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Climatic clustering analysis for novel atlas mapping and bioclimatic design recommendations

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Abstract
Defining and determining climatic zones accurately is crucial to inform the decision making of building designers and planners during early design phases of urban development. Characterizing the climatic zones allows estimation of energy requirements in buildings and develop climate adapted energy polices. Climatic zones can be defined by using the statistical cluster analysis. Data from weather stations can be used after standardization with zero mean and unit variance, to confirm that all variables are weighted equally in the cluster analysis. In this paper, a novel atlas for 19 climatic zones is presented that represent a variety of bioclimatic design strategies and recommendations, for passive design, based on a clustering analysis in Iran. The clustering analysis is based on the statistical analysis of daily temperature and relative humidity from 1995 to 2014. The results visualize 19 different climate zones for Iran and indicate the dominance of passive design strategies. As a result, Iran was divided into eight climatic clusters. The results showed that each of the studied clusters require specific strategies in providing indoor comfort. The outputs of this study shed the light on the importance of up-to-date climate characterization and the effectiveness of climate mapping and recommendations to inform decision makers.

Keywords
Homogeneous climatic zones, Bioclimatic design strategies, Bioclimatology diversity, Climatic chart, Heating and cooling, Iran

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Introduction

Climate classification and clustering is motivated by setting climate types and zones to understand and manage the relationship with natural and bioclimatic conditions. For architectural and building design, the most famous examples are the Köppen[1] and ASHRAE[2] classifications. Climate classification is essential for sustainability and eco-design in today's built environment. Assessing the role of different climate zones is necessary to approach energy efficiency in the built environment and deploy bioclimatic design strategies intelligently into the sustainable urban plans, which includes all efforts to address climate change.[3–5] The bioclimatic architecture of buildings are increasing in popularity as an intelligent way to benefit from climate and environment in order to achieve maximum indoor comfort without active systems.[6,7] Investigating the diversification of climatic zones' clustering is the key to bioclimatology and bioclimatic design.

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Without this classification and clustering, bioclimatic design, which is open to the climate advantages and closed to the climate disadvantages, becomes very challenging. Together with an increasing use of energy from fossil sources, measures taken to reduce energy consumption in Iran would allow the country to comply with Paris Agreement carbon emissions reduction target.[8] The positive impact of thermal mass, thermal insulation, passive heating, natural ventilation, orientation and positioning, passive solar systems and solar protection, and natural lighting should be taken into account, where relevant.[9] However, there is a serious need for simple and accessible climate characterization analysis and informative maps. Thus, the climatic zones established for Iran should be further studied and a wider range should be considered.

As shown in Figure 1, understanding the relationship between habitat, climate and human conditions is necessary to achieve thermal comfort and climate responsive design.[10,11] This understanding requires an accurate characterization and representation of the climate for a given site and building design. In this section, the key climatic diagrams and types of visualization were reviewed, which form a basis for bioclimatic design. Climatic diagrams facilitate our understanding of climatology and application of potential passive design strategies and building construction systems, material types and architectural solutions. More importantly, climatic diagrams inform designers about effective architectural design recommendations, which guide architects and engineers, to apply passive design strategies in future buildings. The energy efficiency of buildings can be improved by implementing passive energy efficiency designs. Appropriate design strategies must be chosen according to local climatic conditions.[12]

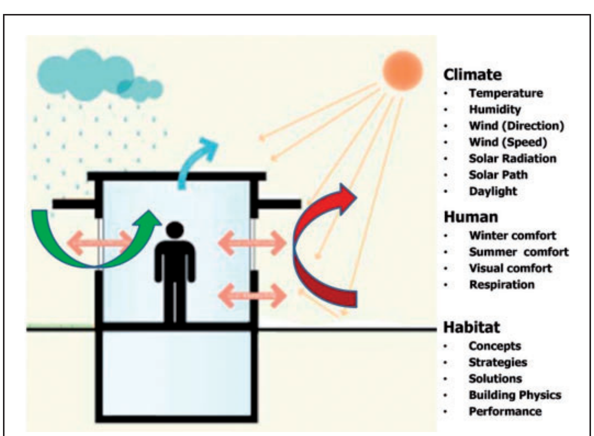


Figure 1. Bioclimatic design is open to the climate advantages and closed to the climate disadvantages.

Bioclimatology specifically refers to the study of human health and climate and balneology to the biological effects of thermo-mineral waters.[13] In urban settlements, bioclimatology is essential to understand the relationship with natural and bioclimatic conditions necessary to achieve optimal comfort conditions. Bioclimatic concepts and design strategies in buildings involve many disciplines, including human physiology, climatology and building physics.[14] The ultimate aim of the bioclimatic approach is to attain the maximum comfort hours passively for building occupants.[15] Comfort concepts include a set of conditions, which are thermally supportable for 80% of people, and in which human feel neither cold nor hot. In fact, thermal comfort is where there is a broad satisfaction with the thermal environment.[16] Thermal comfort is '*that condition of mind that expresses satisfaction with the thermal environment*'.[17,18] As an appropriate strategy to interpret the climatic conditions of a region, a comfort zone has always been determined based on several climatic parameters. Generally, the comfort zone has been displayed on graphs for determining the existence of comfort conditions for occupants of buildings by plotting daily or monthly climatic data.

The first bioclimatic chart was drawn by Victor Olgyay in 1963.[19] In his bioclimatic chart, the comfort zone is specified by dry bulb temperature and relative humidity, but subsequently it is shown by additional lines, how this comfort zone area can be stretched by the presence of air movement in warm conditions and how it can be stretched by radiation in cool conditions.[20] The Olgyay[16] bioclimatic chart was based on men with metabolic activity rate of 1 met and clothing insulation of 1 clo in tropical regions.

