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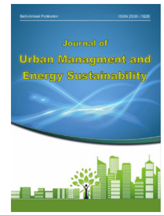

ORIGINAL RESEARCH PAPER

Sustainable Urban-Design Pattern by Explaining an Environment-Based Compatibility Model Founded on Density in the Residential Fabrics of Tehran city

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ABSTRACT

Buildings account for roughly 40% of urban energy use and greenhouse-gas emissions, and the physical form of the city through density, coverage and configuration strongly conditions the urban microclimate and the resulting heating and cooling demand of residential fabrics. Yet a systematic, locally grounded model linking environmental-compatibility indicators to a measurable, density-based sustainable-design pattern is still lacking, particularly for the horizontally sprawling residential areas of Tehran. This study aims to establish such a model for the residential fabrics of District 4 of Tehran. A two-stage design was used: first, environmental-compatibility indicators of residential morphology were screened and weighted through a Fuzzy-Delphi expert panel, in which building density and coverage level obtained the highest consensus and were adopted as the fixed effective variables; second, four dominant morphotypes were modelled and simulated in ENVI-met using 2024 climate data for the hottest and coldest days, in both the existing and a proposed state, comparing air temperature, wind speed, relative humidity and mean radiant temperature. The results, combined into a scale-free composite index, show that under controlled densification the high-rise type achieves the most positive microclimatic change (rank 1), followed by the compact and slab types, while the modern type remains most stable. Overall, applying the optimal model improved the microclimate in about 75% of cases and preserved stability in the remainder, without reducing energy efficiency in any type. A controlled compact form, density raised within an optimal range and matched to each morphotype therefore offers a decision-support pattern for sustainable, energy-efficient urban design.

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INTRODUCTION

According to United Nations reports, the form of the city has a direct impact on energy consumption (Ejiagha et al., 2020). The shape of the city and its design pattern through features such as building density, the mix of uses, the pattern of the communication network and the public-transport network influence energy consumption (Van Esch et al., 2012) (Yao, 2012) (Ma et al., 2021) (Leng et al., 2020). Urban energy consumption is usually divided into five main sectors industry, transport, housing, services and agriculture and in developing countries most consumption occurs in the transport and housing sectors, among which buildings are responsible for the largest share, about 40% of energy use and greenhouse-gas emissions (Huang et al., 2020) (Khatana et al., 2022). The greatest potential for reducing greenhouse-gas emissions about 29% by 2030 can be realised in the case of buildings. Important factors influencing building energy consumption include density, diversity and design; the concept of building energy is therefore formed within urban fabrics through the classification clusters of the morphology concept, and building types, as the cells of this concept, determine the level of energy efficiency (Morris & Pehnt, 2015). To optimise urban energy efficiency, buildings are therefore the main focus of attention; among the energies consumed, incoming solar-radiation energy on the one hand and thermal-energy demand on the other are the most important issues examined in urban energy efficiency. In recent years, issues related to climate change and energy have gained the greatest importance in urban studies (Sun et al., 2020). Cities today are responsible for emitting more than 70% of greenhouse gases, although they cover about 2% of the earth's surface (Zawadzka et al., 2021), their residents consume 60–80% of the world's energy (Mumtaz et al., 2020). As this issue intensifies, energy efficiency is regarded as a key factor in urban development (Zaki et al., 2022), which is why governments make all-out efforts to reduce greenhouse-gas emissions (Qiu et al., 2019). In the relationship between buildings and the surrounding environment, each building alters the weather around it. These changes occur under the heading of the urban microclimate and are governed by factors such as urban geometry and cross-section, the shape, height and size of buildings, the orientation of streets and buildings, and the surface of open spaces (Jamei et al., 2015). Man-made urban elements, through their effect on climatic factors, air temperature, relative humidity, wind speed and direction, and solar radiation create an artificial climate whose components continually interact. The shape of the urban space, in accordance with the form of shelter and the weather conditions, creates a microclimate and thereby different conditions for living (Krüger et al., 2011). Urban geometry plays an important role in determining the urban microclimate (Santos et al., 2021); other parameters such as the type and albedo of materials, greenery, humidity, radiation control and the effect of thermal masses also affect it (Ma et al., 2021). Among these, the aspect ratio and the orientation of roads have the greatest impact on the severity of environmental conditions (Rodríguez Algeciras & Matzarakis, 2016) (Abreu-Harbich et al., 2014).

Beyond their effect on the climatic conditions outside the building, morphological parameters can also change the conditions inside it; a building should therefore not be studied as an independent unit without considering its location and its conditions at the urban scale (Yao, 2012). The effect of horizontal and vertical configuration, the ratio of built area, plot area and coverage level are all important in the formation of the urban fabric (Santos et al., 2021). Measuring the density of the built environment and indicators such as coverage level, open-space ratio and number of floors can also be regarded as the main indicators of research (Wang & Zhang, 2016). The present research seeks to answer three questions: (1) through what mechanism do urban morphological variables act on climatic parameters? (2) through which variables does sustainability in urban form affect the urban climate? (3) what model can be used to assess the sustainability of the urban fabric on the basis of the most effective morphological variable? The main goal is to extract an optimal framework and the structure of the fixed variables in the form of a structural approach to urban design in urban morphology, so that the meta-model of sustainability in the physical form of the city can be explained on the basis of one morphological component as a fixed effective variable and, finally, an optimal proposed model can support policymaking at the intermediate scale of the detailed plan. The problem this research addresses is therefore both practical and conceptual. Practically, planners in Tehran and comparable cities are being asked to densify an existing, largely horizontal residential fabric without a robust, form-specific evidence base for how much density each type of fabric can absorb before its environmental performance deteriorates. Conceptually, the field still lacks a compact procedure that connects the screening of morphological indicators to a controlled, comparable measurement of their microclimatic consequences and, ultimately, to a decision that a detailed plan can implement. Addressing this dual problem is the motivation for coupling an expert-based indicator screening with a physically based microclimate simulation. Accordingly, the objectives of the study are threefold: (1) to identify and prioritise the environmental-compatibility indicators of residential morphology through a fuzzy-Delphi expert panel; (2) to quantify, through ENVI-met simulation, how the four dominant residential morphotypes of District 4 modify their surrounding microclimate in their existing state and under controlled densification; and (3) to synthesise these results into a composite, decision-usable ranking that identifies the optimal, density-based sustainable-design pattern for each morphotype. Meeting these objectives yields both a transferable method and a locally calibrated model for sustainable, energy-efficient residential design (Salvati et al., 2017) (Kamal et al., 2021).

