Research Paper

The Effect of Urban Block Configuration on Buildings' Energy Consumption and Urban Microclimate in a Hot Climate

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Abstract
Buildings have a significant share of global energy consumption and a major role in global warming. Buildings also affect the temperature of their surrounding environment. The present study investigates the effect of Floor Area Ratio (FAR) and urban block configurations on energy consumption, urban microclimate, and outdoor thermal comfort in Tehran with a hot climate, using the simulation method and Ladybug Tools (1.6.0). According to the results, decreasing FAR in an urban block improves urban microclimate while reducing building energy consumption. The results reveal that the effect of FAR on the buildings' energy consumption is more considerable. Decreasing FAR reduces the buildings' energy consumption and outdoor air temperature. Furthermore, the scattered form of urban blocks consumes the highest cooling energy while having the lowest heating load. The lowest cooling and heating loads are found in the linear and scatter organizations. Considering the dominant cost of cooling energy, the case with less FAR would be the best choice from an economic point of view. For three-story urban blocks, the best case is the courtyard form, while for five and nine-story urban blocks, the best option would be the linear form.

Keywords: Urban microclimate, Urban design, Outdoor thermal comfort, Hot climate, FAR.

INTRODUCTION

Building energy usage accounts for about 40% of total energy consumption (UNEP, 2019). However, local climate can affect building energy loads by up to 80% (Waly et al., 2023). Thermal interaction of the buildings with urban microclimate is of utmost importance, although the effects of urban design on urban microclimate, energy consumption, and outdoor thermal comfort were usually investigated separately. Although Buildings' energy performance has been vastly evaluated by simulation and the accuracy of simulations has been studied in huge pieces of research, the simulation results of buildings' energy performance differ when not considered isolated (Cetin et al., 2019; Pereira et al., 2014; Zhou et al., 2008; Gupta, 1987).

To evaluate the effect of urban density on thermal comfort and buildings' energy consumption, various concepts have been defined in previous studies such as Residential Solar Block (RSB), which is a block or group of buildings with rooftop solar panels, that generate electricity for the entire block or neighborhood, and Floor Area Ratio (FAR), which is the ratio of gross area to the area of the built land. Okeil (2010) has compared the energy consumption of three types of urban forms linear, block, and RSB. The author found that RSB was the best-performing form at 48° latitude. On the other hand, Kämpf et al. (2010) have performed multi-objective evolutionary optimization of building-form parameters to find the optimum form for utilizing solar irradiation. Results showed that terrace court formation—a perimeter block arrangement of terrace housing with internal courtyards—was optimal in all trade-off cases.

In previous studies, the most sustainable urban form is suggested to be the compact city (Tsirigoti & Bikas, 2017). Several research studied the density and FAR. In the study by Zhang et al., different cases were evaluated, considering the benefits of sunlight. The result concluded that FAR has a dominant role in benefiting sunlight (Zhang et al., 2019) Another research investigated the demand for heating energy in Paris, Istanbul, Berlin, and London at a scale of 500m*500m. Compact and tall buildings were found to have the greatest heat-energy efficiency (Rode et al., 2014). Leng et al. have concluded that FAR is the most critical factor in saving heating energy (Leng et al., 2020). Hui investigated the low-energy buildings in dense cities. The case study was Hong Kong and some considerations have been presented. The results showed that cities' densification could affect total energy demand (Hui, 2001). In another investigation, Chen et al. empirically estimated the relationships between urban land use patterns and energy consumption for five cities. The results showed the urban size and irregularity of urban land use patterns positively correlate with energy consumption (Chen et al., 2011). Considering the impact of Floor Area Ratio (FAR) on energy consumption, four models of FAR (at 1, 2.5, 3, and 4) were analyzed in a Chinese city, showing that FAR 1 is not suitable for such context, while FAR 3 and 4 are considered to be high for energy-use reductions. However, the optimum building height can be gauged in terms of energy consumption and solar energy production (Dawodu & Cheshmehzangi, 2017). The design lifetime of buildings and floor area per capita are the most important indicators of optimal urban density. Depending on population and building lifetime, the optimal building height was determined in the range of 7-27 stories for the case study (Resch et al., 2016).

Some other studies focused on the effect of the urban form on outdoor conditions. For instance, a study investigated the UHI phenomenon and outdoor thermal comfort on a micro-scale of the different areas in a tropical planned city. They concluded that residential areas should incorporate both high-rise and low-rise buildings. They also concluded that the high-rise residential buildings and streets are 4 °C lower than low-rise buildings and 1°C lower than nearby suburban areas (Qaid et al., 2016). Perini and Magliocco have investigated vegetation, urban density, and building height on outdoor thermal comfort for summer days. They concluded that higher density causes higher urban temperatures, while taller buildings cause lower temperatures and improved thermal comfort on summer days. They mentioned the shading effect of tall buildings as the reason for this result. Regarding the results, vegetation was more effective with higher temperatures and lower relative humidity values in increasing thermal comfort and decreasing the cooling load demand (Perini & Magliocco, 2014). In urban planning, one of the main factors is the desired density of development, which is affected by many factors, such as land availability, economic goals, and environmental and social impacts of the development. When the desired urban density is determined, planners compare different buildings' organizations and FARs inside the urban block. According to previous studies, urban form and FAR affect both the energy consumption of buildings and the surrounding environment. These effects are usually investigated separately, and there is a lack of research investigating the combined effects of urban block configuration and FAR on these two parameters. Therefore, this study aims to evaluate the effect of urban block configuration and density (FAR) on the buildings' energy consumption and the surrounding environment, simultaneously. Sosa et al. analyzed and compared the microclimates of 10 urban canyons in Mendoza-Argentina during the summertime. Based on the results the minimum air temperature is related to the combined effects of the neighborhood grid and the UC configuration and the air temperatures differ up to 10.2 °C during the afternoon, 1.7 °C at night, and buildings consume up to 65% more electricity (Sosa et al., 2017). They also analyzed the thermal behavior and energy consumption of different urban scenarios for low-density social housing neighborhoods considering different neighborhood layouts with various street widths, layout grids, and street orientations. They concluded that a suitable layout orientation, tree selection, and an improvement in the albedo of building materials led to a 21% reduction in building energy consumption (Sosa et al., 2018).