Later, Givoni[21] presented a building climatic diagram based on the psychrometric chart in 1969. Givoni's bioclimatic chart was divided into different zones for which it is necessary to use strategies to achieve human comfort within a building.[22] The Building Bio-Climatic Chart (BBCC)[23] can specify building design guidelines to maximize indoor comfort conditions when the building's interior is not mechanically conditioned. In 1979, Milne and Givoni[23] amended and expanded the BBCC so that they can determine more zones to make design suggestions for architects. The Milne-Givoni BBCC[23] has been widely used in practice and research.[24–28] However, one of the problems of working with BBCC is the complexity of its axis which has made it difficult to find climatic data on it.[29] DeKay and Brown[30] redrew Givoni's bioclimatic chart[31] with the idea of the structure of Olgyay's chart[32] and indeed they implemented Milne-Givoni's different and diverse strategy zones[23] on the

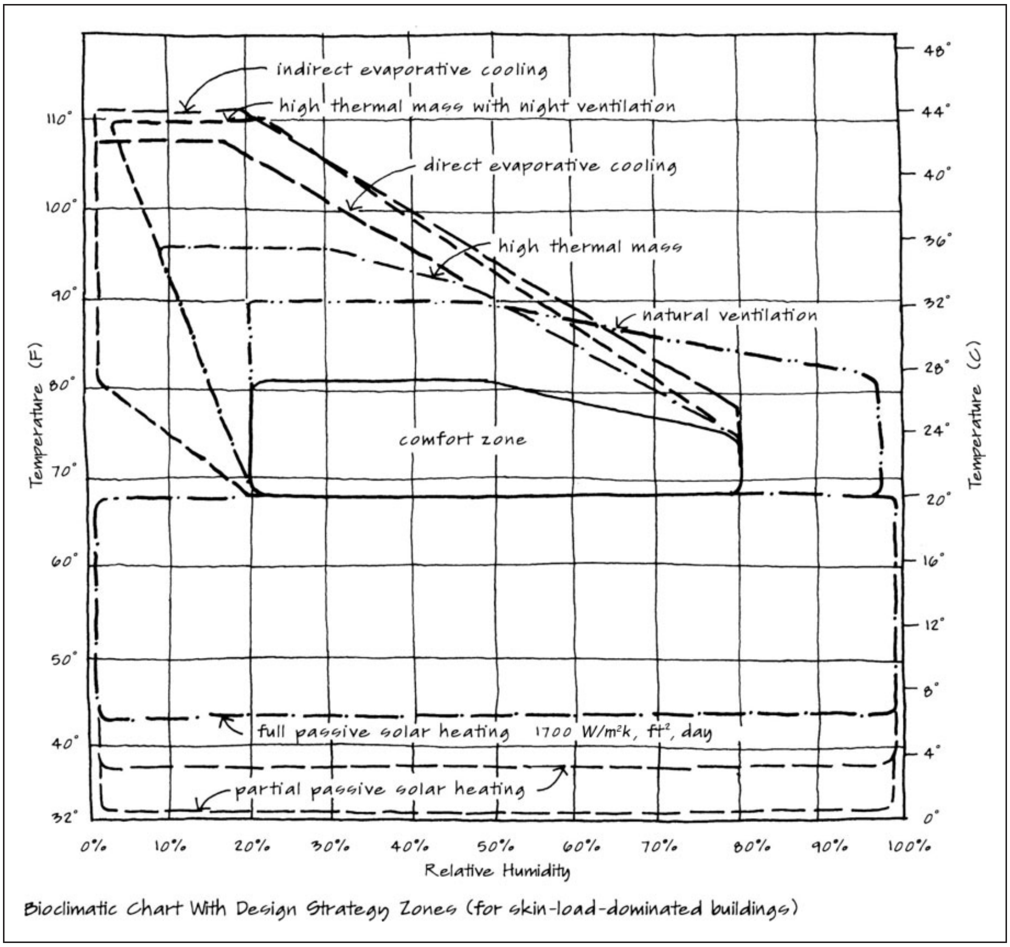


Figure 2. Milne-Givoni[23] bioclimatic chart redrawn by DeKay and Brown.[30]

Olgyay's rectangular chart[32] (Figure 2). In this chart, five cooling strategies and two heating strategies were set.

In the present study, the proposed bioclimatic chart of DeKay and Brown[30] was redrawn more precisely. According to Milne-Givoni[23,31] and the new Givoni's chart,[34] six strategies were added:

- Two heating strategies of 'Internal Gains' and 'Conventional Heating'.
- Three cooling strategies of 'Direct/Indirect Evaporative Cooling', 'Air Conditioning' and 'Air Conditioning with Conventional Dehumidification'.
- 'Humidification' for dry climatic condition was added to this chart.

According to the last research of Givoni about new boundaries of the chart,[34] two new charts were drawn for industrial and non-industrial countries (Figure 3). The authors selected this bioclimatic diagram for its simple use and interpretation by architects.[35] At the same time, the DeKay and Brown bioclimatic chart[30] incorporates 12 different climate zones that correspond to different design strategies. The variety of different climate zones makes it easier to compare weather conditions with a focus on temperature and humidity data.

The general purpose of the land use planning is to organize space for the benefit of the land in the framework of national interests. However, one of crucial roles of the land use planning is to benefit from the bioclimatic potentials in relation to economic activities in different regions of a country. The role of land use planning is to support human communities and provide guidelines and infrastructures for the built environment, including supply and demand for heating and cooling energy to urban areas and residential buildings. Therefore, the main aim of this research is to inform land use planners in Iran and inform designers about buildings bioclimatic design strategies. The research findings shed the light on Iran's bioclimatic abilities and limitations and provide novel atlas maps.