MATERIALS AND METHODS

Sustainable urban design sits at the intersection of urban morphology, climatology and energy. The following review organises the foundations of the study around five threads urban morphology and the microclimate, the compact-city debate, the urban heat island and building energy, microclimate simulation, and multi-criteria screening with the Fuzzy-Delphi method and closes with the research gap that the present study addresses.

Sustainable urban design: principles and scope

Sustainable urban design is the branch of urban studies concerned with shaping the physical form of the city so that environmental, social and economic goals are met simultaneously and across generations. Within this field, the environmental dimension resource and energy efficiency, climate adaptation and the protection of ecological systems has become paramount as cities confront climate change and rising energy demand (Mouratidis, 2019). At the scale of the residential fabric, sustainable design is expressed above all through the management of the built form: the arrangement of masses and open spaces, the calibration of density and height, and the orientation and configuration of blocks all determine how much energy buildings consume and how comfortable the spaces between them are (Erell et al., 2011) (Boccalatte et al., 2020). The present study operates squarely within this environmental strand of sustainable urban design, taking the reduction of building energy demand mediated by the microclimate as the operational criterion of sustainability and the compact urban form as the design hypothesis to be tested and calibrated. Urban morphology the geometry, density and configuration of the built environment is a primary control on the near-surface climate of cities. The canopy-layer climate is shaped by the height-to-width (aspect) ratio of street canyons, the sky-view factor, building orientation and the thermal properties of surfaces, which together govern shortwave trapping, longwave loss and ventilation (Oke et al., 2017) (Erell et al., 2011). Compact, deep canyons reduce daytime solar access and nocturnal cooling, whereas open configurations enhance both radiative exchange and wind flow. Empirical and modelling studies confirm that the aspect ratio and street orientation exert the strongest influence on outdoor thermal conditions (Rodríguez Algeciras & Matzarakis, 2016) (Sharmin et al., 2017), while density, coverage level and building height modulate both the outdoor microclimate and the indoor energy balance (Kamal et al., 2021) (Ma et al., 2021). Because these effects are configurational rather than attributable to any single building, a morphotype—a recurring cluster of built forms is a more meaningful unit of analysis than the isolated building (Stewart & Oke, 2012).

The sustainable urban form and urban heat island

Since the 1990s the "compact city" has been the dominant normative model of the sustainable urban form, promising lower per-capita energy use, shorter trips, the protection of peripheral land and more viable public transport (Mouratidis, 2019). A large body of evidence associates higher density with agglomeration benefits and lower transport energy, although the relationship is neither linear nor free of trade-offs (Ahlfeldt & Pietrostefani, 2019). Critics note that uncontrolled densification can intensify the urban heat island, reduce daylight and ventilation, and raise cooling demand, so that the environmental performance of compaction depends on how density is distributed in three dimensions rather than on density alone (Mirzaei, 2015). This tension is central to the present study: rather than treating density as uniformly beneficial or harmful, the research asks how much and in what configuration density can be added to each residential morphotype before its microclimatic and energy performance deteriorates. The urban heat island (UHI) the tendency of built-up areas to be warmer than their rural surroundings links morphology to energy through its effect on heating and cooling loads (Zhou et al., 2019). In hot periods the UHI raises cooling demand and peak electricity load, whereas in cold periods a moderate UHI can reduce heating demand; the net energy effect therefore depends on climate and season (Palme et al., 2017) (Yang et al., 2020). For cities with pronounced seasonal contrast, an urban form that simultaneously tempers summer overheating and limits winter heat loss is especially valuable. Mitigation research emphasises vegetation, high-albedo materials and ventilation corridors (Lai et al., 2019) (Aboelata & Sodoudi, 2020), but the configurational levers—density, coverage and height remain decisive because they set the boundary conditions within which such measures operate (Boccalatte et al., 2020) (Salvati et al., 2017).

Microclimate and the ENVI-met model

Coupled surface–plant–air models make it possible to quantify how built form reshapes the microclimate. ENVI-met, a three-dimensional, non-hydrostatic model of the interactions among buildings, vegetation, soil and the atmosphere, is among the most widely used tools for this purpose (Bruse & Fleer, 1998). Validation and review studies report that it reproduces air-temperature and mean-radiant-temperature patterns with acceptable accuracy for comparative design studies, while noting sensitivities to boundary conditions and to the treatment of vegetation and materials (Tsoka et al., 2018) (Middel et al., 2014). Holding vegetation, materials and anthropogenic heat constant—as in the present study isolates the effect of built mass and supports a controlled, like-for-like comparison of morphotypes, a strategy consistent with the local-climate-zone logic of comparing forms under identical forcing (Stewart & Oke, 2012). Identifying which morphological indicators matter most is itself a multi-criteria problem under uncertainty and expert disagreement. The Fuzzy-Delphi method extends the classical Delphi by representing each expert's linguistic judgement as a triangular fuzzy number and aggregating these into a defuzzified consensus value, retaining only indicators above an acceptance threshold (Kuo & Chen, 2008). The approach is well suited to sustainability and built-environment problems, where criteria are numerous, partly subjective and interdependent (Bui et al., 2020). In this study it is used to screen and prioritise the environmental-compatibility indicators of residential morphology, providing a transparent basis for selecting density and coverage as the fixed effective variables driving the simulation stage.

