In the Name of God

SOFFEH

A Journal of Architecture and Urbanism

Shahid Beheshti University,
School of Architecture and Urban Planning
Vol. 36, Issue 2, No. 113, 2026
P-ISSN: 1683-870X, E-ISSN: 2645-5900

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"**SOFFEH**" in Persian architecture refers to a type of raised platform or terrace typically built against a hillside or elevated area. These structures were common in traditional Persian gardens, providing a vantage point for relaxation, contemplation, and enjoying scenic views. Soffehs were often adorned with decorative elements such as intricate tile work, carved stonework, and lush vegetation, creating serene and aesthetically pleasing environments. They were also used for social gatherings, poetry readings, and other leisure activities.

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Cover photo: Central part of the space between the central and northern courtyards at the sunken garden floor level; looking towards the northern courtyard, from 'Documenting A National Treasure: Ganj-Nameh and the Iranian Built Environment Heritage, by Keivan Jourabchi, S. H. Iradj Moeini; Photo by K. Jourabchi.

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Editorial

Established in 1990, *Soffeh* is a double-blind peer-reviewed quarterly journal published by the Faculty of Architecture and Urban Planning, Shahid Beheshti University. The journal provides an open access intellectual platform for original researchers working on issues related to architecture, landscape design, urban planning and design, project and construction management, post-disaster reconstruction, restoration and historical studies of architecture. It is dedicated to publishing the highest-quality research reporting findings on issues of concern regarding the built environment. The journal is primarily published in Persian, with abstracts provided in English. In order to reach a wider audience, however, there is a plan to regularly publish special issues in English, starting with the present issue. This, we believe, is a significant opportunity to showcase our faculty's distinguished position among its peers nationally.

This issue is also our very first one with invited papers included, representing a range of topics. Plans are, however, for each future English issue to focus on a particular theme, and to be edited by an invited guest editor.

Hamid Nadimi
Editor-in-Chief

1. In Persian architecture, *Soffeh* refers to a type of raised platform that affords relaxation, leisure gatherings, and the display of goods by peddlers. They were also used for social performances, poetry readings, and similar events.

http://dx.doi.org/10.48308/soffeh.2026.107120

P-ISSN: 1683-870X

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Thermal Comfort in Vernacular Shavadans vs. Contemporary Above-Ground Rooms: A Two-Season Field Study in Dezful, Iran

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ORIGINAL RESEARCH ARTICLE

Babaee, Faezeh, and Shahin Heidari. "Thermal Comfort in Vernacular Shavadans vs. Contemporary Above-Ground Rooms: A Two-Season Field Study in Dezful, Iran". *Soffeh* 36, no. 2 (2026): 3–26. DOI: http://doi.org/10.48308/soffeh.2025.237689.1374

Received: October 26, 2024
Revised: January 14, 2025
Accepted: May 23, 2025
(Pages: 3–26)

Abstract

Background and Objectives: Shavadans—traditional underground spaces in Dezful, Iran—have long served as passive thermal spaces in a hot semi-humid climate. Despite their historical significance and recognised potential for moderating extreme temperatures, comprehensive two-season field studies comparing their thermal comfort performance with co-located above-ground mixed-mode rooms remain scarce.

This study aims to provide empirical evidence on how Shavadans perform in both summer and winter, determine seasonal neutral temperatures, and assess their potential contribution to contemporary climate-responsive design.

Method: A two-season field campaign was conducted in ten Shavadans during winter (December 2022) and summer (July 2023). Air temperature, relative humidity, and air velocity were measured every three hours from 06:00 to 18:00 at multiple depths. Simultaneously, Level-3 adaptive comfort questionnaires were administered to residents, yielding in 422 valid responses (102 winter and 109 summer datasets for both underground and above-ground spaces). Linear regression of TSV–temperature relationships and the Bin Method were used to

Keywords:
Shavadan,
Thermal comfort,
Underground spaces,
Adaptive comfort,
Mixed-mode ventilation.

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http://doi.org/10.48308/soffeh.2025.237689.1374

Research Questions:

1. How do thermal comfort conditions in traditional Shavadans of Dezful compare with those in above-ground buildings?

2. What differences exist in neutral temperature and thermal comfort conditions between underground and above-ground spaces?

3. How can findings from Shavadans contribute to enhancing energy efficiency in the design of contemporary buildings?

derive neutral temperatures and acceptable comfort ranges for each season and space type.

Findings and Conclusion: Summer results showed that Shavadans maintained significantly cooler indoor conditionsthan above-ground rooms. The neutral temperature decreased from 26.6 °C (above-ground) to 24.5 °C (Shavadan), and only depths greater than 5 m remained fully within the comfort range. The deepest zones (>7 m) were up to 16.1 °C cooler than the courtyard at peak heat, demonstrating the strong thermal buffering capacity of underground construction. In winter, both environments exhibited neutral or near-neutral conditions; however, the Shavadan maintained more stable temperatures and slightly warmer sensations due to its high thermal mass, with a neutral temperature of 23.1 °C compared with 22.5 °C above-ground.

Overall, Shavadans mitigate heat stress effectively in summer and provide stable thermal conditions in winter, while above-ground rooms offer slightly better comfort during the cold season. These findings deliver the first dual-season empirical benchmark in Iran and highlight the potential of hybrid underground–surface strategies for low-energy, climate-responsive architectural design.

Introduction

Shavadans are traditional underground spaces found in many residential buildings of Dezful and the northern Khuzestan region, designed to provide thermal comfort in the area's hot semi-humid climate. Typically constructed 5 to 12 metres below ground level and accessed via a flight of stairs, they rely on the high thermal capacity of the earth and natural ventilation to moderate indoor temperatures.[1] Archaeological evidence suggests their existence in Dezful since the Sassanid era.[2]

With the spread of mechanical cooling systems and the reduced use of steep staircases in modern houses, the functional role of Shavadans has declined, raising concerns for sustainable architecture. Architecturally, Shavadans consist of several key elements,[3] (Figure 1): an entrance from the

1. Mohsen Bina, 'Climatic Analysis of Shavadans in the Traditional Houses of Dezful,' *Honar-ha-ye Ziba* 33, no. 33 (2008).

2. Mohammadali Emam (Ahvazi), *Historical Geography of Dezful* (Dezful: Dar al-Mo'menin 2003).

courtyard, a staircase with intermittent wide steps (Peleh-Pahn) serving as landings, a central courtyard (*Sahn*), adjoining chambers (*Kat*), connecting tunnels (*Tal*), and vertical ventilation shafts (*Darizeh*). Together, these elements illustrate an integrated vernacular system of underground design (Figure 2).

On the other hand, thermal comfort— recognised as a subjective and multidimensional indicator of indoor air quality—is shaped by environmental, psychological, cultural, and behavioural factors. However, international standards such as ASHRAE-55[4] and ISO 7730[5] do not fully account for the specific differences between underground and above-ground spaces or for the role of individual adaptability.

This study builds on the authors' earlier research, which focused exclusively on summer conditions in Shavadans in Dezful.[6] In the present work, the scope is extended to include a comparative assessment of thermal comfort in underground Shavadans and above-ground mixed-mode buildings during both hot and cold seasons. The central aim is to provide empirical evidence that can inform the development of optimised passive design strategies for contemporary architecture.

Research Questions and Objectives

Significance of the Study

Since the 1960s, vernacular architecture has been recognised as a valuable source of strategies to address the shortcomings of modern design. Research in this field not only examines its distinctive features but also seeks to identify rational and applicable principles that can inform contemporary architectural practice.[7]

Amos Rapoport distinguishes two main approaches to vernacular architecture. The first is the direct imitation of forms and details, often with a nostalgic outlook. The second is a model-based approach that derives architectural principles by analyzing environmental behaviour.[8]

The use of underground dwellings has a long history worldwide, ranging from cave houses in China and Kandovan (Iran) to the underground villages of Meymand (Iran) and Mesa (United States).[9]

Figure 1 (Left). The elements of Shavadan.

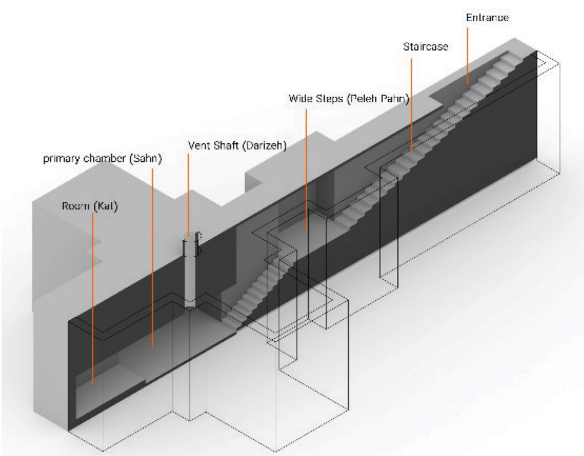


Figure 2 (Right). An image of the wide steps (Peleh-Pahn) in the Tizno House Shavadan.

3. Mostafa Mohebian, Mahnaz Ashrafi, and Amin Kivanloo, 'Investigating the Typology of Troglodytic Shavadans in Dezful,' *Richt-Journals* 43, no. 1 (2022).

4. ASHRAE-55, '55, Thermal environmental conditions for human occupancy,' (Atlanta, 2020).

5. IOF Standardsation, 'Ergonomics of the thermal environment: analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria,' *International Organsation for Standardsation* (2005).

6. Faezeh Babaee and Shahin Heidari, 'Thermal comfort and structural optimisation of Shavadans: a multi-criteria approach: Case study–Hot and semi-humid climate, city of Dezful-Iran,' *Tunnelling and Underground Space Technology* 162 (2025).

In contemporary times, challenges such as population growth, land scarcity, depletion of energy resources, and environmental pollution have intensified interest in the thermal capacity of the earth and the potential of underground buildings.

These spaces can contribute significantly to sustainable design by reducing energy consumption, enhancing thermal comfort, and improving acoustic quality[10]. However, they also present challenges, including limited natural lighting, high humidity, construction costs, and psychological concerns for occupants[11].

In Iran, Shavadans represent a prominent example of traditional underground architecture, historically used for summer habitation in the hot and semi-humid climate of northern Khuzestan.

Despite their cultural and architectural importance, only a limited number of studies have examined the thermal comfort of Shavadans, and most have focused solely on temperature measurements or numerical simulations. This research addresses that gap by combining field data collection with statistical analysis to quantify the thermal comfort range in both Shavadans and above-ground spaces, while also examining user thermal behaviour. In doing so, it validates traditional knowledge and offers strategies for integrating underground architectural principles into sustainable contemporary design.

The aim of this study is to conduct a comparative investigation of thermal comfort conditions in traditional Shavadans of Dezful and above-ground buildings with mixed-mode ventilation during both summer and winter. By collecting data on air temperature, relative humidity, and air velocity, this study identifies the differences in thermal comfort between the two types of spaces and offers design strategies for applying Shavadan principles in contemporary architecture.

Literature Review

In recent years, the high thermal capacity of the earth has increasingly been recognised as a passive system for reducing energy consumption and improving building performance. Underground buildings, in particular, have the potential to meet many of the criteria set by LEED guidelines and net-zero energy building standards.[12]

These advantages have drawn significant research attention to underground spaces and the utilisation of the ground's thermal capacity. Consequently, the number of studies focusing on energy performance in underground environments has shown an upward trend, peaking in 2016 (Figure 3). This trend reflects the growing appeal of the field over the past decade, largely driven by rapid urbanisation and the implementation of incentive policies in many countries.[13]

At the practical and case-study level, numerous field and numerical investigations have demonstrated that semi-underground and fully underground spaces effectively reduce daily and seasonal temperature fluctuations. These spaces provide enhanced cooling performance during summer and ensure more stable thermal conditions in winter compared with above-ground environments.[14]

Despite their long-standing historical role as passive architectural strategies, only a limited number of studies have examined the thermal comfort of Shavadans, with most research pri-

7. Lawrence Wodehouse, *Indigenous Architecture Worldwide: A Guide to Information Sources* (Gale Research, 1980).

8. Amos Rapoport, 'Vernacular design as a model system,' *L. Asquith and M. Vellinga (ed. s), Vernacular Architecture in the Twenty-First Century (Theory, Education, and Practice), Taylor and Francis, London, UK* (2006).

9. Morteza Hazbei et al., 'Reduction of energy consumption using passive architecture in hot and humid climates,' *Tunnelling and Underground Space Technology* 47 (2015). A Benardos, I Athanasiadis, and N Katsoulakos, 'Modern earth sheltered constructions: A paradigm of green engineering,' *Tunnelling and Underground Space Technology* 41 (2014).

10. Akubue Jideofor Anselm, 'Passive annual heat storage principles in earth sheltered housing, a supplementary energy saving system in residential housing,' *Energy and Buildings* 40, no. 7 (2008).

marily focusing on their energy performance. Field measurements consistently demonstrate that Shavadans maintain moderate indoor temperatures while minimising seasonal fluctuations, highlighting their potential as resilient and energy-efficient architectural solutions.[15]

Numerical studies have proposed a range of strategies to enhance performance: Hazbei et al. (2015)[16] recommended shallower Shavadans, mechanical fans, and smart control systems to improve penetration of daylight and reduce humidity; Mohammadshahi et al. (2016, 2019)[17] analysed components such as kat, wide stairs, and shabestan, identifying forms that optimise ventilation; Samsam-Khayani et al. (2018)[18] demonstrated that adding tals improves air flow distribution; and Sadoughi et al. (2019)[19] confirmed effective thermal performance. Collectively, these studies underscore the efficiency of Shavadans in maintaining thermal comfort across seasons.

While these studies demonstrate thermal efficiency, understanding how these conditions affect human sensation requires predictive comfort models. The Fanger PMV–PPD model, developed based on experiments in climate-controlled chambers, is grounded in heat balance equations between the human body and its environment. Over the past fifty years, it has been widely applied and examined[20].

Several studies[21] explicitly or implicitly validated the model, while others(Enescu, 2017; Ikeda et al., 2021; Li et al., 2020) pointed to its limited predictive power.

Cheung et al. (2019)[22] reported that its accuracy in predicting actual thermal sensation was only 34%. Although reliable under uniform, controlled conditions, the model often fails in dynamic and heterogeneous real-world environments.[23] Its tolerance range for individuals in the same environment can exceed one unit[24], and it is valid primarily for healthy adults, often excluding children, the elderly, or people with disabilities.

In contrast, adaptive thermal comfort approaches link occupants' sensations to outdoor air temperature through linear regression and rely primarily on field data[25] . These approaches assume that humans actively interact with their thermal environment, incorporating physiological, behavioural, and psychological adaptation at a general level[26]. Because adaptive models are applied across diverse locations and conditions, they allow a wider acceptable range of indoor temperatures and have been integrated into international and national standards, playing a key role in energy-efficient building design and operation[27].

Despite the substantial body of evidence, a systematic gap remains in the Iranian literature and even in some international studies: the absence of comparative field research that simultaneously and survey-wise evaluates thermal comfort conditions—including temperature, humidity, air velocity, and human/subjective responses—in traditional underground spac-

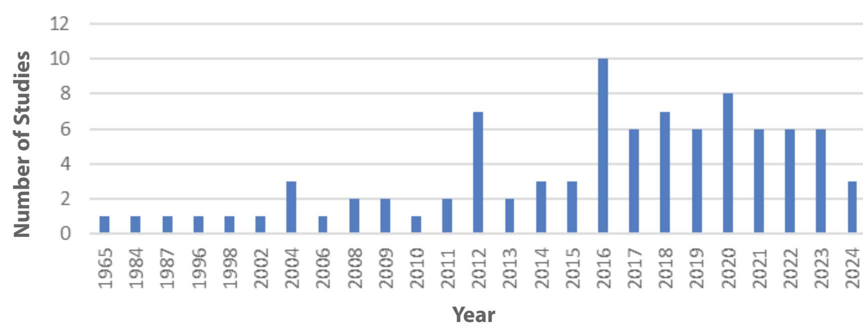


Figure 3. The number of studies on energy performance in underground buildings up to 2024.

11. Rajnish K Goel, Bhawani Singh, and Jian Zhao, *Underground infrastructures: planning, design, and construction* (Butterworth-Heinemann, 2012).

12. H Feng and K Hewage, 'Energy saving performance of green vegetation on LEED certified buildings,' *Energy and buildings* 75 (2014). AJ Marszal et al., 'Zero Energy Building–A review of definitions and calculation methodologies.: 971–9. 2011,' (2011).

es and modern above-ground buildings (with mixed or active ventilation systems) across both summer and winter seasons. Recent reviews have also emphassed the need to integrate field data, conduct statistical analyses (e.g., determining neutral temperature), and incorporate users' behavioural and psychological components into assessment models. This study addresses precisely this gap by collecting data from 10 Shavadans in Dezful and comparing them with above-ground buildings, providing new empirical evidence as well as practical design recommendations and decision-making criteria. Consequently, the scientific relevance and distinctive contribution of this research within the existing literature are clear and well-founded.

Research Methodology

Location and Climate

Dezful is located in the northern part of the Khuzestan Province in southern Iran. The city is built on a type of conglomerate that rises above the Dez River. According to the Köppen climate classification, Dezful has a hot semi-arid climate (BSh), with extremely hot summers and mild winters. Based on the effective temperature throughout the year, Dezful experiences cold conditions for 7.6% of the time, comfortable conditions in shaded areas for 29.1% of the time, and warm conditions for 63.7% of the time.[28]

Meteorological data over a 20-year period indicate that the city's maximum and minimum daily average temperatures are 41.4°C and 2.9°C, respectively. The maximum average relative humidity is 99%, and the minimum is 7.7%. Moreover, the city receives an average of 8.12 hours of sunshine per day (data from Safiabad Meteorological Office). Table 1 shows the 20-year climatic statistics of Dezful from 2002 to 2022 (1381–1401 in the Iranian calendar).

using variational autoencoder,' *Building and Environment* 207 (2022).

15. M. Bina, 'Climatic Analysis of Shavadans in the Traditional Houses of Dezful', *Honar-ha-ye Ziba* 33, no. 33 (2008),https://jhz.ut.ac.ir/article_19039_bdd8626d54f4f9bcae7ca0d993d60902.pdf; H. Moradi and H. Eskandari, 'An experimental and numerical investigation of Shovadan heating and cooling operation', *Renewable Energy* 48 (2012): 364–368.

Table 1. Twenty-Year Climatic Data of City of Dezful.

Month (Gregorian)	Avg Daily Temp (°C)	Max Daily Temp (°C)	Min Daily Temp (°C)	Avg Monthly Precipitation (mm)	Avg Daily RH (%)	Max Daily RH (%)	Min Daily RH (%)	Avg Daily Sunshine Hours
March–April	21.3	29.8	12.3	39	56.4	95.3	24.7	7.3
April–May	27.9	36.4	16.4	20.2	40.9	90	16	8
May–June	33.6	40.7	26.5	0.3	26.5	51.3	7.7	10.4
June–July	36	40.6	30.2	0	25.9	49	8.7	10.8
July–August	36.6	41.4	32.3	0	29.8	59	11	10.7
August–September	33.6	39.5	25.9	1	37.1	69.7	10.3	10.2
September–October	28.3	35	18.4	1.6	44.8	76.5	14.3	9
October–November	21.4	29.5	12.8	41.9	60.1	95	28.5	6.8
November–December	15	22.2	5.2	65	72.2	99	31.5	5.9
December–January	12.5	18.7	4	44.2	73.4	99	36.5	5.8
January–February	13.4	21.4	2.9	44.2	69.4	96.5	33.5	5.8
February–March	17	25	8.1	32.3	62.9	97	33.5	6.7

Measurements

This study was conducted in two stages to estimate the comfort range and examine climatic variables in the Shavadans of Dezful. Ten Shavadans in the old part of Dezful were selected based on their depth and accessibility. Their names and general layout are presented in Figure 4, and the basic information of each is provided in Table 2.

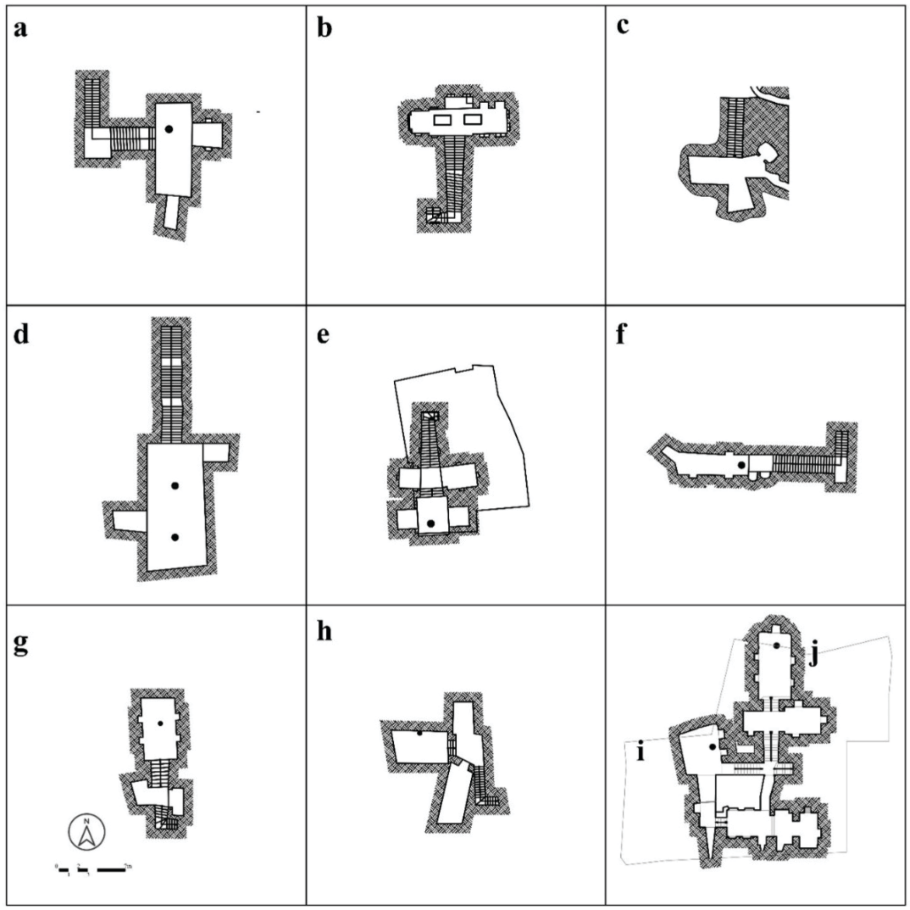
According to the results obtained by Heidari and Sharples, there was a very good agreement between short-term and long-term studies regarding thermal comfort in the city of Ilam. Based on this, the present research was conducted as a short-term study in the winter season from December 24 to December 31, 2022, and from July 1 to July 6, 2023.

Thermal comfort assessments and questionnaire collection were conducted in the main spaces of the Shavadans listed in Table 2, at the deepest section of each Shavadan, as well as in one room within the same buildings that was ventilated naturally and mechanically. However, the western Shavadan of the Saniee House was excluded due to a depth of less than 7 metres, and the Shavadans of Sheikh Rukn al-Din School and the Karnasion Mosque were excluded due to potential collapse and the presence of animals. After completing the measurements, the findings were compared with the climatic data recorded in the Shavadans and generalsed.

The main reason for not using globe temperature was the temperature stability in the basement and the absence of lighting equipment that could affect globe temperature. As noted in the study by Masoudinejad et al., there was no significant difference between globe temperature and air temperature at the depths of Shavadans. In the above-ground rooms, measurements were also conducted away from windows and artificial lighting.

During questionnaire completion, air temperature and relative humidity were measured simultaneously. Participants were required to refrain from eating and drinking for one hour prior to the measurements and to remain seated for at least 30 minutes. Measurements were taken at a height of 120 cm above the ground and in close proximity to the participants. Due to cultural considerations and privacy concerns,

Figure 4. The layout of selected Shavadans.



photographing participants during the survey was not permitted. Figure 5 illustrates the placement of measurement devices relative to the participants in a schematic form.

Air temperature, relative humidity, and airflow were measured at different depths, at points where entrances, landings or main spaces existed, for the ten selected Shavadans according to Figure 6. These measurements were conducted at three-hour intervals from 6:00 a.m. to 6:00 p.m. during both the summer and winter seasons.

Considering the limitations of private ownership of most Shavadans and the lack of calibrated equipment, the measurement schedule was designed to assess three Shavadans consecutively each day, based on the prioritsation in Table 3. This approach allowed for the optimisation of the measurement process and reduced potential errors caused by environmental varia-

16. 'Reduction of energy consumption using passive architecture in hot and humid climates'.

Shavadan Name	Shovadan Label	maximum depth (m)	Number of Darizehs	Number of windows at ground level	Location of Darizehs	Entrance Shape	Area of Main Sections (m^2)
Tizno's house	a	10.2	1		yard	on the floor	52
Ali Malik Shrine	b	8.8	0	1	-	on the wall	37
Sheikh Ruknuddin Dormitory School	c	6.6	0		-	on the floor	33
Dezful Grand Mosque	d	8	2		yard	on the floor	96
Seyed Shams-al-din's house	e	8	1		Roof	on the wall	41
Kornasian Mosque	f	9.8	1		yard (was closed)	on the floor	25
Razavizadeh house	g	9.2	1		The room (was closed)	on the floor	37
Morid house	h	8.35	1		Street on the shade	on the wall	48
Sanaee's house West Shavadan	i	3.6	1		Room	on the floor	21
Saniee's house North Shavadan	j	6.8	1		Room	on the floor	44

Table 2. Properties of Shavadans.

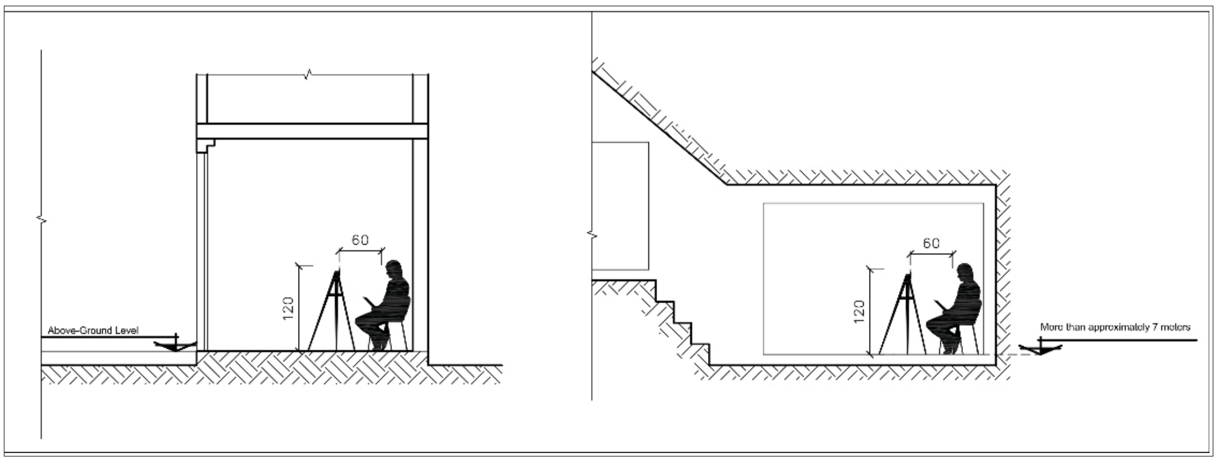


Figure 5. Schematic representation of measuring equipment placement to participants, with sensors positioned at 1.2 metres to align with the breathing zone of seated individuals.

tions. Due to these constraints, the measurements and questionnaire collection were conducted on separate days, with some overlap. Details of the instruments used for both sets of measurements are provided in Table 3.

Study Participants

In this field study, 225 volunteers (116 women and 109 men) residing in residential buildings throughout Dezful participated. Efforts were made to ensure a balanced distribution in terms of age and gender, and residents of the selected houses were also included in the study. In total, 422 valid questionnaire datasets were collected. Specifically, during the winter season, 102 datasets were obtained for above-ground rooms and 102 for Shavadans, while in the summer season, 109 datasets were collected for above-ground rooms and 109 for Shavadans. Table 4 summarses the physical characteristics of the participants. All participants had lived in Dezful for at least 15 years, and their experiences reflect the climatic adaptation of the local residents.

questionnaires

The questionnaires were of the Level 3 type, as described in the study by Nicol et al., meaning that, in addition to environmental measurements, clothing insulation, activity, movement from one point to another, and other factors were also assessed. The questionnaires were completed between 8:00 a.m. and 6:00 p.m. in the deepest section of the Shavadans (over 7 metres) and in above-ground buildings. All questions and subjective scales were explained

Table 3. Detailed information on related instruments.

Parameters	Instrument	Range	Accuracy
Air temperature	CEM-DT-172/172TK	-40 to 70°C	±0.5 ◦C
Relative humidity		0 to 100%	±3.5%
Air velocity	Benetech-GT8911	0 to 30 m/s	±3%

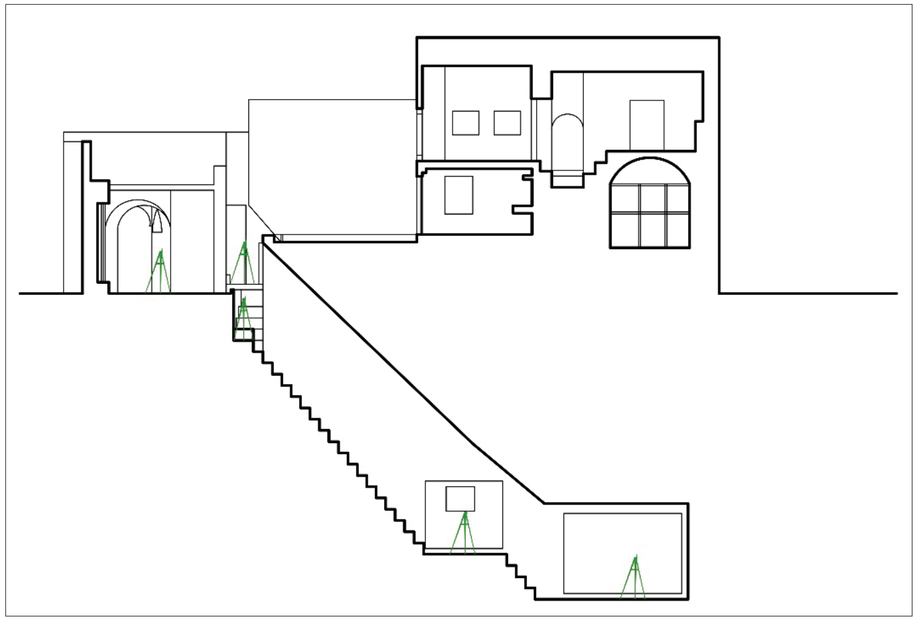


Figure 6. Schematic Position of Measurement Equipment at Various Depths of Shavadans.

Gender	N	Age (years)	Height (cm)	Weight (kg)	BMI (kg/m²)	Clothing Insulation (clo)
Female	116	39.34 ± 15.60*	160 ± 5.69	63.42 ± 12.71	24.57 ± 4.72	0.48 ± 0.17
Male	109	45.48 ± 13.8	170.23 ± 12.59	79.43 ± 9.57	28.00 ± 12.02	0.55 ± 0.25
Total	225	42.52 ± 15.14	165.85 ± 11.03	71.24 ± 13.83	26.50 ± 9.21	0.52 ± 0.22

*. Standard Deviation

Table 4. Physical Information of Participants.

to participants before the start of the survey.

The questionnaire consisted of three sections: the first section included personal information such as gender, age, height, weight, and type of clothing, which was completed by the participant under the supervision of the researcher. The second section focused on evaluating the participants' thermal sensation, using the seven-point ASHRAE scale. In addition, thermal preferences were assessed simultaneously with the measurement and recording of air temperature and relative humidity (Tables 5 and 6).

All scales are presented in the corresponding charts in the Results section. Clothing insulation was determined by summing the insulation values of individual clothing items based on ASHRAE standards and the 2020 guidelines.

The third section of the questionnaire focused on evaluating participants' behavioural priorities under cold and hot weather conditions. For the cold season, the options included: 'drawing curtains to allow sunlight in', 'turning on heating devices', 'moving to a warmer place', 'wearing additional clothing', 'consuming warm food and beverages', 'taking a warm shower,' and 'other actions', For the summer season, the options included: 'opening doors and windows', 'turning on cooling devices', 'moving to a cooler environment', 'wearing lighter clothing,' 'consuming cold food and beverages', 'taking a cold shower', and 'other actions'.

Questionnaire Reliability and Validity

To assess the reliability of the questionnaire, two methods were applied: Cronbach's alpha and split-half reliability. Initially, Cronbach's alpha was calculated for the variables of air temperature and thermal sensation in both summer and winter seasons, yielding values of 0.63 in summer and 0.62 in winter. These values indicate moderate reliability, which is slightly below the reference standard of 0.7 commonly considered acceptable for good reliability. However, in thermal comfort studies, multiple factors such as humidity, airflow, and individual conditions influence the results, so a lower Cronbach's alpha does not necessarily indicate a weak questionnaire.

For a more precise evaluation of reliability, the split-half method was employed, in which the data were randomly divided into two halves and the correlation between them was assessed. The results showed a reliability of 1.0 in both seasons, indicating perfect correlation between the randomly split halves and very high reliability. These findings demonstrate that the questionnaire is sufficiently reliable and provides consistent results across both seasons. They confirm that the relationship between air temperature and thermal sensation in the collected data is stable, making the use

Table 6. Thermal Preference Scale (ASHRAE).

Thermal Preference	Warmer	No Change	Cooler
ASHRAE Scale	+1	0	–1

Table 5. Thermal Sensation Scale (ASHRAE 7-point).

Thermal Sensation	Very Hot	Hot	Slightly Warm	Neutral	Slightly Cool	Cool	Very Cold
ASHRAE Scale	+3	+2	+1	0	–1	–2	–3

17. Shabnam Mohammadshahi, Mahdi Nili-Ahmadabadi, and Omid Nematollahi, 'Improvement of ventilation and heat transfer in Shavadoon via numerical simulation: A traditional HVAC system', Renewable Energy 96 (2016); Shabnam Mohammadshahi et al., 'Investigation of naturally ventilated shavadoons component: Architectural underground pattern on ventilation' *Tunnelling and Underground Space Technology* 91 (2019).

18. Hadi Samsam-Khayani et al., 'Numerical study of effects of Shavadoon connections (a vernacular architectural pattern) on improvement of natural ventilation' *Tunnelling and Underground Space Technology* 82 (2018).

19. Arezou Sadoughi et al., 'Thermal performance analysis of a traditional passive cooling system in Dezful, Iran', *Tunnelling and Underground Space Technology* 83 (2019).

of these indicators for thermal comfort analysis both reasonable and valid. Therefore, although Cronbach's alpha indicated moderate reliability, the split-half results confirm the reliability and suggest that the collected data are trustworthy. Consequently, this questionnaire is considered a valid and reliable tool for analyzing thermal sensation under different climatic conditions.

To ensure the validity of the questionnaire, content validity was applied. The questionnaire was developed based on previous successful studies and reviewed by experts in the field of thermal comfort, with necessary modifications made according to their recommendations. This review confirmed that the designed questions effectively measure the intended variables, indicating that the questionnaire has appropriate content validity.

Results

Environmental Thermal Conditions

Figure 7 illustrates the temporal variations of the outdoor environmental parameters. During the study period, the average daily outdoor temperature was 12.8°C in winter and 36.2°C in summer. The average daily relative humidity was 85% in winter and 25% in summer. These values are in good agreement with the long-term data for the months of Dey (December, January) and Tir (June and July) presented in Table 2, indicating stable climatic conditions during the measurement period. For example, the average daily temperature in Dey and Tir in Table 2 was 12.5°C and 36.0°C, respectively, which corresponds well with the measurements obtained in this study.

Participant Evaluation

Thermal Sensation and Preference

The distribution of thermal sensation votes (TSV) across summer and winter revealed distinct seasonal patterns between the above-ground rooms and the Shavadan. In summer, most responses were concentrated in the neutral (TSV = 0) and slightly warm (TSV = +1) categories. A higher proportion of respondents in the above-ground rooms reported feeling slightly warm, whereas in the Shavadan, a larger share of votes fell into the neutral category. Additionally, a small fraction of votes at votes of TSV = +2 were observed in both spaces, and TSV = +3 appeared only in the above-ground rooms. This pattern indicates that the Shavadan provided more balanced and neutral conditions, while above-ground rooms tended to shift toward warmer sensations (Figure 8).

In winter, the the majority of responses in both spaces were concentrated in the neutral category (TSV = 0), with 77.5% in the above-ground rooms and 72.5% in the Shavadan. A

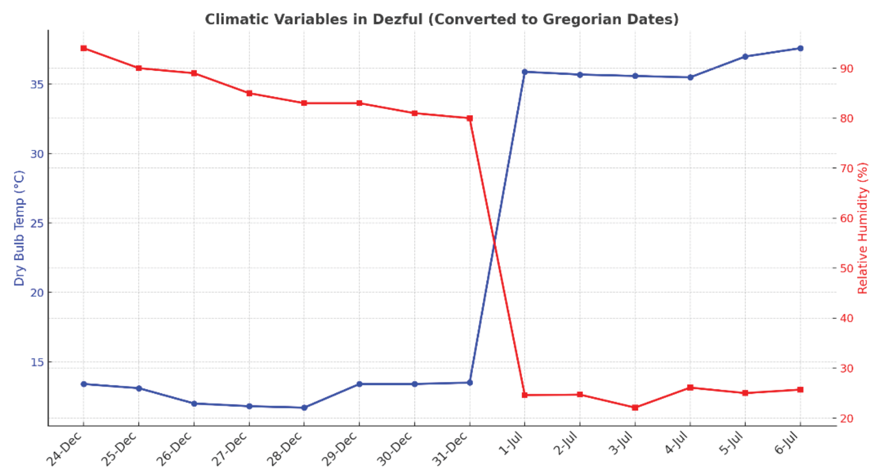


Figure 7. Daily mean outdoor temperature and relative humidity during the study period.

considerable share of respondents reported slightly cool sensations (TSV = -1). However, the proportion of slightly warm responses (TSV = +1) was notably higher in the Shavadan (11.8%) compared with the above-ground rooms (2.9%). This suggests that in winter, the Shavadan exhibited a greater tendency towards warmer sensations, likely due to its higher thermal mass and heat retention properties (Figure 9).

Overall, the comparison across the two seasons shows that the Shavadan acted as a thermally moderating space: reducing the tendency toward heat stress in summer while providing slightly warmer conditions in winter, thereby ensuring a more stable and comfortable indoor environment throughout the year.

As shown in Figure 10, in summer, the majority of responses were concentrated in the cooler (-1) category. More than 70% of respondents in both the above-ground rooms (71.6%) and the Shavadan (72.5%) expressed a preference for lower temperatures. Approximately 28% selected no change (0), while virtually none of the respondents opted for the warmer (+1) category. This pattern suggests that even within the Shavadan, the prevailing tendency in summer was a desire for cooler conditions, reflecting the intensity of outdoor heat stress.

In winter (Figure 11), the distribution shifted, with the majority of responses falling into the no change (0) category (61.8% in above-ground rooms and 58.8% in the Shavadan). At the same time, a significant proportion of respondents expressed a preference for warmer conditions (+1), accounting for 35.3% in above-ground rooms and 25.5% in the Shavadan. A smaller fraction selected the cooler (-1) option, with slightly higher values reported in the Shavadan (15.7%) compared with the above-ground rooms (2.9%).

Overall, the seasonal comparison highlights that in summer, occupants predominantly preferred cooler conditions, whereas in winter, most considered the existing conditions acceptable, with a notable share showing a tendency towards warmer indoor environments (Table 7).

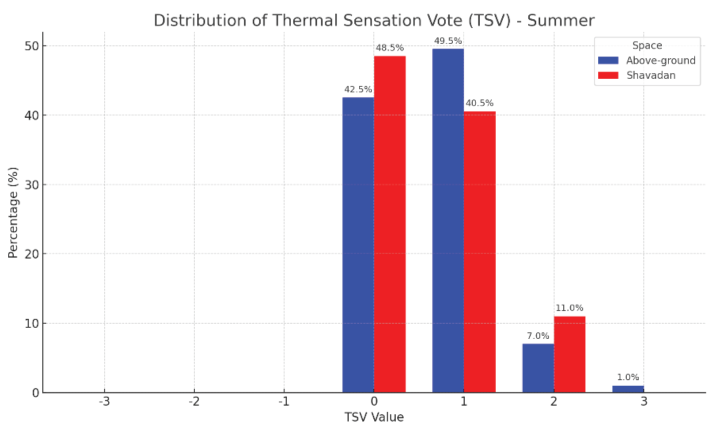


Figure 8. Distribution of participants' thermal sensation votes in summer (Above-ground vs. Shavadan).

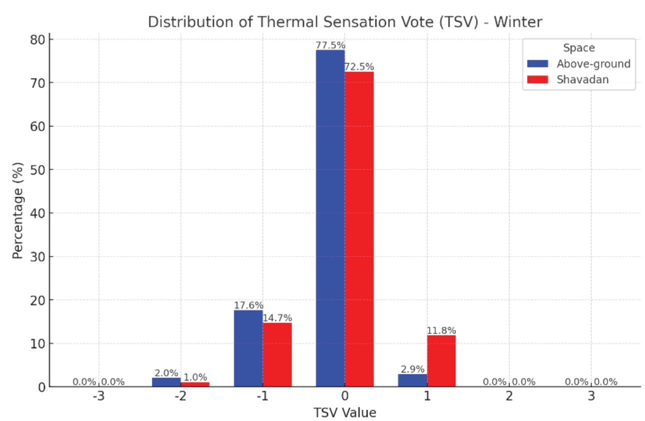
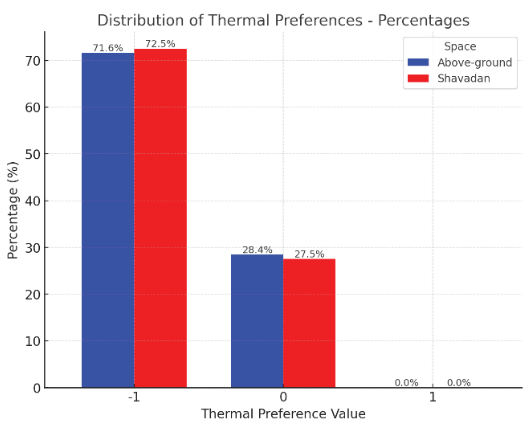


Figure 9. Distribution of participants' thermal sensation votes in winter (Above-ground vs. Shavadan).

In summer, both above-ground rooms and the Shavadan showed a dominant preference for cooler conditions (-1). In above-ground rooms, a considerable share of respondents at TSV = +1 (slightly warm) expressed a desire for cooler environments. By contrast, in the Shavadan, the distribution was more balanced, with a larger proportion of votes concentrated around the neutral category (TSV = 0). This indicates that the Shavadan provided more stable and neutral thermal conditions compared with above-ground spaces (Figure 11).

In winter, neutral sensations (TSV = 0) dominated in both environments. However, thermal preferences revealed differences: in above-ground rooms, the majority selected no change (0), while in the Shavadan a higher share of participants expressed a preference for warmer conditions (+1). This reflects the Shavadan's ability, due to its higher thermal mass and heat retention, to provide slightly warmer and more stable conditions than the above-ground rooms (Figure 12).

Figure 10. Thermal preference distribution in summer (Above-ground vs. Shavadan).



Neutral Temperature and Comfort Range

The regression analysis revealed a clear relationship between air temperature and thermal sensation, enabling the estimation of neutral temperatures and acceptable comfort ranges for both above-ground rooms and Shavadans. As shown in Table 8, in summer the neutral temperature in above-ground rooms was higher, while the Shavadan shifted this point to a cooler level, thereby reducing the sensation of heat stress and providing more favorable indoor conditions. In winter, the neutral temperatures of both spaces were close to each other, but the Shavadan displayed more stable and consistent thermal responses, as indicated by its higher coefficient of determination. The acceptable comfort ranges confirmed this pattern: in above-ground rooms, ranges tended to be slightly wider and more influenced by fluctuations in ambient conditions, while in Shavadans they were narrower and more stable, reflecting the buffering effect of underground construction.

When comparing the two analytical approaches, simple regression (Table 8) suggested

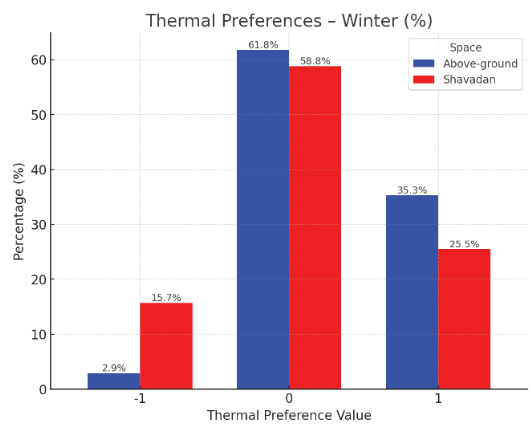


Figure 11. Thermal preference distribution in winter (Above-ground vs. Shavadan).

20. anisius Karyono et al., 'The adaptive thermal comfort review from the 1920s, the present, and the future', *Developments in the Built Environment* 4 (2020). Mohammad Tahsildoost and Zahra S Zomorodian, 'Indoor environment quality assessment in classrooms: An integrated approach', *Journal of Building Physics* 42, no. 3 (2018); Qiantao Zhao, Zhiwei Lian, and Dayi Lai, 'Thermal comfort models and their developments: A review', *Energy and Built Environment* 2, no. 1 (2021).

Season / Index	Space	Dominant TSV Pattern	Dominant Thermal Preference	Key Interpretation
Summer	Above-ground	TSV mostly at 0 and +1, some at +2 and +3	Majority Cooler (-1) (71.6%)	More tendency towards warmer TSV than Shavadan, but still strong desire for cooling
	Shavadan	TSV mostly at 0, then +1, minor at +2	Majority Cooler (-1) (72.5%)	More stable and closer to neutrality compared with above-ground
Winter	Above-ground	TSV mainly 0 (77.5%), then -1, small share at +1	Majority No change (0) (61.8%), followed by Warmer (+1) (35.3%)	Mostly neutral, but noticeable demand for warmer conditions
	Shavadan	TSV mainly 0 (72.5%), then -1, higher share at +1 (11.8%)	Majority No change (0) (58.8%), followed by Warmer (+1) (25.5%)	Slightly greater tendency towards warmer sensations than above-ground, overall stable

Table 7. Seasonal comparison of thermal sensation (TSV) and thermal preference in Above-ground rooms and Shavadan.

meaningful differences in neutral temperatures and comfort boundaries, but the Bin Method (Table 9) provided stronger correlations, with coefficients of determination reaching up to 0.93, reinforcing the robustness of the findings. The distribution of TSV responses, illustrated in Figures 14 and 15, also highlighted distinct seasonal patterns: in summer, responses clustered around neutral (TSV=0) and slightly warm categories, with the Shavadan showing a higher share of neutral votes, while in winter the majority of responses were neutral or slightly cool, again with the Shavadan offering more stable thermal conditions closer to neutrality.

Overall, the combined evidence from regression models, bin-method analysis, and the distribution charts (Figures 14-15, Tables 8-9) highlight that Shavadans are able to lower neutral temperature in hot conditions and maintain a stable, near-neutral indoor climate in cooler seasons.

Correlation between Clothing Thermal Insulation, Humidity, Airflow, and Thermal Sensation

Given that the clothing insulation rate of most participants fell within a narrow range, no con-

21. PO Fanger, 'Fundamentals of thermal comfort', in *Advances In Solar Energy Technology* (Elsevier, 1988). Abed Al-Waheed Hawila et al., 'An analysis of the impact of PMV-based thermal comfort control during heating period: A case study of highly glazed room', *Journal of Building Engineering* 20 (2018). P. Ole Fanger and Jørn Toftum, 'Extension of the PMV model to non-airconditioned buildings in warm climates',

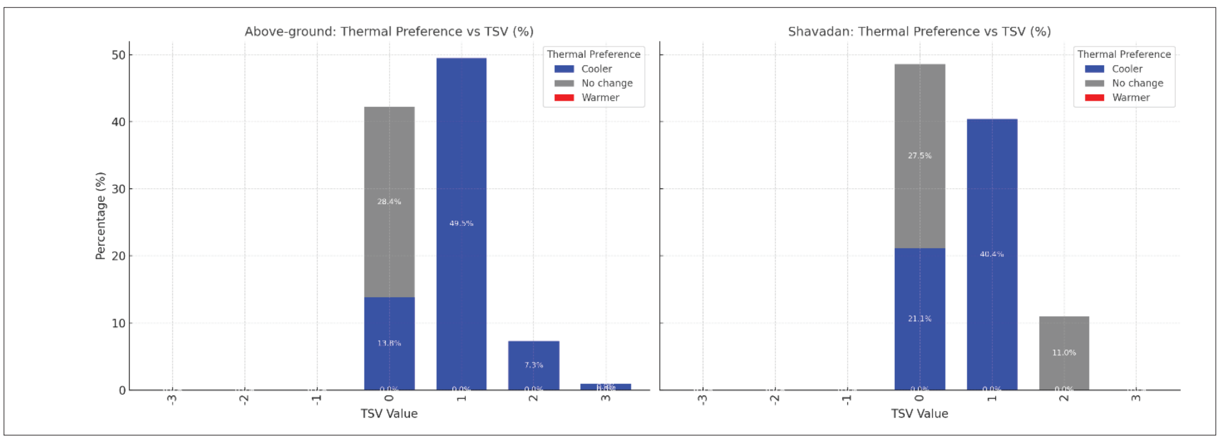


Figure 12. Thermal sensation and preference in summer (Above-ground vs. Shavadan).

siderable variation in clo values was observed. Moreover, the regression analysis indicated that the relationship between clothing insulation, relative humidity, and air velocity with thermal sensation vote (TSV) was weak and statistically insignificant, as the coefficient of determination (R^2) for all cases was found to be below 0.1. This suggests that these factors did not play a decisive role in explaining the variations in TSV.

Behavioural Adaptation

In the summer season, 70% of the respondents reported prioritising the use of cooling devices such as evaporative and air conditioners. Around 30% preferred wearing light and bright clothing, while only 10% referred to changes in dietary habits, such as consuming cold drinks. These findings highlight the greater emphasis of residents on direct strategies for reducing heat stress (Figure 16).

In the winter season, 60% of the respondents indicated that wearing warmer clothing was the most important strategy for coping with cold conditions. Meanwhile, 40% reported using heating appliances such as heaters and fireplaces. Only 15% mentioned reducing the time spent in outdoor spaces, suggesting that the mild winters of Dezful have a limited impact on daily activities (Figure 17).

Environmental Variables in Shavadans and Thermal Comfort Range

Air temperature, relative humidity, and air velocity were monitored at different depths of ten Shavadans during winter and summer, with measurements taken every three hours from 6 a.m.

Energy and Buildings 34, no. 6 (2002); Naji Sirhan and Saar Golan, 'Efficient PMV computation for public environments with transient,' *Energy and Buildings* 231 (2021). Jorn Toftum, Anette S. Jorgensen, and P. O. Fanger', *Energy and Buildings* 28, no. 1 (1998). Jing Wu et al., 'A PMV-based HVAC control strategy for office rooms subjected to solar radiation,' *Building and Environment* 177 (2020).

Season / Space	Regression Equation for TSV	R^2	Slope	Lower Comfort Limit (°C)	Upper Comfort Limit (°C)	Neutral Temperature (°C)
Summer – Above-ground	TSV = 0.28 Air Temperature – 7.57	0.56	0.28	24.9	28.4	26.6
Summer – Shavadan	TSV = 0.24 Air Temperature – 5.97	0.28	0.24	22.4	26.5	24.5
Winter – Above-ground	TSV = 0.20 Air Temperature – 4.53	0.34	0.20	20.0	25.0	22.5
Winter – Shavadan	TSV = 0.24 Air Temperature – 5.44	0.36	0.24	21.0	25.2	23.1

Table 8. Regression models of TSV and comfort temperatures for Above-ground rooms and Shavadan (summer and winter).

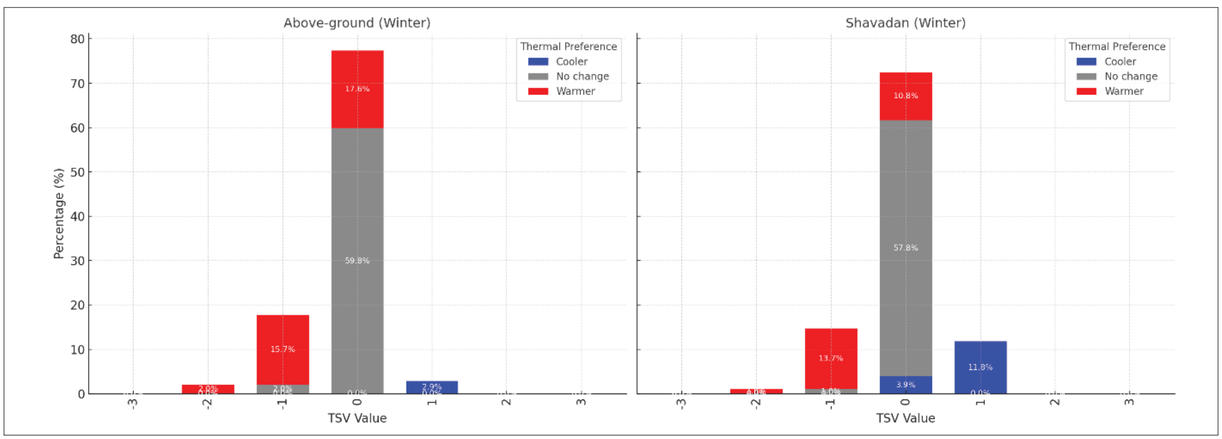


Figure 13. Thermal sensation and preference in winter (Above-ground vs. Shavadan)
Neutral Temperature and Comfort Range.

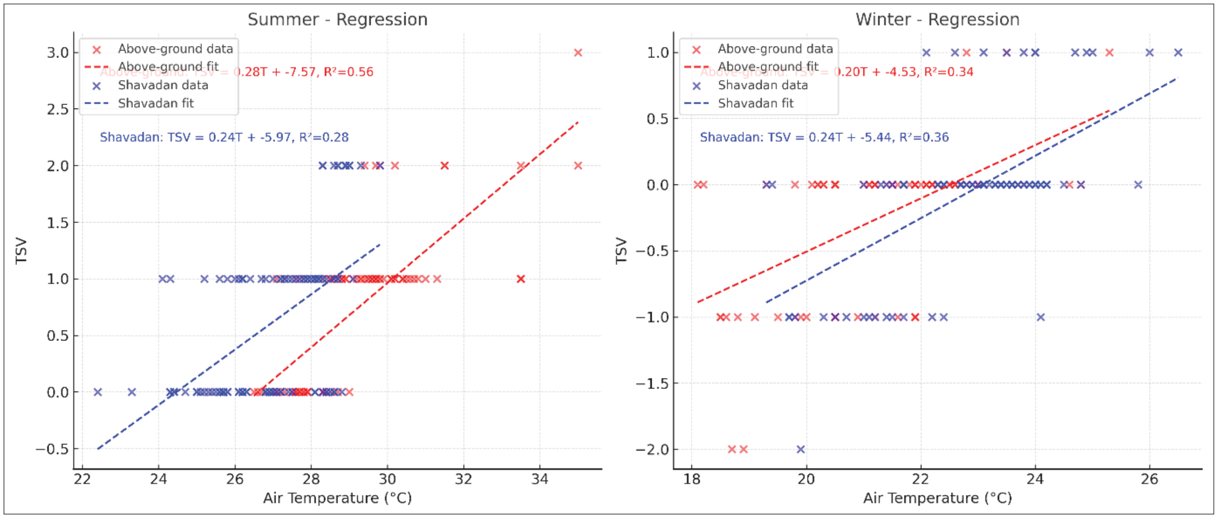


Figure 14. Regression of TSV and air temperature in above-ground rooms (red) and Shavadan (blue) during summer (left) and winter (right).

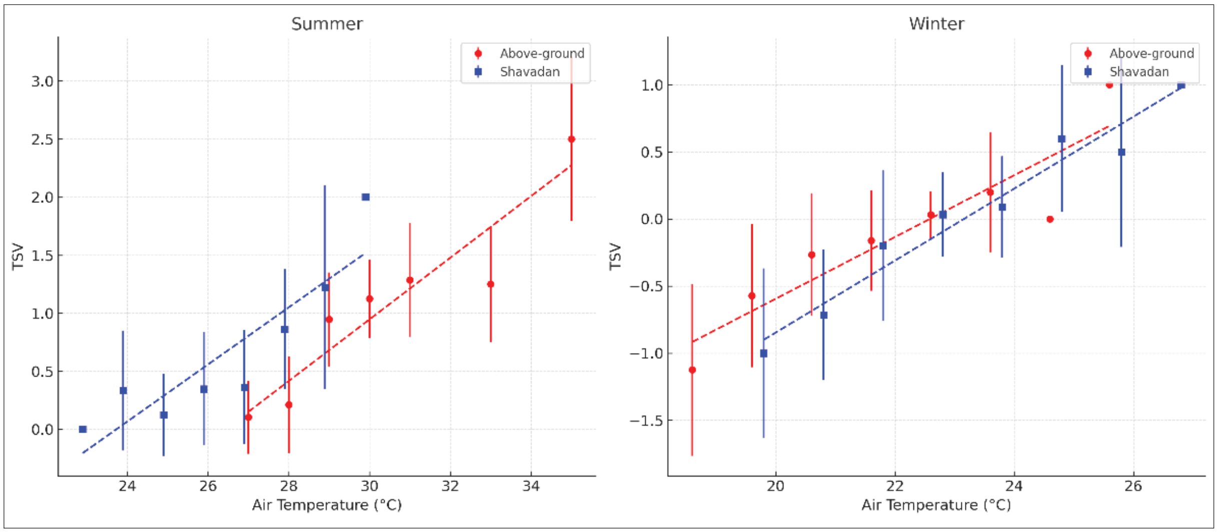


Figure 15. Bin Method analysis of TSV and air temperature in above-ground rooms (red) and Shavadan (blue) during summer (left) and winter (right).

Table 9. Regression models on bin means of TSV and comfort temperatures for Above-ground rooms and Shavadan (summer and winter).

Season/Space	Regression (on bin means)	R^2	Slope	Neutral Temp (°C)	Lower (Neutral–2)	Upper (Neutral+2)
Summer – Above-ground	TSV = 0.21· Air Temperature – 5.54	0.80	0.21	25.9	23.9	27.9
Summer – Shavadan	TSV = 0.22· Air Temperature – 5.23	0.80	0.22	23.6	21.6	25.6
Winter – Above-ground	TSV = 0.23· Air Temperature – 5.10	0.86	0.23	22.6	20.6	24.6
Winter – Shavadan	TSV = 0.26· Air Temperature – 6.08	0.93	0.26	23.2	21.2	25.2

to 6 p.m. In winter, all parts of the Shavadans remained within the thermal comfort range.

Air Temperature

The depth of 5–7 metres showed the closest temperature to the neutral point (22.7 °C). While the courtyard reached a maximum of 19.5 °C, the above-ground room and Shavadans at depths of 1–3 m, 3–5 m, 5–7 m, and >7 m recorded maximum values of 22.4, 21.4, 21.8, 21.9, and 24.2 °C, respectively. Minimum temperatures varied from 16.8 °C in the courtyard to 24.0 °C at depths greater than 7 m, confirming the stabilsing effect of underground spaces (Figure 18).

Detailed results of the summer monitoring campaign were reported in our previous study. In summary, only the average air temperatures below depths greater than 5 m remained within the comfort range, with the deepest zone (>7 m) being up to 16.1 °C cooler than the courtyard during peak heat hours. The present analysis therefore focuses on winter results as a complement to those earlier findings.

Relative humidity

In winter, relative humidity increased with depth and reached its lowest values around noon due to rising air temperature. The courtyard showed maximum and minimum values of 45.1% and 36.7%, while at depths greater than 7 m, values ranged from 49.6% to 44.7%. The above-ground room and Shavadans at 1–3 m, 3–5 m, and 5–7 m recorded maximum values of 45.0%, 43.4%, and 48.3%, respectively. Table 21 summarses these results, alongside the comfort range (Figure 19).

As previously documented, summer results also showed an increase in humidity with depth, with the highest values observed below 7 m (up to 42.8%), while the courtyard and above-ground room had considerably lower values.

Air velocity

Air velocity inside the Shavadans was minimal in both seasons. In winter, the courtyard reached a maximum of 0.45 m/s, while the underground sec-

22. Toby Cheung et al., 'Analysis of the accuracy on PMV–PPD model using the ASHRAE Global Thermal Comfort Database II,' *Building and Environment* 153 (2019).

23. Qian Chai et al., 'Using machine learning algorithms to predict occupants' thermal comfort in naturally ventilated residential buildings,' *Energy and Buildings* 217 (2020).

Figure 16. Behavioural adaptations in summer.

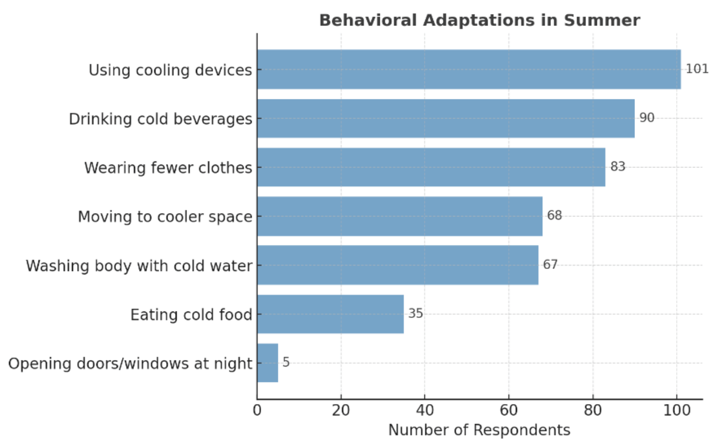
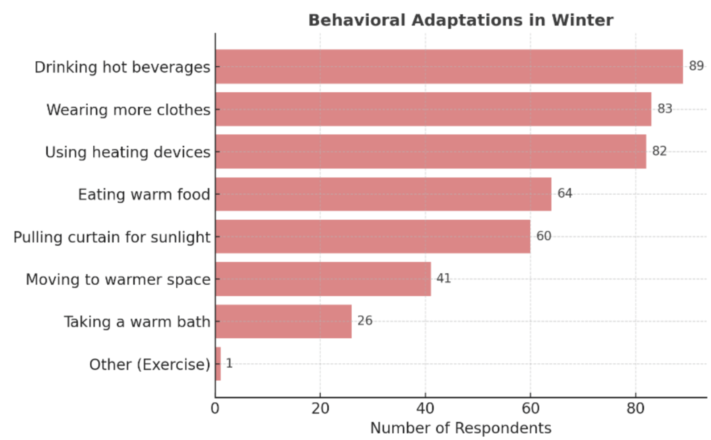


Figure 17. Behavioural adaptations in winter.



tions fell below 0.1 m/s. At depths of 1–3 m, 3–5 m, 5–7 m, and >7 m, maximum values were 0.05, 0.04, 0.02, and 0.02 m/s, respectively (Figure 20).

For summer, velocities were slightly higher in the courtyard (up to 0.47 m/s), but remained very low inside the underground sections, consistent with the stabilising nature of the spaces. Detailed values have been reported previously.

Discussion

The findings of this study reveal that Shavadans maintain significantly cooler and more stable

24. Sunil Kumar Sansaniwal, Mathur Jyotirmay, and Sanjay and Mathur, 'Review of practices for human thermal comfort in buildings: present and future perspectives,' *International Journal of Ambient Energy* 43, no. 1 (2022).