In terms of methodology, the Urban Energy Index for Buildings (UEIB) has been proposed to evaluate urban form's effect on buildings' energy demand (Rodríguez-Álvarez, 2016). Pasandi et al. (2024) have reviewed the tools and applications used for analyzing the interaction between building operation and energy, and urban microclimate. They revealed that coupling strategies are among the most popular methods to measure the building-microclimate interaction. There has been less attention to data-driven techniques as these models need big data to accurately estimate the interaction. Analyzing the relationship between density-related morphological variables, microclimate conditions, and outdoor thermal comfort, the maximum achievable density for specific neighborhoods in Singapore has been proposed (Banerjee et al., 2022).

According to previous studies, urban form and FAR affect both the energy consumption of buildings and the surrounding environment. These effects are usually investigated separately, and there is a lack of research investigating the combined effects of urban block configuration and FAR on these two parameters. Additionally, hot climate contexts lack research covering these topics, and improving outdoor thermal comfort is not guaranteed to improve energy efficiency (Waly et al., 2023). Therefore, this study aims to simultaneously evaluate the effect of urban block configuration and density (FAR) on the buildings' energy consumption and the surrounding environment.

METHODOLOGY

This study is conducted in three steps: 1) defining scenarios and case studies, 2) modeling and simulation, and 3) result analysis. To evaluate the effect of urban block configuration, ten scenarios are defined to organize the constant number of units in different forms and heights. As shown in Figure 1, a 200*320 m urban block which includes 96 units is considered. Three forms of urban block configuration, including courtyard, scattered, and linear have been studied with various numbers of floors. These three forms are the most common forms of the urban blocks that are defined based on previous studies (Shi et al., 2021; Natanian et al., 2019; Merlier et al., 2018).

A special case where a single building incorporates the maximum number of units in a block is also considered. Parameters, including building orientation, ceiling height, window wall ratio (WWR), and materials, are considered the same in all the cases studied.

Urban Design Cases

For each of the ten cases, the dimensions of all units are 20*20 meters with a 3.2-meter ceiling height, and the WWR is 40%. Each block concludes 96 units, differing in the organization of blocks (the form of blocks) and FAR. According to previous studies, A, B, and C are three conventional types of buildings in Iran (Einifar & Ghazzizadeh, 2011) and (Mousavinia et al., 2019). For cases 1 to 3 the organization of buildings differs while FAR is constant, i.e., the number of floors is the same in each group of cases. Therefore, A1, A2, and A3 are the low-rise cases with three floors and different configurations. Cases B1, B2, and B3 have 5 floors as mid-rise buildings, and C1, C2, and C3 can be considered high-rise buildings. Case D the tallest case study with 17 floors is considered to represent the form of a skyscraper. As mentioned before, FAR is the Floor Area Ratio, which halves from cases A to B, B to C, and C to D, so the FAR of D cases is 1/8 of A cases. Notably, the ground floors in all buildings are not occupied, which means that a three-story building has two occupied floors.

A1: Scattered, 3 floors   **A2:** Courtyard, 3 floors   **A3:** Linear, 3 floors

B1: Scattered, 5 floors   **B2:** Courtyard, 5 floors   **B3:** Linear, 5 floors

C1: Scattered, 9 floors   **C2:** Courtyard, 9 floors   **C3:** Linear, 9 floors

D: Scattered, 17 floors
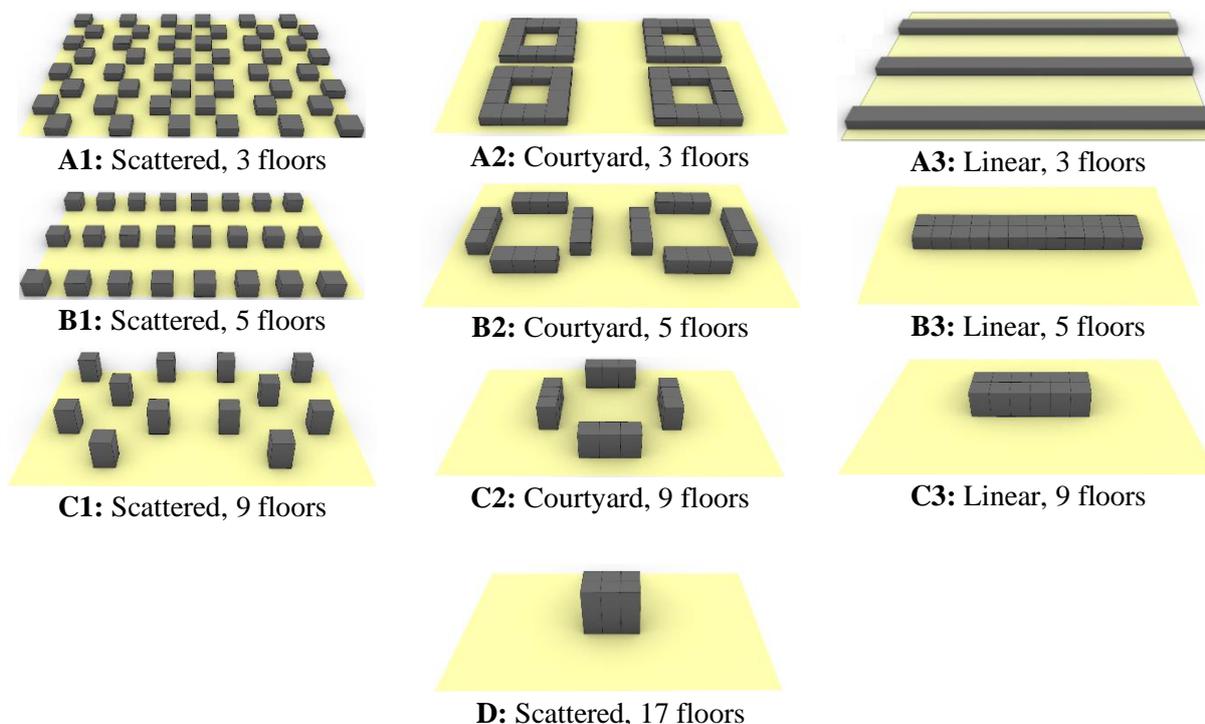
Fig 1. Studied Cases