Research gap and conceptual framework

Although the literature richly documents the effects of urban form on microclimate and energy, three gaps remain. First, most studies examine either outdoor comfort or building energy in isolation, rather than linking configurational indicators to a decision-usable design pattern. Second, comparative morphotype evidence for the cold, semi-arid context of Iran and for the horizontally sprawling fabrics of Tehran in particular is limited, even though densification is now official policy. Third, few studies combine an expert-based screening of compatibility indicators with a controlled microclimate simulation to derive an optimal, density-based pattern. The present research addresses these gaps by coupling a Fuzzy-Delphi screening with an ENVI-met evaluation of four dominant morphotypes, under both existing and densified states, and by synthesising the results into a single composite ranking that supports policymaking at the intermediate (detailed-plan) scale.

Morphological indicators and their measurement

The morphological indicators screened in this study are standard, measurable descriptors of the three-dimensional form of the residential fabric. Building density (or floor-area ratio, FAR) expresses the total floor area divided by the plot area and captures the intensity of development; the ground space index or coverage level (the building footprint divided by the plot area) captures the two-dimensional compactness of the fabric; and the open-space ratio relates unbuilt area to floor area, summarising the availability of space for ventilation, daylight and greenery (Boccalatte et al., 2020) (Xu et al., 2023). The height-to-width or aspect ratio of the street canyon, together with the sky-view factor it implies, governs shortwave access and longwave cooling and is repeatedly identified as the single most influential geometric control on the outdoor microclimate (Rodríguez Algeciras & Matzarakis, 2016) (Sharmin et al., 2017). Building and street orientation determine exposure to solar radiation and prevailing winds, while surface albedo and vegetation modulate the absorbed radiation and the latent-heat exchange (Lai et al., 2019). Because these indicators are partly correlated density, coverage and height cannot be varied wholly independently the study fixes coverage and varies height within each morphotype, so that the marginal effect of vertical densification is measured under an otherwise constant configuration. Adopting a small, measurable and largely orthogonal set of indicators has two advantages. First, it keeps the model operable within the instruments of the detailed plan, which regulate precisely these quantities density, coverage and number of floors. Second, it allows the simulation to be interpreted mechanistically: any change in the microclimate between the existing and proposed states can be attributed to the controlled change in one indicator (height, and hence density) rather than to a confounded bundle of variables (Stewart & Oke, 2012) (Kamal et al., 2021).

Case Study: Tehran City

Tehran, the capital of Iran and one of the largest metropolitan areas of West Asia, lies at the foot of the Alborz range at an elevation of roughly 1,100–1,700 m, producing a marked north–south climatic and topographic gradient. Its climate is cold semi-arid (Köppen BSk), with hot, dry summers and cold winters, so that residential buildings incur substantial cooling loads in summer and heating loads in winter—precisely the seasonal contrast for which a configuration-sensitive design pattern is most valuable (Roshan et al., 2019). Rapid twentieth-century growth expanded the city outward in a largely horizontal, low- to mid-rise fabric, and studies of the metropolitan area document a pronounced urban heat island whose intensity tracks built density and the loss of vegetated and water surfaces (Sodoudi et al., 2014). In response, Iranian urban policy has increasingly promoted densification and vertical growth through detailed (tafsili) plans, making the environmental consequences of added density a live planning question rather than a purely academic one. In energy terms, Iran is among the most energy-intensive economies in the region, and its building sector accounts for a large and growing share of national consumption, driven by heavily subsidised energy, a young and urbanising population and a building stock with limited thermal performance. In cities such as Tehran, the combination of a pronounced seasonal climate and an expanding residential fabric makes the operational energy of buildings particularly for winter heating and summer cooling a strategic concern for both environmental sustainability and energy security. Design interventions that reduce this operational demand indirectly, by improving the microclimate that surrounds buildings, are therefore especially attractive, because they can be delivered through the ordinary instruments of urban planning rather than through costly retrofits.

District 4, in the north-east of Tehran, is among the most populous districts of the city, with 20 neighbourhoods and 9 zones, an area of about 61.3 km² and a population of roughly 804,000. Its residential fabric is morphologically heterogeneous, juxtaposing compact older blocks, mid-rise apartments, high-rise towers and slab and modern apartment forms, frequently within the same access network and microclimatic setting. This diversity, combined with the district's ongoing densification, makes it an informative laboratory for comparing morphotypes under identical climatic forcing: because the selected examples of each type lie close to one another, differences in their microclimatic behaviour can be attributed to built form rather than to background climate. District 4 is therefore treated here not as a unique case but as a representative sample of the mid-scale residential fabric to which the proposed model is intended to apply. In terms of structure the research is analytical–descriptive and, in terms of its main goal, applied. Data collection combined documentary (library) and field methods with data generation, modelling and simulation using energy- and microclimate-analysis software (ENVI-met). The design proceeded in two complementary stages. In the first stage, the environmental-compatibility indicators of residential morphology were identified from the literature and screened and weighted through a Fuzzy-Delphi expert panel. In the second stage, the dominant morphotypes of the study area were modelled and simulated in ENVI-met, and their microclimatic performance was compared between the existing and a proposed (densified) state to extract the optimal, density-based pattern.

