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Research Paper

Analyzing Façade Design in Vernacular Architecture of the City of Bushehr, Iran

Parastoo Eshrati [1], Roza Vakilinezhad [2*], Arezoo Ghahramani [3], Dorna Eshrati [4], Mohammad Kazem Namazi [5]

[1] *Department of Architecture, School of Architecture, College of Fine Arts, University of Tehran, Tehran, Iran*

[2] *School of Art and Architecture, Shiraz University, Shiraz, Iran*

[3] *School of Architecture and Environmental Design, Iran University of Science and Technology, Tehran, Iran*

[4] *Department of Landscape Architecture, R.Wayne Estopinal College of Architecture and Planning, Ball State University, Muncie, IN, USA*

[5] *College of Architecture Planning and Design, Kansas State University, Kansas, USA*

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Abstract
Various methods have been employed in vernacular architecture, to achieve energy efficiency in different regions worldwide, especially in facade designs. In Iran, most vernacular buildings are still in use without major modifications and renovations, even in harsh climatic conditions. This study uses mathematical analysis to conduct a quantitative approach toward principles used in the façade design of Bushehr's vernacular architecture. The research critically examined the physical characteristics of eight residential buildings, which were selected as case studies. These parameters included window-to-wall ratios, the surface area for each facade, and the size of different openings concerning height and weight. These physical characteristics of the selected houses were systematically extracted for both the interior and exterior facades, delineating eighteen criteria. The statistical analyses were done using IBM SPSS Statistics version 16.0. The results revealed fourteen linear models—six models related to the exterior facades, five models concerned with interior facades, and three models about the opening. Although the linear models are specific to the vernacular architecture of Bushehr, the research method and approach outlined in this study have the potential to contribute to a framework that can be used by other researchers to uncover underlying principles in vernacular facades elsewhere around the world.

Keywords: *Façade design, Vernacular architecture, Hot-humid climate, Iran, Bushehr.*

ABBREVIATIONS

^{O}C: Centigrade degree
In: Interior
Ex: Exterior
S: Surface Area
N.: North
S.: South
E.: East
W.: West
WD: Width of Opening
H: Height of Opening
Arch: Arched Opening
Rec: Rectangular Opening

* *Corresponding author: arch.rv@shirazu.ac.ir*

INTRODUCTION

In recent decades, the energy crisis, global warming, and reduction of fossil fuels, along with sustainable development, made a priority in energy efficiency. Building energy consumption has become a major concern as the building sector consumes about one-third of the total energy consumption worldwide (Nguyen et al., 2011). Building façade, including walls, roofs, and openings, can control air temperature, shading, and ventilation and assure thermal and daylight comfort (Thalfeldt et al., 2013). Building façades present the relationship between inner and outer space (Askari & Dola, 2009; Hayashi, 2004). It is like an interface "between the pragmatic worlds of facts and the symbolic world of values" (Frampton, 2002, p. 151) which along with climatic and spatial features creates the identity in a context that can also be affected by culture (Sari et al., 2011). It is one of the most effective factors in the urban landscape and city image (Utaberta et al., 2012; H. Wang, 2007). So, the building facades can be evaluated from various points of view (Namazi et al., 2016) (aesthetic, structural, social, cultural, and climatic) and are determined by the composition, shape, texture, and color of their components (Baper & Hassan, 2012). A proper design and accurate location of openings, coupled with sufficient window and door areas overall, are key factors in designing energy-efficient facades (Heiselberg et al., 2002) that can have significant impacts on the lighting, heating, and cooling load and minimize the usage of air-conditioning (Okba, 2005). As a result, appropriate facade design is decisive for the design of climatic buildings.

Several studies analyzed the facade design's influence on buildings' energy consumption and thermal environment (Boyano et al., 2013; Grynning et al., 2013; Motuziene & Juodis, 2010; Poirazis et al., 2008; Susorova et al., 2013; Tzempelikos et al., 2007). Energy-efficient facade properties include window-to-wall ratio, window sizes and properties, building orientation, wall insulation, external shading devices, and some specific elements such as the shape of louvered windows and different forms of apertures (De Luca et al., 2016; Wang et al., 2007). Accordingly, most studies focus on the relationship between the size, orientation, and glazing properties of facade windows (Goia, 2016; Hachem & Elsayed, 2016; Hoelscher et al., 2016; Ihara et al., 2015; Konstantoglou & Tsangrassoulis, 2016; Lau et al., 2016; Lee & Chang, 2015; Mangkuto et al., 2016; Serralheiro et al., 2017; Thalfeldt et al., 2015; Vanhoutteghem et al., 2015). Some of these studies were done to give guidelines for designing building energy-efficient facades.

As so most of the previous studies investigated new building facades; however, façade properties of vernacular buildings have been rarely studied especially from the environmental point of view. On the other hand, vernacular architecture is recognized as a practical, effective solution for energy-efficient design due to its adaptation to the climate and its context (Anna-Maria, 2009; Bodach et al., 2014; Chandel et al., 2016; Desogus et al., 2016; Dili et al., 2010; Du et al., 2014; Kubota & Toe, 2015; Motealleh et al., 2018; Philokyprou et al., 2017; Singh et al., 2010; Zhai & Previtali, 2010). It is also indicated that reduced operating costs, better thermal comfort, and indoor air quality in vernacular buildings as the advantages of the application of passive design strategies (Aflaki et al., 2015) in creative and different ways.

Exploring climate-responsive building design strategies of vernacular architecture, some façade patterns have been investigated in a few papers. For instance, the potential of some facade designs in the vernacular architecture of hot-arid Cairo has been investigated including window-to-wall ratios and shading mechanisms (Camagni & Gonçalves, 2023). Rini has quantitatively examined the aesthetic qualities of the façades of two vernacular houses in Indonesia (Rini, 2024). Another study has compared the basic geometric shapes of the Lampung vernacular architecture, with the golden section units (Ricardo et al., 2024). The façade of timber houses in Arakawa Village is designed along the wind direction, with a closed front façade to mitigate the effect of wind attacks (Wang & Ochiai, 2022). The facade characteristics of a traditional Turkish house are defined as no window facing the street in the ground-floor walls while double windows facing the street are used on the first floor (Acar Bilgin, 2019). The facades usually have rectangular, arched, or trellised windows. The common features between facades are a cantilevered bay window, central overhangs, wooden buttresses and decorative elements and double-leaf doors partitioned in two or three parts are the characteristics of the entrances (Ayla & Eruzun, 2021).

