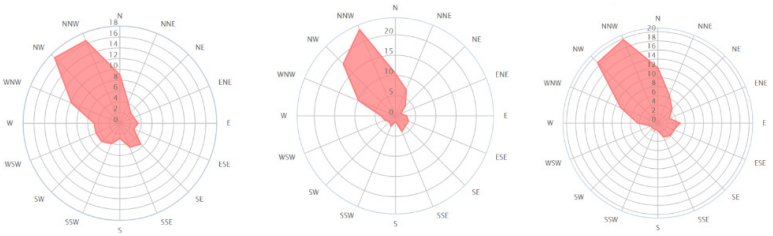
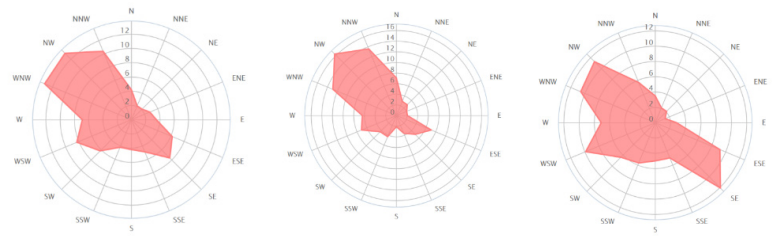
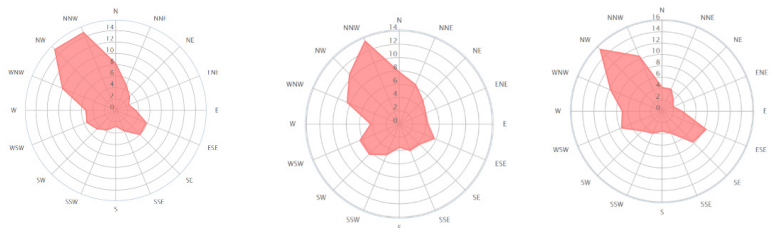
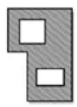
	Month	Graphs
1	April May June (From right to left)	
2	July August September (From right to left)	
3	October November December (From right to left)	
4	January, February, March (From right to left)	

Table 4: Design Pattern of Golshan House, Source: Authors

Building orientation	Northeast-Southwest
Structure Continuity	Dense
Internal plan divisions	Closed plan and central courtyard
Occupying buildings on the ground	
The relationship between empty and full space	Terrace and corridor
Distribution of Empty and Filled Spaces	

Simulation validation

The convergence of the results of the Builder design predictions with field impressions with the KIMO/VT200 instrument was considered for simulation validation. For this purpose, the measured airflow velocity in the case samples was compared at different distances with the predicted air flow rates by Design Builder software at the same conditions and at the same distances. In field harvesting, data on wind flow rate was made by preliminary comparison between four courtyards in two houses (three yards of Golshan and one yard of Lariha's house) (Fig. 2, 3, 4 and 5). Wind speed has decreased in the main courtyard of Golshan House, Lariha House yard, Golshan House middle yard, and small courtyard of Golshan House respectively. The same trend exists in the simulation model, which shows the initial correspondence between the real and the simulated data. The results of this comparison show a similar trend. For example, the average wind speed in the main yard of Golshan House in field harvest mode was 1.4 m/s and its middle yard was 0.65 m/s, and these values in simulation mode were 1.1 and 0.58 m/s, respectively. In this study, numerical results obtained by comparing the results of air flow velocity in the courtyards of two houses indicate that simulation results are close to the results of field harvest. However, the difference in the existing number can be due to the presence of environmental elements in the real state such as furniture, plants, humans, water pond, and so on.