25. R. de Dear et al., 'A review of adaptive thermal comfort research since 1998,' *Energy and Buildings* 214 (2020).

26. Jeetika Malik, Ronita Bardhan, and Pradipta Banerji, 'Rethinking indoor thermal comfort in the era of rebound and pre-bound effect for the developing world: A systematic review,' *Indoor air* 30, no. 3 (2020).

27. Runa T. Hellwig et al., 'A framework for adopting adaptive thermal comfort principles in design and operation of buildings,' *Energy and Buildings* 205 (2019).

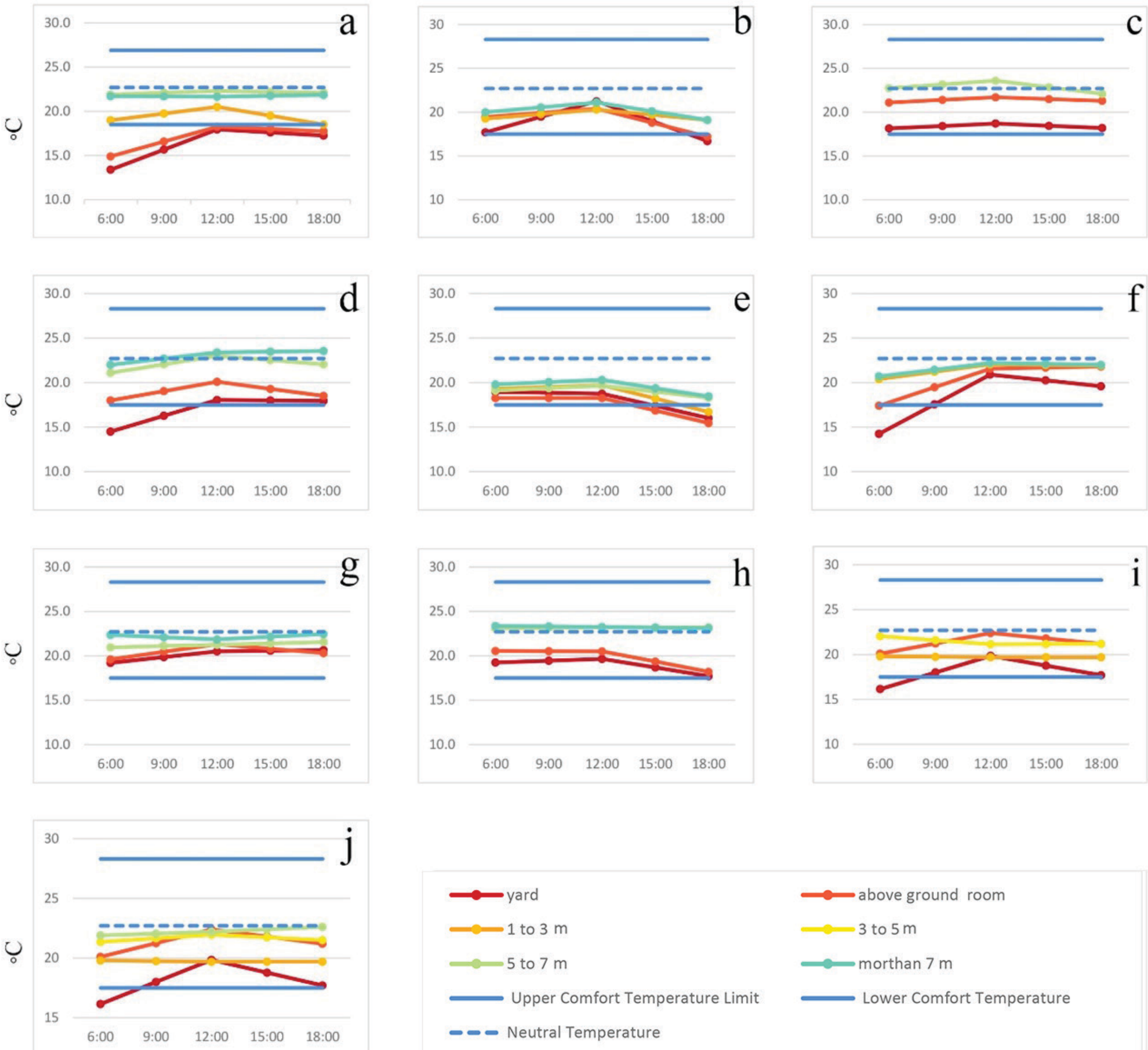


Figure 18. Comparison of air temperature at different depths with the comfort range in winter.

indoor environments in summer compared with above-ground rooms, with temperature differences of up to 16.1 °C relative to outdoor courtyards being recorded. This outcome confirms that Shavadans, through their depth, thick walls, and earthen materials, function similarly to earth-sheltered buildings, as emphassed in previous reviews highlighting the role of ground thermal mass in stabilsing indoor environments[29]. In winter, relatively stable conditions were also observed, although above-ground rooms occasionally provided higher comfort.

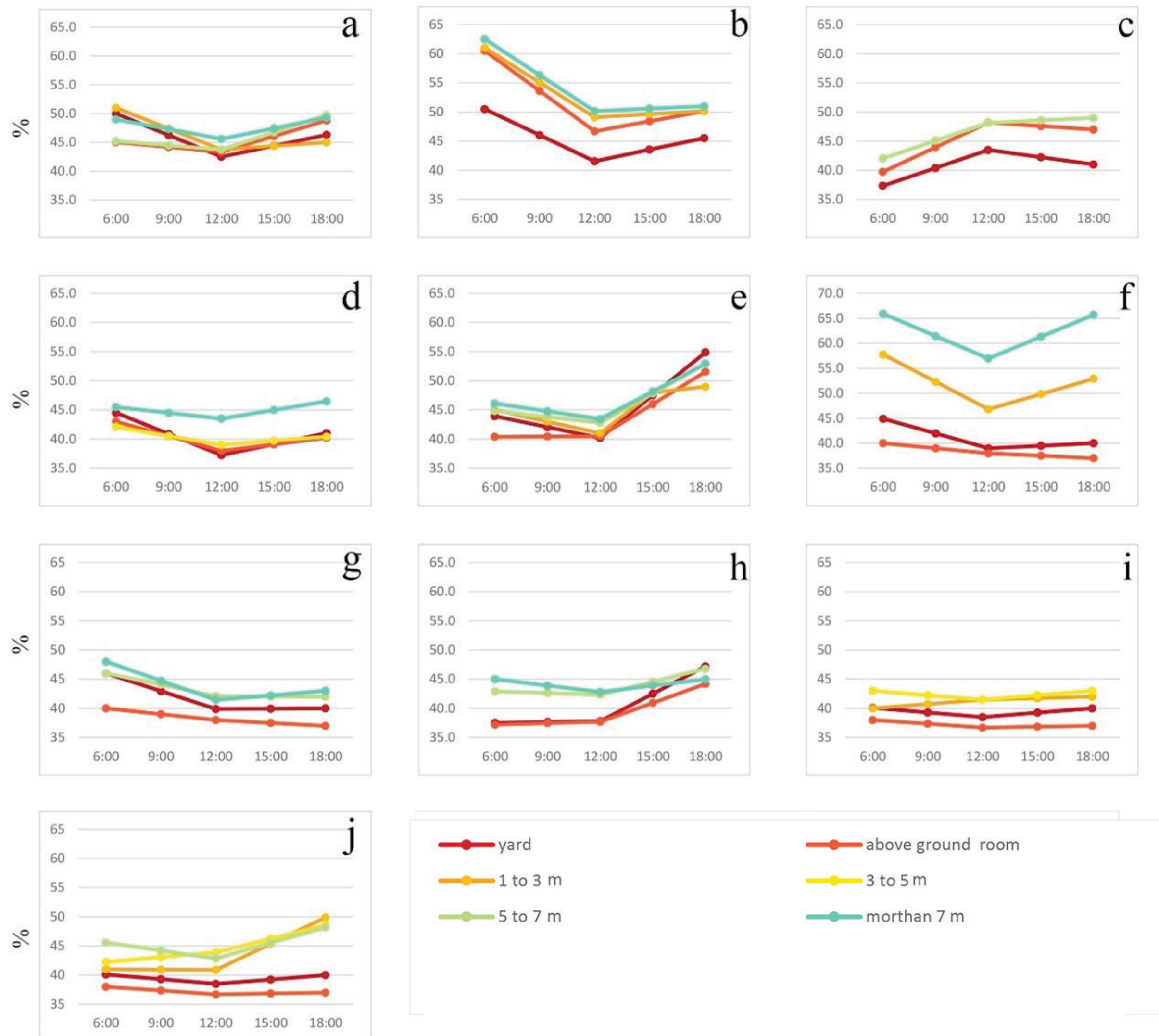


Figure 19. Comparison of relative humidity at different depths in winter.

28. Zahra Hejazizadeh, Seyed Morovat Eftekhari, and Hiva Solki, 'Optimising the orientation of open spaces in Dezful based on climatic conditions,' *Geography* 10, no. 32 (2012).

29. Giouli Mihalakakou et al., 'Earth-sheltered buildings: A review of modeling, energy conservation, daylighting, and noise aspects,' *Journal of Cleaner Production* 472 (2024); Yu, Kang, and Zhai, 'Advances in research for underground buildings: Energy, thermal comfort and indoor air quality.'

A key finding of this study was the important role of seasonal expectations in shaping thermal comfort. In Dezful's hot climate, where high temperatures dominate much of the year, many participants reported that during January and February they expected cooler weather, describing this period as 'a little colder.' This observation is consistent with Luo et al.[30], who argued that seasonal expectations may dominate other comfort factors. Similarly, Cao et al.[31] confirmed that local climate significantly influences thermal comfort and adaptive capacity.

Figure 20. Comparison of air flow velocity at different depths in Shavadans during winter.

30. Maohui Luo et al., 'The underlying linkage between personal control and thermal comfort: psychological or physical effects?,' *Energy and Buildings* 111 (2016).

31. Bin Cao et al., 'Field study of human thermal comfort and thermal adaptability during the summer and winter in Beijing,' *Energy and Buildings* 43, no. 5 (2011).

In Dezful's mild winters, indoor temperatures in residential spaces often remained within the comfort zone, and thus adaptive behaviours were limited to personal strategies such as wearing warmer clothing or drinking hot beverages. This is consistent with Rissetto et al.[32], who demonstrated that occupant expectations positively affect comfort and adaptive actions. Cognitive mechanisms, including attitudes, perceived control, self-efficacy, personal norms, and thermal history, were also found to play a role in shaping indoor expectations.

Regarding physical factors, Bahdad and Fadzil[33] showed that wall thickness and soil thermal conductivity are among the most influential parameters for thermal comfort and energy performance in underground spaces. The results of the present study indicated that Shavadans naturally apply these principles without mechanical energy input. Furthermore, Li et al.,[34] in a large-scale field investigation across 95 Chinese cities, found significant discrepancies between PMV and actual mean thermal sensation (AMTS), confirming that adaptive models provide a more accurate representation in underground environments. Field evidence from the current study aligned with these findings.

Humidity was also found to be a critical factor. Liu et al.[35] demonstrated that dry-bulb temperature alone is insufficient to evaluate comfort in underground hydropower tunnels, and humidity must be considered. Similarly, in Shavadans, high winter humidity at depths greater than 7 m resulted in warmer thermal sensations than air temperature alone suggested. The mean air temperature difference between summer and winter at this depth was approximately 2 °C, which corresponds well with the findings of Sadoughi et al.[36], who reported a difference of 1.22 °C. These consistencies add validity to the results and highlight the natural thermal stability of Shavadans.

Ventilation measurements showed that airflow inside Shavadans was minimal, and thermal stability was primarily achieved through massive walls rather than ventilation. This finding is consistent with Wen et al.[37], who emphassed that effective natural ventilation in underground spaces cannot rely on multiple openings alone but requires integrated above- and below-ground design.

From a behavioural perspective, it was observed that occupants adapted by using cooling devices and lighter clothing in summer and warmer clothes or heating appliances in winter. These adaptive actions are consistent with the adaptive comfort model[38] and confirm that thermal comfort emerges from the interaction between human behaviour and building characteristics. At the same time, psychosocial research[39] suggested that underground spaces may cause feelings of isolation or insecurity; However, Shavadans, rooted in the cultural and historical context of Dezful, can also contribute to strengthening social identity.

In summary, several innovations were achieved in this study:
- Two-season field data collection under real-life conditions.
- Direct comparison between Shavadans and above-ground mixed-mode rooms.
- Simultaneous analysis of thermal, humidity, and adaptive behaviour.
- Consideration of seasonal expectations and psychosocial dimensions of comfort.
- Emphasis on the cultural and social values of

32. Romina Rissetto, Riklef Rambow, and Marcel Schweiker, 'Assessing comfort in the workplace: A unified theory of Behavioural and thermal expectations,' *Building and Environment* 216 (2022).

33. Ali Ahmed Salem Bahdad and Sharifah Fairuz Syed Fadzil, 'An Investigation-Based Optimisation Framework of Thermal Comfort Analysis in Underground Enclosed Spaces Affected by Multiple Parameters for Energy Performance in Tropics,' *Journal of Daylighting* 9, no. 1 (2022).

34. Yong Li et al., 'Study of thermal comfort in underground construction based on field measurements and questionnaires in China,' *Building and Environment* 116 (2017).

35. Fuquan Liu et al., 'Thermal comfort in typical seasons of summer and winter in personnel intensive areas of underground public buildings of Xi'an in China,' *Thermal Science*, no. 00 (2025).

36. Sadoughi et al., 'Thermal performance analysis of a traditional passive cooling system in Dezful, Iran.' (2019)

vernacular underground architecture.

Unlike many simulation-based studies (e.g., EnergyPlus, CFD), which are often limited by the absence of real user data, this study provided a more realistic depiction of thermal comfort in underground environments. As Yu et al.,[40] emphassed, field investigations are essential to complement simulation research. Ultimately, Shavadans were shown to achieve thermal comfort without mechanical energy, effectively resolving the trade-off between energy consumption and comfort, and offering a sustainable and inspiring model for the design of underground spaces in hot-arid climates.

Limitations

This study faced several limitations. One of the main constraints was the private ownership of most Shavadans, which made long-term occupancy impossible. As a result, the investigation was conducted as a short-term study. Nevertheless, comparison of the findings with other studies indicates that no significant differences exist between these results and those of long-term investigations, as discussed in the 'Discussion' section.

In addition, air temperature was used in this study to assess thermal comfort conditions as well as the thermal performance of Shavadans. Although globe temperature was not measured, due to the stability of temperatures at greater depths and the uniformity of thermal conditions, it can be reasonably assumed that the results would have been consistent if globe temperature had also been considered.

Furthermore, the abandoned state of some Shavadans, the risk of structural collapse, and the presence of certain animals prevented the completion of thermal comfort questionnaires directly inside them.

Future Research Directions

The present study highlighted the potential of Shavadans in providing thermal comfort in hot-arid climates. However, further interdisciplinary research is needed to address aspects not fully covered here. Future investigations are recommended in the following areas:

1. Psychological aspects of users – Exploring perceptions, attitudes, and satisfaction to better understand mental comfort and social acceptance of underground spaces.

2. Lighting conditions – Assessing the role of natural and artificial lighting in visual and psychological comfort.

3. Comparative studies – Examining similarities and differences between Shavadans and other underground spaces in Iran and abroad (e.g., qanats, sardabs).

4. Cultural and social factors – Investigating local beliefs and values to identify barriers and opportunities for the reuse of Shavadans.

5. Economic feasibility – Evaluating cost–benefit aspects and energy-saving potential to support sustainable development decisions.

6. Regulatory frameworks – Reviewing building codes and legal requirements to integrate Shavadans into modern urban planning.

Conclusion

The results of this study demonstrate that Shavadans, by harnessing the thermal mass of the ground—particularly at depths greater than 5 m—are able to buffer extreme summer heat while maintaining stable, near-neutral indoor conditions during winter. Nonetheless, above-

37. Wen et al. (2024),

38. (Cheung & de Dear)

39. (De Dear, Burke, & King, 2017)

40. Yu, Kang, and Zhai, 'Advances in research for underground buildings: Energy, thermal comfort and indoor air quality.' (2020)

ground rooms offer certain advantages. This indicates that a hybrid underground–surface strategy can provide an effective, low-energy, and climate-responsive solution for hot and semi-humid regions.

The significance of this study lies in providing novel field-based evidence from Iran comparing the thermal comfort of Shavadans and above-ground spaces, establishing a link between vernacular knowledge and contemporary sustainable design.

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Constrained Possibilities: Housing Typology, Regulation and Non-Deterministic Evolution of Urban Form in Tehran

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ORIGINAL RESEARCH ARTICLE

Shayesteh, Homeira. "Constrained Possibilities: Housing Typology, Regulation and Non-Deterministic Evolution of Urban Form in Tehran". *Soffeh* 36, no. 2 (2026): 27–46.
DOI: http://doi.org/10.48308/soffeh.2026.106790

Received: October 10, 2025
Revised: December 10, 2026
Accepted: December 14, 2026
(Pages: 27–46

Abstract

Background and Objectives: The transformation of Tehran's urban fabric throughout the twentieth century generated a wide spectrum of housing typologies shaped by shifting planning ideologies, regulatory frameworks, and socio-spatial conditions. Existing literature has often interpreted these changes through linear narratives of modernisation or Western influence, neglecting the mediating role of regulation and the significance of intermediate spatial scales. This study aims to examine the evolutionary trajectory of housing typology and urban morphology in Tehran between 1900 and 2000, focusing on the interaction between macro-scale planning mechanisms and micro-scale architectural form. The primary objective is to assess whether housing evolution followed a deterministic path or whether multiple typological outcomes emerged within constrained regulatory and spatial conditions.

Materials and Methods: The research adopts a multi-scalar and interdisciplinary methodology integrating urban history, morphological analysis, and empirical spatial investigation. Three representative residential areas of 500 × 500 m, corresponding to distinct phases of Tehran's urban development, are analysed

Keywords:
Urban Morphology, Housing Typology, Regulatory Frameworks, Archetypal Modelling, Plot–Block Relations, Tehran.

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http://doi.org/10.48308/soffeh.2026.106790

Research Questions:

1. How did the interaction between macro-scale planning mechanisms and micro-scale architectural form shape the evolution of housing typologies in Tehran between 1900 and 2000?

2. To what extent did regulatory frameworks, including plot structure, block morphology, and site-development standards, constrain or enable multiple typological outcomes within the city's residential fabric?

3. Does the transformation of Tehran's housing—from courtyard houses to row houses and apartment buildings—follow a deterministic trajectory, or does it reflect a non-deterministic and probabilistic relationship between regulation and architectural form?

4. How do variations in architectural variables such as access systems, frontage conditions, day-lit depth, and spatial configuration correspond to shifts in planning regulations across different historical periods?

5. What role does the intermediate spatial scale (plots, blocks, and housing types) play in mediating between city-wide planning policies and the emergence of localised morphological patterns?

6. In what ways can the analytical framework developed in this study contribute to contemporary debates on housing policy, regulatory reform, and urban design practices in rapidly transforming contexts?

using Geographical Information Systems (GIS). This is combined with archetypal modelling based on Steadman's geometric principles to examine relationships between block structure, plot subdivision, density, site coverage, and housing layout. Architectural variables—including access systems, frontage conditions, day-lit depth, and spatial configuration—are systematically evaluated in relation to planning regulations, enabling comparative analysis across historical periods.

Results and Conclusion: The results indicate that housing typologies in Tehran were strongly influenced by plot structure, block morphology, and regulatory constraints; however, these influences operated in a non-deterministic manner. Multiple spatial configurations emerged within similar regulatory frameworks, demonstrating a probabilistic relationship between planning rules and architectural form. The transition from inward-oriented courtyard houses to outward-facing row houses and later apartment buildings is therefore interpreted as an adaptive process shaped by functional requirements and regulatory negotiation rather than a direct transplantation of Western models. By foregrounding the intermediate scale of plots, blocks, and housing types, this study challenges reductive interpretations of Tehran's urban transformation and highlights the coexistence of traditional spatial logics and modern planning systems. The research contributes a robust analytical framework for linking regulation to architectural form and offers insights relevant to contemporary housing policy and urban design.

1. Introduction, Research Context and Aims

This study examines the evolutionary development of housing in Tehran with two central questions: whether the observed trajectory of housing change followed a necessary or constrained path, and whether alternative built forms could have emerged within the city's prevailing block dimensions and regulatory conditions.

Housing transformation is analysed across urban and architectural scales, focusing on the relationship between changes in urban layout and housing typology. At the urban scale, Tehran's residential fabric evolved from irregular, fine-grained blocks to larger, more regular grids. At the architectural scale, housing types shifted from inward-looking courtyard houses to terraced houses with south-facing courts, and ultimately to multi-storey apartment buildings. The core analytical concern is the relationship between these two processes: whether changes in urban layout and housing typology constitute a co-evolutionary process or represent parallel developments brought together by circumstance.

Building on the archetypal approach developed by Steadman[1] and extended in subsequent work by Shayesteh & Steadman[2], the study develops an integrated model that links parameters of urban structure - such as block and plot size, density, and ground coverage - with parameters of built form, including access, frontage, day-lit depth, and building configuration (courtyard, C-shaped, L-shaped, and linear forms).

2. Historical Formation of Tehran's Urban Structure

Tehran's morphological transformation occurred across several major historical phases: the Safavid Dynasty (1501–1736), the Qajar Dynasty (1786–1925), the Pahlavi era (1925–1979), and contemporary developments. Although the paper focuses primarily on changes in the 20th century, earlier stages illustrate the origins of the city's spatial structure.

During the Safavid period, the decline of the ancient city of Ray and Tehran's favourable climate contributed to its emerging prominence. Shah Tahmasb's construction of a defensive wall in 1515 - featuring four principal gates - marked the city's formal recognition as an urban settlement, despite limited political or military significance at the time. This enclosure symbolised Tehran's shift from a peripheral village into a place worthy of state attention. Tehran's transformation accelerated under the Qajar Dynasty, when Aqa Mohammad Khan designated it the capital in the late 18th century. Early cartographic records such as Berzin's 1851 map depict the city still contained within its Safavid-era walls and organised around key traditional elements: the Arg (citadel), the Bazaar, major mosques, and four residential quarters (Mahalleh). Social hierarchies were reflected in this spatial structure, where the court, merchants, artisans, and clergy occupied distinct yet interconnected roles within the urban fabric. Throughout this period, domestic architecture largely followed the courtyard-house typology typical of Iranian cities.

More detailed mapping in the late 19th century shows the onset of Tehran's first major phase of physical expansion. Under Naser al-Din (or Naseraddin) Shah Qajar, the old walls were demolished and replaced by new fortifications, forming an irregular octagonal plan reminiscent of Renaissance ideal cities and influenced by French urban design. This period marked the beginning of Tehran's dual morphology: the coexistence of an older, organically developed core and newer, planned extensions. The city expanded in all directions but especially northward, driven by two key forces identified in contemporary accounts - greater European presence and the royal preference for the cooler northern districts. Roads leading to northern gardens became spines of urban growth, and European-style detached houses and villas ap-

1.Philip Steadman, 'Binary Encoding of a Class of Rectangular Built Forms' (A. Alfred Taubman College of Architecture and Urban Planning, University of Michigan, 2001).

2.Homeira Shayesteh and Philip Steadman, 'The Impact of Regulations and Legislation on Residential Built Forms in Tehran', *Journal of Space Syntax* 4, no. 1 (2013): 92–107; Homeira Shayesteh and Philip Steadman, 'Coevolution of Urban Form and Built Form: A New Typo-Morphological Model for Tehran', *Environment and Planning B: Planning and Design* 42, no. 6 (2015): 1124–47, https://doi.org/10.1068/b140002p.

peared along the new, straighter streets. As a result, Tehran's area grew from roughly 4 km² to 19 km² and its population quadrupled, reaching about 200,000 by the end of the 19th century.

Scholars such as Alemi[3] interpret these developments as early indicators of Tehran's modernization, revealing both physical and institutional transformations. New house types, new public institutions, and shifting social patterns accompanied changes in the built form. Yet, despite these European influences, travellers observed that Tehran remained culturally rooted in local traditions - an urban environment 'born in the East' but increasingly shaped by Western models. Traditional courtyard houses persisted as the dominant residential type until well into the 20th century, with only elite houses documented in detail and later preserved by cultural heritage authorities.

Overall, Tehran's historical development reflects a complex interplay of geography, political power, cultural exchange, and modernisation. Its urban morphology emerged not through abrupt shifts but through layered transformations that differentiated the traditional core from its expanding, increasingly western-influenced surroundings.

3. Housing Typology and Urban Morphology in Tehran (1920–2000)

Between 1920 and 2000, Tehran underwent a rapid and profound transformation in both housing typology and urban morphology, driven by modernisation policies, demographic growth, regulatory change, and economic forces rather than by shifts in architectural style alone. Across three main phases, the evolution of housing provides a clear lens through which broader urban dynamics can be understood.

3.1 State-Led Modernisation and the Row House (1920–1942)

During the Pahlavi I Period, demolition of city walls and introduction of a grid enabled regular plot subdivision and the emergence of row houses. These outward-facing dwellings retained residual courtyard space and represented a transitional house type. This period also marked the beginning of Tehran's north-south socio-spatial division.

3.2 Speculative Growth and Regulation (1942–1979)

Rapid, under-regulated expansion characterised this period. Rural migration, land reform, oil revenues, and speculative development produced fragmented suburban growth. Planning regulations - especially plot coverage limits tied to solar orientation - formalised spatial logic but often produced unintended morphological consequences.

3.3 Post-Revolution Densification (1979–2000)

After 1979, housing shortages were addressed through vertical densification. Floor Space Index regulations incentivised apartment construction, leading to widespread demolition of earlier housing types. While increasing supply, this strategy intensified infrastructural strain and resulted in fragmented streetscapes. From courtyard houses to row houses and finally to multi-family apartments, each typological shift embodied broader social, political, and economic processes.

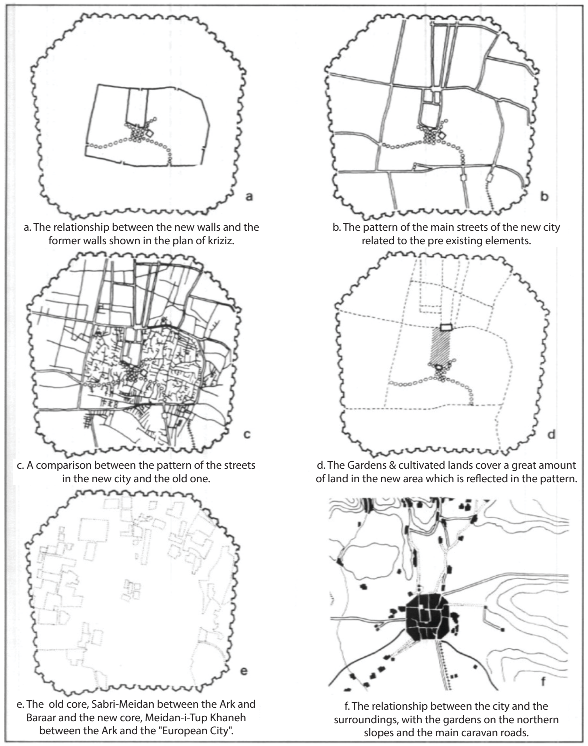
3. Mahvash Alemi, 'The 1891 Map of Tehran: Two Cities, Two Cores, Two Cultures', *AARP Environmental Design* 1 (1985) :74–84.

4. Interpretations of Tehran's Morphological Transformation

This section reviews key intellectual traditions addressing morphological change in Iranian cities, with particular reference to Tehran. It highlights the interdisciplinary nature of urban morphology and argues that no single explanatory framework can fully account for urban transformation, given the interaction of political, social, economic, and environmental forces. Within Iranian scholarship, two dominant perspectives are identified. The first explains urban change primarily through modernisation, attributing new spatial and formal patterns to the introduction of European-inspired technologies, institutions, planning practices, and cultural aspirations. The second challenges this view by arguing that apparent modern grids often extended pre-existing orthogonal structures rooted in agricultural land division and irrigation systems rather than Western influence. The section sets up a critical comparison of these perspectives, focusing especially on the contrasting interpretations of Alemi[4] and Bonine[5], while situating their arguments within a broader body of scholarship on Iranian urban morphology.

4.1 Modernisation and European Influence as Social Drivers of Morphological Change

Alemi[6] interprets Tehran's morphological transformation as part of Iran's broader social and cultural reorientation toward Europe, identifying four interrelated forces shaping the city's spatial change. First, intensified cultural and intellectual exchanges with Europe fostered new ideals of urban order, progress, and architectural representation. Second, technological advances - particularly the introduction of European cartographic and surveying techniques - enabled more regular street layouts and facilitated state-directed urban interventions. Third, the establishment of new institutions such as embassies, ministries, and garden residences introduced unfamiliar building types and actively steered urban growth through the construction of connecting roads. Finally, these processes culminated in the emergence of a 'European city' ideal, expressed in gridded streets, outward-oriented buildings, and new residential forms. Together, Alemi argued, these factors repositioned streets as instruments of cultural expression and marked a deliberate shift away from the irregular, inward-looking patterns of



a. The relationship between the new walls and the former walls shown in the plan of kriziz.

b. The pattern of the main streets of the new city related to the pre existing elements.

c. A comparison between the pattern of the streets in the new city and the old one.

d. The Gardens & cultivated lands cover a great amount of land in the new area which is reflected in the pattern.

e. The old core, Sabri-Meidan between the Ark and Baraar and the new core, Meidan-i-Tup Khaneh between the Ark and the "European City".

f. The relationship between the city and the surroundings, with the gardens on the northern slopes and the main caravan roads.

Figure 1. Tehran, morphological stages of change. (Alemi, 1985).

4. Ibid.

5. Michael E. Bonine, 'The Morphogenesis of Iranian Cities', *Annals of the Association of American Geographers* 69, no. 2 (1979): 208–24, https://doi.org/10.1111/j.1467-8306.1979.tb01252.x.

6. Ibid.

traditional Iranian urbanism toward a more rational, extroverted urban form.

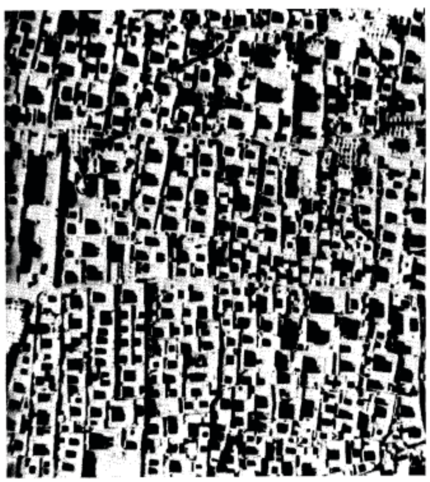
4.2. Land Division and Irrigation-Based Morphology

Bonine[7] challenged the view that traditional Iranian cities were inherently irregular, arguing instead that their morphology was structured by the geometric logic of irrigation-based agriculture. He contends that rectangular agricultural plots, shaped by irrigation channels aligned with topography, formed the original spatial matrix of early settlements. Paths running along these channels later became streets, with houses orienting themselves to access routes rather than to the underlying orthogonal system, creating an appearance of irregularity. As cities expanded and absorbed surrounding villages, these rural field patterns were incorporated into the urban fabric. Bonine further argued that modern 20th-century grids largely extended or overlaid these pre-existing networks rather than replacing them. Applied to Tehran, this perspective suggests that new streets often followed established routes, and that northward expansion was primarily guided by the direction of water flow from the Alburz Mountains rather than by climate or institutional location.

4.3 Complementary Perspectives: Urban Evolution, Housing Change, and External Influence

Several scholars offer complementary perspectives on Tehran's morphological transformation, though most stop short of detailed morphological analysis. Costello[8] provided a descriptive account of Tehran's growth, tracing the shift from garden houses to apartments and high-rise blocks, but largely calls for future morphological studies rather than undertaking one himself. Mirmoghtadaee[9] focused on the transformation of housing types and the mismatch between rapid adoption of apartment living and slower cultural adaptation, offering valuable social insight but limited spatial or geographic specificity. Sintusingha and Mirgholami[10] framed Tehran's development through the concept of self-colonisation, arguing that imported Western urban models - particularly wide, vehicular streets - conflicted with local practices and contributed to the deterioration of the historic core. Madanipour[11] emphasised environmental factors such as water systems and solar orientation in shaping Tehran's form, though his analysis remains at a macro scale. Mazumdar[12] interpreted Tehran's evolution politically, linking urban expansion to autocratic interventions across different dynastic periods; however, like the others, his work lacks detailed examination of urban morphology at the levels

Figure 2. Orientation of houses along linear regular (left) and irregular (right) streets of Yazd. (Bonine, 1979, p.214 & 215).



Linear streets and linear rows of open courtyard houses in Yazd.

Irregular streets and open courtyards oriented to the direction of the streets in Yazd.

7. Ibid.

8. Vincent F. Costello, 'The Morphology of Tehran: A Preliminary Study', *Built Environment* (1978-))1998) 201–16.

9. Mahta Mirmoghtadaee, 'Process of Housing Transformation in Iran', *Journal of Construction in Developing Countries* 14, no. 1 (2009).

of plots, blocks, and buildings.

4.4 Synthesis and Analytical Reflections

The literature shows that Tehran's morphological evolution cannot be explained by a single factor. Modernisation perspectives stress cultural aspiration, technology, and European influence; environmental approaches emphasise irrigation systems and land geometry; political analyses focus on centralised power and state intervention; and socio-cultural studies highlight tensions between changing lifestyles and inherited spatial forms. Despite these insights, research largely concentrates on the citywide scale and gives little attention to the intermediate scales of plot, block, and housing form. In particular, the incremental transformation of dwellings in response to regulation, lifestyle change, and speculative development remains underexplored[13]. This gap motivates the present study's focus on linking macro-scale urban change with housing morphology.

5. Typology as theory and historiography: Theoretical and Methodological Framework

This section outlines the theoretical and methodological foundations of the study by situating it within key debates on typology, urban morphology, and housing form. It argues that typology should be understood not as a classificatory end in itself, but as a purpose-driven analytical tool that is essential for explaining how built forms emerge, persist, and transform over time. Drawing on architectural theory, housing typology is framed here as a fundamentally morphological concern, aligned with interpretations of the city as a repository of historical continuity, cultural values, and collective meaning[14]. The discussion draws on a range of established typo-morphological traditions, which, despite methodological differences, share a commitment to historical analysis and to the study of ordinary residential buildings as key indicators of urban change. The Italian school of urban morphology, associated with Muratori and Caniggia[15], foregrounds typological process and the gradual evolution of basic housing types (tipo portante) through incremental transformation. Central to this tradition is the parcel or plot as the fundamental unit of the urban fabric, through which continuity and change can be traced across successive phases of development.

The English school, exemplified by Conzen[16], contributes a rigorous cartographic and analytical framework centred on the interrelationship between streets, plots, and buildings. Concepts such as plot cycles, fringe belts, and morphological regions enable the reconstruction of urban morphogenesis over long time periods, offering a systematic means of linking changes in land subdivision to broader patterns of urban growth.The French tradition, often associated with the Versailles school and articulated through the work of Moudon[17] and Talen[18], extends morphological analysis by incorporating social practices, regulatory frameworks, and everyday decision-making processes. This approach emphasises how cumulative, small-scale actions -shaped by planning controls, economic pressures, and cultural norms - gradually reshape neighbourhood form, thereby bridging the gap between formal urban structure and lived experience.

In addition to these theoretical traditions,

10. Sidh Sintusingha and Morteza Mirgholami, 'Parallel Modernization and Self-Colonization: Urban Evolution and Practices in Bangkok and Tehran', *Cities* 30 (2013):122–32, https://doi.org/10.1016/j.cities.2012.02.001.

11.Ali Madanipour, *Tehran: The Making of a Metropolis*, World Cities Series (Chichester: Wiley, 1998).

12. Sanjoy Mazumdar, 'Autocratic Control and Urban Design: The Case of Tehran, Iran', *Journal of Urban Design* 5, no. 3 (2000): 317–38.

13. Homeira Shayesteh, 'Typo-Morphological Approach to Housing Transformation in Tehran' (PhD diss., University College London, 2013); Shayesteh and Steadman, 'The Impact', 92–107; Shayesteh and Steadman, 'Coevolution', 1124–47; A. M. Milani, 'The Impact of Regulations on the Typo-Morphological Transformation of Residential Buildings in Tehran', *Urban Morphology* 25, no. 2 (2021): 173–87, https://doi.org/10.51347/UM25.0012.

the study reviews a number of practical housing classification systems developed by Sherwood[19], Kirschenmann & Muschalek[20] and Scoffham[21]. These studies demonstrate how housing forms can be systematically categorised according to orientation, access, aggregation, scale, and evolutionary change. Although largely descriptive, such classifications provide important precedents for form-led analysis of residential environments and help establish a common vocabulary for comparing housing types across different contexts.

5.1 Typology as Analytical Method: Configurational and Archetypal Approaches

Building on the typo-morphological traditions outlined, this study adopted two complementary analytical frameworks in order to move beyond descriptive accounts of urban form and toward an explicitly explanatory and testable methodology. While classical typo-morphological approaches provide robust tools for reconstructing historical transformation, they are less equipped to analyse the internal spatial logic of housing layouts or to evaluate alternative formal outcomes under shared dimensional and regulatory constraints. To address these limitations, the research combined configurational analysis derived from Space Syntax with Steadman's archetypal modelling approach.

Space Syntax is employed to examine the configurational structure of housing plans and to identify recurring spatial genotypes that reflect culturally embedded patterns of domestic use[22]. By analysing the relational organisation of rooms and circulation, this method enables systematic comparison across housing types and historical periods, revealing continuities and shifts in patterns of access, privacy, and social interaction. In the context of Tehran, configurational analysis helps clarify how successive housing types accommodated changing lifestyles while retaining underlying spatial logics rooted in Iranian domestic culture.

However, Space Syntax engages only indirectly with the dimensional, geometric, and plot-based constraints that condition housing production at the scale of the parcel and block. For this reason, it is supplemented by Steadman's archetypal approach, which systematically explores the geometric possibilities of built form within rectangular plots under defined constraints[23]. This method enables quantitative analysis of relationships between plot dimensions, building configuration, density, and layout, while explicitly accounting for generic spatial requirements such as street access, daylighting, adjacency, and building depth.

Recent extensions of this approach by Shayesteh and Steadman demonstrate how archetypal modelling can be applied to residential blocks to examine the probabilistic relationship between regulation, plot structure, and housing typology[24]. Their work shows that planning codes do not determine a single formal outcome but instead narrow the field of viable typological options, making certain configurations more likely than others. This insight is central to the present study, which adopts archetypal modelling not only as an analytical tool but also as a generative framework for testing alternative housing forms under identical morphological and regulatory conditions. While Space Syntax reveals how internal spatial organisation responds to cultural and social practices, archetypal model-

14. Aldo Rossi, *The Architecture of the City* (Cambridge, MA: MIT Press, 1982); Adrian Forty, *Words and Buildings: A Vocabulary of Modern Architecture* (London: Thames & Hudson, 2000).

15. Gianfranco Caniggia and Gian Luigi Maffei, *Architectural Composition and Building Typology: Interpreting Basic Building* (Florence: Alinea Editrice, 2001).

16. Michael R. G. Conzen, 'Alnwick, Northumberland: A Study in Town-Plan Analysis', *Transactions and Papers (Institute of British Geographers)* 27 (1960): iii–122.

17.Anne Vernez Moudon, 'Urban Morphology as an Emerging Interdisciplinary Field', *Urban Morphology* 1, no. 1 (1997): 3–10, http://www.urbanmorphology.org.

18.Emily Talen, *City Rules: How Regulations Affect Urban Form* (Washington, DC: Island Press, 2012).

19. Roger Sherwood, *Modern Housing Prototypes* (Cambridge, MA: Harvard University Press, 1978).

20. J. C. Kirschenmann and Christian Muschalek, *Residential Districts* (London:

ling makes it possible to examine how housing form is conditioned by plot geometry, density targets, and regulatory constraints. Combined, configurational analysis and archetypal modelling enable analysis of both realised and alternative housing forms under shared constraints. This methodological synthesis frames the central research question of the article: how the evolution of housing types in Tehran relates to the development of residential urban layouts, and whether prevailing forms were the result of regulatory necessity, morphological constraint, or contingent design choices rather than inevitable outcomes of modernisation or Western influence. The following section operationalises this framework through GIS-based analysis of selected urban areas, translating theoretical models into empirically grounded morphological evidence.

5.2 Typology as empirical test and explanatory model: Housing Transformation, Regulation, and Morphological Constraint

Changes in Iranian society over the past century, particularly its rapid movement toward modernism, have been expressed across all domains of urban life. While transformation in housing was substantial, it proceeded at a slower pace than changes in political institutions and public architecture, where shifts in governance enabled earlier and more explicit adoption of modern forms. Housing, however, could not remain insulated from broader social change. Despite higher economic and material costs, domestic architecture underwent accelerated transformation as new lifestyles, technologies, and patterns of everyday life took hold.

This study argues that even in the absence

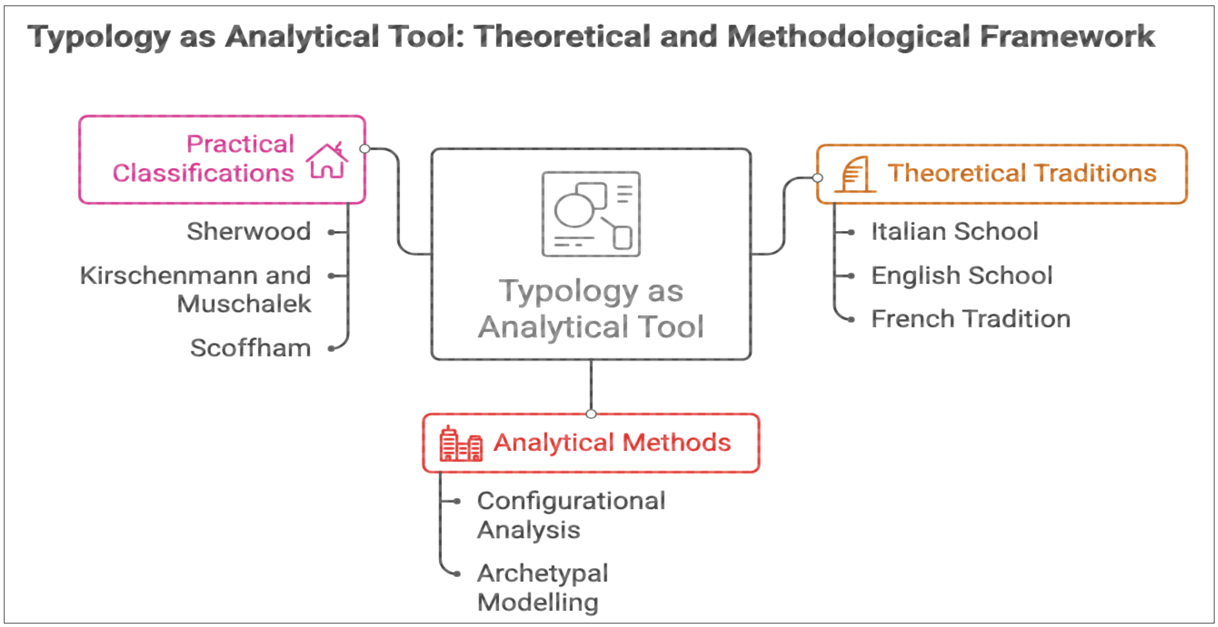


Figure 3. Typology as analytical tool, theoretical and methodological framework.

Granada, 1977).

21. Ernie Scoffham, Sustainable Housing: *Principles and Practice* (London: E & FN Spon, 2000).

22.Bill Hillier, *Space Is the Machine: A Configurational Theory of Architecture* (Cambridge: Cambridge University Press, 1996).

23. Philip Steadman and Stephen Marshall, 'Archetypal Layout: Extending the Concept of the Archetypal Building to Streets and Block Layouts', paper presented at the Solutions Conference, London, 2005.

24. Shayesteh and Steadman, 'The Impact', 92–107, quoted in John Smith, *Urban Design in London* (London: Routledge, 2020).

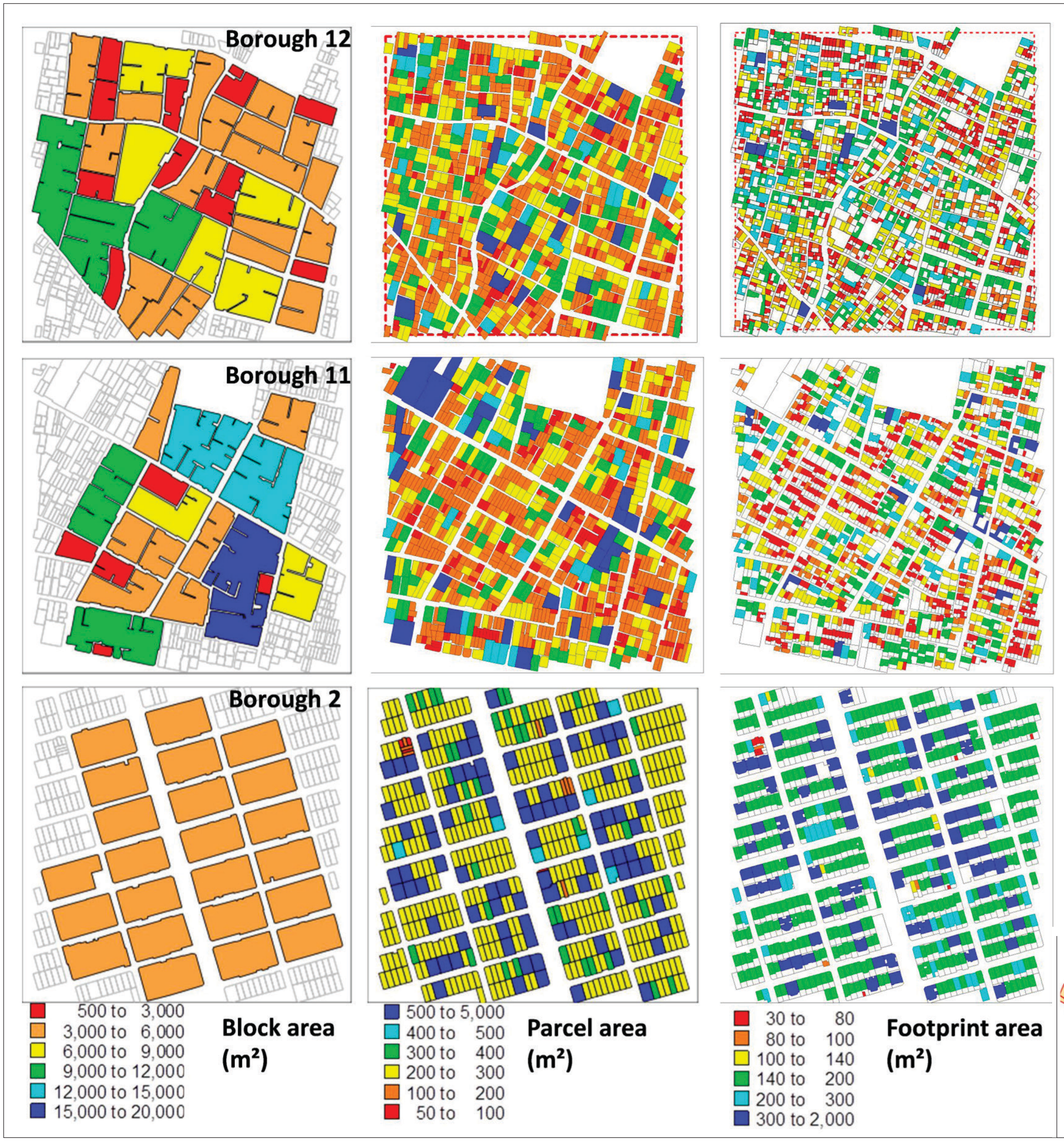
of direct Western architectural influence, the emergence of a modern way of life - most notably the widespread adoption of car ownership - would have necessitated significant adaptation in housing form. The pace of change was sufficiently rapid that social adjustment lagged behind spatial transformation, yet this accelerated rate of evolution itself became the prevailing condition and continues to shape Tehran's residential development. The analysis is both explanatory and generative. At the urban scale, Tehran's residential fabric is shown to have evolved from irregular, fine-grained blocks into larger and more regular grids. At the architectural scale, housing types shifted from inward-looking courtyard houses to terraced houses with south-facing courts, and ultimately to multi-storey apartment buildings. The central analytical concern is the relationship between these two processes: whether changes in urban layout and housing typology constitute a co-evolutionary process, or whether they represent parallel developments brought together by contingent social, economic, and regulatory forces.

Building on Steadman's archetypal approach and its subsequent extension by Shayesteh and Steadman, the study develops an integrated analytical model linking parameters of urban structure - such as block and plot size, density, and ground coverage - with parameters of built form, including access frontage, daylit depth, and building configuration (courtyard, C-shaped, L-shaped, and linear forms). To operationalise this model, GIS-based analysis was conducted on three 500 × 500 m areas of Tehran representing successive stages of urban growth. Dominant values for each parameter were extracted and used to construct archetypal representations of typical residential blocks and housing forms.

Then archetypal models of possible plots and blocks with the similar dimensional and density measurements generated. The results demonstrated that these archetypal models closely approximate observed conditions, validating their use as analytical tools for understanding Tehran's housing fabric. More significantly, design experiments using blocks of identical dimensions reveal that multiple housing forms can satisfy similar requirements for density, daylight access, and street frontage. These finding challenges deterministic interpretations of Tehran's urban form and indicates that the relationship between block morphology and housing typology is probabilistic rather than fixed.

The analysis further shows that generic functions - particularly access and daylight - systematically influence block and plot dimensions, while certain dimensional ranges make specific housing forms more likely. These relationships, however, are consistently mediated by planning regulations, which emerge as a critical force shaping typological outcomes. Regulations governing plot coverage, building placement, and density do not merely constrain architectural form; they actively steer the evolution of housing types and produce long-term morphological consequences that were often not explicitly anticipated.

By focusing on the intermediate scale between the city and the individual dwelling, this study addresses a significant gap in Tehran's urban scholarship. Existing literature has tended to privilege macro-scale narratives of modernisation and Western influence or micro-scale



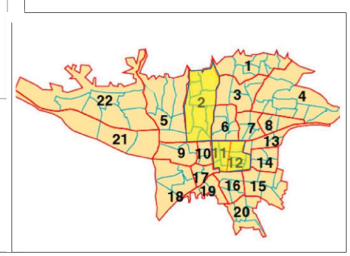


Figure 4. Analysis of plot sizes in Tehran.

analyses of individual houses, leaving the relationship between block structure and housing form underexamined. Through the combined use of GIS analysis and archetypal modelling, the research demonstrates that housing typology and urban morphology in Tehran are tightly interrelated yet not uniquely determined, and that alternative evolutionary paths were - and remain - possible within similar spatial and regulatory conditions.

6. Planning Regulation as a Morphological Driver

Building on the finding that housing typology and block morphology in Tehran are related but not deterministically fixed, the analysis identifies planning regulation as a decisive mediating force in this relationship. While regulations were initially treated as one among several factors shaping residential form, their cumulative and structuring impact became increasingly evident. In this respect, the Tehran case aligns

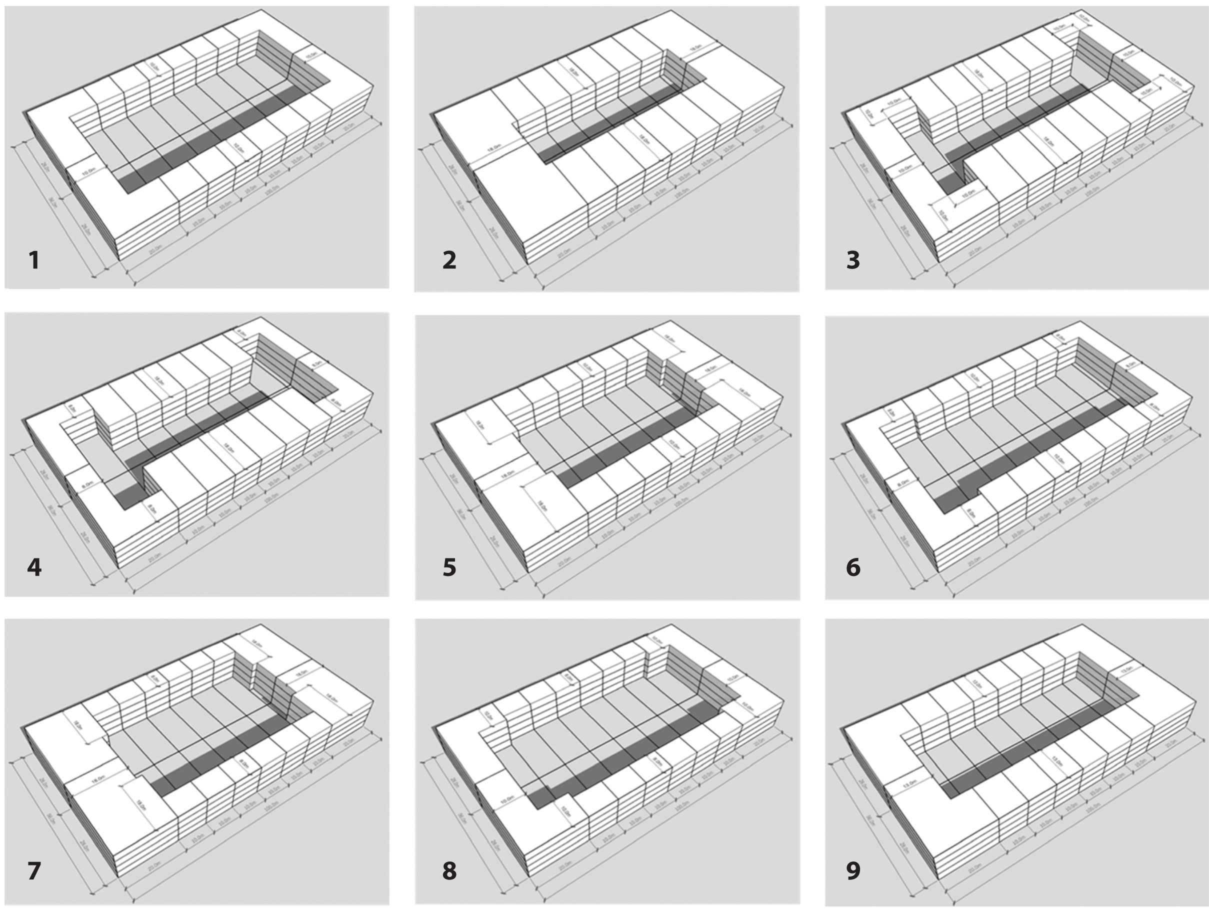


Figure 5. Archetypal model of alternative blocks for Tehran

with the argument that planning codes operate not merely as constraints on individual buildings but as configurational mechanisms that systematically shape spatial outcomes across neighbourhoods and cities.

Comparative references to regulatory frameworks in cities such as New York and Paris illustrate how relatively simple physical codes can generate coherent morphological and aesthetic effects when applied consistently[25]. In Tehran, however, a small number of seemingly straightforward regulations - most notably those governing building placement within plots and limits on ground coverage - have had disproportionately strong and often unintended consequences for housing typology, block form, and streetscape continuity. The absence of coordinated redevelopment, particularly in the piecemeal replacement of single-family or low-rise terraced housing with apartment buildings, has resulted in fragmented skylines and visually incoherent residential streets.

These regulatory effects intersected with powerful economic, social, and technological forces. The shift from single-family housing to apartment living, combined with the transition from load-bearing masonry to steel and reinforced concrete construction, facilitated vertical densification, accelerated redevelopment cycles, and increased profitability through thinner structural walls and higher floor area yields. As Shayesteh[26] & Shayesteh & Steadman's[27] configurational analyses suggest, such interactions between regulation, construction technology, and economic logic tend to reinforce specific spatial patterns over time, even in the absence of explicit design intentions. Particular attention is drawn to two regulations with far-reaching morphological implications: the requirement to locate buildings on the north side of plots and the restriction of ground coverage (initially 40 per cent, later increased to 60 per cent). Although these rules can be interpreted as environmentally motivated - seeking to maximise solar access and climatic comfort - they have produced a distinctive urban condition in which many north–south streets lack continuous façades. This pattern, now widespread across both residential and commercial areas of Tehran, demonstrates how environmental logics, when narrowly applied, can override broader considerations of urban continuity and public space.

At the level of housing typology, regulatory constraints interacted with cultural practices to shape internal layouts. The brief dominance of two-up, two-down terraced houses reflects a misalignment between imported spatial models and local lifestyles. Their deep, sequential plans proved poorly suited to Iranian domestic patterns, leading to their rapid replacement by apartment types organised around a central hall. This space effectively reinterprets the social and symbolic role of the courtyard within a compact, multi-storey form, illustrating how typological adaptation occurs within regulatory and dimensional limits rather than through stylistic change alone.

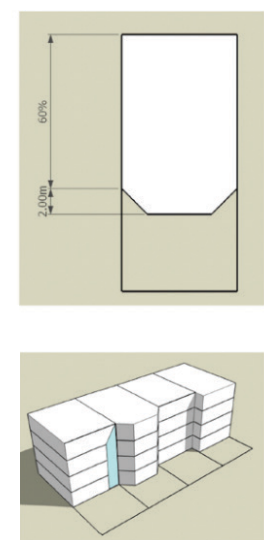
Overall, the Tehran case demonstrates that housing evolution is best understood as a mul-

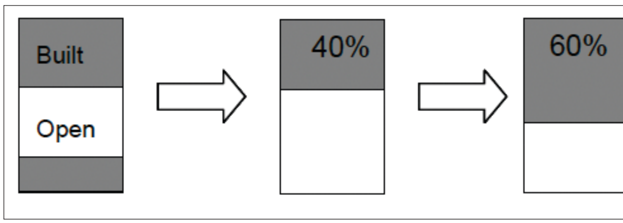
25. Shayesteh and Steadman, 'The Impact', 92–107.

26.Shayesteh, 'Typo-Morphological Approach'.

27.Shayesteh and Steadman, 'Coevolution', 1124–47.

Figure 6. regulations and planning policies governing built form and open space on plots.





ti-variable, evolutionary process in which planning regulations play a primary structuring role. Consistent with Shayesteh & Steadman's[28], the findings show that regulations shape not only density and land use but also the configurational logic of access, frontage, and internal spatial organisation. Rather than producing a single inevitable outcome, these codes narrow the field of possibilities, making certain housing types more probable while foreclosing others, and in doing so leave a lasting imprint on the city's morphological structure.

7. Geographical Constraints and Generic Functions

Following the identification of planning regulation as a key mediating force between housing typology and block morphology, the analysis turns to the role of geographical and spatial constraints - specifically street access and daylighting - as generic functions shaping residential form.[29] To investigate these constraints empirically, the study examined three boroughs of Tehran representing successive phases of morphological growth. Measurements of plot size, building footprint, frontage width, depth, and density were undertaken at both the borough scale and within selected 500 × 500 m samples using GIS. In parallel, a detailed analysis of thirty-one representative dwellings was conducted using Steadman's archetypal representation method, enabling systematic comparison between observed built forms and theoretically possible alternatives under similar dimensional conditions[30].

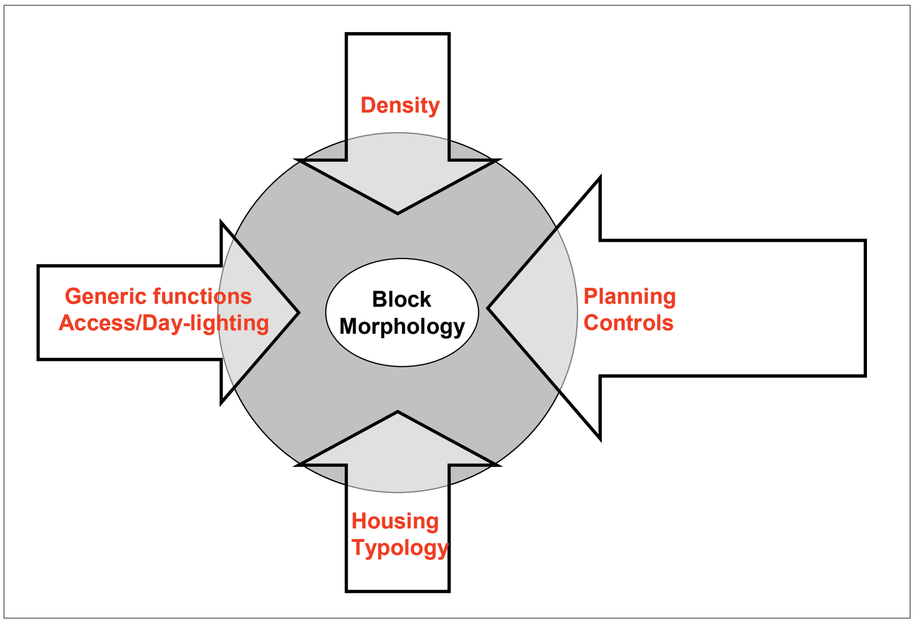
Comparative analysis of average plot widths, depths, and building envelopes revealed consistent relationships between daylighting requirements and block structure. Habitable rooms require direct access to external space, placing clear limits on building depth and, by extension, on block thickness. In Tehran's post-Qajar expansions, this constraint has resulted in blocks typically no more than two plots deep, a configuration that simultaneously satisfies daylighting standards and ensures direct street access for each plot. This finding is consistent with broader morphological research demonstrating how environmental requirements stabilise certain block dimensions across different cultural contexts[31].

By contrast, the length of urban blocks proved less directly constrained by environmental factors and more dependent on access-related considerations. Block length was found to be shaped by a combination of factors, including the proportion of land allocated to streets, the need to minimise travel diversion, and the

28. Ibid.

29.Philip Steadman, 'How Day-lighting Constrains Access', in *Proceedings of the Fourth Symposium on Space Syntax* (London: University College London, 2003), 05.1–05.12; Caniggia and Maffei, *Architectural Composition and Building Typology*.

Figure 7. The factors involved in block morphology.



distribution of plot frontages along the street. These findings resonate with configurational studies in Space Syntax, which show that access economy and movement efficiency exert strong influence on street segmentation and block articulation[32].

At the level of housing typology, the analysis demonstrates that the transition from courtyard houses to terraced houses cannot be explained solely as a cultural or ideological shift associated with Westernisation. While modernist influences were significant, the change also reflected functional adaptation to increased car ownership and the growing importance of direct street access to individual dwellings. Terraced houses offered a more effective interface between plot, street, and domestic space than inward-facing courtyard houses aggregated into irregular blocks. This functional explanation complicates narratives that frame typological change primarily as a symbolic rejection of traditional forms.Nevertheless, the analysis also raises unresolved questions. In principle, courtyard houses could have been reaggregated into accessible, two-plot-deep blocks while retaining their introverted spatial logic. That this did not occur suggests that regulatory frameworks, plot subdivision practices, and market pressures collectively narrowed the range of viable typological options - an issue that warrants further investigation. Density emerges as the dominant driver in the subsequent transition from single-family terraced housing to multistorey apartment buildings. Rapid population growth, economic centralisation, and rising land values rendered horizontal expansion insufficient, shifting planning priorities toward vertical densification. In this context, increased allowable densities - rather than changes in plot size alone - became the principal mechanism guiding housing form. The archetypal modelling demonstrates that, given prevailing plot dimensions, multiple housing configurations could theoretically achieve similar density, daylighting, and access ratios, reinforce the argument that observe forms were not inevitable outcomes but the result of specific regulatory and economic choices[33].