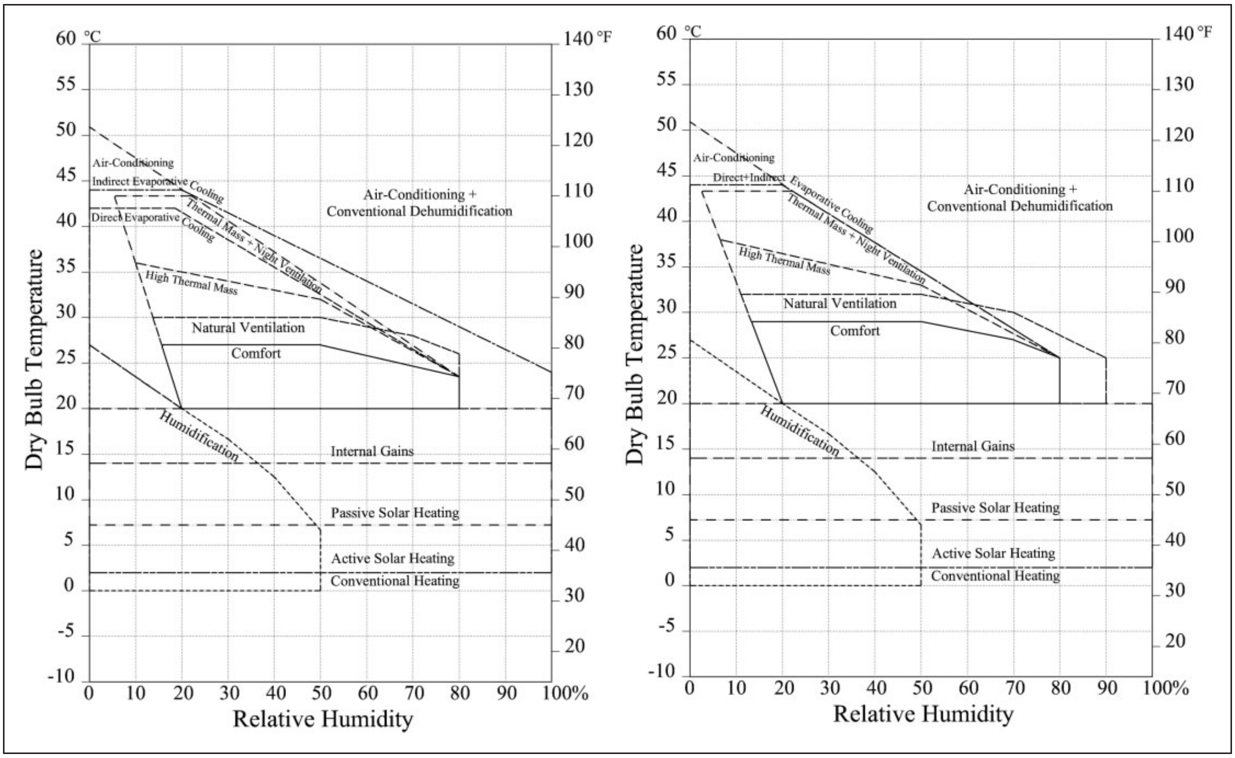


Figure 3. Completed exactly drawn building bioclimatic chart of Givoni[34] by authors; left: industrial countries, right: hot non-industrial countries.[36]

Methodology

The research methodology was based on clustering analysis of 48 weather stations in Iran. The clustering analysis implies the Euclidean distance and Ward's D analysis method.[37] The weather data include daily temperatures and relative humidity from 1995 to 2014. The methodology includes the creation of 19 novel atlas maps, visualizing the spatial distribution of different climatic zones. The different climatic regions in Iran were classified into eight main groups. The eight classified groups were associated with bioclimatic design recommendations based on DeKay and Brown[30] building bioclimatic chart. The clustering provides a comparison of frequency of different climate zones for representative sample cities of each climatic region. The following sections elaborate further on the research methodology.

Comfort boundaries and meteorological data

The boundaries of comfort zone and the different design strategies for insuring indoor comfort, demarcated on the BBCC were based on the expected indoor temperatures in buildings without mechanical air-conditioning and with still air (0.15 m/s in winter and 0.25 m/s in summer), properly designed for the location where they were built.[23] The applicability of these boundaries would vary with the type of building and the local climate. The boundaries of the climatic condition under which a given cooling system can be applied are not the same in different countries. People living in hot regions, especially in non-industrial countries, usually accept higher temperatures and/or humidity levels because of lower expectations and natural acclimatization.[38] For people living in hot industrial countries, Givoni[34,38] suggests elevation of 2°C in the upper temperature limits of BBCC, and 2 g/kg in the upper vapour content, taking into account the acclimatization resulting from living in unconditioned buildings in hot climate. Finally, Givoni[34] concludes that a BBCC should be planned for hot-industrial countries vs a BBCC for developed countries.

Iran is a non-industrial country; therefore, the hot regions were defined to separate them from other ones. Thus, the Köppen climate classification[39] was suggested. Based on Köppen classification,[39] the stations that are in the BWh and BSh groups were suitable for evaluating the non-industrial BBCC. According to Köppen classification of climate, BW is representative of the desert and BS is representative of the steppe lands. The letter ‘h’ shows that the average annual temperature of a region is more than 18°C.[39] Figure 4 shows the geographical location and the climatic zone

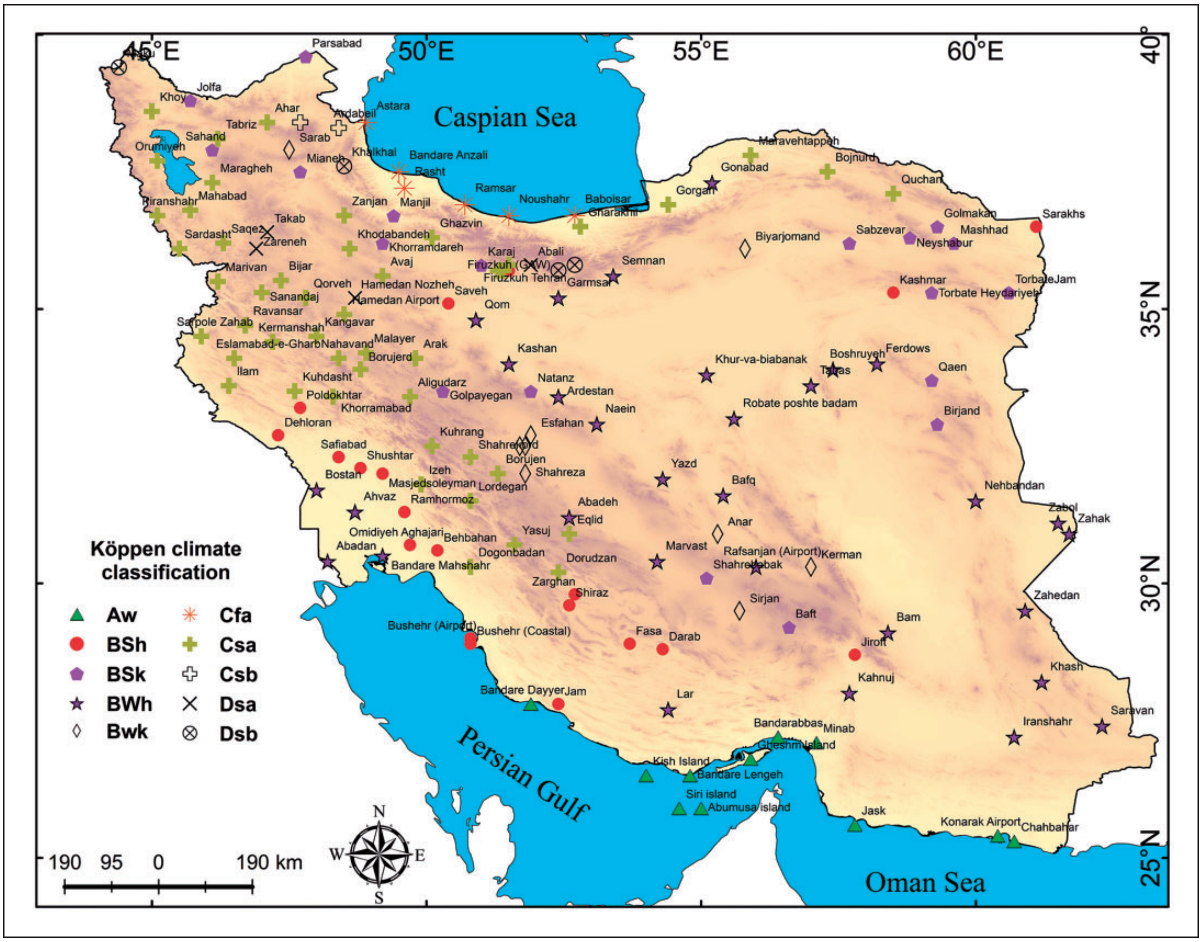


Figure 4. Map of Iran, indicating the geographical location and the climatic zone classification of all meteorological stations whose data was used in the present study.