Location and Climate

Due to the vast developed areas and various geographic characteristics, Tehran has different climate categories of BSh (Mehrabad International Airport), BSk, and Csa (in the northern regions) according to the Koppen climate classification. Overall, Tehran has hot-dry summers and relatively cold winters. Figure 2 illustrates the average daily dry bulb temperature in a typical year. The dry bulb temperature on the hottest day of the year exceeds 35 centigrade, while this amount is below zero for the coldest day. The prevailing wind is from the west and the average wind velocity is 2.72 m/s. The epw file for Mehrabad International Airport is used for the simulations considering 2007-2021.

Simulation Tools

In this study, Ladybug Tools (1.6.0) has been used to calculate urban weather files on a large scale. Then, the cooling and heating load of buildings have been evaluated on a smaller scale by utilizing EnergyPlus. EnergyPlus is a well-known tool for simulating energy consumption and has been validated in many pieces of research (Ahmad et al., 2020; Ancrossed D Signelković et al., 2016; Du et al., 2011; Mardaljevic, 1995; Queiroz et al., 2020; Tabares-Velasco et al., 2012). Based on EnergyPlus, URBANopt is a simulation platform to perform environmental performance analysis within a geographically cohesive area smaller than a city. This tool combines multiple modeling tools, to achieve a holistic energy analysis of our district (El Kontar, Et al.).

Parameters and Indexes

Table 1 shows the materials applied to buildings for simulations. These materials are the common materials for buildings in Iran. The land properties are presented in Table 2. Since the effect of vegetation coverage is an intervening variable for urban weather, it has been neglected to let us emphasize the role of buildings in our study.

The UTCI index was used to evaluate outdoor thermal comfort conditions with the ranges defined in Table 3. As shown, the range of +9 to +26 has a neutral condition with no thermal stress, however, the values between 0 to +32 can be considered acceptable thermal conditions with moderate or no thermal stress.
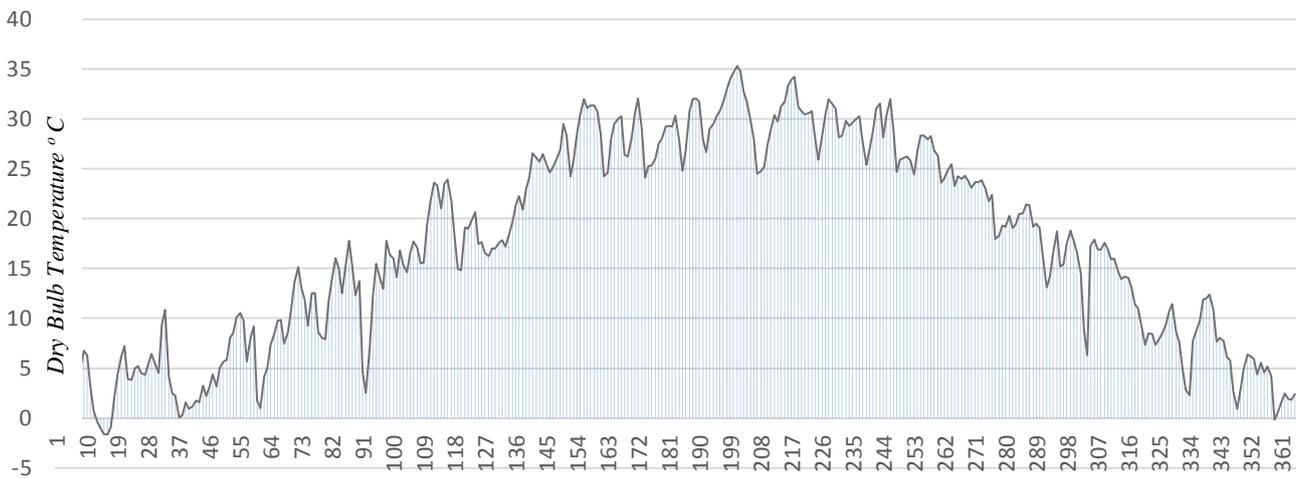
Fig 2. Daily Average of Dry Bulb Temperature in Tehran (epw file for Tehra Mehrabad airport)

Table 1. Thermal Properties of the Buildings (Office of National Regulations and Building Control, 2020)

Construction	Materials	R-value
Exterior Wall	Brick Low weight Concrete Insulation Wall Air Gap Gypsum Board	2.196
Exterior Roof	Roof Membrane Insulation Low weight Concrete Ceiling Air Gap Acoustic Tile	2.431
Window	Low-E Glass Window Air Gap Clear Glass	0.423
Ground Floor	Ground Slab 50mm Insulation High-weight Concrete	1.769

Table 2. Landscape Properties

Property	value
Land albedo	0.1
Land thermal conductivity	1 W/m-k
Land volumetric heat capacity	1.6e6 J/m2-k
Land thickness	0.5 meter
Vegetation coverage	0.0%

RESULT ANALYSIS

To investigate the effect of different urban forms on the surrounding environment thermal comfort is evaluated using the Universal Thermal Climate Index (UTCI) index. The energy consumption for heating and cooling of the whole city block and per area unit is evaluated.