Table 5: Quantitatively Structure of Golshan House

			Space Type	Area (square meters)	Compared to the total building	
Open Space			main yard (west)	293,41	13,58%	
			East yard	193,57	8,96%	
			North Yard	58,88	2,73%	
			Total	545,86	25,27%	
Pure infrastructure	Close space		rooms (ground floor)	811,59		37,57%
Impure infrastructure			Hashti	15,19		0,7%
	Communication spaces		Entrances	69		3%
			Hallways	345,71		16%
			Total	425,9.		19,72%
			area Floor tiles	376,65		17,44%

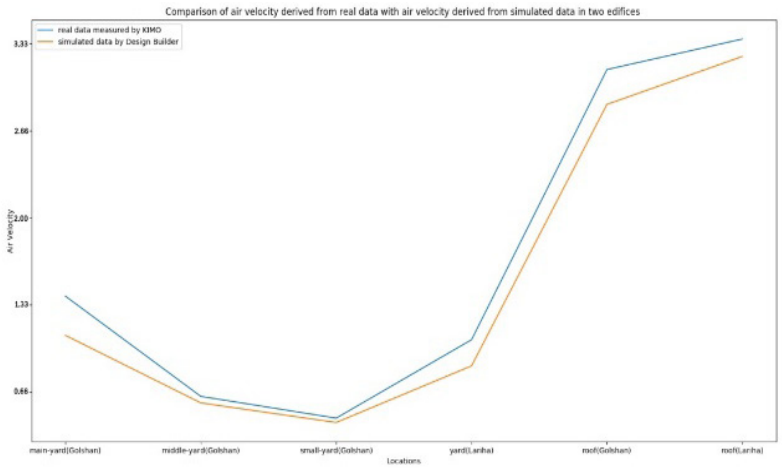


Figure 2: Comparison of the average wind speed in the field survey with the simulation software data from the status quo

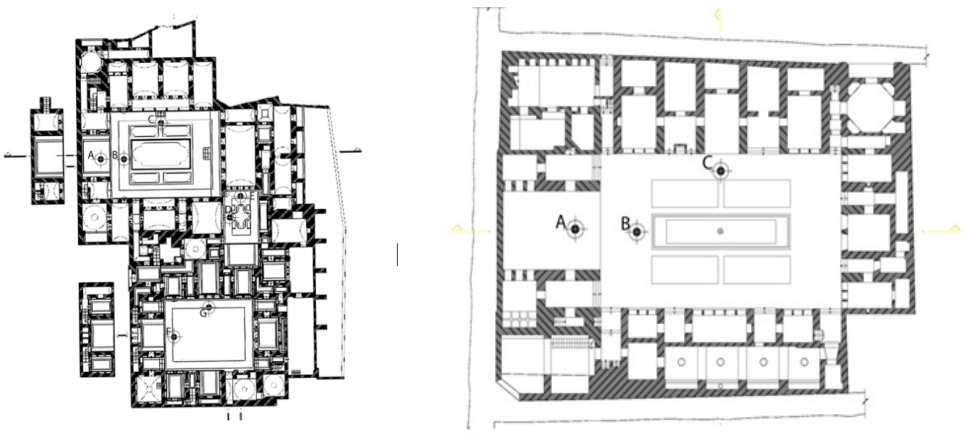


Figure 3 and 4 (from right to left): points marked in the Larry House to measure wind speed (point A on the roof of the summer House and points B andC inside the yard) and the specified points in the Golshan House to measure the wind speed (point A on the roof of the summer House and points B to G in the yard