Iran has rich and diverse vernacular architectural design due to the different climatic conditions throughout the country (Brown et al., 2006: 23). Some of the elements of Iranian vernacular architecture, such as courtyards and wind-catchers, have been studied in previous literature. Soflaei et al. analyzed the physical elements of vernacular courtyard houses in Kerman including orientation, extension, rotation angle, dimensions, and proportions of enclosed and

open spaces, opaque walls, openings, and natural elements. Based on the results Iranian courtyards were designed to enable orientation, dimension, and proportion to act as microclimate modifiers (Soflaei et al., 2016). Dimensional ratios of central courts in Yazd with hot-dry and Bushehr with hot-humid climates have been compared. The results revealed differences in shadow densities on the best internal facades in Yazd and Bushehr that lead to different indoor temperatures. In Bushehr, the shadow density on three internal facades is greater than in Yazd (Khajehzadeh et al., 2016).

However, studies that specifically have evaluated façade designs are rare. A Comparative Study of vernacular architecture in Hot–Arid and Hot–Arid–Windy Regions of Iran, revealed that despite different appearances, either of these architectures follows the sustainable adaptation to context. In Sistan, openings are designed on various levels in exterior facades. In Yazd, building facades are higher than in Sistan resulting in more shaded alleys (Sahebzadeh et al., 2017). Considering Bushehr vernacular architecture, there are also studies on design strategies or a special element of the facades including passive cooling (Nikghadam, 2016; Ranjbar et al., 2010; Vakilinezhad, et al., 2013), Tarmeh (Amuzegar et al., 2021; Hedayat & Eshrati, 2021), and Shanashil (Vakilinezhad, et al., 2013). The Study on Orosi openings in daylight performance and thermal comfort confirmed a significant potential of Orosi to address visual comfort, especially on the South façade (Hosseini et al., 2020; Raisi et al., 2024). The mentioned studies are among a few research conducted on façade design in Iranian vernacular architecture.

Reviewing previous studies on vernacular façade design, the research gap was revealed. Although various strategies and physical elements of Bushehr vernacular buildings have been studied as microclimate modifiers in previous studies, studies on the vernacular building facade design are rare. Additionally, studies on facade patterns in vernacular Bushehr architecture are mostly qualitative. In this article, a new method is used to identify facade patterns in the vernacular architecture of Bushehr. It aims to reveal the quantitative relations in the façade design of vernacular houses in Bushehr.

MATERIALS AND METHODS

This study is conducted in several steps. At first, eight houses have been selected as the case studies. Then, data collected from a field study of the cases were classified and prepared to be analyzed using SPSS. The findings were categorized into four groups: exterior façade, interior façade, parallel façade, and opening. Figure 1 shows the research Diagram and steps.

City of Bushehr

The city of Bushehr is a peninsula in the south of Iran, on the north margin of the Persian Gulf. It has very hot and humid summers and temperate winters. Based on Köppen's climate classification, the climate of this port is hot and humid. Table 1 shows the climatic information of Bushehr. The average temperature is 26.2 degrees Celsius, reaching 45.6 C° on the hottest days, but rarely drops below 7 C°. Based on the meteorological data analysis of Bushehr synoptic stations by the Terjang method in July, August, September, and October, it is extremely hot during the day and very hot at night. Its average humidity is 81% and can reach 98%. The prevailing annual wind is from the northwest with a maximum speed of 25 meters per second (90 kilometers per hour). Also, there are various local winds (Bushehr Meteorological Statistical Yearbook, 2021). Figure 2 illustrates the location of the historical texture of Bushehr at the tip of the peninsula.

Façade & Opening Characteristics

Bushehr vernacular buildings have an introverted-extroverted pattern. It means that facades open both toward the central courtyard and also the urban passageway (Eshrati et al., pp. 45-47, 2016; Karimi, pp. 2012: 85). This pattern helps to reduce the humidity of interior spaces by making cross-ventilation possible (Brown et al., 2006; Vakilinezhad et al., 2013, pp. 6-7) (Figure 3).

Bushehr buildings generally have two floors (Khajehzadeh et al., 2016: 473) There may be rooms in two, three, or four directions of the central courtyard. Facades have openings with different dimensions in both arched and rectangular shapes. Due to the diversity of sizes, this article divided openings into three categories based on their sizes, including small, medium, and large. Openings that occupy an area of less than 1 square meter are classified in the category of small openings, openings between 1 and 3 square meters are classified in the category of medium openings, and openings that occupy more than 3 square meters of the facade are classified in the category of large openings. In this article, the term "opening" includes both windows and door windows in the facade (Figure 4).

