A Design Framework for a Climate-Responsive Interactive Building Envelope Using Locally Calibrated Thermal Comfort Models: The Case of Isfahan, Iran

Abstract

Thermal comfort in buildings located in Iran's hot–arid regions, and in Isfahan in particular, remains a difficult problem for designers to solve. Among the layers that mediate between occupants and the outdoor environment, the building envelope is arguably the most consequential, since it shapes both indoor comfort and the energy a building draws to maintain it. The climatic variety across Iran, together with the well-documented shortcomings of static, universally applied comfort models, has made the case for locally calibrated and climate-specific envelope strategies hard to ignore. This paper sets out to develop and assess, at a conceptual level, an interactive building envelope informed by the indigenous thermal comfort equations derived for Iranian conditions, with the analysis anchored in the climate of Isfahan. Methodologically, the work is a climate-data-driven design study supported by documentary analysis and complemented by the fabrication of a functional prototype for operational validation; it draws on long-term meteorological records from ten Iranian cities together with a review of the relevant comfort literature and standards. The analysis suggests that coupling passive climatic measures with an adaptive, movable envelope—one whose configuration tracks occupants' thermal behavior, which we term an interactive envelope—offers clear potential to moderate indoor conditions and raise indoor environmental quality. To demonstrate the feasibility of this concept, a 1:20 functional prototype was fabricated, confirming that the control chain—temperature sensing, control logic, motorized actuation, and louvre movement across open, half-open, and closed states—operates as intended. It should be stressed that this prototype was built to validate the kinematic and control behavior of the system rather than to reproduce or measure its full-scale thermal performance, which remains to be tested through measurement or simulation. On this basis we propose a design framework for an interactive envelope built on the comfort equations calibrated for Isfahan. The framework is intended to respond to the demands of a hot–arid setting while allowing thermal adaptability, control of solar gain, better use of natural ventilation, and reduced reliance on mechanical conditioning alone. Taken together, the study offers a reasoned starting point for climate-responsive and adaptive envelope design in contemporary Iranian architecture.

Keywords: Thermal comfort; Indigenous thermal comfort equations; Hot–arid climate; Interactive building envelope; Isfahan

Introduction

Thermal comfort is one of the central components of indoor environmental quality, and it bears directly on occupants' health, well-being, and productivity. What counts as comfortable depends on a mix of environmental and personal variables: air temperature, relative humidity, air velocity, and mean radiant temperature on one side, and clothing insulation and metabolic rate on the other. Personal characteristics such as gender and health status further shape how a given environment is perceived. Delivering conditions that satisfy occupants is therefore a genuinely difficult design problem, complicated by differences in individual preference and by climatic and cultural context (World Health Organization, 2021).Over the past few decades, a good deal of effort has gone into models and indices for predicting comfort, the Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD) chief among them. Questions persist, however, about how well these indices transfer to specific local climates and cultures. International standards—ISO 7730, EN 15251, and ASHRAE Standard 55—each define their own acceptable comfort ranges. Iran's national standard, ISIRI 14384, was developed on the basis of ISO 7730, but shifts in lifestyle and building practice suggest it may be due for revision (National Standards Organization of Iran, 2011). Inconsistencies between the bodies that set comfort and indoor-quality policy add another layer of difficulty. The national standard, for example, sets summer and winter operative temperatures at 24.5 °C and 22.0 °C, while the National Building Regulations give 25.0 °C and 20.0 °C for the same conditions. Energy policy for buildings has leaned mainly on technological fixes—better envelope performance and more efficient building systems (Hu et al., 2020). Those measures have helped lower energy use, yet similar buildings still show substantial differences in consumption, much of it traceable to occupant behavior and construction quality (Hu et al., 2020). Building energy use turns on six broad factors: climate, the thermal envelope, mechanical systems, operation and maintenance, occupant behavior, and indoor environmental quality (Yoshino et al., 2017). The last three are bound up with human behavior. In Iran, comparatively little research has quantified how occupant behavior affects building energy use. A closer reading of human–environment interaction, paired with design that takes comfort seriously, has real potential to ease energy demand (Lan et al., 2011). How comfort conditions are defined across climates also feeds directly into thermal calculations, the sizing of heating and cooling systems, insulation thickness, material choice, spatial layout, window-to-wall ratios, and ultimately the building's overall energy use and losses (Khan Ahmadlou et al., 2016). Occupant satisfaction is an essential part of any building-performance evaluation, all the more so because people spend upward of 80 % of their time indoors. For that reason, thermal comfort is widely treated as a fundamental criterion in judging how a building performs. Subjective ratings of thermal sensation, usually gathered through surveys, serve as common indicators for assessing and predicting indoor conditions. When occupants feel uncomfortable, they tend to adapt in one of two ways: by adjusting the environment or by changing their own behavior. Those who can control their immediate surroundings generally report fewer building-related complaints and less discomfort. Occupant behavior is thus a major source of uncertainty in building performance and one of the main reasons predicted and measured energy use diverge. Where that behavior is poorly understood, the result tends to be higher energy use and worse indoor comfort; occupants' comfort expectations can shape energy demand to a significant degree (Rezazadeh Pileh Darbani et al., 2022). More recently, interactive architecture has emerged as a fresh way of meeting both functional and aesthetic demands in built space (Terzidis, 2003). Advances in digital technology and computer science have opened new room for developing interactive architectural systems. Many reactive environments get grouped under the interactive-architecture label, but a sharper conceptual line between "interactive" and "responsive" space is worth drawing (Haque, 2007). On that reading, responsive architecture is a subset of interactive architecture, marked by the ability to adapt form and function to environmental and human conditions (Edmondson, 2001). By bringing together intelligent technologies and dynamic mechanisms, the approach aims to tackle architectural problems while improving user experience and supporting sustainability (Parsaee et al., 2016). In systems of this kind, buildings take in data from sensors and respond to changing conditions by altering color, form, lighting, or other spatial qualities (Beesley, 2006). Given the many-sided nature of thermal comfort, the spread of individual and cultural preference, the inconsistencies among existing standards, and the decisive part occupant behavior plays in energy performance, fixed criteria and purely mechanical solutions on their own are unlikely to meet the needs of contemporary built environments. Interactive architectural approaches—adaptive and responsive envelopes in particular—offer a promising frame for setting up a dynamic relationship among occupants, buildings, and climate. Building on that premise, this study develops a conceptual framework for an interactive building envelope suited to the hot–arid climate of Isfahan, grounded in the theory of thermal comfort, an analysis of environmental and behavioral variables, and the application of comfort equations calibrated for Iran. The framework is intended to enhance indoor environmental quality, reduce reliance on active heating and cooling, and support occupants' thermal adaptability. More specifically, the study asks how an interactive envelope—tuned to both climate and occupant behavior—might widen the thermal comfort range and improve indoor environmental quality while lessening dependence on mechanical systems.