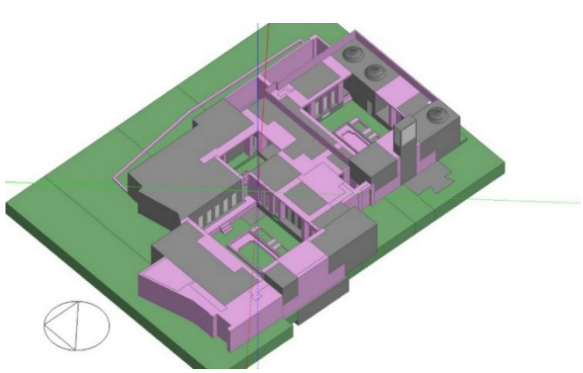


Figure 5: Simulated initial model of Golshan House

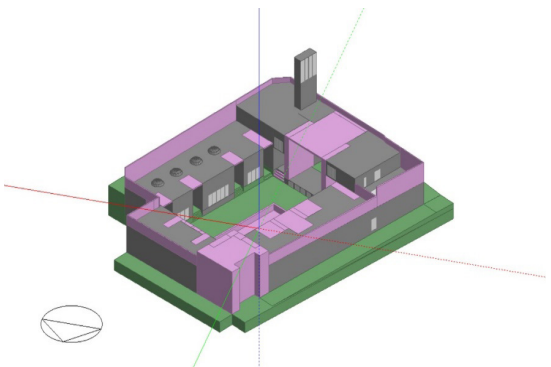


Figure 6: The first simulated model of the House of Lariha

Air pressure caused by wind flow in the central courtyard

The most important cause of creating air flow and air conditioning along it is the pressure difference between high pressure and low air pressure areas, which indicates that it is necessary to pay attention to the pressure exerted on buildings due to wind (Fig. 7, 8, 9, and 10). Also, the creation of natural ventilation in the building depends on the pressure difference created by the wind on its external walls, and the air flow created by the temperature difference of different surfaces of a building in its interior is insignificant and negligible, and mainly only the wind affects how to ventilate. It affects the natural and indoor air temperature of a building and as a result its comfort. It can be seen carefully in figures 11 and 12 that in the first place, after the wind hits the north-west wall of the building, positive pressure will be created in that wall, and the pressure will be negative in the other walls, and in the same way, the pressure will be negative in the central courtyards, which is the incident causes a suction flow in the yards and directs the air flow to the inside of the yard. (Fig. 13 to 18)

CONCLUSION AND RESULTS

In the next step, the simulation of the state of air flow speed in the central yard was investigated under the influence of the direction (angle) of the main (larger) axis of the yard compared to the wind angle. In this comparison, angles of 0, 45, and 90 degrees were evaluated) Fig. 19(. The results of this simulation are shown in the graphs and pictures below. According to these results, the initial investigation shows that the index of the orientation angle has the greatest effect on the amount of change in air flow speed. For example, in the main yard of Golshan House, with a 45-degree rotation of the yard compared to the existing situation, the wind speed has reached 1.1 m/s to 2.26 m/s, which is a 1.16 m/s increase in speed compared to the factors of length and height.

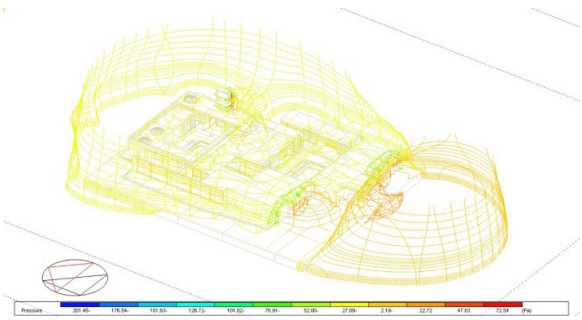


Figure 7: Simulation of effective pressure due to wind in Golshan House Figure 8- Simulation of effective pressure due to wind in Golshan House (plan)

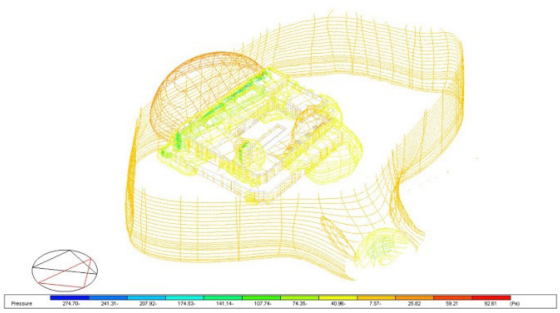


Figure 9: Simulation of the effective pressure due to wind in the Larry house

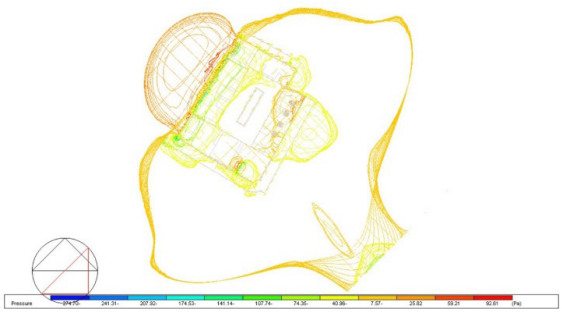


Figure 10: Simulation of the effective pressure due to the wind in the Lariha house (plan