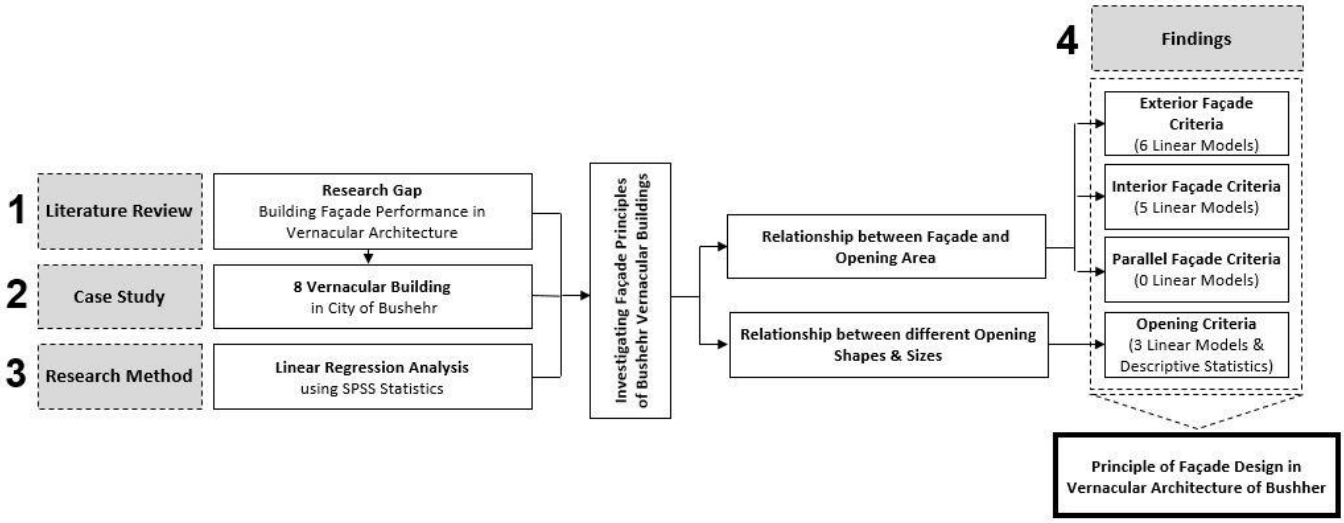


Fig 1. Research Process

Table 1. Monthly Avirago of Weather Conditions in Bushehr (Bushehr Meteorological Statistical Yearbook, 2020)

Bushehr	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Average Dry Bulb Temperature (°C)	14.9	16.5	19.9	24.2	29.3	31	33.1	33.7	31.3	28.4	22	17.1
Average Relative Humidity (%)	74	72	69	66	59	65	67	72	70	68	65	75

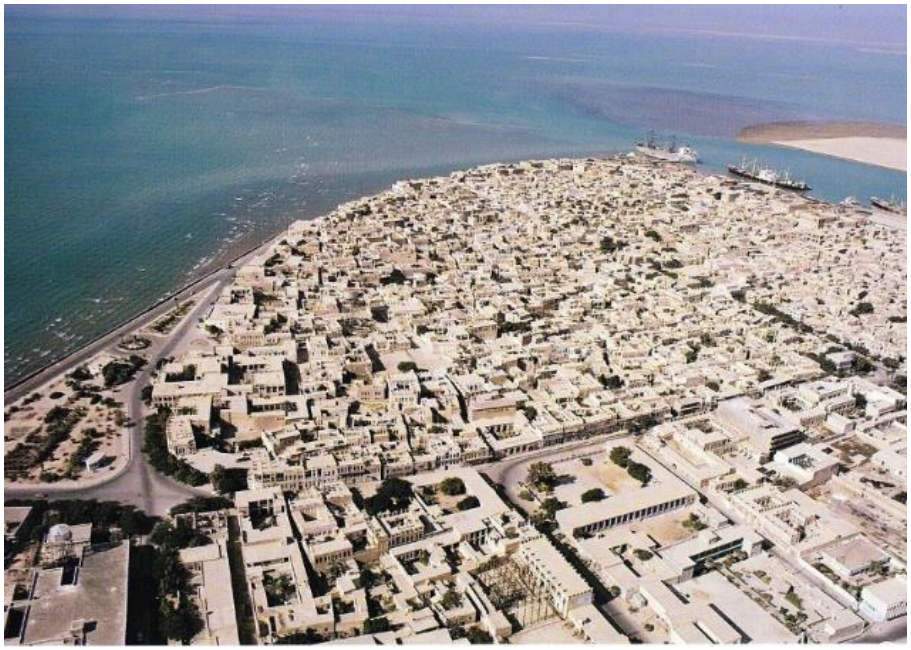


Fig 2. Location of Bushehr's historical urban fabric in the peninsula; Source: (Document Centre of Bushehr)

Fig 3. Vernacular architecture with introverted-extroverted pattern of Bushehr city: (left) Exterior views facing the urban passage; (Right) interior views facing the central courtyard; Source: (Document Centre of Bushehr)

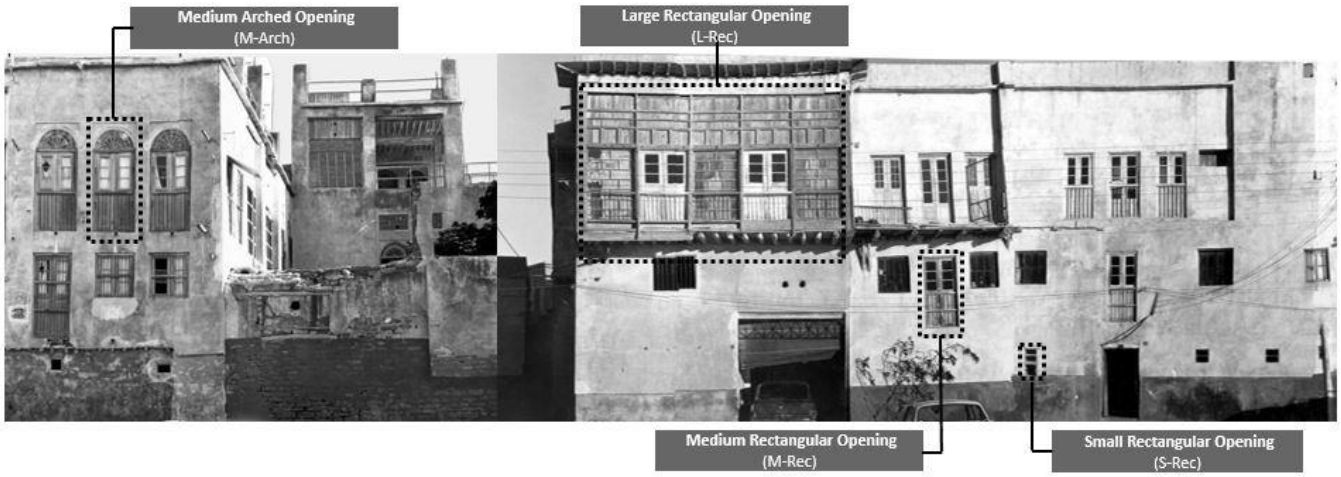


Fig 4. Classification of types of openings in vernacular buildings of Bushehr port based on shape and size; Source: (Authors based on Document Centre of Bushehr)

Case Studies

The following criteria were considered for selecting the case samples: 1) The main historical land use of the building should be residential; 2) Since the prevailing model of Bushehr historical buildings is two-floor, the building should be two-floor; 3) The building should be a registered by Iran's Cultural Heritage Organization to show that it has special heritage values; 4) The plan pattern of the building should be one of the most frequent patterns based on the categories of Bushehr Cultural Heritage Organization; 6) the historical pattern of the building, whether in the plan or the facade, should have been remained intact; 7) Available sufficient evidence of the building. 8) The possibility of visiting the building to update its documents if necessary. 9) Having various sizes and being located in different parts of the historic quarter of Bushehr except the coastal strip (because the buildings located in the coastal strip have a different pattern than other parts of the historical core) .Finally, eight houses have been selected as the case studies (Figures 5 to 7). Physical characteristics of each case have been extracted, including window-to-wall ratio, area of each façade as well as height and weight of different openings. Data have been collected for all facades; in this study, facades face courtyards called 'interior façade' since they face the interior open spaces. Facades that face the alley are called 'exterior façade' since they face the exterior open spaces. Table 2 shows the physical characteristics of these houses.