Fuzzy-Delphi screening of the compatibility indicators

The Fuzzy-Delphi method was used to convert experts' linguistic judgements into triangular fuzzy numbers and, after defuzzification, to retain only those indicators whose consensus value exceeded the acceptance threshold (0.70). From the morphological and environmental literature, an initial pool of indicators building density, coverage/occupancy level, floor-area ratio (FAR), aspect ratio (H/W), building and street orientation, open-space ratio, number of floors (height) and vegetation/albedo was compiled and submitted to the panel. The screened indicators and their (illustrative) defuzzified consensus values are summarised in Table 1 and Figure 3; "building density" and "coverage/occupancy level" obtained the highest consensus, which motivated the choice of density as the fixed, effective variable governing the sustainable-design pattern examined in the simulation stage. (Tab. 1 and Fig.

1)

Table 1: Fuzzy-Delphi screening of the environmental-compatibility indicators

No.	Environmental-compatibility indicator	Triangular fuzzy number (l, m, u)	Defuzzified value	Status
1	Building density	(0.80, 0.92, 1.00)	0.92	Accepted
2	Coverage / occupancy level	(0.76, 0.88, 0.98)	0.88	Accepted
3	Floor-area ratio (FAR)	(0.72, 0.85, 0.96)	0.85	Accepted
4	Aspect ratio (H/W)	(0.70, 0.83, 0.95)	0.83	Accepted
5	Building & street orientation	(0.66, 0.79, 0.92)	0.79	Accepted
6	Open-space ratio	(0.62, 0.76, 0.90)	0.76	Accepted
7	Number of floors (height)	(0.60, 0.74, 0.88)	0.74	Accepted
8	Vegetation & albedo	(0.57, 0.71, 0.85)	0.71	Accepted

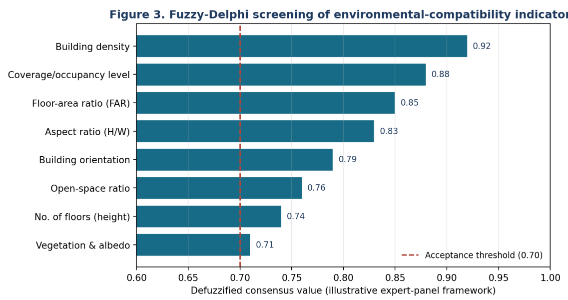

Figure 1: Fuzzy-Delphi screening of the environmental-compatibility indicators against the 0.70 acceptance threshold

Because the analysis is founded on the physical form of the residential fabric, density (with coverage level as its complement) was adopted as the fixed effective variable, and the remaining indicators were held constant during the simulation so that the isolated effect of controlled densification on the microclimate could be measured consistent with the compact-city reading of the sustainable urban form.

The Fuzzy-Delphi procedure followed four steps. First, experts rated the relevance of each candidate indicator on a five-point linguistic scale (very low to very high). Second, each linguistic term was mapped to a triangular fuzzy number, and the panel's judgements for each indicator were aggregated by taking the minimum of the lower bounds, the geometric mean of the modal values and the maximum of the upper bounds, so that both consensus and the range of opinion were preserved (Kuo & Chen, 2008). Third, each aggregated triangular fuzzy number was defuzzified into a single crisp consensus value by the centre-of-gravity method. Fourth, indicators whose defuzzified value met or exceeded the acceptance threshold of 0.70 were retained, and the remainder would be discarded; in this study all eight candidate indicators passed the threshold, with density and coverage obtaining the highest values (Bui et al., 2020). The retained indicators and their weights then informed the simulation stage and the construction of the composite index reported in the findings. Because the four microclimatic parameters are measured in different units, the change of each parameter between the existing and proposed states was first made scale-free by dividing it by the column total, and the normalised changes were then summed for each morphotype and season to yield a single composite score. This two-step expert weighting followed by data-driven normalisation keeps the ranking transparent and reproducible, while acknowledging, as a limitation, that equal implicit weighting of the four parameters could be replaced by stakeholder-specific weights in future work.

ENVI-met simulation in case study

District 4 of Tehran has 20 neighbourhoods and 9 zones, an area of about 61,288,367 m² and a population of 803,789. From an initial set of about 25 building configurations, five types common in the Tehran metropolis were identified and four dominant residential morphotypes compact, high-rise, slab and modern were selected for simulation, chosen so that they lie close to one another (sharing the same microclimate and access network) near the main transport nodes. The four morphotypes are shown schematically in Figure 2, and the figure–ground map of the morphologies is presented in Figure 1 of the case-study base maps. (Fig. 2)

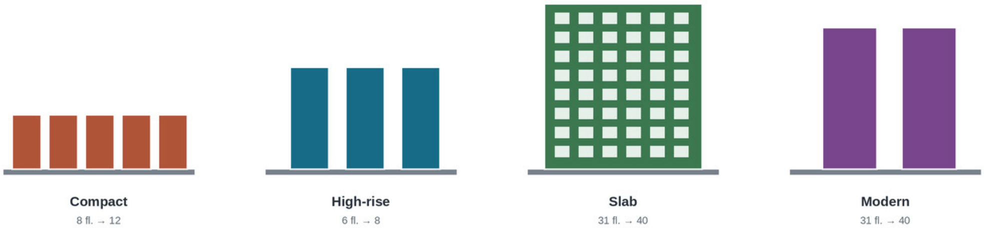

Figure 2: The four residential morphotypes evaluated in District 4, Tehran, with existing and optimal numbers of floors