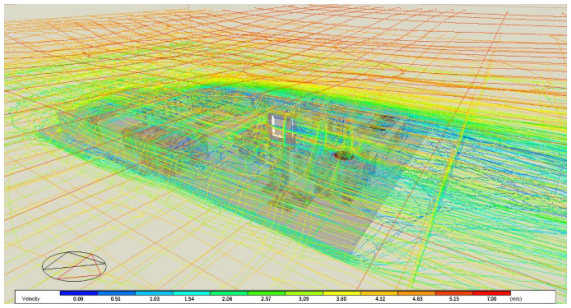


Figure 11: Simulation of wind speed in the Larry House

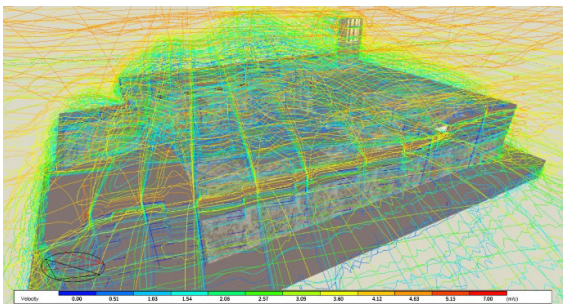


Figure 12: Simulation of wind speed in Golshan House

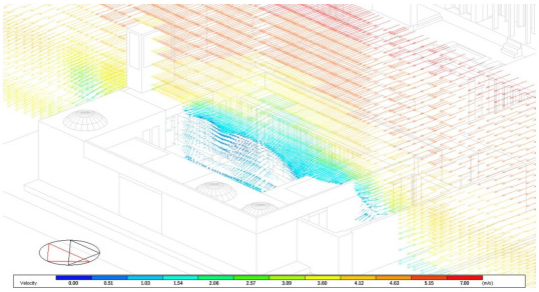


Figure 13: Vector simulation of wind speed in two-dimensional dimensional cross-section of a three-dimensional model of Lariha House

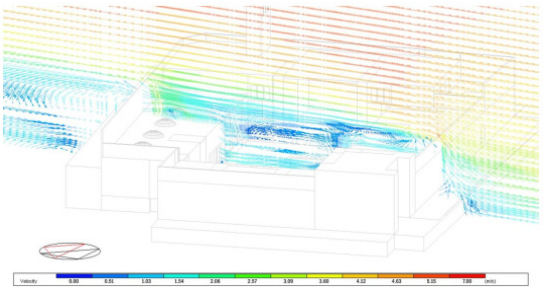


Figure 14: Vector simulation of wind speed in a two- section of the three-dimensional model of Golshan House

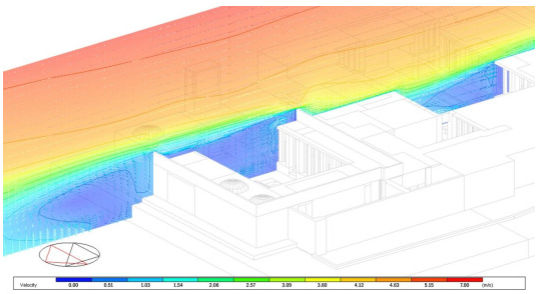


Figure 15: Simulation of wind speed in 2D section of 3D model of Golshan house

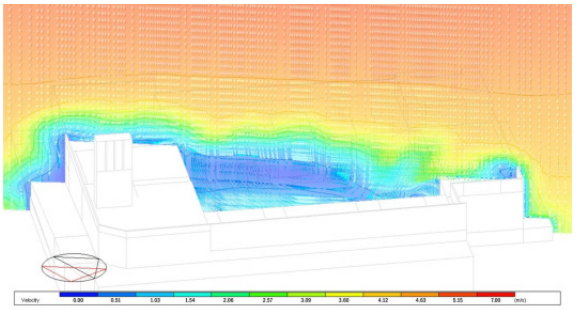


Figure 16: Simulation of wind speed in two-dimensional section of the three-dimensional model of Lariha's house