Overall, the findings underline the importance of generic spatial functions - access and daylighting - as stabilising forces in urban form, while also showing how their interaction with regulation and density targets shapes the probabilistic emergence of particular housing types. This reinforces the broader argument of the paper: that Tehran's residential morphology evolved through a constrained field of possibilities structured by geographical requirements, regulatory codes, and economic pressures, rather than through deterministic cultural or stylistic trajectories.

8. Architectural Form, Plot Geometry, and Functional Fit

Building on the analysis of geographical constraints and generic functions, this section focuses on the architectural scale, examining how plot shape, block dimension, and regulatory parameters condition the emergence of specific housing forms. The central concern is the relationship between architectural layout and functional performance, and the extent to which certain spatial configurations lend themselves more readily to particular building types under given dimensional and regulatory constraints.

30. Philip Steadman, *Linear City: A Morphological Approach*, vol. 1 (Hong Kong: University of Hong Kong, 2005); Shayesteh and Steadman, 'Coevolution', 1124–47.

31. Moudon, 'Urban Morphology as an Emerging Interdisciplinary Field', 3–10; Steadman, 'How Day-lighting Constrains Access', 05.1–05.12.

32. Hillier, *Space Is the Machine;* Shayesteh and Steadman, 'The Impact', 92–107.

33.Steadman, *Linear City*, vol. 1; Shayesteh and Steadman, 'The Impact', 92–107; Shayesteh and Steadman, 'Coevolution', 1124–47.

A key question addressed here is what defines the dimensions of plots and blocks in contemporary urban development. Unlike medieval towns - where construction techniques and structural modules directly determined plot width and building depth - modern urban form is shaped by a more complex interaction of factors, including access requirements, daylighting standards, density controls, land value, and planning regulation. As a result, no single variable can be identified as determinative; rather, housing form emerges from the relative weighting of multiple constraints that vary over time and context. To disentangle these relationships, the study combined GIS-based measurement of urban fabric with Steadman's archetypal representation method. Ground coverage, Floor Space Index (FSI), plot frontage, building depth, and density were analysed across three boroughs of Tehran representing successive phases of urban growth. This approach made it possible to relate observed housing types to both their dimensional conditions and to alternative configurations that could theoretically have occupied the same plots[34].

The analysis demonstrates a clear sequence of typological transformation associated with progressive plot narrowing. At larger plot widths, four-sided courtyard houses were viable, allowing inward-facing layouts with adequate daylight and ventilation. As plot widths decreased - largely in response to subdivision pressures aimed at maximising street access - this configuration became untenable. Three-sided and two-sided courtyard forms (C- and L-shaped buildings) emerged as adaptive responses, preserving some courtyard qualities while accommodating reduced frontage. When plot widths narrowed further, typically to around six metres or less, even partial courtyard arrangements became impractical. At this threshold, narrow and elongated plots favoured terraced housing forms, which maximised frontage efficiency and facilitated direct street access. The widespread adoption of two-up, two-down terraced houses reflects this morphological logic. However, despite their formal efficiency, these houses proved poorly aligned with prevailing domestic practices in Tehran, particularly due to their deep, sequential internal layouts. As a result, they were rapidly supplanted by terraced apartment buildings, which offered greater internal flexibility and better accommodated social patterns of living, gathering, and privacy. While narrowing plots made certain forms more probable than others, multiple configurations remained theoretically possible within similar dimensional envelopes. Archetypal and configurational analysis revealed systematic changes in key parameters - such as ground coverage and daylit depth - across different housing types, demonstrating how architectural layouts respond to functional thresholds rather than stylistic preference alone[35]. This reinforces the argument that the dominance of particular forms in Tehran was not an inevitable outcome of plot size or density requirements, but the result of how planning regulations, market forces, and cultural preferences converged at specific historical moments[36]. Taken together, these findings position archetypal modelling as a powerful analytical and generative tool. By systematically relating architectural form to plot geometry, density, and functional performance, the method bridges planning criteria with typological and formal design considerations. This

34.Steadman, *Linear City*, vol. 1.

35. Steadman, *Linear City*, vol. 1; Shayesteh and Steadman, 'Coevolution', 1124–47.

36. Steadman, 'How Day-lighting Constrains Access', 05.1–05.12.

integrated approach offers a basis not only for retrospective morphological analysis, but also for exploring alternative residential layouts capable of meeting contemporary planning objectives while expanding the range of architectural possibilities in dense urban contexts.

9. Synthesis and final evaluation

This study makes a twofold contribution to knowledge. First, it advances understanding of the reciprocal relationship between housing-built form and urban structure in Tehran, demonstrating that these are not parallel but causally interrelated processes. Second, it contributes methodologically by extending and operationalising archetypal and typo-morphological modelling as a rigorous analytical and generative framework for linking architectural form, plot morphology, and urban layout. The methodological extension - particularly the adaptation of archetypal modelling to blocks more than two plots deep - enables the simultaneous analysis of architectural and urban scales. This addresses a persistent gap in typo-morphological research, which has often privileged either building typology or urban structure in isolation[37].

Empirically, the study extends existing accounts of Tehran's urban development by quantifying the historical evolution of housing typologies and block morphologies across successive phases of growth. In doing so, it reinforces and deepens earlier qualitative arguments regarding the role of vehicular access and regulation in shaping Tehran's residential fabric[38], while also demonstrating how planning codes acted as primary morphological drivers rather than merely administrative instruments. The findings show that changes in housing form - from courtyard houses to terraced houses and subsequently to apartment buildings - were tightly coupled with shifts in plot dimensions, density allowances, and block structure, revealing clear causal links between urban layout and architectural typology.

A further contribution lies in the study's generative dimension. By using average dimensional parameters derived from empirical analysis to construct theoretical blocks, the research tested whether archetypal modelling could reproduce densities and spatial characteristics comparable to those observed in reality. This procedure functions as methodological validation rather than circular reasoning. This makes it possible to evaluate not only what was built, but what could have been built, thereby situating Tehran's housing evolution within a wider field of theoretical possibilities[39]. The synthesis of planning, geographical, and architectural dimensions is a central strength of the study. By explicitly linking access, daylighting, density, and plot geometry to architectural form, the research provides a framework through which planning objectives can be more directly translated into spatial and typological outcomes. This has practical implications for urban regulation, suggesting that performance-based criteria - such as street frontage continuity or daylight access - may offer greater formal flexibility and improved urban aesthetics than rigid plot-based controls. In the context of Tehran, revisiting regulations governing building positioning within plots could enable more coherent street façades and skyline conditions while accommodating comparable densities.

More broadly, the study proposes a shift in

37. Conzen, 'Alnwick, Northumberland', iii–122; Moudon, 'Urban Morphology', 3–10.

38. Ali Madanipour, 'Urban Planning and Development in Tehran', *Cities* 23, no. 6 (2006): 433–38, https://doi.org/10.1016/j.cities.2006.08.002.

39. Steadman, 'How Day-lighting Constrains Access', 05.1–05.12; Shayesteh and Steadman, 'Coevolution', 1124–47.

typo-morphological inquiry from static description toward an explicitly evolutionary and transformational perspective. Rather than treating urban form as a snapshot divorced from its history, the analysis situates housing morphology within a temporal process shaped by regulation, technology, lifestyle change, and economic pressure. This approach aligns with calls for more explanatory and model-based urban morphology capable of testing hypotheses and comparing alternative configurations[40]. The research also opens several avenues for further investigation. One promising direction concerns the relationship between block morphology and environmental performance, particularly energy demand. Given that the archetypal models already quantify building volumes and envelope surfaces, they could be extended to evaluate the thermal implications of alternative block layouts. This would resonate with recent comparative studies linking urban morphology and residential energy consumption in European and Middle Eastern cities[41]. Such work would be especially relevant in Tehran, where planning regulations have historically been justified on climatic grounds.

Finally, while the analysis focuses on physical form, it does not imply physical determinism. Built form is understood here as the spatial embodiment of cultural, social, and regulatory processes rather than their replacement. Ordinary housing is treated as an evolving artefact shaped by residents, markets, and planning frameworks alike. By establishing a robust morphological baseline, the study provides a conceptual framework within which socio-economic and political influences on Tehran's urban development can be more systematically

40. Leslie Martin and Lionel March, 'The Grid as Generator', in *Urban Space and Structures*, ed. Leslie Martin and Lionel March (Cambridge: Cambridge University Press, 1972), 6–27; Steadman, *Linear City*, vol. 1.

41. Philipp Rode and Ricky Burdett, 'Cities: Investing in Energy and Resource Efficiency', in *Towards a Green Economy: Pathways to Sustainable Development and Poverty Eradication* (Nairobi: United Nations Environment Programme, 2011), 453–92.

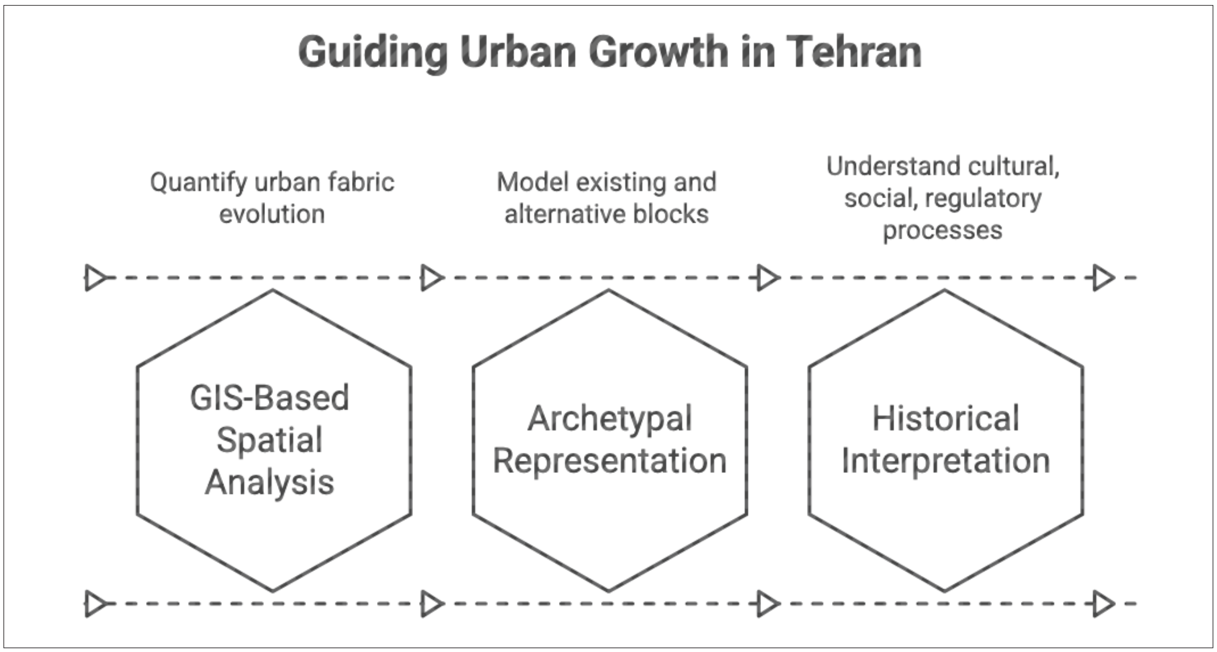


Figure 8. Guiding framework for urban growth in Tehran

examined in future research. Taken together, the findings demonstrate the value of integrating archetypal modelling, GIS analysis, and historical interpretation in understanding housing transformation. Using Tehran as a case study, the research illustrates how a relatively stable urban structure of streets and blocks can accommodate - and constrain - changing architectural forms over time. Recognising these limits and possibilities is essential for designers, planners, and regulatory authorities seeking to guide urban growth toward more coherent, adaptable, and sustainable residential environments.

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The Role of Narrative in Design Frames: Demystifying Framing in Design Research through Narratives in the Architectural Design Process

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ORIGINAL RESEARCH ARTICLE

Alaei, Amir Ali, Seyed Abbas Yazdanfar, and Mohsen Faizi. "The Role of Narrative in Design Frames; Demystifying Framing in Design Research through Narratives in the Architectural Design Process". *Soffeh* 36, no. 2 (2026): 47–64. DOI: http://doi.org/10.48308/soffeh.2025.239859.1417

Abstract

Background and Objectives: In response to criticisms of the rationalist approach to ill-structured problems, the design situation was viewed by some design researchers from a constructivist perspective, which led to the concept of framing and frame-making as one of the main activities in the design process. While there is a theoretical foundation for framing in design studies, its concrete understanding remains ambiguous. Meanwhile there is a history of using narratives and stories as a perspective for studying the design process in general. In these studies, narratives are tools that simultaneously guide the designer's thinking and serve as reasoning devices that structure what should be done about the subject of the design. From this perspective, framing seems to be a context that allows different values to coexist in the design without being mutually exclusive, and in the form of co-construction of verbal stories in design. Thus, This research aims to examine the capacity of narrative in the concept of

Received: May 10, 2025
Revised: June 24, 2025
Accepted: July 19, 2025
(Pages: 47–64)

Keywords:
Framing, Narrative, Storytelling, Design process,
Design research.

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http://doi.org/10.48308/soffeh.2025.239859.1417

frames as representational constructs that embody designers' situated knowledge and to find a model for demystifying them.

Materials and Methods: Employing a fundamental-theoretical research paradigm with a qualitative strategy, and based on library-based studies and logical reasoning on top of a general review of design research, the present paper examines the concept of framing from a constructivist perspective. It then attempts to provide a structure for using an often-underexplored capacity of narrative in this context.

Results and conclusion: The study demonstrates the significant potentials of the concept of design framing: a tangible, actionable narrative-based strategy in four interrelated activities. It starts with naming, which takes place in the form of interpreting the situation through constructing a story, followed by the creation of a frame as an inclusive narrative based on the superimposition of stories. The next step is to move towards frames, in the form of solution-oriented stories through the lens of these narrative frames. Finally, and continuously throughout the design process, there is a reflection on design that refines, removes, and adds stories. This process goes on until the inclusive narrative (the last frame) best manages the situation and complexities of the design.

Research Questions:

1. How can a narrative approach be used to clarify what goes on through framing in the design process?

2. What is the meaning of frames and framing in design?

3. What interpretations of framing have been offered to understand the design process?

Introduction

An increasing number of studies have been conducted in recent years to examine designers' working methods and analyse design processes in both lab and field settings[1]. One of the most influential concepts in the study design processes is the constructivist concept of framing, which suggests that the main activity in the design process[2] is the construction of a frame. A frame is a viewpoint that allows a designer to encounter a problem in an ambiguous, uncertain, and indeterminate design situation. According to definitions of framing[3], its main function is to define or make sense of a situation. This sense-making allows a person to understand a situation by constructing a mental representation of the important elements of it and speculating a

1. Ilpo Koskinen, et al. 'Design Research through Practice: From the Lab, Field, and Showroom.' IEEE Transactions on Professional Communication 56, No. 3 (2013): 262-263.

2. Bryan Lawson, *How Designers Think*. Routledge, 1980.

3. Donald A. Schön, *The Reflective Practitioner: How Professionals Think in Action*. Routledge, 1983.

4. Donald A. Schön, ibid; Robert Drazin, et al. 'Multilevel Theorising About Creativity in Organisations: A sensemaking perspective.' *Academy of management review* 24, No. 2 (1999): 286-307.

set of relationships, and thereby facilitating decision-making and action[4]. From the perspective of existing studies, adopting a constructivist approach to design appears to have two major consequences: first, frames and framing are at the core of the design process, used by the designer to understand the existing situation and imagine new situations. These frames are not objective reflections of the outside world, but rather structures that are formed through sense-making and giving order to the elements of the world; second, design frames are constantly changing structures as designers interact with givens of the situation. Therefore, framing is a dynamic process that is shaped by interactions between the design world and the design situation[5].

Despite the emphasis on the role of framing in design research and the design process, a visual description of the structure and content of frames has rarely been provided. While such a description would allow frames to be identified and their transformations to be tracked during the design process, the proposed models to describe them remain relatively underdeveloped. The issue is that although frames, as a perspective or viewpoint, allow designers to address a problem, their specific and precise definition remains elusive[6]. While concepts such as point of view or metaphor are useful for communicating the concept of frames[7], they are often too broad and vague to allow for a specific definition. This research, therefore, attempts to address this gap to enable a more in-depth identification and representation of frames for describing and understanding the design process. It is anticipated that such representations and models will allow for the emergence of new perspectives for describing and understanding the design process.

Based on the studies of Donald Schön and building upon the interpretations of scholars[8] such as Bryan Lawson[9], Peter Lloyd[10], Wegener and Cash[11], it is argued that a version of Schön's framing process can be conceptualised as a reflective practice. This act has been translated into the realm of narrative and storytelling for the purpose of disambiguation. Given the aforementioned purpose, this investigation is considered a fundamental-theoretical study with a descriptive-analytical nature. The data collection was achieved through library research, focusing on the history of design research studies and the evolution of design generations, specifically within the two general axes of framing in design and narrative in design. Qualitative strategies and logical reasoning are employed for the method of analysis. The research attempts to provide a structure or suggestion regarding the use of the lesser-known capacity of narrative in relation to the frame. Although this research does not systematically utilise semi-structured interviews, content analysis of their texts, or a data-based theory, observations and transcribed excerpts from verbal interviews with practitioners or professors of architecture are included as examples for scrutiny and comparison with the library-based findings.

1. Theoretical background

After World War II, the problems facing design in the crisis of solving complex problems in Europe and the inefficiency of the traditional view of design led to a shift in the attitude towards it. Formerly considered a process reliant on the 'magical' power of creativity, individual genius,

5. Babak Soleimani. 'Design Frames: A Narrative and Network Approach.' Doctoral dissertation, 2020.

6. Babak Soleimani, ibid.

7. Jon Kolko, *Wicked Problems: Problems Worth Solving*. Austin Centre for Design: Ac4d, 2012; Donald A. Schön, 'Generative Metaphor: A Perspective on Problem-Setting in Social Policy.' Metaphor and Thought (1993): 137-163; Suat Hoon Pee, et al. 'Understanding Problem Framing through Research into Metaphors.' In *2015 IASDR International Design Research Conference*, pp. 1656-1671. 2015.

8. Rianne Valkenburg and Kees Dorst. 'The Reflective Practice of Design Teams.' *Design Studies* 19, No. 3 (1998): 249-271; Norbert FM Roozenburg and Kees Dorst. 'Describing Design as A Reflective Practice: Observations on Schön's Theory of Practice.' In *Designers: The Key to Successful Product Development*, pp. 29-41. London: Springer London, 1998.

9. Bryan Lawson, ibid; Bryan Lawson, *What Designers Know*, Elsevier, Oxford: Architectural press, 2004.

and the artistic sense of the designer, design began to be viewed as a more conscious, regulated, and evaluable process. In response, the theorising of design methods was initiated in the late 1950s and early 1960s. Decades of research have resulted in the proposal of many prescriptive or descriptive models for the methodology and process of design. These are generally classified into three generations by design research scholars[12]: First Generation[13] or the 'analysis-synthesis' models; Second Generation[14] or the 'participatory' models; and Third Generation[15] or the 'conjecture-analysis' model, which is more descriptive[16]. These efforts are related to various paradigms and epistemologies. According to studies spanning more than half a century of design research, two main types of paradigms have been proposed[17] to describe design activity[18]: 1) 'Rational Problem Solving' Proposed by Herbert Simon[19], in which design is seen as a methodical process for finding a solution to a problem; and 2) 'Reflective Practice' presented by Donald Schön[20], where design is an attempt to gain knowledge about the practice existing in intuitive and artistic processes. Criticising the positivist and methodological scientific epistemology, a new epistemology for design practice was proposed by Schön. This was based on a constructivist approach. The point was highlighted by studies and experiences was that design problems—referred to as ill-defined, ill-structured, and wicked—could

10. Peter Lloyd. 'Storytelling and the Development of Discourse in the Engineering Design Process.' *Design Studies* 21, No. 4 (2000): 357-373; Peter Lloyd and Arlene Oak. 'Cracking Open Co-Creation: Categories, Stories, and Value Tension in a Collaborative Design Process.' *Design Studies* 57 (2018): 93-111.

11. Frithjof E. Wegener and Philip Cash. 'The Future of Design Process Research? Exploring Process Theory and Methodology.' In *Design Research Society 2020*, pp. 1977-1993. Design Research Society, 2020.

12. Nigan Bayazit, 'Investigating Design: A Review of Forty Years of Design Research.' *Design Issues*20, No. 1 (2004): 16-29.

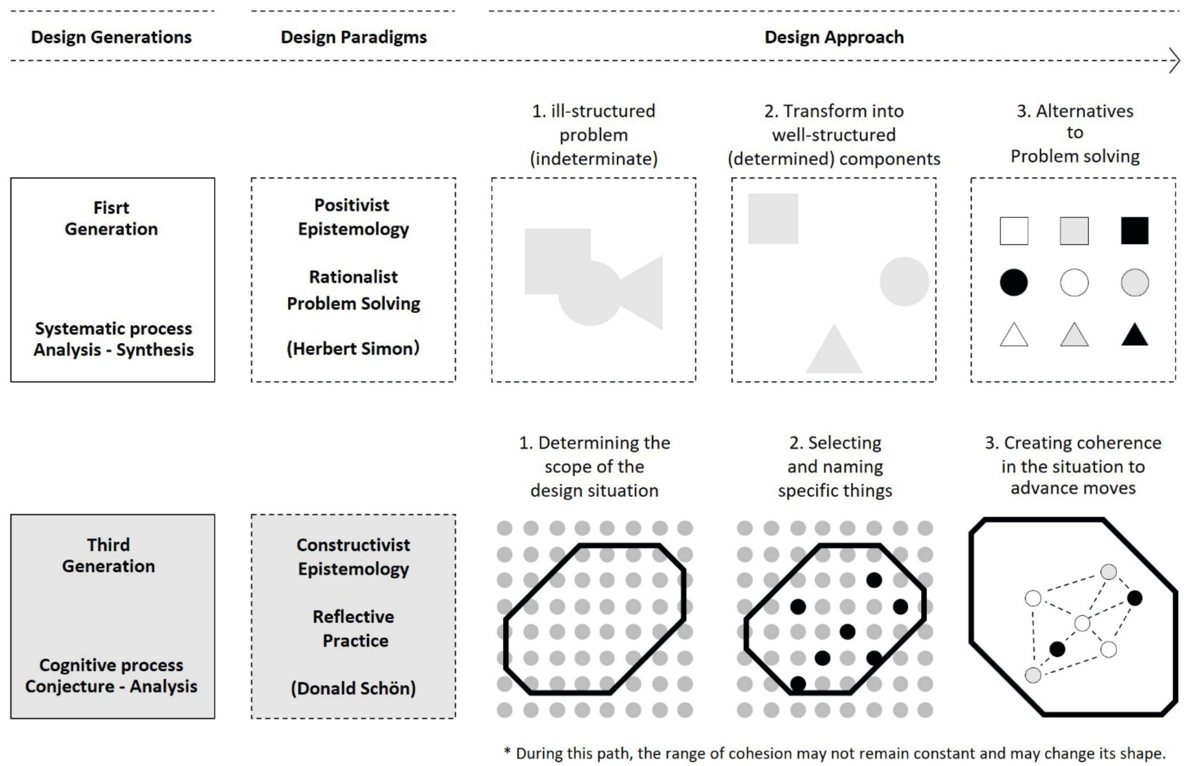


Figure 1. A summary of the relationship between the two design paradigms and the approach to design problems through the lens of each of them, drawing: authors.

not be adequately analysed within a scientific epistemology. Instead, it was found that newer epistemologies offered perspectives closer to the reality of design.

In the context of design, alternative approaches have been seen to focus on a localised problem rather than the overall problem as an abstract entity[21]. It is suggested that the only way to deal with complex problems is to have a localised understanding at any given moment[22]. In this view, the problem is understood as the design situation itself, in which a gap exists between what is and what should be. It has been argued that '*instead of solving wicked and ill-structured problems, one can expect to manage them and, in fact, to open them up rather than solve them*[23].' Thus, the term problem-unrolling can be used to refer to the process by which a designer encounters an ill-structured problem. The ill-structured nature of a design problem necessitates that, prior to any problem-solving activities, a certain amount of structuring or framing of the problem must occur[24]. According to Schön[25], problem framing is the process by which a designer interactively names the elements that will be addressed and frames the context in which they will be addressed. This places the designer in a reflective conversation with the materials of a design situation[26], a process that stems from a reflective practice approach and, under a constructivist epistemology, emphasises problem framing (Figure 1).

1.1. Framing in Design

In Frame Analysis, Erving Goffman[27] states that frames are the way in which situations are made sense of by individuals, serving as the story that might be told when asked about what was occurring. The concept of framing entered the design world most notably through the writings and studies of Donald Schön and his early references to James[28] and Dewey[29]. According to Schön[30], a difficult design situation is framed by designers through the setting of its boundaries and the selection of specific elements and connections that provide it with a sense of coherence. Occasionally, efforts to organise the situation produce unexpected results, which in turn give the situation new meaning. As such, the problem is listened to and reframed by designers.

The concept of frames is considered by Lawson to be the basis and essence of design thinking and the heart of the design process. It is argued that designers hold on to a relatively simple idea early on when faced with a complex problem[31]. When examining the design methods of expert architects, it is often seen that statements are made about how they view the problem. This, which can also be observed in interviews with designers, points to the framing activities of the designers[32]. Also, Cross states that the process of structuring and formulating the problem has been repeatedly introduced as key features of design expertise, and the idea of problem framing seems to best reflect the nature of this activity[33].

These frames are not fixed, predetermined, and separate from their creator, but rather they are posited and dependent on the designer. According to studies, designers, in their reflective conversation with the situation, identify and name the factors of the situation, frame the problem in a specific way, move towards providing a solution, and then evaluate those moves. In this cycle, designers use frames as

13. The first generation of design methodologies, prominent from the 1960s to the 1970s, originated from the positivist paradigm, which is rooted in the natural sciences. Within this framework, design is approached as a systematic process of decomposition and synthesis. A complex design problem is first broken down into smaller, more manageable sub-problems. These sub-problems are then individually solved, and their partial solutions are subsequently combined to form a comprehensive, final solution. This approach is characterised by an objectivist viewpoint, emphasising the use of objective, external data and components. The non-interference of the designer›s subjective mental schemas is considered a core principle, as the formation of an idea is seen as a product of logical induction, independent of the designer›s personal mentalities or cognitive structure. Notable works from this period include those by Christopher Alexander and Bruce Archer.

structures of belief, perception, and value from which they look at the problem and try to respond to it. Framing can be said to be a key and important activity in the design process, to the extent that Schön considers it a major factor in the success of a design process[34]. He and Martin Raine outline four perspectives for looking at frames[35]: 1) As scaffolds and internal structures that support subsequent constructions, 2) as boundaries and limits, 3) as schemata that support interpretation, and 4) as diagnostic/prescriptive stories (a view that Rein and Schön themselves agree with). Indeed, frames appear in part in Schön's studies to provide narrative accounts of how designers change their perception of a design problem[36].

1.2. Narrative in Design

In narratology a narrative is conceptualised as a form of representation that encompasses both story and narrative discourse[37]: 1) The story is the content level, consisting of an event or a series of events, while 2) The narrative discourse is the means by which these events are represented. From this perspective, it is argued that a story is never directly encountered but is instead always mediated through a narrative discourse. Researchers in this domain have therefore depicted the story at the core, with the narrative serving as the outermost membrane of communication with the surrounding world.

According to Manfred Jan, a primary distinction among narrative types is drawn between fictional and non-fictional narratives. Non-fictional narrative is a literary form that emerged in Europe during the latter half of the 20th century, having been formed from a fusion of journalism and fiction. While both narrative types are understood to possess the elements of story and discourse, non-fictional narratives are also said to contain a third determining factor that is absent in fiction: a reference to the real world[38]. Furthermore, it is argued that in non-fiction, the relationship between the reference and the story can become more significant than that between the story and the discourse. Consequently, while the story is of primary importance for fiction (often at the expense of reality), truthfulness is prioritised in non-fiction, even though storytelling techniques may be utilised. From this perspective, it is suggested that architecture, given its external relationships with other forces, more closely resembles a non-fictional narrative (which is grounded in reality) than other genres, such as the novel, which rely more heavily on imagination. Another feature of non-fictional narrative is its connection to creativity. The reality presented in non-fiction is given a personal quality, with the author narrating the truth through various creative techniques in a manner that transcends a mere recounting of events[39]. This manipulation, however, is not intended to falsify reality but rather to highlight certain aspects while consciously diminishing others, often in a non-linear sequence[40]. This approach is considered to be highly analogous to the act of making and looking through a frame.

In architecture, narrative can be instrumental throughout the design process, from the initial stages of enriching an idea to the final decision-making[41]. According to some researchers, its effectiveness can be seen at all stages: at the outset, by helping to identify and define the problem; in the middle, by aiding in the identification of design nodes and the introduction of

14. A shift in design approach occurred in the late 1970s and early 1980s with the emergence of the second generation of design methods, known as participatory models. These models challenged the traditional role of the designer as the sole decision-maker. Instead, design decisions were reconceptualised as a collective endeavour involving the participation of users and stakeholders. In this model, the designer›s function is limited to that of an expert who provides the necessary information for the collective decision-making process. This approach was influenced by concurrent developments in urban and regional planning, where a greater emphasis was being placed on stakeholder participation in the decision-making process.

solutions; and finally, by providing the possibility of testing proposed solutions[42]. From Lawson's perspective, the formulation of a problem appears to have similarities to narrative, and is also related to Schön's concept of problem setting. This is because in explaining this activity, Lawson uses the example of introducing characters and examining their role in a story. Schön had previously described a similar activity as the act of naming the elements of a situation. In this view, the designer, as the director of the design scene or the writer of its scenario, not only identifies the elements, actors, and characters of a work, but also redefines them and assigns them new roles based on their perspective and the knowledge gained from those elements[43].

2. Interpretations of Framing

Based on a broader review of the literature on the subject and historical studies of design frames, three general conceptual locations can be identified[44]. For some, frames are situated within the internal world of cognition, while for others, they are a type of representation external to cognition. For a third group, however, frames are considered to be tools for thinking, defined by their ability to move and shift between the realms of cognition and representation. The distinction between the internal (conceptual sets) and external (externalised representations of a perception) aspects of a frame is therefore a fundamental point of consideration. This is also reflected in the evolution of framing studies; initially, the focus was on frames as a means of understanding and defining situations—that is, as an internal tool for comprehension. More recently, however, the research trajectory has shifted toward viewing frames as an external tool for understanding[45]. The concept of boundaries is mentioned by Dorst[46] in the context of defining frames as tools that exist in a world of actions and intentions (Figure 2). In this view, the designation of a metaphor or pattern of relationships as a frame is entirely dependent on the designer. An externally displayed frame can also be utilised as a tool for thinking about a design problem[47].

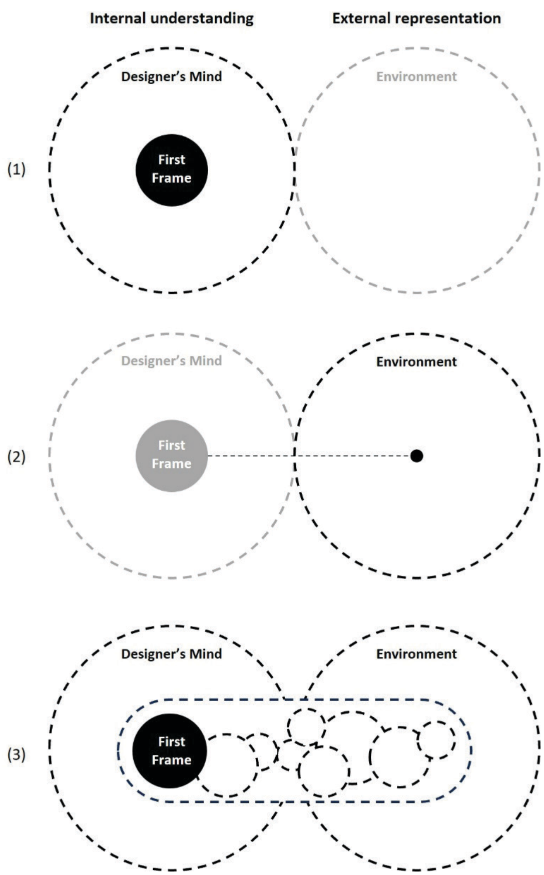


Figure 2. Positioning design frames across different studies. Drawn by the authors, adapted from Nick Kelly and John S. Gero, 'Reviewing the Concept of Design Frames towards a Cognitive Model'.

15. The third generation of design method is grounded in constructivism, a philosophical approach associated with the humanities and arts. In this paradigm, the design process is understood to begin with initial hypotheses or ‹estimated design responses›. These initial conjectures are then tested and refined through the application of analytical methods. This approach is heavily dependent on the designer›s mental schemas or schemata, as the design process is understood to be derived from their existing cognitive capabilities and mental structure. The designer›s internal cognitive framework is thus seen as fundamental to the generation of design solutions. Key studies belonging to this generation include the work of Bill Hillier et al., Jane Darke, and Nigel Cross.

16. Hamid Nadimi, 'A Study in the Design Process.' *Soffeh* 9, No. 29 (1999): 94-103 [in Persian].

For example, representations of a design problem are frequently shared and interpreted by design teams in order to develop shared mental models[48]. This perspective is considered crucial for understanding how norms are shared within design teams.

While a theoretical basis for framing exists in the literature, concrete efforts to understand the concept from a constructivist perspective, to map frames, and to examine how their structure is transformed during the design process remain relatively limited. This clarification of the concept can be used to improve the design process from two perspectives:

1) The framing of a design problem is considered to play a fundamental role in design creativity. Previous studies have demonstrated that the act of changing a frame is key to the creation of innovative solutions[49]. It is through reframing that a situation is viewed through new lenses, and solutions are imagined that could not have been achieved with the old frame. However, since frames are embedded in design materials and conversations[50], they can remain hidden from a designer's conscious perspective. Making frames clear and understanding how they enter the design space is believed to open up new avenues for designers to reimagine their understanding of a situation and explore new design environments.

2) Frames can also be considered strategic tools in the design process that facilitate the creation of a shared vision among different members of a design team. As noted in various studies[51], the growing complexity of design problems, the increasing interdisciplinary nature of design teams, and the invisibility of design artifacts have heightened the importance of clarifying the design process. It is believed that by making design frameworks more transparent, a shared understanding of complex and unique design problems can be improved.

In line with these research efforts, four main design activities for reflective practice have been proposed by Valkenburg and Dorst[52]: Naming, Framing, Moving, and Reflection (Figure 3).

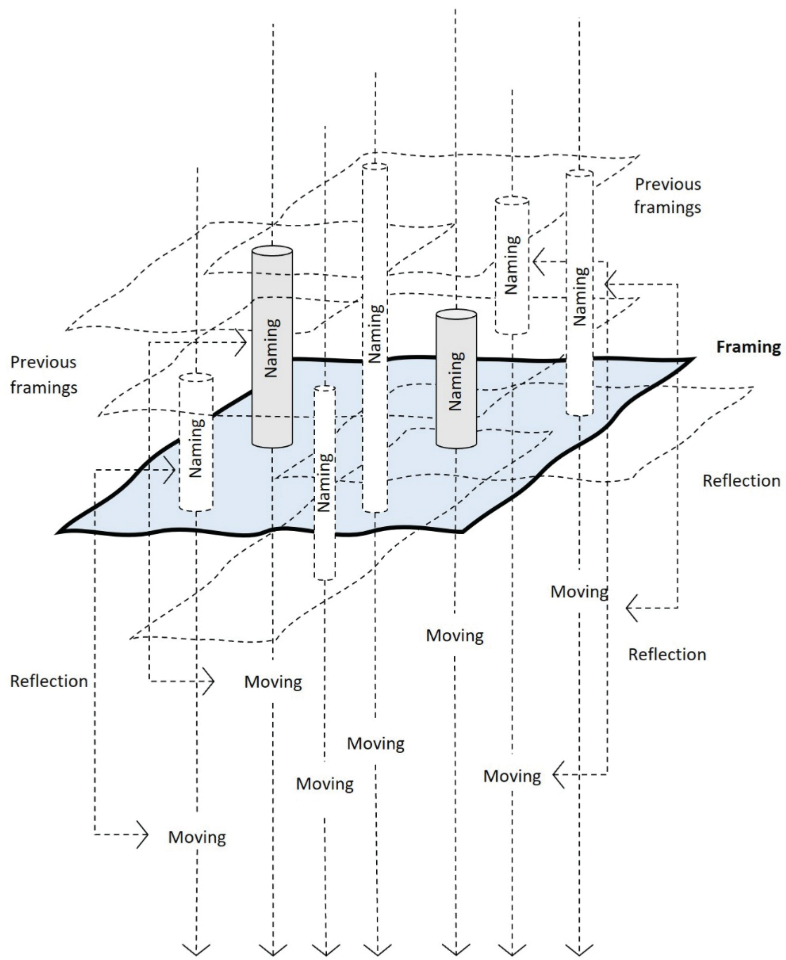


Figure 3. The reflective practice mechanism based on Schön's theories, drawing: authors, adapted from: Rianne Valkenburg and Kees Dorst, 'The Reflective Practice of Design Teams.'

It should be noted that with each reflection on frames and the movements made towards them, the overall structure may be altered, and the process may be faced with reframing. Design activities were divided and examined into episodes[53] based on the protocol analysis study method. In this approach, the four activities were examined as separate stages in order to describe the design process. Research similar to this method was also conducted by Rozenburg and Dorst[54]. However, criticisms have been levelled against this group of studies, which are related to the use of protocol analysis and a somewhat linear conception of activities within the design process. The nature of a reflective practice and how a design is framed are themselves considered to be a sub-section of a larger body of research on design processes, within which various research gaps have also been identified.

More generally, and based on studies by Wegener and Cash[55], more insights into design research have been gained at both the micro and macro levels (Figure 4). However, it appears that fewer approaches to design process research are capable of theorising at a meso-level and thus transcending mere analysis. The challenge and research necessity of such issues are seen as the analysis and theorisation across the entire design process, with an emphasis placed on the meso-levels as mediators of interactions. Of the three major approaches to design research studies—protocol studies, ethnographic approaches, and narrative approaches—the third is considered closer to the nature of design due to its process-based nature.

While protocol analysis studies may be suitable for analysing micro-level design sessions (typically around ninety minutes), and ethnographic approaches for a full, macro-level de-

17. Subsequent research endeavours have also sought to integrate these two approaches, with studies, such as the one conducted by Keys Dorset, aiming to achieve a more comprehensive perspective.

18. Kees Dorst and Judith Dijkhuis. 'Comparing Paradigms for Describing Design Activity.' *Design Studies* 16, No. 2 (1995): 261-274.

19. Herbert A. Simon, 'The Sciences of the Artificial.' *Cambridge, MA* (1969).

20. Donald A. Schön, *The Reflective Practitioner: How Professionals Think in Action*. Routledge, 1983.

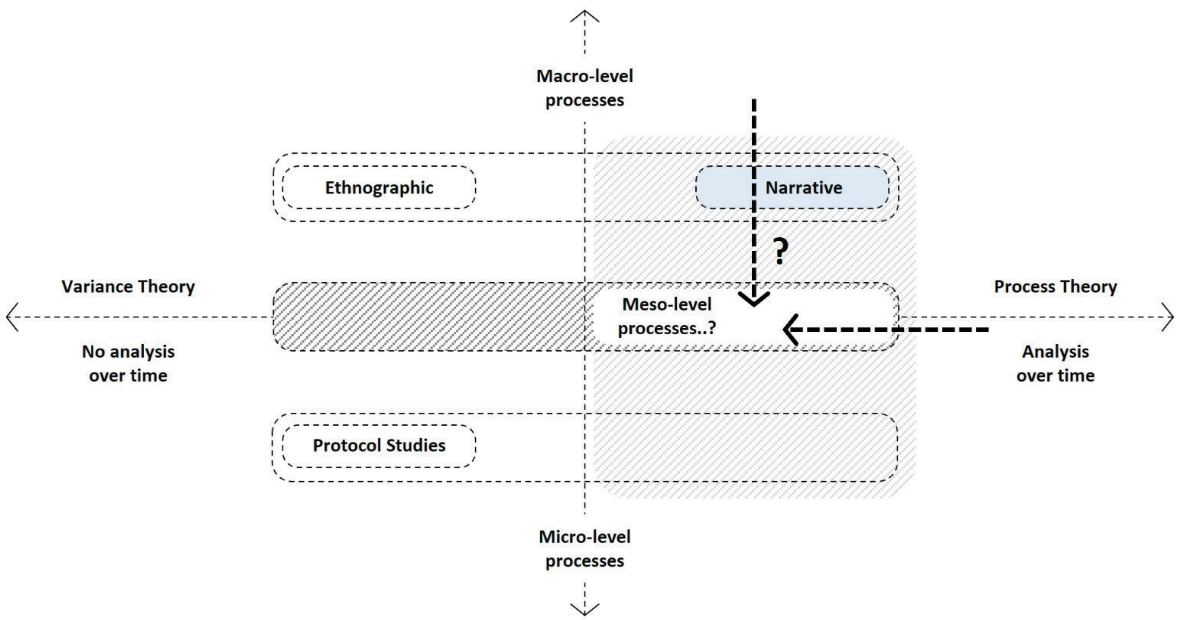


Figure 4. General approaches to design research and the potential of meso-level processes. Drawn by the authors, adapted from Frithjof E. Wegener and Philip Cash, 'The Future of Design Process Research? Exploring Process Theory and Methodology'.

Approach	Strengths	Weaknesses
1. Protocol studies	Given the inherent analysis of variance in such studies, they are considered more suitable for the testing of existing theory rather than the construction of new theory. These methods are also seen as being suitable for the analysis of micro-aspects of design sessions.	It's challenging to scale up this approach to include a larger number of participants or to cover longer time periods. Furthermore, it's theoretically difficult to relate insights from the micro to the macro level of longer design processes.
2. Ethnographic approaches	In a theoretical context, a wealth of insight is developed, which is useful for theory building. This approach is also considered strong in its ability to facilitate design positioning and explain designers' actions.	A considerable amount of time is devoted to them, which reduces the time available for analysis. When used in design, they can also cause the analysis of the individual's role to be lost, as they were primarily invented to depict collective culture.
3. Narrative approaches	Due to its closeness to the experience of designers, a richness of theoretical insight is developed, which allows for theorising that is both relevant and meaningful. This insight is gained by connecting the dots over a longer design process.	There's a lack of a clear explanation regarding how narrative is embedded in empirical data, especially given the multiplicity of narratives provided by different individuals. While the content is present, the way in which the content and narrative processes influenced one another isn't clear.

Table 1. Review of the strengths and weaknesses of general approaches in design process studies. Drawing: authors, adapted from Frithjof E. Wegener and Philip Cash, 'The Future of Design Process Research? Exploring Process Theory and Methodology'.

sign process (typically several months), what is missing are approaches capable of connecting these forces[56]. Even if data about the design process is collected, the analysis and theorisation of such data either adhere to an analysis of variance—ignoring the elements of the process—or lack the empirical and reflective basis needed for a deeper analysis[57]. From this perspective, it is suggested that narrative approaches are more relevant to the experience of designers. When accompanied by a basis in reflective practice and capable of empirically enabling the location and multiplicity of narratives, these approaches can fill the gap in the middle ground and provide a processual view of what goes on in design. The temporal view of design research taken by narrative approaches is considered to be more aligned with the nature of design processes.

3. Narratives as mediators in interpreting framing

Drawing upon an analysis of Broadbent's methods of form production, a potential is spotted by Lawson for the inclusion of a method similar to narrative design. According to Lawson, Broadbent's analogical methods are considered the most promising of his four. This could lead to the development of a device called the narrative method, which is viewed as an extension of Broadbent's method of deference that transcends its simple analogy[58]. In this method, a

21. Kees Dorst, 'Design Problems and Design Paradoxes.' *Design Issues*22, No. 3 (2006): 4-17.

22. Marvin Minsky, 'Jokes and the Logic of the Cognitive Unconscious.' In *Methods of Heuristics*, pp. 171-193. Routledge, 2014.

23. Farhad Shariatrad and Hamid Nadimi. 'Problem Framing: The Designer's Way of Tackling Design Problems.' *Soffeh* 26, No. 3 (2016): 5-24 [in Persian].

story can be defined by the designer, or often a design team, which is used to relate the main features of a design to each other. It appears that narratives are, in fact, analogies (whether direct or indirect) that can be combined and repeated to more coherently solve design problems. It has also been noted in Lawson's 2018 book that narrative can be considered a fully elaborated version of analogy, in which a story is told. And it gives form and structure to certain aspects of a plot[59].

The importance of this point is also highlighted in Bryan Lawson's *How Designers Think*, where Chapter 15, 'Design as Conversation and Perception,' is dedicated to the topic[60]. It is suggested that a conversation-like process is used by designers to understand problems and conceive of solutions. A process that involves changing the way the situation is perceived by 'talking it through.' It is as if you have to look around... to find something, and then it suddenly dawns on you[61]. In a professional context, due to its size or complexity, design is often implemented by teams rather than individuals. Sometimes, the nature of the object being created necessitates many areas of expertise, requiring a multidisciplinary design team. In both cases, the design process is understood to proceed, at least in part, through conversations between team members. However, since such conversations are not typically recorded, their importance as part of the design process is often underestimated in design research. The significance of such conversations is only made apparent when designers are studied in actual practice, and interviewed about their process[62]. On the other hand, design can be viewed as a conversation conducted not by a team, but by an individual designer. This idea was first introduced by Donald Schön[63], who discussed how a designer 'has a conversation with a drawing,' which enables new possibilities or problems to be seen. It was later pointed out by Lawson that designers have more recently been using computers, resulting in a conversational interaction with the computer about their designs. The entire idea of design conversations has thus been explored, whether they occur between individuals, between designers and their drawings or computers, or even as reflections that take place individually in the minds of designers. Indeed, this range of conversations and dialogues appears to be related to the category of narrative.

According to Lawson and other theorists[64] with a linguistic background, the base mode of conversation is narrative. While designers employ various conversational styles when communicating, they are often observed returning to a style similar to storytelling. In dramatic narratives, a scene is typically set with a clear description of the situation and the characters. The main characters are generally not named but are given characteristics that allow their words and actions to be interpreted. This process is also seen to be the case in design, where a number of characters are introduced and are said to be important to the narrative of the design. It is then explained by Lawson how, within the design team's conversation, the nature of these characters is explored and personalities are created for them[65]. A process is observed in which objects are introduced as characters, their desired characteristics are defined, and differences in terms of their physical realisation are identified through conversation[66]. Thus, the

24. Vinod Goel and Peter Pirolli. 'The Structure of Design Problem Spaces.' *Cognitive Science* 16, No. 3 (1992): 395-429.

25. Donald A. Schön, ibid.

26. Donald A. Schön, 'Designing as Reflective Conversation with the Materials of a Design Situation.' *Knowledge-Based Systems* 5, No. 1 (1992): 3-14.

27. Erving Goffman, *Frame Analysis: An Essay on the Organisation of Experience*. Harvard University Press, 1974.

28. William James

29. John Dewey

30. Donald A. Schön, ibid.

31. Bryan Lawson, *How Designers Think*. Routledge, 1980.

32. Farhad Shariatrad and Hamid Nadimi, ibid.

33. Nigel Cross, 'Expertise in Design: An Overview.' *Design Studies* 25, No. 5 (2004): 427-441.

34. Donald A. Schön and Martin Rein. 'Frame Reflection: Toward the Resolution of Intractable Policy Controversies.' *Basic Book* (1994).

first important step in the design conversation is defined as identification, which is considered very similar to what is referred to by Schön as naming[67]. However, for Lawson significant elements are not just named, but their very character begins to be explored. This central and detailed process of introducing characters is considered more than simple naming, and for this reason, it is referred to as identification.

From a broad perspective, it is suggested that narratives and stories can be used as a lens through which to study the design process in general, and design frames in particular, in a story-like format. Peter Lloyd refers to this as the storytelling approach[68]. In this approach, the present situation is made sense of, and the future is imagined, through narrative structures. At its core, design is depicted as a process of storytelling that links the present reality of a situation (what is occurring) with imagined possibilities for the future (what could be). In this case, design is understood to be the creation, negotiation, and connection of two sets of stories: 1) past particulars and 2) imagined particulars. While the former structures existing experiences and behaviours, the latter places specific actors, objects, and relationships in an imagined context. The storytelling perspective, which takes into account the constructivist approach, conceives of framing as a process of co-construction of verbal stories. This allows designers to discuss and negotiate opposing values without the need to resolve them. It is worth noting that a relatively emerging paradigm in the practical and professional realm of urban design also considers urban design as a form of persuasive storytelling. In this view, the designer is seen not as an architect-hero, but rather as a conductor or 'curator' who selects and weighs different voices and narrative producers. In other words, the designer is considered a mediator between potentially conflicting narratives in the formation of a design[69].

In the context of design, narratives are considered to be both tools that guide one's thinking about a subject and reasoning devices that shape the proposed course of action. It is also suggested by Schön and Rein that framing is a storytelling act in which seemingly unrelated elements are brought together by designers. In linking elements to form a coherent narrative of a situation, two things are followed by storytelling: naming and selecting. These situation-based stories help designers to structure their understanding of a problem and make connections with it[70]. Compared to Schön's reflective practitioner framework, the first process is considered to be similar to naming (elements of a situation) and the second to moving (towards a solution).

A design frame can be conceptualised as a narrative that connects stories constructed from a situation, allowing for the creation of solutions. In this process, actors (human and non-human) are identified, and a coherent set of connections is established through actions and aggregations between them. Designers may construct multiple stories of a situation before a narrative is initiated, with each story representing a different situation, and a distinct set of actors and actions. Narratives are what connect these stories to create an overarching structure that guides a practical situation. It is important to distinguish between the concepts of story and narrative. A story is the structure that is constructed by designers to give mean-

35. Martin Rein, and Donald Schön. 'Frame-Critical Policy Analysis and Frame-Reflective Policy Practice.' *Knowledge and Policy* 9, No. 1 (1996): 85-104.

36. Donald A. Schön, *The Reflective Practitioner: How Professionals Think in Action*. Routledge, 1983.

37. H. Porter Abbott, *The Cambridge Introduction to Narrative*. Cambridge University Press, 2020.

38. H. Porter Abbott, ibid.

39. Theodore Albert Rees Cheney, *Writing Creative Nonfiction: Fiction Techniques for Crafting Great Nonfiction*. Springer Science & Business, 2001.

40. Theodore Albert Rees Cheney, ibid.

41. Hamid Nadimi, Somayyeh Sharifzadeh and Zakiyeh Tabatabaei, 'The Roles of Narrative Thinking and its Potentials for Architecture Education at Design Studios,' *Journal of Fine Arts: Architecture & Urban Planning*, 24 1 (2019): 85-100.

42. Sylvain De Bleeckere, and Sebastiaan Gerards. *Narrative Architecture: A Designer's Story*. Routledge, 2017.

43. Bryan Lawson, ibid.

ing and externalise their understanding of a situation. A narrative, however, is an inclusive structure that connects these stories into a coherent, open-ended, and practical problem. Within the narrative, new stories can be created by designers to move toward a solution. In this way, a hierarchical relationship in the analysis of the design process is created, with narratives at the highest level and stories being connected to them. The narrative becomes the structural unit for describing frames that bring together scattered stories into a coherent and meaningful structure. Now, by distinguishing between stories and narratives, a direct boundary can be drawn between the proposed narrative model and the theory of reflective practice[71]. If the steps involved in reflective practice were to be formulated by Valkenburg and Dorst as follows: 1) naming relevant factors in the situation, 2) framing a problem in a specific way, 3) moving toward a solution, and 4) evaluating moves, based on existing studies, these stages in reflective practice can be reinterpreted as follows (Figure 5):

1) Naming: The interpretation of the situation through story construction.

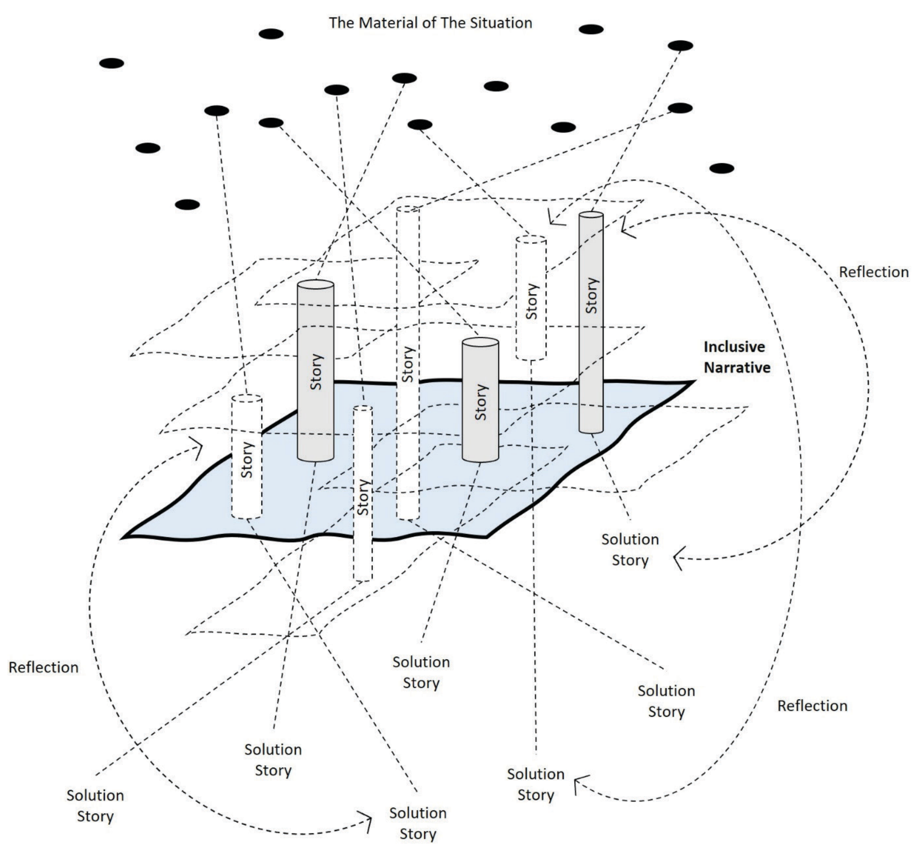
2) Framing: The creation of an inclusive narrative frame based on these stories.

3) Moving: The creation of stories to imagine solutions within these narrative frames.

4) Reflection: Present in all stages of the design process, as designers are constantly engaged in thinking about the stories and narratives they create. It is important to note that the relationship between story and narrative is a two-way street. While narratives provide structure to stories, they also act as a magnet for new stories that can reinforce or challenge them. New moves will respond to the narrative by reinforcing or challenging it, and designers are seen to be constantly moving between narratives to create new stories or refine existing ones.

Narratives are constructed by designers around stories, which in turn enable the imagining of new situations. They are considered frames that guide a designer's inquiry for new stories and structure their understanding of existing stories. New stories can be attached to a narrative, and existing stories can be detached without disrupting their core structure. From

Figure 5. A conceptual model of the adaptation of the narrative approach to framing and reflective practice by Donald Schön. Drawing: authors, adapted from Rianne Valkenburg and Kees Dorst, 'The Reflective Practice of Design Teams'; Babak Soleimani, 'Design Frames: A Narrative and Network Approach'.



this perspective, design can be analysed as constructive narratives that encompass stories and create inclusive themes throughout the design process.

While a comprehensive examination of narrative frames in the design process and the subtleties of the process itself would require a larger text, a brief excerpt from an interview with an architectural practitioner or an architecture professor can illuminate the current discussion. An architectural practitioner says:

> ...In my experience, anyone can prepare a brief of some kind, but for us, it has often been text. Of course, before the text, there is this talk and conversation about the design; it is as if we are turning the fruit of those talks into text. Because it is in a way the easiest way to exchange and there is the possibility of alignment and agreement on it. We write something and there are words that work. For example, we had a project around Darakeh, for a family who wanted parents and children to each have a unit and of course have a communal life together. Well, we kept thinking about different plans and sectional modes... Somewhere along conversations and meetings, we came up with the word 'house-in-house'. You know, it was like something that they suddenly showed a lot of interest in and it also included our design and idea. The work actually took shape there in a way. It was like it created a basic diagram by itself...[72]

In this example, it can be seen that the design team initially seeks to understand the situation and name its elements in order to reach a common understanding with the client (stage 1). At some point, by putting together different stories, a narrative of the design (house-in-house) is arrived at, and that becomes the frame through which most of the design issues are organised (stage 2). The continuation of the process is actually a series of steps and back-and-forths about the quality and how that narrative frame is made possible (stage 3). If, through reflections during and after, one of the important points of the design was raised at that moment or in the future that could not be answered appropriately within the framework of this general narrative, the frame would break or change shape (stage 4) so that it could also cover that new issue. In another verbal interview, an architecture professor says in a section about how the design was organised through the lens of the frame:

> ... It was a narrow plot of land with three open sides and a tall building behind it. I turned two sets of stairs and lifts and toilets and so on (all of which were supposed to be about two and a half metres wide) into a solid box at the end of the plot and opened the rest to the sides, the whole project was just the floor and then the outer volume also rose a little from the sides. One end turned out to be bulky with the rest being transparent; then I also turned that into a structural element like a chunky wall. It actually became dense both functionally and structurally. But the reality is that when I was looked at this plot of land and the wide view it offered, I wanted to have a rear and three open sides, so I shoved everything to one side, apparently for service elements, namely toilets and stairs, but in reality, I wanted to do this. Those needs could have been met in some other way. Framing per-

44. Nick Kelly and John S. Gero. 'Reviewing the Concept of Design Frames towards a Cognitive Model.' *Design Science* 8 (2022): e30.

45. Farhad Shariatrad and Hamid Nadimi, ibid.

46. Kees Dorst. *Frame Innovation: Create New Thinking by Design*. MIT press, (2015).

47. Jonathan H.G. Hey. *Effective Framing in Design*. University of California, Berkeley, 2008; Andy Dong, et al. 'Investigating Design Cognition in the Construction and Enactment of Team Mental Models.' *Design Studies* 34, No. 1 (2013): 1-33; Mithra Zahedi and Lorna Heaton. 'A Model of Framing in Design Teams.' *Design and Technology Education* 22, No. 2 (2017): n2.

48. Nick Kelly and John S. Gero, ibid.

49. Donald A. Norman and Roberto Verganti. 'Incremental and Radical Innovation: Design Research Vs. Technology and Meaning Change.' *Design Issues*30, No. 1 (2014): 78-96; Kees Dorst, 'The core of 'design thinking 'and its application.' *Design Studies* 32, No. 6 (2011): 521-532.

50. Donald A. Schön, ibid.

haps means processing the problem in a way that fits with the end result that we want, meaning that we probably solve the project from the beginning to the end... We look into the distance, we have seen something, and at the end of the work, we process the problem in a way that is consistent with what we saw at the end of the work. It seems that there is something from the future in framing...[73].

Due to their natural going back and forth during the design process, reflections (stage 4), seem to deal with time in a non-linear manner. Perhaps, in line with what was stated in the above interview, reflections on the design cause the framing to be drawn in a way that is consistent with a desired solution for the future. This kind of temporal view of the narrative is also evident in part of another interview conducted with an architectural practitioner. He says:

... I think sometimes during the design process a narrative pushes through, which is not yet in the current frame but can cause the frame to collapse. Sometimes the designer's description of the design process has changed and this has produced different forms of framing. I think narratives, in this sense, give us the ability to play between frames and kind of bridge them...[74].

Conclusion

As the boundaries between design disciplines blur, there is a growing need to understand the cognitive structures that enable designers to work effectively on complex problems. Despite the relatively short history of studying designers' strategies for approaching problems, significant efforts have been made to better understand the mental mechanisms at play. Following criticisms of the rationalist approach to design, constructivism has offered a more realistic view of design activity. This perspective shifts the focus from merely solving a problem to a deeper engagement with the design situation, where the goal is to give it some kind of coherence and

51. Jon Kolko, *Wicked Problems: Problems Worth Solving*. Austin Centre for Design: Ac4d, (2012).

52. Rianne Valkenburg and Kees Dorst. 'The Reflective Practice of Design Teams.' *Design Studies* 19, No. 3 (1998): 249-271.

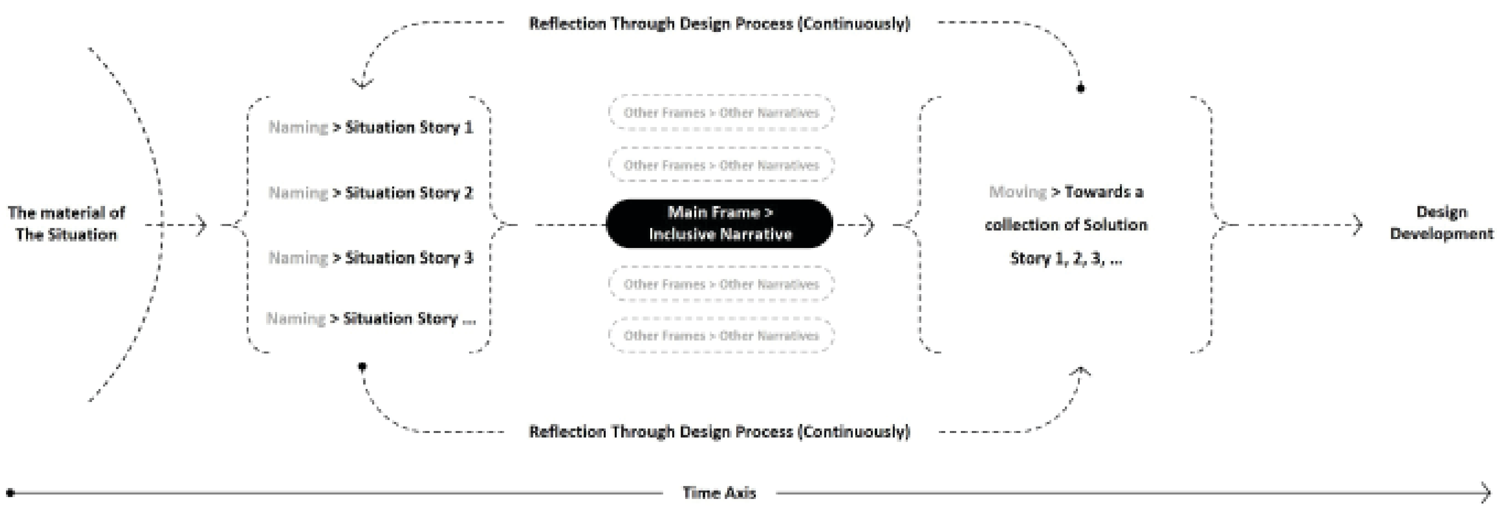


Figure 6. A conceptual model of comparing design framing and its reinterpretation based on the narrative approach, drawing: authors.

structure. This constructivist view leads directly to the framing process: a subject of research to investigate its working mechanisms. The present study aimed to clarify what occurs during framing and design talks by utilising concepts from existing research to provide a theoretical basis for analysing frames. The focus is on their transformation and refinement as a narrative-oriented and storytelling activity (Figure 6). This structure, which is organised on a time spectrum from left to right, illustrates the designer's process. In the initial encounter with the material of a design situation, a reflective conversation (stage 0) is initiated. Through this dialogue, the designer attempts to bring coherence to stories by naming them, thus creating relationships between the design forces. This is done, first, for self-understanding (correct and appropriate perception), and then, to make others understand (stage 1). All these stories can be told when placed in a broader and more comprehensive context called the design narrative (stage 2). At the heart of this narrative, moves are made to advance the design in line with the stories (stage 3). These moves are constantly reflected upon throughout the process. Through this reflection, parts of a story can be deleted or edited, or a new story can be added (stage 4). This stage, due to its cyclical nature, has a two-way direction. With each reflection on the moves, the potential exists for the frame structure to change, in part or in whole, leading to the establishment of a new narrative. The process continues until the design is felt to have reached its most appropriate response for managing the design situation. In this way, such a structure is always accompanied by relative flexibility and is ready to change the story relationships and, consequently, the shape of the overall narrative. The design process continues until the designers and other forces involved in the design create the most appropriate narrative to organise the design issues. After this stage, based on the passage of time, the direction of time moves toward the future in a one-way manner, as the design structure has now gained relative consistency. The continuation of the process is then aimed at implementing the inclusive narrative and design development. It is in this development stage that a reference to and adherence to the inclusive narrative helps to maintain the overall coherence of the design in future decisions.