classification of all meteorological stations used in this research. In order to define the bioclimatic design strategies for passive cooling and heating of Iran's settlements, using the maximum number of stations, the weather data of 20 years were statistically analysed. For this purpose, only 154 stations had the most complete daily statistics of temperature and relative humidity from 1995 to 2014. The only limitation was that 5% of the selected stations had data gaps of 3%. The data gaps were recreated using neighbouring stations based on linear regression. The meteorological data were obtained from Iran's Meteorological Organization.[40]

After surveying the climatic data, 48 stations were determined as hot stations and so their data were modelled by the non-industrial BBCC. Other stations were modelled by the developed BBCC. In this model, the frequency of occurrence of each of these zones was calculated for the selected stations based on the observed statistical period. In the next step, the atlas of each bioclimatic strategy zone was generated for Iran. Finally, Dekay's and Brown chart[26] was digitalized to quickly and easily plot the output data points for each station.

Identification of climatic zones and their spatial distribution

In order to create the bioclimatic atlas and climatic charts, a classification of different design strategies was used. 20 climatic zones were identifiable. However, results showed that the strategy of using only air conditioning to achieve thermal comfort cannot be observed in any of the stations in Iran. Therefore, all analyses were done based on 19 zones.

Z1 was the first studied zone. In this zone, the focus was on the strategy of conventional heating. Z2 represents data points that require conventional heating with humidification. For Z4 and Z5 passive solar heating and internal heat gains would be the most effective. Z6 represents climatic regions that would require mainly humidification. For Z7, Z8 and Z9, active and passive solar heating would be required with internal gains. Z10 would provide optimal thermal comfort conditions. Z11 and Z14 represent evaporative cooling design strategies including direct and indirect evaporative cooling. Z12 represents natural ventilation. In Z13, the use of thermal mass, night ventilation and indirect evaporative cooling would be the most effective strategies. Z15 involves areas which would need mechanical air conditioning systems because of high temperature and high relative humidity. Z16, Z17 and Z18 correspond to regions with hot summers where thermal mass, natural ventilation and evaporative cooling would be required. Z19 is related to evaporative cooling strategies for areas with hot and dry climates. Z20 represent regions that would require air conditioning and conventional dehumidification strategies.

Cluster analysis

Cluster analysis is an effective statistical tool to determine homogeneous climate zones on the basis of similarities in meteorological parameters and the resultant thermal indices. Unlike other commonly used statistical methods, cluster analysis is not based on theoretical a priori distributions but rather explores similarity and differences in data values. Therefore, the selection of appropriate clustering methods requires careful consideration.[41,42]

In climatological research, hierarchical clustering methods are commonly used as they are well suited for exploratory analyses, determining climatic regions on the basis of mean similarity in data assemblages.[43,44] Hierarchical clustering outputs are graphically represented by a dendrogram.[45] The base of the dendrogram, or root, represents a single cluster containing all data points; each branch represents clusters of increasing levels of similarity between smaller groups of data points. The height of the dendrogram and of successive clusters, represents a measure of similarity, calculated through the dissimilarity index.[46] The values from 19 climatic zones were thus clustered through the calculation of similarity using Euclidean distance and grouped using Ward's D method. The values from 19 climatic zones were clustered through the cluster analysis using Euclidean distance. Then the 154 synoptic stations were clustered and grouped using Ward's D method. A matrix of 19×154 was used for the 154 stations based on the frequency of occurrence of each climatic zone.

The silhouette index[47] defined in equation (1) was used as a cut off measure to determine the appropriate number of clusters and also as a measure of assessing the quality of any clustering candidate. Each cluster member has an index value referred to S(i) that allows evaluating the degree of similarity of that member to the other members of the same cluster as well as to the members of the other clusters. The average of S(i) for a given cluster allows evaluating the homogeneity of that cluster, but when the index is averaged over all the clusters, this provides a measurement of the overall performance of the clustering. The values of the index vary between –1 and +1. The values close to 1 (-1) suggest that the member is in the correct (incorrect) cluster, and the near-zero values indicate that the member is in the marginal boundary between two clusters, and thus, it is hard to properly assign it to one cluster or another.[48]

$$S(i) = \frac{\left(b(i) - a(i)\right)}{\max[a(i),\, b(i)]} \tag{1}$$

In equation (1), $a(i)$ is the average distance from the ith member of a cluster to all other members within the same cluster and $b(i)$ is the minimum average distance from the ith member of a given cluster to all members of another cluster.[48]

Finally, the results of all clustering were compared and showed that the division of the stations in eight clusters has been the most appropriate clustering, which indicated maximum similarity between the stations of each cluster. At the same time, the climatic and bioclimatic conditions of Iran justify the number of clusters. The dendrogram of the eight clusters with their stations are drawn in Figure 5.

Results

Identification of climatic zones and their spatial distribution

All analyses were done based on 19 climatic zones and are listed in Table 1. These are visualized as an atlas in Figure 6. This step was necessary for the analysis of the different bioclimatic strategies and their spatial distribution.