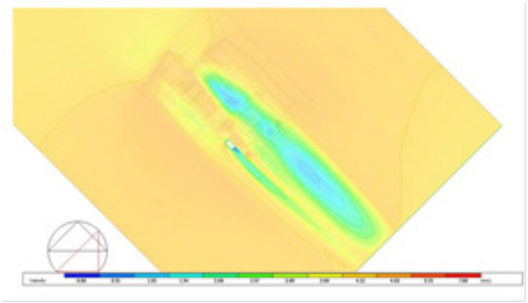


Figure 17: Wind speed on the roof level of Golshan House

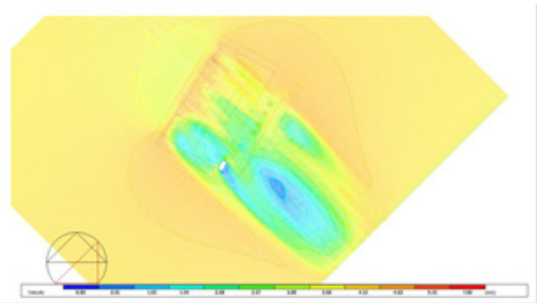


Figure 18: Wind speed on the roof level of the Lariha House

Figure 19 indicates the change of wind speed after applying the variable direction. In the initial state, the angle of the main (bigger) axis of the yard is 90 degrees with respect to the direction of the wind, which means that the wind direction is perpendicular to the main axis of the Golshan House yard, after applying this change to the values of 45 degrees and 0 degrees (that is, the direction the wind blowing tangentially to the main axis of Golshan's yard) will reach (Dig. 1 to 3)

In a more detailed examination of the effect of variable orientation in the courtyards of Golshan House according to Figure 19 and diagrams 1-3, it can be seen that with the 45 degree rotation of the courtyard, the wind speed increases significantly in all the courtyards. In this way, in the main yard of Golshan House, the wind speed will reach 2.26 m/s from 1.2 m/s, and this means an increase of about 110% of the wind speed. According to Figure 19, after applying this change, the wind speed in the middle courtyard of Golshan House will reach 1.7 m/s from 0.58 m/s, which means an increase of about 190% in wind speed. Also, according to after applying this change in wind speed in the small yard of Golshan House, the wind will reach 0.43 m/s to 1 m/s, and this means an increase of about 230% in wind speed.

Figure 20 shows the change in wind speed after applying the variable direction. In the initial state, the angle of the main (bigger) axis of the yard compared to the direction of the wind is 90 degrees, which means that the direction of the wind is perpendicular to the main axis of the yard of Lariha's House, after applying this change to the values of 45 degrees and 0 degrees (i.e., The direction of the wind is tangential to the main axis of the yard of the truckswill reach. (Dig. 4)