The aim of this research was to provide a new perspective for educators, students, and practitioners in architecture on the perception of their own and others' framings, thereby enriching reflections on the design process. The continuation of research in this field could be achieved by conducting a series of studies and experiments based on the proposed structure. These studies could be carried out within the context of design workshops, involving both educators and students, as well as design teams in the profession. The research could be facilitated through the utilisation of methods such as observation, interviews, recording, and content analysis, along with the coding of various audio and written narratives. Furthermore, a discussion of the different methods and techniques inherent in each could be undertaken.

53. Within this framework, each episode is conceptualised as a segment in which a specific activity transpires. A system of coding has been established for these activities, where, for instance, a group›s explicit consideration of a task component (problem statement) is coded as naming. In the case of framing, an activity that influences and provides a template for subsequent activities is coded. Because the frame can predetermine these subsequent activities, it has been conceptualised by Valkenburg and Dorst as a container within which other activities may occur.

54. Norbert FM Roozenburg and Kees Dorst. 'Describing Design as A Reflective Practice: Observations on Schön's Theory of Practice.' In *Designers: The Key to Successful Product Development*, pp. 29-41. London: Springer London, (1998).

55. Frithjof E. Wegener and Philip Cash, ibid.

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65. Bryan Lawson, *How Designers Think (4th ed.)*. Routledge, (2005).

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73. The authors› verbal interview with an architecture professor, August (2024).

74. The authors› verbal interview with an architectural practitioner, September (2024).

A Conceptual Model of the Architectural Design Process Focusing on Geometric Knowledge within Design Thinking

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ORIGINAL RESEARCH ARTICLE

Naseri, Hosein, Mehdi Mahmoudi kamelabad, and Enrico De Angelis. 2026. "A Conceptual Model of the Architectural Design Process Focusing on Geometric Knowledge within Design Thinking". *Soffeh* 36, no. 2 (2026): 65–82. DOI: http://doi.org/10.48308/soffeh.2026.242519.1473

Received: November 16, 2025
Revised: January 01, 2026
Accepted: February 04, 2026
(Pages: 65–82)

Abstract

Background and Objectives: Geometry in architectural design has often been approached primarily as a formal and technical instrument for generating spatial configurations. However, its deeper cognitive, epistemological, and conceptual dimensions within the architectural design process have received comparatively limited attention. This study aims to investigate the role of geometric khnowledge in architectural design thinking and to formulate a conceptual framework that explains how this generative system contributes to the understanding, organisation, transformation, and realisation of architectural ideas. The research seeks to clarify spatial logic not merely as a representational tool, but as a foundational language embedded in the logic of design phases.

Materials and Methods: This research adopted a qualitative methodology based on the Grounded Theory Method (GTM). Data were collected through semi-

Keywords:
Architectural Design, Geometric Knowledge, Grounded Theory, Conceptual Model, Design Thinking.

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http://doi.org/10.48308/soffeh.2026.242519.1473

Research Questions:

1. How does the architectural design process operate with a focus on geometric knowledge within design thinking?

2. What is the role of geometry in guiding design decisions throughout this process?

structured interviews with 20 prominent architects and university professors specialising in architecture and design studies. The collected data were analysed using ATLAS. ti software through three stages of coding: open coding, axial coding, and selective coding. This analytical process enabled the identification of key concepts, categories, and interrelationships, ultimately leading to the development of a conceptual model explaining the function of these structural principles in architectural design processes.

Results and Conclusion: The findings demonstrate that spatial configuration beyond its conventional role as a form-generating tool and functions as a language for perception, cognition, organisation, and realisation in architecture. The study identified several influential dimensions shaping the role of geometry, including cultural-historical, philosophical-epistemological, aesthetic, educational-professional, and environmental factors. Based on the analysis, a five-stage geometric model was developed, consisting of geometric cognition, geometric perception, geometric organisation, geometric transformation, and geometric realisation. This model conceptualises architectural design as an iterative and evolutionary process through this spatial logic evolves from mental abstraction into spatial manifestation.

The proposed framework positions it as a structural foundation integrating conceptual, functional, and spatial aspects of design. Furthermore, the model synthesises major architectural design theories—including design thinking, Lawson's three-stage model, and Alexander's pattern-based approach—within a coherent geometric logic. The study contributes a novel theoretical perspective on architectural design as a process of geometric transformation and provides a practical framework applicable to architectural education, geometry-based digital design tools, and contemporary architectural practice.

1. Introduction

The architectural design process comprises a complex set of mental, cognitive, cultural and technical interactions.

1. A. Khiabanyan, *Creativity in the Architectural Design Process* (Tabriz: Mehr-e Iman Publications, 2009), 50; H. Beyti et al., 'The Participatory Role of Users in the Design Process of Residential Spaces,' *Spatial Planning*, no. 1 (June 2023): 117–138; S. Rezaei Ashtiani, 'Explaining the Research-Oriented Design Process Model in Architectural Design Studios' (Shahid Rajaee University, Tehran, 2020), 20; G. Rahimi, 'The Concept of Body in Avicennian Physics,' *Journal of Avicennian Wisdom*, no. 44 (Autumn & Winter 2010): 176; M. Hadian and H. Pourmand, 'Design Concept in Architecture: A Necessity in the Design Process and the Challenges of Its Education in Schools of Architecture,' *Biannual Journal of Applied Arts*, no. 4 (September 2014): 75; A. NooriMokaram et al., 'Investigating the Components of Concept Formation in Architectural Design Education with a Background-Oriented Approach,' *Bagh-e Nazar*, no. 120 (June 2023): 31; N. Cross, *Designerly Ways of Knowing* (London: Springer-Verlag, 2007); D. Schön, *The Reflective Practitioner: How Professionals*

It begins when an architect decides to create a work and continues until the design is ready for implementation. This process constitutes the core essence of architectural practice and distinguishes the nature of architecture from other fields of art and engineering. Numerous scholars have defined this path as the design process and have identified specific stages for it, including problem identification, idea formation, evaluation, and the realisation of the design,[1] Since the nature of architecture is fundamentally intertwined with design, architectural theories are also directly or indirectly engaged with design knowledge and its processes. However, due to the distinctive nature of architecture and its particular modes of thinking and expression, theories of architectural design have continually been subjects of discussion and reconsideration.[2] In recent decades, alongside social, economic, and philosophical transformations, design theories have increasingly focused on the cognitive dimensions of design, including perception, mental activities, and the designer's way of thinking[3].

Among these discussions, one of the areas that has received less systematic attention in relation to the process is the position of geometric knowledge.[4] Although geometry has always been present in architecture as a tool for drawing, spatial organisation, and form generation, in many prevailing models of the design process its role has largely been limited to the level of a tool or a language of form, while its cognitive dimensions have been less thoroughly explained[5]. This condition, both in theoretical models and in architectural education systems, has led to geometric thinking being given less conscious attention as one of the fundamental bases of design thinking[6]. Conversely, research in design cognition indicates that the use of various modes of thinking, including visual, analogical, and geometric thinking, can contribute to improving the quality of the design process.[7] Moreover, technological developments in recent decades, along with the emergence of digital, algorithmic, and parametric tools, have transformed the role and nature of geometry in architectural design. Nevertheless, many design process models still fail to provide a clear framework for analysing these transformations and explaining the role of complex and computational geometry in design thinking. In response to this theoretical gap, this article examines how geometric knowledge operates within architectural design thinking, proposing a conceptual framework to clarify its role throughout the design process.

Research Questions:

This study seeks to answer the following questions:

1. How does the architectural design process operate with a focus on geometric knowledge within design thinking?
2. What is the role of geometry in guiding design decisions throughout this process?

2. Research Objectives

The article aims to formulate a conceptual framework for comprehending the architectural design process, paying particular attention to the evolutionary role of geometric knowledge across the successive stages of design thinking.

3. Research Methodology

This qualitative study employs a systematic

Think in Action (New York: Basic Books, 1983); B. Lawson, *How Designers Think: The Design Process Demystified*, 4th ed. (Oxford: Architectural Press, 2005).

2. H. Rezaei et al., 'A Psychological Meta-analysis of the Relationship Between Form and Function in the Architectural Design Process from the Perspective of Creativity,' *Innovation and Creativity in Human Sciences*, no. 2 (Autumn 2018): 266.

3. K. Mardomi and M. Dehghani Tafti, 'Presenting an Applied Model of the Architectural Design Process Based on Islamic Ontology,' *Islamic Architecture Research*, no. 16 (Autumn 2017): 105, A. Mahmoudi, 'Thinking in Design: Introducing the Interactive Thinking Model in Design Education,' *Fine Arts Journal*, no. 20 (January 2005) , J. Anderson, *Cognitive Psychology and Its Implications* (New York: Macmillan, 1995).

4. R. Oxman, 'Theory and Design in the First Digital Age,' *Design Studies*, 3 (2006): 229–265.

5. H. Pottmann et al., *Architectural Geometry* (Bentley Institute Press, 2007).

Grounded Theory Method (GTM), predicated on the Strauss and Corbin model, to formulate a conceptual framework for architectural design. Data were garnered via semi-structured interviews with 20 to 30 purposively selected experts, complemented by an extensive review of scholarly literature, continuing until theoretical saturation was unequivocally achieved.

Concurrently with data collection and upon attaining theoretical saturation, the data were subjected to a tripartite coding process: open, axial, and selective coding. This analytical procedure was executed utilising ATLAS.ti software to guarantee both the precision and comprehensiveness of the analysis. Following the development of the conceptual (paradigmatic) model, its validity was rigorously evaluated through qualitative methods—encompassing theoretical saturation, expert review and corroboration,[8] and comparative analysis with extant literature—to ascertain the model's robustness and reliability Figure 2.

To guarantee reliability and validity, this research employed participant validation, peer review, and expert evaluation. Credibility was established through iterative cross-checking and constant comparative analysis, thereby ensuring intersubjective consistency across all categories. Furthermore, findings derived from observations and document analyses were triangulated with participant feedback to corroborate content validity.[9]

Consequently, the study rigorously implemented all validation protocols, including interviewee verification of categories, expert appraisal of conceptual credibility, iterative data cycling, and constant comparison. These measures collectively facilitated theoretical saturation and model integration, thereby substantiating the model's overall validity and reliability.

4. Literature Review

Since the mid-twentieth century, the process has emerged as a pivotal theoretical discourse. Herbert Simon's seminal work, *The Sciences of the Artificial*, initially defined design as a decision-making and problem-solving activity, bridging extant and desired states via analytical reasoning; this inherently established the rational, linear model of design.[10] In direct response to this rationalist view, critics such as Christopher Alexander, in *Notes on the Synthesis of Form*, challenged these rationalist paradigms by accentuating the complex, interdependent nature of design variables. He posited that design amalgamates analysis and synthesis, guided by an apprehension of underlying structures rather than pure logic, thereby demonstrating how geometric and structural order bridge form and function.[11] In the 1980s, Donald Schön's theory of reflective practice conceptualised design as 'thinking-in-action', emphasising the designer's intuition, experiential knowledge, and reflec-

6. A. M. Salama and N. Wilkinson, *Design Studio Pedagogy: Horizons for the Future* (The Urban International Press, 2007).

7. G. Goldschmidt, 'The Dialectics of Sketching,' *Creativity Research Journal*, 2 (1991): 123–143.

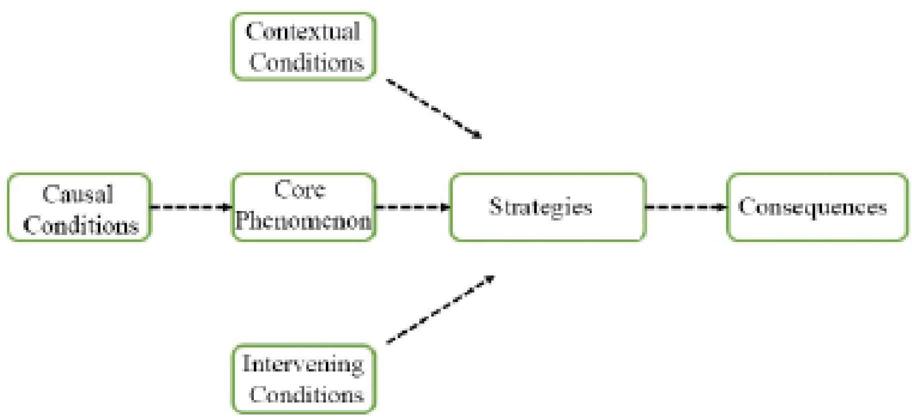


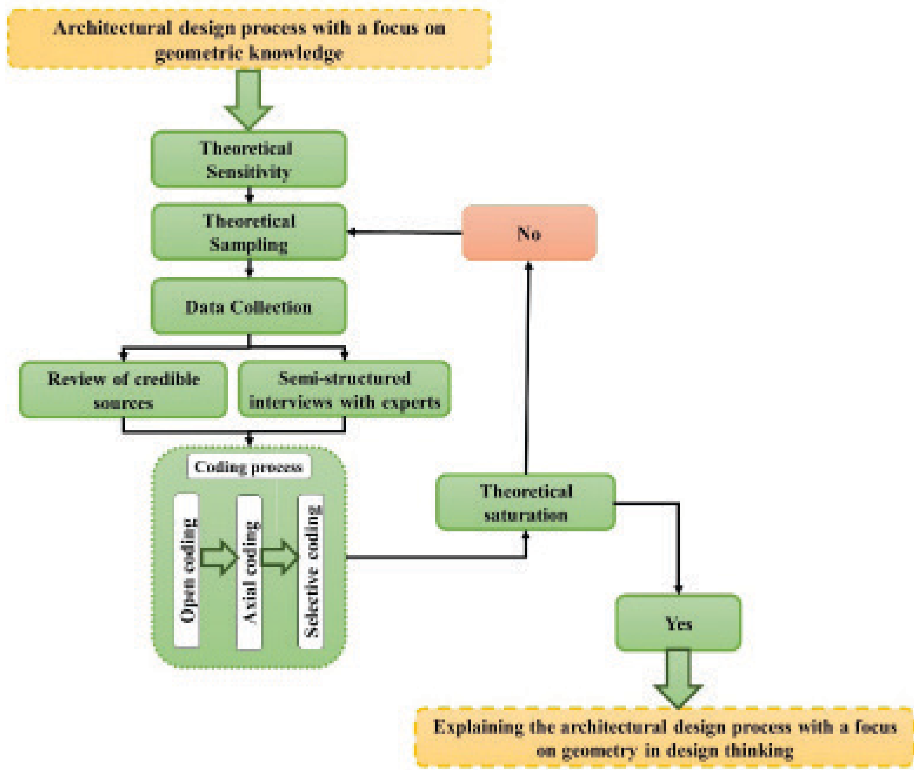
Figure 1. Strauss and Corbin Model. Source: Maqsood Fereydoun Farasatkhah, *Qualitative Research Methods in Social Sciences with Emphasis on Grounded Theory* (Tehran: Farhangban Publications, 2019), 101.

tion in ideation, alongside the critical role of the creative cognitive process.[12] From the 1990s onwards, design cognition theories like Dorst and Cross's Function–Behaviour–Structure (FBS) framework conceptualised design as a complex system of interactions. This model, evolving through designer-mental model feedback, was an early framework to explain design logic through complex systems rather than purely intuitive descriptions.[13]

Furthermore,the co-evolutionary model postulates design as the concurrent evolution of problem and solution, where the designer actively redefines the problem throughout the process. This perspective illuminates the dynamics of design in complex contexts.[14] In a parallel development focused on process stages, the UK Design Council's Double Diamond model delineates a four-stage process: Discover, Define, Develop, and Deliver. By emphasising iterative and cyclical oscillations between divergent and convergent thinking, it establishes the foundation for numerous contemporary design methodologies.[15]

A distinct but related shift concerns geometry's role. Generative geometry, coalescing with the advent of digital technologies, conceptualises geometry not merely as a representational tool but as an active medium for generative, creative cognition. This approach enables the creation of complex structures and new design possibilities[16]. Nevertheless, despite geometry's historical presence in architecture, much of the design literature has treated it reductively, primarily as a tool for formal expression rather than a more integral element of the design process. Turning to regional contexts, studies concerning Iranian architecture reveal geometry's dualistic role, signifying both aesthetic harmony and cosmic/ontological unity within traditional paradigms. Although recent scholarship explores the integration of these principles via digital methodologies, a systematic, geometry-centric framework for the design workflow remains conspicuously absent.

As a result of these gaps,existing literature, by focusing narrowly on either the formal/geometric aspects of form or cognitive design processes, has under-examined geometry's structural role. This research gap prompts the question: How can geometry serve as a framework for thinking, organising, and realising design? To address this question directly,this



8. Strauss and Corbin Model, Source: Maqsood Fereydoun Farasatkhah, *Qualitative Research Methods in Social Sciences with Emphasis on Grounded Theory* (Tehran: Farhangban Publications, 2019), 101.

Figure 2. Research Process Diagram, Source:authors.

study employs grounded theory to investigate this creative sequence through the lens of geometry's role.

5. Theoretical Framework

5.1. Models of the Architectural Design Process

This process is inherently complex, seamlessly blending analytical reasoning with creative intuition. Historically, various models have been formulated by theorists and practitioners to encapsulate the diverse facets of this multidimensional activity.[17] Design models function as conceptual frameworks that organise design stages, decision-making protocols, ideation, and evaluation. Their structural typologies vary contingent upon project scope, designer objectives, user engagement, and intrinsic complexity. Models founded upon the analysis–synthesis–evaluation triad, originating from rationalist paradigms, remain foundational within architectural planning literature.[18] Conversely, methodologies such as design thinking and concept testing prioritise creative, open-ended, iterative, and user-centric processes.[19] These iterative frameworks are particularly efficacious for complex projects with heterogeneous requirements, facilitating continuous conceptual refinement. In parallel, systems-based and Building Information Modelling (BIM) approaches mitigate the technical and data-driven complexities of contemporary design, emphasising interdisciplinary coordination across sectors such as energy, building services, construction, and lifecycle maintenance.[20]

Participatory and human-centred models, exemplarily embodied in Christopher Alexander's *A Pattern Language*, foster unmediated interaction between architects and users. They conceptualise design as a collaborative synthesis of dialogue, spatial experience, and the comprehension of human environments. Systematically categorising these models empowers architects to select the optimal methodological approach and rigorously guide the design trajectory.[21] Consequently, to analyse and formulate the final model, extant architectural design paradigms were classified into five primary categories predicated on their methodological approaches Table 1. This taxonomy facilitates pattern identification, perspective differentiation, and the recognition of critical gaps regarding geometric application.

Architectural design process models vary in their approach to complexity. Linear and cyclical models focus on stage sequence or iteration, respectively. Concept-test and problem-solving models emphasise continuous evaluation. Functional, systems-based, and analysis-synthesis-evaluation models offer a structural, logic-based view, while creative, participatory, and analogical models highlight intuitive, collective, and adaptive aspects of design.

Various architectural design process models presented in the literature have each sought to explain the complexity and multidimensional nature of this process and to analyse it from different perspectives. Linear and cyclical models emphasise either the sequence of stages or the iterative nature of the design process, respectively, whereas concept–test and problem-solving models focus on the continuous evaluation of concepts and solutions. Furthermore, functional, systems-based, and analysis–synthesis–evaluation models adopt a structural and logic-based perspective on the design process, while

9. M. Farasatkhah, *Qualitative Research Methods in Social Sciences with Emphasis on Grounded Theory* (Tehran: Farhangban Publications, 2019), 158.

10. H. Simon, *The Sciences of the Artificial* (Cambridge, MA: MIT Press, 1969)

11. Ch. Alexander, *Notes on the Synthesis of Form*. (Cambridge, MA: Harvard University Press, 1964).

12. D. Schön, *The Reflective Practitioner: How Professionals Think in Action*, (New York: Basic Books, 1983).

13. J.S. Gero and U.Kannengiesser, 'The Situated Function–Behaviour–Structure Framework', *Design Studies* 25 (2004): 373–391.

14. K.Dorst, and Nigel Cross, 'Creativity in the Design Process: Co-evolution of Problem–Solution', *Design Studies* 5 (2001): 425–437.

15. Design Council, *The Double Diamond: A Universally Accepted Model of the Design Process*, (London: Design Council, 2005)

creative, participatory, and analogical models emphasise the intuitive, collective, and adaptive dimensions of design.

A notable limitation of contemporary architectural design models is their disproportionate focus on the sequential 'how' and the procedural 'stages' of design activity, often obfuscating the specific epistemological bodies of knowledge employed. Consequently, the operational role of geometric knowledge remains largely implicit, rarely articulated as a discrete cognitive or structural mechanism. Therefore, the present study does not seek to critique or invalidate these existing models; rather, it aims to reinterpret and re-evaluate their latent capacity for elucidating the role of geometric knowledge within design thinking. In this vein, the research investigates how the cognitive and organisational dimensions of geometry facilitate process analysis, shape ideation, configure spatial layouts, and establish profound dialectics between form, function, and meaning.

5.2. Conceptualisation of Geometry in This Study

In this research, geometric knowledge is understood as a body of knowledge concerned with the quantitative and qualitative relationships of form, space, and order, through which the structure, proportions, organising patterns, and spatial logic of architecture can be analysed and designed. This knowledge can be examined from several perspectives. Proceeding to the first perspective, spatial ordering system may be understood as the science of measurement and proportion, employed in scaling and defining dimensional relationships, and manifested in both traditional and classical architecture through concepts such as the golden ratio and modular systems. Second, and complementarily, configurational logic functions as a language of order and structure, serving as an organising logic in plans, volumes, and façades, and establishing internal relationships among components within an integrated design system. Third, shifting from structure to process, formal language operates as a tool for design thinking, shaping ideas and translating concepts into form, thereby enabling a cognitive and conceptual understanding of the design process. Fourth, extending into the cultural realm, morphological framework can be regarded as a cultural and semantic language that, particularly in Islamic and Iranian architectural traditions, embodies meaning and symbolises unity, symmetry, and cosmic order. Synthesising these four perspectives, in this study, proportional system is not considered merely as a tool for measurement or formal ordering, but rather as a multidimensional design language and a framework for organising space, shaping form, and analysing the cultural and cognitive dimensions of the design process.

6. Discussion and Analysis

Employing a Grounded Theory Method (GTM), this study aimed to construct an independent conceptual framework derived empirically from field data. To ensure the acquisition of valid and comprehensive insights, semi-structured interviews were conducted with architectural academicians and practitioners. These dialogues captured expert perspectives and practical heuristics germane to the research inquiry. Complementary data were garnered via a systematic review of relevant archival documents

16. I.G. Dino, 'Creative Design Exploration by Parametric Generative Systems in Architecture', *ODTÜ MimarlıkFakültesi*, 1 (2012): 207-224; S, Nasiri, and Ali Reza Sarvdalir, 'Geometrical Origin of Generative Shape Grammars for Islamic Tectonics', *Nexus Network Journal*, 1 (2023): 177-195.

17. B. Lawson, *How Designers Think: The Design Process*,(Oxford: Architectural Press, 2006); N. Cross. *Research in Design Thinking*. (Delft: Delft University of Technology, 2006)

18. W. Peña, and S. Parshall, *Problem Seeking: An Architectural Programming Primer*,(New York: Wiley, 2001).

19. V. Kumar, *101 Design Methods: A Structured Approach for Driving Innovation in Your Organisation*, (Hoboken, NJ: Wiley, 2013); N. Cross,*Design Thinking: Understanding How Designers Think and Work*, (Oxford: Berg Publishers, 2011).

and specialised literature, substantially enriching the analytical depth. This methodological triangulation facilitated a multidimensional, evidence-based approach to qualitative data analysis, ultimately culminating in the extraction of a robust conceptual model. Following data saturation, qualitative analysis was executed employing the tripartite coding protocol (open, axial, and selective coding) intrinsic to systematic GTM. This analytical rigour was designed to transparently map the logical linkages between raw data, emergent concepts, and core categories, thereby ensuring the study's replicability.

Commencing with the open coding phase, raw textual data from transcripts and documents were disaggregated into discrete units of meaning. Initial codes were subsequently assigned to each segment predicated on its

Approach	Model	Description	Gap related to geometry
Classical–Structural	Linear Model	It views design as a continuous linear sequence of stages including analysis, concept generation, design, and implementation. This model is highly simple but offers limited flexibility.[22]	Geometry is implicitly present, primarily at the level of a tool for drawing and organising design outputs; its role as a cognitive mechanism within the design process is not explicitly articulated.
	Analysis-Synthesis-Evaluation	A logical and linear process consisting of initial data analysis, followed by synthesis to generate solutions, and finally evaluation of design outcomes. It has served as a foundational model for architectural design education in many schools of architecture.[23]	
Iterative and evaluation-oriented	Cyclical or iterative model	Design proceeds through cycles of ideation, testing, feedback, and refinement. In this model, the designer can repeatedly return to earlier stages and make revisions. It is particularly suitable for complex and creative projects[24].	The focus is on feedback and the refinement of ideas; however, the role of geometry in shaping spatial logic and guiding design thinking is not systematically articulated.
	Concept-test Model	A process of evaluating and testing design ideas prior to full development. Each concept is assessed against criteria such as performance, aesthetics, sustainability, cost, and user satisfaction.[25]	
User-centred and participatory	Design Thinking Model	Derived from innovative and user-centred approaches, it includes the stages of empathy, problem definition, ideation, prototyping, and testing. It is widely used in contemporary architecture and social design.[26]	The main focus is on user needs and participation; however, geometry has not been conceptualised as a structuring language of space or as a cognitive tool in the design process.
	Participatory Model	End users are actively involved in the design process. This approach is suitable for projects such as schools, residential housing, and urban spaces. It employs tools such as design workshops, interviews, voting, and collaborative model-making.[27]	

Table 1. Architectural Design Process Models, Source: authors.

20. D.W. Orr, *The Nature of Design: Ecology, Culture, and Human Intention*. (Oxford: Oxford University Press, 2002);American Institute of Architects (AIA),*The Framework for Design Excellence*. (Washington, DC: American Institute of Architects, 2022).

21. B. Lawson, *How Designers Think: The Design Process*,(Oxford: Architectural Press, 2006).

22. American Institute of Architects (AIA),*The Framework for Design Excellence*. (Washington, DC: American Institute of Architects, 2022).

23. Ibid

24. N. Cross,*Design Thinking: Understanding How Designers Think and Work*, (Oxford: Berg Publishers, 2011).

25. V. Kumar, *101 Design Methods: A Structured Approach for Driving Innovation in Your Organisation*, (Hoboken, NJ: Wiley, 2013); N. Cross, *Design Thinking: Understanding How Designers Think and Work*, (Oxford: Berg Publishers, 2011).

thematic substance, yielding an initial corpus of 420 preliminary codes were synthesised into cohesive conceptual clusters, each encapsulating a specific dimension of the geometry-design nexus. Proceeding to the axial coding stage,similar and related codes derived from open coding were grouped and organised into conceptual categories. This process involved identifying relationships among concepts, clustering codes based on semantic similarity, and determining core axes for each group. At this stage, the 420 initial codes were transformed into coherent conceptual clusters, each representing a specific dimension of the architectural

Approach	Model	Description	Gap related to geometry
Analytical and systems-based	Problem-Solving Model	It conceives architecture as a process of solving a specific problem. It emphasises the stages of problem definition, option generation, analysis, and selection of the best solution.[28]	Geometry is mainly addressed at the level of functional and spatial organisation; its role in conceptual decision-making and cognitive aspects of design is not explicitly articulated.
	Functional Model	It is based on the analysis of spatial functions and the relationships between them. The focus is on spatial performance, spatial relationships, circulation, and detailed functional programming.[29]	
	systems-based models	It views the project as a complex system composed of various components (users, environment, function, energy, climate, etc.). It emphasises the relationships between these components. It is suitable for large-scale and interdisciplinary projects.[30]	
Technological /digital	BIM-Based	It is based on Building Information Modelling (BIM). The design process takes place in a coordinated digital environment involving the architect, structural engineers, MEP engineers, and the client.[31]	Geometry is employed at a computational and operational level; its relationship with cognitive processes and design thinking has not been theoretically articulated.
	Generative Model	It involves the use of rules, algorithms, and data to generate adjustable and flexible forms. It is commonly applied in contemporary digital architecture (rule-based methods, evolutionary algorithms, and deep generative methods).[32]	
Intuitive/Creative	Intuitive/Creative Model	It emphasises intuition, creativity, and the designer's personal mindset. It is typically used in conceptual or artistic projects and employs tools such as freehand sketching, conceptual writing, and experimental models.[33]	The use of geometry is dependent on the designer's intuition and individual style; no systematic framework is provided for the guiding role of geometry in the design process.

Table 1 (continued). Architectural Design Process Models, Source: authors.

26. Ibid

27. Wacnik, P., Shanna R. D., & Aditi, V. 'Participatory design: a systematic review and insights for future practice.' Design Science 11 (2025): e21

28. N. Cross,*Design Thinking: Understanding How Designers Think and Work*, (Oxford: Berg Publishers, 2011).

29. W. Peña, and S. Parshall, *Problem Seeking: An Architectural Programming Primer*, (New York: Wiley, 2001).

30. D.W. Orr, *The Nature of Design: Ecology, Culture, and Human Intention*. (Oxford: Oxford University Press, 2002)

31. American Institute of Architects (AIA),*The Framework for Design Excellence*. (Washington, DC: American Institute of Architects, 2022).

32. Jiang, F., Ma, J., Webster, C. J., Chiaradia, A. J., Zhou, Y., Zhao, Z., & Zhang, X. 'Generative urban design: A systematic review on problem formulation, design generation, and decision-making.' *Progress in Planning* 180 (2024): 100795.

design process and its relationship with geometric framework.

In the selective coding phase, the objective was to distil the study's core category and articulate its relational dynamics with peripheral categories. The analysis revealed the central phenomenon to be: *Geometry as a cognitive pattern, an ontological axis, and a mediating construct in the manifestation of architectural concepts*. Peripheral categories were subsequently integrated into the theoretical framework based on their interactional influence on this central axis, thereby formalising the research's final paradigmatic model. Ultimately, the emergent categories were structured within a quintuple paradigmatic model Table 2: contextual conditions (7 categories), intervening conditions (6 categories), causal conditions (8 categories), strategies (5 categories), and consequences (6 categories).

In this study, based on a grounded theory approach, geometry is not conceived merely as a representational or computational tool, but rather as a cognitive, ontological, and meaning-generating pattern within the architectural design process. The findings indicate that geometry operates in the architect's mind as a language of thought and a structuring mechanism for concepts, establishing a connection between reason and imagination, intuition and

33. Lawson, Bryan. How Designers Think: The Design Process Demystified. 4th ed. London: Architectural Press, 2006

Table 2. An Overview of the Components of the Model Derived from Grounded Theory. Source: Authors.

No.	Conceptual Range	Categories	Conceptual Model
1	Connection with Tradition - Oral Transmission of Patterns and Archetypes - Conscious Geometry in Traditional Architecture - Hierarchy of Traditional Design - Organic Fabric of the City and Geometric Buildings	Cultural–historical contexts	contextual conditions
2	Creation through Synthesis - Hierarchy of Imagination to Visualisation - Forming of Imagination - Order of Creation - Gradual Growth of Knowledge - Geometry as the Understanding of Creation - Interconnection of Mind and Heart in Design	Philosophical–epistemological contexts	
3	Culture-dependent Beauty - Intrinsic Beauty - Evolutionary Beauty - Contextual Beauty - Symbolic Beauty - Secularisation of Beauty and Historical Shift in Perspective	Aesthetic contexts	
4	Critical Education - Gradual Teaching of Geometry - Formation of Design Personality - Skill in Sketching Ideas - Western-based Education - Superficial Understanding of the Past by Contemporary Architects - Traditional Theoretical Education	Educational–professional contexts	
5	Duality of Logic/Emotion - Designer/Engineer Approach (Solution-oriented/Problem-oriented) - Inspiration and Concept - Unity and Personalisation in the Design Process - Logical Rationalism and Historical Rationality	Design epistemology and process contexts	
6	Dominance of Form over Content - Fusion of Form and Content - Approach to Nature - Unity and Multiplicity of Form - Crisis of Modern Aesthetics - Contradiction between Function and Form - Reduction of Form Complexity	Intellectual–discourse contexts in architecture	
7	Climate and Environmental Harmony - Compatibility with Function and Human Needs - Sustainability and Resource Efficiency	Environmental and functional contexts	

representation, as well as logic and creativity.

The resulting theoretical model is structured around seven main components. Contextual conditions include cultural, historical, philo-

Table 2 (continued). An Overview of the Components of the Model Derived from Grounded Theory. Source: Authors.

No.	Conceptual Range	Categories	Conceptual Model
8	Mental Organisation through Geometry - Geometric Language - Skill-Based Foundation of Design - Visualised Design Thinking	Geometry as a thinking tool	causal conditions
9	Initial and Causal Presence - Step-by-Step Design Guidance - Performance and Environmental Evaluation Criteria - Geometry in Creative and Critical Aspects of the Design Process - Objectifying the Designer's Mental Schemas	Geometry as the core of the design process	
10	Simultaneous Performance and Meaning through Geometry - Relationship between Form and Essence Based on Geometry - Order and Flow of Space Based on Geometry	Geometry as a medium for meaning	
11	Harmony with Nature - Readability of Form and Space - Meaning Transfer and Feasibility of Execution	Human experience based on geometry	
12	Reflection of the Laws of Creation - Creation of Spatial Harmony and Balance - Translation of Dimensions and Scales into Geometric Structure	Geometric logic of the world	
13	Poetic Moment of Concept Creation - Creation of New Forms - Creative Composition	Inspirational aspects of geometry	
14	Structural Support - Stability of Forms - Coordination of Structure and Form	Geometry and structure	
15	Alignment with Function - Human Scale - Optimised Planning	Geometry and spatial function	
16	Poeticism and the Poetics of Architecture - Meaning and Beauty - Emotional Intelligence and Self-Awareness of the Designer	Values and poetics	intervening conditions
17	Experience and Skill in Geometry - Self-awareness and Other-awareness of the Designer - Cognitive/Perceptual Capacity of the Designer - Mastery of Techniques in the Realm of Form	Designer's perception and skills	
18	Simultaneous Rationality and Intuition - Imagination and Creativity - Production of New Combinations - Mental and Skill Limitations	Creativity and imagination process	
19	Geometry as a Tool, Not a Trap - Regularity and Geometric Character - Conscious Use of Numbers and Parameters - Avoiding Incorrect and Inauthentic Compositions	Use of geometry and tools	
20	Impact of Knowledge and Education - Experience and Imagination Alongside Drawing and modelling - Interaction with Works and Places - Adaptation to Contemporary Culture and Lifestyle	Interaction with culture, experience, and place	
21	Controlled Geometry - Mismatch Between Mentality and Reality (Idea and Form) - Excessive Transparency and Reduced Artistic Impact	Constraints and risks	
22	Geometry as a cognitive framework, vital core, and mediator of concepts in the architectural design process		Phenomenon

sophical, aesthetic, educational, epistemological, intellectual, and environmental contexts that define the presence and role of geometry in design thinking and decision-making. Causal conditions consist of internal and cognitive drivers that lead to the centrality of geometry in design, including geometry as a tool of thinking, a core axis of the design process, a means of meaning expression, human experience, the logic of the world, inspiration, structure, and spatial functionality. In contrast, intervening conditions include values, skills, creativity, the

Table 2 (continued). An Overview of the Components of the Model Derived from Grounded Theory. Source: Authors.

No.	Conceptual Range	Categories	Conceptual Model
23	Inspiration from Forms and Patterns - Mimesis and Poiesis - Deductive, Inductive, and Abductive Thinking - Importance of Framing and Defining the Design Problem	Inspiration and idea generation	strategies
24	Sketching Practice and Rapid Idea Visualisation - Two-Dimensional and Three-Dimensional Thinking - Ability to Transform Concept into Reality - Digital Design Tools and Advanced Geometry	Drawing and modelling skills	
25	Geometry as a Medium and Design Tool - Combining Shapes Based on Their Intrinsic Characteristics - Aligning Geometry with Function, Human Scale, and Context - Analysing Site Geometry and Layout	Geometry-based design thinking	
26	Control of Mind and Imagination (The Wild Horse of the Mind) - Decision-Making Based on the Geometric Identity of Shapes - Conscious and Justified Use of Geometry - Awareness of the Difference Between Design Process and Design Method	Design process control and decision-making	
27	Gradual Teaching and Master/Apprentice Relationship - Observation and Analysis of Works by Various Architects - Practice of Shape Combination and Transformation - Mastery of Rules and Creative Ability While Maintaining Geometric Consistency	Education and skill development	
28	Outstanding Artistic Work Emerging from Geometric Skill - Sustainable and Beautiful Composition - Durability of the Work and Continuous Discovery - Visual Appeal and Impact - Optimisation of Design Performance - Design Based on a Logical, Conscious, and Creative Process - Stronger Defense and Documentation of the Design	Design quality and durability	consequences[14]
29	Geometry as the Basis for Constructability - Stable Geometric Composition - The Relationship Between Geometry and Structural and Environmental Goals - Alignment of Digital Geometry with Tools and Advanced Construction Technologies	Structural strength, stability, and feasibility	
30	Geometry as the Language of Meaning - Symbolism and Secondary Meaning - Geometry-based Aesthetics - Reference to Hidden and Visible Layers	Integration of beauty and meaning	
31	Unity of Form and Meaning - Manifestation of the Inner in the Outer - Multilayered Expression in the Work - Geometry as the Mediator of the Material and Spiritual	Relationship between appearance and essence	
32	Coordination of Elements Based on Geometry - Legibility, Clarity, and Comprehensibility of Forms for the Audience - Overall Cohesion of the Design	Geometric unity and order	
33	Connection with Functional Musts and Must-Not's - Enhancing the Architect's Imagination - Strengthening Spatial Awareness and the Ability to Manipulate Forms Mentally - Creativity in Geometric Composition - Geometry as an Organising Tool and Design Guide - Creating Dynamic and Unique Forms and Spaces - Strengthening Analytical, Systematic, and Logical Thinking	Enhancing spatial thinking, perception, creativity, and organised innovation in design	

use of tools, cultural and spatial interaction, and constraints, all of which may strengthen or weaken this process. Accordingly, design strategies represent the conscious actions of the architect that shape the realisation of geometry in practice, ranging from inspiration and ideation to drawing, modelling, process control, and skill development.

The application of these strategies yields outcomes such as quality, durability, structural integrity, sustainability, aesthetic and semantic integration, geometric coherence, and enhanced structured creativity and innovation. Central to this theory is geometry, viewed as a cognitive and ontological pattern within the architectural design process, elevating design from a purely technical to a conceptual and ontological level. Accordingly, the model demonstrates that geometry in architectural design is not only a tool for organising form and space, but also a mental framework for thinking, meaning-making, decision-making, and creation. This model transforms design into a rational, creative, systematic, and meaningful process in which geometry plays a central role in shaping the architect's design thinking Figure 3.

The conceptual model derived from the findings of grounded theory revealed a paradigmatic framework of the core phenomenon of the study, namely geometry in the architectural de-

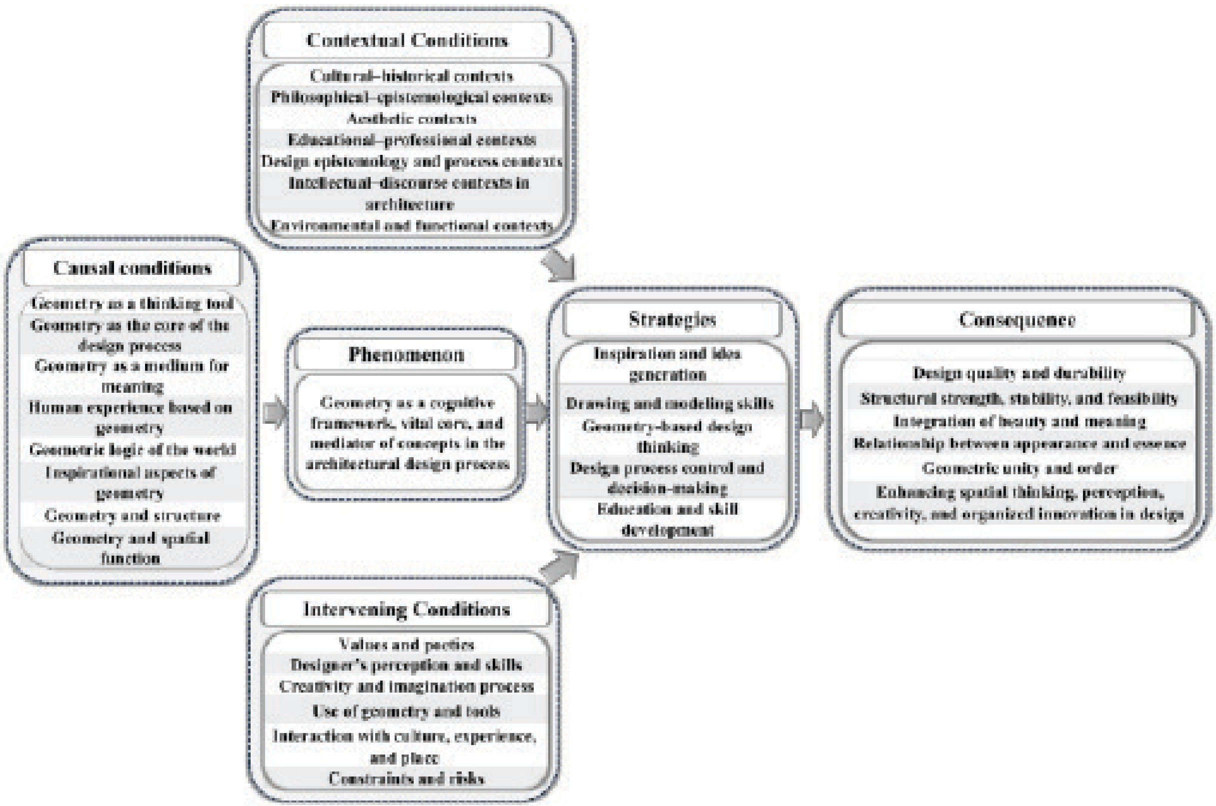


Figure 3. The conceptual model of geometry-centered architectural design based on the Strauss and Corbin paradigmatic framework. Source: Authors.

sign process. In this model, a set of contextual conditions, causal conditions, intervening factors, strategies, and consequences were identified, which, through their interaction, indicate that geometry is not merely a tool for form generation, but an epistemological and perceptual structure that is present throughout the entire design process and guides the designer's thinking. However, the paradigmatic model alone is not sufficient to explain the dynamics and continuous flow of geometric thinking within the design process.

Therefore, the dimensions of the grounded theory model were reorganised into a five-stage geometric model in order to clarify the process of formation and realisation of geometric thinking in architectural design. These stages include cognition, perception, organisation, transformation, and geometric realisation, reflecting the main dimensions of the paradigmatic model and illustrating the transition from theoretical understanding to design action. Accordingly, the design phases based on geometry is explained as a systematic and evolutionary movement from within to without; a movement that begins with cultural and cognitive foundations, continues through perceptual and mental organisation, is transformed into design action, and culminates in the material realisation of the architectural work. Within this evolutionary and recursive process, geometry acts as an intermediary language between the designer's mind and architectural reality, providing the foundation for the formation of meaning, structure, and creativity in design Table 3.

It is worth noting that in developing the

Five-Stage Geometry-Based Model	**Corresponding Categories from the Grounded Theory Conceptual Model**	**Description**
Geometric Cognition	Contextual Conditions	This stage focuses on the designer's intellectual and cultural foundations, where the understanding of the world and existence is shaped through geometry, and the theoretical principles of geometric design are established in the designer's mind.
Geometric Perception	Causal Conditions and Phenomenon	In this stage, geometry comes into play as a cognitive framework in the designer's mind, initiating the process of understanding, interpreting, and perceiving geometric structures in space and form.
Geometric Organisation	Intervening Conditions	In this stage, geometric perceptions are organised into a network of semantic and spatial relationships, allowing the designer to connect values, experiences, and skills.
Geometric Transformation	Strategies	At this step, geometric thinking is transformed into design action; ideas are materialised through geometry, and creativity takes shape within geometric order and logic.
Geometric Realisation	Consequences	The final outcome of the process is the emergence of the architectural work, where geometry unifies form and meaning, structure and concept, and mind and reality.

Table 3. A Five-Stage Conceptual Model, Source:authors.

proposed model of this study, three well-established design process frameworks—design thinking, Lawson's three-stage model, and Christopher Alexander's theoretical approach—were used as comparative theoretical foundations. It should be emphasised that these selected models are not considered complete frameworks in this research; rather, they are employed as interpretive structures with cognitive and structural capacity for re-examining the role of geometry in the process. Specifically,design thinking reflects a cognitive-exploratory and human-centred approach, Lawson's model highlights the analysis–synthesis–evaluation structure as the cognitive core of the design process, and Alexander's theory conceptualises design as an evolutionary process grounded in spatial patterns. The proposed model is positioned in continuity with these three theoretical perspectives and demonstrates that geometry-based design begins with contextual cognition, continues through the organisation of spatial relationships, and ultimately leads to transformation and material realisation. From this perspective,, the selection of these three models is intentional, situating the proposed model within three contemporary theoretical traditions: cognitive-analytical, human-centred, and pattern-based evolutionary design Figure 4.

7. Conclusion

Grounded in rigorous theoretical analysis and empirical expert interviews, this research sought to epistemologically reposition geometry within the design continuum – transitioning it from a mere formal and representational utility to the foundational cognitive structure of design thinking. In conventional paradigms, geometry appears only at certain stages, typically as a means of organising or representing form; however, the proposed five-stage model demonstrates that geometry can be situated at the very foundation of the design process rather than at its end. Accordingly, architectural design is understood as an experience of geometric thinking, in which the designer thinks, decides, and organises within a dynamic geometric framework from cognition to realisation.

Elaborating on these five stages, the proposed model, consisting of five stages – geometric cognition, perception, organisation, transformation, and realisation – depicts the design process as a continuous trajectory of geometric transformation. In the cognition stage, geometry is internalised as a cultural, historical, and theoretical foundation. In perception, it becomes a mental and spatial construct. In organisation, spatial relationships, rules, and hierarchies are defined. In transformation, these structures are translated into tangible and testable forms. Finally, in realisation, geometry is embodied in material, space, and lived experience. Thus, geometry is not merely a technical instrument but a cognitive and semantic system that integrates and guides the entire design process. What distinguishes this model from previous approaches is its conception of geometry as the structural foundation of architectural design thinking – an underlying system that integrates functional, conceptual, and spatial elements into a coherent framework. Within this perspective, architectural design emerges from the ongoing interaction between mind and world, geometric order and human intuition, analysis and creativity. Geometry functions not only as a tool for form-mak-

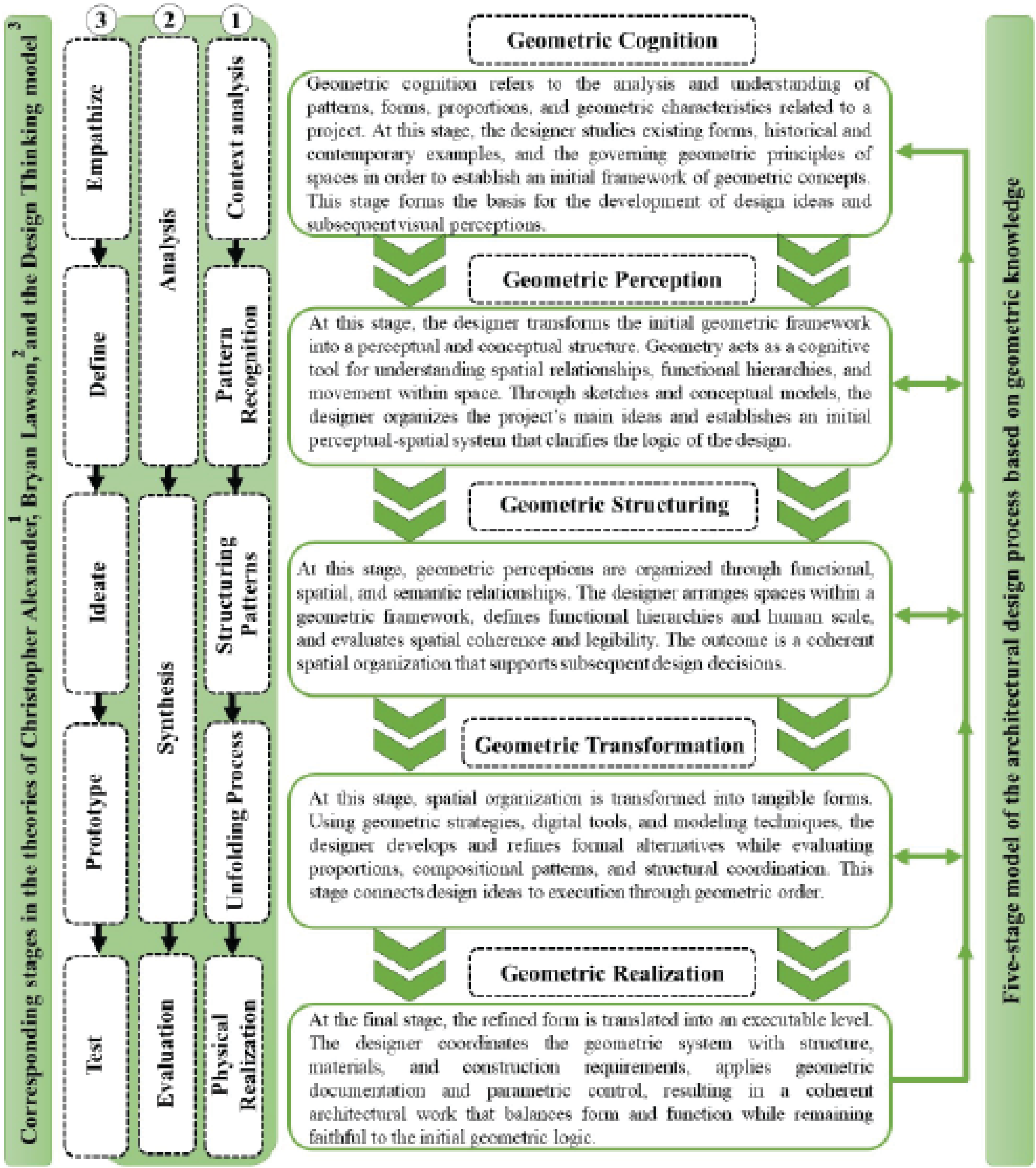


Figure 4. Five-Stage Model of the Architectural Design Process with a Focus on Geometry in Design Thinking, Source: authors.

ing but also as a framework for understanding, organising, and decision-making.

The model's connection to three established design frameworks – design thinking, Lawson's three-stage model, and Christopher Alexander's theory – demonstrates its theoretical depth and multidimensional grounding. Design thinking highlights the cognitive-exploratory and human-centred aspects of design; Lawson provides a structured analytical framework of analysis, synthesis, and evaluation; and Alexander reveals the evolutionary and pattern-based nature of form generation. The proposed model integrates these traditions within a coherent geometric logic, showing how geometry can act as a bridge between contextual understanding, spatial organisation, and material realisation. Ultimately, this five-stage model advances a paradigmatic shift, portraying design as an act of continuous morphogenesis that is simultaneously analytical and deeply creative, thereby equipping future scholarship and pedagogy with a profound mechanism for decoding the essence of spatial creation.

Acknowledgements

This article is based on the first author's doctoral thesis, entitled 'A Conceptual Model of the Architectural Design Process Focusing on Geometric Knowledge within Design Thinking', completed in the Department of Architecture at the Art University of Isfahan. The author gratefully acknowledges the supervision of Dr Mehdi Mahmoudi Kamelabad and the valuable guidance of Professor Enrico De Angelis.

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Integrated Framework for IFC Model Generation and Structural Layout from Architectural Sketch Plans

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ORIGINAL RESEARCH ARTICLE

Afshar, Shima, and Mohammad Tahsildoust. "Integrated Framework for IFC Model Generation and Structural Layout from Architectural Sketch Plans". *Soffeh* 36, no. 2 (2026): 83–108. DOI: http://doi.org/10.48308/soffeh.2026.242295.1468

Abstract

Background and Objectives: Recent advances in Artificial Intelligence (AI) and Building Information Modelling (BIM) have enabled closer integration between data-driven automation and architectural design processes. Nevertheless, current AI-based BIM modelling approaches—particularly in the plan recognition stage—remain heavily reliant on large labelled datasets, making data preparation time-consuming and labour-intensive. This dependency limits rapid iteration in early-stage architectural design, where speed and responsiveness are essential. To address these challenges, this study proposes an integrated automation framework that leverages hybrid computational methods to accelerate the translation of sketch-based floor plans into structured BIM models.

Materials and Methods: The proposed workflow comprises three main components. First, 2D raster floor plans are converted into vector data using a hybrid approach that combines deep learning-based opening detection (YOLOv11) with rule-based wall extraction. Second, the framework automatically recommends initial column layouts optimised according to spatial and functional design criteria. Third, it programmatically generates Industry Foundation Classes (IFC)-

Received: October 30, 2025
Revised: December 02, 2025
Accepted: December 14, 2025
(Pages: 83–108)

Keywords:
Building Information Modelling (BIM), Deep Learning, Industry Foundation Classes (IFC), Architectural Plan Interpretation, Structural Layout Optimisation.

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http://doi.org/10.48308/soffeh.2026.242295.1468

compliant 3D models. Geometric information extracted from sketch plans produces an IFC file encompassing walls, floors, doors, windows, and preliminary structural column layouts, closely reflecting the original design intent.

Research Questions:

1. .How can hybrid computational methods integrate deep learning and rule-based techniques to efficiently convert sketch-based floor plans into structured BIM models?

2.In what ways can reliance on large labelled datasets be minimised during the plan recognition stage of AI-based BIM modelling?

3.How effectively can the proposed framework automatically recommend and optimise initial structural column layouts according to spatial and functional design criteria?

4.What is the accuracy and efficiency of the integrated framework in object detection, wall recognition, and IFC-compatible 3D model generation?

5.How can this integrated automation framework reduce manual effort and accelerate the early-stage architectural design process by bridging manual plan interpretation and BIM workflows?

Results and Conclusion: Experimental evaluation demonstrates robust performance across all stages. The object detection model achieved a mAP50:95 of 81%, with an inference time of 0.0041 seconds per image. Wall recognition reached 100% accuracy, while the column layout algorithm attained 95.83% alignment with executed plans. IFC generation was completed in under one minute, ensuring efficiency and practicality. These results underscore the framework's capacity to substantially reduce manual effort, minimise reliance on large labelled datasets, and expedite the transition from conceptual sketches to BIM. By integrating hybrid computational techniques, the proposed approach offers a reliable, automated, and scalable solution for early-stage architectural design, bridging the gap between manual plan interpretation and BIM workflows, and providing a foundation for future research in intelligent architectural modelling.

1. Introduction

In recent decades, the architecture, engineering, and construction (AEC) industry has increasingly adopted digital technologies for generating three-dimensional (3D) models, ranging from NURBS-based modelling to computer-aided design (CAD) systems, and, more recently, Building Information Modelling (BIM). Among these, object-oriented BIM platforms have become particularly influential, offering the ability to exchange detailed information among stakeholders, preserve data consistency across the project lifecycle, and minimise errors caused by rework or interdisciplinary clashes. This shift is reflected in the global market, where BIM was valued at approximately USD 8.1 billion in 2022 and is projected to reach USD 14.6 billion by 2028, representing a compound annual growth rate (CAGR) of 11.3%.[1]

Architectural design is an iterative, multi-phase process

1. Prasad Padwal, 'Building Information Modeling (BIM) Market Size & Outlook,' *Leadership and Management in Engineering*, (2024), https://www.researchgate.net/publication/377969878_Building_Information_Modeling_BIM_Market_Size_Outlook.

2. Farzad Jalaei et al., 'Integrating Decision Support System (DSS) and Building Information Modelling (BIM) to Optimize the Selection of Sustainable Building Components,' *Journal of Information Technology in Construction* 20 (2015): 399–420, https://www.itcon.org/paper/2015/25.

3. Farzad Jalaei and Ahmad Jrade, 'Integrating Building Information Modelling (BIM) and Energy Analysis Tools with Green Building Certification System to Conceptually Design Sustainable Buildings', *Journal of Information Technology in Construction* 19 (2014): 500, https://doi. org/10.1061/9780784413517.015.

in which early-stage decisions critically affect downstream performance, cost, and constructability outcomes[2]. Inadequate consideration during these stages often leads to design inefficiencies and increased project costs. BIM provides an integrated framework to support informed decision-making by enabling multidisciplinary collaboration and interoperable data exchange, thus minimising redundant modelling efforts. Integrating real-time structural layout recommendation systems within BIM environments can further enhance early design workflows by allowing architects to evaluate alternative configurations based on structural performance and constructability criteria, fostering more holistic and data-driven design outcomes.[3]

Despite these advantages, BIM adoption in the early design stages remains limited,primarily due to the high costs and time required to create detailed models, the need for specialised expertise, and the adjustments required in conventional workflows. Recent research has attempted to address these barriers through automation, particularly by leveraging artificial intelligence (AI) and intelligent application programming interfaces (APIs) to generate initial building components with minimal manual intervention. A central focus of these efforts is the automated creation of Industry Foundation Classes (IFC) models – anopen, platform-independent standard that ensures bothgeometric and semantic data exchange across BIM platforms. Automation not only reduces human error and accelerates updates but also ensures that models remain consistent and synchronised across stakeholders. Prior studieshighlight that IFC automation improves data-to-model conversion, increasesproductivity, and enhances model quality. In theearly design stages, timely 3D models enable spatial analysis, clash detection, and performance simulations. However, manual conversion from two-dimensional (2D) drawings toBIM remains aslow and error-prone process, underscoring the need for automation to support rapid iterations, greater accuracy, and efficiency in both new construction and renovation projects.Previous studies have explored this challenge from multiple perspectives. Some have focused on automating the transformation of CAD files into 3D BIM models[4], using rule-based geometric algorithms that apply predefined geometric rules. Others have concentrated on raster- to- BIM pipeline, which combine deep learning, rule-based, or hybrid methods.[5] Liang et al.presented a fully automated BIM dataset generation framework that integrates a modified ResNet-34 and U-Net to produce paired synthetic 2D floor plans and 3D BIMs, introducing the novel ResBIM dataset for standardised 2D-to-BIM evaluation.[6] Additionally,some recent advances increasingly leverage deep learning to enhance point cloud segmentation and automate BIM creation. For example, Wang et al.[7] utilised a hybrid approach that combines RANSAC-based multi-plane segmentation with a lightweight convolutional encoder–decoder network to automate BIM reconstruction from drone-acquired point clouds. In parallel, Erişen et al.[8] introduced a Vision Transformer–based multi-task deep learning pipeline that jointly performs single-image depth estimation and semantic segmentation to reconstruct BIM-compatible, semantically enriched 3D indoor models directly from RGB imagery, while also enabling domain adapta-

4. Joie Lim et al., 'Automated Generation of BIM Models from 2D CAD Drawings,' paper presented at Computer Aided Architectural Design Research in Asia, (2018), https://doi.org/10.52842/conf.caadria.2018.2.061.

5. Aleixo Cambeiro Barreiro et al., 'Automatic Reconstruction of Semantic 3D Models from 2D Floor Plans, ' *18th International Conference on Machine Vision and Applications (MVA)*, (2023), https://doi.org/10.23919/MVA57639.2023.10215746; Sungsoo Park and Hyeoncheol Kim, '3DPlanNet: Generating 3D Models from 2D Floor Plan Images Using Ensemble Methods,' *Electronics* 10, no. 22 (2021), https://doi.org/10.3390/electronics10222729%3Furlappend=%3Futm_source=researchgate; Yunfan Zhao et al., 'Reconstructing BIM from 2D Structural Drawings for Existing Buildings,' *Automation in Construction* 128, no. 103750 (2021), https://doi.org/10.1016/j.autcon.2021.103750.

tion to recognise previously unrepresented object classes in 3D point-cloud space.

Another key challenge during early-stages design is thegeneration of structural layout, particularly when architectural forms are still evolving, and complete structural information is not yet available. Early decisions regarding column placement and structural grid configuration significantly influence constructability, spatial performance, and structural integrity. Traditionally, these decisions rely heavily on engineers' expertise and iterative adjustments, which can be time-consuming and inconsistent. Automated structural layout generation has the potential to accelerate decision-making, reducehuman error, and enable rapid exploration of alternatives.

Prior research on structural layout automation has applied optimisation algorithms[9] and generative deep learning models,[10] to recommend structural layouts, focusing primarily on parameters such as cost, structural member sizing,[11] code compliance,[12] environmental constraints[13] and column coordinates.[14] However, in the early design stages, functional alignment between the column grid and the architectural layout is critical for ensuring usable and efficient spaces. Accordingly, this study prioritises functional criteria in generating initial column layouts,thereby providing a design solution that supports both architectural intent and downstream structural analysis.

By integrating architectural modelling automation with structural layout generation,this research establishes a unified and intelligent workflow for conceptual building design. The resulting IFC models are compatible with widely used platforms, including Autodesk Revit, Graphisoft ArchiCAD, Navisworks, and BlenderBIM for modelling and coordination; Autodesk Robot Structural Analysis, Tekla Structures, and ETABS for structural analysis; and Simergy, IES-VE, and RIUSKA for energy simulations.[15] Automating IFC model creation at the early design stages not only accelerates multidisciplinary evaluations but also strengthens the foundation for subsequent architectural, structural, and performance-based analyses.

In response to these challenges and opportunities, this studyproposes an integrated framework, as illustrated in Figure 1,which:

- Combines a hybrid deep learning, YOLO (You Only Look Once), and rule-based approach to interpret raster floor plan images and convert them into vectorised data.
- Employs a brute-force search algorithm to recommend an optimised initial column arrangement according to predefined performance criteria, derived from the vectorised plan.
- Automatically generates a 3D IFC model from structured JSON data generated in previous stages, ensuring compatibility with BIM platforms and analysis tools.

The deep learning and IFC automation modules were implemented in Google Colab, while

6. Xing Liang et al., 'Fully Automated Synthetic BIM Dataset Generation Using a Deep Learning-Based Framework,' *Automation in Construction* 181, no. 106584 (2025), https://doi.org/10.1016/j.autcon.2025.106584.

7. Dejiang Wang et al., 'Existing Buildings Recognition and BIM Generation Based on Multi-Plane Segmentation and Deep Learning,' *Buildings* 15, no. 691 (2025), https://doi.org/10.3390/buildings15050691.