Clustering of Iran and climatic design strategies recommendations

In this study we provided 19 bioclimatic design strategies. Therefore, percentage frequency of each of these nineteen strategies was prepared for different cities in Iran. A separate map was then prepared for each of these strategies. By using clustering techniques, stations that were similar in terms of frequencies of different strategies were clustered in the same cluster. According to Figure 7, the most appropriate number of clusters for this study is eight geographical clusters. In the following section, the general characteristic of each cluster is provided. Also, a representative city for

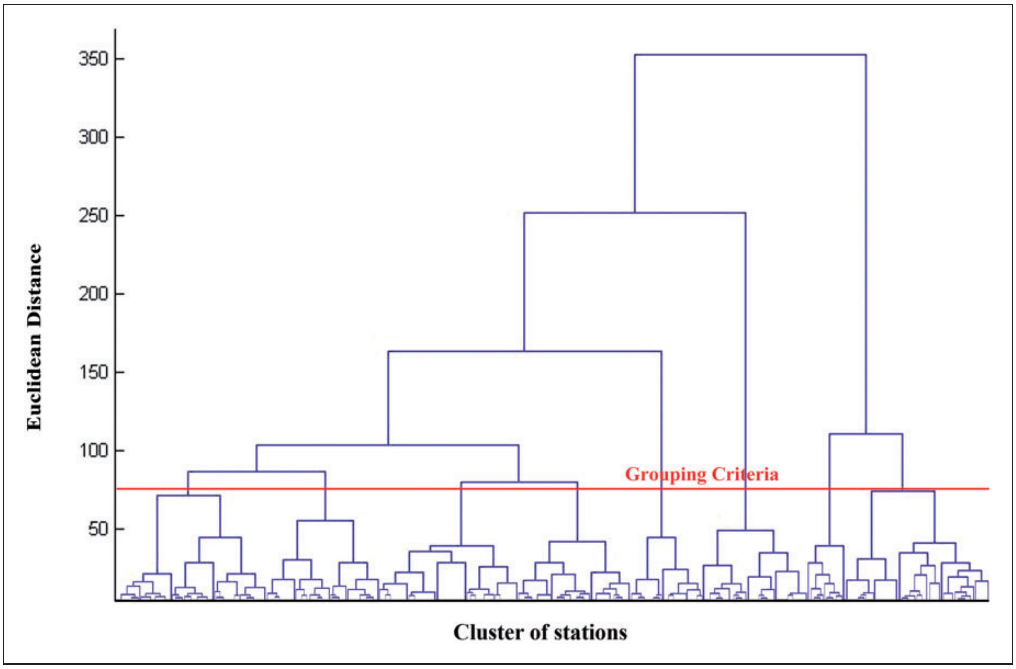


Figure 5. Cluster dendrogram of passive cooling and heating strategies' values of 154 synoptic stations in Iran.

each cluster was selected and analysed in detail. The climatic design strategies and recommendation for each cluster is presented too. A unique name was selected, as mentioned in Table 2, for each cluster, according to its geographical location and climate in Iran.

Mountain climate (cold). Generally, Cluster 1 is known by the specific title as Mountain Climate (cold). For stations located in this cluster, the average of Zones 11–15, 18 and 19 was zero and the average of occurrences for Zones 2 and 6 was very small, even negligible. In total, strategies 11 to 19 are recommended for areas with a weather condition that are warm during a part of the year. Therefore, the removal of these zones for a cluster shows that the temperature in these areas in most months of the year does not exceed the maximum comfort zone. For this cluster, the maximum of strategies needed to provide indoor comfort conditions is related to Z9 strategies with average occurrence of 15.74%, Z1 with 16.10% and Z10 with 22.46% (Table 2). The areas of this cluster in a large part of the year are located in the cold weather conditions. The most important recommended strategies are primarily:

- increasing internal gain in order to keep the heat generated inside the building through proper insulation of external envelope.
- the use of Conventional Heating strategy which is based on the use of mechanical heating systems.
- maximize the passive solar heating for the southern parts of the building.
- enable heat storage inside the fabric with high thermal capacity.
- prepare to host solar thermal and electric collectors.

There are 32.4% of study stations are located in this cluster, so this cluster was introduced as the dominant cluster of the current study. Geographical distribution of these stations in this cluster is related to the mountainous areas of North, North West and North East of the country (Figure 6).

Coastal climate (very humid and warm). Among the features of this cluster, there is no need for heating strategies in zones 1 to 8 and no need for cooling strategies in zones 11 and 19. Also, due to high humidity, direct evaporative cooling strategies are not needed. For stations of this cluster, the strategies of Z16 with overall average of 17.23% and Z14 with 48.65% and Z15 with 80.56% are the most important strategies to achieve indoor comfort conditions (Table 2). Areas of this cluster experience the highest temperature of the warm season together with high relative humidity. So, the most important strategy is to:

- take advantage of Air-Conditioning + Conventional Dehumidification as active systems are effective in hot and humid climates.
- apply strategies which supply daily natural ventilation.

Table 1. Summary of the features of bioclimatic strategy zones of Iran.

Zones	Givoni's building bioclimatic chart strategies	Used chart: Non-industrial (*) Industrial (**) Both of them (***)	Max %	Station with maximum %	Total average in Iran %	% of stations that experienced this category
Z1	Conventional Heating	***	37.40	Firuzkouh-GAW	6.51	83
Z2	Conventional Heating + Humidification	***	2.61	Borujen	0.38	64
Z3	Active Solar Heating + Humidification	***	10.83	Borujen	2.54	77
Z4	Passive Solar Heating + Humidification	***	14.72	Rafsanjan	5.10	83
Z5	Internal Gains + Humidification	***	9.8	Rafsanjan	2.8	90
Z6	Humidification	***	2.2	Zahedan	0.28	45
Z7	Active Solar Heating	***	19.23	Parsabad	8.15	91
Z8	Passive Solar Heating	***	44.83	Noshahr	13.59	97
Z9	Internal Gains	***	31.20	Qeshm	15.1	100
Z10	Comfort	***	61.37	Abumusa Island	23.21	100
Z11	DirectEvaporative Cooling	**	16.66	Khash	1.2	46
Z12	Natural Ventilation	***	13.50	Chabahar	1.06	20
Z13	Thermal mass + Night Ventilation + Indirect Evaporative Cooling	**	2.64	Bandaredayyer	0.14	11
Z14	Indirect Evaporative Cooling	**	69.27	Chabahar	4.86	16
Z15	Air Conditioning + Conventional Dehumidification	***	90.57	Chabahar	4.68	24
Z16	Natural Ventilation + High Thermal Mass + Night Ventilation + Direct & Indirect Evaporative Cooling	***	19.04	Konarak	8.51	97
Z17	Direct & Indirect Evaporative Cooling + High Thermal Mass + Night Ventilation	***	22.3	Zahak	6.65	85
Z18	Direct & Indirect Evaporative Cooling + Thermal Mass + Night Ventilation	***	27.7	Shushtar	3.1	43
Z19	Direct & Indirect Evaporative Cooling	*	18.34	Yazd	1.28	28
Z20	Air Conditioning	***	0.00	–	0.00	0.00

- enable thermal mass in the building fabric.
- apply night ventilation.