Literature Review

Work on thermal adaptation and climate-responsive design points to a consistent conclusion: thermal comfort need not rest on mechanical systems alone, but can also be reached through passive and adaptive architectural strategies. Heidari (2014), in Thermal Adaptation in Architecture, makes this case directly, stressing the part that climate-based design, a building's physical characteristics, and occupant behavior play in lowering energy use and securing comfort. He frames thermal adaptation as something that emerges from the dynamic interplay among people, buildings, and the surrounding climate. Mortaheb (2016), in Energy Saving Patterns in Housing Architecture, takes up a related question, examining how thermal adaptation might be improved under Iran's particular climatic conditions. Reading the spatial and physical traits of climate-responsive housing, the study argues for pairing passive design strategies with newer technologies as a route to lower energy use and better comfort. Khan Ahmadlou et al. (2016) turn to the envelope itself, studying the thermal behavior of residential building skins and showing that careful analysis of envelope performance can sharpen construction practice and cut energy losses. Kasmaei (2013), for his part, examines the broader relationship between climate and architecture, holding that sound climatic design is central to a building'senergy performance and to occupants' comfort. A summary of selected studies bearing on the present research appears in the table below.

Table 1. Summary of Previous Research

Research Title	Authors	Year	Objectives (Concise)	Key Findings (Condensed)
Adaptive in Comfort Different Iranian Climates	Rezaei, Vahid	2025	Assess passive strategies for thermal comfort in Iranian regions	Highest adaptive comfort in Zahedan; design strategies enhance passive comfort
RayMan Model for Thermal Comfort Simulation	Meng, F.; Qin, M.; et al.	2025	Review RayMan model for thermal comfort assessment	Effective, with clear strengths and limitations
Parametric Perforated Envelopes for IEQ	Fawaz, M.; Megahed, N.A.; et al.	2025	Develop framework for IEQ improvement via parametric design	Optimized perforations improve comfort, airflow, daylight
Multi-Objective Optimization: Energy, Thermal Comfort, IAQ	Al Mindeel, T.; Spentzou, E.; Eftekhari, M.	2024	Synthesize approaches to multi-objective optimization	Balancing multiple criteria is complex; trade-offs critical
Double-Skin Façade Performance in Hot-Humid Climates	Keshavarz Saleh, S.; Abdoli, N.	2024	Evaluate double-skin façades for energy savings	16–20% reduction in cooling energy with optimal cavity size
Vernacular Patterns for Climatic Envelopes in Bushehr	Zangenehpour, F.; Alizadeh, S.	2023	Integrate traditional elements for solar control and comfort	“Shanashir” and shading devices improve comfort, reduce energy use

Taken together, these studies confirm the value of climate-responsive and passive strategies, yet they tend to fall into two largely separate streams. One body of work concentrates on the building envelope—double-skin façades, parametric perforations, vernacular shading devices—treating the skin mainly as a fixed or parametrically optimized layer. A second stream focuses on comfort modeling and adaptive thermal limits, often drawing on indices and tools developed for other climatic and cultural settings. What remains comparatively underexplored is the point where the two meet: an envelope that is not merely optimized once and fixed, but interactive—capable of adjusting in response to changing conditions—and driven by comfort criteria calibrated for Iran rather than imported wholesale from international standards. The present study addresses that gap. Working from four decades of climatic data and from comfort equations developed for Iranian conditions, it sets out a conceptual framework for an interactive building envelope in the hot–arid climate of Isfahan, with the aim of linking locally grounded comfort criteria to the control logic of an adaptive skin.

Research Methodology

This study follows a climate-data-driven design approach supported by documentary analysis. The research unfolds in two complementary phases.

In the first phase, the theoretical and contextual foundation was established through a systematic review of peer-reviewed literature and authoritative sources on adaptive thermal comfort theory, climate-responsive architecture, and interactive building envelopes. This documentary review served to identify the relevant comfort models, define the design parameters, and clarify the research gap—namely, the absence of studies integrating kinetic façade systems with indigenous thermal comfort equations calibrated for Iran's hot-arid context.

In the second phase, long-term climatic data recorded by meteorological stations were compiled and processed to derive monthly neutral temperatures and comfort boundaries using the Humphreys adaptive comfort equation. Computational analysis was carried out in Python, selected for its robust scientific libraries (NumPy, Pandas) and suitability for environmental data processing. Based on the resulting comfort thresholds, a rule-based control logic was formulated to govern envelope behavior across three operational states—open, half-open, and closed—corresponding to distinct thermal intervention levels.

To demonstrate the feasibility of this control logic, a 1:20 scale functional prototype was developed using an Arduino microcontroller as an open-source platform for sensor data acquisition and real-time actuation. C++ was employed at the firmware level for its precise low-level hardware control, enabling direct communication between the temperature sensor and the servo motor driving the louvre mechanism. The prototype validates the kinematic and control-chain performance of the proposed system—confirming that sensor input is correctly translated into the intended mechanical response—rather than measuring thermal or energy performance.

Data collection methods encompassed library and documentary research, analysis of meteorological records, and electronic databases. The outcomes of these processes informed the development of a conceptual design model for an interactive building envelope adapted to the hot-arid climate of Isfahan.

Theoretical Background

This section outlines the core theoretical concepts underpinning the study: user–building interaction profiles, thermal comfort and its determinants, the psychrometric chart, the relationship between neutral and outdoor temperature, and field studies of thermal comfort in Iran.

User–Building Interaction Profiles

User–building interaction profiles aggregate physiological, behavioural, and environmental data collected via smart sensors and analyzed in real time to enable intelligent adjustments in temperature, lighting, and ventilation. The primary goals are to enhance individual occupant comfort and reduce energy consumption (Becerik et al., 2022).

Comfort and Thermal Comfort

Comfort encompasses physical, functional, and psychological dimensions and represents a state of satisfaction arising from the alignment between environmental conditions and individual needs (Vischer, 2007). Thermal comfort, as a subset of this broader concept, is defined by ASHRAE as a subjective condition expressing occupants' satisfaction with the thermal environment. While some researchers have questioned this definition's completeness—noting the difficulty of measuring subjective states—it remains the most widely accepted framework in the field (Heidari, 2013).

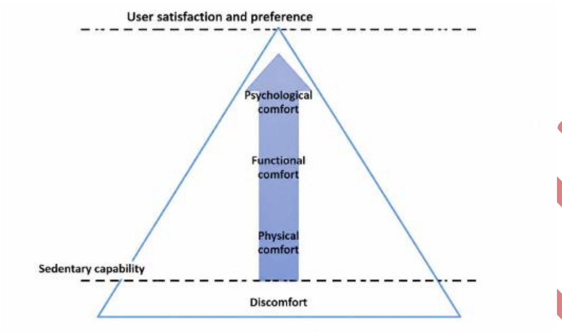


Figure 1. Environmental Comfort Range. Source: Vischer (2007).

Environmental Variables of Thermal Comfort

Thermal comfort is primarily governed by four environmental variables—air temperature, mean radiant temperature, humidity, and air movement—alongside two personal variables: metabolic rate and clothing insulation. Additional factors including age, gender, cultural background, health status, and psychological expectations can also influence thermal perception (Szokolay, 2014). Humidity and air movement interact to modify perceived temperature; for instance, at 35 °C, increasing air velocity from below 1 m/s to 3 m/s while reducing relative humidity from 70% to 50% can lower perceived temperature by more than 9 °C (Auliciems & Szokolay, 1997).