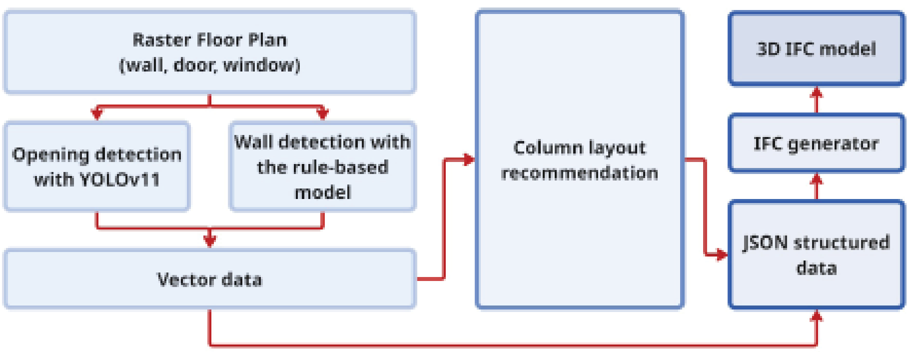


Figure 1. Overall workflow of the proposed framework for converting a raster floor plan into a 3D IFC model with a recommended column layout.

the column layout algorithm was developed in Grasshopper for Rhinoceros. Evaluations confirmedboth accuracy and practicality:the object detection module achieved an mAP50 of 81.85% at a 0.0041 second per image (SPI) inference time, the structural layout recommendation reached 95.83% alignment with executed projects, and the IFC generator produced complete models significantly faster than expert manual modelling. The resulting IFC modelsincluded both geometric and semantic data for walls, doors, windows, columns, and slabs, ensuring usability for further development in BIM platforms such as Autodesk Revit.

2. Literature Review

This section reviews prior research relevant to automated BIM workflows, focusing on three core components of the present study: (1) automated extraction of architectural elements from 2D raster floor plans, (2) structural layout recommendation in the early design stages, and (3) automated generation of IFC-compliant models. The review synthesises journal articles, conference proceedings, and review studies, selected through targeted search strategies designed to match the capabilities of different academic databases.

2. 1. Automated Data Extraction from 2D Raster Floor Plans

As illustrated in Figure 2, raster images of 2D floor plans are the most frequently used input for automated 3D model reconstruction, representing 49% of studies by 2024 due to their wide availability, ease of access, and strong compatibility with computer vision techniques[16]. In line with this trend, the present research also adopts raster floor plans as its primary input for automated BIM conversion.

Two principal approaches dominate the extraction of architectural information from raster images: rule-based methods and data-driven approaches. Rule-based strategies rely on predefined heuristics, geometric recognition, and vectorisation techniques to identify and classify architectural elements (e.g., walls, doors, and windows). Data-driven approaches, by contrast, employ deep learning models trained on labelled datasets to detect and classify objects. Hybrid pipelines often combine these approaches, using rule-based post-processing to refine the outputs of object detection networks.

Early developments in this field were dominated by rule-based techniques. For example,Gimenez et al.[17] identified walls as pairs of parallel lines, assigned openings as voids within those walls, and defined spaces as closed loops. Similarly,Q. Lu et al.[18] extracted structural information from CAD drawings by detecting columns via the Circle Hough Transform and using Optical Character Recognition (OCR) to classify textual annotations.

Recent advances, however, are increasingly data-driven. Faster R-CNN has been widely adopted, as demonstrated by Zhao et al.[19] for beam and column detection, and by Barreiro et al.[20] for door and window detection combined with semantic wall segmentation via Feature Pyramid Networks (FPN) with ResNet.Urbieta et al.[21] applied Mask R-CNN with OCR to detect and extract semantic attributes from both architectural and structural plans.

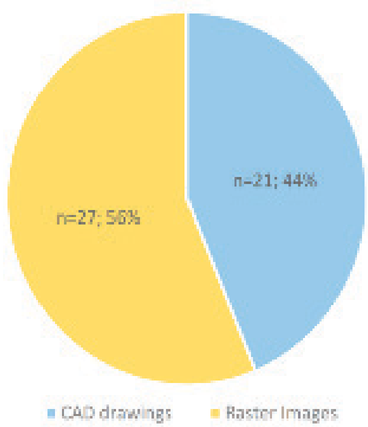
Some studies integrate multiple deep learning architectures within a single pipeline to le-

8. Serdar Erişen et al., 'Single Image to Semantic BIM: Domain-Adapted 3D Reconstruction and Annotations via Multi-Task Deep Learning,' *Remote Sensing* 17, no. 2910 (2025), https://doi.org/10.3390/rs17162910.

9. Alper Kanyilmaz et al., 'A Genetic Algorithm Tool for Conceptual Structural Design with Cost and Embodied Carbon Optimization,' *Engineering Applications of Artificial Intelligence* 112, no. 104711 (2022), https://doi.org/10.1016/j.engappai.2022.104711; Xianchuan Meng et al., 'Optimizing Support Locations in the Roof–Column Structural System,' *Applied Sciences* 11, no. 6 (2021), https://doi.org/10.3390/app11062775; Wenchen Shan et al., 'Integrated Method for Intelligent Structural Design of Steel Frames Based on Optimization and Machine Learning Algorithm,' *Engineering Structures* 284, no. 115980 (2023), https://doi.org/10.1016/j.engstruct.2023.115980; Mohamed Sherif et al., 'Automated BIM-Based

verage the strengths of different models. For instance,Kippers et al.[22] combines U-Net and Fast-SCNN for wall segmentation with Faster R-CNN, CentreNet, SSD MobileNet, and RetinaNet for door and window detection, and incorporates LSTM-based OCR for reading space labels. Likewise,Jang et al.[23] employs CNN models such as DarkNet53, Deeplabv3, and PSPNet for wall and door segmentation, applies ensemble modelling to improve Intersection over Union (IoU) scores, and uses centreline and corner detection to generate topological representations. Inthe study by Liu et al.,[24] raster floor plans were converted into CAD-compatible vector models by combining a ResNet-152 convolutional network with integer programming to enforce geometric and semantic constraints. In Z. Lu et al.,[25] a shared neural network detected both graphical elements and textual labels in rural residential floor plans, followed by Mixed-Integer Quadratic Programming (MIQP)-based segmentation of rooms and extraction of topological connectivity graphs.Finally, Zhao et al.[26] uses a YOLO-based framework to detect structural components from 2D plans using a model pre-trained on ImageNet and fine-tuned with 360 annotated images, demonstrating robust detection of structural components with post-processing via Non-Maximum Suppression for refinement.

Hybrid approaches have also been proposed to combine the interpretability of rule-based logic with the adaptability of data-driven detection. For instance,Leon-Garza et al.[27] applied fuzzy logic to classify pixels as wall or background using contextual information, refined by experts refining the rules.Doukari and Greenwood[28] employed a knowledge-base-driven approach, applying image processing techniques to aerial building imagery to infer semantic attributes such as building type and material usage. The 3DPlanNetEnsemble framework by



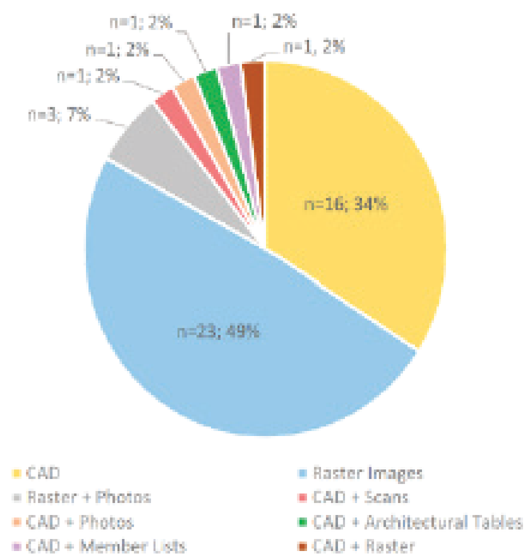


Figure 2. Proportion of different input data sources employed in previous studies on automated 3D model generation (Feist et al., 2024).

Structural Design and Cost Optimization Model for Reinforced Concrete Buildings,'*Scientific Reports* 12, no. 1 (2022), https://doi.org/10.1038/s41598-022-26146-6.

10. Bochao Fu et al., 'Dual Generative Adversarial Networks for Automated Component Layout,'*Automation in Construction* 146, no. 104661 (2023), https://doi.org/10.1016/j.autcon.2022.104661; Chong Zhang et al., 'End-to-End Generation of Structural Topology for Complex Architectural Layouts with Graph Neural Networks,'*Computer-Aided Civil and Infrastructure Engineering* 39 (2022): 756–75, https://doi.org/10.1111/mice.13098%3Furlappend=%3Futm_source=researchgate.

Park and Kim[29] merged logistic regression for wall detection and TensorFlow-based object detection for openings and spaces with geometric rules, including alignment checks, duplicate line removal, and merging of disconnected areas.

2. 2. Structural Layout Recommendation

In early design, structural layout generation is increasingly addressed through computational strategies that balance constructability, cost, and performance. Recent studies addressing structural layout recommendation in the early design stages adopt a spectrum of computational strategies, each leveraging distinct input types and optimisation objectives. These methods can be categorised as evolutionary algorithms, generative deep learning modules, hybrid combinations of machine learning and optimisation, and deterministic methods, with some frameworks bridging more than one category.

Evolutionary algorithms remain a well-established choice for multi-objective structural optimisation, particularly when balancing economic and performance considerations.Sherif et al.[30] integrate Revit, Dynamo, and Python with a genetic algorithm to minimise combined concrete and steel costs in reinforced concrete buildings, using architectural plans, spatial constraints, material properties, loading conditions, and dimensional limits as inputs. Similarly, Kanyilmaz et al.[31] employ the Non-dominated Sorting Genetic Algorithm(NSGA-II) to simultaneously optimise construction cost, embodied carbon, and usable free space, driven by basic project parameters such as site dimensions, number of floors, soil conditions, material characteristics, and gravity loads.

Generative deep learning methods extend the capability of structural design automation by learning spatial and topological patterns directly from data.The ApproxiFramer model by Ampanavos et al.[32]'s ApproxiFramer applies a CNN–ResNet–LSTM architecture to iteratively generate column positions from low-resolution, sketch-like plans, trained on an augmented synthetic dataset and optimised for both positional and categorical accuracy. InZhang et al.,[33] StrucTopo-GAN combines a pix2pixHD Generative Adversarial Network(GAN) for node detection with a Graph Neural Network (GNN)-based generator–discriminator pair to predict beam connectivity, reconstructing realistic topology graphs from paired architectural and structural plan datasets. Building on the same generative paradigm, FrameGAN by Fu et al.,[34] uses a two-stage pix2pixHD GAN workflow to sequentially produce column layouts and bracing configurations for steel frame–braced structures, validating results through expert evaluation, material cost comparison, and structural performance analysis.

Hybrid strategies bridge the adaptability of machine learning with the efficiency of optimisation.Shan et al.[35] demonstrate this integration by combining metaheuristic searches with LightGBM surrogate models trained on finite element analysis results. This reduces computational cost while guiding the search toward minimum-weight steel frame designs under constraints on drift, stress, stability, and geometry.

Deterministic optimisation approaches, while less data-driven, offer mathematically rigorous control over layout refinement.Meng et al.[36] adopt an Optimality-Criterion-based method

11. Shan et al., 'Integrated Method for Intelligent Structural Design of Steel Frames Based on Optimization and Machine Learning Algorithm'; Sherif et al., 'Automated BIM-Based Structural Design and Cost Optimization Model for Reinforced Concrete Buildings.'

12. Shan et al., 'Integrated Method for Intelligent Structural Design of Steel Frames Based on Optimization and Machine Learning Algorithm.'

13. Kanyilmaz et al., 'A Genetic Algorithm Tool for Conceptual Structural Design with Cost and Embodied Carbon Optimization.'

for column placement in slab–column systems, starting from a candidate grid and iteratively removing inefficient supports using finite element–derived stress data, while maintaining stiffness balance and ensuring smooth stress distribution.

Taken together, these strategies illustrate a progression from conventional optimisation toward increasingly data-driven and hybridised methods, reflecting a broader shift in structural design automation toward approaches that integrate domain-specific engineering knowledge with the adaptive learning capabilities of modern AI. However, a notable limitation across existing studies is the lack of consideration for functional criteria—such as spatial usability, circulation efficiency, or architectural intent—when optimising structural layouts in the early design stages. In practice, the early phases of building design demand a harmonious balance between architectural and structural systems, ensuring that structural efficiency is achieved without compromising the functional and aesthetic qualities of the space.

2. 3. Automated Generation of IFC Models

In the reviewed literature, automated IFC model generation has been implemented using a variety of toolkits and platforms.Doukari and Greenwood[37] employed the XBIM toolkit to programmatically construct IFC entities from enriched semantic data. The approaches by Urbieta et al.[38] andLeon-Garza et al.[39] utilised the open-source IfcOpenShell library to translate extracted geometric and semantic information into IFC-compliant models. Furthermore, Zhao et al.,[40] a custom IFC creation platform developed in C# was used to generate BIM objects from detected structural components and associated attributes. These tools collectively illustrate the range of available solutions, from specialised open-source libraries to bespoke software environments, for converting processed building data into standardised IFC models.

2. 4. Summary of Gaps and Research Direction

The literature highlights promising advances in raster-to-BIM automation, structural layout generation, and IFC model creation, as summarised in,yet, several gaps remain:

- Purely data-driven approaches often rely on extensive, manually labelled datasets that are costly and time-consuming to produce. The proposed hybrid method aims to achieve comparable performance using a more compact dataset, thereby alleviating the burden of large-scale data preparation.
- Few structural layout algorithms explicitly integrate **functional and spatial criteria**, which are essential in early-stages design.
- Existing IFC workflows vary in interoperability and robustness, with limited optimisation for early-phase architectural data.

To address these gaps, the present research adopts a hybrid detection pipeline (YOLO + rule-based refinement) for efficient floor plan interpretation, introduces a functionality-oriented structural layout algorithm, and employs IfcOpenShell for streamlined IFC generation. Additionally, the influence of image resolution on detection accuracy and computational speed was examined by repeating the training process on multiple input sizes.

14. Spyridon Ampanavos et al., 'Structural Design Recommendations in the Early Design Phase Using Machine Learning,' preprint, 2021, https://doi.org/10.48550/arXiv.2107.08567; Fu et al., 'Dual Generative Adversarial Networks for Automated Component Layout'; Kanyilmaz et al., 'A Genetic Algorithm Tool for Conceptual Structural Design with Cost and Embodied Carbon Optimization'; Zhang et al., 'End-to-End Generation of Structural Topology for Complex Architectural Layouts with Graph Neural Networks.'

15. Mohamed Elagiry et al., 'IFC to Building Energy Performance Simulation: A Systematic Review of the Main Adopted Tools and Approaches,' *8th Conference of IBPSA*, 2020.

16. Sofia Feist et al., 'Automatic Reconstruction of 3D Models from 2D Drawings: A State-of-the-Art Review,' *Eng* 5, no. 2 (2024), https://doi.org/10.3390/eng5020042%3Furlappend=%3Futm_source=researchgate.

3. Methodology

This research develops a hybrid algorithm combining deep learning and rule-based logic to automatically convert simplified 2D floor plan images into initial 3D IFC models, alongside a structural layout recommendation system for early-stage design. The workflow comprises

Table 1. Summary of previous studies on IFC model generation from 2D drawings.

	Study	Objectives	Methodology	Input Data	Final Results
1	(Zhao et al., 2021)	BIM reconstruction from existing 2D structural drawings	Faster R-CNN detection and IFC generation in C#	500 structural 2D drawings	Precision 94%, recall 91%, mAP 90.41%, weighted mAP 91.28%
2	(Barreiro et al., 2023)	Semantic 3D reconstruction from 2D floor plans	Faster R-CNN for door/window detection, FPN for walls	5,000 labeled floor plans from CubiCasa5K	IoU 80%
3	(Urbieta et al., 2023)	BIM model generation from architectural plans	Mask R-CNN for component detection, IFC creation via IfcOpenShell	50,000 training images over 2,500 epochs	mAP 96.7%
4	(Kippers et al., 2021)	3D building modelling using CityJSON and deep learning	U-Net, Fast-SCNN, CentreNet, RetinaNet for component detection	5,000 CubiCasa floor plans	F1-scores: walls 0.90, doors 0.93, windows 0.85
5	(Jang et al., 2020)	Indoor space reconstruction from floor plans, conversion to IndoorGML and CityGML	CNNs (DarkNet53, Deeplabv3, PSPNet), vector graph extraction, corner and centreline detection	319 floor plan images	IoU: doors 0.7805, walls 0.688 (ensemble: 0.7283)
6	(Gimenez et al., 2016)	IFC reconstruction from scanned architectural drawings using rule-based methods	C++ implementation, wall through geometric rules	90 scanned floor plans	Detection accuracy: walls 86%, openings 62%; Jaccard index: walls 0.76, openings 0.53
7	(Leon-Garza et al., 2022)	IFC generation by combining Type-2 fuzzy logic with CNN classification	Fuzzy inference system and wall/background classification	Architectural floor plan images	Accuracy: fuzzy logic 97.5%, CNN 99.3%; fuzzy logic improved decision transparency
8	(Doukari & Greenwood, 2020)	BIM model enrichment using knowledge base and aerial imagery	building density analysis, IFC completion via XBIM API	Aerial images of building sites	Extraction of unit types and materials, insertion into IFC via API
9	(Q. Lu et al., 2020)	Geometric digital twinning using rule-based techniques	Column detection with Circle Hough Transform, morphological operations	Scanned 2D CAD architectural drawings	Four output text files for IFC generation, evaluated by extraction and matching accuracy
10	(Park & Kim, 2021)	3D modelling through hybrid data-driven and rule-based approach	Logistic regression, TensorFlow object detection API, geometric rules	30 training and 30 testing plans from a dataset of 110,000 raster plans	Wall detection accuracy >95%, dimensional accuracy >97%
11	(Liu et al., 2017)	Accurate raster-to-CAD vector conversion with geometric/semantic constraints	ResNet152, Integer Programming for constraint enforcement	870 manually labeled architectural plans	Opening detection accuracy 67%, recall 91.4%
12	(Z. Lu et al., 2021)	Interpretation of rural architectural plans using joint neural network and MIQP	Component detection, room segmentation, topological graph extraction	800 real-world floor plans	Overall accuracy 87–92%, IoU 74–82%
13	(Zhao et al., 2020)	Structural component detection from 2D drawings	YOLO, pre-trained on ImageNet	450 structural drawings	Precision >80%, recall >90%

three main sections:
3.1. Floor Plan Interpretation: detection of openings (doors and windows) using YOLOv11, and wall extraction using OpenCV-based geometric rules, combined through a lightweight Graphical User Interface (GUI) that allows interactive sketching and editing.
3.2. Structural Layout Recommendation: generation of initial column placements in Grasshopper, guided by parking requirements, opening positions, and spatial constraints.
3.3. IFC Model Generation:transformation of processed vector data into IFC files via IfcOpenShell.
The methodology and its main phases are illustrated in Figure 3.

3. 1. Floor Plan Interpretation

The first stage of the proposed framework focuses on extracting building components from simplified 2D floor plan raster images through a dual approach combining deep learning-based object detection and rule-based geometric processing, a hybrid strategy that reduces the need for extensive data labelling while maintaining accuracy in raster-to-BIM tasks.[41] To fa-

Table 2. Summary of Previous Studies on Structural Layout Recommendation.

	Study	Methodology	Inputs	Outputs	Limitations
1	(Sherif et al., 2022)	Integration of BIM, structural design, and a genetic algorithm within the Revit–Dynamo environment using Python scripting	Architectural plan, performance limits, material properties, structural loads, dimensional constraints	Optimised structural layout, section dimensions for columns, reinforcement and concrete quantities, cost estimation	Limited to regular rectangular plans; suitable for late design stages
2	(Kanyilmaz et al., 2022)	NSGA-II multi-objective optimisation implemented in Python	Plot dimensions, material type, loads, number of floors, soil conditions, building function	Column and beam layout, slab type, material usage, total cost, embodied carbon	Limited to rectangular plans with uniform spans
3	(Ampanavos et al., 2021)	CNN model with LSTM for stepwise prediction of columns from plan images	Floor plan image, previously generated columns, pixel coordinates	Column coordinates	Predicted columns may not align with existing walls
4	(Zhang et al., 2022)	GAN combined with GNN for generating structural topology from floor plan images	Architectural floor plan image	Column positions and beam connections	Column placement deviation from intended axes
5	(Fu et al., 2023)	Two-stage GAN with pix2pixHD architecture for column and bracing arrangement	Stage 1: architectural plan; Stage 2: column layout and paired structural images	Column and bracing layout	—
6	(Shan et al., 2023)	Combination of machine learning models and classical optimisation with finite element analysis	Geometric parameters of I-shaped members, gravity and seismic loads, code-based constraints	Optimised structural member design in terms of lightness, cost-effectiveness, and code compliance	Suitable for late design stages
7	(Meng et al., 2021)	Optimality-Criterion algorithm for column layout optimisation	Slab geometry, material properties, number of columns, initial candidate grid	Optimal column locations based on stiffness and preservation of architectural form	Architectural plan and functional considerations not integrated into column placement

cilitate user interaction and enable direct plan input with precise placement of architectural elements such as openings, a graphical user interface (GUI) was developed using Konva.js. Through this interface, users can draw their desired floor plan, which is then processed within the proposed framework. The framework automatically detects and classifies building components, generates a structurally aligned column layout based on the recognised geometry, and ultimately produces a 3D model in IFC format. The interface layout and its main features are illustrated in Figure 4.

3. 1. 1. YOLO-Based Object Detection for Openings

Following best practices in recent floor-plan detection literature, we generated a synthetic dataset from RPLAN-inspired layouts and applied geometric augmentations (mirroring, rotation, scaling, translation) to improve generalisation. Synthetic dataset strategies follow recent large-scale floor-plan pipelines that combine programmatic layout generation and geometric augmentation to improve model generalisation. The synthesised dataset comprises 9,600 annotated images and was partitioned into 70/30 train /test splits for all experiments (see Appendix A for dataset examples). The YOLOv11Lmodel, the latest version of YOLO for the detection task released by Ultralytics, was then trained on this dataset for 100 epochs with a learning rate of 0.0001, a batch size of 32, and an image size of 768 pixels, using the defaultpre-trained weights on the COCO dataset. The YOLO model was chosen as it generates a separate label file for each image, unlike models such as Fast R-CNN or Mask R-CNN that store all annotations in a single JSON. This structure simplifies automated dataset generation in Grasshopper and

17. Lucile Gimenez et al., 'Automatic Reconstruction of 3D Building Models from Scanned 2D Floor Plans,'*Automation in Construction* 63 (2016): 48–56, https://doi.org/10.1016/j.autcon.2015.12.008.

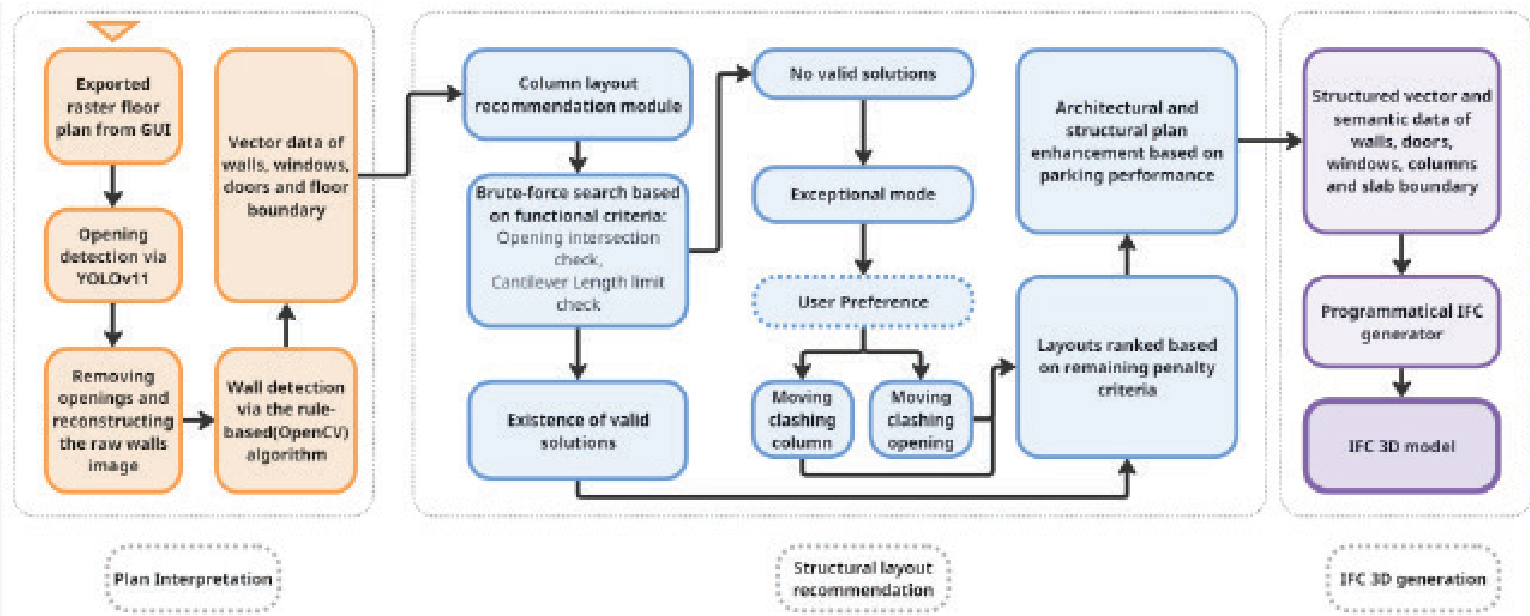


Figure 3. Methodology phases.

supports efficient large-scale data preparation. YOLOv11 was selected as it offers the highest detection accuracy among previous YOLO versions, according to Ultralytics documentation.

To evaluate the influence of input resolution on both detection performance and computational efficiency, the training process was repeated at two additional resolutions: 512 and 864 pixels. YOLO-family detectors have been shown to deliver strong trade-offs between speed and detection accuracy on architectural floor plans, particularly when combined with multiscale training and dataset augmentation strategies.[42]

3. 1. 2. Data Preparation and Labelling Process

The dataset generation process was fully automated using a custom algorithm implemented in Grasshopper,with 200 floor plans from the RPLAN dataset serving as the primary source for data generation. For placing doors and windows in the dataset, existing walls in each plan were first filtered based on length to identify those long enough to host an opening. Then, for each plan, a random selection of 1 to 4 walls longer than 3 metres was chosen to host windows, and 1 to 4 walls longer than 1 meter were selected to host doors. The bounding rectangles of the openings were automatically drawn in each plan, allowing the extraction of coordinate information for the YOLO dataset, which was saved automatically. Since a dual approach combining deep learning and rule-based processing was used for floor plan interpretation, there was no need to label the walls for segmentation separately. This eliminated the requirement for a dedicated wall dataset and significantly reduced the time-consuming labelling process.

To introduce variability and better represent realistic architectural scenarios, a different number of openings was assigned to each floor plan, ensuring diversity in placement and density. Furthermore, the generated plans were scaled at three factors (0.8, 0.9, and 1.0) and rotated in multiple directions. These variations enabled the YOLO model to learn to detect objects across different sizes and orientations, enhancing its robustness and accuracy in recognising openings in diverse floor plan layouts.

3 .1. 3. Rule-Based Wall Extraction

Following the detection of doors and windows using the trained YOLO model, the next step involved wall identification through a rule-based algorithm and vectorisation in Grasshopper. The detection process relied on distinguishing white pixels, representing walls, from the black background. To achieve this, the YOLO output underwent preprocessing, in which detected openings were removed and the corresponding wall segments reconstructed. The image was then converted into a binary format, ensuring that walls were represented in white and the background in black, thereby facilitating accurate image processing.

The binarised image was imported into Grasshopper, where a rule-based algorithm, implemented via OpenCV, extracted wall positions by tracing white pixel boundaries against the black background. These boundaries were then converted into sets of points and subsequently into polyline vector paths for further processing.

In parallel, the YOLO predictions for openings were processed to restore their geometric posi-

18. Qiuchen Lu et al., 'Semi-Automatic Geometric Digital Twinning for Existing Buildings Based on Images and CAD Drawings,' *Automation in Construction* 115, no. 4 (2020), https://doi.org/10.1016/j.autcon.2020.103183.

19. Zhao et al., 'Reconstructing BIM from 2D Structural Drawings for Existing Buildings.'

20. Barreiro et al., 'Automatic Reconstruction of Semantic 3D Models from 2D Floor Plans.'

21. Martin Urbieta et al., 'Generating BIM Model from Structural and Architectural Plans Using Artificial Intelligence,' *Journal of Building Engineering* 78, no. 107672 (2023).

22. R. G. Kippers et al., 'Automatic 3d Building Model Generation Using Deep Learning Methods Based on CITYJSON and 2d Floor Plans,' *The International Archives of the Photogrammetry Remote Sensing and Spatial Information Sciences* XLVI-4-W4-2021 (2021): 49–54, https://doi.org/10.5194/isprs-archives-XLVI-4-W4-2021-49-2021.

tions within the plan. The model's output files, containing object class and normalised bounding box coordinates, were read into Grasshopper and converted into numerical lists. By denormalising these values relative to the image dimensions and aligning them with a defined plan origin, each opening was accurately drawn as a rectangular representation in its correct spatial location.

3. 1. 4. Extracting Relevancies

To ensure that each opening is accurately matched with its corresponding host wall, a two-step procedure was applied. First, due to inevitable discrepancies between the predicted coordinates of openings (obtained from the deep learning model) and their actual host walls in the Grasshopper environment, a geometric correction was introduced. Each wall was enclosed in a rectangular boundary generated using the Centre Box command, with its length equal to the wall's length and a constant width of 1.5 metres, a limit that was experimentally tuned. Whenever the centroid of an opening fell within this boundary, that wall was designated as its host. Subsequently, the centroid of the opening was projected onto the wall's centreline to guarantee precise alignment. This process was performed independently for doors and windows. Figure 5 shows the overall process of data extraction from the floor plan raster image.

In the implementation stage, the name of the host wall for each opening was extracted by midpoint matching: the midpoint of every detected opening host wall was compared against the placement coordinates stored in the JSON file of walls. When a correspondence within the predefined tolerance was found, the script assigned the respective wall's name to the opening. This ensured that each door and window in the output JSON was explicitly linked to its correct host wall.

23. Hanme Jang et al., 'Indoor Reconstruction from Floorplan Images with a Deep Learning Approach,' *International Journal of Geo-Information* 9, no. 2 (2020), https://doi.org/10.3390/ijgi9020065%3Furlappend=%3Futm_source=researchgate.

24. Chen Liu et al., 'Raster-to-Vector: Revisiting Floorplan Transformation,' *2017 IEEE International Conference on Computer Vision (ICCV)* (Venic), 2017, https://doi.org/10.1109/ICCV.2017.241.

25. Zhengda Lu et al., 'Data-Driven Floor Plan Understanding in Rural Residential Buildings via Deep Recognition,' *Xiaopeng* 567 (2021): 58–74, https://doi.org/10.1016/j.ins.2021.03.032.

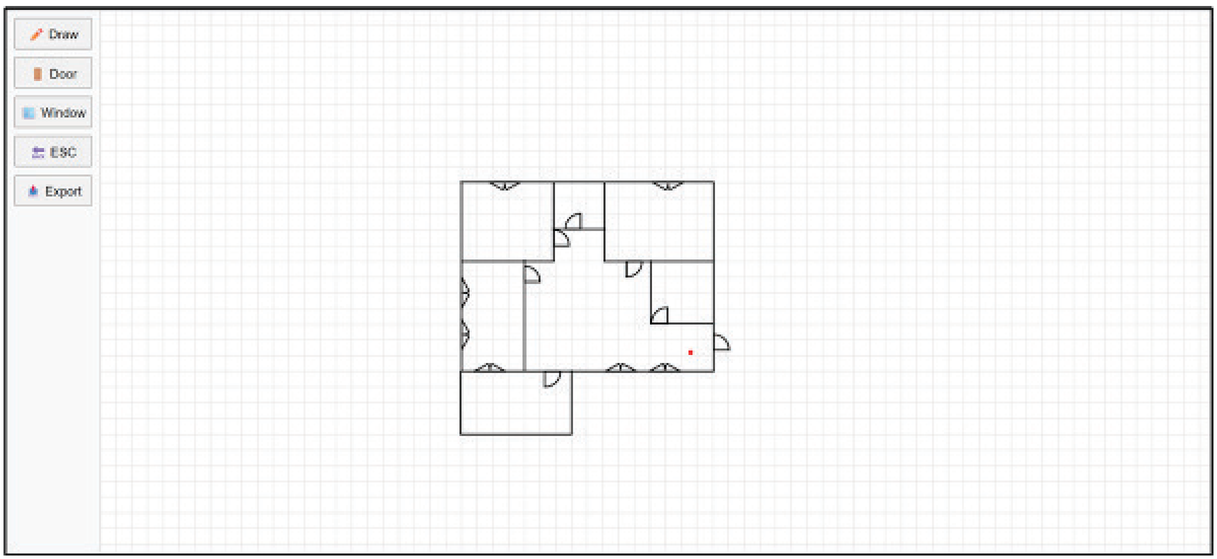


Figure 4. Developed GUI Environment for Plan Drawing.

3. 1. 5. OptimisationParameters and Penalty Functions

Although evolutionary multi-objective methods (e.g., NSGA-II) have been widely applied to structural optimisation,[43] discrete axis permutations in small-n combinatorial search may produce unstable convergence; hence, exhaustive screening with strict feasibility filtering was preferred. Candidate structural axes were extracted from wall positions and encoded as binary variables (0 = inactive, 1 = active). For n axes, 2^n permutations defined potential layouts (e.g., 512 configurations for nine axes). Column positions were derived from intersections of active axes within the floor boundary. To ensure that the optimised solution satisfies both structural and architectural requirements, six penalty functions are defined:

(1) Column–opening conflicts
(2) Cantilever lengths exceeding limits
(3) High variance in span lengths
(4) Spans outside permissible ranges
(5) Excessive column count
(6) Columns outside the plan boundaries

User-defined limits for span ranges and cantilever lengths provided adaptability across design contexts.

3. 1. 6. Optimisation Filtering and Exceptional Case Strategy

After structuring the permutations of potential structural axes and their associated penalty values, the next step involves identifying the optimal layout. Due to the discrete and non-gradual nature of variable changes, evolutionary algorithms such as the Genetic Algorithm failed to produce stable optimal solutions. Therefore, a brute-force search approach was adopted, evaluating all possible configurations while applying a strict screening system to eliminate infeasible options and prioritise solutions with lower penalty scores. The screening process consists of two main stages. In the first stage, any configuration violating hard constraints—such as exceeding the maximum allowable cantilever length or directly intersecting with existing openings—is removed. In the second stage, the remaining layouts are ranked based on a hierarchical evaluation of penalty criteria, with the most acceptable solutions placed at the top of the shortlist. Finally, the algorithm returns the five best-performing column arrangements as the final recommendation set.

Given the significant influence of parking

26. Yunfan Zhao et al., 'A YOLO-Based Method to Recognize Structural Components from 2D Drawings,' paper presented at Construction Research Congress: Computer Applications, Tempe, 2020, https://doi.org/10.1061/9780784482865.080.

27. Hugo Leon-Garza et al., 'A Type-2 Fuzzy System-Based Approach for Image Data Fusion to Create Building Information Models,' *Information Fusion* 88 (2022): 115–25, https://doi.org/10.1016/j.inffus.2022.07.007.

28. Omar Doukari and David Greenwood, 'Automatic Generation of Building Information Models from Digitized Plans,' *Automation in Construction* 113, no. 103129 (2020), https://doi.org/10.1016/j.autcon.2020.103129.

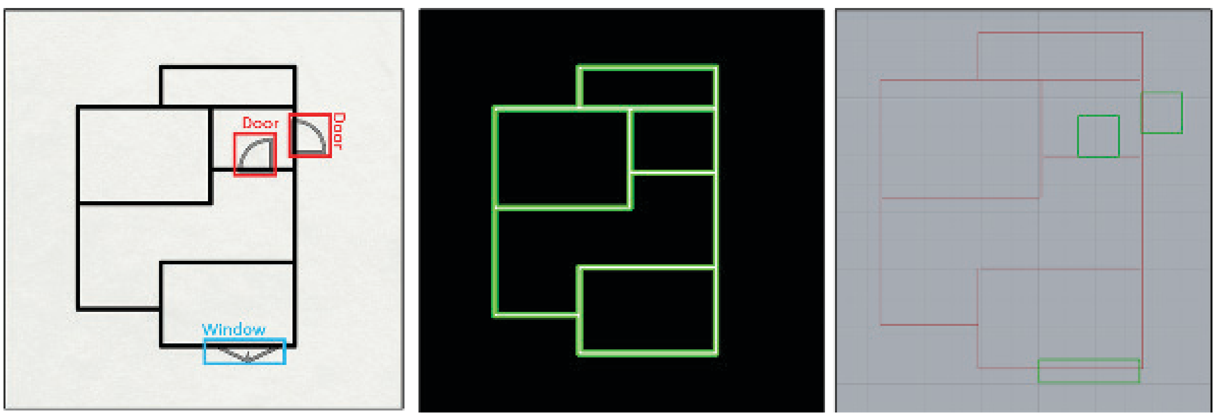


Figure 5. Data extraction process: (a) Opening detection using YOLO, (b) Wall extraction using OpenCV, (c) Vector data.

requirements on structural layouts, the optimisation process integrates parking design regulations. Based on Section 4 of the *National Building Regulations of Iran, Topic Four: General Building Requirements*,[44] the minimum centre-to-centre spacing between columns is set to 5 m for two parking bays and 7.5 m for three bays. Consequently, axis positions are adjusted to align with multiples of 2.5 m, ensuring compatibility with single,double- and triple-vehicle layouts. Internal walls and their associated openings are then aligned with the nearest parallel structural axes, while four boundary axes remain fixed to preserve the site limits.

In cases where no arrangement satisfied the strict constraints, an exceptional mode was activated, as shown in Figure 6. This mode allowed the introduction of off-grid columns and provided the user with the option to resolve conflicts either by relocating the opening or by shifting the column. In either case, the nearest potential structural axis perpendicular to the chosen relocation direction was identified, and the element was repositioned along this axis so that conflicts were removed while maintaining the regularity of the initial grid. This interactive adjustment ensured that even under highly constrained conditions, the final configuration preserved both architectural coherence and structural feasibility. Through this dual-stage screening process, combined with an exception-handling strategy, the proposed approach ensures that the selected structural layout achieves both geometric alignment with the architectural plan and compliance with performance-based constraints.

3. 2. IFC Model Generation

The final stage of the proposed framework focused on generating the IFC model from the processed floor plan data. All extracted and refined geometric information from Grasshopper was exported in a structured JSON format, automatically produced by custom scripts to ensure direct compatibility with the IFC generation workflow. This JSON file contained both geometric and semantic attributes for each architectural element, including walls, openings (doors and windows), columns, and slabs. For every element, properties such as name, type, dimensions (length, height, thickness), spatial coordinates (position and orientation),

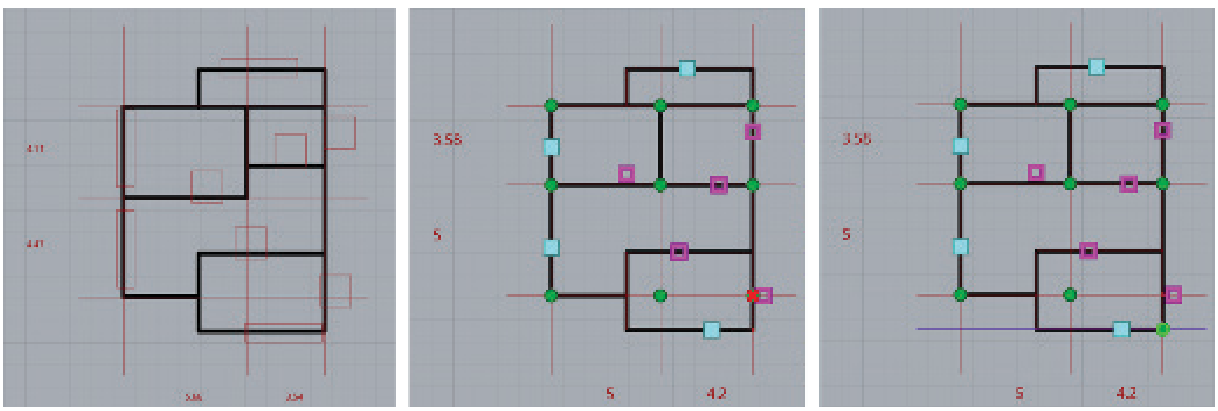


Figure 6. Plan adjustment based on parking performance on an exceptional mode.

29. Park and Kim, '3DPlanNet: Generating 3D Models from 2D Floor Plan Images Using Ensemble Methods.'

30. Sherif et al., 'Automated BIM-Based Structural Design and Cost Optimization Model for Reinforced Concrete Buildings.'

31. Kanyilmaz et al., 'A Genetic Algorithm Tool for Conceptual Structural Design with Cost and Embodied Carbon Optimization.'

32. Ampanavos et al., 'Structural Design Recommendations in the Early Design Phase Using Machine Learning.'

33. Zhang et al., 'End-to-End Generation of Structural Topology for Complex Architectural Layouts with Graph Neural Networks.'

34. Fu et al., 'Dual Generative Adversarial Networks for Automated Component Layout.'

and, where relevant, dependencies on other elements (e.g., the host wall for an opening) were defined.Table3 presents the data inputs required for each element category in the IFC creation process. The proposed workflow for automated IFC model generation is presented as a pseudocode in Algorithm 1.

Using the IfcOpenShell Python library, the JSON data was programmatically transformed into a structured IFC model. IfcOpenShell with Python scripting is now a common, robust approach to programmatic IFC generation that preserves both geometry and semantic attributes. This process ensured that the resulting 3D BIM model was ready for use in downstream design, coordination, and analysis workflows.

4. Results and Discussion

In this study, a three-stage framework was designed and implemented in which an initial architectural floor plan image is first interpreted through a dual approach, followed by the generation of an initial structural column layout based on functional design criteria, and finally, the automatic, programmatic conversion of 2D components into a 3D IFC model—a standard, interoperable format supported by BIM software.

Accordingly, this chapter presents the results and final evaluation of the research, focusing on these three main stages. In the first stage, the proposed hybrid method for floor plan interpretation is assessed in terms of accuracy, execution speed, and computational cost. The second stage evaluates the performance of the column layout recommendation algorithm by applying it to four real-world executed projects and comparing the proposed layouts with the actual column arrangements in the construction drawings. Finally, the third stage analyses the efficiency of IFC model generation in terms of speed and computational cost, comparing the proposed method with conventional IFC modelling approaches.

4. 1. Floorplan Interpretation Evaluation

In the rule-based component, the wall detection algorithm achieved a 100% accuracy rate in correctly identifying wall lines. Compared to the study by, which reported an 86% accuracy, this represents a substantial improvement in extracting precise linear structures from 2D plans.The results of the deep learning module were assessed using four metrics: precision, recall, mAP50, and mAP50:95. Precision measures the proportion of correctly predicted positive instances among all predictions the model labelled as positive. A high precision value indicates fewer false positives.Recall represents the proportion of correctly identified positive instances among all actual positive instances in the dataset. A high recall score means the model rarely misses actual elements, even if it produces some false positives.mAP50 (mean Average Precision at IoU = 0.5) is the average of the precision values calculated across all classes when the Intersection over Union (IoU) threshold is set to 0.5. This metric evaluates whether

35. Shan et al., 'Integrated Method for Intelligent Structural Design of Steel Frames Based on Optimization and Machine Learning Algorithm.'

36. Meng et al., 'Optimizing Support Locations in the Roof–Column Structural System.'

37. Doukari and Greenwood, 'Automatic Generation of Building Information Models from Digitized Plans.'

38. Urbieta et al., 'Generating BIM Model from Structural and Architectural Plans Using Artificial Intelligence.'

39. Leon-Garza et al., 'A Type-2 Fuzzy System-Based Approach for Image Data Fusion to Create Building Information Models.'

Table 3. Data inputs for IFC generation in IfcOpenShell.

Category	Data Inputs
IfcWall	name, length, height, placement, x_axis, z_axis, predefined_type
IfcSlab	slab_outline, slab_depth,
IfcWindow, IfcDoor, IFCOpeningElement	name, type, length, height, thickness, placement, x_axis, z_axis, host_wall_name
IfcColumn	name, size, height, placement, x_axis, z_axis

the predicted bounding boxes sufficiently overlap with the ground truth, providing a measure of overall detection accuracy under a moderate standard.mAP50-95 extends this evaluation by calculating mean Average Precision across multiple IoU thresholds, ranging from 0.5 to 0.95 in steps of 0.05. This stricter metric requires higher overlap between predictions and ground truth to count as correct, and thus offers a more rigorous assessment of a model's localisation accuracy and robustness.

A comparison of the trained YOLO model's performance in this study with results from previous research (Table4) shows that, although the precision value of 0.63 is lower than in some earlier works, the recall of 0.97 is significantly higher[45]. The high recall indicates that the model successfully detected almost all actual doors and windows in the floor plans, whereas the relatively low precision reflects false positivecases where the model predicted the presence of an element that was not actually in the image. This limitation may stem from visual similarities between classes, low-quality or noisy images, or an imbalance in the number of training samples. To address this, several improvements are suggested, such as increasing the diversity and quality of training data, fine-tuning the confidence threshold, applying post-processing filters to remove low-confidence detections, and including training images deliberately devoid of certain classes to improve the model's understanding of 'object absence' and thus reduce false positives. Overall, the model demonstrated better performance in detecting windows compared to doors, likely due to the greater geometric detail in window forms, which makes them more distinguishable from the background.

```
Procedure Build_IFC()

file ⟵ create IFC4 file
assign units + contexts
create site, building, storeys

define surface styles (wall/slab/door/window/column)

# Walls
load Walls.json
for each wall:
  create IfcWall
  assign to Ground Storey
  add wall representation (extrusion)
  place via placement_matrix
  apply wall style

# Slab (as IfcFooting)
load Slab.json
create IfcFooting
assign to Ground Storey
profile + extrude geometry
apply slab style

# Openings (voids only)
load Opening.json
for each opening:
  create IfcOpeningElement
  assign to Ground Storey
  add rectangular void geometry
  place via placement_matrix
  link to host via IfcRelVoidsElement

# Doors / Windows (no Fills relation)
create IfcDoor / IfcWindow from JSON where type matches
assign to Ground Storey
add representation + style

# Columns
load Columns.json
create IfcColumn
assign to Ground Storey
square profile + extrude
place + style

# Multi-storey replication
duplicate_elements_to_storeys(walls, slab, doors, windows,
columns)
duplicate_openings_to_storeys(openings)

file.write(output_path)
```

Algorithm 1. Automated multi-storey IFC model generation from JSON-based architectural and structural data.

40. Zhao et al., 'Reconstructing BIM from 2D Structural Drawings for Existing Buildings.'

41. Leon-Garza et al., 'A Type-2 Fuzzy System-Based Approach for Image Data Fusion to Create Building Information Models.'

42. Myunghyun Jung et al., 'Analysis of the Floor Plan Dataset with YOLOv5,' *Journal of the Korean Society for Industrial and Applied Mathematics* 26 (2023): 311–23, https://doi.org/10.12941/jksiam.2023.27.311; Zhongguo Xu et al., 'Multiscale Object Detection on Complex Architectural Floor Plans,' *Automation in Construction* 165, no. 105486 (2024), https://doi.org/10.1016/j.autcon.2024.105486.

In terms of accuracy metrics, the model achieved an mAP50 of 0.902, indicating precise localisation and sizing of elements at the 0.5 IoU threshold, comparable to prior studies.[46] The mAP50-95 score of 0.816—higher than those reported in previous works.[47]—confirms the model's robustness in maintaining high prediction accuracy under stricter IoU thresholds. These results collectively demonstrate that the proposed dual-approach method effectively combines rule-based precision for wall extraction with deep learning's high recall for opening detection, resulting in a reliable interpretation of floor plan images.In terms of computational efficiency, the optimal model processed each image in an average of 0.0041 seconds, outperforming previous studies utilising YOLO[48] by 99% and Faster R-CNN[49] by 46%.

Notably, since the YOLO model was trained on images with dimensions of 640×640 pixels for opening detection, reducing the input resolution is expected to increase the likelihood of errors in identifying either the presence or the precise location of these elements. In contrast, for wall detection using the rule-based algorithm, a reduction in resolution does not affect performance, provided that the input image is free from noise.

4. 1. 1. Hyperparameter Sensitivity Analysis

In the training process of the YOLO model, the outcomes were significantly influenced by the selected hyperparameter values; however, the model exhibited varying levels of sensitivity to each parameter. In this study, the number of epochs was set to 100. Nevertheless, due to an early stopping threshold of 20 epochs and the absence of improvements in evaluation metrics between epochs 60 and 80, the training process was terminated at epoch 80. This indicates that increasing the number of epochs did not yield meaningful performance gains and merely increased computational costs. The batch size was set to 32, which provided a suitable balance between training speed and gradient stability. Although larger batch sizes could potentially enhance learning, they would also considerably increase computation time and resource requirements. Among all hyperparameters, the learning rate was identified as the most influential factor in determining model performance. A very small initial learning rate of 0.0001 was adopted to ensure stability in reaching optimal weights and to prevent high fluctuations in results, despite reducing the convergence speed. Furthermore, a weight decay value of 0.0005 played a crucial role in controlling model complexity; higher values reduced overfitting, whereas lower values impaired generalisation. Overall, the sensitivity analysis revealed that the final accuracy of the model was most dependent on the learning rate parameters (Lr0 and lrf) and the weight decay.

4. 1. 2. Noise Sensitivity Analysis

To evaluate the impact of image resolution on model performance, the YOLOv11L network was trained on three input sizes: 512, 768, and 864 pixels. The results, illustrated in **Figure 7,** indicate that the total precision reached its peak value of 0.637 at a resolution of 768 pixels, with no further improvement at higher resolutions. Similarly, mAP50 achieved its highest score of 0.902 at 768 pixelsand remained nearly unchanged when the image size was increased to 864. The mAP50–95 metric exhibited a moder-

43. Yaping Lai et al., 'BIM-Based Intelligent Optimization of Complex Steel Joints Using SVM and NSGA-II,' *Journal of Constructional Steel Research* 223, no. 109086 (2024), https://doi.org/10.1016/j.jcsr.2024.109086.

44. *National Building Regulations of Iran, Topic Four: General Building Requirements*, Road, Housing & Urban Development Research Center, 2017.

45. Liu et al., 'Raster-to-Vector: Revisiting Floorplan Transformation'; Zhao et al., 'A YOLO-Based Method to Recognize Structural Components from 2D Drawings'; Zhao et al., 'Reconstructing BIM from 2D Structural Drawings for Existing Buildings.'

46. Urbieta et al., 'Generating BIM Model from Structural and Architectural Plans Using Artificial Intelligence'; Zhao et al., 'Reconstructing BIM from 2D Structural Drawings for Existing Buildings.'

47. Barreiro et al., 'Automatic Reconstruction of Semantic 3D Models from 2D Floor Plans'; Jang et al., 'Indoor Reconstruction from Floorplan Images with a Deep Learning Approach.'

ate rise from 0.755 to 0.816 as the resolution increased from 512 to 768, but did not show further enhancement beyond that point. In contrast, the recall metric demonstrated a steady improvement, increasing from 0.979 to 0.996 as resolution grew. Although the overall detection accuracy metrics were only slightly affected by resolution, the computational speed showed a significant variation—rising from 0.0024 SPI at 512 to 0.0041 SPI at 768 and 0.0051 SPI at 864. These results suggest that a resolution of 768 pixels offers the optimal balance for this dataset, achieving the highest precision and mAP50 values while maintaining a favourable processing speed.

4. 1. 3. Assessment of Geometric Relation Extraction

The performance evaluation of the proposed algorithm for extracting geometric relationships indicates that this method, by relying on the detection of the central point of an opening within the boundaries of its host wall, could accurately identify the corresponding host wall and correctly classify the opening type (door or window) in all experiments. The extracted geometric relationships play a critical role in generating the IFC model, as the accurate creation of elements in the model depends on the precise association of each opening with its host wall.

4. 1. 4. Efficiency Gains through the Hybrid Detection Pipeline

The dual approach proposed in this research, despite relying on a simpler labelling process, achieved enhanced accuracy in opening detection compared to previous studies and reached 100% precision in wall recognition. Notably, the object labelling and dataset generation process—which is typically a labour-intensive and time-consuming task—was automated through the developed data preparation method, achieving an average generation speed of 1.27 images per second. This performance represents an acceptable rate for such computationally demanding processes.

48. Zhao et al., 'A YOLO-Based Method to Recognize Structural Components from 2D Drawings.'

49. Zhao et al., 'Reconstructing BIM from 2D Structural Drawings for Existing Buildings.'

Table 4. Comparison of the Performance of the Proposed Deep Learning Model with Previous Studies.

Method	Precision	Recall	mAP50	mAP50-95	Number of Initial Data	Hardware Capacity (GB)	Computational Speed (seconds/ image)
Proposed model in this study (YOLO)	0.63	0.97	0.902	0.816	9,600	Nvidia A100 (80)	0.0041
YOLO (Zhao et al., 2020)	0.80	0.90	—	—	450	Nvidia GeForce GTX 1080 (8)	0.63
Faster R-CNN(Zhao et al., 2021)	0.94	0.91	0.90	—	4000	GeForce RTX 2080 Ti (11)	0.0077
Faster R-CNN (Barreiro et al., 2023)	—	—	—	0.80	5,000	—	—
Mask R-CNN (Urbieta et al., 2023)	—	—	96.7	—	50,000	Nvidia A100	0.0002
CNN (Jang et al., 2020)	—	—	—	0.78	319	—	—
ResNet (Liu et al., 2017)	0.67	0.91	—	—	870	—	—

4. 2. Evaluation of the Proposed Column Layout Recommendation Algorithm

Beyond producing automated recommendations, the framework is designed to actively involve users in the decision-making process. Designers can define key parameters—such as allowable cantilever length and permissible span range—and adjust the relative hierarchies of penalty functions that guide the sorting procedure. This flexibility enables them to prioritise criteria such as structural regularity, span uniformity, or minimal column count according to project-specific needs. From the ranked set of five optimal layouts generated for each plan, users can then select their preferred arrangement.

To evaluate the effectiveness of this interactive recommendation process, the algorithm was tested on four real-world architectural floor plans from previously executed projects. For each case study, the algorithm produced five candidate solutions, with the configuration exhibiting the highest similarity to the actual built layout selected as the representative output for assessment. A geometric matching criterion was employed to quantify similarity, where a proposed column location was considered a match if it fell within a predefined threshold radius (e.g., 50 cm) of any actual column location. The overall similarity percentage was subsequently calculated as the ratio of matched columns to the total number of proposed columns.

The results demonstrated that, in three out of the four examined cases—including one involving exceptional design conditions—the proposed algorithm achieved complete alignment (100%) with the real-world column arrangement. In the remaining case, the match rate was 83.33%, still indicative of a high degree of agreement with structural engineering decisions. Overall, the algorithm attained an average prediction accuracy of 95.83% across the four case studies, which is competitive with prior research, including[50] (97.79%),[51] (97%), and[52] (93.6%) performance score relative to expert evaluations). A visual comparison between the proposed and actual layouts is presented in Figure8.

In terms of ranking the final valid column layouts, the predefined prioritisation scheme yielded satisfactory results in most experimental cases. However, altering the order of these priorities led to variations in the outcomes: in some cases, producing configurations with higher applicability, while in others reducing the overall quality of the results. Consequently, it was determined that the order of the criteria should be made user-adjustable, thereby allowing practitioners to tailor their influence according to the specific requirements of each project.

4. 3. Performance and Applicability of the Proposed IFC Model Generation Algorithm

Figure 9 illustrates the workflow results on three sample floor plans, from plan interpretation through column recommendation to 3D IFC generation. Visual inspection indicates that the generated IFC model occasionally exhibits minor deficiencies in details—such as the connection of orthogonal walls—which can be resolved through refinement of the input data. Nevertheless, in conventional BIM-authoring software such as Revit, the process of producing an IFC model, even for experienced users, may require several hours to an entire working

50. Ampanavos et al., 'Structural Design Recommendations in the Early Design Phase Using Machine Learning.'

51. Zhang et al., 'End-to-End Generation of Structural Topology for Complex Architectural Layouts with Graph Neural Networks.'

52. Fu et al., 'Dual Generative Adversarial Networks for Automated Component Layout.'

day, depending on the plan's complexity. In contrast, the algorithm developed in this research, implemented using the IfcOpenShell library, is capable of converting vectorised floor plan data into a 3D IFC model—including walls, doors, windows, floors, and columns—in less than one minute. This initial model can subsequently be semantically enriched with additional data for use across a wide range of structural and energy analysis software, such as Simergy and ETABS, as well as other IFC-based modelling tools. Providing such a model in the early design stages, particularly during conceptual phases, can play a significant role in fostering coordination among multidisciplinary teams and facilitating engineering decision-making. Figure 10illustrates the application of the model in Revit for generating preliminary material estimates.

4. 4. Computational Resources

In terms of computational requirements, the deep learning model was trained on an NVIDIA A100 GPU with 80 GB of memory using Google Colab. The complete training process required approximately 2.7 hours,

which is considered efficient given the dataset size and model complexity. The column arrangement recommendation algorithm, in turn, was implemented on an NVIDIA GeForce RTX 3070 GPU with 8 GB of RAM.

5. Limitations

This research introduces a three-stage framework that improves upon previous methods in floor plan interpretation, structural layout suggestion, and automated IFC model generation. By integrating geometric logic with a lightweight YOLO-based detection model, the proposed approach achieves competitive accuracy with high processing speed. The column layout algorithm uniquely incorporates architectural and spatial performance criteria, producing arrangements that are both structurally efficient and spatially coherent. The IFC generation process further accelerates early design workflows and enhances multidisciplinary collaboration by providing a ready-to-use, BIM-compliant 3D model. However, the framework has certain limitations that will be discussed in this section.

5. 1. Limitations in Input Data

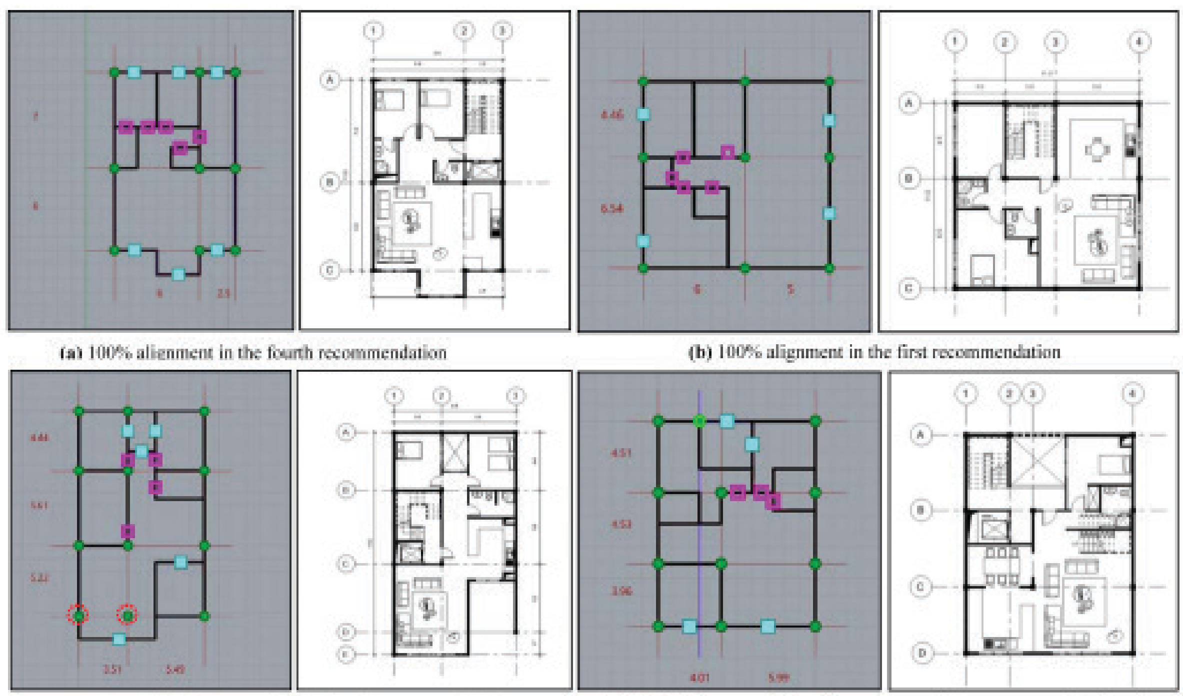
In this study, certain architectural features—such as spatial functions, enclosed or semi-open configurations, the presence of voids, staircases, and other specialised elements—were not incorporated into the modelling process. Including these features in future studies could enhance the accuracy of analyses and improve the model's alignment with real-world project conditions. From the perspective of plan image interpretation, the YOLO model employed in

Figure 7. Comparison of achieved metrics (Precision, Recall, mAP@50, mAP@50–95) across three training runs using input resolutions of 512, 768, and 864.

this study is currently capable of detecting only a limited and specific set of door and window symbols. Other elements, such as furniture or uncommon symbols, fall outside the model's recognition scope. Expanding the range of detectable classes could improve the model's accuracy and applicability when processing diverse architectural plans. Furthermore, the current plan geometry analysis algorithm is compatible only with orthogonal structures and straight walls, and does not support plans with unconventional angles, hand-drawn irregular lines, or curved walls. Extending the capability to recognise and model such structures represents a key avenue for future development of this research.

5. 2. Limitations in Column Arrangement Recommendation

In the structural layout recommendation section, the optimisation algorithm is designed solely based on initial geometric and functional criteria, without incorporating technical and structural considerations such as load-bearing capacity, stability, ductility, or code compliance. Integrating structural requirements with functional criteria could enhance the accuracy and reliability of the proposed algorithm. Another limitation of the algorithm is the extended processing time required for complex initial plans; as plan complexity increases, the algorithm's runtime grows nonlinearly. Figure 11illustrates the execution time of the algorithm for plans



(a) 100% alignment in the fourth recommendation

(b) 100% alignment in the first recommendation

(c) 83.33% alignment in the fourth recommendation

(d) 100% alignment in the first recommendation on exceptional mode

Figure 8. Results of the Algorithm for Initial Column Placement in Four Built Plan Case Studies.