Fig 5. Location of case studies houses in the historic city of Bushehr;
Source: (Authors based on Document Centre of Bushehr)

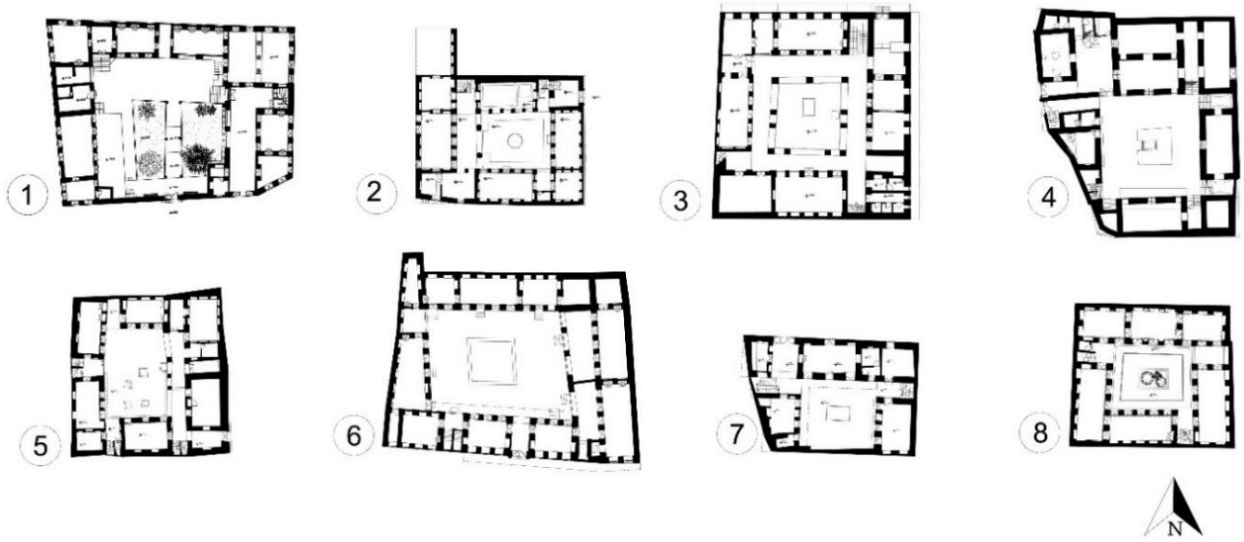


Fig 6. Eight vernacular buildings in the city of Bushehr;
Source: (Authors based on Document Centre of Bushehr)

Fig 7. Facades of a case study house, Asiaei house. (Left) Exterior Facades, (Right) Interior Facades; Source: (Authors based on Document Centre of Bushehr)

Table 2. Physical characteristics of eight selected vernacular houses of the city of Bushehr

No.	Building Orientation	Number of Floors	Number of Exterior Façade	Number of Interior Façade	Exterior Façade Surface Area (m^2)	Interior Façade Surface Area (m^2)	Exterior Opening Surface Area (m^2)	Interior Opening Surface Area (m^2)
1	North-South	2	4	3	678.68	271.65	139.63	55.75
2	North-South	2	3	4	597.67	135.86	67.24	70.01
3	North-South	2	2	4	410.97	493.10	87.21	108.62
4	North-South	2	4	4	395.55	386.77	96.53	114.79
5	North-South	2	1	4	105.80	165.89	12.30	55.50
6	North-South	2	1	4	138.38	430.80	64.33	120.39
7	North-South	2	2	3	246.69	201.82	36.08	43.56
8	North-South	2	4	4	629.03	312.64	117.34	112.75

Criteria

This study focuses on identifying strategies for vernacular façade design in Bushehr. It examines case analyses based on specific criteria to uncover the potential a) correlations between façade areas and the dimensions of openings, and b) relationships between various shapes and sizes of openings. These two objectives are investigated as follows:

A) The relationship between the façade area and the area of the openings includes the following sixteen criteria:

Exterior facade criteria

Criteria 1 to 4: Relationship between the facade area and the openings area in north, south, east, and west exterior facades

Criterion 5: Ratio of 'total area of first floor exterior openings' to 'area of exterior first-floor façade'

Criterion 6: Ratio of 'total area of the second-floor exterior openings' to 'area of the second-floor exterior façade'

Interior facade criteria

Criteria 7 to 10: Relationship between facade area and openings area in north, south, east, and west interior facades

Criterion 11: Ratio of 'Total area of first-floor openings of interior façade' to 'area of the first-floor interior façade'

Criterion 12: Ratio of 'total area of the second-floor openings of the interior façade' to 'area of the first-floor interior façade'

Parallel faces criteria

Criteria 13 to 16: Ratio of 'total area of north exterior openings to north exterior facade area' to 'ratio of the total area of north interior façade openings to the area of north interior façade area' and similar to south, east, and west facades

B) Relationships of openings include the following two criteria:

Criterion 17: The level of using all types of openings, including rectangular, arched, and small, medium, and large openings, and also the most

frequent small, medium, and large openings in exterior and interior facades

Criterion 18: Relationship between height and width of openings (average height-to-width ratio in rectangular and arched openings, as well as small, medium, and large openings)

To find an appropriate formula for obtaining the desired relationships, different statistical methods such as distribution, correlation between the desired variables, and a scatter plot were used to determine the relationships. Finally, linear regression models were used for cases where a linear relationship between variables could be seen with slight negligence. Also, for cases where there was no linear relationship between the variables (criteria 10, 13, 14, 15, and 16), attempts were made to use multiple regression models, but using the available data, the fit of the multiple regression model was not significant. Descriptive statistics were used to determine the use of different types of openings (criterion 17) based on available data and the percentages were reported. All the statistical analyses were performed in IBM SPSS Statistics version 16.0.