Outdoor Thermal Comfort

Figure 3 shows the annual average dry bulb temperature for each case of urban block. As can be seen, the air temperatures inside urban districts are higher than in suburban areas, noting that the number of units is considered constant for all cases. By FAR reduction, the decrease in dry bulb temperature is more observable in an urban environment with low-rise buildings. Additionally, since there are no appreciable variations in the annual averages of dry bulb temperatures, it can also be deduced that the block's form does not significantly affect the average annual dry bulb temperatures.

Table 4 presents the daily average dry bulb temperatures for the hottest and coldest days of the month. Since these are the extreme values used for calculating building thermal loads, their differences in the studied cases would be important considering energy consumption. Hence, the results from this table can be used to compare the peak cooling loads that change the pressure on the power grid supply. Based on the table, the temperature variation follows a pattern similar to the average annual dry bulb temperature (Figure 4). The highest differences occur between A and D cases in all months. The variation of maximum dry bulb temperatures reaches $0.13C^0$ in January, while in summer, it equals $0.1C^0$ in August. Comparing the minimum dry bulb temperatures, the highest difference of $0.15C^0$ is in January, March, and December. Overall, it can be concluded that the differences in peak thermal loads are not significant.

Table 3. UTCI thermal sensation and ranges (Zare et al., 2018)

UTCI (°C) range	above +46	+38 to +46	+32 to +38	+26 to +32	+9 to +26	+9 to 0	0 to −13	−13 to −27	−27 to −40	below −40
Stress Category	extreme heat stress	very strong heat stress	strong heat stress	moderate heat stress	no thermal stress	slight cold stress	moderate cold stress	strong cold stress	very strong cold stress	extreme cold stress
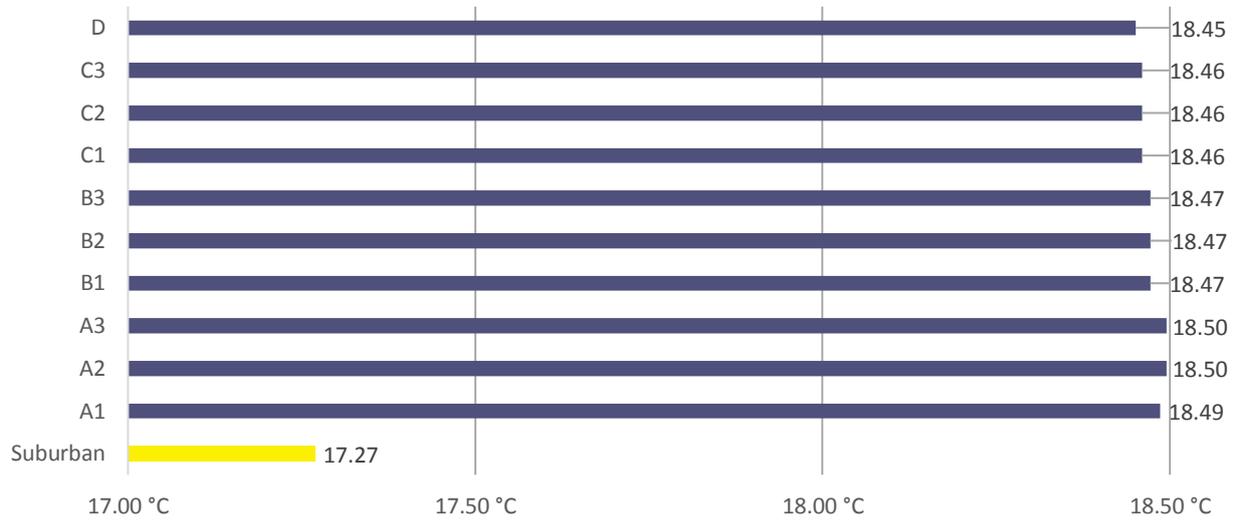
Fig 3. Average Annual Dry Bulb Temperatures in Different Cases

Table 4. Daily Average Dry Bulb Temperatures for the Month's Hottest and Coldest Days

Case		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
A1	Coldest	-0.19	0.85	1.54	2.79	16.89	24.29	24.97	26.09	24.36	7.12	2.92	0.63
	Hottest	8.72	11.18	18.71	25.03	30.52	34.47	36.49	36.81	33.76	24.87	19.63	13.77
A2	Coldest	-0.17	0.86	1.55	2.80	16.90	24.29	24.97	26.09	24.36	7.13	2.95	0.65
	Hottest	8.73	11.19	18.72	25.04	30.52	34.48	36.50	36.83	33.78	24.88	19.64	13.79
A3	Coldest	-0.17	0.86	1.55	2.80	16.90	24.29	24.97	26.09	24.36	7.13	2.95	0.65
	Hottest	8.73	11.19	18.72	25.04	30.52	34.48	36.50	36.83	33.78	24.88	19.64	13.79
B1	Coldest	-0.20	0.81	1.51	2.76	16.87	24.28	24.95	26.07	24.35	7.10	2.90	0.60
	Hottest	8.68	11.17	18.70	25.02	30.50	34.46	36.48	36.80	33.76	24.86	19.62	13.74
B2	Coldest	-0.20	0.81	1.51	2.76	16.87	24.28	24.95	26.07	24.35	7.10	2.90	0.60
	Hottest	8.68	11.17	18.70	25.02	30.50	34.46	36.48	36.80	33.76	24.86	19.62	13.74
B3	Coldest	-0.20	0.81	1.51	2.76	16.87	24.28	24.95	26.07	24.35	7.10	2.90	0.60
	Hottest	8.68	11.17	18.70	25.02	30.50	34.46	36.48	36.80	33.76	24.86	19.62	13.74
C1	Coldest	-0.23	0.81	1.49	2.75	16.85	24.28	24.94	26.05	24.34	7.10	2.88	0.58
	Hottest	8.67	11.15	18.69	25.00	30.49	34.45	36.48	36.80	33.74	24.86	19.61	13.74
C2	Coldest	-0.23	0.81	1.49	2.75	16.85	24.28	24.94	26.05	24.34	7.10	2.88	0.58
	Hottest	8.67	11.15	18.69	25.00	30.49	34.45	36.48	36.80	33.74	24.86	19.61	13.74
C3	Coldest	-0.23	0.81	1.49	2.75	16.85	24.28	24.94	26.05	24.34	7.10	2.88	0.58
	Hottest	8.67	11.15	18.69	25.00	30.49	34.45	36.48	36.80	33.74	24.86	19.61	13.74
D	Coldest	-0.32	0.72	1.40	2.73	16.86	24.27	24.93	26.03	24.33	7.05	2.85	0.50
	Hottest	8.60	11.14	18.64	24.96	30.48	34.39	36.44	36.73	33.71	24.83	19.57	13.70