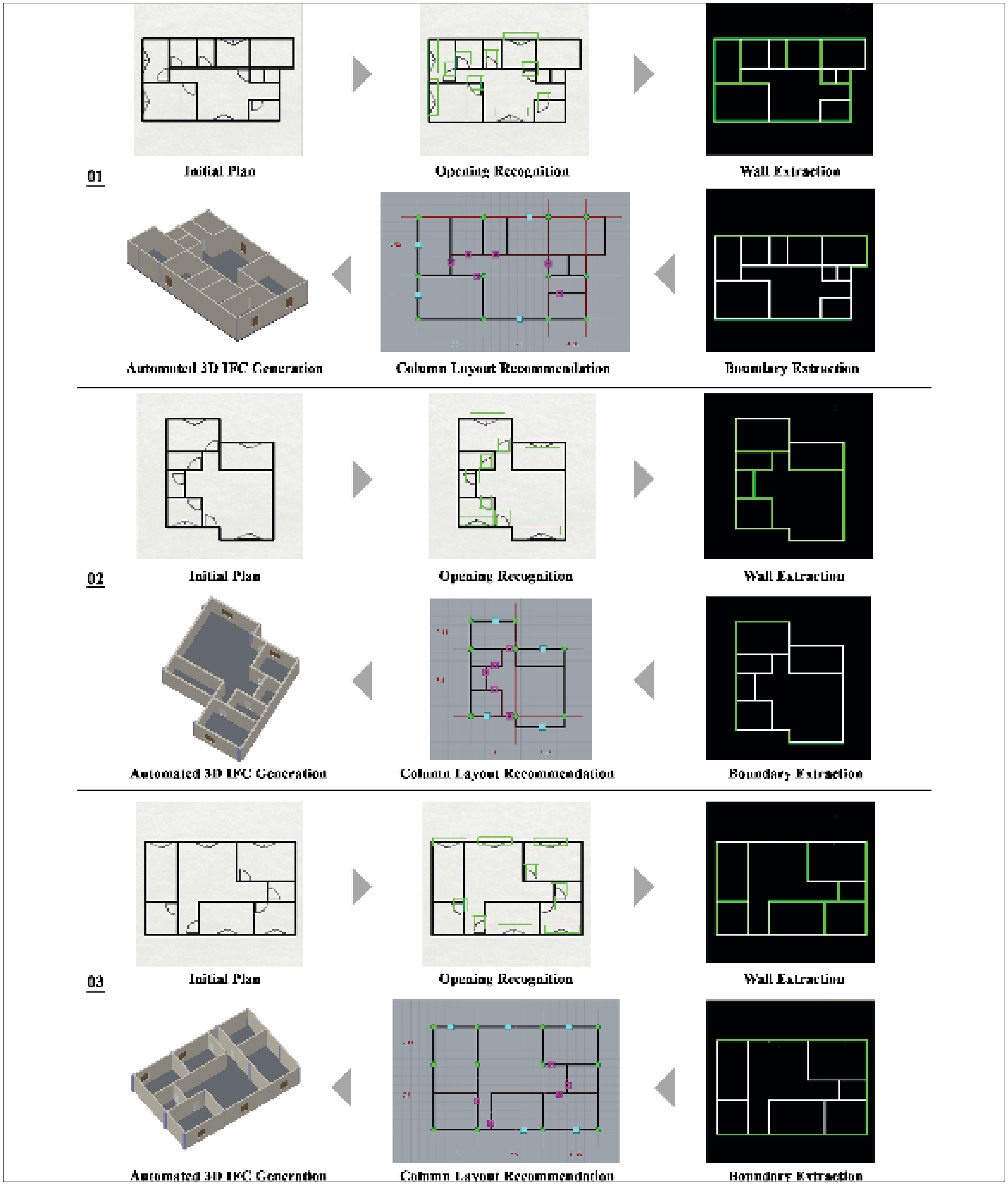


Figure 9. Overall workflow on sample plans.

with varying numbers of layouts. Modifications in the solution generation structure and the filtering of invalid solutions, combined with the adoption of metaheuristic approaches, could reduce processing time.

5. 3. Limitations in IFC Model Generation

In the IFC generation algorithm, horizontal structural elements, such as beams, have not been considered. Incorporating these components in future developments could significantly enhance the completeness of the structural model and its analytical capabilities. Moreover, to improve the compatibility of the generated 3D model with structural and energy analysis software, it is essential to enrich the model across multiple dimensions, enabling accurate and comprehensive analyses.

6. Conclusion and Further Work

The developed framework introduces an automated three-stage pipeline for converting simplified 2D architectural floor plans into fully BIM-compliant IFC models, integrating hybrid drawing interpretation, a performance-oriented column layout suggestion algorithm, and a structured IFC generation strategy. In this workflow, the purpose of IFC creation is not merely

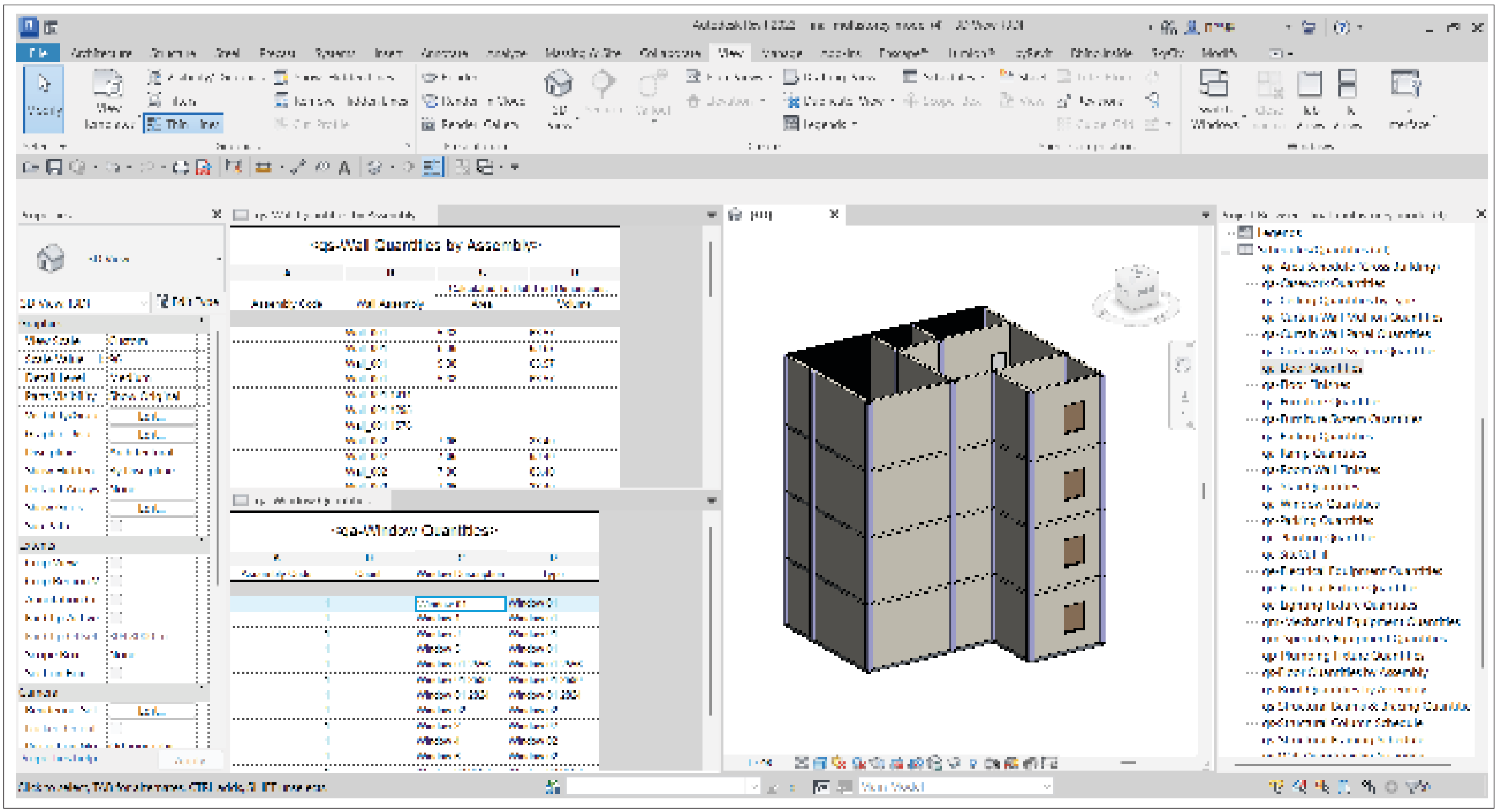


Figure 10. Application of the IFC model in Revit for generating preliminary material estimates.

the geometric reconstruction of building components; instead, it establishes a reliable data backbone that enables direct interoperability with widely adopted multidisciplinary platforms. The resulting IFC models seamlessly support architectural modelling and coordination in Revit, Archicad, Navisworks, and BlenderBIM; structural design and assessment in Robot Structural Analysis, Tekla Structures, and ETABS; and energy-performance simulation in environments such as Simergy, IES-VE, and RIUSKA.

By enabling these analytical pathways at the conceptual design stage, the proposed pipeline significantly accelerates early decision-making, facilitates communication among architects, engineers, and energy analysts, and strengthens the foundation for performance-driven design exploration long before detailed modelling typically begins. The evaluation results confirmed its competitive accuracy, high computational efficiency, and adaptability to practical design contexts, highlighting its potential to enhance collaboration across disciplines and reduce rework in downstream phases.

However, current constraints—including the limited scope of recognised architectural symbols, the assumption of orthogonal geometries, the absence of certain structural elements in the output, and increased processing time in highly intricate plan configurations—still restrict the full generalisation of the approach. Future extensions focused on enriched object recognition, support for non-standard and freeform geometries, deeper incorporation of structural and energy-performance metrics, and improved semantic modelling can further elevate the applicability and intelligence of this framework. With these advancements, the pipeline can evolve into a domain-ready solution that effectively bridges the gap between early-stage design intent and comprehensive BIM-based analytical workflows, ensuring that IFC generation becomes a catalyst for the integrated, high-quality development of the built environment.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Declaration of Generative AI and AI-Assisted Technologies in the Writing Process

During the preparation of this work, the authors used ChatGPT (OpenAI) as a writing assistant in order to improve the clarity, coherence, and readability of the manuscript. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

Data Availability

Data will be made available on request.

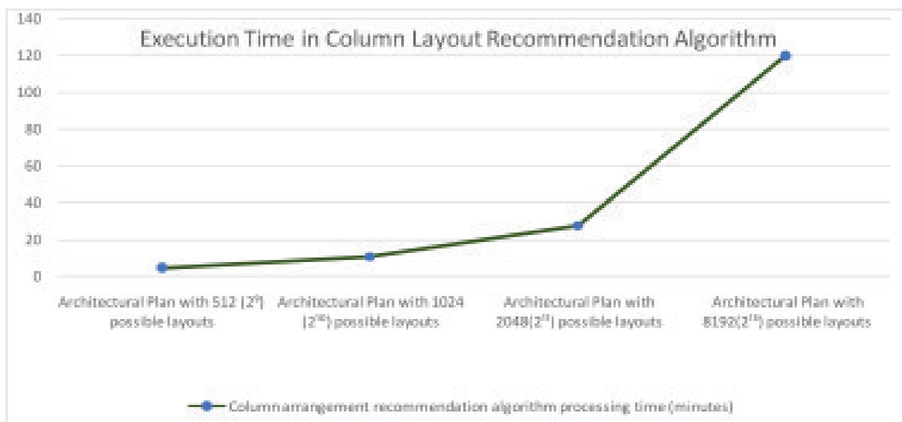


Figure 11. Execution Time in Column Layout Recommendation Algorithm.

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The Structure of Form: Le Corbusier's 'The Five Points of a New Architecture'

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ORIGINAL RESEARCH ARTICLE

Hadighi, Mehrdad. "The Structure of Form: Le Corbusier's 'The Five Points of a New Architecture'". *Soffeh* 36, no. 2 (2026): 109–126. DOI: http://doi.org/10.48308/soffeh.2026.106789

Abstract

Background and Objectives: Le Corbusier is predominantly recognised for his declarative and often dogmatic writing style, particularly regarding 'The Five Points of a New Architecture'. This paper investigates the parallels between the recorded written histories of these points and Le Corbusier's built works during the 1920s. The primary aim is to provide a nuanced perspective on the development of the 'Five Points', contextualising them within a body of architectural works rather than treating them as a sudden theoretical epiphany. By re-examining what appears to be a rigid doctrine, this study explores the architectural and aesthetic potential of reinforced concrete as a cohesive structuring system.

Materials and Methods: The study employs a comparative methodology, juxtaposing written histories with built artefacts. Archival research at the Foundation Le Corbusier and historical analyses of various editions of the *Œuvre* Complète were combined with detailed case studies of four pivotal villas: Villa Besnus (1922), Villa Stein-de Monzie (1927), the Weissenhofsiedlung Houses (1927), and Villa Savoye (1929). The analysis involves comparing as-drawn and as-built drawings

Received: October 05, 2025
Revised: November 14, 2025
Accepted: November 17, 2025
(Pages: 109–126)

Keywords:
Framing, Narrative, Storytelling, Design process, Design research.

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http://doi.org/10.48308/soffeh.2026.106789

Research Questions:

1. How did Le Corbusier's 'Five Points of a New Architecture' evolve practically through his built works during the 1920s, rather than emerging as a sudden theoretical epiphany?

2. What are the key incongruities between Le Corbusier's theoretical proclamations (and published drawings) and the actual constructive realities in pivotal case studies such as Villa Besnus, Villa Stein-de Monzie, and the Weissenhofsiedlung Houses?

3. In what ways did the architectural and aesthetic potential of the reinforced concrete frame drive the codification and materialisation of the 'Five Points'?

4.How do Le Corbusier's built works from this period reflect the tension between systematic geometric organisation and the singularity of spatial experience (or plastic form)?

to identify incongruities between theoretical proclamations and constructive realities. The analysis reveals that the 'Five Points' were not formulated instantaneously but evolved through successive construction trials. In the 1922 Villa Besnus, while the 'free plan' was nascent, the other points remained uncodified, with columns concealed within perimeter walls. By 1927, Villa Stein-de Monzie demonstrated an advanced exploration of reinforced concrete, yet exhibited a 'misalignment' between technical necessity and aesthetic ideal; notably, Le Corbusier eliminated two structural columns from the published plans to preserve the appearance of geometric order. Full alignment was achieved in the Weissenhof houses, where the technical requirements of the reinforced concrete frame finally mirrored the aesthetic expression predicted by the 'Five Points'.

Results and Conclusion: The study concludes that the 'Five Points' emerged from a constant tension between systematic geometric organisation and the singularity of spatial experience. Rather than mere stylistic dogmas, these principles served to concretise the architectural possibilities afforded by the reinforced concrete frame. The findings suggest that Le Corbusier's architecture was a persistent struggle to materialise plastic form within rationalised building systems.

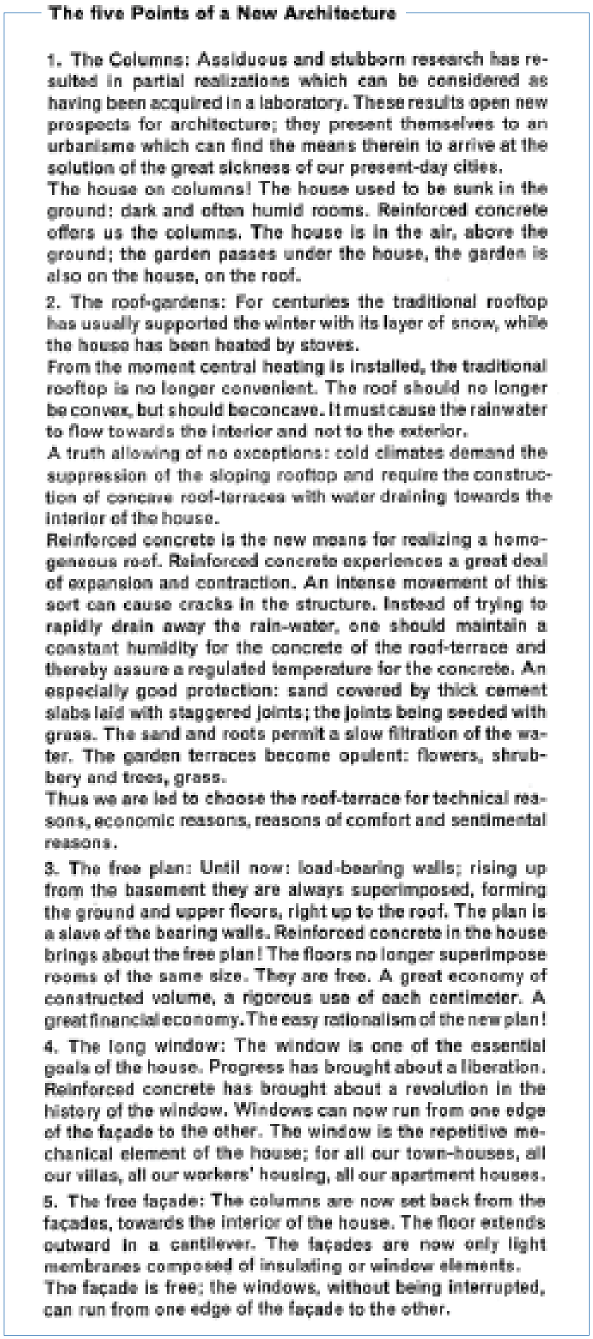
1.Introduction

Le Corbusier is recognised for a distinctive style of writing—emphatic, declarative, and bordering on dogmatic. In a book-length study,[1] I have argued that behind the mask of dogma, constructed by Le Corbusier himself and perpetuated by architects and historians, the buildings convey a different message. When examined through close reading, his built work reveals the architect's persistent struggle to materialise singular formal and spatial experiences within the framework of rationalised building systems. He sought to create plastic experiences that could not be conceived within the strict geometry of technical building systems. Le Corbusier manipulated the components of these two architectural conditions, technical systems and plastic forms

1. Mehrdad Hadighi, *Le Corbusier's Ahmedabad Millowners' Association Building: Between the Beautiful and The Sublime* (Basel, Switzerland: Birkhäuser, 2025).

and spaces, to simultaneously address systemic technical requirements and intensify plastic spatial and formal qualities. While deeply committed to the ideal of rationality and geometric order inherent in building systems, his work pursued a more complex agenda: to craft singular plastic experiences of space and form through the deliberate engagement of an architecture conceived within systemic and geometric terms. Ultimately, his architecture emerged from a constant tension between these two realms: the systematic and geometric organisation of building systems (structural, plumbing, sun-shading, circulation) and the singularity of spatial experience realised through movement in space. The 'Five Points' exemplify this proposition, as they stem from the strict geometry and principles of reinforced concrete construction, yet they formulate an aesthetic experience of form and space that has been freed from the regimens of the building systems. In this light, I will analyse four villas designed by Le Corbusier and Jeanneret during the 1920s that coincide with the timing of the texts that have been associated with the 'Five Points'. The villas will be examined in the context of the relationship between structure and form in reinforced concrete.

As regimens the abstract, Le Corbusier's 'Five Points' have been associated with multiple sources ranging from the essays of the early 1920s to the formally published version of 1929. The first of these sources are the essays Le Corbusier published in *L'Esprit Nouveau*, the journal he founded in 1920 with painter Amédée Ozenfant, and poet Paul Dermée. Twenty-eight *L'Esprit Nouveau* issues were published between 1920 and 1925, including regular con-



The five Points of a New Architecture

1. The Columns: Assiduous and stubborn research has resulted in partial realizations which can be considered as having been acquired in a laboratory. These results open new prospects for architecture; they present themselves to an urbanisme which can find the means therein to arrive at the solution of the great sickness of our present-day cities.
The house on columns! The house used to be sunk in the ground: dark and often humid rooms. Reinforced concrete offers us the columns. The house is in the air, above the ground; the garden passes under the house, the garden is also on the house, on the roof.

2. The roof-gardens: For centuries the traditional rooftop has usually supported the winter with its layer of snow, while the house has been heated by stoves.
From the moment central heating is installed, the traditional rooftop is no longer convenient. The roof should no longer be convex, but should beconcave. It must cause the rainwater to flow towards the interior and not to the exterior.
A truth allowing of no exceptions: cold climates demand the suppression of the sloping rooftop and require the construction of concave roof-terraces with water draining towards the interior of the house.
Reinforced concrete is the new means for realizing a homogeneous roof. Reinforced concrete experiences a great deal of expansion and contraction. An intense movement of this sort can cause cracks in the structure. Instead of trying to rapidly drain away the rain-water, one should maintain a constant humidity for the concrete of the roof-terrace and thereby assure a regulated temperature for the concrete. An especially good protection: sand covered by thick cement slabs laid with staggered joints; the joints being seeded with grass. The sand and roots permit a slow filtration of the water. The garden terraces become opulent: flowers, shrubbery and trees, grass.
Thus we are led to choose the roof-terrace for technical reasons, economic reasons, reasons of comfort and sentimental reasons.

3. The free plan: Until now: load-bearing walls; rising up from the basement they are always superimposed, forming the ground and upper floors, right up to the roof. The plan is a slave of the bearing walls. Reinforced concrete in the house brings about the free plan! The floors no longer superimpose rooms of the same size. They are free. A great economy of constructed volume, a rigorous use of each centimeter. A great financial economy. The easy rationalism of the new plan!

4. The long window: The window is one of the essential goals of the house. Progress has brought about a liberation. Reinforced concrete has brought about a revolution in the history of the window. Windows can now run from one edge of the façade to the other. The window is the repetitive mechanical element of the house; for all our town-houses, all our villas, all our workers' housing, all our apartment houses.

5. The free façade: The columns are now set back from the façades, towards the interior of the house. The floor extends outward in a cantilever. The façades are now only light membranes composed of insulating or window elements.
The façade is free; the windows, without being interrupted, can run from one edge of the façade to the other.

Figure 1. Le Corbusier and Pierre Jeanneret, 'The Five Points of a New Architecture,' as translated in the single-volume *Œuvre* Complète, Le Corbusier 1910-1965 (Zurich, Switzerland: Les Editions d'Architecture Zurich, 1967), 44.

tributions on architecture by Le Corbusier. Many of the essays were collected into the book *Towards a New Architecture*,[2] with the French title, *Vers Une Architecture*, published in 1923 by Éditions Crès.[3] Had the 'Five Points' been outlined in these essays, it would suggest that many of the early villas, Besnus in Vaucresson of 1922, Ozenfant in Paris of 1922, the L'Esprit Nouveau pavilion of 1922, and the La Roche-Jeanneret house in Paris of 1923 would have been developed along with the 'Five Points'. The analysis of the Villa Besnus will show whether the 'Five Points' were outlined succinctly enough to be theoretically and constructively clear for this early villa. Werner Oechslin published an original typed text with handwritten corrections by Le Corbusier and Pierre Jeanneret sent to Alfred Roth, dated July 24, 1927, on the occasion of the two residential buildings designed for Weissenhofsiedlung in Stuttgart. A modified version of this text was then published in the 1929 printing of the first edition of the *Œuvre Complète de 1910-1929*.[4] Oechslin points to a revision in the 1927 text: from 'fréquentes,' (frequent) to 'successives' (successive). The opening remarks of Le Corbusier and Pierre Jeanneret's typed text read: 'These are the theoretical conclusions drawn from frequent (→successive) observations made on construction sites over several years. The theoretical explication leads to the simplicity of the formula.'[5] The revision from frequent to successive highlights the decisive nature of the trials on the construction site. These were not just frequent observations, rather successive, repeated and consecutive construction trials. Thus, tying the five points to construction practices, and not simply theoretical observations. In this light, we recognise that the five points did not and could not emerge suddenly from a burst of genius. They were, rather, the result of many years of construction practice, observations, analyses, and conclusions. They could only have emerged after the many trials that were conducted in the 1920s by Le Corbusier and Pierre Jeanneret. The following analysis will point more specifically to the ideas that were tested in each villa toward their development as the 'Five Points'.

2. Methods

First and foremost, this is a comparative study, comparing written histories with built artifacts. For the written histories, I combine archival research at the Foundation Le Corbusier with historical research of different editions of the *Œuvre Complète*, and other texts on the villas. For the built artifacts, I utilise a set of case studies and analyse them to understand the role of material, construction technique, and structure in their formulation. I also compare as-drawn, and as-built drawings with images of the physical conditions. The earliest of these free-standing villas is the 1922 Villa Besnus at Vaucresson. Its timing aligns perfectly with *Vers Une Architecture*, one of the commonly assumed sources of the 'Five Points'. The next Villa is the 1927 Villa Stein-de Monzie, aligning with the publication of the essay in *L'Architecture Vivante* on 'The Theory of the Roof Garden.' Next in my analysis is the double-house, Houses 14 and 15, designed for the Weissenhofsiedlung exhibition of 1927, noted by the architects as the pretext for the announcement of the 'Five Points'. In addition, the opening of the building exhibition aligns perfectly with the typed text of the 'Five Points' sent by Le Corbusier and Jeanneret to Al-

2. Charles-Éduard Jeanneret (Le Corbusier). *Towards a New Architecture.* Translated by Frederick Etchells. (New York, Toronto, London, Sydney: Holt, Reinhart and Winston, 1946).

3. Le Corbusier and Pierre Jeanneret, *Vers Une Architecture* (Paris, France: Éditions Crès, 1923)

4. Le Corbusier and Pierre Jeanneret, *Œuvre Complète de 1910-1929* (Zurich, Switzerland: Les Editions d'Architecture, 1929), 128-129.

5. The original typed text by Le Corbusier and Pierre Jeanneret sent to Alfred Roth, published in: Werner Oechslin, 'Les Cinq Points d'une Architecture Nouvelle.' *Assemblage* (Cambridge, Massachusetts: The MIT Press, Oct 1987, No. 4), 82-93.

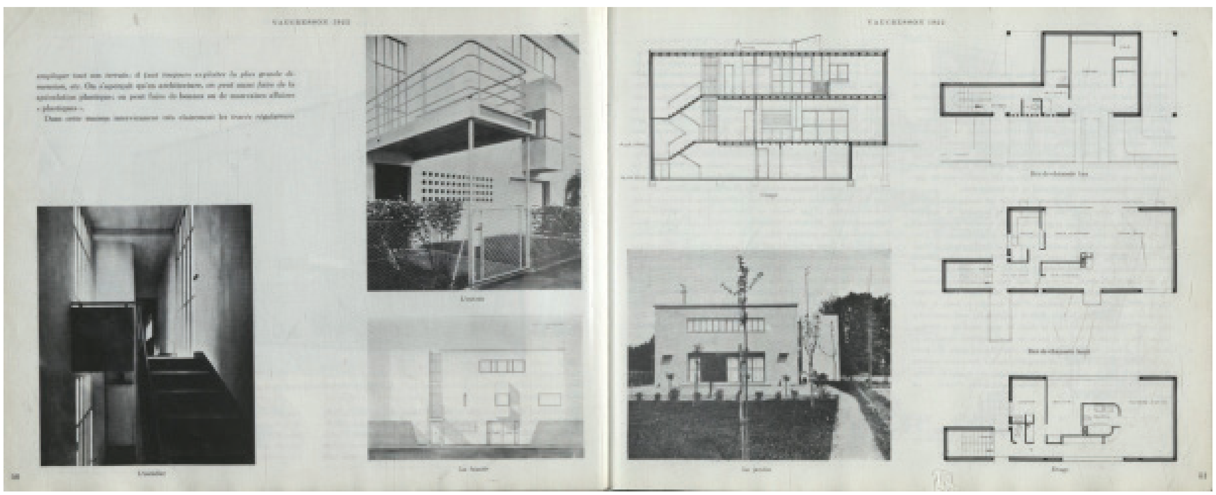
fred Roth. Finally, the 1929 Villa Savoye comes next in my analysis, aligning with the publication of the 'Five Points' in the *Œuvre Complète de 1910-1929*.

1922: Villa Besnus at Vaucresson

In the first edition of the *Œuvre Complète de 1910-1929*, published in 1929, Le Corbusier and Pierre Jeanneret introduce us to Villa Besnus as the first building where solutions to a set of architectural problems had to be sought in construction (Figure 2). These problems, they note, had been theoretically outlined in the essays published in the *L'Esprit Nouveau* journal. Here, they make a distinction between ideas that were defined theoretically in the essays and their practical architectural resolutions, which they argue were first tested here in Villa Besnus. In the introduction to this villa, they write:

> This design was the direct practical outcome of the Town-Planning Stand at the Paris 'Salon d'Automne' of 1922. It dates from a period when every kind of difficulty presented itself simultaneously. Though theories had been put forward and principles developed for clearing the ground in 'L'Esprit Nouveau', everything in this house had, architecturally speaking, to be created anew: methods of construction, an efficient structural solution of the roof problem and of the window frames, parapet, etc. The design reveals its free plan - the bathroom being placed in the centre of the floor area. It likewise defines the form of the window and its proportions, which are correctly adjusted to the human scale.[6]

In addition to the architectural solutions to the construction problems that had been newly outlined by Le Corbusier and Jeanneret in *L'Esprit Nouveau*, the house presents us with a free plan, 'the bathroom being placed in the centre of the floor area' organises the entire floor plan, without being a part of the perimeter wall or the structural grid. The bathroom (on the second floor) and the fireplace/library (on the first floor) in the centre of the house also gives us the first glimpse of the 'promenade architecturale.' In combination with the staircase–



6. Le Corbusier and Pierre Jeanneret, *Œuvre Complète de 1910-1929* (Zurich, Switzerland: Les Editions d'Architecture, 1929), 48.

Figure 2. Le Corbusier and Pierre Jeanneret, Villa Besnus at Vaucresson as published in *Œuvre Complète de 1910-1929*, pages 50-51.

turned 90 degrees from its initial location–the movement into and around the house is defined by a series of continuous left-hand turns. Starting from the main entrance on the ground floor, one is invited left onto the stairs, continues left up the stairs and, entering either first or second floors, continues along the Vaucresson road façade, with views front and back, turning left around the sculptural wall of the library/fireplace or the bathroom into the main space of each floor. The 'promenade architecturale' comes to fruition in villas La Roche-Jeanneret and culminates in the Villa Savoye, but one sees its inception here.

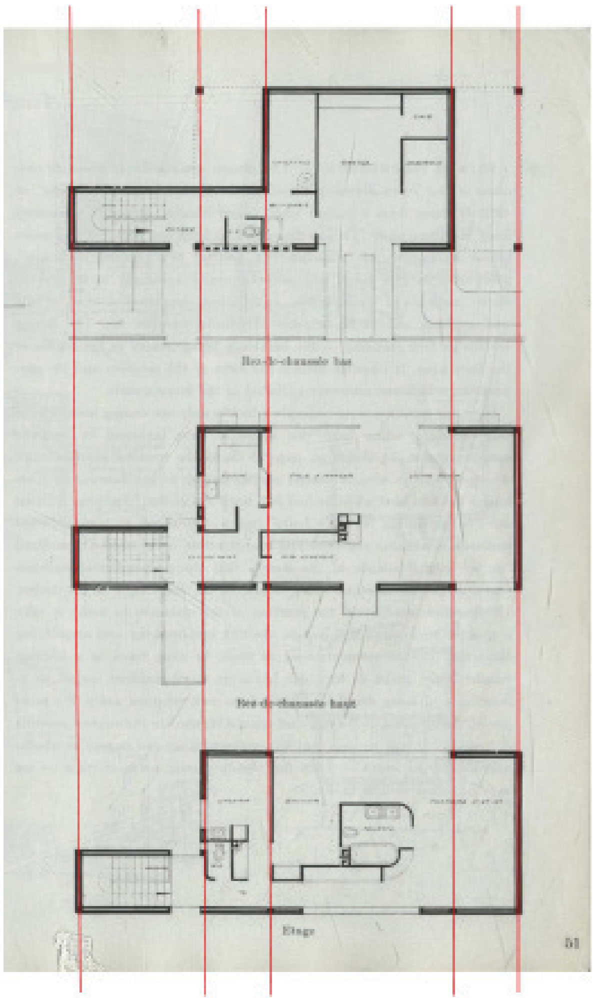


Figure 3. Le Corbusier and Pierre Jeanneret, Villa Besnus at Vaucresson, Floor plans as published in *Œuvre Complète de 1910-1929*, page 51. Red highlights by the author marking the structural column lines, with the columns embedded in the perimeter walls.

The house is executed using a reinforced concrete frame concealed in the perimeter walls of the house. As such, the columns are not visible anywhere in the house, nor do they elevate the house above the ground to permit the garden to pass through. In fact, the house negotiates a grade change between the front and the back of the house. It remains grounded and embedded in the earth. The columns do not play a formal or spatial role in the villa, only structural. They determine the locations of most of the windows. This is especially important on the garden side as the largest structural bay provides the largest window with views of and access to the garden (Figure 3). Given that the structure is embedded and concealed in the perimeter walls, 'free façade' and 'long window' are not possible. The house does not have a roof terrace either. We note that of the five points, the house explores the free plan, but not the remaining four. It is therefore fair to conclude that at this point in Le Corbusier's career, the 'Five Points' had not yet been codified. They existed as ideas, but remained untested, and were not yet cohesively theorised. Although the structure of the villa is reinforced concrete, the house does not yet explore the formal and aesthetic possibilities afforded by the construction method. We can certainly conclude that at the time villa Besnus was designed, the 'Five Points' were not yet defined and codified.

1927: Villa Stein-de Monzie at Garches

In the first edition of the *Œuvre Complète de 1910-1929*, published in 1929, Le Corbusier and Pierre Jeanneret included all four floor plans, ground, first, second and roof, of the Villa Stein-de Monzie at Garches (Figure 4). The plans were specifically redrawn for this publication in September of 1928.[7]

The villa is constructed in a manner anticipated by the Maison Dom-Ino sketch of 1914, a grid of reinforced concrete columns supporting concrete floor slabs with stairs connecting different floors. The villa follows an ABABA column grid in the east-west direction. On the first-floor plan, the main floor of the villa, two columns are missing from the plan, while all others on all plans are shown exactly where they belong, at the intersection of the north-south and east-west grids. These columns are the ones in front of the figural wall separating living and dining areas (Figure 5).

In all subsequent editions of the *Œuvre Complète* the same plan with the two eliminated columns is shown. Of course, at first glance, one imagines that the columns were not built, and transfer beams transferred the loads to the neighbouring columns in the figural wall. However, in the same 1929 first edition, there is a photograph of the area showing exactly the two columns in front of the figural dining room wall (Figure 6). The columns are also shown on the floor plan studies drawn in Le Corbusier's studio at 35 rue de Sèvres. The mystery is why did Le Corbusier decide to eliminate the two columns from the drawing in the book, while he knew full well, they needed to be there and were constructed as such. This mystery prompted the investigation of the parallels between Le Corbusier's stated doctrines and their practice in built form.

1927, the year Villa Stein-de Monzie was completed is also the year attributed to the 'Theory of the Roof Garden,' and the codification of the 'Five Points' published in Roth's book. It appears logical to imagine that while Le

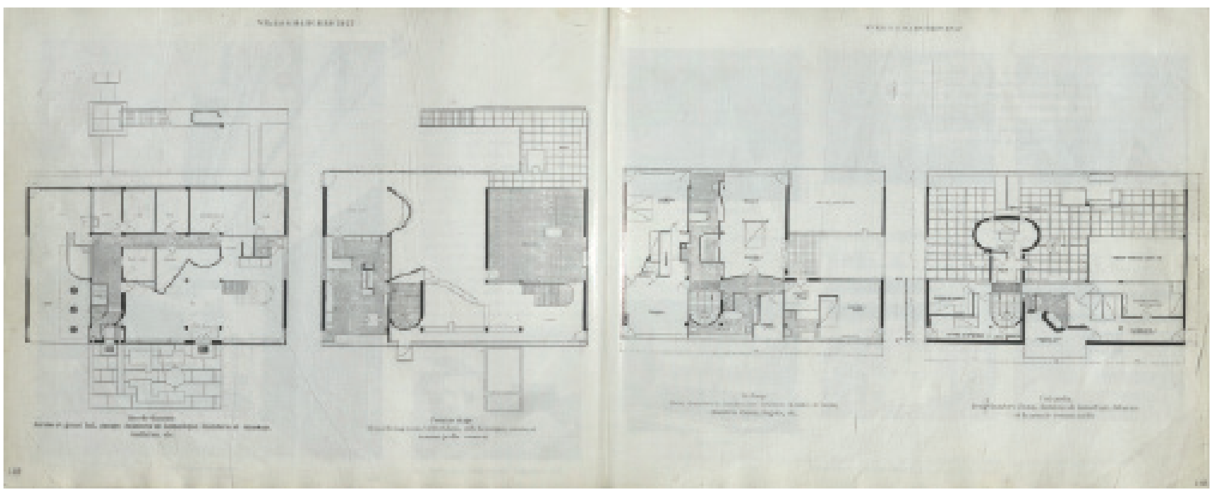


Figure 4. Le Corbusier and Pierre Jeanneret: Floor plans of the Villa Stein-de Monzie at Garches, as they appeared on pages 142 and 143 of the *Œuvre Complète de 1910-1929*.

7. Tim Benton, *The Villas of Le Corbusier 1920-1930* (New Haven and London: Yale University Press, 1987), 176.

Corbusier was working on the villa, he was also testing and refining some if not all of the five points. It may be useful to include the translation of the explanatory text that Le Corbusier and Jeanneret used to head the section on Villa Stein-de Monzie in the *Œuvre Complète*.

This house represents an important milestone in which the problems of comfort, luxury and architectural aesthetics are combined. The house is entirely supported by columns disposed along a grid of 5m by 2.5m without regard for the interior plan. If these columns were to be assembled together in a tight bundle, the total cross-section of this bundle would be 110 x 80 cm. Thus, this large house is entire supported by a concrete cross-section 110 x 80 cm. The independent disposition of the columns diffuses a constant scale, a rhythm, a restful cadence through-out the house. The façades are considered as carriers of light. Not one of them touches the ground. On the contrary, they are suspended from the cantilevered floors. Therefore, the façade carries neither floors nor the roof; it is nothing more than a veil of glass or masonry enclosing the house.

On the interior, the plan is free, each floor having a disposition totally independent from that of another, rigorously proportioned to its particular function: the partitions are nothing more than membranes. The impression of richness is not conveyed by luxurious materials, but simply by the interior disposition and propor-

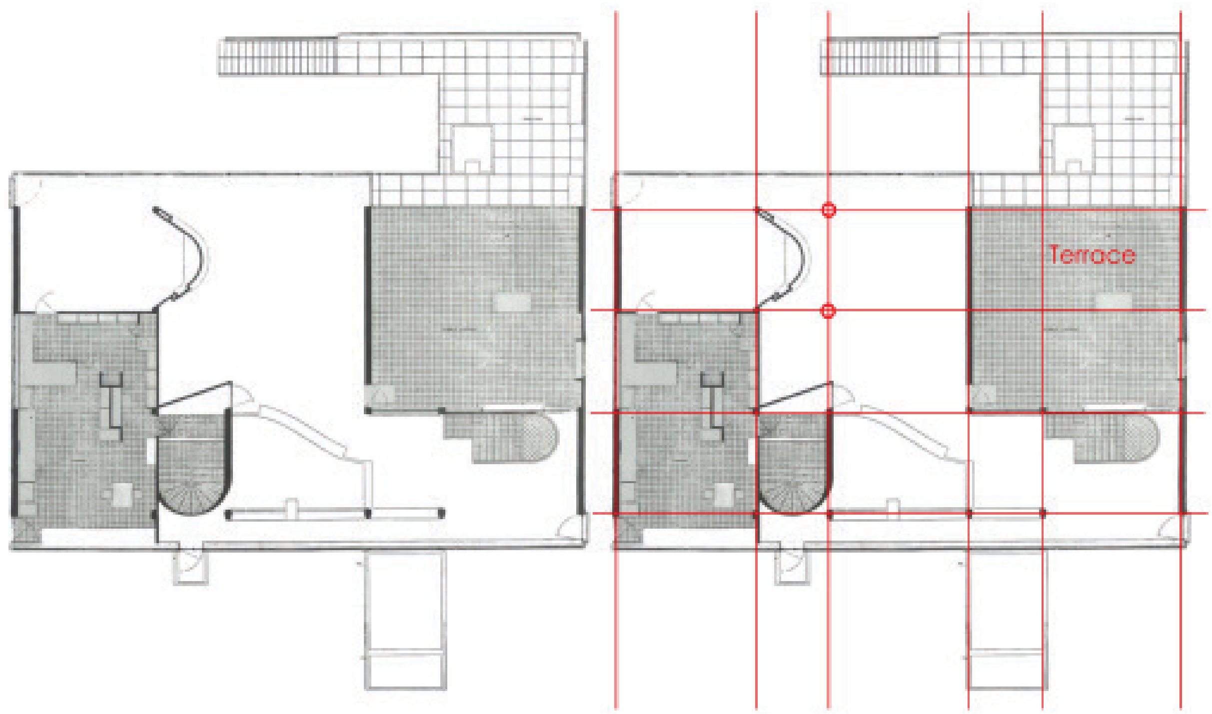


Figure 5. Le Corbusier and Pierre Jeanneret. L: First floor plan of the Villa Stein-de Monzie at Garches, as it appeared on page 142 of the *Œuvre Complète de 1910-1929*. R: Same plan with column grid and two missing columns highlighted by author.

tioning. This entire house adheres to strict regulating principles that led to adjustments, down to the centimetre, in the dimensions of the different sections. Mathematics provides reassuring truths here: one leaves the project with the certainty of having arrived at the exact result.[8]

Le Corbusier and Pierre Jeanneret start the explanatory note with addressing problems of comfort, luxury and aesthetics, responding to two of the three principles of the Vitruvian triad, commodity and delight. They immediately move to the third principle, firmness, expressing the structural grid, its efficiency and its independence from all else. The columns (les pilotis) are there, but they do not lift the building from the ground, from the 'great sickness of our present-day cities,'[9] and to permit the garden to continue below the volume of the house, as the 'Five Points' suggest. Nor do they yet have a clear and consistent expression. Some assimilate into walls, invisible, others become figurative, shaped beyond their round section, others remain round, yet act as figures in spaces, and others become dividers in a glazed surface. Le Corbusier and Jeanneret then move to the façade, declaring it free from bearing any building load and expressing it as a veil (the free façade,) unencumbered by structure. Next comes the free plan, with partitions being described as nothing more than membranes. And finally they end with the exactitude and precision of a

8. Le Corbusier and Pierre Jeanneret, *Œuvre Complète de 1910-1929* (Zurich, Switzerland: Les Editions d'Architecture, 1929), 140-144.

9. Charles-Éduard Jeanneret (Le Corbusier), *Œuvre Complète, Le Corbusier 1910-1965* (Zurich, Switzerland: Les Editions d'Architecture Zurich, 1967), 44.

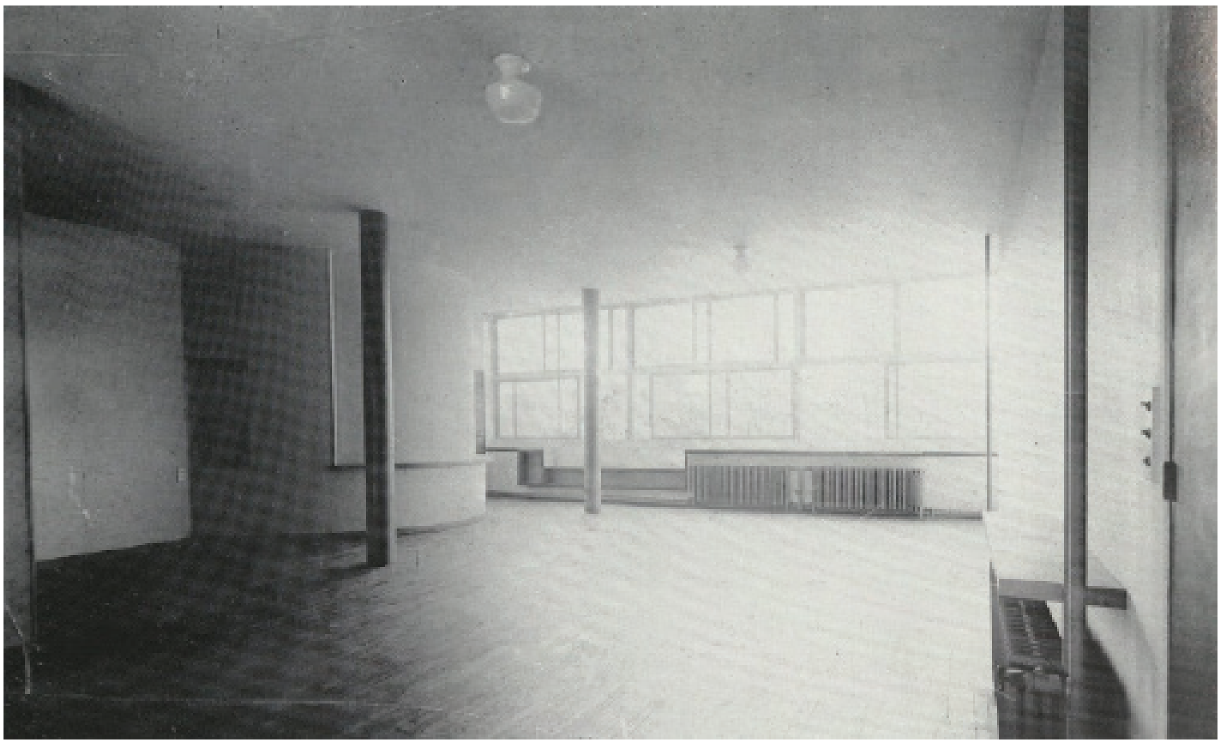


Figure 6. Photograph showing the view from the living room toward the dining room on the first floor of the Villa Stein-de Monzie at Garches, as it appeared on page 149 of the *Œuvre Complète de 1910-1929*. Photographer not known. The two columns which were eliminated from the plan are documented here as built.

scientific laboratory, mathematics as truth. Importantly, the roof terraces, though abundant, and connecting the garden to the highest roof terrace in a stepped fashion, are not mentioned in the introductory text. Nor are the long windows brought up, though present in the building. We note that the five points were exercised in the Villa Stein-de Monzie, but the pilotis do not yet take full expression on the interior. Nor do they elevate the volume of the building above the ground, allowing the garden to pass through, as suggested in 'The Five Points of a New Architecture.' 'Promenade architecturale,' however, reaches new heights here, as human ambulation and circulation involves a much more complex spatial/visual sequence than villa Besnus. Double-height spaces introduce vertical glimpses, as do encounters with multi-layered exterior spaces and volumes. We note that Villa Stein-de Monzie at Garches presents an advanced exploration of the aesthetic and constructional consequences of the reinforced concrete frame.

As noted above, the structural columns in Villa Stein-de Monzie follow the model posed by the 1914 Dom-Ino diagram, reinforced concrete columns on a grid supporting reinforced concrete slabs. The 'Five Points' do not outline a particular role for the columns beyond structure, however, if the columns were to permit the organisation of a free plan, their structural role must be identified from the role of partitions. There are 22 columns on a 4x6 grid, with two columns falling in the terrace, and therefore unnecessary. Of these, only five are visible as individual structural elements, including the two not shown in the plan published in *Œuvre Complète*. The remainder are assimilated into the two exterior and many interior partition walls, hence blending structural and partitioning wall systems. If a partition is free to be placed as dictated by 'comfort, luxury, and architectural aesthetics,' then it cannot be dictated by the location of the structure. Although the 'Five Points' do not explicitly state the independence of the columns from other systems, they do implicitly, through their pairing with the free plan. Thus, Le Corbusier's solution to the two independent columns in front of the figural dining room wall, the decision to not draw them, suggests an incongruity between the systematicity of the structural grid and the aesthetic and formal ambitions of the architects.

The 'Five Points,' in their inception, in the *L'Architecture Vivante* version, 'The Theory of the Roof Garden' provide a congruity, an absolute alignment of technical matters with formal matters. In fact, the essay proposes that aesthetic possibilities are only afforded by technical solutions. The essay opens with a very detailed explanation of the drainage problems of sloped and tiled roofs in the cold northern climate. Le Corbusier argues that what worked when the heat source was in the chimney and the corresponding flue in the wall, no longer works with central heating that heats the entire volume of air in the house, including the part that is in contact with the roof. Thus, the roof garden solution is born out of a technical drainage/icing resolution. He continues and provides even more detail on the construction of the roof, again, based on a technical resolution: how to keep a roof humid, so that the concrete would retain humidity and not crack due to drying.

He then returns to reinforced concrete as the construction solution that supports pilotis, free façade, and the free plan. He writes:

Here we see the fundamental forms dictated by climate and materials, followed by the aspirations of an ideal confronted with constructive realities. Reinforced concrete, by giving us the flat roof, brings liberation from age-old constraints.[10]

We note how the technical necessities of architecture and their aesthetic possibilities go hand in hand, they are one. One brings about the other, at least, that is the argument. In the elimination of the two columns from the plan of the Villa Stein-de Monzie published in the *Œuvre Complète de 1910-1929* Le Corbusier confirms this mis-alignment. The technical necessities, the two structural columns, did not correspond with his aesthetic sensibilities, hence their elimination in plan. His idealised formal proposal, once faced with constructive realities, forced the elimination of the two columns from the drawing.

1927: Weissenhofsiedlung Houses 14 and 15, Stuttgart

On the pages immediately following the Villa Stein-de Monzie in the first edition of the *Œuvre Complète de 1910*-1929 appear the two residential buildings designed by Le Corbusier and Jeanneret for the Weissenhof housing exhibition, built for the Deutscher Werkbund in Stuttgart.[11] The introductory text opens with: 'Since the inauguration of the Weissenhof Colony, these houses have served as a pretext for the announcement of "the five points of a New Architecture".'[12] We know that Le Corbusier and Jeanneret wrote to Alfred Roth supplying him with the codified five points, which Roth later published in his book on the two houses. Thus, the connection between the Weissenhof houses and the 'Five Points' in definitive, at least as far as Le Corbusier was concerned. In addition, the houses were completed for the opening of the Weissenhof building exhibition on July 23, 1927, and the note to Roth was dated July 24, 1927, the day after the opening. If nothing else, the Weissenhof buildings and the codified five points were brewing at the same time. We can thus assume a distinct correlation between the buildings and the 'Five Points' in the most succinct manner.

Le Corbusier and Jeanneret designed two buildings for the housing estate, one was a single-family house, a development of maison Citrohan, a type originally proposed in 1920. The other was a double house, Houses 14 and 15, which were based on the organisation of a train sleeping car (Figure 7). Given that over the last century, the double house has become recognised as more of an icon of the 'Five Points,' we will examine it for this study. Weissenhof houses 14 and 15 appear as one from the outside, a long, elevated, stretched house. The only sign of the existence of the two houses on the outside is a dividing fin that breaks the linearity of the long window. On the interior, the two houses are completely independent, each with its own entrance and circulation stair. The double house is nine structural bays long, house 14 to the South is five bays and house 15 to the North is four bays. The main living spaces are on the first floor which is elevated above

10. *L'Architecture Vivante* 5, no. 18 (Autumn 1927), 18.

11. This order was reversed in the one-volume version of the *Œuvre Complète* published in 1967 by Verlag Für Architekture, Zurich.

12. Le Corbusier and Pierre Jeanneret, *Œuvre Complète de 1910-1929* (Zurich, Switzerland: Les Editions d'Architecture, 1929), 150.

the ground floor, itself almost a floor above the street due to the contours of the land. The recessed ground floor is for the utilities and the entire floor above the living quarters is the roof garden.

Houses 14 and 15 are made of a reinforced concrete frame with masonry infill. They literally embody the free plan, as the plan of the houses changes at least twice daily with movable partitions. Expansive living areas during the day transform into individual sleeping quarters at night by sliding partitions into place and rolling out beds from the built-in storage units. Free plan is here conceptually, but also literally. There are twenty columns in two rows of ten, not accounting for the four in the stairways. The east row, facing the street, is expressed as columns (pilotis) and figural. It elevates the main building volume above the ground, permitting the landscape to pass below the building. The west column row is embedded in the rear (west) perimeter wall. The north and south end-walls and the division wall between the two houses also assimilate the columns. Even with the embedded columns, their expression in the building form is undeniable. All of the interior partitions are simply that, non-structural partitions. Although their location is defined by the location of the structural grid, the partitions do not assimilate the columns, except in two minor bathroom walls. Here we see a much more precise handling of the legibility of the structure and the relationship between the structure and non-structural components of the house (Figure 8).

As mentioned, the entire second floor is occupied with the roof terrace, expressed on the main façade. This façade exemplifies the free façade and the long windows of the 'Five Points'. The structural columns are pushed back from the perimeter wall, making the building skin free from all structure. It is literally a veil. The long window encompasses the entire length of the two houses, stopping only short of the end

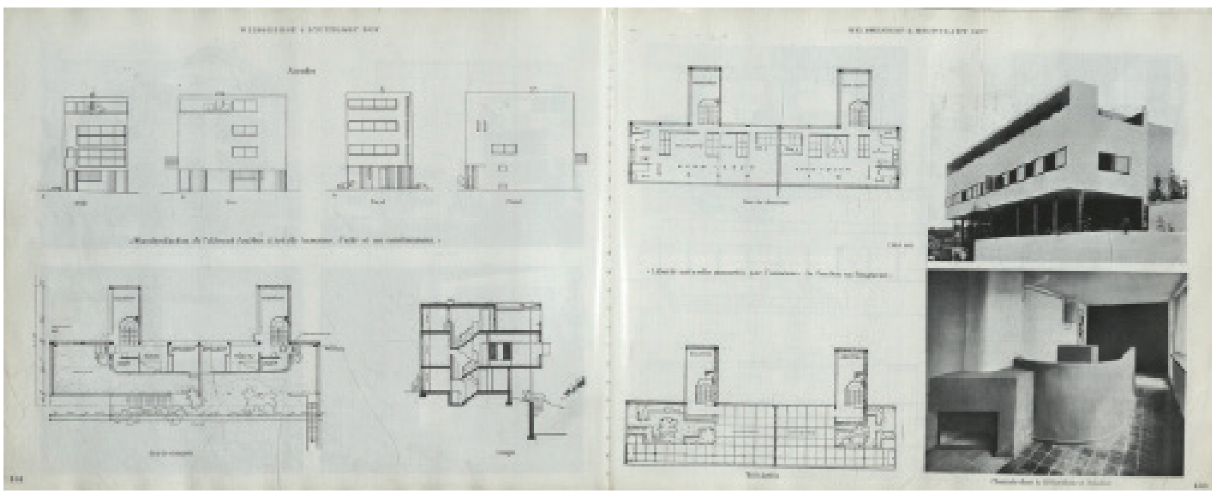


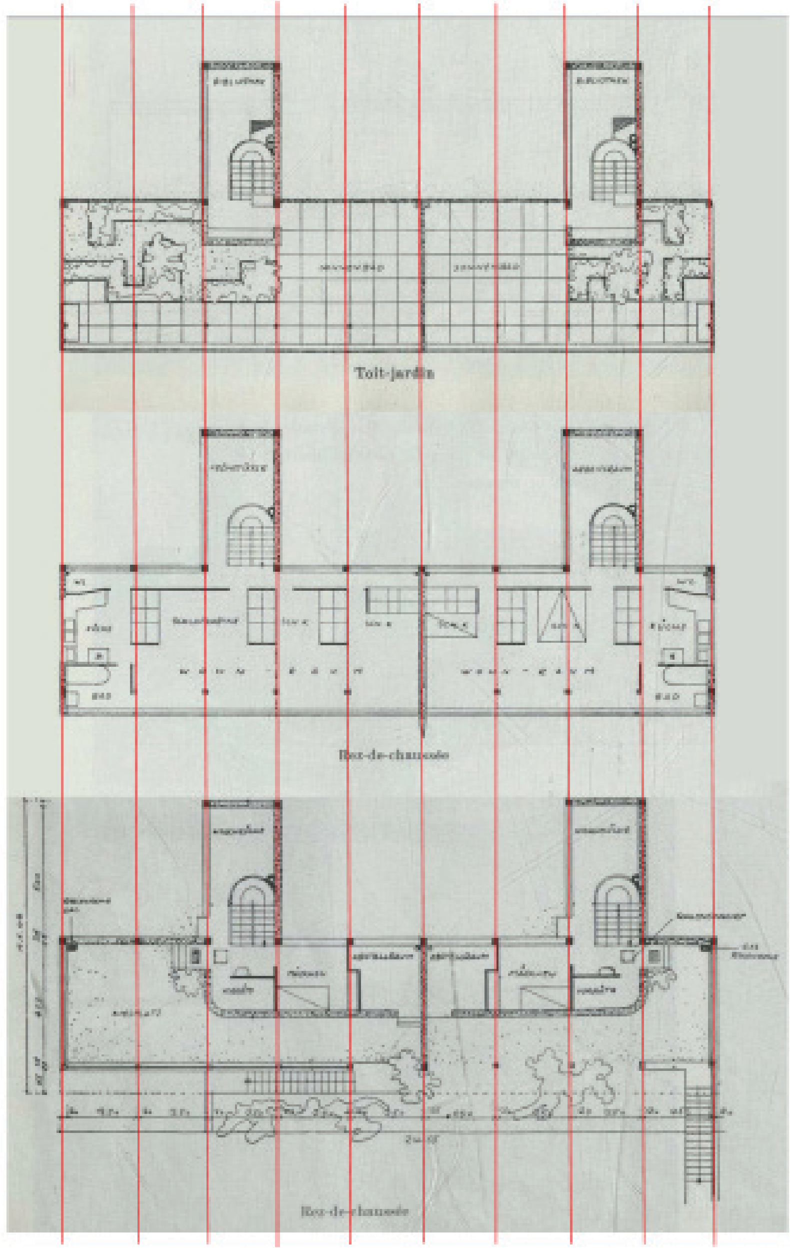
Figure 7. Le Corbusier and Pierre Jeanneret, Weissenhofsiedlung houses 14 and 15. Building plans, sections, and photographs as published in *Œuvre Complète de 1910-1929*, pages 154-155.

wall to accommodate its thickness. The west wall, on the contrary, houses the columns and expresses them in the masonry breaks between the windows. Houses 14 and 15 indeed embody the ‘Five Points’. Even where they break with it, such as the west façade containing the columns, they do so with full legibility of what is structural and what not. Here we see a complete alignment of the technical necessities of architecture and their aesthetic possibilities. The reinforced concrete frame not only structures the building with its regular geometry, but it also provides it aesthetic expression in the way that the ‘Five Points’ predicted.

1929: Villa Savoye at Poissy

Villa Savoye has come to be considered as the example in which the ‘Five Points’ are best displayed. Its visible and iconic roof garden, the pilotis surrounding the building and lifting the main volume above the ground with the landscape passing underneath, the long windows declaring the free façade, only leaves the free plan to be determined from the interior. The building shouts the ‘Five Points’ from its exterior formal organisation. It has served as the icon for the ‘Five Points’. In the first edition of the *Œuvre Complète de 1910-1929*, this villa appears toward the end of the book, as its date places it at the end of the period covered in the first volume. It occupies a brief 4-page spread. At the time of the publication of the first volume of the *Œuvre Complète*, the villa was still being debated with the client and had not been finalised. As such, the plans that appear in this volume were not the final plans (Figure 9). They are similar, but not the same as the as-built plans. In the later editions of the *Œuvre*

Figure 8. Le Corbusier and Pierre Jeanneret, Weissenhof houses 14 and 15. Floor plans as published in *Œuvre Complète de 1910-1929*, pages 154-155.



Complète, the final plans were published. In the introduction to this villa, Le Corbusier and Jeanneret do not mention the ‘Five Points,’ its principles, the construction of the villa, nor its reinforced concrete frame. They discuss the site being at the crown of a hill, beautiful views, and the ‘promenade architecturale’ from the ground through the ramp to the roof.

The structural concrete columns, the pilotis, encircle almost the entire perimeter of the building on the ground floor. On the north and south sides, the columns are inset from the main volume of the house, and on the east and west they are in-line with it, almost exactly as described in the Dom-Ino diagram of 1914. The shape of the floor plans is a square, slightly stretched to accommodate the north and south overhangs. The building declaratively pronounces four equal bays on each of its four sides, marked by the columns: a square plan with a square structural grid, the perfect geometric matrix. Tim Benton, in his *The Villas of Le Corbusier and Pierre Jeanneret 1920-1930,* has documented multiple building arrangement studies leading to the final configuration.[13] The original plans from October 1928 and the final plans hold much similarity. In between, from November and December 1928, there were four other formal studies. In all of them, the regularity and precision of the structural grid is maintained. In the final iteration, two matters of circulation come to the fore, one for the car, the other for people, both of which diminish the relationship between the regular geometry of the structural grid and the building form. The two matters of circulation were the ‘promenade architecturale’ via the ramp, and the enclosed car circulation/parking within the volume of the house. These two circulatory items introduced anomalies in the regularity of the square structural grid in the square plan. A smaller bay was introduced in the interior of the house for the ramp, and the columns in the parking area were removed (Figure 10).

As noted in the previous sections, Le Corbusier and Jeanneret had developed a struc-

13. Tim Benton, *The Villas of Le Corbusier and Pierre Jeanneret 1920-1930* (Basel, Boston, Berlin: Birkhäuser, 2007), 190.

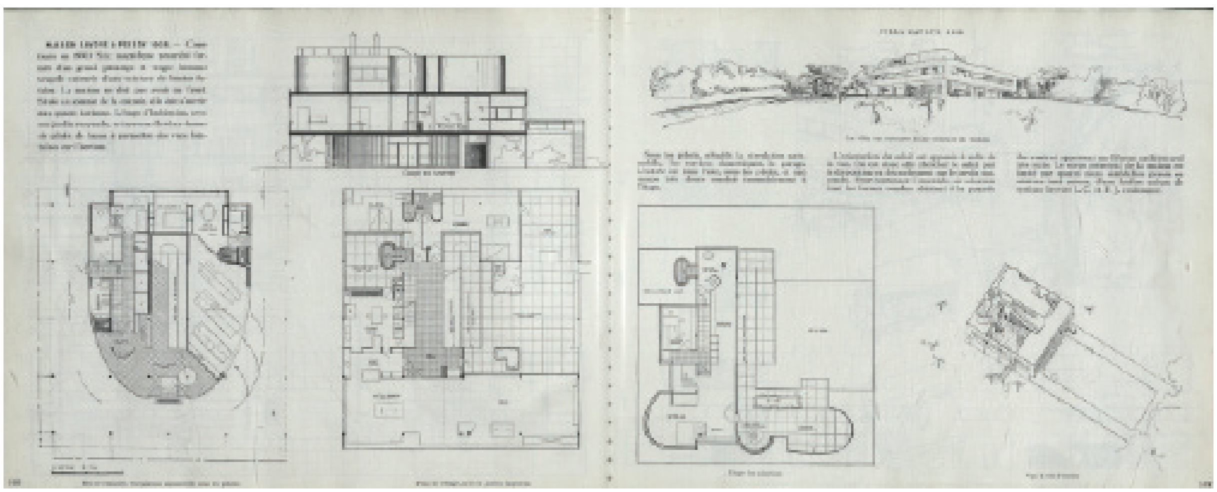


Figure 9. Le Corbusier and Pierre Jeanneret, Villa Savoye at Poissy. Floor plans as published in *Œuvre Complète de 1910-1929*, pages 186-187.

tural grid for the Stein-de Monzie house that had unequal bays, ABABA. A similar approach could have been taken in the north-south direction to address the ramp. The car parking would have needed a more complex solution. Nonetheless, the architects decided to privilege the appearance of order and geometric precision on the four façades and address the structural issues locally. Thus, an interior north-south bay was introduced to accommodate the ramp, yet maintain the square grid at the north and south faces. To accommodate the interior car parking, Le Corbusier and Jeanneret showed one column removed in the published plans, exactly where a car would need to park (Figure 10). In the later iteration of the plan which was used for construction, the column is shown relocated off-grid to accommodate the pattern of the car parking (Figure 11). In the published version of the plan, we note the ramp splitting the centre column line into two, in essence creating three smaller structural bays in the interior of the villa. In the same plans, the architects removed, at least in drawing, a column from the car-park. Unlike the published plans of 1929, in the revised, as-built plans, the structural grid is manipulated much more aggressively, adding many new column lines, and making small local adjustments off-grid (Figure 12). Given all these adjustments, the perimeter columns always maintain a distinct figural role, exactly on the square grid, lifting the volume of the house and allowing the landscape to pass underneath. On the interior of the villa, not unlike Villa Stein-de Monzie, the columns take on many roles. Some assimilate into walls, invisible, while others remain free-standing, figural elements in the plan.