RESULTS AND DISCUSSION

The findings are presented in four parts: exterior facades, interior facades, parallel facades, and openings.

Exterior Façades

Criterion 1: North Exterior Façade

Among the 5 houses that have a north exterior facade, the ratio of the total area of the north exterior façade openings to the area of the north exterior façade is a minimum of 9%, with an average of 20% and a maximum of 28%. The result of fitting a simple linear regression model is as follows:

$$S_{\text{N.Ex Opening}} = -34.65 + 0.42\ S_{\text{N.Ex Facade}}$$

It means that, for example, for every 10 square meters of increase in the area of the north exterior facade, the area of openings of that facade increases by 4.2 square meters. The value of the coefficient of determination or R2 for this linear equation is 0.73, which is an acceptable value.

Criterion 2: South Exterior Façade

The ratio of the area of the openings to the area of the south exterior facade in 6 houses with a south facade is a minimum of about 13%, with an average of 19% and a maximum of 27%. The result of fitting a simple linear regression model is as follows:

$$S_{\text{S.Ex Opening}} = 3.71 + 0.18\ S_{\text{S.Ex Façade}}$$

It means that, for example, for every 10 square meters of increase in the area of the south exterior facade, the area of openings of that facade increases by 1.8 square meters. The value of the coefficient of determination or R2 for this linear equation is 0.82, which is an acceptable value.

Criterion 3: East Exterior Façade

The ratio of the area of the openings to the area of the exterior east facade in 6 houses with an east facade is a minimum of 12%, with an average of about 19% and a maximum of about 27%. The result of fitting a simple linear regression model is as follows:

$$S_{\text{E.Ex Opening}} = 3.71 + 0.18\ S_{\text{E.Ex Façade}}$$

It means that, for example, for every 10 square meters of increase in the area of the west exterior facade, the area of openings of that facade increases by 1.8 square meters. The value of the coefficient of determination or R2 for this linear equation is 0.81, which is an acceptable value.

Criterion 4: West Exterior Façade

The ratio of the area of the openings to the area of the west exterior facade in 5 houses with a west facade is a minimum of about 5%, with an average of about 17% and a maximum of about 29%. The result of fitting a simple linear regression model is as follows:

$$S_{\text{W.Ex Opening}} = 9.11 + 0.13\ S_{\text{W.Ex Façade}}$$

It means that, for example, for every 10 square meters of increase in the area of the west exterior facade, the area of openings of that facade increases by 1.3 square meters. The value of the coefficient of determination or R^2 for this linear equation is 0.71, which is an acceptable value.

Criterion 5: First Floor of Exterior Façade

The ratio of "total area of first-floor of exterior openings" to "area of first-floor exterior facade" was examined. The results show that among the 8 houses that have a first-floor exterior facade, the ratio of the total area of the first-floor openings to the area of the first-floor exterior facade is a minimum of about 4%, with an average of about 11% and a maximum of about 20%. The result of fitting a simple linear regression model is as follows:

$$S_{\text{First Floor Ex Opening}} = -0.28 + 0.12\ S_{\text{First Floor Ex Façade}}$$

It means that, for example, for every 10 square meters of increase in the area of the first-floor exterior facade, the total area of the openings of that facade increases by about 1.2 square meters. The value of the coefficient of determination or R2 for this linear equation is 0.69, which is an acceptable value (Figure 8. a).

Criterion 6: Second Floor of Exterior Façade

The ratio of the "total area of the second-floor exterior openings" to the "area of the second-floor exterior facade" was examined. The results show that among the 8 houses that have a second-floor exterior, the ratio of the total area of the second-floor openings to the area of the second-floor exterior façade is a

minimum of about 16%, with an average of about 27% and a maximum of about 49%. The result of fitting a simple linear regression model is as follows:

$$S_{\text{Second Floor Ex Opening}} = 7.56 + 0.23\, S_{\text{Second Floor Ex Façade}}$$

It means that, for example, for every 10 square meters of increase in the area of the second-floor exterior facade, the total area of the openings of that facade increases by about 2.3 square meters. The value of the coefficient of determination or R2 for this linear equation is 0.61, which is an acceptable value (Figure 8. b). Despite the above results, no formula was obtained to show the variation of the opening area to the total exterior façade area ratio for each floor.

Interior Façades

Criterion 7: North Interior Façade

The ratio of the "total area of north interior openings" to the "area of north interior facade" was examined. The study shows that among the 8 houses that have a north interior facade, the ratio of the total area of the north interior facade openings to the north interior facade area is a minimum of about 19%, with an average of about 26% and a maximum of 34%. Also, to examine the relationship between these two variables, the results of fitting a simple linear regression model can be used:

$$S_{\text{N.In Opening}} = 2.26 + 0.22\, S_{\text{N.In Facade}}$$

It means that, for example, for every 10 square meters of increase in the area of the north interior facade, the total area of the openings of that facade increases by about 2.2 square meters. The value of the coefficient of determination or R2 for this linear equation is 0.7, which is an acceptable value.

Criterion 8: South Interior Façade

The ratio of the "total area of south interior openings" to the "area of south interior facade" was examined. Among the 6 houses that have a south interior facade, the ratio of the total area of the south interior facade openings to the area of the south interior facade is a minimum of 22%, with an average of 27% and a maximum of 35%. Also, to examine the relationship between these two variables, the results of fitting a simple linear regression model can be used:

$$S_{\text{S.In Opening}} = 4.04 + 0.23\, S_{\text{S.In Facade}}$$

It means that, for example, for every 10 square meters of increase in the area of the south exterior facade, the total area of the openings of that facade increases by about 2.3 square meters. The value of the coefficient of determination or R2 for this linear equation is 0.66, which is an acceptable value.