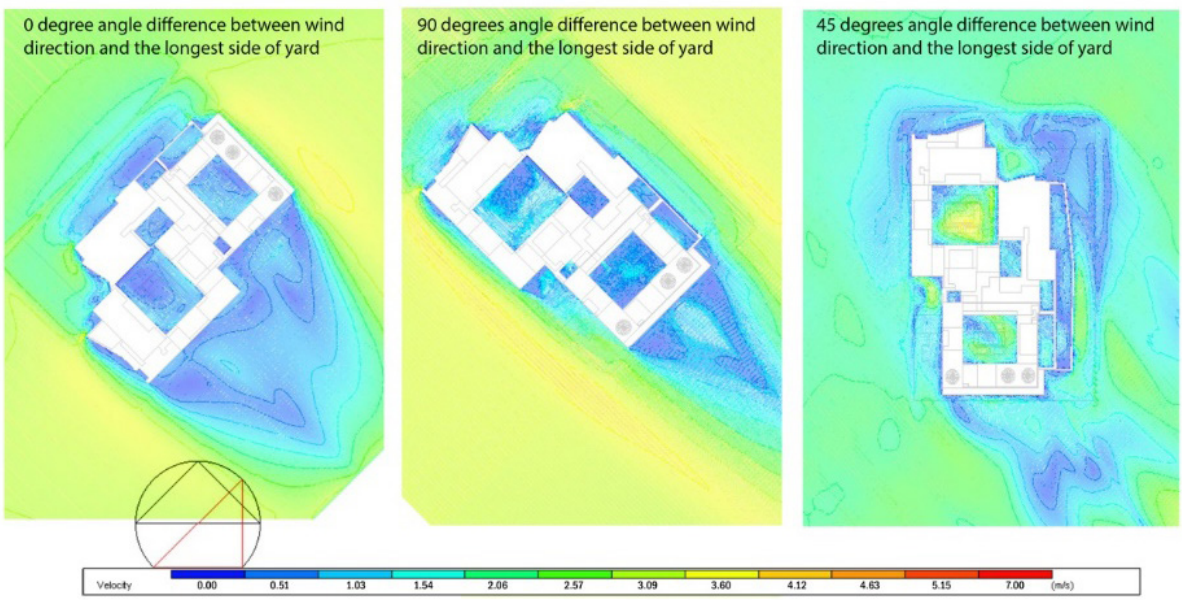


Figure 19: Investigating the parameter of rotation angle change in relation to the wind direction in Golshan House and its effect on air speed

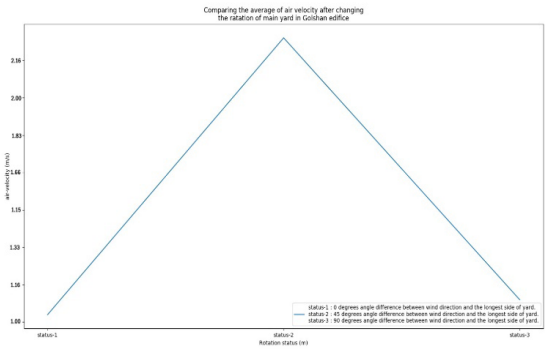


Diagram 1: The effect of the orientation of the long length of the yard in relation to the direction of the wind on the air speed in the main yard of Golshan House

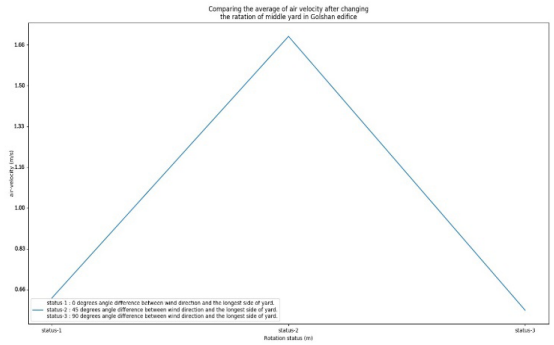


Diagram 2: The effect of the orientation of the long length of the yard in relation to the direction of the wind on the air speed in the middle yard of the house

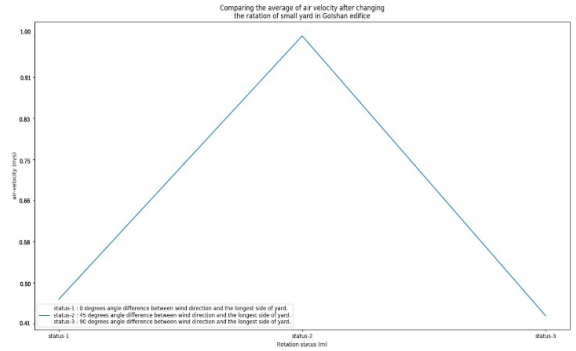


Diagram 3: The effect of the direction of the long length of the yard compared to the direction of the wind on the air speed in the small yard of Golshan House

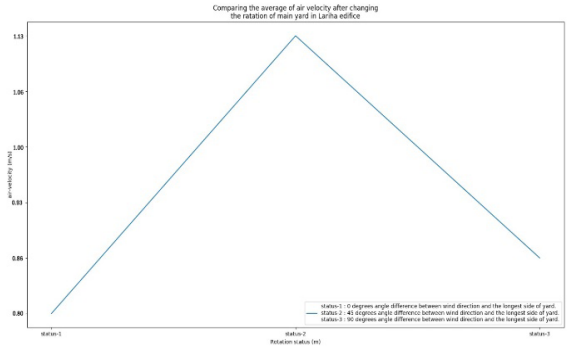


Diagram 4: The effect of the direction of the long length of the yard in relation to the direction of the wind on the air speed in the yard of the Lariha House