Each morphotype was modelled three-dimensionally in the ENVI-met (v4) Space environment and simulated for 48 hours on the hottest day (22 June) and the coldest day (22 December), using climate data obtained from Climate Consultant for 2024. To isolate the effect of built mass, vegetation, materials and anthropogenic heat from transport and buildings were held constant, so that only the effect of mass on the creation and modification of the microclimate was considered. Four microclimatic parametersair temperature, wind speed, relative humidity and mean radiant temperature were extracted in the space around the masses and compared with the proposed (densified) state, in which the number of floors of each morphotype was raised to the nearest optimal value at the same building-coverage scenario. The overall research framework is summarised in Figure 3. (Fig. 3)

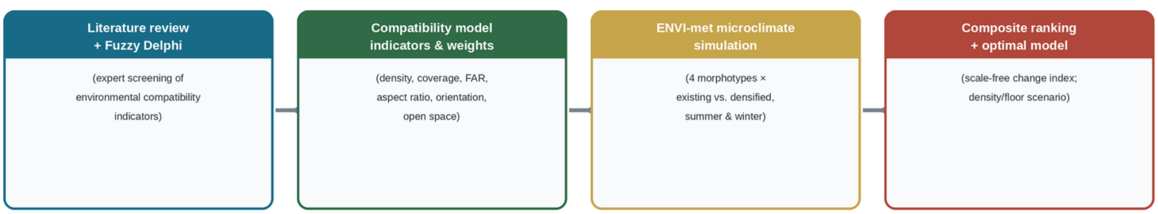

Figure 3: The research methodology framework: Fuzzy-Delphi indicator screening, ENVI-met evaluation and composite ranking

Model configuration and simulation settings

Each morphotype was represented in the ENVI-met Space editor as a three-dimensional array of building masses on a regular grid, with the model domain sized to enclose the studied block and a buffer of surrounding cells to stabilise the boundary conditions. Simulations were run for a continuous 48-hour cycle so that the model could pass an initial spin-up period before the results were read, and outputs were extracted at the critical hours the hottest hour of the hottest day and the coldest hour of the coldest day as well as as 24-hour averages. Meteorological forcing (air temperature, relative humidity, wind speed and direction) was derived from the 2024 Climate Consultant dataset for Tehran and applied identically to the existing and proposed states, so that the only difference between the two runs of each morphotype was the change in built form itself (Bruse & Fleer, 1998) (Tsoka et al., 2018). Four microclimatic parameters were extracted in the pedestrian-level space around the masses:

air temperature, wind speed, relative humidity and mean radiant temperature. Air temperature and mean radiant temperature jointly determine outdoor thermal comfort and the radiative load on facades; wind speed governs convective exchange and the potential for natural ventilation; and relative humidity conditions both comfort and the latent component of the energy balance. Reading all four together, rather than any single index, avoids privileging one comfort model over another and supports a balanced, multi-parameter comparison of the morphotypes (Middel et al., 2014) (Sharmin et al., 2017).

FINDINGS AND DISCUSSION

Four selected morphotypes of District 4 were modelled in ENVI-met and, using the 2024 climate data, simulated for 48 hours on the hottest and coldest days in both the existing and the proposed (densified) state. The behaviour of each morphotype in shaping the surrounding microclimate and hence in raising or lowering building energy demand was then evaluated. Significant differences were observed among the four morphotypes in their effect on the surrounding air temperature under identical conditions. In the hot season, the high-rise structure produced the highest temperature in its surrounding space (repeating this behaviour in the cold season, where it correspondingly lowers heating demand). The compact type produced a lower temperature during the day but raised the surrounding air temperature to nearly 40°C at critical hours, which is a fundamental driver of higher energy consumption. The modern-apartment type showed the most favourable behaviour in the hot season, producing smaller changes in the surrounding temperature.

Tables 2 and 3 report the maximum and minimum values of the four parameters for the existing and proposed states, respectively, on the hottest and coldest days. (Tab. 2 and 3)

Table 2: Maximum and minimum values of the evaluated parameters in the existing state of the selected morphotypes (hottest and coldest day)

Season	Morphotype	Air T max	Air T min	Wind max	Wind min	RH max	RH min	MRT max	MRT min
S	Compact	39.703	19.296	3.994	3.879	101.58	41.046	64.770	16.324
S	High-rise	33.102	19.179	3.883	3.337	101.97	49.830	62.019	19.272
S	Slab	35.262	19.163	4.185	3.817	57.527	28.940	66.614	12.513
S	Modern	31.259	19.760	4.153	3.557	88.281	76.550	64.698	13.071
W	Compact	12.026	8.150	1.317	1.049	106.17	87.152	8.277	1.864
W	High-rise	11.410	8.286	1.480	1.104	95.693	68.145	30.073	1.727
W	Slab	9.726	6.573	2.765	2.659	109.16	76.454	6.435	-0.534
W	Modern	9.580	6.571	1.858	1.653	109.57	78.853	5.851	-0.015

Table 3: Maximum and minimum values of the evaluated parameters in the proposed (densified) state of the selected morphotypes

Season	Morphotype	Air T max	Air T min	Wind max	Wind min	RH max	RH min	MRT max	MRT min
S	Compact	43.387	18.457	4.533	4.057	54.065	18.106	65.152	15.325
S	High-rise	30.174	19.535	4.039	3.538	100.94	47.205	60.107	17.520
S	Slab	33.645	19.646	4.476	4.210	58.405	31.305	66.170	12.868
S	Modern	31.259	19.760	4.153	3.557	88.281	76.550	64.698	13.071
W	Compact	13.243	8.587	1.297	1.230	103.72	88.685	9.073	2.452
W	High-rise	11.266	8.252	1.523	1.129	95.911	67.322	30.044	1.748
W	Slab	9.683	6.579	2.886	2.805	109.65	76.334	6.581	-0.381
W	Modern	9.580	6.571	1.858	1.653	109.57	78.853	5.851	-0.015