Criterion 9: East Interior Façade

The ratio of ‘total area of east interior openings’ to ‘area of east interior façade’ was examined. Among the 8 houses that have an east interior facade, the ratio of the total area of the east interior facade openings to the east interior facade area is a minimum of about 18%, with an average of about 27% and a maximum of about 41%. Also, to examine the relationship between these two variables, the results of fitting a simple linear regression model can be used:

$$S_{\text{E.In Opening}} = 0.96 + 0.25\, S_{\text{E.In Facade}}$$

It means that, for example, for every 10 square meters of increase in the west interior façade, the total area of the openings in that façade increases by about 2.5. The value of the coefficient of determination or R2 for this linear equation is 0.61, which is an acceptable value.

Criterion 10: West Interior Façade

The same examinations were performed to obtain the ratio of ‘total area of west interior facade openings’ to "area of the west interior facade", but no specific pattern was obtained between the variables.

Criterion 11: First Floor of Interior Façade

The ratio of ‘total area of the first-floor interior façade openings’ to ‘area of the first-floor interior façade’ was examined. The results show that among the 8 houses that have a first-floor interior facade, the ratio of the total area of the first-floor interior facade openings to the area of the first-floor interior facade is a minimum of about 19%, with an average of about 26% and at a maximum of about 41%. The result of fitting a simple linear regression model is as follows:

$$S_{\text{First Floor In Opening}} = 6.86 + 0.22\, S_{\text{First Floor In Façade}}$$

It means that, for example, for every 10 square meters of increase in the area of the first-floor interior facade, the total area of the openings of that facade increases by about 2.2 square meters. The value of the coefficient of determination or R2 for this linear equation is 0.63 which is an acceptable value (Figure 9. a).

Criterion 12: Second Floor of Interior Façade

The ratio of ‘total area of openings of the second-floor interior façade’ to ‘area of the second-floor interior façade’ was examined. The results show that among the 8 houses that have a second-floor interior facade, the ratio of the total area of the second-floor openings to the second-floor interior façade is a minimum of about 19%, with an average of about 29% and a maximum of about 49%. The result of fitting a simple linear regression model is as follows:

$$S_{\text{Second Floor In Opening}} = 13.93 + 0.17\, S_{\text{Second Floor In Façade}}$$

It means that, for example, for every 10 square meters increase in the area of the first-floor interior facade, the total area of the openings of that facade increases by about 1.7 square meters. The value of the coefficient of determination or R2 for this linear equation is 0.64, which is an acceptable value (Figure 9. b). Despite the above results, no formula was obtained to show the variation of the opening area to the total interior façade area ratio for each floor.

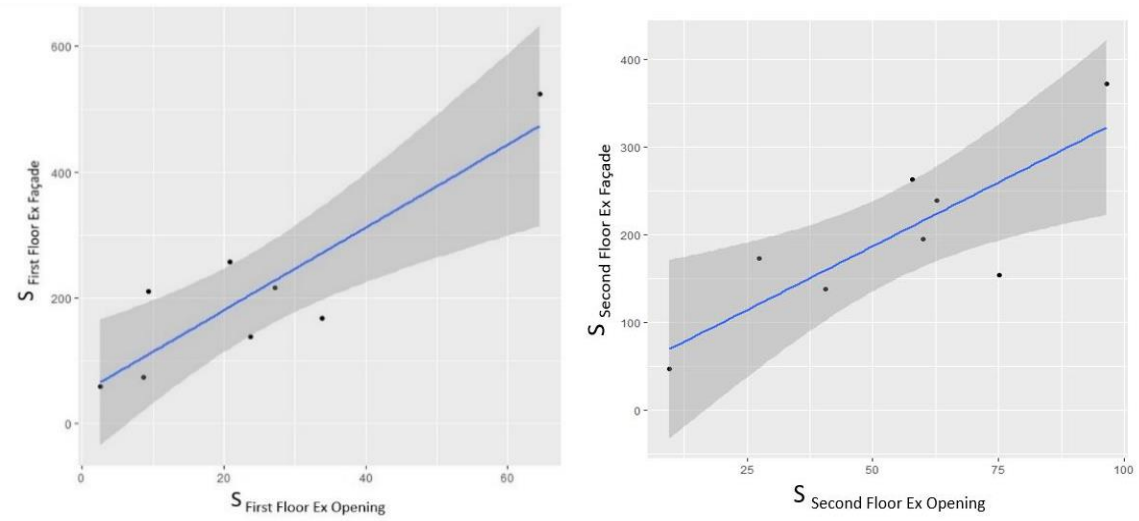


Fig 8. a) The ratio of "total area of the first-floor openings of the exterior façade" to "area of the first-floor exterior façade" (left), **and b)** The ratio of "total area of openings to the second-floor exterior façade" to "area of the second-floor exterior façade" (right)

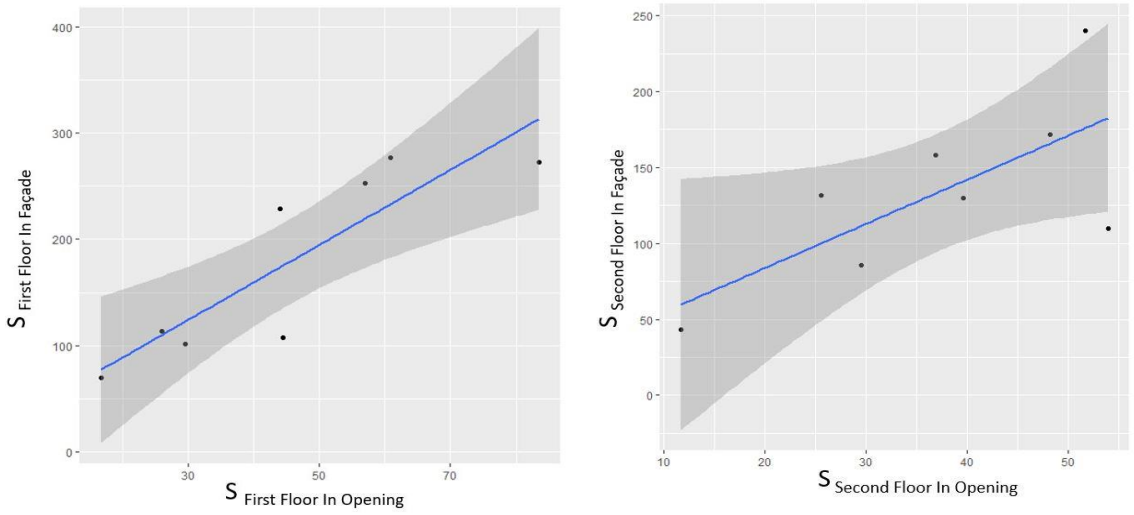


Fig 9. (a) The ratio of "total area of the first-floor openings of the interior facade" to "area of the first-floor interior facade" (left) **and (b)** The ratio of "total area of the second-floor openings of the interior facade" to "area of the second-floor interior facade" (right)