Z10, which is the representative of establishing thermal comfort, is among the highest bioclimatic occurrences with 59.66% and this is because of the elimination of the cold period of the year in this region and the establishment of favourable climatic conditions in most times of spring and autumn. Since 2.7% of study stations are located in this cluster, this cluster and the fourth one are known as the smallest clusters. The maximum concentration of different stations of the second cluster belongs to areas of the Oman Sea Coast stations and islands located in the Persian Gulf (Figure 6).

Foothill and semi-desert climate (dry). The third cluster or foothill climate and semi-desert dry includes 27% of the study stations, which they are mostly distributed in the margins of the Desert and Eastern and Western Foothills of Zagros (Figure 6). These areas experience less humidity compared to the stations of the sixth cluster but in comparison to the stations of the cluster 5, they experience more humidity. Among features of this cluster there is no need for cooling strategies of zones 12–15 and even zones 18 and 19.

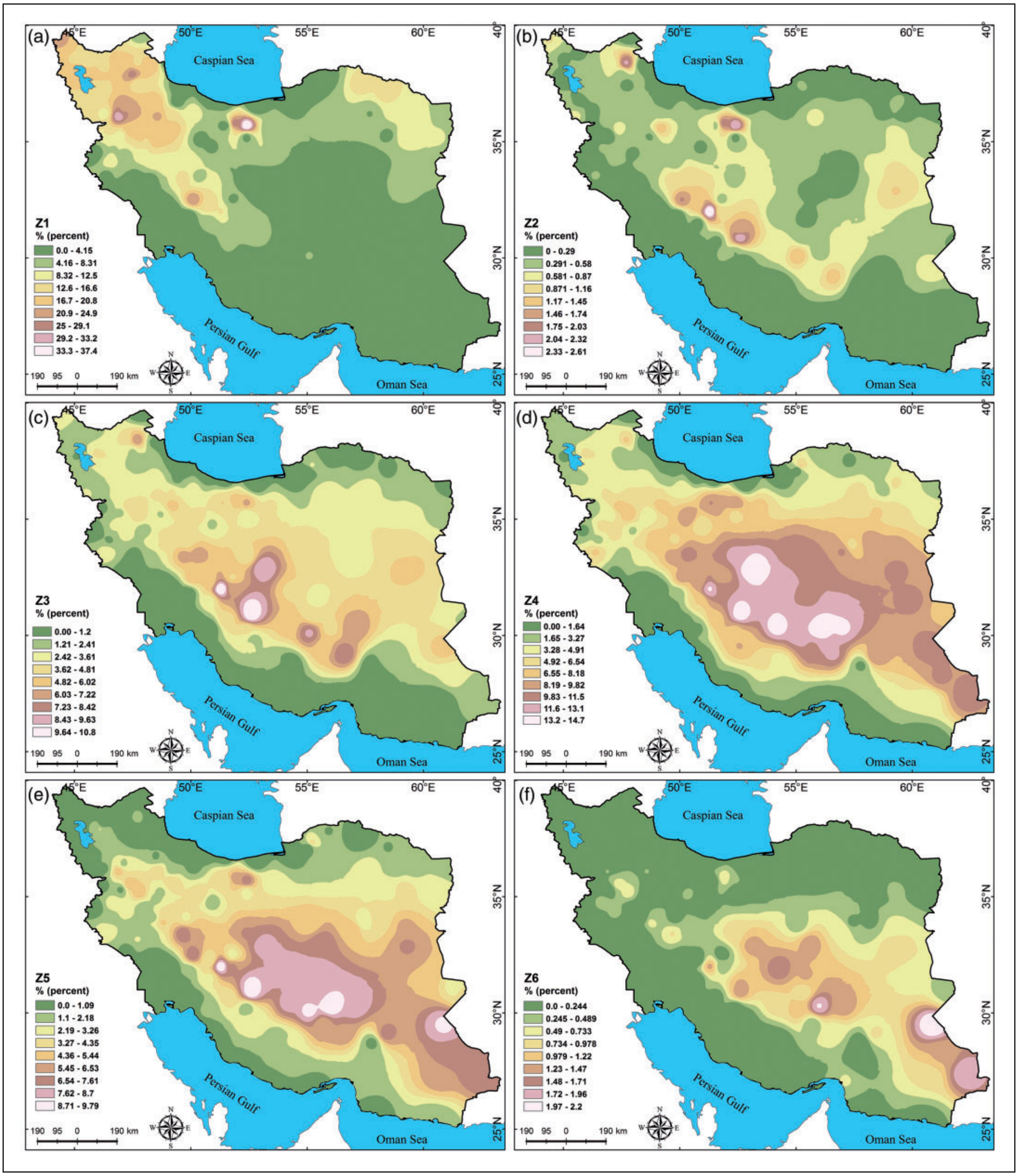


Figure 6. The spatial distribution of different climatic zones occurrence based on statistical period of 1995 to 2014.

Applying Humidification strategy by itself or in combination with Conventional Heating has no place for stations located in this cluster. Because some stations in this cluster are influenced by the cold mountainous condition of Zagros Mountain Range, the use of passive heating methods for indoor spaces is proper for them. In fact, although the use of active strategies for heating of indoor spaces is limited, the use of passive strategies for the cold period of the year is sufficient in most stations of these areas:

- maintaining the generated heat inside the building (Internal Gains) through paying attention to the details of external envelopes.