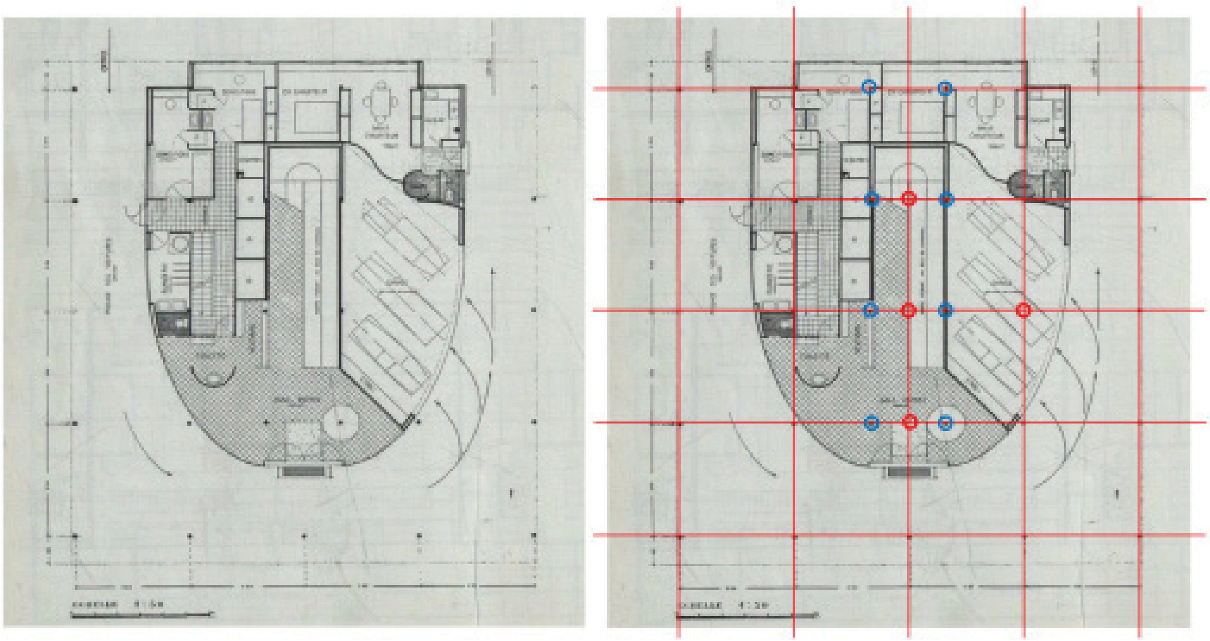


Figure 10. Le Corbusier and Pierre Jeanneret, Villa Savoye at Poissy. L: Ground floor plan as published in *Œuvre Complète de 1910-1929*, page 186. R: Same plan with highlights by author: red circles note on-grid columns that were removed. Blue circles note off-grid columns that were added.

In Villa Savoye, Le Corbusier and Jeanneret heavily favoured the idealised, almost fetishised, form of the house over its structure. Clearly, the building was built and has been standing for nearly a century. This analysis is not to say that its structure did not work, of course it did. The analysis only suggests that despite its iconic relationship with the 'Five Points,' Villa Savoye does not present a coherent alignment of Le Corbusier's aesthetic and formal ambitions with his structural and constructive promises. In a sense, the theoretical framework that tied the building form to structural and constructive practices is weakened in this villa. Le Corbusier saw the absolute geometry inherent in buildings' technical systems, such as its structure, as the imprint of universal laws of nature. In distinction, the building's forms and spaces, its profiles and contours abided by a different order, that of affecting our senses acutely. In his 1923 *Towards a New Architecture*, Le Corbusier spoke of the roles of the engineer and the architect. To this end, he wrote: 'Profile and contour are the touchstone of the Architect. Here he reveals himself as artist or mere engineer....Profile and contour are a pure creation of the mind; they call for the plastic artist.'[14]

'The Architect, by his arrangement of forms, realises an order, which is a pure creation of his spirit; by forms and shapes he affects our senses to an acute degree and provokes plastic emotions; by the relationships which he creates he wakes profound echoes in us, he gives us the measure of an order which we feel to be in accordance with that of our world, he determines the various movements of our heart and of our understanding; it is then that we experience the sense of beauty.'[15]

Conclusion

The four Le Corbusier/Pierre Jeanneret 1920s

14. Jeanneret, Charles-Éduard (Le Corbusier). *Towards a New Architecture.* Translated by Frederick Etchells (New York, Toronto, London, Sydney: Holt, Reinhart and Winston, 1946), 186.

Figure 11. Le Corbusier, Villa Savoye at Poissy. Floor plans as published in the single volume *Œuvre Complète* 1910-1965, page 59.

villas analysed above confirm that the 'Five Points' were in development during this period. Despite their attribution to many sources from the early 1920s to 1929, in fact, they developed gradually over time, and over many constructive trials. Although all four villas were built using reinforced concrete, they do not take advantage of the aesthetic possibilities outlined in the 'Five Points' to the same degree. In the 1922 Villa Besnus, only the free plan was implemented. The reinforced concrete structure was embedded in the perimeter walls, undermining the independence of the frame from the walls and thus making legibility of the pilotis unlikely and the free façade impossible. There was also no roof garden, as the 'Theory of the Roof Garden' did not appear till 1927. The 1927 Villa Stein-de Monzie, which was being designed in Le Corbusier's studio at 35 rue de Sèvres in 1926, incorporated multiple terraces and roof gardens, made the structure independent from the skin, thus added the free façade, and incorporated the long windows. For the first time, in the 1927 Houses 14 and 15 of the Weissenhofsiedlung all five points were incorporated and supported a singular theoretical, constructive, and formal proposal. In Houses 14 and 15, the building's structural system and 'profile and contour' are one and the same. They are congruent. The opening of the Weissenhof Estate and the houses coincided with the date on the note from Le Corbusier and Pierre Jeanneret to Alfred Roth that outlined the five points. It is thus clear that the 'Five Points' were in development throughout the 1920s, both theoretically and constructively. Their first formal appearance in writing as a codified set of points that outline the aesthetic and formal possibilities of

15. Jeanneret, Charles-Éduard (Le Corbusier). *Towards a New Architecture.* Translated by Frederick Etchells (New York, Toronto, London, Sydney: Holt, Reinhart and Winston, 1946), 7.

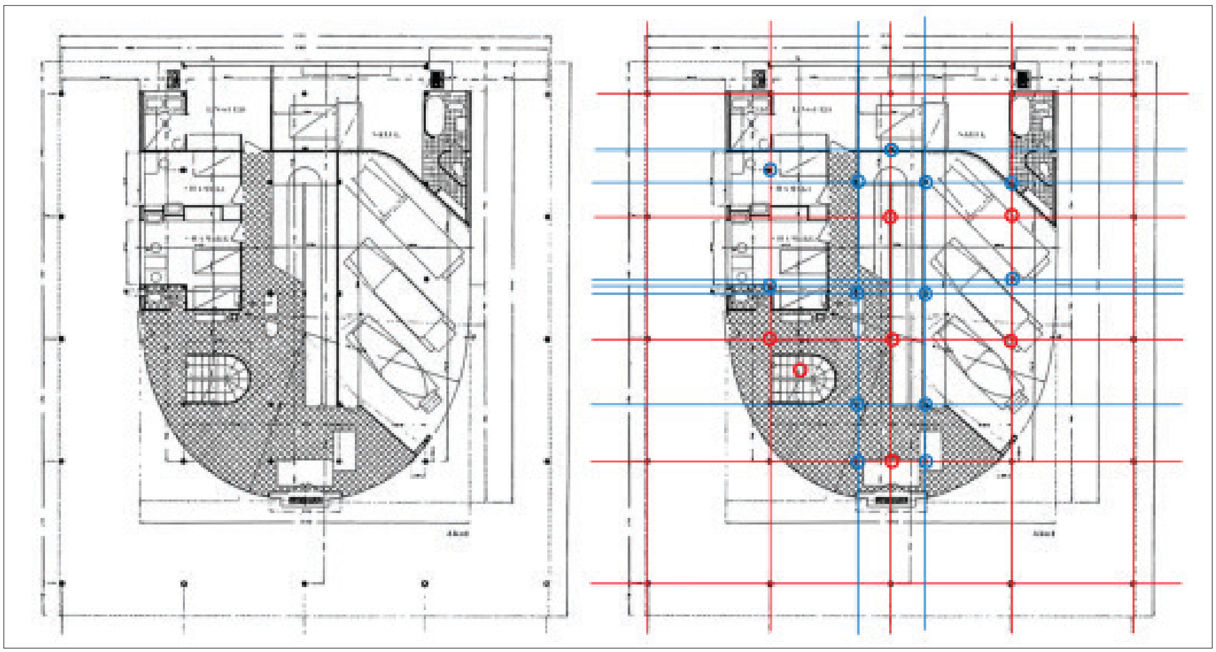


Figure 12. Le Corbusier, Villa Savoye at Poissy. L: Ground floor plan as published in the single volume *Œuvre Complète 1910-1965*, page 59. R: Same plan with highlights by author: red circles note on-grid columns that were removed. Blue circles note off-grid columns that were added, and blue lines the added column lines.

the reinforced concrete structural system is in this note to Roth, as documented by Werner Oechslin. Houses 14 and 15 serve as the built confirmation of the synthesised and codified 'Five Points'.

The Villa Savoye, though attributed to 1929 in the *Œuvre Complète de 1910-1929*, was designed in the studio starting in 1928 and continued till the completion of its construction in 1931. This iconic villa accentuated formal priorities over a congruence of technical and formal attributes. This may be why it became a formal icon. At first glance and from the exterior viewpoint, it totally adhered to the 'Five Points'. However, a close reading proved a discord between the technical/structural concerns and the formal ones. This building moved away from the coherence of structural geometry with profile and contour, undermining the unified and cohesive proposal put forth by the 'Five Points'. The Villa Savoye is a breathtaking building. Its spaces and circulatory promenade leave one speechless. It truly affects our senses to an acute degree. We can agree that Le Corbusier achieved his formal and spatial ambitions in this building. This monumental achievement, however, is at the expense of the discord between the absolute geometry of its plan, its structure as visible on the perimeter and the re-structuring of its interior necessitated by the circulation promenades. We can assess that once the 'Five Points' were conclusively achieved in the Weissenhof Houses 14 and 15, both theoretically and constructively, Le Corbusier and Jeanneret prioritised other architectural matters, while still remaining wedded to the reinforced concrete construction system.

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Evaluation of the effect of kinematic axes and the geometric model of the kinetic facade on providing natural lighting in an office building in Tehran

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ORIGINAL RESEARCH ARTICLE

Sangtarash, Fataneh, Niloufar Nikghadam, Rima Fayaz, and Mohammad Reza Matini. "Evaluation of the effect of kinematic axes and the geometric model of the kinetic facade on providing natural lighting in an office building in Tehran". *Soffeh* 36, no. 2 (2026):127–148. DOI: http://doi.org/10.48308/soffeh.2024.236665.1349

Received: September 23, 2024
Revised: October 09, 2024
Accepted: December 04, 2024
(Pages: 127–148)

Abstract

Background and Objectives: Kinetic façades represent a dynamic design approach that integrates movement to adapt to environmental conditions the concept of motion as a design input. One of the strategies of this facade is to control the light entering the interior. Fixed or dynamic horizontal shades are the best choice for south orientation, while vertical shades are usually used in east and west directions. Studies have shown that horizontal shading is more efficient than vertical shading. Indoor lighting conditions can affect the occupants' visual comfort, satisfaction, thermal comfort, health, mood, motivation, performance,

Keywords:
Motion axes, geometric model, kinetic facade, natural lighting, office building in Tehran, façade lighting direction.

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http://doi.org/10.48308/soffeh.2024.236665.1349

Research Questions:

1. Which rotational motion axes of the kinetic façade (horizontal, vertical, and diagonal) provide optimal daylight performance for the north, south, east, and west façades of an office building in Tehran?

2. How do the two geometric models of the kinetic façade (rectangular and circular) affect daylight performance indicators (ASE, UDI, and DGP) across the four façade orientations?

3. Which combination of geometric model and rotational motion axis provides the most effective daylight performance for each façade direction in the climate of Tehran?

and productivity. Literature indicates that geometric and movement models play a role in controlling daylight and glare, although less attention has been given to movement axes in four directions. Also, it is unclear what kind of movement axis is appropriate for each façade direction. This research aims to utilize natural lighting using geometric models and rotational motion axes of the kinetic facade in the north, south, west, and east facades of an office building in Tehran. The novelty of this article is in examining the motion axes of the kinetic facade in response to Tehran's climate. For this purpose, the rotational motion axes in three horizontal, vertical, and diagonal modes in four directions have been measured to create optimal light in the interior space. The selection of samples is based on constructed examples that have not been used in previous studies, and the focus of this research is more on rotation motion axes and two geometric models, circle and rectangle.

Methods:This study utilises an applied, quantitative research methodology and is quantitative in nature. Using the simulation tool, the rotational motion axes of the kinetic facade are analyzed and evaluated in four directions, considering both circular and rectangular geometric models, and in relation to daylight in an office building in Tehran. Rhino software version 6.32, Grasshopper plugin and Honeybee Plus plugin version 0.0.06, and Ladybug version 1.5.0 were used for simulation. The Python programming language has also been used to calculate averages. The first step is to simulate the movement of the sun with the Ladybug plugin according to the weather file of Tehran. In the next step, a sample office room with an open plan, measuring 4 m in width, 6 m in length, and 3 m in height, accommodating six employees, was evaluated according to the dynamic daylight indicators. The room had a window-to-wall ratio of 90% of the facade without shades. In the next step, the existing two geometric modes of the kinetic facade, circle and rectangle, have been measured and compared according to the rotational movement axes (horizontal, vertical, and diagonal) in four facade directions. Then, according to the responsiveness of the facade to natural lighting, the most optimal geometric model and movement axes based on angle and dimensions (length, width, and radius) are suggested for all four directions of an office building in Tehran.

Results and conclusion :Recent research on kinetic facades in Iran and around the world indicates that kinetic facades are more responsive than fixed types in reducing glare and controlling daylight. Among them, geometric models, kinematic modes, movement axes, geometric model dimensions, room dimensions, the opening and closing angle of the geometric model of the facade in relation to the location of the sun, and the climate of the region play a significant role in optimising natural lighting in the interior space. According to the glare index (ASE) findings, the north facade does not require a shade, as the interior space receives sufficient daylight without one. Therefore, natural lighting simulation analysis with a kinetic facade has been done only for three directions of the south, east, and west facades. According to the simulation results, the two indicators, ASE and UDI, are of special importance. This is because when the shade opening or angle is half-closed, less light enters the space. As the percentage of useful light index decreases below 500 lux, the interior space may receive less than 500 lux of useful daylight at its far end.

Additionally, when the aperture or angle of view is open, more light enters the interior space and the amount of glare (ASE) shows values above 10%, which means that indoor glare and visual discomfort may occur. Therefore, optimising these two indicators is necessary to receive useful daylight in the interior. In the next step, the values of the two indices ASE, UDI less and DGP were averaged using the Python programming language. The simulation results show that the geometrical models of rectangle and circle with a rotating movement model with the horizontal axis at the top in the south, west, and east walls and with the diagonal axis at the top, both geometrical models in the east and west facade of an office building in Tehran are appropriate for providing optimal dynamic daylight indices. After comparing the geometric models based on the ASE and UDI indices in three directions, it is evident that the rectangular geometric model with a rotating movement model on horizontal and diagonal axes outperforms the circle geometric model with a rotating movement model on horizontal and diagonal axes. Also, the most suitable rotational motion axes of the kinetic facade for the two western and eastern facades are the horizontal and diagonal axis at the top and for the southern facade the horizontal axis at the top. Among the limitations of this research is the lack of an office building built with a kinetic facade in the field, so that a comparison can be made between the simulated results and field measurements.

On the other hand, natural lighting measurement devices in the indoor environment have limitations and cannot simultaneously measure the amount of daylight and glare in the indoor environment. In future research, it is possible to evaluate the kinetic facade with a rectangular geometric model and rotational movement model with horizontal and diagonal axes in four directions of the facade based on the amount of energy consumption, visual comfort, and thermal comfort using simulation or field observations. Furthermore, this facade can be studied in different climates and cities to determine its use with a geometric model and a proportional movement model in each city, according to the internal daylight. The results of this research can be applied to similar climates outside of Iran.

Introduction

Kinetic facade is a research field that considers movement as an input to designa primary objective of employing such facades is to control the amount of light entering the interior space. A kinetic facade can provide protection from solar radiation, enhance natural lighting efficiency, and create visual and thermal comfort conditions[1]. Optimal passive solar control dictates that horizontal shading devices are the most effective solution for minimsing solar heat gain on southern exposures, while vertical shading is typically employed for controlling low-angle sunlight on the east and west[2]. The most suitable fixed shading device for the south, southeast, and southwest facades is the frame-shaped shade. Studies have also shown that horizontal shading is more efficient than vertical shading[3]. Research indicates that lighting conditions in an environment can affect visual comfort, satisfaction, thermal comfort, health, mood, motivation, performance, and productivity of occupants. Poor lighting conditions that do not meet essential regulations fail to satisfy the lighting requirements of various activities, and insufficient lighting fixtures lead to inadequate illumination in workspaces[4]. Satisfaction with lighting conditions relates to desk illuminance, the amount of reflected light on computer screens, illuminance levels for computer work, access to exterior views, and overall light quality in the workspace. The European standard emphasises the minimum lighting requirements for an actual work area rather than the entire room[5]. According to this standard[6], a typical office workplace requires an illuminance level of 500 lux. Similarly, in accordance with Part 13 of Iran's National Building Regulations[7], the illuminance level for a typical office is considered to be 500 lux. Another study suggests that the optimal illuminance intensity in office spaces ranges from 600 to 650 lux, and illuminance levels between 550 and 600 lux provide comfortable conditions. Illuminance below 550 lux is not desirable for users[8]. This study aims to optimise daylight harvestingthrough geometric models and rotational movement axes of the kinetic facade on the north, south, west, and east facades of an office building in Tehran. The innovation of this research lies in investigating the kinetic facade's movement axes in response to Tehran's climate. For this purpose, rotational movement axes in three types horizontal, vertical, and diagonal have been evaluated on the four facade orientations to achieve optimal interior lighting. The selection of samples is based on those that have not been used in previous studies, with a focus on rotational movement axes and two geometric models: circle and rectangle.Additionally, in previous research, two influential natural lighting indicators, ASE and UDI less, have received less attention. The results of this study can be applied in similar climates. Considering the objective, the following questions are posed: Which of the rotational movement axes ,diagonal, horizontal, or vertical, in the kinetic façade of each orientation of an office building responds better to natural lighting? Which geometric model, either a circle or a rectangle, combined with the kinetic rotational movement model in the façade, optimally provides natural lighting in an office space in Tehran?

Research Background

Research on kinetic façades, focusing on movement mechanisms and geometric models, has primarily addressed daylight performance, glare control, visual comfort, and façade optimisation. Most of these studies have been conducted through simulation-based methods and in hot-arid climates. The present paper, however, specifically concentrates on visual comfort and

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indoor daylighting performance. Rasouli et al.[9] investigated the annual performance of double-skin façades for an office space in Tehran, incorporating horizontal and vertical louvers in both fixed and movable states. The building was modeled in Rhinoceros, and the parametric design of the louvers was developed using Grasshopper. The findings indicated that movable shading systems outperformed their fixed counterparts, with movable horizontal louvers delivering the most effective results. Tabadkani et al.[10] examined an adaptive façade designed to improve daylight use and visual comfort in an office building in Tehran. The façade employed a hexagonal geometry combined with a folding (origami-inspired) mechanism. The computational model utilised an open-plan office space (the case study zone) defined by the dimensions 7.0 m (length) × 5.5 m (width) × 3.0 m (height). This space featured a Window-to-Wall Ratio (WWR) of 81% on its southern façad. Results showed that the origami-based geometry enhanced daylight penetration, while its impact on glare reduction was limited to certain interior areas.

A prior study examined a modular, responsive façade system specifically designed to optimise indoor daylight harvesting and enhance visual comfort. Hosseini et al.[11] explored an interactive façade system for daylight and glare control through simulation. The case study was situated in a hot-arid climate, and the façade incorporated a square pattern with three-dimensional movable shading modules, which operated in response to the sun's movement and occupants' positions. The study revealed that the system was effective in mitigating both perceptible and imperceptible glare.

A study[12] has investigated a responsive facade with a modular model to utilise daylight and visual comfort. The geometric model consists of triangles, hexagons, and circles in both regular and irregular patterns. The geometric dimensions of the office room in Izmir, Türkiye are 12 m wide, 15 m long, and 6.5 m high. Results confirmed that the implementation of the kinetic façade led to a substantial mitigation of visual discomfort and glare when compared against the static baseline model.. The triangular folding geometric pattern offers greater flexibility in controlling daylight and airflow than the square pattern. In addition, they can adapt to different daylight needs. in a study by Li et al.[13], The influence of various adaptive façade parameters on indoor daylight performance within an office environment was assessed utilising the environmental analysis plugins, Ladybug and Honeybee, integrated within the Grasshopper computational framework. For multi-objective optimisation, the *Wallacei X* plugin and the *XGBoost* machine learning algorithm were applied to account for environmental variations in daylight. The façade was simulated with three geometric patterns—triangle, rectangle, and hexagon combined with horizontal and vertical kinetic movements at different sizes and angles under the climate conditions of Shanghai. The results showed that the length, width, and height of the room, in relation to its orientation and angle, had a greater impact on glare reduction and dynamic daylight availability. In a study by Samadi et al.[14], a computational approach was developed to achieve optimal daylight in interior spaces with a southern façade equipped with a shading system. Optimisation was carried out using the *Galapagos* plugin.

6. BS EN-12464-1. *Light and lighting. Lighting of work places Indoor work places.* BSI standards (2021).

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The optimisation results indicated that the upper window height between 0.08 and 1.65 m, room geometry with a height of 3 m, length of 9.5 m, and width of 6 m, along with the distance from the window and the use of a hexagonal rather than a square pattern, had a more significant influence on glare mitigation and dynamic daylight performance.

In related work, Sangtarash et al.[15] conducted a comparative analysis of two kinetic movement patterns—rotational and folding—applied to a triangular geometric façade to achieve optimal daylighting on the southern exposure of an office building in Tehran.The simulations were conducted using the *Honeybee* and *Ladybug* plugins. The results demonstrated that the rotational movement model outperformed the folding movement model in responding to natural daylight requirements. In a study[16], a biomimicry approach was applied to enhance daylight performance in an office building in Egypt, where a geometric pattern inspired by the behavior and organisation of a snake was examined. Ultimately, a rhombus-shaped geometry with folding along both horizontal and vertical axes was considered for daylight analysis. The geometry of the simulated space was parameterised with the following internal dimensions: 6.0 m (depth) × 4.0 m (width) × 3.0 m (height).. In this analysis, the window was placed within a frame with depths of 0.5 m and 1 m for comparison. The results indicated that a frame depth of 1 m performed better than a 0.5 m depth in improving daylight availability. It was further highlighted that the most influential parameters in enhancing daylight performance were the rotation angle, the distance of the façade from the window frame, and the degree of horizontal and vertical folding.

The review of prior research indicates that the geometric and kinetic patterns of shading devices play a significant role in controlling daylight and glare. However, less attention has been paid to movement axes across the four façade orientations. Moreover, it remains unclear which movement axis is most suitable for each orientation. The present study therefore, focuses on two geometric patterns, circular and rectangular, combined with rotational kinetic movements along diagonal, horizontal, and vertical axes to investigate daylight performance across the four façade orientations.

Theoretical Framework

Geometric and Kinematic models of Kinetic Façades

Geometric and kinematic models represent two key axes in the design of kinetic façades. These models play a crucial role in defining how the façade opens and closes, its control mechanisms, choice of materials, and structural stability. Movement within the façade (or its modules) requires geometric adaptability of its components to maintain structural coherence while transforming[17]. Unlike static façades, the design of a kinetic façade demands an interactive design process beginning with the selection of geometry and movement analysis, followed by the development of both digital and physical models, and culminating in the selection and design of joints and materials in relation to the intended movement mechanism. The classification of kinetic structures generally follows three main domains: the typology of movement (kinematics), the material properties, and the inherent characteristics of the dynamic el-

11. Hosseini, Seyed Morteza, Masi Mohammadi, and Olivia Guerra-Santin.'Interactive kinetic façade: Improving visual comfort based on dynamic daylight and occupant's positions by 2D and 3D shape changes.' *Building and Environment 165* 106396.(2019). www.elsevier.com/locate/buildenv.

12. Kızılo¨renli, Ecenur, and Feray Maden.'Modular responsive facade proposals based on semi-regular and demi-regular tessellation: daylighting and visual comfort.' *Frontiers of Architectural Research*. (2023). doi:DOI:10.1016/j.foar.2023.02.005.

13. Li, Yuanyuan, Huang Chenyu, Zhang Gengjia, and Jiawei Yao. 'Machine Learning Modeling And Genetic Optimisation Of Adaptive Building Facade Towards The Light Environment.'*Proceedings of the 27th International Conference of the Association for ComputerAided Architectural Design Research in Asia (CAADRIA)*.(2022): 141-150.

ements.. In general, movement is categorised into sliding, rotation, folding and opening/closing. Depending on the design of the mechanism, multiple types of movement may coexist within the same structure[18]. Schumacher et al.[19] classified kinetic movement structures into partial and overall displacement. Herzog et al.[20] further categorised façade and window movements into vertical flat, angled, horizontal and vertical planar, horizontal curvature, vertical curvature, and combined horizontal–vertical types.

From the perspective of movement typologies, kinetic façades are generally divided into four categories: folding, sliding, scaling, and rotation[21]. In another study, kinetic façade movement was classified into translational, rotational, scaling, and material-based deformation[22]. Among these, scaling movements are less common due to material limitations and high costs. In contrast, rotational and folding mechanisms have become increasingly popular in recent years, although many designs still lack sufficient performance-based optimisation. Overall, dynamic façade design is a complex process that requires consideration and definition of multiple factors, including available resources, the type of dynamic systems employed, aesthetic qualities, and user preferences and acceptance, all in relation to the building's functional performance.

Daylighting

Several indices have been introduced to evaluate daylight performance in indoor spaces. These indices are generally classified into two groups: static and dynamic. **(a) Static index:** Evaluation using static indices is carried out for a fixed condition, usually under an overcast sky[23]. **(b) Dynamic index:** Due to the limitations of the static approach, dynamic indices were developed. These indices take into account design parameters, climate conditions, and sky variations. Based on meteorological data, they allow the evaluation of indoor lighting conditions and users' visual comfort throughout the year. The most important indices for assessing visual comfort are as follows:

Useful Daylight Illuminance (UDI): This index represents the percentage of occupied time during a year when horizontal illuminance at a specific point falls within a defined range. Considering the lower and upper thresholds of illuminance, the evaluated time is divided into three categories: (i) periods when daylight is too low (UDI less), (ii) periods when daylight is within the useful range (UDI useful), and (iii) periods when daylight is too high (UDI more), which can cause visual discomfort. Although the exact thresholds may vary in different sources, the range of 300–3000 lux is commonly recommended as sufficient daylight[24].

Daylight Autonomy (DA): This index indicates the adequacy of daylight in an indoor space. It is defined as the percentage of the annual occupied time when the required illuminance level at a given point is met solely by natural daylight. According to the Illuminating Engineering Society (IES) standard, a space is considered 'acceptable' if daylight provides at least 300 lux 50%<55% of the occupied hours, and 'preferred' if daylight provides 300 lux 50%< 75% of the time.

Spatial Daylight Autonomy (sDA): This index evaluates whether a work plane in a space receives sufficient daylight during annual working hours[25].

14. Samadi , Sahba , Esmatullah Noorzai , Liliana O Beltra, and Saman Abbasi. 'A computational approach for achieving optimum daylight inside buildings through automated kinetic shading systems.' *Frontiers of Architectural Research*.(2020): 335-349.

15. Sangtarash, F.; Nikghadam, N.; Fayaz, R.; Matini, M.R. A comparative study of the kinetic movement pattern of a triangular geometric facade regarding natural lighting in an office building in Tehran. *Journal of Iranian Architecture & Urbanism*. (2023), 14(2): 159-175.

16. H. F. Hassan, Fayrouz, Khaled A. Y. Ali, and Salwa A M. Ahmed. 'Biomimicry as an Approach to Improve Daylighting Performance in Office Buildings in Assiut City, Egypt.' *Journal of Daylighting*. (2023):1-16.

17. Sharaidin, Kamil. 'Kinetic Facades: Towards Design for Environmental Performance'. PhD diss., RMIT University, (2014).

18. Başar, C. 'Topolojik ve Deneyimsel Bağlamlar Üzerinden İncelenmesi'. Master's thesis, Istanbul Technical University, (2014).

Annual Sunlight Exposure (ASE): Since *Spatial Daylight Autonomy (sDA)* does not define an upper limit for daylight levels, the ASE index was introduced to identify the portion of a space exposed to excessive direct sunlight. ASE evaluates the potential source of visual discomfort or glare[26]. It is defined as the percentage of a target area that receives direct sunlight with an illuminance of 1000 lux or more for over 250 hours per year[27].

Daylight Glare Probability (DGP): DGP is one of the most common indices for assessing glare in indoor environments. It measures the illuminance entering the eye in relation to time. The values are interpreted as follows: > 0.35 = imperceptible glare, 0.35–0.40 = perceptible glare, 0.40–0.45 = disturbing glare and < 0.45 = intolerable glare[28].

Materials and Methods

This study is applied in purpose and quantitative in nature. Using simulation tools, it analyzes and evaluates rotational movement axes with circular and rectangular geometric patterns of kinetic façades on the four orientations of an office building in Tehran, based on daylight performance. the simulations were conducted using Rhinoceros version 6.32, the Grasshopper plugin, Honeybee Plus version 0.0.06, and Ladybug version 1.5.0. In addition, the Python programming language was employed for averaging the numerical data.

In the first step, as illustrated in Figure 1, the solar path for Tehran was simulated using the Ladybug plugin and the corresponding weather file. In the subsequent step, a reference open-plan office space with a window-to-wall ratio (WWR) of 90% was modeled. The base case model, without any shading devices, was evaluated using dynamic daylight performance metrics. The simulation results[29] in Figure 2 and Table 1, indicated that the north façade does not require kinetic shading; therefore, the south, east, and west façades were further investigated. In the next phase, two geometric configurations of kinetic façades (circular and rectangular) were examined with respect to three rotational movement axes (horizontal, vertical, and diagonal). The kinetic façade modules were programmed to respond adaptively to the solar path, opening and closing according to the incident solar angles, such that the degree of openness gradually decreased as the sun's altitude and azimuth shifted[30]. Finally, simulation data for the south, east, and west façades were compared and analyzed in terms of daylight availability. Based on façade responsiveness to natural illumination, the optimal geometric configuration, movement axis, rotation angle, and dimensions (length, width, and radius) were proposed for the three primary façades of a typical office building in Tehran.

Simulation

As depicted in Figure 3 the geometry of the simulated office space was defined with a width of 4 m, a length of 6 m, and a height of 3 m, resulting in a floor area of 24 m², designed for four occupants. The transparent façade was placed only on one side of the room along its width, and the model was rotated toward the cardinal orientations. The reference model was located in Tehran at a latitude of 35.69° and a longitude of 51.32°. No surrounding obstructions were considered to eliminate external shading effects. The façades were programmed

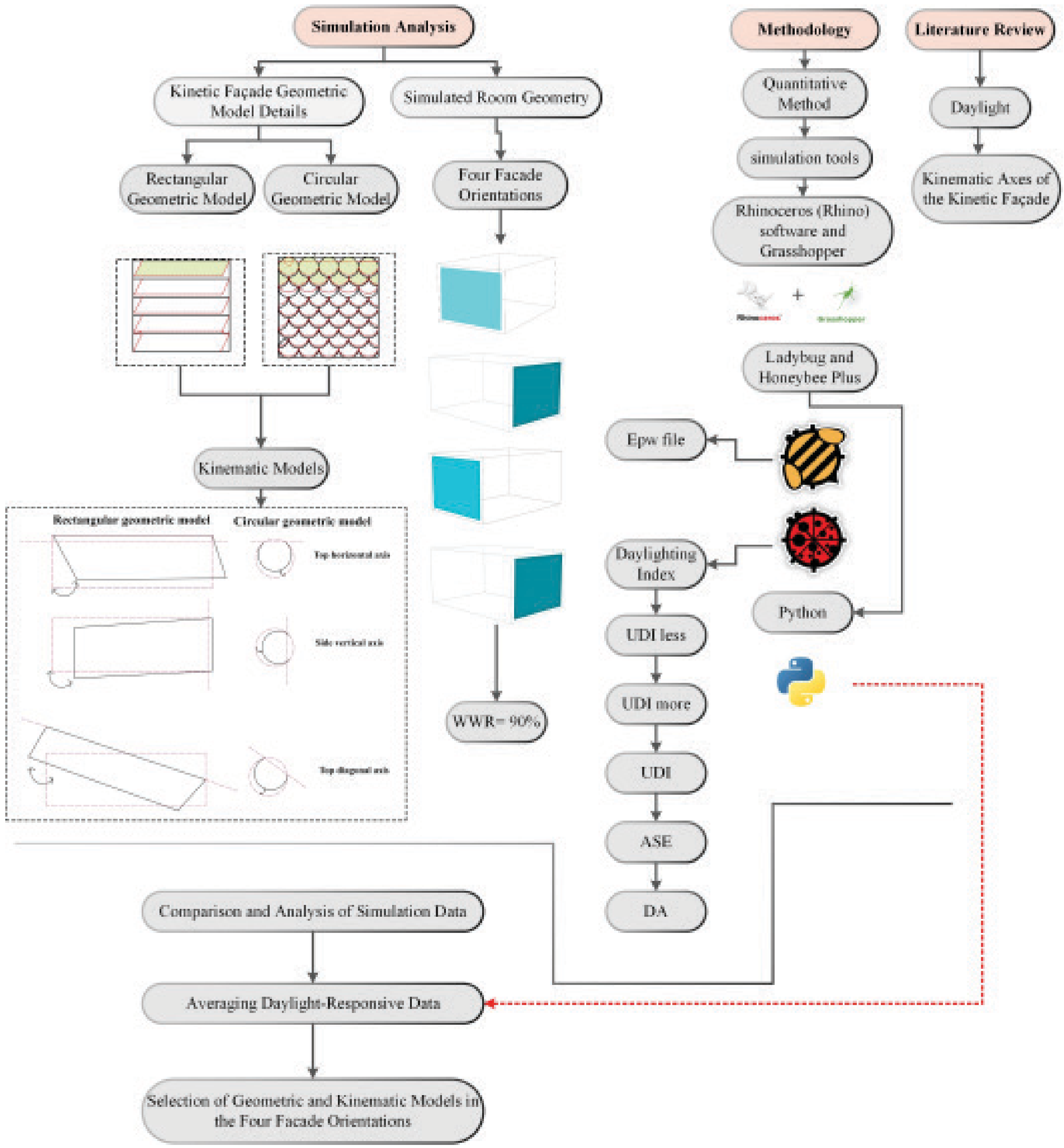
19. Schumacher, Michael, Michael Marcus, Vogt Luis A, and Cordón Krumme. *Architektur in Bewegung – Neue dynamische Komponenten und Bauteile*. German: Birkhäuser, (2019).

20. Herzog, T., Krippner, R., & Lang, W. Facade Construction MANUAL. Munich: DETAIL Business Information GmbH, (2017).

21. A.H.A. Mahmoud and Y. Elghazi, 'Parametric-based Designs for Kinetic Facades to Optimise Daylight Performance: Comparing Rotation and Translation Kinetic Motion for Hexagonal Facade Patterns', *Solar Energy* 126 (2016): 111–127, https://doi.org/10.1016/j.solener.2015.12.039.

22. Jaafar Ahmad Ibrahim and Halil Zafer Alibaba, 'Kinetic Façade as a Tool for Energy Efficiency', *International Journal of Engineering Research and Reviews* (2019): 1–7.

23. Housing in Hot and Dry Climate of Iran (Case Study: five-door rooms in Yazd Traditional Houses)', *Journal of Architectural Thought* 4, no. 8 (Autumn/Winter 2020–21), https://doi.org/10.30479/AT.2020.10857.1231.



24. Nabil, A., and J. Mardaljevic. 'Useful daylight illuminances: A replacement for daylight factors.' *Energy Build.no* 38 (2006): 905–913.

25. Hosseini, N, and M HeiraniPour. 'The Role of Orosi's Islamic Geometric Patterns in the Building Façade Design for Improving Occupants' Daylight Performance.' *Published by solarlits.com. This is an open access article under the CC BY license, (2020):201-221. (https://creativecommons.org/licenses/by/4.0/).*

26. Elghazi, Y, A Wagdy, S Mohamed, and A Hassan. 'DAYLIGHTING DRIVEN DESIGN: OPTIMISING KALEIDOCYCLE FACADE FOR HOT ARID CLIMATE.' *Fifth German-Austrian IBPSA Conference RWTH Aachen University,*(2014): 314-321.

Figure 1. Research process, Source: Authors.

27. Erlendsson, Ö. *Daylight Optimisation-A Parametric Study of Atrium Design: Early Stage Design Guidelines of Atria for Optimisation of Daylight Autonomy*. Sweden: School of Architecture and the Built Environment.

28. Suk, J. Y., Schiler, M., & Kensek, K. 'Investigation of existing discomfort glare indices using human subject study data.' *Building and Environment,Sol Energy, no78* (2016): 15–28.

29. Sangtarash, Fataneh, et al. 'Utilising Kinematic Models of Kinetic Facades to Obtain Optimal Natural Lighting in an Office Building'. Journal of Architectural Engineering 31, no. 1 (2025): 04024050. https://doi.org/10.1061/JAEIED.AEENG-1705.

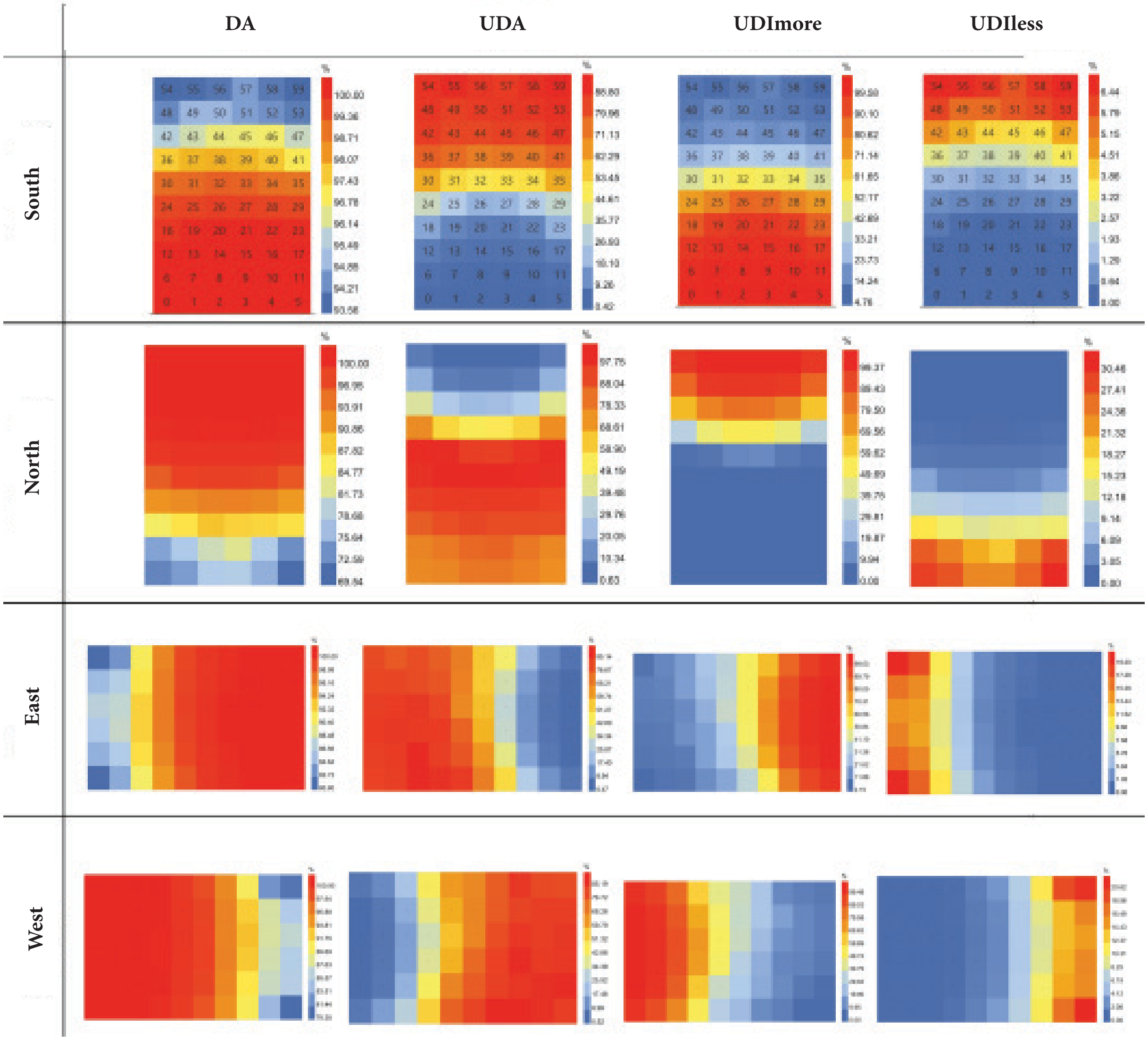


Figure 2. Simulation results of annual dynamic daylight in four directions.[31]

Table 1. Annual dynamic daylight analysis in four façade orientations.[31]
Note: ASE values exceeding 10% (highlighted in Gray color & Underline) indicate a potential risk of glare and visual discomfort.

Façade orientation	Dynamic daylight index					
	DA	UDI	UDI more	UDI less	sDA	ASE
South	100%	88.80%	99.58%	6.44%	100%	50%
North	100%	97.58%	99.37%	30.46%	100%	0%
East	100%	85.14%	99.53%	19.20%	100%	48.33%
West	100%	85.19%	99.48%	20.62%	100%	40%

to open and close adaptively in response to the sun's position and the surface normal vector. The Tehran (Mehrabad) weather file (2004–2018) was downloaded[32] and imported into the simulation patch. Daylight simulations were conducted for three representative days of the year: March 21 (spring equinox), July 21 (summer solstice), and December 21 (winter solstice). The autumn equinox was excluded due to its similarity to the spring equinox. Simulations were performed for every working hour between 08:00 a.m. and 4:00 p.m.The daylight performance of the reference model was evaluated based on a sensor grid of 59 points, distributed at 0.6 × 0.6 m intervals. A reference workplane[33] at 0.76 m above the finished floor level was selected, representing the average desk height in office spaces. Public holidays on Thursdays and Fridays were considered in the occupancy schedule. Peak occupancy hours were calculated using the software, and three representative times (09:00 a.m., 12:00., and 4:00) were chosen for daylight analysis.

Artificial lighting was not included in the simulations, and dynamic daylight performance metrics, including DA, UDI, UDI more, UDI less, sDA, and ASE, were analyzed. The geometric and kinetic movement patterns of the façades are summarised in Table 2, while the characteristics of the simulated office room are presented in Table 3.

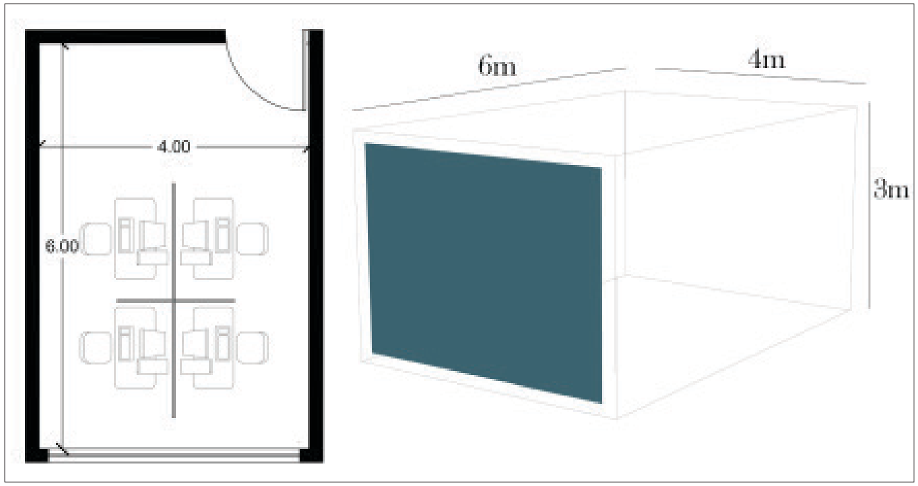


Figure 3. Plan (right) and mass (left) of the simulated model, Source: Authors.

Constructed Samples

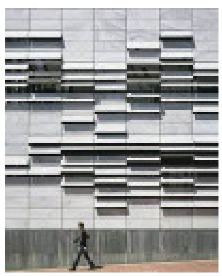
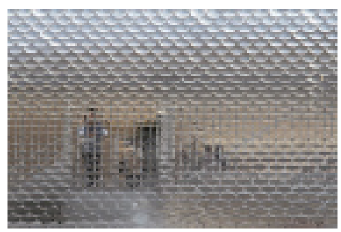
name	Hôpital Jean Mermoz (arch. F.-H. Jourda, 2008)	North Mediterranean Health Center / Ferrer Arquitectos, 2010	BBC Pavilion- 2019
Geometric model	rectangle		circle
Kinematic Model and Axis	Rotational Kinematic Model with Diagonal Axis	Rotational Kinematic Model with Horizontal Axis at the Top	Rotational Kinematic Model with Horizontal Axis at the Top
figure			

Table 2. Geometric and Kinematic Patterns of Kinetic Façades.

30. Fataneh Sangtarash, 'The Explanation of the Geometric and Movement Pattern of the Kinetic Façade for Optimal Response to Natural Light Case Study: Office Building in "hot and dry" Climate of Tehran', Dr.Arch. diss., Faculty of Art and Architecture, Azad University, South Tehran Branch, (1402).

Utilising the Honeybee plugin, the daylight performance and visual comfort indices were assessed via the Radiance and DAYSIM simulation engines.The main assumptions for the Radiance parameters are summarised in Table 4.

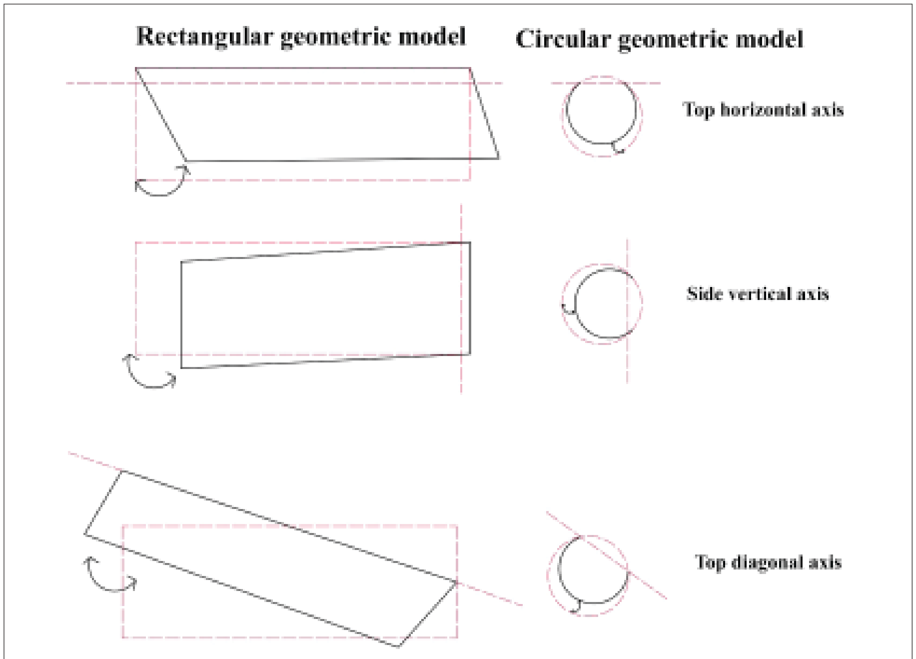
Table 3. Specifications of the Simulated Room.

Room Dimensions	Width: 4 m, Length: 6 m, Height: 3 m
Ceiling Reflectance	80%
Wall Reflectance	50%
Glass Visible Transmittance	90%
Floor Grid Dimensions	0.6 m
Floor Measurement Points	Point 59
Window-to-Wall Ratio (WWR)	90%

Table 4. Radiance Parameters for Daylight Availability Metrics.

Ambient Divisions	Ambient bounces
512	2

Figure 4. Circular and rectangular geometric models with three rotational axes of kinematics.



Results

Phase I involved the computation of annual dynamic daylight metrics for the south, east, and west façades, utilising a static baseline model (i.e., without kinetic shading). The resulting performance values are summarised in Table 4.

Subsequently, Phase II focused on the systematic application and performance simulation of two main geometric patterns—circular and rectangular—each integrated with three distinct rotational movement axes: horizontal (top pivot), vertical (side pivot), and diagonal (top pivot), as illustrated in Figure 4.

As shown in Table 5,circular and rectangular geometric patterns with three rotational movement axes were simulated and analyzed for the south, west, and east façades on three representative days of the year: July 21, March 21, and December 21. Based on dynamic daylight performance metrics, including UDI less and ASE, each pattern was compared and analyzed in terms of movement axis, geometric configuration, and, for each day, the optimal angle and dimensions (length, width, and radius) for the three façades were determined. It should be noted that the dimensions of the geometric patterns and their movement axes were kept constant across the three façades, Conversely, the rotation angle (or degree of openness) was treated as the primary independent variable, which was iteratively adjusted for each façade to achieve optimal dynamic daylight performance.

Intolerable glare (indicated in Gray color & Underline in Table 5) was observed in some cases. The vertical-axis rotation pattern at the side, combined with both circular and rectangular patterns, was unsuitable for all façades, producing intolerable glare at 4:00 p.m. on the selected days. For the south façade, the diagonal-axis rotation pattern at the top caused intolerable glare in both circular and rectangular patterns at the same time,whereas the east and west façades responded adequately to daylight. The top-pivoted horizontal-axis rotation mechanism, implemented for both circular and rectangular modules, proved highly effective in maintaining a favorable balance between Useful Daylight Illuminance (UDI) and Annual Sunlight Exposure (ASE) criteria across all three cardinal façades, given the specific design constraints (90% WWR) and the Tehran (Iran) climate reference file.The optimal range of façade openness for the circular pattern is 5° to 90° (south), 5° to 20° (west), and 5° to 10° (east). For the rectangular pattern, optimal openness ranges are 40° to 60° (south and west) and 80° to 90°(east).

Detailed performance data for the diagonal-axis rotation pattern with both circular and rectangular geometries are provided for reference.

Circular Geometric Model with Rotational Kinematic Axis at the Top (Diagonal Axis)

The circular geometric model, integrated with a top-pivoted diagonal rotation axis (as depicted in Figure 5, The radius of each circle is 0.18 m. In the first step, the opening angle of the western and eastern façades was simulated from fully open (0°) to fully closed (95°). The opening angle of the façade ranges from 95° (open) to 0° (closed), while the most suitable angles are as follows: 95° to 85° in 5° increments for the western façade and 90° to 95° for the eastern façade. The façade opens according to the sun's position (95°) and gradually closes (0°) during the simulation.

After simulating the façade on the 21st day of March, June, and December at 9:00 a.m., 12:00 p.m. and 4:00 p.m., it was determined, according to Table 6, that the circular geometric model with a rotational kinematic axis at the top (diagonal axis) provides adequate daylight response for both the western and eastern façades.

Rectangular Geometric Model with Rotational Kinematic Axis at the Top (Diagonal Axis)

The rectangular geometric module was configured with a top-pivoted diagonal rotation mechanism, the setup of which is detailed in Figure 5.Each rectangle measures 0.5 × 1 m. In the first step, the opening angle of the western and eastern façades was simulated from fully closed (0°) to fully open (95°). The opening angle ranges from 95° (open) to 0° (closed), while the most suitable angles are: 90° to 65° in 5° increments for the western façade and 90° to 75° for the eastern façade. The façade opens according to the sun's position (95°) and gradually closes (0°) during the simulation. (Figure 6.)

After simulating the façade on the first day of March, June, and December at 9:00 a.m., 12:00, and 4:00 p.m, it was determined, according to Table 7, that the rectangular geometric model with a rotational kinematic axis at the top (diagonal axis) provides adequate daylight response for both the western and eastern façades.

Discussion

Based on recent research on kinetic façades in Iran and worldwide, it is observed that kinetic façades perform better than their fixed counterparts in reducing glare and controlling day-

31. Sangtarash, Fataneh, et al. 'Utilising Kinematic Models of Kinetic Facades to Obtain Optimal Natural Lighting in an Office Building'. *Journal of Architectural Engineering* 31, no. 1 (2025): 04024050. https://doi.org/10.1061/JAEIED.AEENG-1705.

32. *climate.onebuilding.org*.

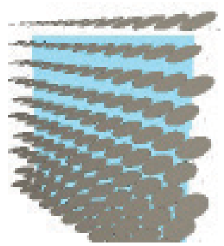
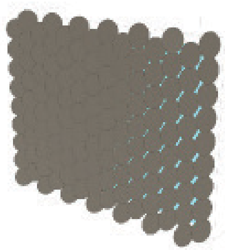
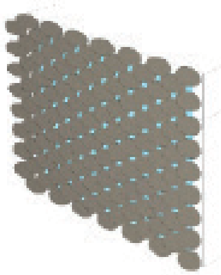
33. National Building Regulations Office, *Saving Energy Consumption/Topic 19* (Tehran: Iran Development Publishing House, 1401).

light. The performance of adaptive façades in achieving optimal interior daylight is critically determined by the synergistic relationship between several interdependent factors: module geometry, kinematic movement typology, room volume and configuration, and the dynamic control strategy relative to solar position and local climate Evaluating these factors comprehensively, while considering the overlap of daylight indices such as UDI, UDI less, UDI more, ASE, and DA, can further highlight their importance.

Comparison of Circular and Rectangular Geometric Models

As shown in Figure 7, the data for useful daylight below 500 lux (UDI less) indicate that the rectangular geometric model with a horizontal axis provides more optimal dynamic daylight

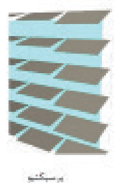
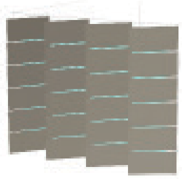
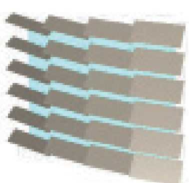
Table 5. Comparison of Circular and Rectangular Geometric Models with Three Rotational Kinematic Axes in the Southern, Western, and Eastern Façades.

Models	Geometric models	Motion axis	Daylight Index	South	East	West
	Circle	Top Horizontal axis	Dimensions	0.18m	0.18m	0.18m
			Open angle (°)	5° to 30°	5° to 10°	5° to 20°
			Avg UDI Less	47.84%	51.46%	59/86%
			Avg ASE	1%	1.66%	4%
			DGP	0	0	0
		Side Vertical axis	Open angle (°)	50° to 40°	20° to 25°	20° to 25°
			Avg UDI Less	86.20%	84.81%	45.84%
			Avg ASE	30.22%	12%	11.85%
			DGP	0.62 Intolerable at 12:00 p.m. on the 21st day of each quarter	0.68 Intolerable at 09:00 a.m. on day 21st of each quarter	1 Intolerable at 4:00 p.m. on 21st July
		Top Diagonal axis	Open angle (°)	50° to 95°	90° to 95°	95° to 85°
			Avg UDI Less	70.81%	49.74%	52.88%
			Avg ASE	14%	6.66%	8.33%
			DGP	0.71 Intolerable at 4:00 p.m. in 21st December, and a level of 0.56 was recorded at 12:00 p.m. on day 21st of June and March.	0	0

performance for the interior of an office building in Tehran compared to the circular geometric model with a horizontal axis at the top, with differences of 16% in the southern façade, 9% in the western façade, and 7% in the eastern façade. This performance is significant, as it indicates comprehensive daylight coverage where the Useful Daylight Illuminance (UDI) threshold of 500 lux is met across the entire reference workplane, ensuring no under-lit zones within the space. However, the values for useful daylight below 500 lux (UDI less) are similar for both circular and rectangular models with a rotational diagonal axis at the top in the eastern and western façades. Conversely, the Annual Sunlight Exposure (ASE) values for the southern façade with the top-pivoted diagonal axis surpass the 10% tolerance level across both geometric models (circular and rectangular). This breach suggests a significant risk of direct sun penetration, resulting in visual discomfort and potential glare for the occupants. In contrast, for the eastern and western façades, the ASE values are below 10%. Moreover, for the southern, eastern, and western façades with a horizontal axis at the top, the ASE values are below 10%, indicating that these spaces are free from glare and the results are acceptable.

The results unequivocally confirm that a horizontal-axis kinetic shading device offers su-

Table 5. Comparison of Circular and Rectangular Geometric Models with Three Rotational Kinematic Axes in the Southern, Western, and Eastern Façades.

Models	Geometric models	Motion axis	Daylight Index	South	East	West
	Rectangular	Horizontal Top axis	Dimensions	1 × 0.5m	1 × 0.5m	1 × 0.5m
			Open angle (°)	60° to 90°	80° to 90°	60° to 90°
			Avg UDI Less	31.66%	44.70%	50.71%
			Avg ASE	2.29%	6%	0
			DGP	0	0	0
		Side Vertical axis	Open angle (°)	60° to 30°	65° to 40°	60° to 30°
			Avg UDI Less	68.22%	86.95%	90.47%
			Avg ASE	33%	10%	12%
			DGP	0.66 Intolerable at 12:00 and 4:00 p.m. on the 21st of each quarter	0	0
		Top Diagonal axis	Open angle (°)	80° to 40°	90° to 75°	90° to 65°
			Avg UDI Less	66.78%	49.86%	54.54%
			Avg ASE	24.44%	2.22%	7%
			DGP	0.56 Intolerable at 12:00 p.m. on the 21st of each quarter	0	0

perior performance for the southern façade of a Tehran office building when compared to its vertical-axis counterpart, particularly in mitigating high-angle solar heat gain. The rotational kinematic model performs better in responding to natural daylight than the folding kinematic model, and using a kinetic façade significantly reduces glare compared to a model without movable elements. Kinetic façade factors, including room length, width, and height relative to orientation, the distance of the façade from the glass, as well as the depth and angle of the shading device, have a significant impact on glare, dynamic daylight, and energy savings in an office building in a hot and arid climate[34]. Moreover, daylighting not only contributes to energy savings but also enhances occupant productivity and comfort[35]. These façades[36] Overall, kinetic façades demonstrated improved energy efficiency and enhanced visual comfort relative to static shading systems. This improvement is quantified by a significant increase in Spatial Daylight Autonomy (sDA), which directly translates to better daylight distribution and a substantial improvement in Useful Daylight Illuminance (UDI) availability.[37]. A recurrent methodological limitation in recent literature is the incomplete evaluation of dynamic daylighting

34. Zekraoui, Djamel, and Noureddine Zemmouri. 'SMART AND DYNAMIC FACADES: A PATH TO ENERGY OPTIMISATION IN ARID ENVIRONMENTS.' *journal of Architectural and Engineering Research*, (2024): 84-102

35. Sureshkumar Jayakumari, S.D., S.T. Imalka, R.J. Yang, C. Liu, S. Yang, M. Marschall, P.S. Corradini, A.F. Benito, and N Williams. 'Energy and Daylighting Performance of Kinetic Building-Integrated Photovoltaics (BIPV) Façade.' *Sustainability* 16,(2024): 9739. doi:https://doi.org/10.3390/su16229739.

36. Zheng, Yiqian, Jinxuan Wu, Hao Zhang, Caifang Lin, Yu Li, Xue Cui, and Pengyuan Shen. 'A novel sun-shading design for indoor visual comfort and energy saving in office space in Shenzhen.' *Energy and Buildings*, (2024): 115083. doi: https: //doi.org/10.1016/j.enbuild.2024.115083.

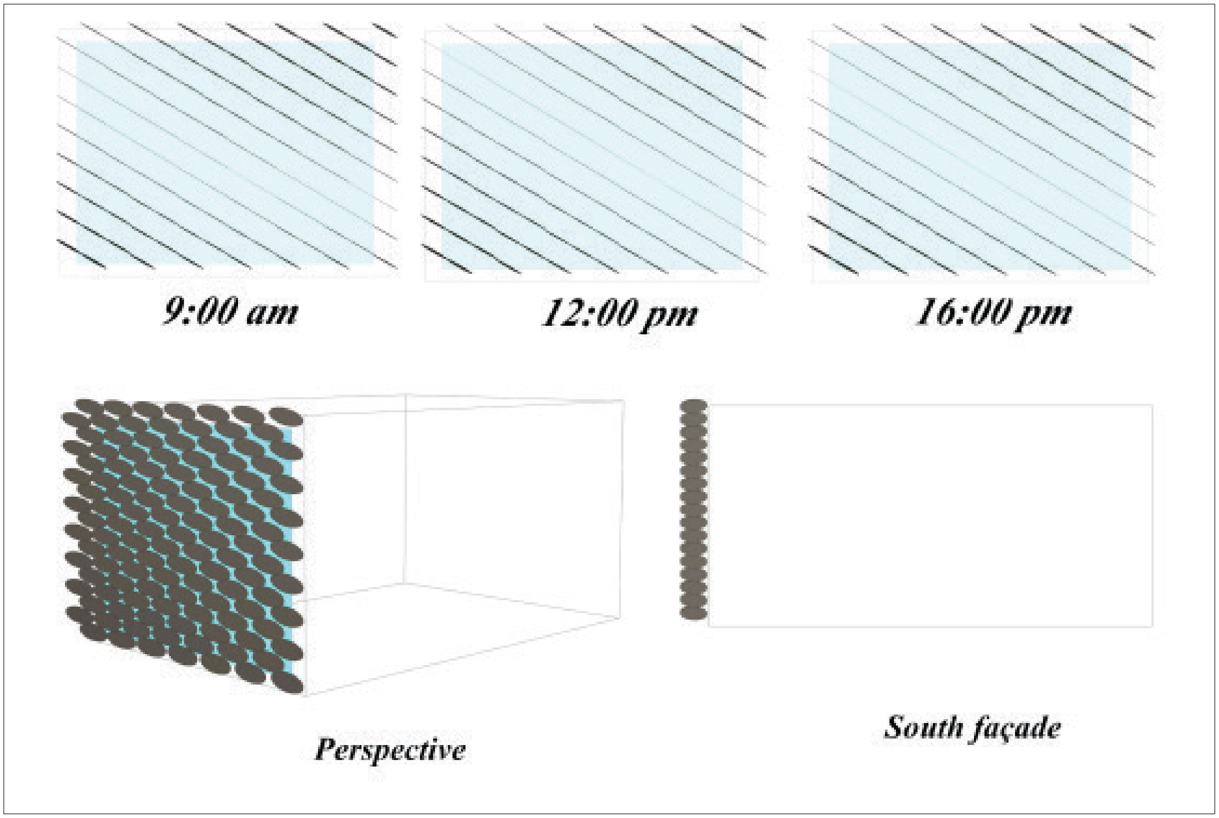


Figure 5. Façade Angle of the Circular Geometric Model with Diagonal Kinematic Axis According to the Sun's Position at 9:00 a.m., 12:00 and 4:00 p.m.. for the Western Façade.

performance, often relying exclusively on metrics such as Annual Sunlight Exposure (ASE) and Spatial Daylight Autonomy (sDA) without incorporating a comprehensive set of indices. While several geometric and kinematic models have been explored, none have proposed a specific, unified geometric and kinematic model tailored to the Tehran climate (hot and arid) that optimises daylighting and visual comfort for all four façades. The findings of this study are therefore consistent with previous research, confirming that kinetic façades effectively improve natural daylighting and visual comfortThe successful performance is attributable to the adaptive control strategy, wherein the façade modules modulate their openness in direct response to the sun's position. Furthermore, the rotational kinematic model utilising a horizontal axis consistently outperformed the vertical-axis rotation model in optimising internal daylight availability. Additionally, the size of the geometric pattern and room dimensions significantly affect daylight performance.