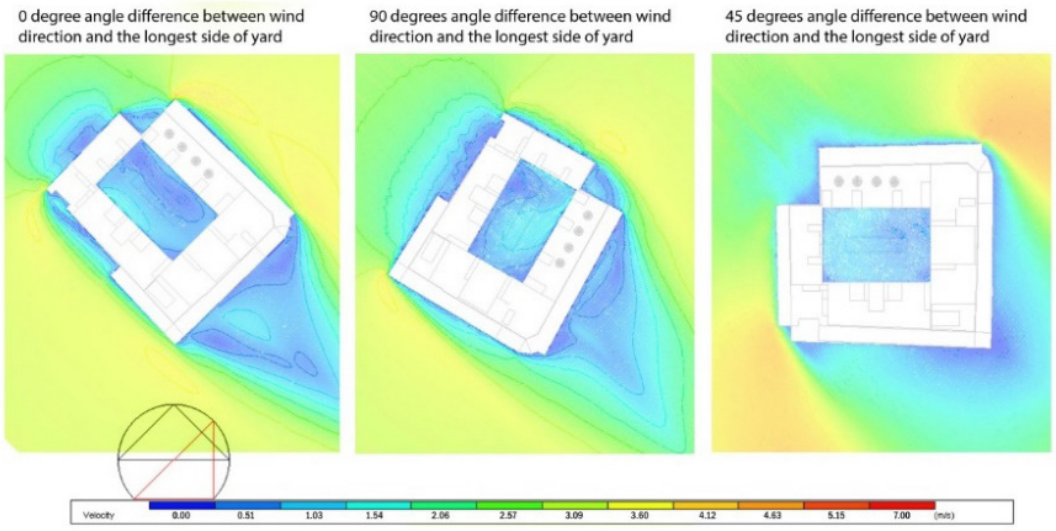


Figure 20: Examining the parameter of the rotation angle change in relation to the wind direction in the House of the trucks and its effect on the air speed

According to figure 20 and diagram 4, after applying this change, the wind speed in the yard of the trucks will reach from 0.86 m/s to 1.13 m/s, and this means an increase of about 30% in wind speed. The findings of this study highlight the crucial role of courtyard orientation in influencing wind speed and airflow patterns. As illustrated in Figures 19 and 20 and Diagrams 1–4, adjusting courtyard orientation can significantly enhance wind speed, in some instances nearly tripling its velocity—for example, a 45-degree rotation in the middle yard of Golshan House. However, unexpected outcomes were observed where anticipated wind speed increases did not occur. Specifically, when the courtyard's main axis aligned tangentially with the wind direction, as seen in Golshan House, wind speed decreased from 1.1 m/s to 1.03 m/s, marking a 6% reduction. Similarly, in the yard of the Mud Houses, wind speed dropped from 0.86 m/s to 0.8 m/s, reflecting an 8% decrease. These variations can be attributed to the complex interplay of pressure zones within the courtyard. When the longer axis is perpendicular to the wind direction, it creates a stronger pressure differential compared to when the shorter axis is perpendicular, enhancing airflow under specific conditions. For instance, in the small courtyard of Golshan House, a 90-degree rotation increased wind speed from 0.43 m/s to 0.46 m/s by orienting the shorter dimension perpendicularly to the wind direction. These results underscore the need for a nuanced approach when analyzing courtyard orientation, considering both pressure dynamics and spatial configurations to maximize ventilation efficiency. This study emphasizes the importance of optimizing courtyard orientation to enhance natural ventilation performance. While strategic adjustments can yield significant airflow improvements—such as tripling wind speed in certain cases—some configurations unexpectedly reduce wind velocity due to pressure dynamics. The findings suggest that orienting the longer axis of a courtyard perpendicularly to prevailing winds generally improves ventilation efficiency, whereas tangential alignments may lead to reduced airflow due to diminished pressure differentials. These insights have meaningful implications for sustainable architectural design, particularly in hot and arid climates such as Yazd. By refining traditional courtyard designs based on a deeper understanding of airflow behavior, architects can improve passive cooling strategies and overall environmental performance. Future research should examine additional architectural variables, including courtyard height-to-width ratios and surface materials, to further advance sustainable design methodologies.

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