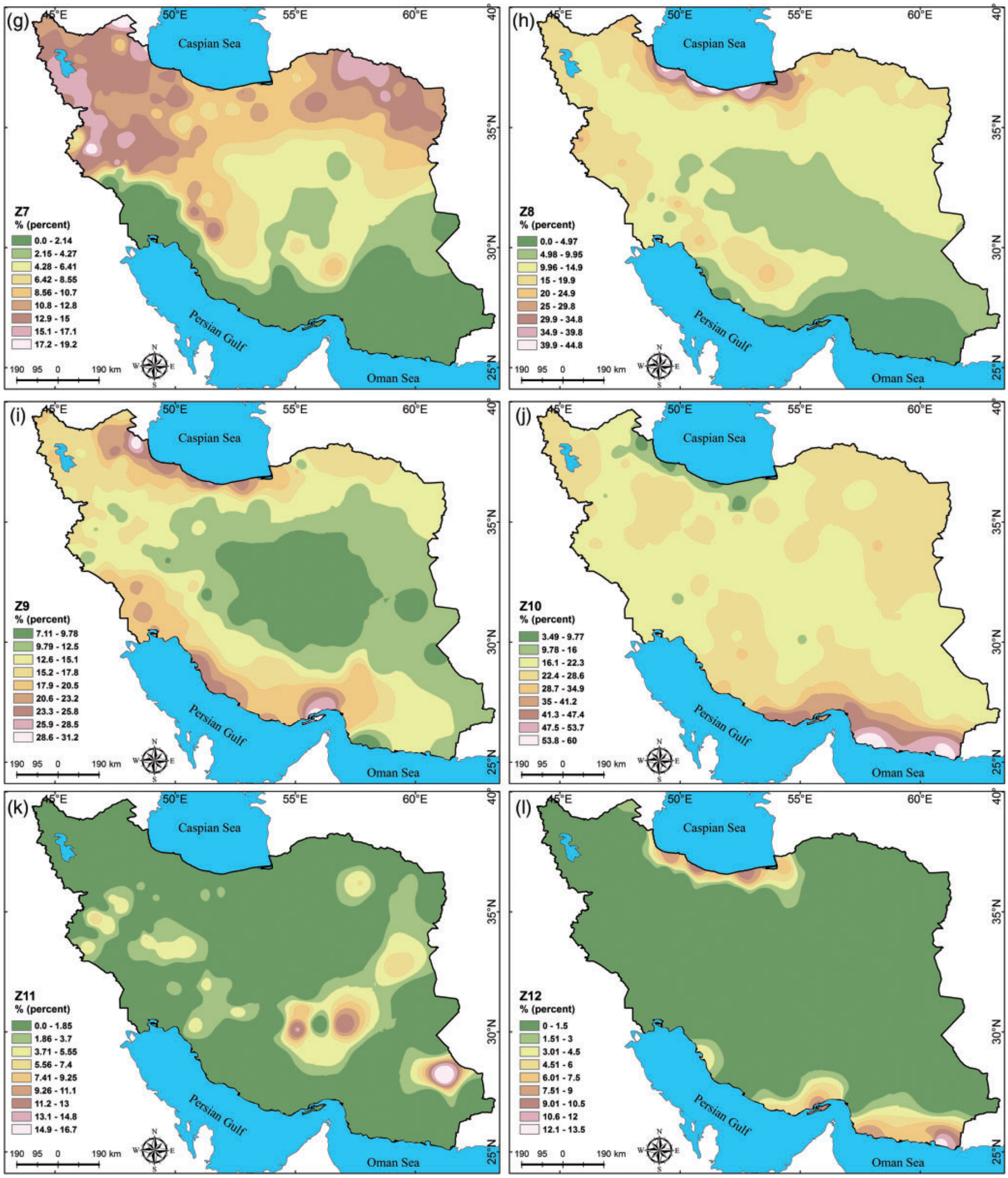
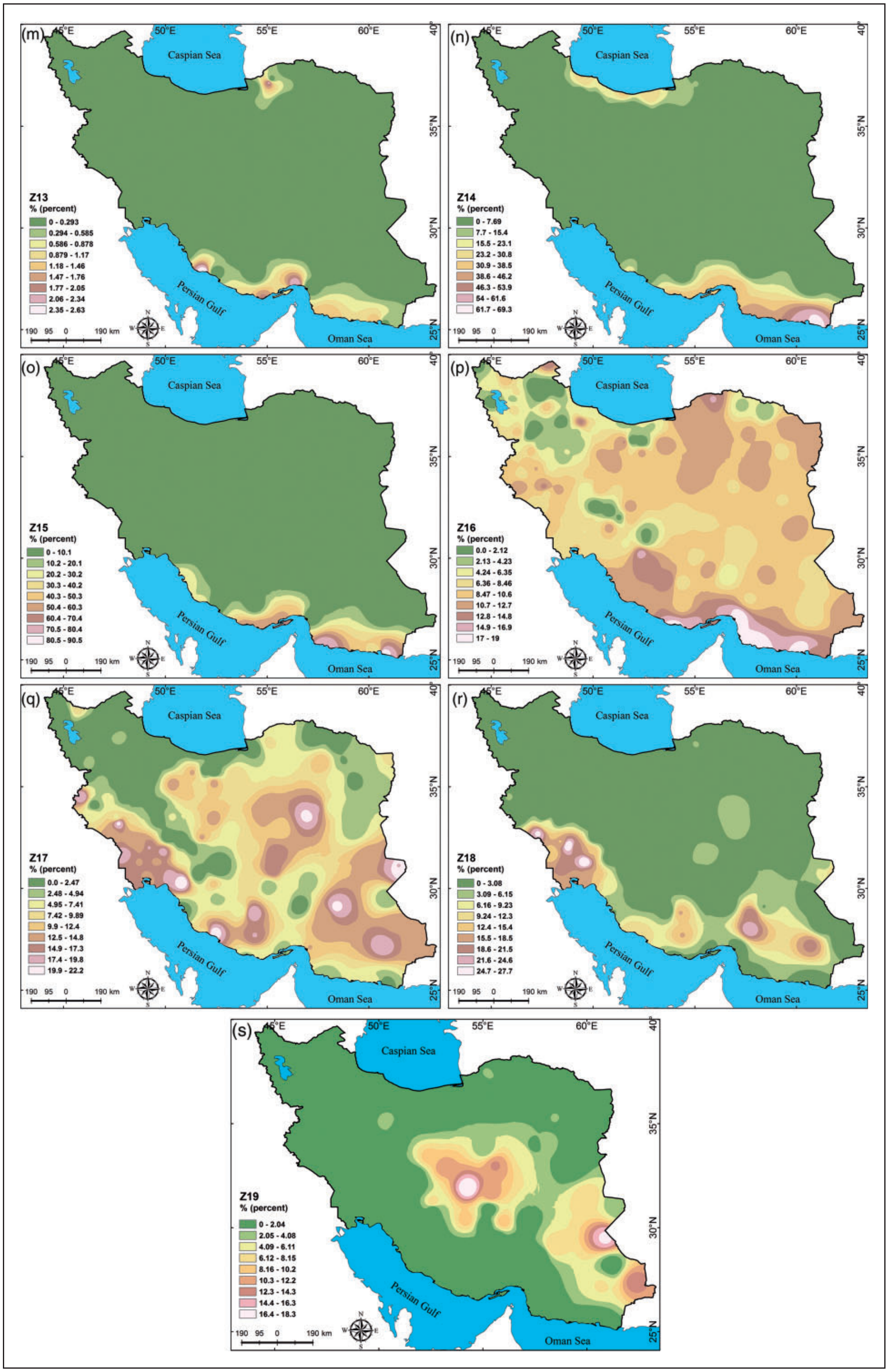


Figure 6. Continued.