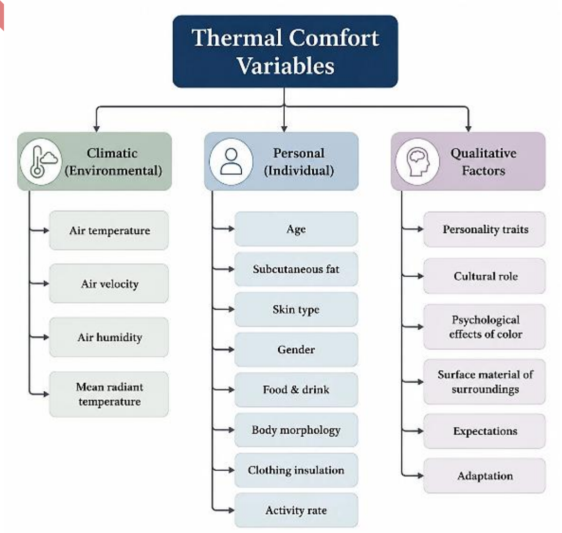


Figure 2. Thermal comfort and its interactions with quantitative and qualitative factors, adapted from Mortaheb (2022).

Psychrometric Chart

The psychrometric chart represents the thermodynamic relationships among dry-bulb temperature, humidity ratio, relative humidity, and enthalpy of moist air. It is a standard analytical tool in HVAC design. Key processes plotted on the chart include sensible heating—which raises temperature at a constant humidity ratio—and humidification, which can be achieved either by steam injection (increasing latent heat with negligible temperature change) or by evaporative cooling (decreasing temperature at constant enthalpy). These processes are directly relevant to evaluating passive and active strategies for maintaining comfort in hot-arid climates (Auliciems & Szokolay, 1997).

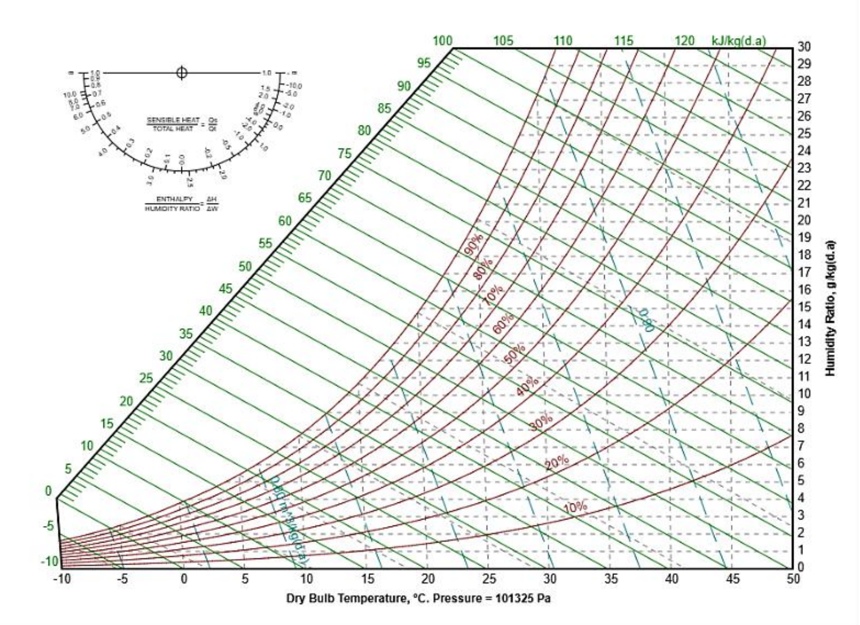


Figure 3. Relationship between temperature, humidity ratio, and relative humidity on the psychrometric chart. Source: (flycarpet.net).

Neutral Temperature and Outdoor Temperature

Humphreys (1978) established a statistically robust relationship between comfort temperature and mean outdoor temperature across a dataset of approximately 200,000 observations, achieving a correlation coefficient of 97% and a standard deviation of roughly 1 °C, over the range of 10–33 °C. For naturally ventilated buildings, he proposed: For buildings equipped with heating and cooling systems, Humphreys proposed the following equation for determining the neutral temperature:

$$T_n = 0.534T_o + 11.9$$

Where:

- T_o: outdoor air temperature in °C (Humphreys considered the monthly mean outdoor temperature as the reference parameter)
- T_n: comfort or neutral temperature in °C

This linear relationship confirms that outdoor air temperature is the dominant predictor of comfort in free-running buildings, and it forms the basis for the Iran-specific equation used in the present study.

Field Study of Thermal Comfort in Iran

A landmark study presented in *Thermal Adaptation in Architecture* conducted field investigations across ten climatically and culturally diverse Iranian cities, drawing on forty years of meteorological records. Measurements covered both environmental parameters and personal variables (clothing insulation, metabolic rate), correlated against the seven-point ASHRAE and Bedford thermal sensation scales. Regression analysis yielded an Iran-specific comfort equation, defined neutral temperatures, and established the corresponding comfort range—findings that serve as the primary comfort model for the envelope control logic developed in this study.

Iran's Thermal Comfort Equation and Its Correspondence with Humphreys' Model

As established earlier, Humphreys identified a direct linear relationship between the monthly mean outdoor temperature and the neutral temperature: as the monthly mean temperature rises, the neutral temperature increases accordingly. This relationship allows the neutral temperature to be predicted directly from the monthly average outdoor temperature, expressed as:

$$T_n = 11.9 + 0.534T_o$$

where:

- T_n: neutral temperature
- T_o: monthly mean outdoor temperature

The comfort equation derived from field studies conducted in Iran provides a reliable and practical reference for architects and mechanical engineers. For hot conditions:

$$T_n = 17.6 + 0.36T_o$$

For cold conditions, the neutral temperature is adjusted by a fixed offset:

$$T_{n,\text{cold}} = T_{n,\text{hot}} - 1.2K$$

The principal advantage of this formulation is that the acceptable indoor temperature can be readily estimated from the monthly mean outdoor temperature alone.

The application of the equation is illustrated in Figure 6, in which the average monthly maximum and minimum temperatures are plotted on the horizontal axis, and the neutral temperature together with its upper and lower comfort limits is shown on the vertical axis. Below 6 °C and above 32 °C, the neutral temperature is held constant at the values corresponding to these boundary points. With respect to slope, the Iranian equation differs from the ASHRAE equation by approximately 0.05, while no meaningful difference is observed in the intercept (Heydari, 2014).

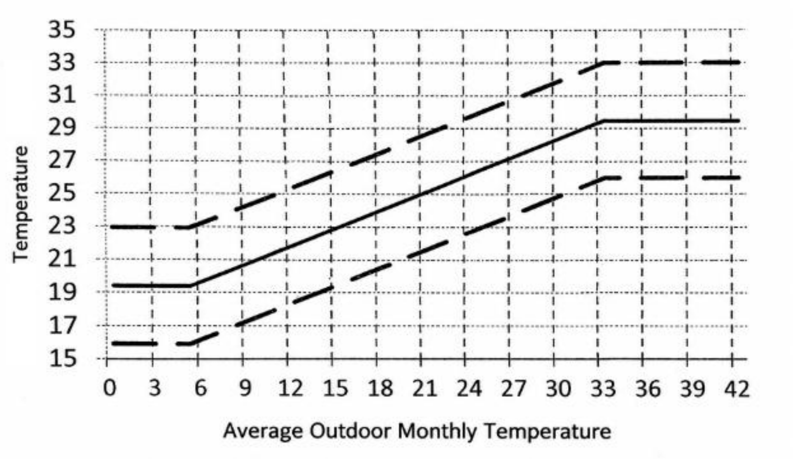


Figure 4. Acceptable thermal comfort temperature for the population of Iran. Source: Heydari (2014).