UTCI is defined as the air temperature of the reference condition causing the same model response as actual conditions. This index is based on dry bulb temperature, relative humidity, solar radiation, and wind speed into account (Blazejczyk et al., 2013). Figure 5 illustrates the average UTCI for the coldest and hottest days of the year in each case. It can be seen that the effect of FAR on the UTCI of the coldest day of the year was significant as its value for A2 and C3 differ by $5.4C^0$, and changes in the hottest day's UTCI are less significant as the most difference is $1.6C^0$. The differences can be the result of a higher shading area made by the buildings in the A case. According to Figure 4, case A has the best outdoor thermal comfort condition in both summer and winter. However, none of the cases can provide summer thermal comfort conditions.

Buildings' Energy Consumption

As for energy consumption, it is directly related to the FAR. Results also show that the scattered urban form has the least energy efficiency, compared to the other two forms. FAR has a dominant role in reducing energy and the block organization has a minor effect.

In a previous study, the results showed that compact-tall buildings are more efficient in reducing heating energy consumption (Rode et al., 2014). This is also evident in this study. Table 5 illustrates the cooling and heating loads of the studied cases per square meter of the buildings. Both cooling and heating loads decrease when FAR decreases, with the highest reduction in B and C cases when the floor number changes from five to nine.

Figure 5 shows the total annual energy consumption for cooling and heating of buildings in megawatts (MW). FAR and the amount of used energy are directly related. There is little difference between the three urban forms. It can be stated that using the scattered form (cases A1, B1, C1) slightly increases the energy consumption.

Figures 6 and 7 illustrate the cooling and heating load of cases. Since the cases are located in a hot climate the cooling load is considerably higher than the heating load for all cases. It can be seen that FAR directly relates to both cooling and heating loads since the thermal loads are reduced by decreasing FAR and the least thermal load is for case D. For a constant FAR, using scattered form increases the cooling load and reduces the heating load.
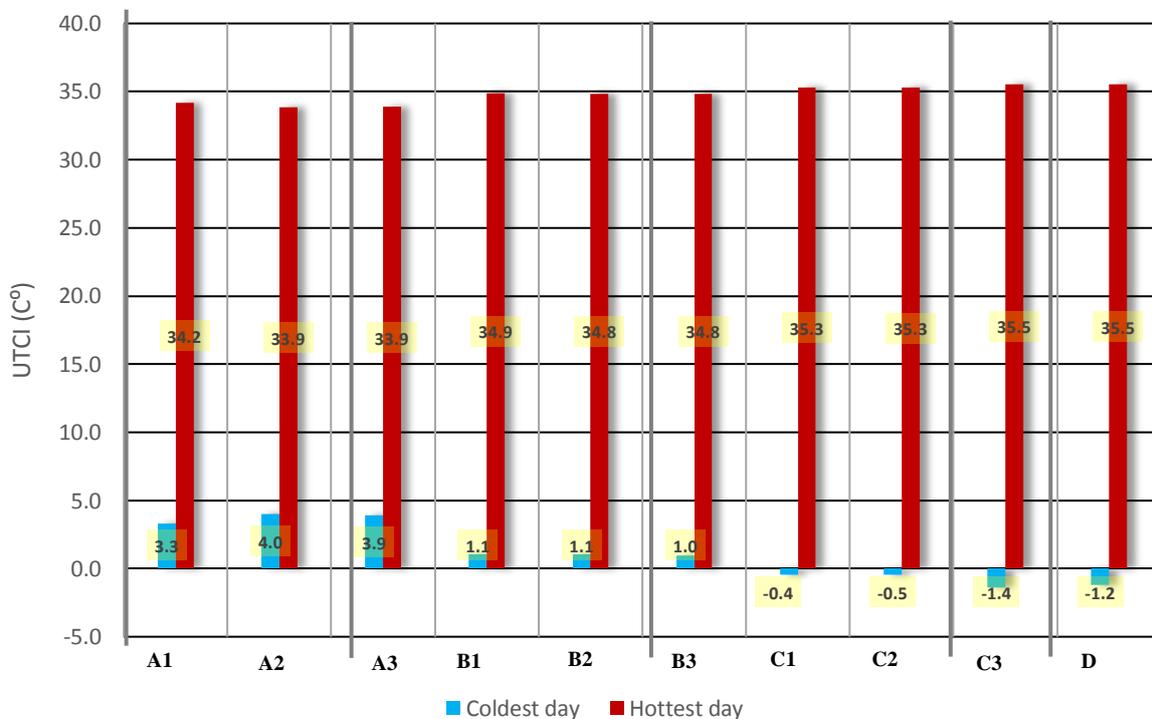
Fig 4. Universal Thermal Climate Index (UTCI) for the Coldest and Hottest Day of the Year

Table 5. Buildings' Thermal Loads (kw/m^2)