Parallel Façades

The ratio of "total area of north exterior façade openings to the area of the north exterior facade " to the ratio of "total area of openings of the north interior facade to the area of north interior facade" was examined but no valid result was obtained. The same work was done for three other directions, but no special pattern was found for them. Therefore, criteria 13 to 16 in Bushehr vernacular architecture were not met.

Openings

Criterion 17: Usage Rate of Different Shapes and Size of Openings

Descriptive statistics show that in total 55% of the openings are rectangular and 45% are arched. In terms of size, 65% of the openings used are medium, 30% are small and only 5% are large. Figure 10 shows to what extent each category of opening is arched or rectangular.

Results of this study on different sizes of opening show that in the exterior facade, among 101 small openings, openings with length and height of 1.1 and 0.68, respectively, with 14 frequencies and openings with length and height of 1 and 0.7, respectively with 17 frequencies had the highest frequency. Among 220 medium openings, openings with length and height of 1 and 2.5, respectively, with 42 frequencies had the highest frequency. Among 18 large openings, openings with length and height of 2 and 3.5, respectively, with 3 frequencies had the highest frequency and openings with length and height of 2.6 and 3.2, respectively, with 3 frequencies had the highest frequency.

In the interior facade, among the 68 small openings, the openings with length and height of 0.83 and 0.48, respectively, with 19 repetitions, had the highest frequency, and the openings with length and height of 1 and 0.7, respectively with 17 frequencies had the highest frequency. Among 260 medium openings, openings with length and height of 1 and 2.6, respectively, with 75 frequencies had the highest frequency, and openings with length and height of 0.74 and 2.39, respectively, with 20 frequencies had the highest frequency. Among 30 openings, large openings with length and height of 1.5 and 2.6, respectively, with 21 frequencies had the highest frequency. Table 3 shows the most frequent small, medium, and large openings in exterior and interior façade.

Criterion 18: Relationship between height and width of openings

The results of fitting a simple linear regression model show that the height of rectangular openings is on average 83 cm lower than the height of arched openings. It means that more elongated openings are generally arched ($R^2 = 0.80$):

$$H_{\text{Arch Opening}} = 2.1 - 0.83\ H_{\text{Rec Opening}}$$

According to the result of fitting a simple linear regression model in arched openings, the ratio of width to height in small, medium, and large-size openings follows the following equation ($R^2 = 0.73$):

$$WH_{\text{Large Arch Opening}} = 3.95 - 1.83\ WH_{\text{Medium Arch Opening}} - 2.5\ WH_{\text{Small Arch Opening}}$$

According to the result of fitting a simple linear regression model in rectangular openings, the ratio of width to height in small, medium, and large-size openings follows the following equation ($R^2 = 0.73$):

$$WH_{\text{Large Rec Opening}} = 2.73 - 0.83\ WH_{\text{Medium Rec Opening}} - 2.02\ WH_{\text{Small Rec Opening}}$$

The values of the coefficient of determination (R^2) are presented for all the equations, which demonstrates that the model's fit is within acceptable ranges, thereby supporting the validity and reliability of the results. The key findings of the study are summarized in Table 4.

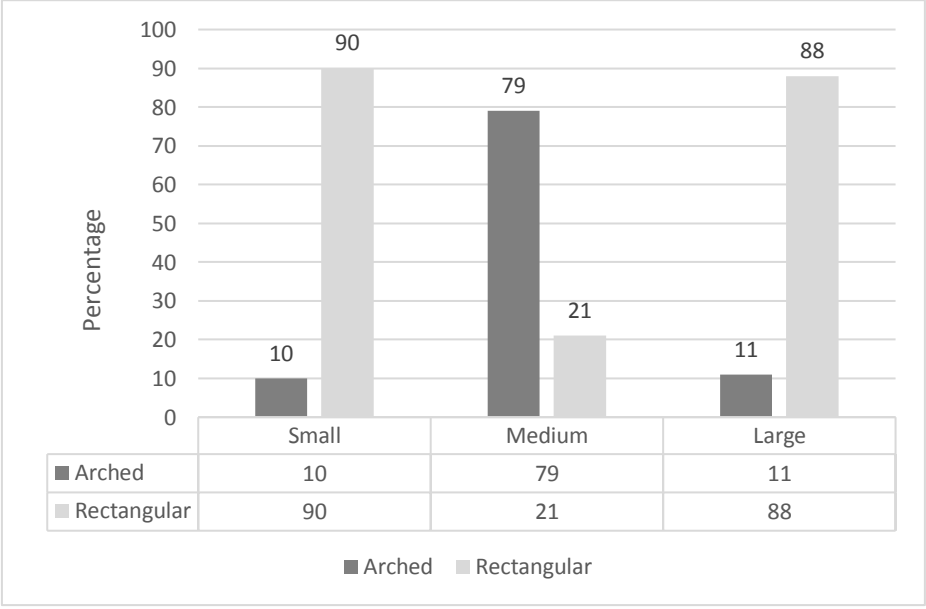


Fig 10. The use of arched and rectangular openings by opening size in vernacular residential architecture in Bushehr historic buildings except the coastal strip

Table 3. The most frequently used types of small, medium, and large openings in exterior and interior facades