Tables 4 and 5 present the average values of the four parameters for the existing and proposed states. Figure 4 compares the mean air temperature of the two states on the hottest and coldest days. (Tab. 4 and 5, Fig. 4)

Table 4: Average values of the climatic parameters in the existing state of the selected morphotypes

Season	Morphotype	Air temperature (°C)	Wind speed (m/s)	Relative humidity (%)	Mean radiant temp. (°C)
S	Compact	28.703	4.313	77.679	35.511
S	High-rise	31.510	3.808	99.528	36.239
S	Slab	26.354	4.315	50.186	31.799
S	Modern	26.557	4.074	92.036	35.988
W	Compact	9.347	1.094	95.313	3.980
W	High-rise	9.366	1.196	83.447	5.238
W	Slab	7.131	2.569	93.357	1.372
W	Modern	7.149	1.635	94.297	1.628

Table 5: Average values of the climatic parameters in the proposed (densified) state of the selected morphotypes

Season	Morphotype	Air temperature (°C)	Wind speed (m/s)	Relative humidity (%)	Mean radiant temp. (°C)
S	Compact	28.409	4.689	44.933	31.758
S	High-rise	29.269	3.991	97.158	33.696
S	Slab	26.388	4.712	50.754	31.941
S	Modern	26.557	4.074	92.036	35.988
W	Compact	9.921	1.172	93.925	4.648
W	High-rise	9.254	1.230	82.933	5.212
W	Slab	7.113	2.694	93.629	1.511
W	Modern	7.149	1.635	94.297	1.628

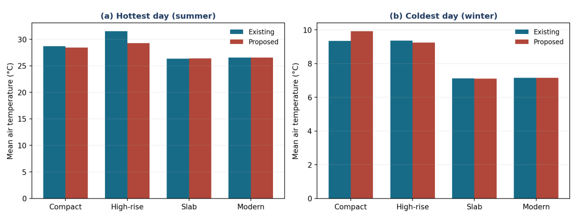

Figure 4: Mean air temperature in the existing vs. proposed (densified) states on the hottest and coldest days of 2024

The comparison of mean air-temperature changes shows that, except for the compact block form, the changes are minor. For the compact type, the proposed model raises the temperature on both the coldest and hottest days (slightly on the cold day and by more than one degree in the heat). On the cold day, the high-rise type shows a temperature decrease of less than 0.2°C and the slab type less still, while the modern type shows no significant change. On the hottest day, the slab and high-rise types decrease by 0.6°C and 1.2°C respectively, and the modern type is unchanged. In terms of wind speed, there is little difference among the types in the hot season, whereas in the cold season compact and high-rise buildings produce the lowest wind speed; the slab type produces the highest cold-season wind speed. Relative humidity is higher around the modern and high-rise types, especially at midday in summer, while the mean radiant temperature shows the strongest response for the high-rise type, which records the largest hot-season reduction under densification. Because the parameters have different units, the mean changes between the two states (Tab. 6) were first made scale-free (Tab. 7) and then combined for ranking (Tab. 8). (Tab. 6) gives the raw change of each average parameter between the existing and proposed states.

Table 6: Change in the average parameters between the existing and proposed states

Season	Morphotype	Δ Air temp. (°C)	Δ Wind (m/s)	Δ RH (%)	Δ MRT (°C)
S	Compact	0.294	-0.376	32.745	3.753
S	High-rise	2.241	-0.183	2.370	2.543
S	Slab	-0.034	-0.398	-0.568	-0.142
S	Modern	0.000	0.000	0.000	0.000
W	Compact	-0.574	-0.078	1.388	-0.668
W	High-rise	0.112	-0.034	0.514	0.027
W	Slab	0.018	-0.125	-0.272	-0.139
W	Modern	0.000	0.000	0.000	0.000

Table 7: Scale-free (normalised) change in the average parameters between the existing and proposed states

Season	Morphotype	Δ Air temp. (°C)	Δ Wind (m/s)	Δ RH (%)	Δ MRT (°C)
S	Compact	1.143	2.519	7.241	5.586
S	High-rise	8.719	1.228	0.524	3.785
S	Slab	-0.133	2.666	-0.126	-0.211
S	Modern	0.000	0.000	0.000	0.000
W	Compact	-2.232	0.520	0.307	-0.994
W	High-rise	0.435	0.229	0.114	0.040
W	Slab	0.068	0.840	-0.060	-0.206
W	Modern	0.000	0.000	0.000	0.000

Table 8: Ranking of the selected morphotypes by microclimatic change in the proposed vs. existing state

Morphotype	Summer	Winter	Total	Rank
High-rise	3.564	0.204	1.884	1
Compact	4.122	-0.600	1.761	2
Slab	0.549	0.160	0.355	3
Modern	0.000	0.000	0.000	4

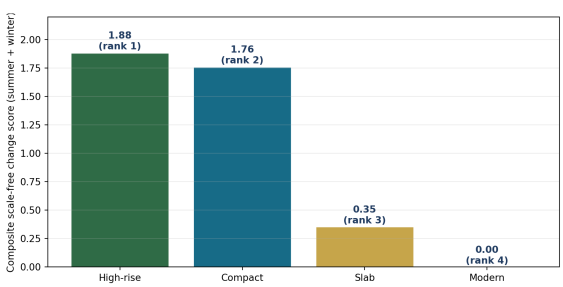

Figure 5: Composite ranking of the morphotypes by microclimatic improvement under the proposed densification

As the ranking shows, the high-rise type records the most positive changes under the proposed conditions, followed by the compact and slab types; the modern type, which received the smallest density increase, changes least its near-zero change being a positive sign that increased density did not degrade its already favourable microclimate. Overall, applying the optimal model to the case sample produced improvement in about 75% of cases and microclimatic stability in the remaining 25%; in no morphotype did it reduce energy efficiency, and in three-quarters of cases it was associated with an indirect increase in the energy efficiency of the building blocks.