Among the limitations of this study is the absence of an actual office building with a kinetic façade for field measurement, which would allow comparison between simulation and real-world results. Furthermore, measuring devices for natural daylight in interior spaces have limitations, as it is not possible to simultaneously measure incoming daylight, useful daylight below 500 lux, and glare. Consequently, quantifying these disparate metrics simultaneously introduces a substantial computational challenge, even within multi-objective optimisation frameworks. This inherent conflict contributes to

Index	December 21			March 21			June 21		
	9	12	16	9	12	16	9	12	16
West Facade									
DA	99.95%	99.95%	99.95%	99.90%	99.95%	99.90%	99.90%	99.90%	99.90%
UDI	88.59%	88.33%	87.49%	88.70%	88.07%	88.02%	88.64%	87.18%	88.64%
UDI Less	50.76%	52.01%	51.57%	51.07%	55.94%	54.63%	53.06%	53.03%	53.69%
UDI more	65.15%	65.88%	64.94%	64.21%	65.04%	64.15%	65.36%	64.47%	64%
sDA	100%	100%	100%	100%	100%	100%	100%	100%	100%
ASE	8.33%	8.33%	8.33%	8.33%	8.33%	8.33%	6.66%	10%	8.33%
East Facade									
DA	100%	99.90%	99.90%	100%	100%	100%	99.90%	99.90%	100%
UDI	88.12%	87.81%	88.80%	87.76%	86.08%	87.13%	87.70%	87.39%	87.34%
UDI Less	49.35%	53.22%	51.96%	49.35%	46.05%	50.03%	50.18%	47.93%	49.56%
UDI more	70.02%	70.80%	70.38%	71.32%	70.80%	71.85%	69.18%	68.29%	70.17%
sDA	100%	100%	100%	100%	100%	100%	100%	100%	100%
ASE	6.66%	6.66%	6.66%	6.66%	6.66%	6.66%	6.66%	6.66%	6.66%

Table 6. Façade with Circular Geometric Model and Rotational Kinematic Axis at the Top (Diagonal Axis).

37. Bahdad, Ali Ahmed, Nooriati Taib, Fahad Saud Allahaim, and Ali Mohammed Ajlan. 'Parametric Optimisation Approach to Evaluate Dynamic Shading Within Double-Skin Insulated Glazed Units for Multi-Criteria Daylighting Performance in Tropics.' *Journal of Daylighting*, (2024): 349-371. doi:10.15627/jd.2024.24.

the complexity and dimensionality of the final parametric design space. Future research could evaluate rectangular kinetic façades with horisontal and diagonal rotational axes on all four façades, considering energy consumption, visual comfort, and thermal comfort, using either simulation or field measurement. Moreover, these façades could be assessed in different climates and cities to identify the most appropriate geometric and kinematic configurations for optimal interior daylighting in each location. The results of this study could also be applied to similar climates outside Iran.

Conclusion

This study aimed to optimise natural daylighting in an office building in Tehran using kinematic façades with horizontal, diagonal, and vertical rotational axes and two geometric models (circular and rectangular) on the north, south, west, and east façades. Initially, the geometry of a sample office room without a kinetic façade was simulated to assess natural daylight. Initially, the geometry of a sample office room without a kinetic façade was simulated to assess natural daylight. Based on the glare index (ASE), it was inferred that the northern façade

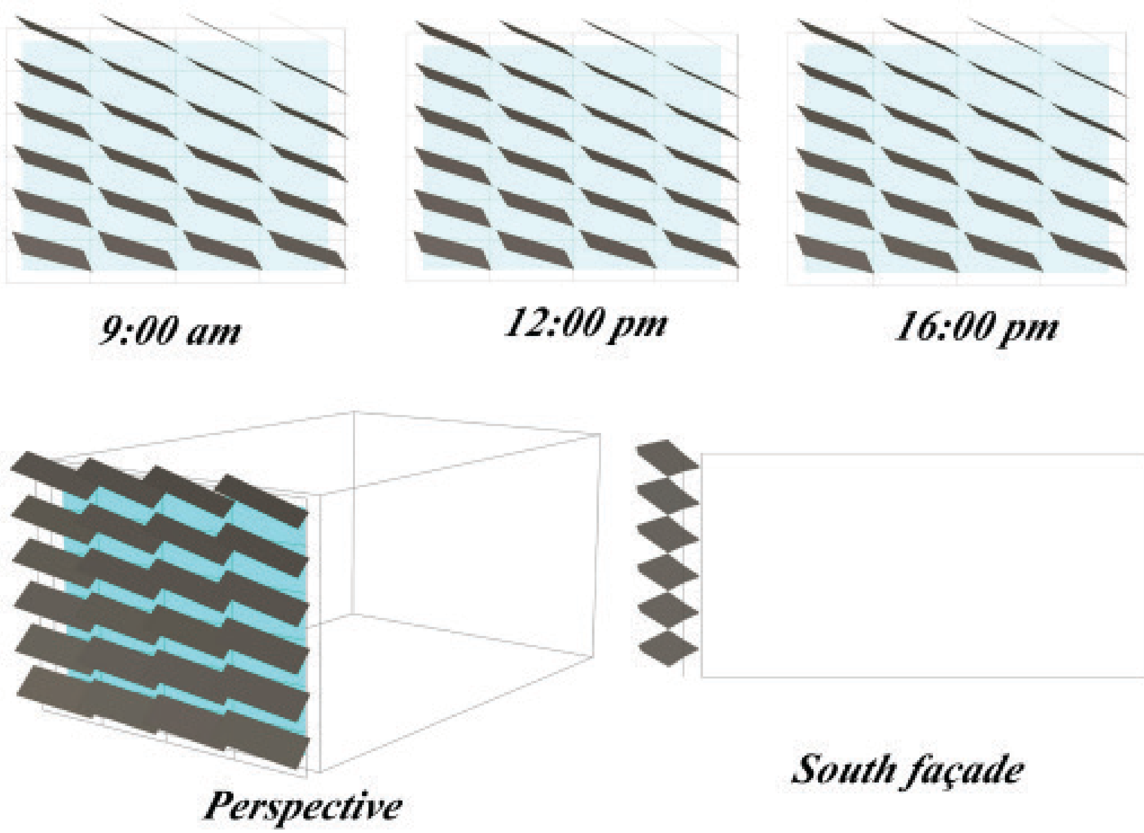


Figure 6. Façade Angle of the Rectangular Geometric Model According to the Sun's Position at 9:00 p.m., 12:00 and 16:00 p.m. for the Western Façade.

required no dedicated shading, as the space received adequate useful daylight even without a shading system. Therefore, the kinetic façade analysis was conducted only for the southern, eastern, and western façades. The circular and rectangular geometric models with a rotational kinematic structure and three axes (horizontal, vertical, and diagonal) were simulated and compared for the southern, western, and eastern façades. The simulation results highlighted the critical importance of the ASE and UDI less indices. When the shading device is partially closed, less light enters the interior, and a higher percentage of UDI less than 500 lux may result in areas of the interior receiving insufficient daylight. Conversely, when the façade is fully open, excessive daylight admission results in ASE values exceeding 10%, indicating a high risk of glare and visual discomfort. Therefore, optimising these two indices is essential for achieving adequate useful daylight in interior spaces. Next, the values of ASE, UDI less, and DGP for the rotational kinematic models with horizontal, vertical, and diagonal axes for both circular and rectangular geometries were averaged for the 21st day of March, June, and December using Python. Based on these analyses, the optimal kinematic axes and geometric models were selected.

The simulation results indicated that:

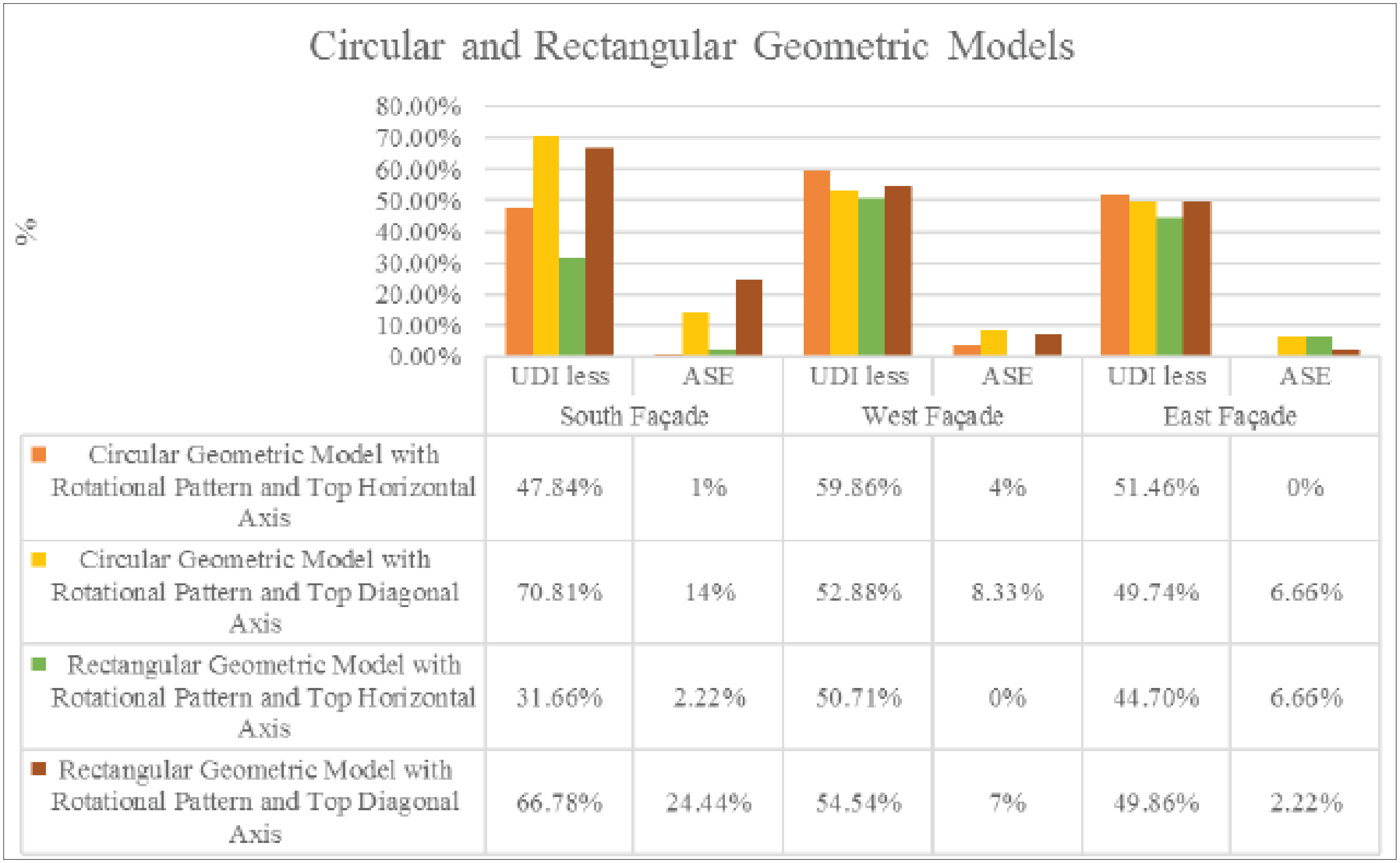
- Circular and rectangular geometric models with a horizontal rotational axis at the top respond adequately to dynamic daylight for the southern, western, and eastern façades.
- Circular and rectangular models with a diagonal rotational axis at the top provide sufficient

Index	December 21			Murch 21			June 21		
	9	12	16	9	12	16	9	12	16
West Facade									
DA	100%	100%	100%	100%	100%	100%	100%	100%	100%
UDI	89.95%	90.74%	90.32%	89.43%	89.80%	89.01	89.95%	89.74%	91.89%
UDI Less	53.22%	54.42%	53.79%	55.36%	56.04%	55.36%	53.64%	54.63%	54.42%
UDI more	87.60%	87.49%	88.07%	85.30%	85.03%	86.03%	83.31%	82.42%	983.99%
sDA	100%	100%	100%	100%	100%	100%	100%	100%	100%
ASE	6.66%	6.66%	6.66%	6.66%	6.66%	6.66%	10%	1.66%	10%
East Facade									
DA	100%	100%	100%	100%	100%	100%	100%	100%	100%
UDI	89.06%	89.38%	90.32%	88.96%	88.54%	88.75%	89.95%	89.80%	91.89%
UDI Less	47.10%	52.96%	51.13%	45.63%	48.98%	49.87%	57.56%	50.34%	45.26%
UDI more	88.59%	87.91%	88.12%	89.06%	86.66%	87.96%	83.62%	84.35%	85.24%
sDA	100%	100%	100%	100%	100%	100%	100%	100%	100%
ASE	3.33%	1.66%	5%	1.66%	1.66%	1.66%	1.66%	1.66%	1.66%

Table 7. Façade with Rectangular Geometric Model and Rotational Kinematic Axis at the Top (Diagonal Axis).

daylight for the western and eastern façades.

The simulation also demonstrated that parameters such as the façade opening angle, size (length, width, radius), clockwise or counter-clockwise rotation, and the reflectance of glass and wall surfaces are important factors affecting daylight performance in kinetic façades. Finally, by comparing geometric models based on ASE and UDI less indices, it was concluded that the rectangular geometric model with horizontal and diagonal rotational axes at the top provides more optimal daylighting than the circular geometric model with the same axes for the southern, western, and eastern façades of an office building in Tehran. The most suitable rotational axes for the kinetic façades are: horizontal and diagonal for the western and eastern façades and horizontal for the southern façade.



	South Façade		West Façade		East Façade	
	UDI less	ASE	UDI less	ASE	UDI less	ASE
Circular Geometric Model with Rotational Pattern and Top Horizontal Axis	47.84%	1%	59.86%	4%	51.46%	0%
Circular Geometric Model with Rotational Pattern and Top Diagonal Axis	70.81%	14%	52.88%	8.33%	49.74%	6.66%
Rectangular Geometric Model with Rotational Pattern and Top Horizontal Axis	31.66%	2.22%	50.71%	0%	44.70%	6.66%
Rectangular Geometric Model with Rotational Pattern and Top Diagonal Axis	66.78%	24.44%	54.54%	7%	49.86%	2.22%

Figure 7. Comparison of Circular and Rectangular Geometric Models.

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Documenting A National Treasure: Ganj-Nameh and the Iranian Built Environment Heritage

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BOOK REVIEW

Jourabchi, Keivan, and S. H. Iradj Moeini. "Documenting A National Treasure: Ganj-Nameh and the Iranian Built Environment Heritage". *Soffeh* 36, no. 2 (2026): 149–170.
DOI: http://doi.org/10.48308/soffeh.2026.107121

Despite its several-millennia long history, it was only quite recently that systematic documentation efforts aimed at identifying and introducing of Iranian architectural heritage were undertaken. It is actually only a few decades since scholars and researchers first began their scrutiny of these works in order to wipe the dust from the face of this vastly neglected albeit invaluable heritage.

Among these efforts *Ganj-Nameh* (*An Anthology of Treasures*) – SBU's Faculty of Architecture and Urban Planning compilation of Iranian Architecture – arguably stands out for its gargantuan scope, scholarship standards and rigorous documentation accuracy. The reference to 'treasure' in the title reflects the driving forces' belief in the values of The Iranian architectural heritage and how it can inspire a sense of identity for modern Iranians, whilst offering lessons to learn on a wider global scene.

Ganj-Nameh is also a response to frustrations with previous accounts crafted by non-Iranian scholars whose efforts, whilst being valuable in their own right, are often seen as lacking the thoroughness and quality any such

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http://doi.org/10.48308/soffeh.2026.107121

documentation requires. What is more, those accounts tend to be published sporadically, with occasionally less than noteworthy results, leaving researchers short of reliable references.

Bringing together information-rich and legible plans, clear, telling images and a thematic history of about six hundred significant historic realisations – ranging from mosques and madrasas to houses and baths – the *Ganj-Nameh* series seeks to not only promote research in this domain, but also encourage researchers, experts and all those interested, to initiate their own research on this rich heritage.

This is why a thematic order was adopted for the series – rather than the more common geographic alternative – in order to make it act as a handy tool for research. It is noteworthy that, wherever similar instances of a certain building type exceed a certain limit, a geographic, city-by-city, classification is introduced. For instance, wherever the number of documented houses has exceeded a certain number, a full volume is dedicated to the houses of that city. Alternatively, wherever the specimens of a type of building are scattered in various cities, they come as one collection, be it in one or more volumes. In this way, the thematic order is kept whilst the geographic order has been taken into

Figure 1. Northeastern and northwestern sides of the central courtyard.

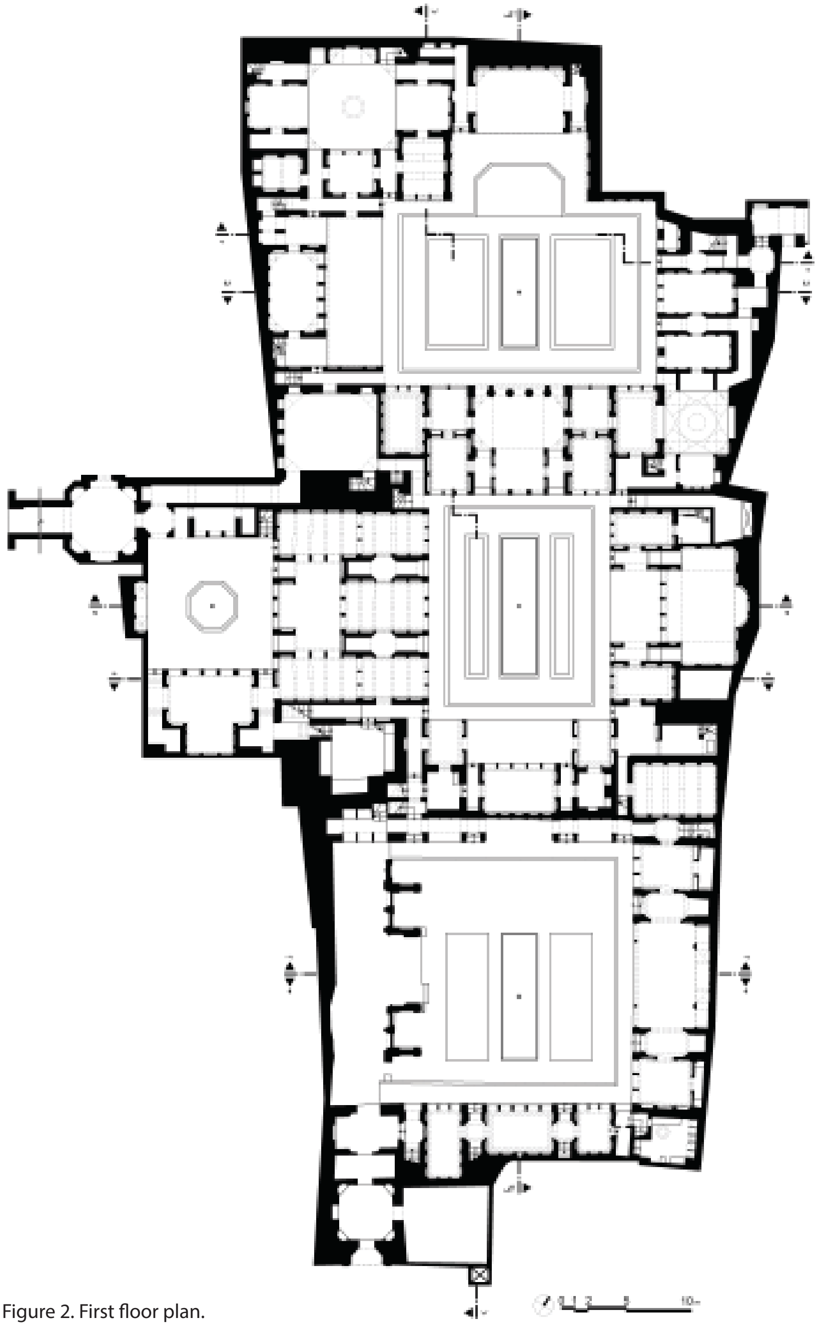


Figure 2. First floor plan.

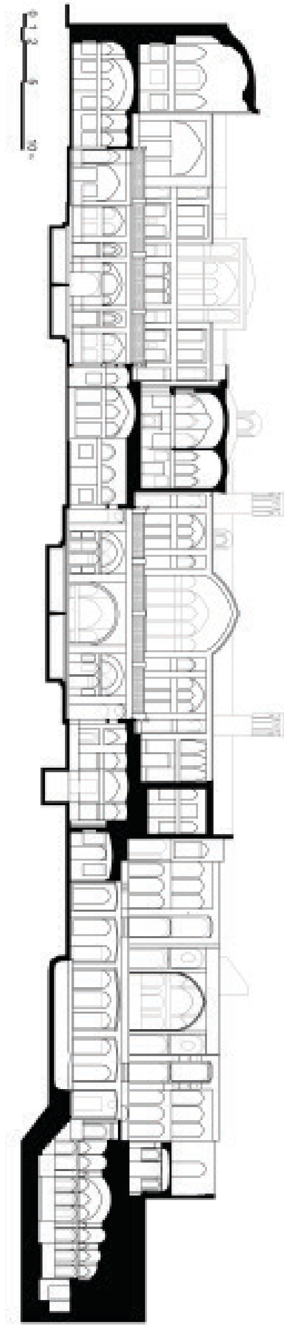


Figure 3. Section A-A.

consideration as a secondary measure.

Another point to mention is the fact that the collection was compiled in a short period of time: some fifty years of relentless efforts by both tutors and students of the faculty is behind the anthology. It may therefore be said that a great number of the students of this major faculty, past and present, have contributed to its development. The final preparations for publication began in 1992, with the first volume published in 1995; after more than 20 years, it came to its conclusion in 2015. During this period, the first five volumes were revised and published in its second edition.

The collection addresses almost every building type and introduces a total of 573 buildings in 98 towns and cities.

Four volumes of the series are allocated to introducing historic mosques. Put together, they introduce 107 monumental structures in 57 cities. Among them 49 buildings are congregational mosques in 49 cities, which are represented in volumes VII and VIII; and 58 buildings are ordinary mosques of our cities which are depicted in volumes VI and II: due to the importance of Esfahan and its architecture and multiplicity of mosques in this beautiful city, 18 historic mosques of this city are represented

Figure 4. Northwestern and southwestern sides of northern courtyard.

independently in volume II and finally, volume VI contains 40 monumental structures from 25 different cities.

The fifth volume introduces historic madrasas (schools) in different Iranian cities. In this volume, the reader becomes acquainted with 38 ancient madrasas belonging to various periods. Undoubtedly, many more ancient madrasas exist in our cities, but it may be boldly asserted that the most important ones are included here.

Volumes eleven, twelve and thirteen are dedicated to yet another facet of Iranian Islamic architecture, that of '*emamzadeh*'s (shrines of Shia saints) and mausoleums, which they introduce through numerous examples. Innumerable shrines and mausoleums belonging to saints, mystics, scientists, writers, poets, governors, kings and political figures are scattered across Iran. Almost no region, city or village of this country is without a shrine dedicated to one or another great personality. In the popular mind, the mausoleums of these eminent individuals are considered secure havens against spiritual woes and revered as such. The very multitude of these mausoleums, which belong to different periods, bespeaks both the long history of this country`s rich culture and the ceaseless respect of successive generations of its people for their spiritual and secular leaders. The 128 buildings introduced in these three volumes represent but a small fraction of the remaining mausoleums; however, as they include the most important and the most famous among these, they present a relatively clear picture of the architectural characteristics of these buildings in the course of history. In geographic terms, they cover most of present-day Iran, and historically, they span a period of approximately 1,000 years, from the early 10th to the late 19th centuries.

The ninth and tenth volumes have been allocated to introduce the bazaar buildings. These buildings which are one of the most important parts of the Islamic period heritage are rarely studied. Although our bazaars are widely renowned, one hardly finds books or articles dedicated mainly to their architectural aspects.

Whilst being the spinal column of our cities, our bazaars are also a collection of different buildings interconnected in a special way. In

Figure 5. Northeastern façade in the northern courtyard.

general, each bazaar consists of a main body, or a main passage (Rasteh Bazaar) with several buildings attached to it. In some cases, the main passage is straight and in others takes a shape of a plant form leading to branches, but is always comprised of a simple four-vaulted space (Chahar-Taqi) with two chambers on either side. In contrast to this repeated symmetry, attached buildings to the main passage are very diverse including different kinds of governmental, commercial, religious, educational and service buildings. However, the commercial buildings are considered to be the essential part of the bazaar, and have been introduced thoroughly in the two Volumes of the *Ganj-Nameh*.

Buildings like caravanserais, both urban and countryside, bathhouses, cisterns, mills, both water and wind mills, ice-houses, '*chapar-khaneh*'s (postal services) and so on that served people in their everyday life were essential components in Iranian civic life during last centuries. Because of their sophisticated architecture, countryside caravanserais and bathhouses attracted the attention of scholars. Two volumes of the *Ganj-Nameh* are dedicated to these building types. The seventeenth volume is dedicated to countryside caravanserais and the eighteenth volume introduces the historic bathhouses of Iran.

Numerous books have been written about caravanserais, introducing almost every existing specimen. The caravanserais introduced in this volume represent a mere handful of the multitude of caravanserais scattered across this country. These twenty-two caravanserais date back to Safavid and Qajar times, the oldest being probably anterior to the reign of Shah Abbas the Great. The present volume, therefore, does

Figure 6. Section D-D.

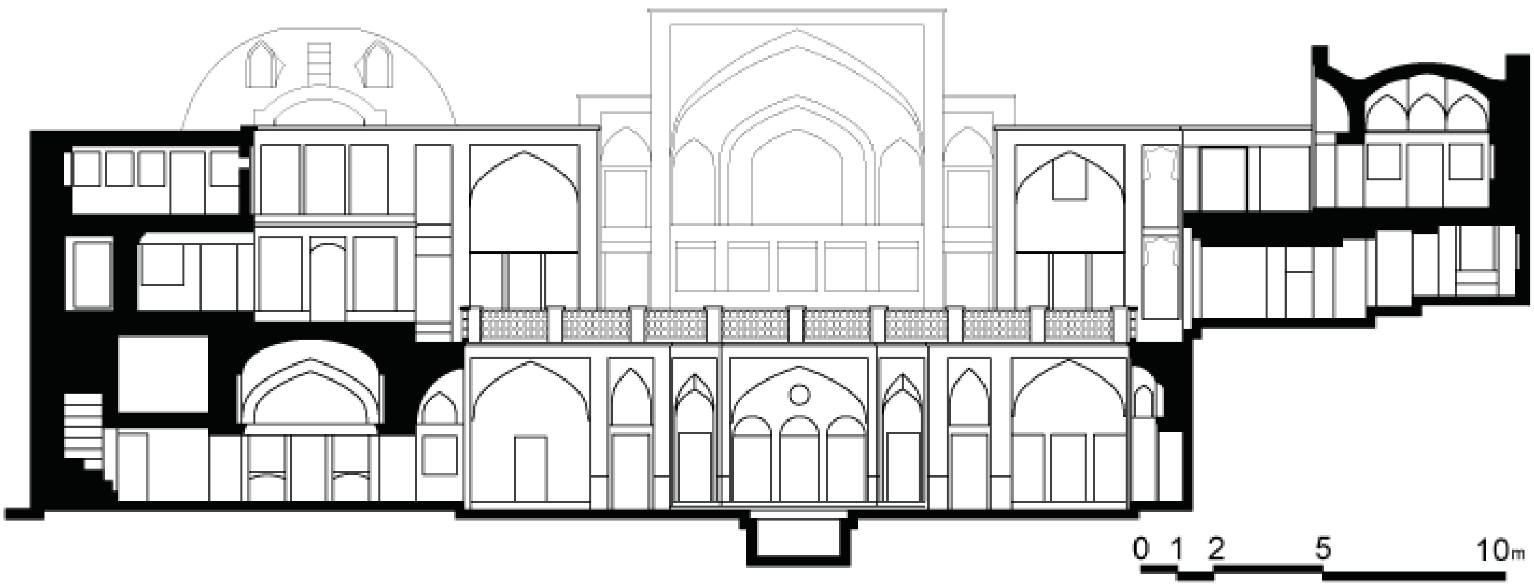


Figure 5. Section D-D.

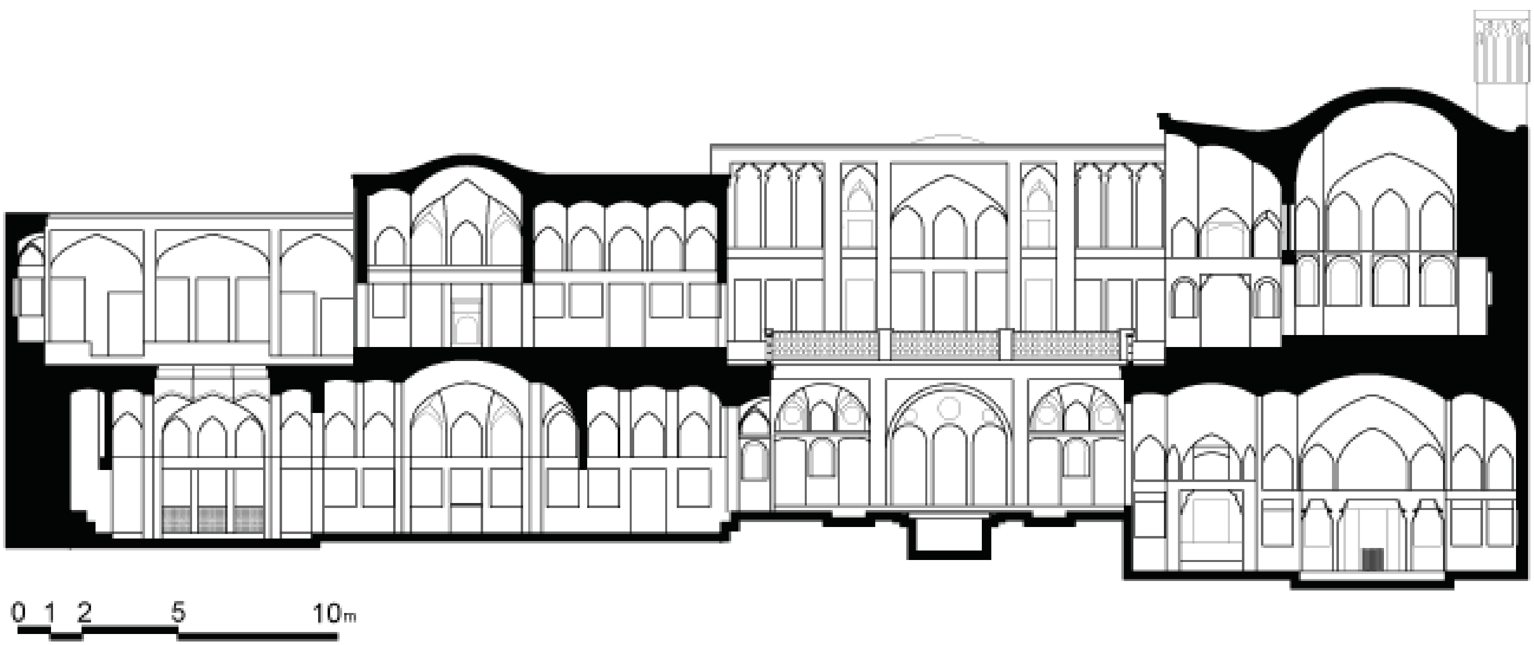
not represent all types of caravanserais built in different periods; however, its detailed plans, ample illustrations and extensive architectural explanations fully describe the prevailing types of caravanserais, paving the way for a deeper, more accurate, understanding of the architecture of Iranian caravanserais

As mentioned, the above volume focuses on countryside caravanserais. Urban caravanserais, which often occur in combination with bazaars, are introduced in the ninth and tenth Volumes of the *Ganj-Nameh*, titled Bazaar Buildings, alongside other auxiliary bazaar buildings. Built beside desert roads, countryside caravanserais bear essential differences with urban ones as regards their architectural features, spatial organisation, function and environment; hence, these two types of caravanserais should not be confused.

Houses have always existed as part of human habitation, reflecting their culture and beliefs. No building better illustrates architecture as a response to the physical needs and spiritual desires of man than a house. Therefore, houses are unique entities in the context of cultural studies, or in terms of space creation and architecture of any ethnic group. They are also significant components of the history of architectural development.

Despite this significance, information on house architecture is truly limited. This negligence is also present in architecture books. Fortunately, though, five volumes of the series introduce 135 houses in 25 cities: vol. I: 19 mansions in Kashan, vol. IV: 21 mansions in Esfahan, vol. XIV: 24 houses in Yazd and finally volumes XV and XVI also introduce traditional houses of 22 other cities, totalling 71 houses.

Figure 7. Section E-E.



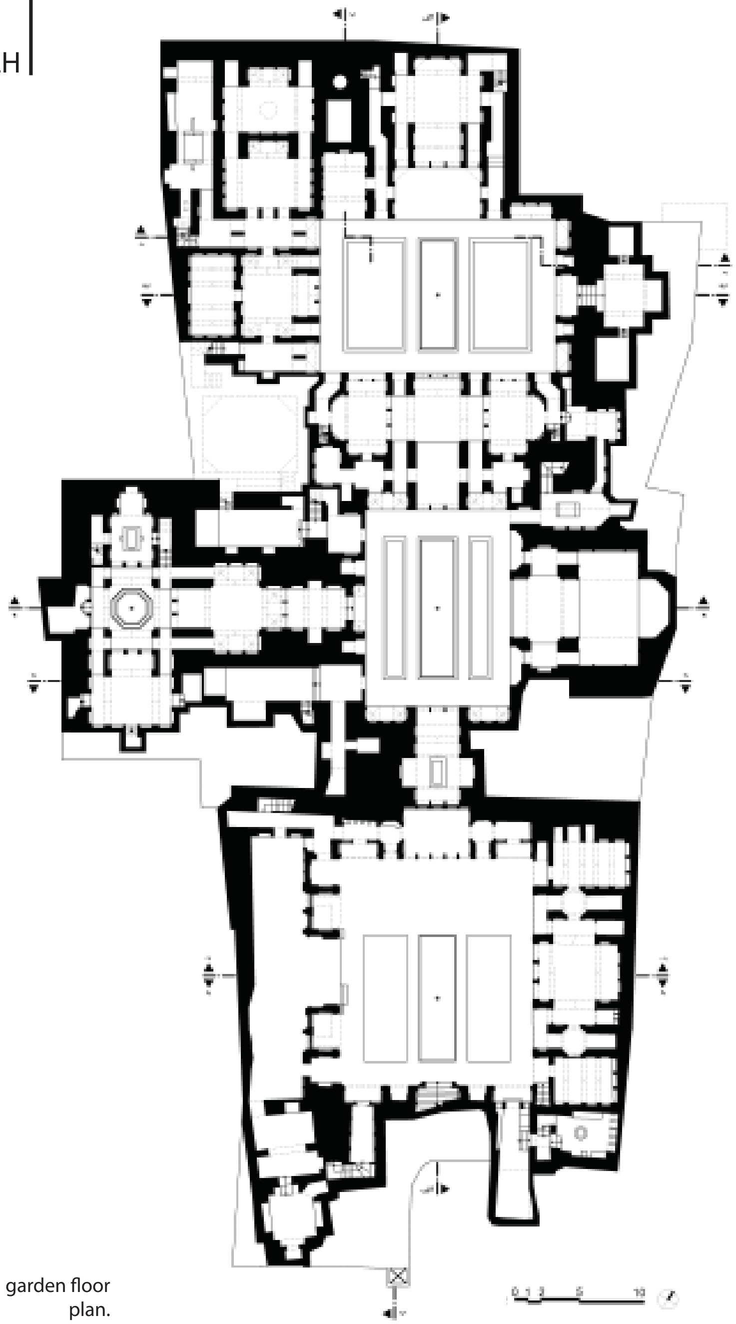


Figure 8 .Sunken garden floor plan.

Houses often lack precise construction dates. However, most of the houses presented in these five volumes can be estimated to be built in the 19th to the early-20th century, which is contemporary with the Qajar rule in Iran. A few may belong to before this era, especially Safavid period (16th and 17th centuries), as well as, some of them may be constructed during the early Pahlavi period (mid-20th century). Therefore, this collection of houses is, in fact, reflective of house architecture during the Qajar era, and highlights the tastes and trends in space creation and house design during the transformation period of Iranian architecture.

Scrutinising the collection of houses presented in these five volumes reveals some essential connections and similarities beyond the differences in the initial encounter. It is as though they all speak the same word although in different forms, in different regions and cities which have their own specific conditions and characteristics. They are all the same in their principal essence, and the differences are in form and according to circumstances. This is like the common language of people across regions that varies according to their different conditions and preferences, and each form is called a dialect.

As the defined set of words and certain rules of combination and word order in any language, there are defined sub-spaces in Iranian architecture, and clear rules governing their connections and compositions. Different architectural form of houses in different cities can be likened to dialects or branches of a main language, which is composed of intended yet limited changes in the form of sub-spaces or their combinations. These changes, however, do not cut the connection with the main language, but rather reorganise it according to new conditions and preferences.

Volumes 19 and 20 of the series introduce the most significant among extant gardens and palaces of Iran. A sum of 33 gardens and palaces, plus one major ensemble comprising many buildings, are introduced in these two volumes. It is true that palaces and gardens are two different types of construction, and distinct examples of both types have remained. However, since palaces are usually accompanied by gardens, there are also many examples that are simultaneously a palace and a garden.

If we take no notice of the original foundations of some of the introduced works presented here, however, most of the extant examples date from the 17th to the 20th centuries. The earlier examples have changed through centuries to match a figure according to the tastes of the time.

The third volume of the series introduces religious buildings of Tehran, and is unique among other volumes in that it introduces several types of buildings. This is because the present volume was the first of the series to take shape in view of the 200th anniversary of Tehran's adoption as capital. However, when the layout of the rest of the series was finalized, owing to the particular status of historic buildings of Tehran and the benefits the publication of this book was judged to bear, it was decided not to upset the present composition.

The truth is that historic works (religious buildings in particular) are actually lost amid the turmoil of Greater Tehran, and that Tehran today appears as a rootless city with no particular sense of identity. The first outcome of the

Figure 9. Northwestern and southwestern sides of central courtyard.

Figure 10. Southeastern side of the northern courtyard.

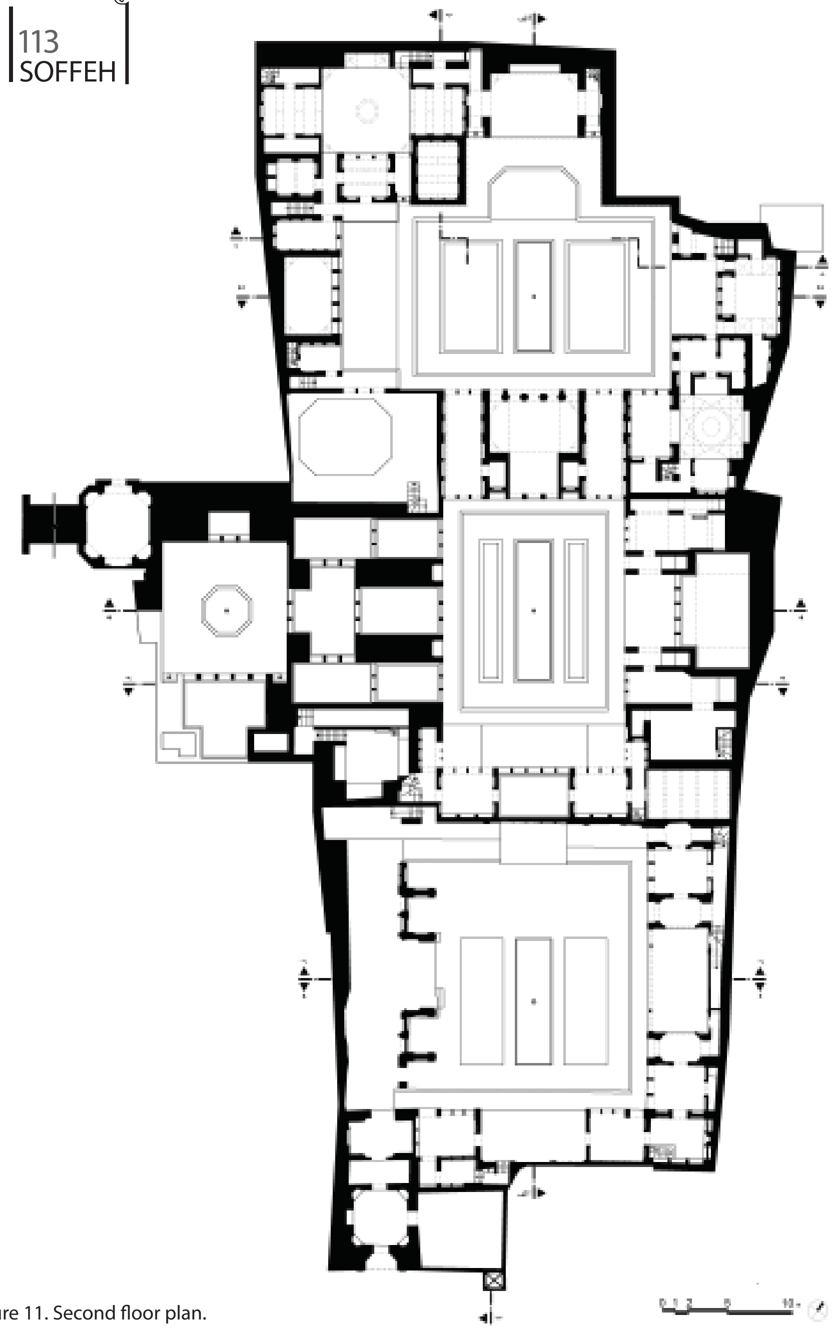


Figure 11. Second floor plan.

publication of this book can be to endow Tehran with a religio-historic prestige and restore its rightfulness as a city bearing a time-honoured historic past. Obviously, this book does not include all the religious buildings of Tehran, but the compilation of the most important among them within a single volume will show that Tehran boasts a varied and valuable collection of historic buildings ranging from mosques and madrasas to mausoleums, *emamzadeh*s, and *tekieh*s, many of which remain unattended amid the large and small buildings of contemporary Tehran.

Kashan, Haj Seyyed Mohammad-Ebrahim Tajer House

This house, which is predominantly known as the Abbasian House, is one of Iran's most architecturally significant historic residential houses. Like the preponderance of historic buildings in Iran, its architect is unknown; its patron, however, is known to be Haj Seyyed Mohammad Ebrahim, a porcelain and crystal merchant from Kashan in the mid-thirteenth century.[1] A benedictory inscription dated 1255 (AH) is visible in one of its *sardab*s (cellars). Consequently, this house was built during the heyday of Qajar architecture, which it represents well.

The house comprises three large courtyards and two smaller ones. Each represents a distinct part of the house, and each part, while connected to the others, has its own independent entrance. The common axis of symmetry of the three larger courtyards runs in an approximately north-south direction. All three courtyards are enclosed in three-storey-high buildings. In all three, the middle floor is on the same level as the street, and houses the entrance. The three courtyards are one storey below ground level, and constitute sunken gardens that exhibit an upward-expanding volumetric profile. In all three, the longitudinal side is the main side, which is distinguished by an *eivan* (roofed palace or palatial ensemble) in the centre. The longitudinal axes of the first two courtyards are in line with the common axis, while that of the third (northern) courtyard is perpendicular to it. Hence, this axis culminates in the rotated orientation of the third courtyard by the rotated direction of the third courtyard. The broken roofline at the centre of the northwestern side of the third courtyard plus the *eivan* in its middle marks the end of this axis and concludes the masses. In all three courtyards, the main space

Figure 12. Section B-B.

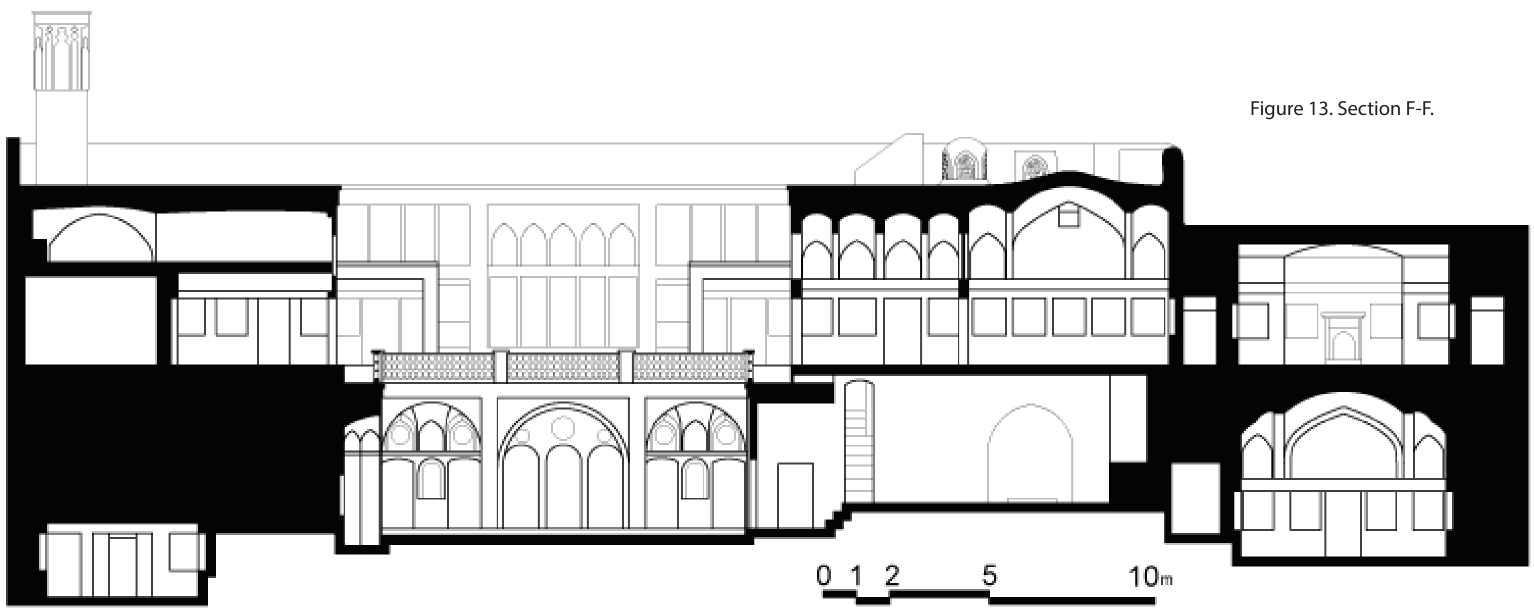


Figure 13. Section F-F.

Figure 14. Western part of the space between the central and northern courtyards at the sunken garden floor level; looking toward the northern courtyard.

behind the *eivan* or the central space on its opposite side houses a two-storey-high *talar* or *panj-dari* (large room with five large adjoining windows) flanked by two- or three-storey-high rooms. *Kafsh-kan*s (semi-open narrow vestibule linking the courtyard to any of the areas surrounding it), which sometimes take the form of *eivancheh*s (small *eivan*s), connect these spaces to their flanking rooms both physically and visually. All three courtyards are rectangular and contain no oblique lines, except in the recessed area of the northern courtyard. The problem concerning the design of the corners is equally well resolved, in a manner evocative of Safavid buildings. The geometry of the design is just as structurally robust and splendid everywhere. Indeed, with all the diverse forms, masses, and surfaces involved, no exaggeration or superfluous ornamentation is perceptible. The courtyards have different sizes and their surrounding structures are different even though they follow the same general model. Nevertheless, they are beautifully composed, and the problem of the geometric transition between each courtyard with its neighbour has been masterfully resolved. What makes this quality yet more important is that the spaces at the interface between each pair of courtyards are

1. After Haj Seyyed Mohammad Ebrahim's death, the house was divided among his heirs. One of his sons, Seyyed Mohammad 'Alavi Borujerdi, a religious leader in Kashan, transformed his part (probably the southern house) into a *madrasa*. Under Pahlavi I, when the activity of theologians was restrained by the government, he held congregation prayers in that courtyard (or perhaps in a previous adjoining garden), which therefore became known as Aqa Seyyed Mohammad Garden. Thus, part of this ensemble once housed a *madrasa* and a prayer area (interview with the Director of the Cultural Heritage Office of Kashan, Mr. Seifollah Aminian, Autumn 2000).

Figure 15. Central part of the space between the central and northern courtyards at the sunken garden floor level; looking towards the northern courtyard.

two-sided, with each side matching its facing courtyard while retaining a harmonious and ordered interior. In addition, although the courtyards have a smaller sideline at the lower level, order and harmony also dominate the interior masses of each courtyard. In other words, far beyond merely creating order and symmetry in areas surrounding a simple yard, the designer has designed each courtyard on two levels, while adjusting it with that of the neighbouring courtyard and matching each interface with its adjacent courtyard. These constraints were compounded by the irregularity of the plot of land, which appears to have been shaped haphazardly amid the neighbouring buildings.

The landscaping across all three courtyards adheres to the vernacular paradigm of the era. Centrally positioned longitudinal pools, flanked by symmetrical parterres, occupy the vast majority of the courtyard area. This configuration serves as a micro-climatic regulator, mitigating the effects of the arid environment through evaporative cooling while providing essential shade to prevent solar glare within the interior chambers.

Although larger, the southern courtyard is surrounded by fewer spaces. The upper floor areas of the northwestern side are not dual-

Figure 16. Northeastern talar at the sunken garden floor level of the central courtyard.

sided, and only face their adjacent courtyard. As a result, this part of the house appears more independent. This independence is probably attributable to the transformation of this courtyard into a *madrasa* in the past century. Parts of the house on the lower floor of the southeastern side and on the upper floor of the southwestern side have fallen into ruin, making it difficult to describe them. At any rate, the main side of this courtyard is the northeastern side, distinguished by a wide *eivan* on its upper floor. This side ends at *sehdari*s (room with three large adjoining windows) which flank the *eivan* through the intermediary of *kafsh-kan*s. The northwestern side consists of an *eivan*, two *eivancheh*s, and several *kafsh-kan*s. Each floor in the southeastern side comprises a *panj-dari*, two *seh-dari*s, and *kafsh-kan*s, which contain a stairway to the useful rooftop of the house. In this way, the façade of this side displays an undulating façade rhythm resulting from the repetition of the small windows of the *panj-dari*s and *seh-dari*s. The entrance of this part is located on the southern corner. It starts with a small portal and an octagonal vestibule (*hasht-o-nim-hasht*: a square with equally chamfered corners, which appears as a semi-regular octagon) that is followed by two rectangular vestibules.

On the lower floor, too, the most important area is located in the centre of the northeastern side, which is a cross-shaped *talar* with the façade of a *seh-dari*. This façade is flanked by *eivancheh*s leading to rooms at either side. The southeastern side has a stairway at its centre which leads down to a large *sardab* with an elaborate *yazdi-bandi* (a type of *kar-bandi* visually at the limit between *rasmi-bandi* and *mogarnas*) adorned ceiling. The main area of the northwestern side is a relatively deep *eivan* fronting a *seh-dari*. This *seh-dari* is a spatially refined chamber with a central pool and *shah-neshin*s (recess in the main side of a *talar*, an *eivan*, etc., which is for sitting.) on either side, which faces the second courtyard on its other end.

The second courtyard is the most elaborate and most ornamental complexity part of the house, and the focal point of its numerous and diverse surrounding spaces. The central spaces on its sides are all two-storey-high; however, the *eivan* at the centre of the northeastern side, which is taller than the other sides, protrudes above the roofline and is the most distinctive. Behind this beautifully decorated *eivan*, there is a large *panj-dari*, whose *yazdi-bandi*-adorned ceiling is inlaid with mirror pieces. It also features a *bad-gir* (tall element rising above the roof that conducts air flow in to the building.). The similarity of its windows and those of the *seh-dari*s and their flanking *kafsh-kan*s gives this façade a mellow rhythm in which the high pitch of the *eivan* is more accented. The plastered surfaces of the courtyard façades, enhanced by a cream-coloured decoration, accentuate the diversity of masses and the play of shadows on surfaces. The absence of an *eivan* on the opposite (southwestern) side also contributes to this effect. The southwestern side displays a more subdued façade, consisting of the repetition of identical windows belonging to the *seh-dari*s. *Orosi* (large wooden window with sashes and tinted glass panes spanning an entire side of a room) windows connect the central *seh-dari* to a long *talar.* The façade of the northwestern side is largely analogous to that of the southwestern side; the southeastern elevation, however, fea-

Figure 17. Covered space at the eastern corner of the first floor of the northern courtyard.

tures a broad central *soffeh* (a raised platform or terrace utilised for seating and observation) that overlooks the *gowdal-baghcheh* (a sunken courtyard or garden, typically situated at a lower elevation than the primary courtyard to provide thermal comfort and privacy), accompanied by two unconventional yet aesthetically distinct semi-open areas at either extremity. A *panj-dari*, which likely opened onto the initial (southern) courtyard from its opposite side, is situated at the head of this *soffeh.*

On the lower floor, the façades surrounding the *gowdal-baghcheh* are humbler. Unlike all the pointed arches of the upper floor, arches are semi-circular on this floor. The semi open areas, which are located in the centre of the upper floor sides, are faced as *eivanchehs* located at the sides, making the central spaces closer to the pool and flowerbeds. The composition of the façade on all four sides is similar, except that the deep central spans of the northeastern and, to a lesser degree, the southwestern side façades are more conspicuous than the *seh-dari* façades of the two other sides. The most important area on this floor is also the *talar* on the northwestern side, with numerous interconnected sections, one of which is a *sardab* on the northern corner. Despite its simplicity, the simgel-lined walls, *rasmi-bandi* (a type of *kar-bandi*

Figure 18. Talar between the central courtyard and the courtyard above the howz-khaneh at the first-floor level.

consisting of a geometric lattice of usually non-bearing intersecting curves) decoration, gypsum ribs, columned *shah-neshins*, and flanking *bad-girs* render this talar one of the most aesthetically distinguished rooms in the residence. Opposite this talar on the southwestern side, a room connects to an ornamentally complex, cross-shaped talar behind it via *orosi* windows. This talar leads to yet another remarkable space within the house, namely the *howz-khaneh* (a summer room, typically of an octagonal plan, featuring a central pool [*howz*], which serves as a space for relaxation and receiving guests). It comprises a multitude of interconnected areas, wooden *orosi* windows and lattices, *qatar-bandi* (a type of decorative vaulting or stalactite work—a variant of *kar-bandi*—applied in a straight line between the ceiling and the walls) panels, and delicate vegetal stucco carvings. A deep pool in the northwestern section of the *howz-khaneh* was likely utilised for bathing or swimming during the summer months.

An octagonal light aperture above the central pool in the *howz-khaneh* opens into the centre of another courtyard on the upper floor. It is the fourth courtyard of the house: a secluded is a secluded square yard bordered on its south by a *panj-dari*, a *shah-neshin,* and *moqarnas*-adorned *kafsh-kan*s. Its northeastern façade,

Figure 19. Space between the central and northern courtyards at the sunken garden floor level.

however, comprises a long *talar* already mentioned in the description of the southwestern side of the second (middle) courtyard. The western side is a closed off blind-arcaded wall with an ornate central *eivan*. The northwestern side consists of a semi-open *seh-dari*, two *kafsh-kan*s, and two flanking areas at either end. One of them is a stairway leading to the enclosed rooftop of the house, and the other is a small vestibule connected to the vestibule of the main entrance.

This large vestibule, shared by several houses in the neighbourhood, leads after the aforementioned small vestibule via a long corridor to a corner yard, which serves as the entrance to the third courtyard-the last of large courtyards of the house-through its southwestern *kafsh-kan*. As stated earlier, the longitudinal axis of the third courtyard (northern courtyard) is perpendicular to the common axis of symmetry, whereas its pool and flowerbeds remain aligned in the quasi north-south direction. The recessed central part of the northwestern side

Figure 20. Courtyard above the howz-khaneh.

Figure 21. Howz-khaneh.

also emphasises this axis. At the head of this recessed area, there is an independent *eivan* and two flanking *kafsh-kan*s on the upper floor, without any other area behind them. The *eivan* protrudes above the roofline, further marking its hegemony over the courtyard. Its vault bears a delicate *yazdi-bandi* decoration, and the contrast between its interior surfaces lined with *sim-gel* (a mixture of gypsum and clay applied as a smooth, durable lining) and the plastered surfaces of the courtyard creates a very subtle composition. On the lower floor, next to the *gowdal-baghheh*, the recessed part serves as a *shah-neshin* backed by a cross-shaped *talar*.

Figure 22. Northeastern talar on the first floor of the central courtyard.

The façade of the opposite side of the *eivan* (the southeastern side) is finely divided to highlight it, as is usual. At the centre of this side on the upper floor, a *panj-dari* with a *yazdi-bandi*-adorned ceiling faces the second courtyard on its other side. Its adjoining *eivancheh*s, which at once constitute a visual counterpart to the *eivan* and enrich the play of shadows in this façade, link the *panj-dari* to the flanking *seh-dari*s. One of these *seh-dari*s leads to a beautiful room with a *rasmi-bandi*-adorned ceiling on the eastern corner, to which the second courtyard is connected by way of a corridor. This side also has a mezzanine floor, consisting of two elongated areas above the *eivancheh*s. The lowermost floor of this side consists of a long hall connected by *orosi* windows to a pair of flanking *seh-dari*s. These *orosi* windows not only create a pleasant, colourful atmosphere, but also allow the hall and the *seh-dari*s to be merged into one large area stretching all across this side. This large area also has *shah-neshin*s at both ends, inside the walls of the *sehdari*s. In this way, the large area resulting from the merger of all spaces is given a beginning and an end, and its spatial unity is emphasised.

The northeastern side is three storeys high, as the southeastern side. The façade of the lower floor is on the same level as the other façades around the *gowdal-baghcheh*; however, the spaces behind it are sunken and constitute a *sardab*. The *sardab* comprises a hall with ledges in its walls and rooms on its either side.

A deep *seh-dari* is located in the centre of the ground floor on this side. On the upper floor, the central space is a *talar* flanked by *kafshkan*s, whose façade breaks the roofline. The independent entrance of this part including vestibules and corridors is located on this side.

The façade of the southwestern side is similar to that of the northeastern side. On its lower floor, it houses an *eivan*, two *moqarnas*-adorned *eivancheh*s, and a *talar* behind. On the upper floor, a spacious *soffeh* tops these areas, and produces variation in the massing of the courtyard. A high, ornate *panj-dari* flanked by a pair of *eivancheh*s stands at the head of this *soffeh*. The ornamentally complex, elaborate *howz-khaneh* located at the intersection of the northwestern and southwestern sides is yet an-

Figure 23. Southwestern panj-dari of the northern courtyard at the first-floor level.

other example of the spatial diversity found in the closed spaces of this ensemble. The domed *howz-khaneh* and its soaring *bad-gir*s are among the rare exterior manifestations of the building mass.

Acknowledgment

The original version of the second part of this text, introducing Haj Seyyed Mahammad-Ebrahim Tajer House in Kashan was written in Persian by Mehrdad Qayyoomi Bidhendi under Kambiz Haji Qassemi's supervision. These authors were both faculty members in the Faculty of Architecture and Urban Planning, Shahid Beheshti University, and their text was published in *Ganj-Nameh* Vol.16. The second part of present text is a retrospective reworking of that text for the international audience.

Figure 24. Talar between the central and northern courtyards on the first floor.

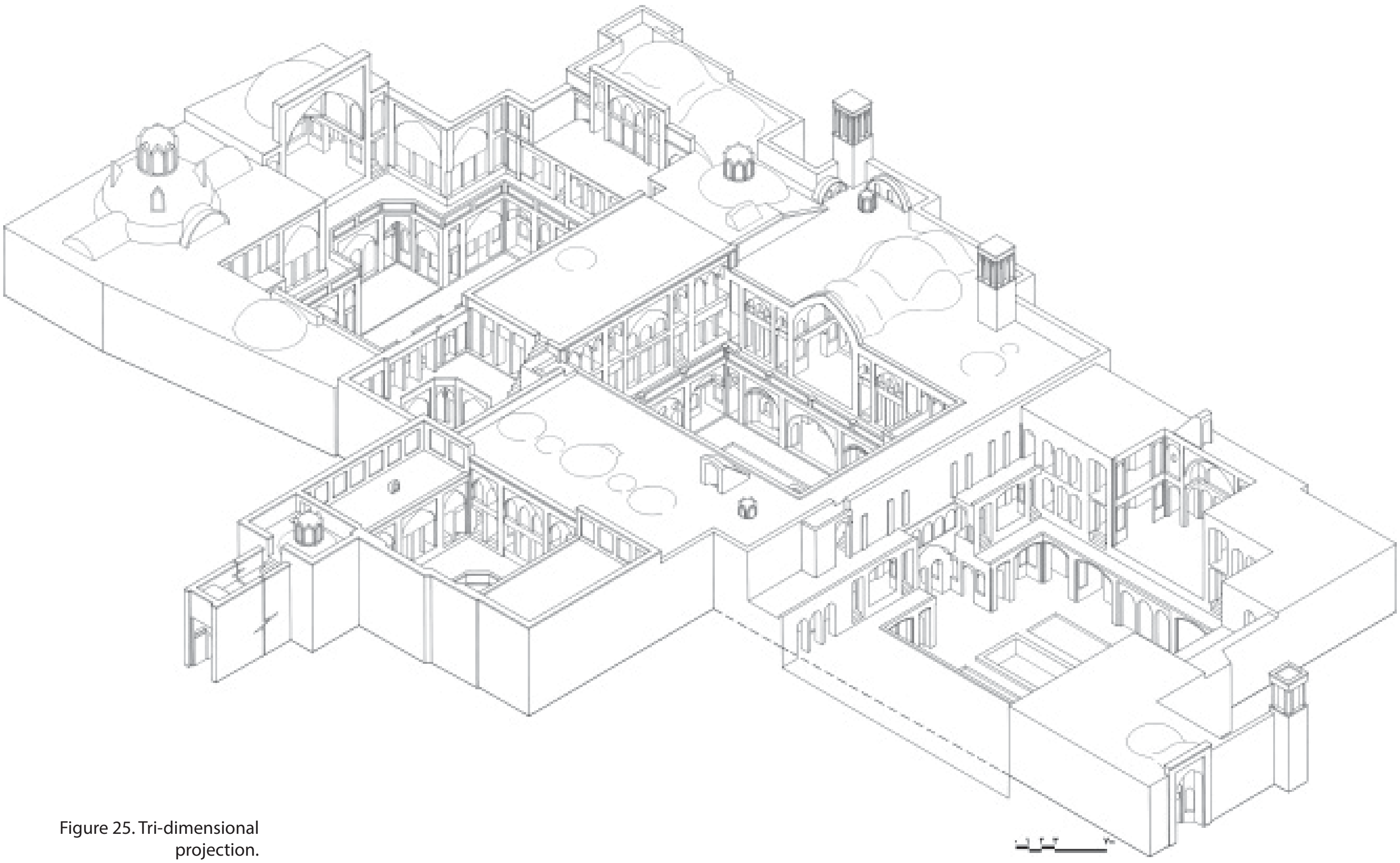


Figure 25. Tri-dimensional projection.