Definition of Climate

Climate is broader than the immediate weather around a building. The Oxford Dictionary defines it as "a region characterized by particular conditions of temperature, dryness, wind, light, and other atmospheric features," while Koenigs Berger (1973) gave a more scientific account: within a region of specific geographical character, physical environmental factors can be classified into categories, each of which may represent a distinct climate type (Heydari, 2014).

Climatic comfort is a fundamental pillar of environmental quality in human settlements, denoting a balance between climatic elements (solar radiation, airflow, humidity, temperature) and the body's physiological needs. Traditional architects, drawing on experiential knowledge of their environment, both exploited climatic potentials and mitigated adverse climatic effects through intelligent design (Shahabi Nejad et al., 2016).

Characteristics of Hot and Arid Climates

Hot and arid climates are generally marked by (Qiabaklou, 2013): low annual precipitation; summer daytime temperatures of about 40–50 °C and nighttime temperatures of 15–25 °C; seasonal variation dependent on latitude; relatively constant absolute humidity but highly variable relative humidity; predominantly clear skies; low morning wind speeds rising to an afternoon maximum; and frequent dust and sand storms.

The Impact of Climate-Responsive Architecture on the Thermal Comfort Range

Beyond meeting functional needs and occupant comfort, sustainable design makes optimal use of the opportunities and constraints of its context, with strategies selected according to site characteristics (Mortaheb, 2016). Givoni argues that rational, climate-responsive design can moderate outdoor conditions by up to 8 °C in either direction. Larger gains have been reported elsewhere, Fathy's work in Egypt found reductions of up to 14 °C, and Heydari's study in Dezful found Shavadan spaces differing from courtyards by as much as 22 °C, but Givoni's 8 °C is treated as a realistic, conservative benchmark.

Personal adaptive factors add to this. Adjustments in clothing, activity level, or posture may lower perceived temperature by about 4 °C, so architecture and adaptive behavior together can shift perceived conditions by roughly 12 °C. With a neutral temperature of 25 °C, for example, an outdoor temperature of 37 °C could be brought to comfort through design and adaptive behavior. What matters, then, is less the absolute magnitude of outdoor variables than the degree of exposure and its effect on thermal perception.

Figure 7 illustrates this. The comfort zone is shown as a bold line and outdoor temperature as a thin dashed line, with three intermediate curves between them representing the influence of appropriate urban design, climate-responsive architecture, and light equipment use with adaptive behaviors. The vertical axis is temperature and the horizontal axis the periods of the year. When ambient temperature equals comfort temperature, no discomfort occurs; adaptive behavior extends comfort to the second curve, responsive architecture to the architectural-design curve, and good urban design to a still higher threshold. Once outdoor temperatures exceed all three limits, mechanical and electrical systems become necessary to maintain acceptable indoor conditions (Heydari, 2014).

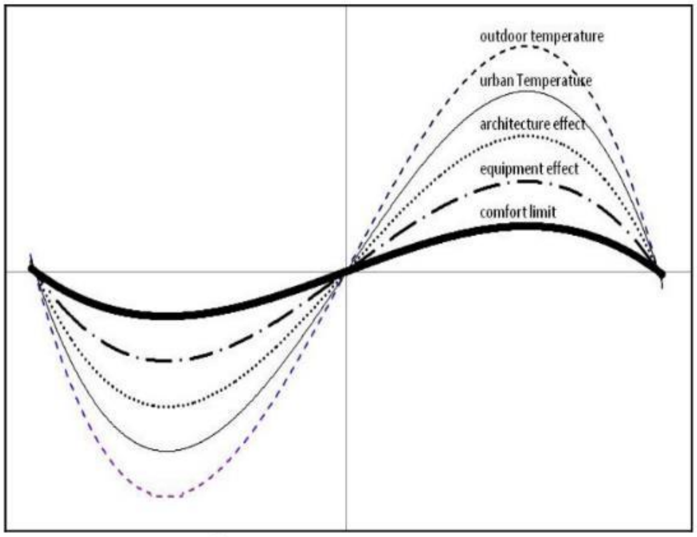


Figure 5. Stepwise curves governing human thermal comfort conditions. Source: Heydari (2014).

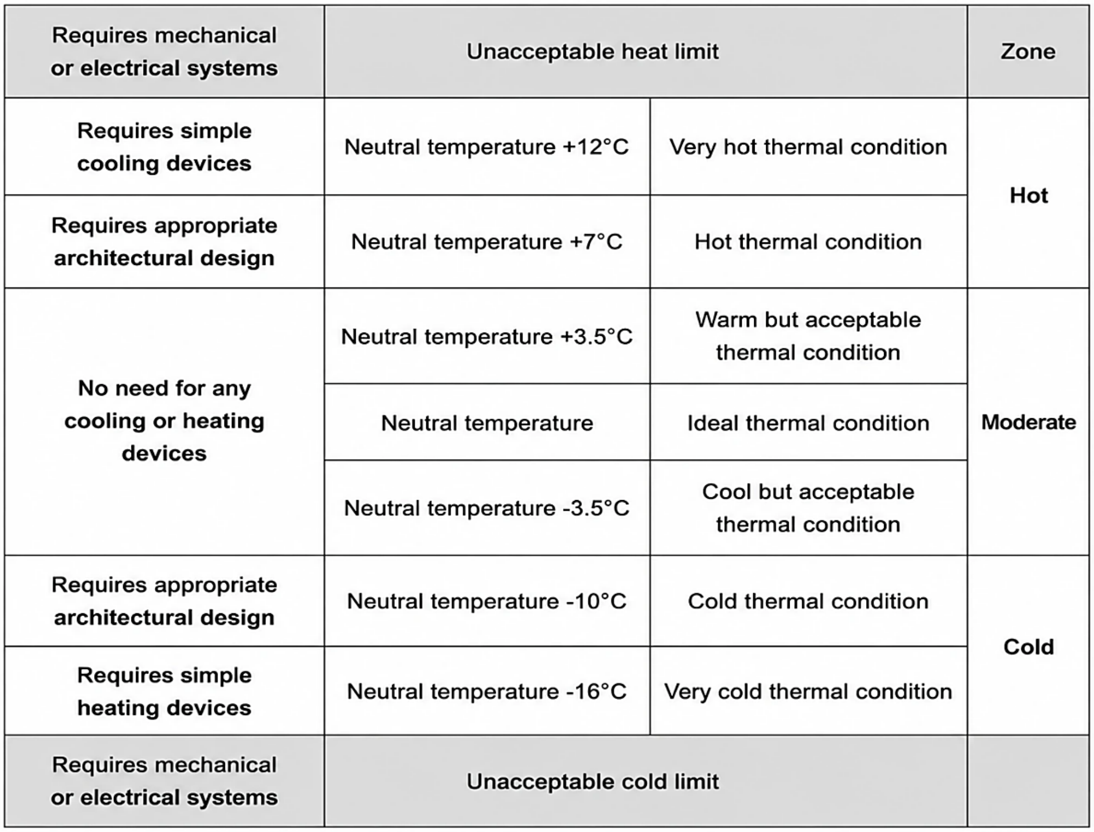
Table 2 presents the concept of comfort limits and the environmental requirements of architectural spaces from a complementary perspective. The three central rows of the table define the thermal comfort range, within which neither heating nor cooling devices are required. This range is commonly referred to as the “no-building zone,” denoting conditions under which thermal comfort can be attained without reliance on architectural or mechanical intervention.