Parameter-by-parameter analysis

Air temperature. The clearest differences among the morphotypes appear in the surrounding air temperature. Under existing conditions, the high-rise type records, the highest summer mean, while the modern and slab types record the lowest; under densification the largest changes again occur for the compact and high-rise types, whereas the slab and modern types are almost unchanged. This pattern reflects the trapping of heat within deeper, more enclosed configurations and confirms that the temperature response to added density is strongly type-dependent rather than uniform (Kamal et al., 2021). Wind speed. In summer the four types differ little in wind speed, but in winter the compact and high-rise types produce the lowest wind speeds an advantage in the cold season because it limits convective heat loss while the slab type produces the highest. Under densification wind speed rises modestly in most cases, remaining within a comfortable range except for the compact type in summer, where the increase is less desirable. These results are consistent with the sheltering effect of taller, more compact configurations documented in canyon-ventilation studies (Lai et al., 2019).

Relative humidity and mean radiant temperature. Relative humidity is higher around the modern and high-rise types, especially at midday in summer, and changes only slightly under densification—with the notable exception of the compact type, whose summer humidity falls markedly as its surrounding air temperature is moderated. The mean radiant temperature, which most strongly conditions outdoor comfort and facade radiative load, responds best in the high-rise type, which records the largest hot-season reduction under densification, and improves in the compact type in winter through a favourable rise. Taken together, the four parameters indicate that controlled densification shifts the microclimate of the vertical morphotypes toward greater seasonal favourability (Palme et al., 2017) (Salvati et al., 2017).

Interpretation and comparison with the literature

The simulation results are consistent with, and extend, the configurational reasoning of the reviewed literature. The finding that the high-rise type produces the warmest surrounding air yet responds most favourably to densification recording the largest reduction in mean radiant temperature and the highest composite rank reflects the dual role of height documented elsewhere: tall forms increase heat storage and can trap radiation, but they also cast deep shade and enlarge the sky-view contrast, so that adding height within an already vertical fabric improves the radiative environment more than it harms it (Kamal et al., 2021) (Salvati et al., 2017). The compact type's spike to nearly 40°C at critical hours illustrates the canyon-trapping mechanism emphasised in canyon-geometry studies (Rodríguez Algeciras & Matzarakis, 2016) (Sharmin et al., 2017), and explains why further compaction yields mixed results for that type. The near-invariance of the modern type under a small density increase is likewise consistent with the non-linear, threshold-like response of microclimate to density reported in the literature (Mirzaei, 2015) (Boccalatte et al., 2020): below a certain increment, added density neither degrades nor improves the surrounding microclimate. Read through the lens of building energy, these microclimatic differences matter because they shift the boundary conditions for heating and cooling. In the cold, semi-arid climate of Tehran, a form that moderates summer overheating while limiting winter heat loss is preferable, and the results suggest that controlled vertical densification of the high-rise and, to a lesser extent, compact fabrics moves the microclimate in that direction without penalising any type—echoing evidence that the urban heat island's energy effect is season- and form-dependent rather than uniformly adverse (Palme et al., 2017) (Yang et al., 2020). The overall pattern improvement in about three-quarters of cases and stability in the remainder therefore supports a qualified, rather than an unconditional, endorsement of the compact-city model: compaction is beneficial when it is calibrated to the morphotype and kept within an optimal density range (Mouratidis, 2019) (Ahlfeldt & Pietrostefani, 2019).

Policy implications for Tehran's detailed plans

Because the model operates at the intermediate scale, its results translate directly into the instruments of the detailed plan: permissible building density, coverage level and number of floors per plot. The evidence that the optimal floor increments differ by morphotype modest for the already-vertical high-rise and larger for compact and slab forms argues against uniform, city-wide density bonuses and in favour of morphotype-specific density envelopes. For District 4 and comparable fabrics, this implies a calibrated upward adjustment of floors within each existing coverage scenario, coupled with the complementary levers highlighted in the mitigation literature street-tree canopy, high-albedo surfaces and preserved ventilation corridors (Lai et al., 2019) (Aboelata & Sodoudi, 2020) so that configurational and surface measures reinforce one another. The results also speak to the Iranian and Tehran-specific literature. Studies of the Tehran metropolitan area report a strong, density-linked urban heat island and a projected intensification of cooling demand under climate change, which together argue for design guidance that is sensitive to both summer overheating and winter heat retention (Sodoudi et al., 2014) (Roshan et al., 2019). The present finding that controlled vertical densification can improve the microclimate of the dominant residential morphotypes without penalising any of them—offers a constructive counterpoint to the common assumption that densification necessarily worsens the thermal environment, provided the increment is calibrated to the morphotype and kept within an optimal range. In this sense the study operationalises, for a cold semi-arid Iranian context, the broader international conclusion that the energy and comfort outcomes of compaction are configuration-dependent rather than monotonic (Palme et al., 2017) (Mouratidis, 2019).