	A1	A2	A3	B1	B2	B3	C1	C2	C3	D
Cooling (kW/m^2)	243.97	227.90	231.12	123.31	119.54	111.68	44.05	41.20	38.65	19.26
Heating (kW/m^2)	18.51	22.96	21.66	8.17	10.30	12.76	2.79	3.54	4.28	0.54
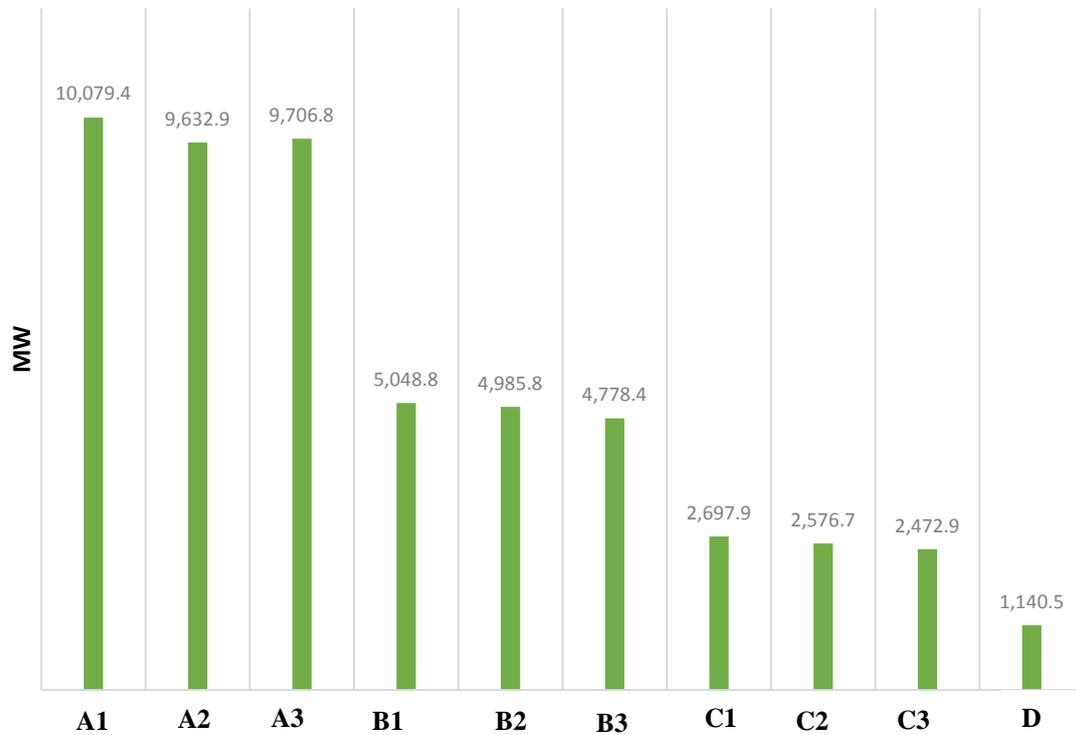
Fig 5. The Sum of Annual Cooling and Heating Loads in MW
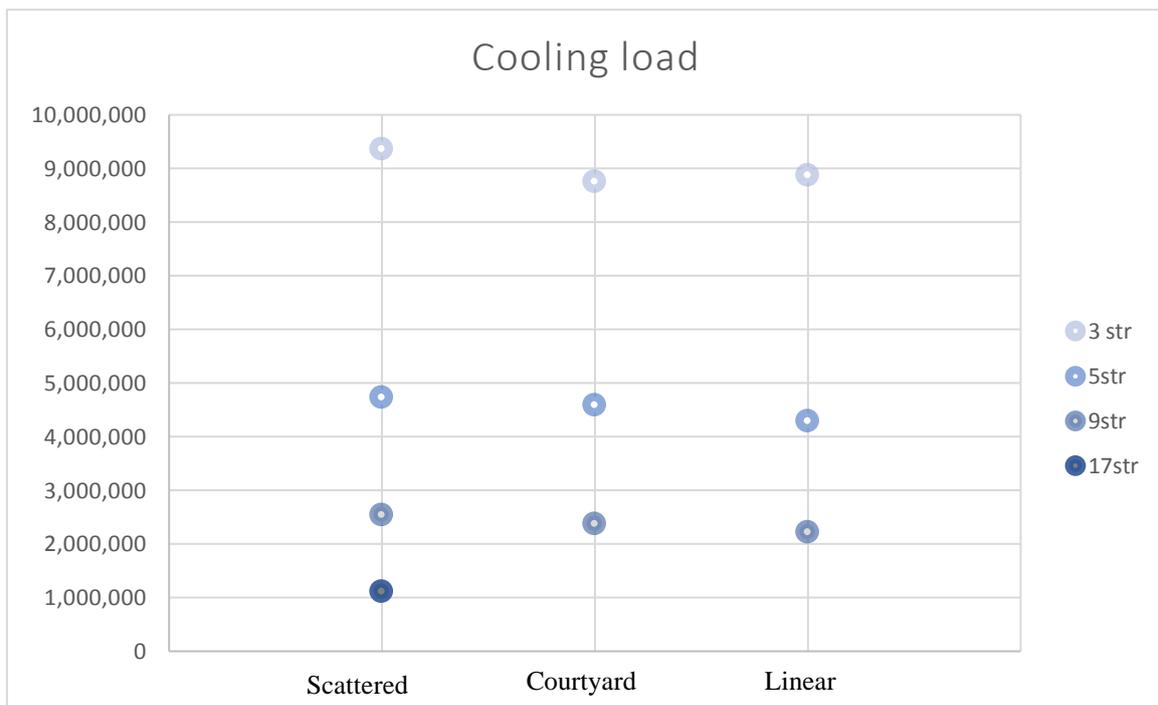
Fig 6. Cooling Loads Of Different Cases in kW
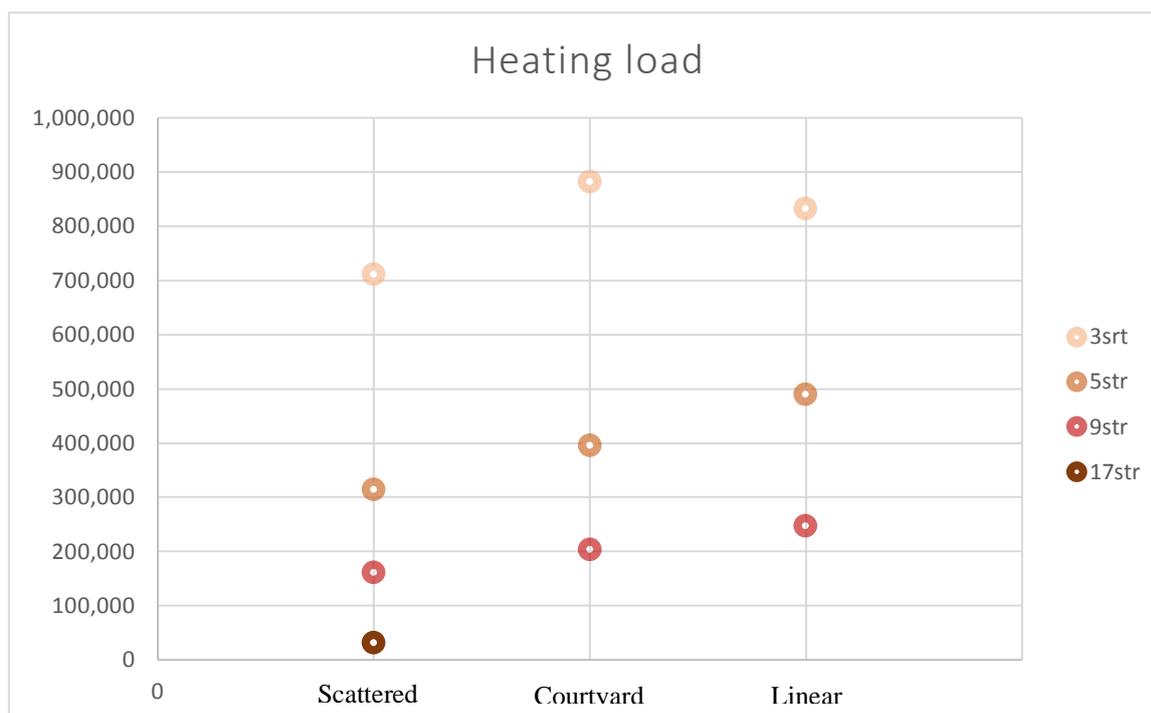
Fig 7. Heating Loads of Different Cases in kW