The two rows situated immediately above and below these central rows deviate from the neutral temperature by approximately 7 °C and 10 °C, respectively. These bands illustrate the potential contribution of appropriate architectural design. In other words, when a building is properly designed, occupants may remain thermally comfortable across a span of roughly 17 °C centered on the neutral temperature, without recourse to mechanical heating or cooling systems.

As indicated in Rows 2 and 8 of Table 2, once this range expands to approximately 28 °C, simple conditioning devices—such as fans, evaporative coolers, or heaters—become necessary. Where the temperature range exceeds 28 °C, more advanced mechanical or electrical systems are required to maintain acceptable indoor conditions.

The greater tolerance toward colder conditions, relative to warmer ones, around the neutral-temperature boundary may be attributed to the fact that the cooling process is generally more complex than the heating process (ibid.).

Table 2. Thermal comfort limits and environmental requirements of architectural spaces. Source: Heydari (2014).



Requires mechanical or electrical systems	Unacceptable heat limit		Zone
Requires simple cooling devices	Neutral temperature +12°C	Very hot thermal condition	Hot
Requires appropriate architectural design	Neutral temperature +7°C	Hot thermal condition	
No need for any cooling or heating devices	Neutral temperature +3.5°C	Warm but acceptable thermal condition	Moderate
	Neutral temperature	Ideal thermal condition	
	Neutral temperature -3.5°C	Cool but acceptable thermal condition	
Requires appropriate architectural design	Neutral temperature -10°C	Cold thermal condition	Cold
Requires simple heating devices	Neutral temperature -16°C	Very cold thermal condition	
Requires mechanical or electrical systems	Unacceptable cold limit		

Findings

Humidity and Temperature

sfahan lies at longitude 51°39′40″ E and latitude 32°38′30″ N, and is the third largest city in Iran after Tehran and Mashhad (Mortaheb, 2016). To ground the analysis in the most current climatic data available, an official request was issued through the university, and a field visit was made to the Isfahan Provincial Meteorological Organization. Climatic records spanning the ten-year period ending in 2024 were then obtained directly from this source.

The data reveal a markedly dry climate with pronounced seasonal contrast. The average maximum relative humidity reached 77% in December, whereas the average minimum dropped to just 9% in June. Air temperature, by contrast, remained comparatively moderate on an annual basis: the mean monthly temperature stayed above 0 °C throughout the year, and sub-freezing minima occurred only on rare occasions.

Table 3. Ten-year monthly air humidity data for Isfahan[1]. Source: Authors.

Humidity Parameter (%)	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar
Minimum RH	18	15	9	10	10	11	16	29	33	31	24	20
Average RH	36	30	18	19	20	22	31	49	55	52	45	39
Maximum RH	54	46	27	28	29	32	46	70	77	73	66	58

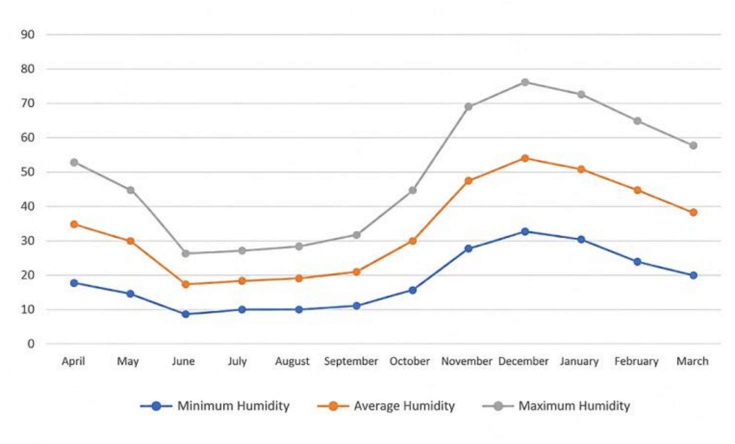


Figure 6. Monthly relative humidity in Isfahan — ten-year average. Source: Authors.

Table 4. Ten-year monthly air temperature data for Isfahan. Source: Authors.

Temperature Parameter (°C)	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar
Minimum Temp	11	16	21	23	20	17	11	4	0	-2	1	6
Average Monthly Temp	18	23	29	31	29	25	19	11	7	5	8	13
Maximum Temp	25	30	37	39	37	34	27	18	14	12	15	20

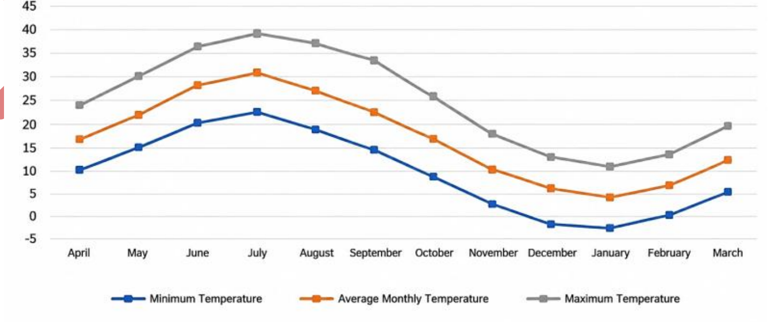


Figure 7. Monthly air temperature in Isfahan — ten-year average. Source: Authors.

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[1] Note: The monthly values are presented based on the Iranian calendar year, starting from April (Farvardin) through March (Esfand).

Climatic Information

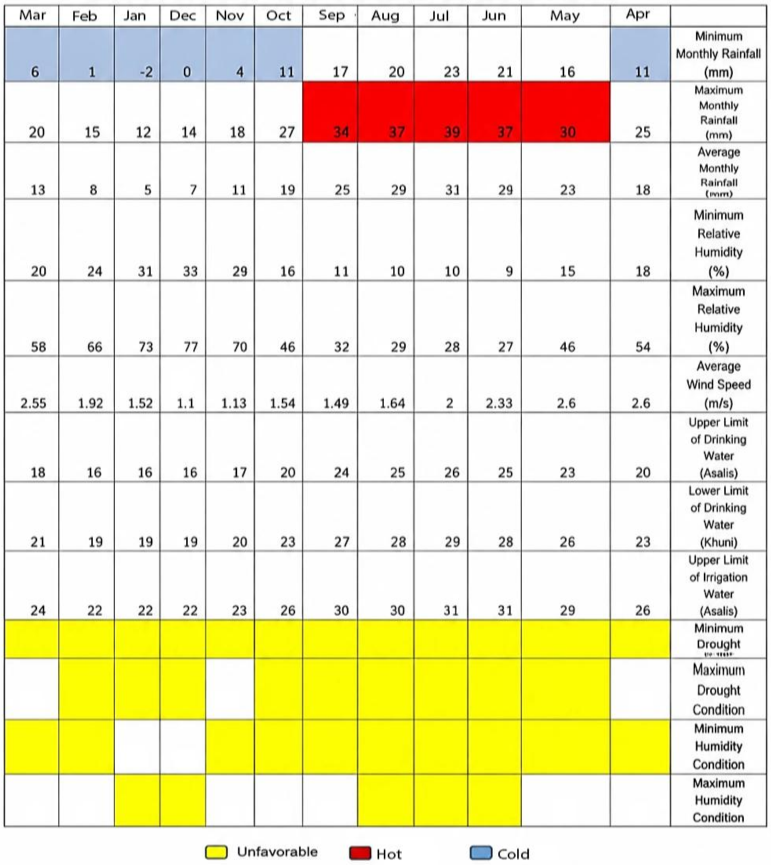
Table 5 is built from a detailed month-by-month classification of the ten-year climatic record (ending in 2024) obtained from Station 40800 of the Isfahan Provincial Meteorological Organization. For each of the twelve months across this decade, it reports four variables: the mean minimum temperature, the mean maximum temperature, the mean relative humidity, and the mean wind speed.