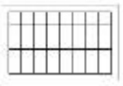
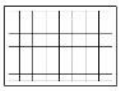
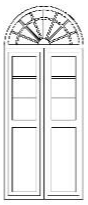
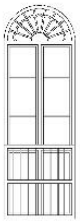
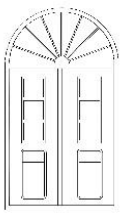
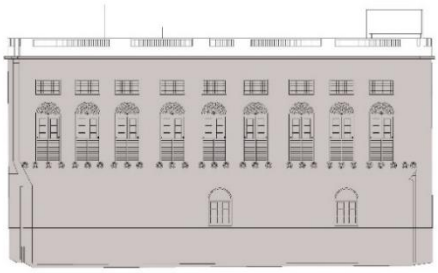
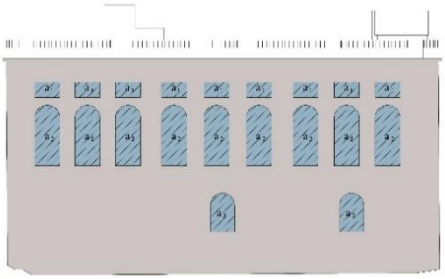
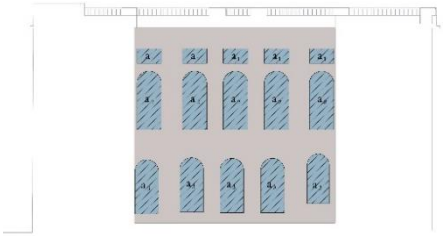
Façade	Opening Size	WD	H	Number of Repetition	Figure
Exterior	Small	1.1	0.68	16	
		1	0.7	18	
	Medium	1	2.5	42	
	Large	2.5	3.2	6	
Interior	Small	0.83	0.48	19	
		1	0.7	17	
	Medium	1	2.6	75	
		0.73	2.39	20	
	Large	1.25	2.6	21	

Table 4. Summary of Key Findings on Façade Design in Vernacular Architecture of Bushehr

	Façade Figures		A/B	
Exterior façade	Real façade		South	13-27%
			North	9-28%
			East	12-27%
			West	5-29%
	Simple edition		South	A = 3.71 + 0.18 B
			North	A = -34.65 + 0.42 B
			East	A = 3.71 + 0.18 B
			West	A = 9.11 + 0.13 B
	AF= total area of the exterior openings BF= area of the exterior facade		first-floor	$AF_1 = 9.11 + 0.13\ BF_1$
			second-floor	$AF_2 = -0.28 + 0.12\ BF_2$
Interior façade	Real Facade		South	22-35%
			North	19-34%
			East	18-41%
			West	-
	Simple edition		South	A = 4.04 + 0.23 B
			North	A = 2.26 + 0.22 B
			East	A = 0.96 + 0.25 B
			West	-
	AF= total area of the interior openings BF= area of the interior facade		first-floor	AF = 6.86 + 0.22 BF
			second-floor	AF = 13.93 + 0.17 BF
Description	A= Sum of openings area= $a_1 + a_2 + a_3 + \ldots$ B= Total Façade area			

Limitations of the Study

One of the limitations of the present study is that buildings with comprehensive and accurate facade maps are scarce. Furthermore, many valuable buildings have undergone alterations due to contemporary developments, and the original documentation necessary to illustrate the architectural design before these modifications are often unavailable. Additionally, many precious historical buildings are privately owned, with access restrictions for visitors. Consequently, expanding the sample size for case studies within the statistical population was time-consuming and costly. Moreover, it was challenging to justify the relevant institutions to provide funding in the short term. However, presenting the findings of this research can help underscore the issue and facilitate the acquisition of grants for future research.

CONCLUSION

This study sought to discover the potential correlation between various parameters in designing

facades of Bushehr's vernacular buildings. It uses mathematical analysis to conduct a quantitative approach toward principles used in the façade design of Bushehr's vernacular architecture and express them in a mathematical language. The results revealed fourteen linear models—six models related to the exterior facades, five models concerned with interior facades, and three models about the opening. The main findings are as follows:

Exterior Façades

The area of the exterior facades on all the north, south, east, and west fronts with the area of the openings of the same facade (criteria 1 to 4) follows the linear equations with the same equation for south and east. The ratio of openings to façade is larger on the second floor compared to the first floor, to receive favourable breezes and ventilation.

Interior Façades

For North, South, and East, the interior facade area follows the specific linear equations as the same front façade, with no formula for the West facade. This can be due to the change in the priority of receiving radiation and wind considering the shading of adjacent buildings in different environments. Additionally, "the ratio of the total area of the interior facade openings to the area of the interior facade in both the first and second floors is at the lowest level (19%) and equal. Similar to the exterior facades, the interior facades of the second floor have a larger ratio of openings to façade compared to the first floor,

Parallel Façades

The ratio of "exterior façade openings to façade area" does not follow any linear model on the four sides.

Openings

The openings are used in different shapes and sizes that can be presented in three categories (criterion 17). The majority of the openings are in medium and small sizes due to the importance of receiving breeze and ventilation along with reducing received radiation. Arched openings are used 10% more than rectangular ones. Most medium openings are arched, while small and large openings are predominantly rectangular. The height-to-width ratio in small, medium, and large openings follows a linear equation for both arched and rectangular openings (criterion 18).

It is recommended that future studies investigate the obtained results of the present study in vernacular facade design for a higher number of case studies and consider the passageways and surrounding buildings . It is also suggested to examine the efficiency of the findings in contemporary façade design and to combine them within the new solutions. Although the linear models are specific to the vernacular architecture of Bushehr, the research method and approach outlined in this study have the potential to contribute to a framework that can be used by other researchers to uncover underlying principles in vernacular facades elsewhere around the world.

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AUTHOR (S) BIOSKETCHES

P. Eshrati., *Department of Architecture, School of Architecture, College of Fine Arts, University of Tehran, Tehran, Iran*
Email: *eshrati@ut.ac.ir*

R. Vakilinezhad., *School of Art and Architecture, Shiraz University, Shiraz, Iran*
Email: *arch.rv@shirazu.ac.ir*

A. Ghahramani., *School of Architecture and Environmental Design, Iran University of Science and Technology, Tehran, Iran*
Email: *Ar.ghahramani1992@gmail.com*

D. Eshrati., *Department of Landscape Architecture, R.Wayne Estopinal College of Architecture and Planning, Ball State University, Muncie, IN, USA*
Email: *deshrati@bsu.edu*

M. Namazi., *College of Architecture Planning and Design, Kansas State University, Kansas, USA*
Email: *kazemnamazi@ksu.edu*

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