DISCUSSION

The results of the simulation of urban temperature were compatible with the previous studies, and by increasing FAR, the urban temperature increases. The results of the previous studies showed that tall buildings in urban areas have the benefit of mitigating UHI due to the shading effect of the buildings (Qaid et al., 2016, Perini & Magliocco, 2014). In this study, the urban density was the same in all cases, and increasing the number of floors was coincident with decreasing the FAR. According to the results, FAR significantly affects the coldest day's UTCI value. The results show that FAR affects building energy consumption more than urban block configuration. The scattered form of urban blocks consumes the highest cooling and lowest heating energy. This can be a result of an increased building external surfaces in these cases that increases the surfaces to gain solar radiation. Considering the building layouts, the lowest cooling loads are in linear (B3 and C3) and courtyard

layouts (A2), while the lowest heating loads can be seen in scattered layouts for all cases. The sum of buildings' thermal loads in the A case is twice as high as in the B case, four times higher than in the C case, and nine times higher than in D. Hence, regarding the buildings' energy consumption, the best form would be D, the most compact one.

Figure 8 illustrates the energy cost in the studied cases. The cooling price is doubled in B cases compared to C cases while in case D it is almost half of the C cases. The same happens when comparing B with A cases as the cooling price in the latter is twice as high as that in B cases. Assuming in Iran, each kW of heating costs 0.01$ and this value is 0.05$ for cooling (Globalpetrolprices, n.d), the cooling load has a dominant role in the overall energy cost. It is noteworthy that energy is relatively cheap for households in Iran and the demonstrated values are lower than the real value costs. Therefore, case D would be the best form based on the cooling energy cost.

9

■ Cooling ■ Heating
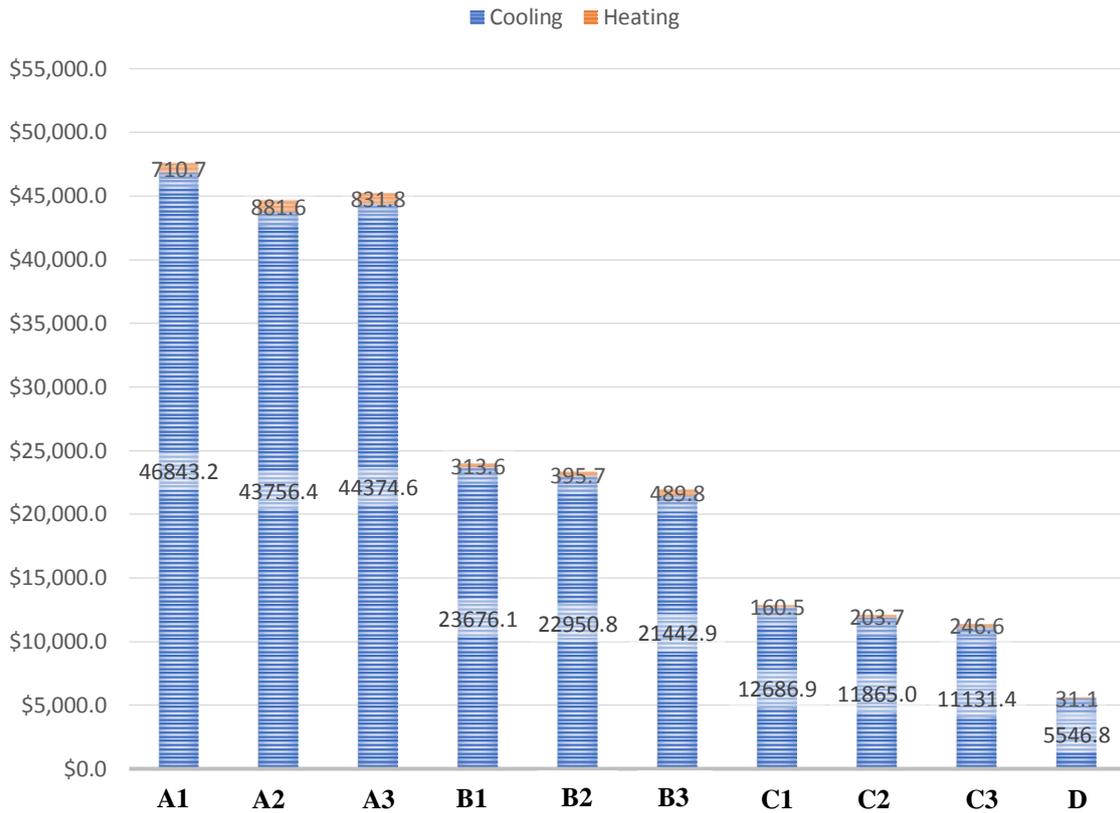
Fig 8. Energy Cost of Studied Cases