The mean minimum and maximum temperatures were first used to classify each month's overall thermal condition as either cold or warm. This classification then governed the calculation of the neutral temperature, which was derived using the indigenous formulas developed specifically for cold and warm conditions in Iranian climatic studies. Following ISO 7730, the comfort range for each month was bounded by setting its lower and upper limits at 3 °C below and 3 °C above the neutral temperature, respectively.

As noted earlier, January's mean outdoor temperature falls below 6 °C, so its neutral temperature was fixed at 19 °C. The final four rows of the table flag each value as suitable (S) or unsuitable (U). For temperature, the mean minimum is judged against the lower comfort limit and the mean maximum against the upper limit. For humidity, both the minimum and maximum readings are checked against the acceptable relative-humidity band of 30% to 70% specified in the ISO standard.

Figures 10 and 11 illustrate the monthly humidity and temperature conditions in relation to the upper and lower humidity limits defined by the ISO standard and the thermal comfort temperature range, respectively.

Table 5. Climatic information and its analytical results. Source: Authors.



Mar	Feb	Jan	Dec	Nov	Oct	Sep	Aug	Jul	Jun	May	Apr	
6	1	-2	0	4	11	17	20	23	21	16	11	Minimum Monthly Rainfall (mm)
20	15	12	14	18	27	34	37	39	37	30	25	Maximum Monthly Rainfall (mm)
13	8	5	7	11	19	25	29	31	29	23	18	Average Monthly Rainfall (mm)
20	24	31	33	29	16	11	10	10	9	15	18	Minimum Relative Humidity (%)
58	66	73	77	70	46	32	29	28	27	46	54	Maximum Relative Humidity (%)
2.55	1.92	1.52	1.1	1.13	1.54	1.49	1.64	2	2.33	2.6	2.6	Average Wind Speed (m/s)
18	16	16	16	17	20	24	25	26	25	23	20	Upper Limit of Drinking Water (Asalis)
21	19	19	19	20	23	27	28	29	28	26	23	Lower Limit of Drinking Water (Khuni)
24	22	22	22	23	26	30	30	31	31	29	26	Upper Limit of Irrigation Water (Asalis)
🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	Minimum Drought
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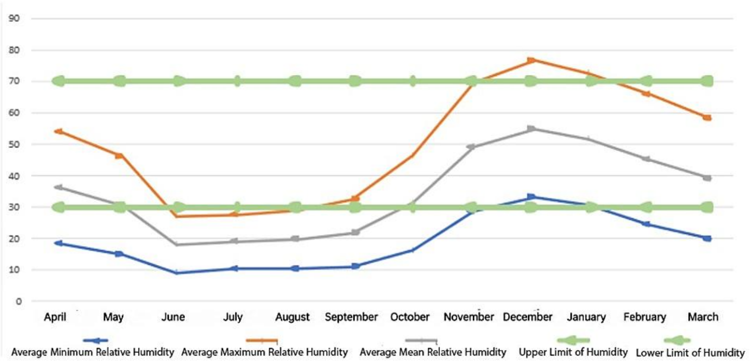

Figure 8. Monthly humidity conditions relative to the standard limits. Source: Authors.

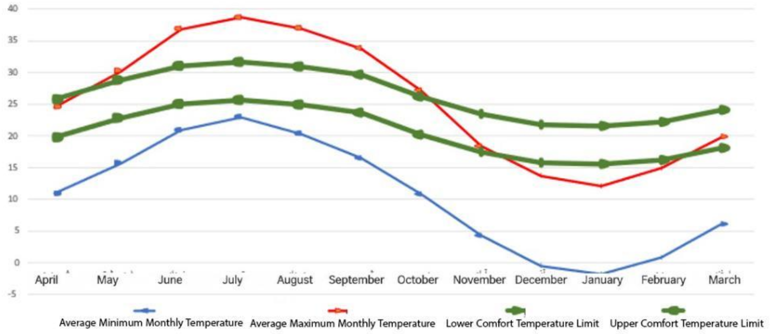

Figure 9. Monthly temperature conditions relative to the comfort range. Source: Authors.

Breakdown Table of Climatic Problems

presents Table 6 sets out, month by month, exactly where the humidity and temperature problems lie. Working from the figures in Table 5, and allowing a 1% tolerance for shortfalls in minimum humidity, November emerges as the only month free of any humidity-related issue.

December and January are the wettest cases, with maximum relative humidity climbing as much as 7% above the 70% threshold. Figure 2 indicates that raising the air temperature by 1 °C offsets roughly 10% of the negative effect of humidity. Increasing air movement, the more usual remedy, is not a realistic option here: the cold conditions of these two months make it impractical.

The picture reverses across April, May, September, October, February, and March. None of these months suffers from excess humidity, yet their minimum humidity drops as much as 19% below the lower acceptable limit. June, July, and August are drier still. Their minimum relative humidity falls short by up to 21%, and even the maximum humidity sits as much as 3% under the 30% threshold. A single corrective therefore does a lot of work: adding 21% to relative humidity resolves the minimum-humidity deficit for every month from April through October, together with February and March, while at the same time closing the maximum-humidity gap in June, July, and August.

That correction is not free of side effects. The same 21% increase would push maximum humidity to 75% in April, 87% in February, and 79% in March, overshooting the upper standard limit by as much as 17% in the worst case. Where this happens, raising the air temperature by 2 °C trims the resulting humidity problem by roughly 20%.

Several environmental strategies can supply the needed moisture. Vegetation works in both cold and warm seasons, while water features and wetted surfaces are well suited to the warm months, where they carry the added benefit of evaporative cooling.

Table 6. Classification of the type and magnitude of monthly humidity and temperature problems. Source: Authors.