With respect to generalisability, the composite ranking should be read as context-specific: it applies to the four dominant morphotypes of a mid-scale, cold semi-arid residential fabric under two extreme days of a single year. The method, however, is transferable. The pairing of a Fuzzy-Delphi indicator screening with a controlled ENVI-met comparison, synthesised into a scale-free composite index, can be reapplied to other cities and climates, with the indicator weights and the optimal density increments re-estimated locally. Replication across Iranian cities of differing size and climate and coupling the microclimatic evaluation with whole-building energy simulation would test the robustness of the density-based sustainable-design pattern and quantify the energy savings that this study infers from microclimatic improvement (Tsoka et al., 2018) (Yang et al., 2020).

RESULTS AND CONCLUSION

The density-based compatibility model

Bringing the two stages together, the study yields a density-based environmental-compatibility model in which density and coverage identified by the Fuzzy-Delphi panel as the highest-consensus indicators act as the fixed effective variables, and the number of floors is the operative lever adjusted within an optimal range for each morphotype. The model is “compatibility-based” in that it does not prescribe a single ideal form but instead matches the admissible density increment to the environmental response of each existing morphotype, so that compaction is pursued only where and to the extent that it improves, or at least does not degrade, the surrounding microclimate (Mouratidis, 2019) (Ahlfeldt & Pietrostefani, 2019). In this way the model reconciles the macro-level policy goal of a compact city with the micro-level reality that the thermal and energy consequences of density are configuration-dependent. Operationally, the model is intended to sit at the intermediate scale of the detailed plan, translating the abstract goal of sustainability into the concrete parameters that plans regulate: permissible density, coverage level and number of floors per plot. Its outputs the morphotype-specific optimal floor increments and the composite ranking of microclimatic improvement constitute a decision-support layer that planners can apply after the plot-segmentation stage, complementing rather than replacing the calculations of urban-planning practice (Stewart & Oke, 2012). Because the model is procedural, it can be updated as new morphotypes emerge or as climate data are revised, giving it a durability that a fixed, one-off prescription would lack.

To explain the sustainable urban-design model, sustainability was first taken as the point of departure within urban design, and the review of the literature confirmed the compact urban form as the sustainable urban form endorsed by the majority of scholars. Because the research approach is sustainability in the urban fabric, the focus is on the energy consumed by buildings above all the operational energy required for cooling and heating. The final results make it clear that the proposed model a specific amount of density and an optimal coverage level for compacting the urban fabric has positive effects on reducing energy consumption: it couples an increase in density with an improvement of the microclimatic conditions. In other words, it is an urban-design model that is based on a sustainable (compact) urban form and results in lower energy consumption. The model therefore calls for a method of decision-making in which, by placing urban design at the appropriate point in the production of detailed plans and by setting construction rules and standards, the outcomes of these decisions are guided toward sustainability and energy efficiency. On the basis of the final evaluation of the proposed model, and given the variable "number of floors" together with the building-density and coverage-level scenario, the optimal base-density model is summarised in (Tab. 9).

Table 9: Building density and number of floors proposed for the optimal base-density model.

Morphotype	Existing floors	Optimal floors	Scenario	Change (m)	Proposed-model floors
Compact	8	12	Same BSC	12	12
High-rise	6	8	Same BSC	6	8
Slab	31	40	Same BSC	27	40
Modern	31	40	Same BSC	27	40

The model and the way numerical data are used in introducing the optimal states (in the form of scenarios) depend on knowledge of the studied platform, the determination and correction of the form, and the evaluation of the existing and optimal states. The proposed model is presented as one of the sustainability modes of the morphologies of District 4 of Tehran, and the structure of each morphology is treated systematically on the basis of the evaluation results. In a systemic view of urban fabrics, the density-based (compaction) model can take countless states, since each variable involved in urban morphology generates a state according to the number of its component units; the present result therefore explains the basis of a proposed model built on the principles of urban density. The explanation of the optimal model rests on limited evaluation conditions the data under study are adapted on the basis of mathematical and geometric principles and its effect in urban design is taken at the intermediate scale of urban planning, so that the results apply to a specific range of the middle scale, after the detailed-plan segmentation process.

Finally, a sustainable urban-design model founded on the concept of sustainability can be formed when a compact urban form is applied in a developed manner within the morphology. Achieving such a model first requires compacting the urban form and establishing the necessary technological and policy principles an especially important and novel matter in developing countries and in cities such as Tehran that have expanded in a wide, horizontal manner. After reaching the compaction standard, the model requires calculations and the involvement of other disciplines such as urban planning. The conceptual mechanism of the article can therefore be proposed through the following steps: a compaction pattern based on the principles of vertical urbanisation; a compact urban form composed of regular forms; the explanation of policymaking within the structure of the detailed plan; the determination of the segmentation of forms by urban planners; the determination of the initial density on the basis of the basic calculations of urban-planning science; and the determination of the building density on the basis of the coverage level of each plot, including the number of floors. As directions for future research, other combinations of the evaluated and fixed parameters and variables can be examined in particular the change in building-coverage level and the effects of the orientation of roads and masses, of vegetation and of materials in order to achieve energy efficiency in further modes.

In sum, this study contributes a method and a model. The method couples a Fuzzy-Delphi screening of environmental-compatibility indicators with a controlled ENVI-met comparison of residential morphotypes, synthesised into a transparent composite ranking. The model, derived for the residential fabrics of District 4 of Tehran, shows that a calibrated, density-based compaction adjusting the number of floors within an optimal range for each morphotype at a constant coverage level can improve the surrounding microclimate in the majority of cases and preserve it in the remainder, without reducing energy efficiency in any type. For a horizontally sprawling, cold semi-arid metropolis, this reframes densification not as an environmental cost to be tolerated but as a design opportunity to be steered, and it equips planners with a concrete, morphotype-specific basis for guiding that densification toward sustainability.

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