Therefore, the results confirm the preference for the compact urban form with the aim to reduce energy consumption. However, this result is not applicable regarding the outdoor thermal comfort and urban microclimate.

LIMITATIONS OF THE STUDY

In this study, some of the effective parameters of the microclimate were ignored in the simulation process. One of these factors is greenery, which is hard to simulate accurately. As mentioned, no greenery was considered in the simulated cases, which is usually not true in real cases. As the results indicate that the less the FAR value, the lower the temperature we have in the urban microclimate, considering greenery will intensify the conclusion of the results. The land topography is another limitation of the study since flat land is considered in all cases.

CONCLUSIONS

This study evaluated the energy consumption, outdoor thermal comfort, and urban microclimate for various urban block configurations differing in form and FAR in Tehran with hot and dry climates. The results reveal that both urban block configuration and density (FAR)

affect the buildings' energy consumption and the surrounding environment. However, the effect of FAR on the buildings' energy consumption is more considerable. The sum of buildings' thermal loads in A cases is twice as high as in B cases, four times higher than in C cases, and nine times higher than in D.

According to the results, decreasing FAR reduces the buildings' energy consumption and outdoor air temperature. Furthermore, the scattered form of urban blocks consumes the highest cooling energy while having the lowest heating load.

The difference between forms with various heights is more considerable than the difference between various layouts and organization types. Comparing the cooling load values, in all cases, it increases when changing from linear to courtyard and scatter forms. Considering the heating load values, the pattern of changes is the same in the cases with five and nine stories, increasing from scatter to courtyard and linear. The lowest cooling loads are in linear and courtyard layouts, while the lowest heating loads can be seen in scattered layouts for all cases. In all cases, the cost of cooling energy is dominant compared to the heating energy cost due to the hot and dry climate of Tehran. Additionally, the cooling price is doubled in B cases (five-story blocks) compared to C cases (nine-story blocks) while in case D (seventeen-story block) it is

almost half of the C cases (nine-story blocks). The same happens when comparing B (five-story blocks) with A cases (three-story blocks) as the cooling price in the latter is twice as high as that in five-story cases. Therefore, if the desired form should be chosen based on the cooling energy cost, case D (seventeen-story block) with less FAR would be the best choice. Furthermore, from an economic point of view, the best case for three-story urban blocks is the courtyard form, while for five and nine-story urban blocks, the best option would be the linear form. Overall, using the scatted layouts is not recommended due to the high area of external surfaces leading to high heat transfer.

Figure 9 illustrates the summary of the results. The results can be used in newly designed neighborhoods with similar climates.

AUTHOR CONTRIBUTIONS

All authors contributed substantially to all aspects of this study.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.
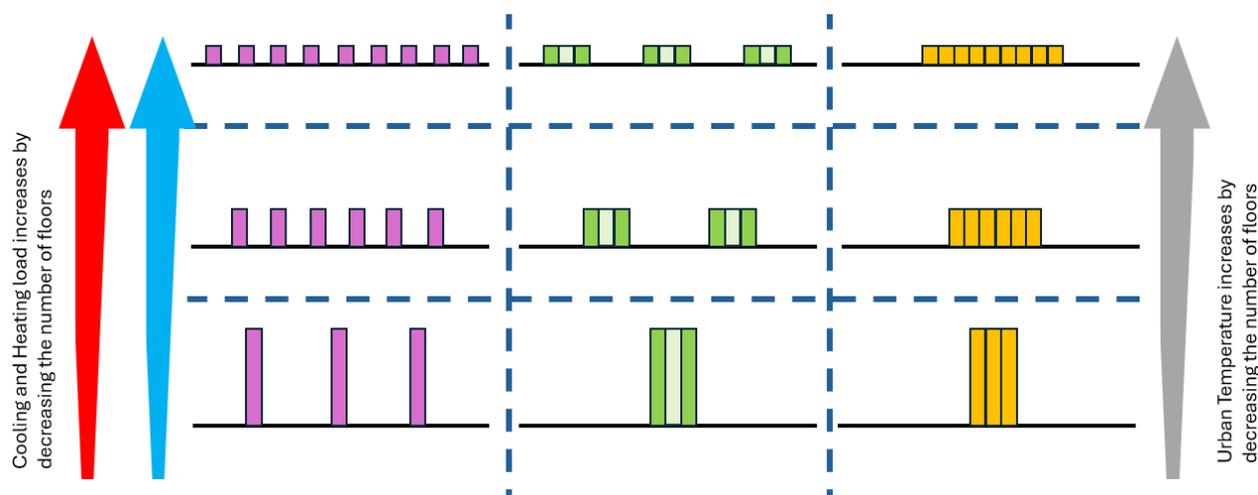
Fig 9. Summary of the Results

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