Month (Gregorian)	Humidity Issue	Temperature Issue
Farvardin (April)	Minimum humidity is 18%	Minimum temperature is 9°C below the lower comfort limit
Ordibehesht (May)	Minimum humidity is 15%	Minimum temperature is 7°C below the lower comfort limit and maximum temperature 1°C above the upper comfort limit
Khordad (June)	Minimum humidity is 9% and maximum is 27%	Minimum temperature is 4°C below the lower comfort limit and maximum temperature 6°C above the upper comfort limit
Tir (July)	Minimum humidity is 10% and maximum is 28%	Minimum temperature is 3°C below the lower comfort limit and maximum temperature 7°C above the upper comfort limit
Mordad (August)	Minimum humidity is 10% and maximum is 29%	Minimum temperature is 5°C below the lower comfort limit and maximum temperature 6°C above the upper comfort limit
Shahrivar (September)	Minimum humidity is 11%	Minimum temperature is 7°C below the lower comfort limit and maximum temperature 4°C above the upper comfort limit
Mehr (October)	Minimum humidity is 16%	Minimum temperature is 9°C below the lower comfort limit and maximum temperature 1°C above the upper comfort limit
Aban (November)	No issue	Minimum temperature is 13°C below the lower comfort limit
Azar (December)	Maximum humidity is 77%	Minimum temperature is 16°C below the lower comfort limit and maximum temperature 2°C below the lower comfort limit
Dey (January)	Maximum humidity is 73%	Minimum temperature is 18°C below the lower comfort limit and maximum temperature 4°C below the lower comfort limit
Bahman (February)	Minimum humidity is 24%	Minimum temperature is 15°C below the lower comfort limit and maximum temperature 1°C below the lower comfort limit

Temperature-related problems are observed to some extent throughout all months of the year. Except for **April, November, and March**, where only the **minimum temperature** falls outside the comfort range, in the remaining **nine months** both minimum and maximum temperatures exhibit some form of thermal discomfort.

In **February**, the minimum temperature falls **18 °C below the lower comfort limit**, representing the greatest deviation on the cold side. Conversely, **July**, with a maximum deviation of **7 °C above the upper comfort limit**, records the largest difference between maximum temperature and the upper comfort boundary.

It should be noted that in the previous humidity analysis, it was proposed that in order to mitigate excessive humidity, the air temperature should be increased by **1 °C in December and January**, and by **2 °C in February, March, and April**. As the minimum and maximum temperatures of these months indicate, there is an evident and unavoidable need to increase temperature in order to resolve thermal discomfort; such an increase would simultaneously help address the humidity problem.

According to **Givoni**, the implementation of **passive design strategies** in buildings can extend the comfort range from the neutral temperature by up to **7 °C above** and **10 °C below** the neutral temperature. If these passive strategies can be applied in both **cold and warm seasons**, their impact on heating can be comparable to their cooling effects.

Strategies for Temperature

Table 7. Range for resolving temperature-related problems. Source: Authors.

Month	10-Year Avg. Min Temp (°C)	10-Year Avg. Max Temp (°C)	No-Building Range Lower Comfort Limit (°C)	Neutral Temp (°C)	Upper Comfort Limit (°C)	Appropriate Design Range Lower Comfort Limit (°C)	Upper Comfort Limit (°C)	Simple Heating & Cooling Devices Range Lower Comfort Limit (°C)	Upper Comfort Limit (°C)
Farvardin (April)	11	25	20	23	26	13	30	7	35
Ordibehesht (May)	16	30	23	26	29	16	33	10	38
Khordad (June)	21	37	25	28	31	18	35	12	40
Tir (July)	23	39	26	29	32	19	36	13	41
Mordad (August)	20	37	25	28	31	18	35	12	40
Shahrivar (September)	17	34	24	27	30	17	34	11	39
Mehr (October)	11	27	20	23	26	13	30	7	35
Aban (November)	4	18	17	20	23	10	27	4	32
Azar (December)	0	14	16	19	22	9	26	3	31
Dey (January)	-2	12	16	19	22	9	26	3	31
Bahman (February)	1	15	16	19	22	9	26	3	31
Esfand (March)	6	20	18	21	24	11	28	5	33

As previously noted, a sustainable architectural design maximizes the opportunities and minimizes the constraints present in the design context, thereby producing a climate-responsive solution that reduces environmental threats while benefiting from existing potentials. As can be inferred from **Table 7**, the problem of **maximum temperature** in **May, September, and October** can be resolved through appropriate architectural design, while in **June, July, and August** it can be mitigated through the use of **simple cooling devices**, requiring only a **3 °C reduction** in temperature.

The issue of **minimum temperature** can similarly be addressed through **proper design strategies** during the months of **May to September**, and through **simple heating devices** during **April, October, November, and March**. Only during the **three months of December, January, and February** is the use of **mechanical or electrical systems** necessary.

As discussed earlier, **air temperature, mean radiant temperature, humidity, and air movement** are the four principal environmental factors influencing thermal comfort. The significant difference between **daytime and nighttime temperatures** during various months (Table 5) highlights the importance and influence of **radiant temperature** in determining air temperature conditions. Moreover, as illustrated in the **psychrometric chart (Figure 3)**, increasing temperature intensifies humidity-related problems during the **warm months**, while decreasing temperature exacerbates **excess humidity during colder seasons**.

For this reason, identifying a strategy capable of **controlling solar radiation and regulating air movement**, and consequently **managing both temperature and humidity**, becomes essential. This necessity ultimately leads to the concept of designing an **interactive and movable building envelope**.

Design and Performance of the Interactive and Movable Envelope

The findings establish a strong relationship between neutral temperature and outdoor temperature, supported by a high correlation coefficient. On that basis, placing an interactive and responsive envelope at the boundary between the indoor and outdoor environments becomes a logical design move. Such a system carries clear potential: by mediating solar gains and airflow at the façade, it could help bring indoor conditions toward the comfort range while easing reliance on mechanical conditioning. Whether that potential translates into measurable energy savings remains to be confirmed through monitoring or simulation, which lies beyond the scope of this study.

The proposed envelope is conceived to manage solar radiation gains and regulate airflow. It brings together several components:

- Temperature sensor, which detects and reports indoor environmental conditions.
- User interface panel, through which the occupant interacts with the system.
- Software component, built around a profile derived from the Iranian thermal comfort formula. It handles communication with the user along with data analysis and the decisions that govern the position of the envelope elements.
- Hardware component, comprising a computer and an electronic board that store part of the control code and manage communication between the sensor, the control panel, and the remaining components.
- Electric motor, which carries out the commands and adjusts the position of the envelope elements.
- Movable façade elements, forming the dynamic outer layer of the envelope.

The interface offers three operating modes: open, closed, and automatic. In the closed mode, the elements of the secondary envelope sit flush against one another, forming a continuous surface that blocks solar radiation and airflow from reaching the building. Rotating the elements through 90 degrees switches the system to the open mode, where radiation and air movement are free to pass.

The automatic mode is the more involved case. Here the movement of the façade is governed by several parameters at once: the monthly comfort limits drawn from the Iranian thermal comfort formula, the indoor temperature, and the time of day.

To make the fullest use of solar radiation during the cold periods, the daily cycle is split into three intervals, as set out in Table 8.

Table 8. Time-range classification table. Source: Authors.

Month	Latest Sunrise	Between Sunrise & Noon	Noon	Between Noon & Sunset	Earliest Sunset
April (Farvardin)	06:06	09:03	12:06	03:05	18:16
May (Ordibehesht)	05:27	09:17	12:01	03:18	18:38
June (Khordad)	05:00	09:32	12:02	03:29	19:00
July (Tir)	05:11	09:31	12:07	03:31	19:09
August (Mordad)	05:32	09:22	12:08	03:16	18:40
September (Shahrivar)	05:51	09:05	12:01	02:59	18:00
October (Mehr)	06:13	08:45	11:52	02:45	17:22
November (Aban)	06:39	08:28	11:48	02:35	16:59
December (Azar)	07:01	08:24	11:55	02:32	16:59
January (Dey)	07:04	08:36	12:08	02:27	17:02
February (Bahman)	06:43	08:54	12:16	02:35	17:26
March (Esfand)	06:06	09:11	12:14	02:49	17:53

There is a practical reason for this subdivision. In the morning and the evening, solar radiation reaches the southern façade at an oblique angle. Left unaddressed in the design, this geometry can cause the main façade elements to shade one another during cold periods, precisely when the interactive envelope is meant to stay open and admit as much radiation as possible. With detailed solar data unavailable, the times of sunrise, solar noon, and sunset were established first. Taking the midpoint between these moments then divided the day into the three intervals above, which limits the self-shading problem. The stretch between sunset and sunrise was treated as the night interval.

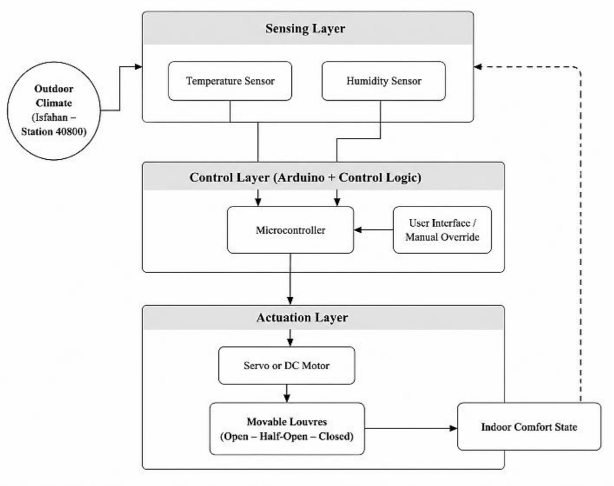

Figure 10. Conceptual control architecture of the interactive envelope, showing the sensor–controller–motor loop validated through the 1:20 functional prototype. Source: Authors.

In operation, the sensor passes the indoor temperature to the electronic board. That reading is compared against the monthly thermal comfort range, and depending on the current time interval, the board issues the corresponding command to the controller and motor, following Table 9.

Table 9. Positioning of the main façade elements. Source: Authors.

Internal Temperature Condition	Morning Period	Noon Period	Afternoon Period	Night Period
Above Comfort Range	Closed	Closed	Closed	Open
Below Comfort Range	With 45° East	90°	With 45° West	Closed
Within Comfort Range	*Fixed in Previous Position*			

The logic behind the table is straightforward once the objective for each case is clear.

When the indoor temperature rises above the comfort range between sunrise and sunset, the elements close. This shuts out solar radiation and checks any further rise in temperature. Should the same overheating occur during the night, the façade opens instead, letting cooler air move through and drawing the indoor temperature back down.

When the indoor temperature falls below the comfort range, the priority shifts to capturing as much solar radiation as the geometry allows:

- In the morning interval, the elements turn 45 degrees toward the east.
- At solar noon, with sunlight close to perpendicular on the southern façade, the elements open fully to 90 degrees.
- In the evening interval, they turn 45 degrees toward the west.

If this cold condition arises at night, the façade stays closed. Keeping it shut preserves the indoor heat and prevents cold air from washing directly over the main envelope, which would otherwise pull the indoor temperature down further.

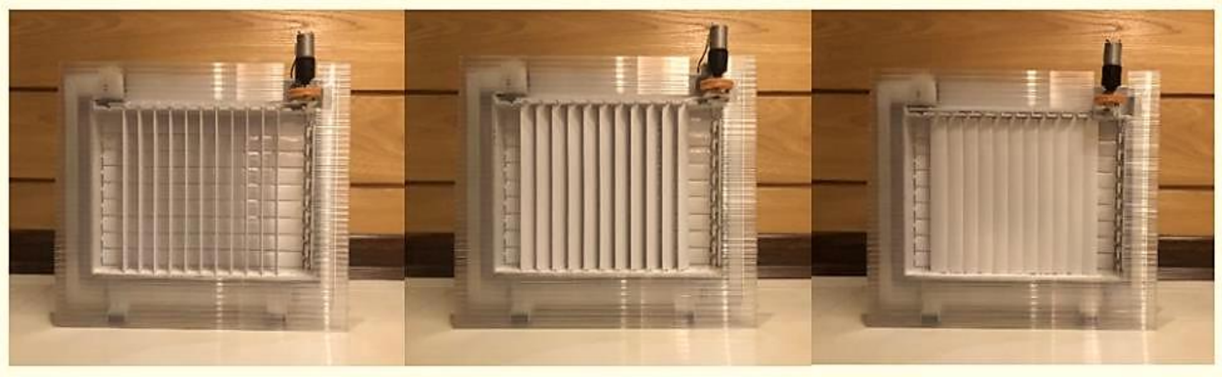

Figure 11. Small-scale prototype of the designed movable façade in three states: open, semi-open, and closed. Source: Authors.

Figure 12. Different applications of the designed movable façade on building elevations through dimensional variation, according to the preferences of the architect or client. Source: Authors.

Conclusion

This study set out to examine whether global thermal comfort indices, applied on their own, can capture the lived requirements of occupants in the hot and dry climate of Isfahan. The evidence points the other way. When local climatic characteristics are set aside, the conventional ranges leave a gap between what the standards prescribe and what the setting actually demands. The analysis of long-term climatic records made that gap visible: the monthly swings in temperature and humidity in Isfahan form distinct patterns of mismatch with the conventional comfort bands. Envelope design, then, has to engage those patterns directly rather than work from imported defaults.

The research asked how an interactive envelope might be conceptualized around thermal comfort equations calibrated for Iran. Two things proved central to answering that question. The first is a quantitative reading of the psychrometric chart together with a clear account of the environmental factors that shape thermal comfort. The second is the comparison of at least ten years of local climatic data against comfort models adapted to Iranian conditions. Brought together, these provide the basis for a user–climate interactive profile capable of guiding the behavior of the envelope month by month.

The envelope developed here controls solar radiation, adjusts its openings, and supports natural ventilation. By mediating these factors at the boundary between inside and outside, it offers clear potential to moderate indoor conditions, to widen the effective comfort range, and to extend the occupant's adaptive capacity. In principle, this points toward lower reliance on mechanical systems and a richer spatial experience. These outcomes are presented as design potential rather than demonstrated results: the functional prototype built in this study, at a scale of 1:20, validated only the kinematic and control behavior of the system, the loop running from sensor input through the control logic to motor actuation. Thermal and energy performance were not measured, and confirming the expected gains will require monitoring or simulation in future work.

Taken as a whole, coupling an interactive envelope to both climatic conditions and user behavior offers a promising direction for addressing thermal challenges in contemporary Iranian architecture. The flexibility and programmability of the proposed design suggest it could be adapted to a range of new and existing buildings across different climatic zones, though the practical and economic aspects of implementation remain to be tested. On this basis, the study contributes a conceptual and methodological framework for advancing the design of intelligent, climate-responsive envelopes in comparable urban settings.

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