- insulating the building envelope.
- enabling direct sunlight in the southern spaces of building can be good ideas to provide comfort in the interior of the building.
- passive solar solutions such as Trombe wall,[49,50] greenhouse space,[51] double skin façade[50] and locating the main places of living and working in the south side of the building together with large windows.
- in some cases, the provision of passive heating is required in combination with humidification. Although during rainy periods due to higher relative humidity, the need for combining humidification with heating strategies is reduced.

The occurrence of thermal comfort with 19.68% in these areas is considerable because the condition of spring and early autumn with regards to temperature



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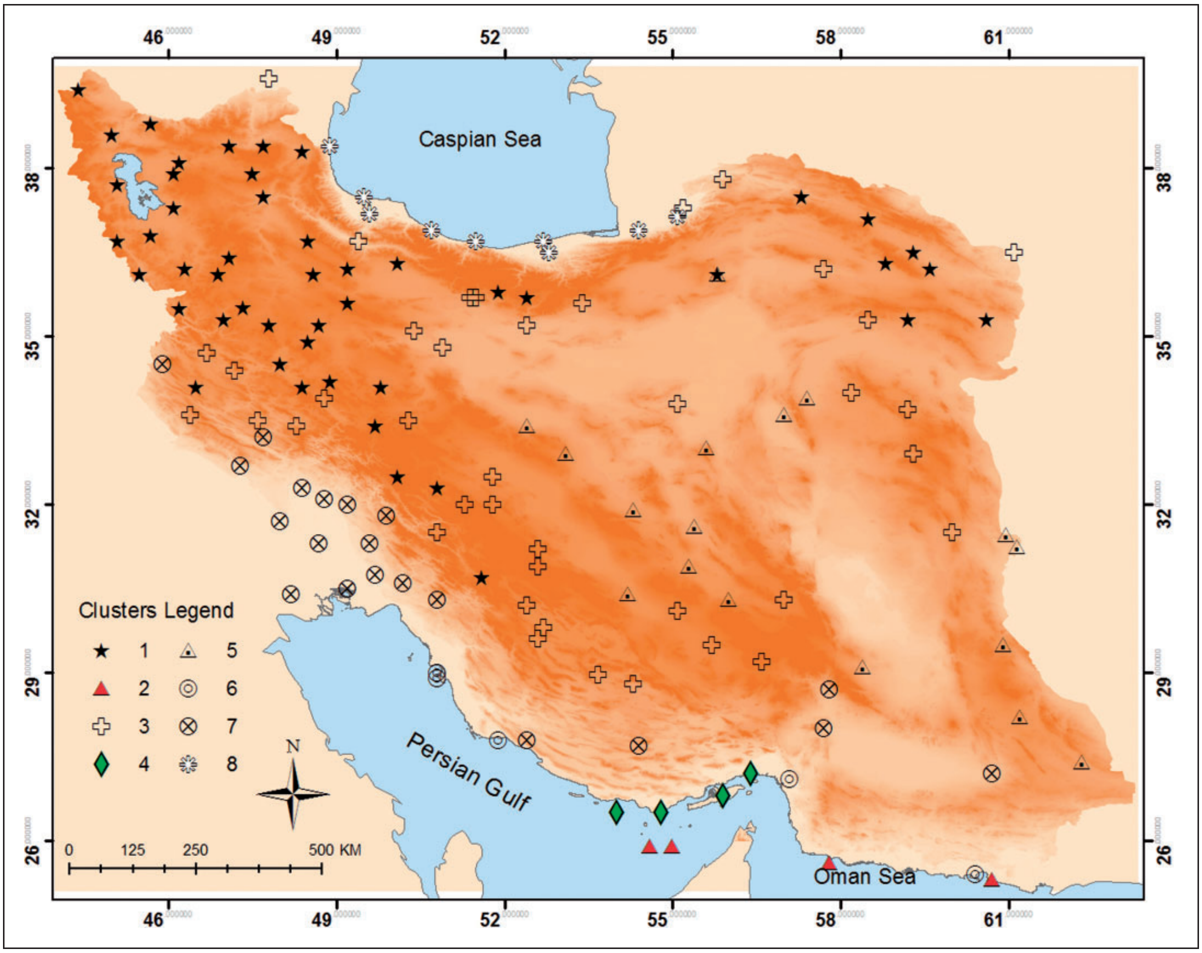

Figure 7. Eight cluster zoning of bioclimatic diversity of stations.

and humidity is relatively favourable in these areas. However, the cooling strategy of zone 16 and especially zone 17, which are a combination of Natural ventilation, Thermal mass, Night ventilation and Evaporative cooling are required during the cold period of the year in these areas. Ultimately, these areas require both passive cooling and passive heating strategies during the year. The distribution of warm and cold seasons in these areas is approximately the same.

Coastal climate (humid and warm). The fourth study cluster is known by the title of Coastal humid and warm climate that is similar to the second cluster, 2.7% of the country's stations are located in this cluster. The scope of distribution of this cluster in Iran includes Islands and coastal stations of the Persian Gulf and the North of Strait of Hormuz (Figure 6). Outputs indicate that the overall average for zones 2, 3, 4, 6, 7, 11 and 19 for stations of this cluster was zero and the total average in zones 1 and 8 was also close to zero. Similarly, to the second cluster stations active and passive heating strategies do not work in this climate. Due to high humidity in most times of the year, Humidification strategies are not suitable for different stations in this cluster. Stations in the third cluster satisfy the maximum need for indoor comfort regarding the strategies of zones 9, 14, 10 and 15.

- Passive solar heating should be used as the most important strategy in this climate. Passive strategies such as utilizing thermal capacity (Internal Gains and Thermal Mass).
- Natural Ventilation.
- heat disposal by Night Ventilation are recommended.
- active strategies in the form of Air-Conditioning with Conventional Dehumidification in the design of mechanical construction is necessary.

However, like the second cluster, Z10 i.e. establishing thermal comfort with an average of 42.38 is among the highest bioclimatic strategy zones, which is due to

Table 2. Specific name and the general characteristics of all eight selected clusters.

Cluster number	Cluster 1	Cluster 2	Cluster 3	Cluster 4	Cluster 5	Cluster 6	Cluster 7	Cluster 8
Cluster special name	Mountain cold climate	Coastal very humid and warm climate	Foothill and semi-desert dry climate	Coastal humid and warm climate	Warm to extremely hot central desert climate	Coastal semi-humid and warm climate	Warm semi-desert climate	Caspian coastal humid climate
Z1 in %	16.10	0.55	4.01	0.43	0.95	0.17	0.03	0.96
Z2 in %	0.56	0.00	0.57	0.00	0.35	0.00	0.00	0.00
Z3 in %	3.03	0.00	4.08	0.00	3.82	0.00	0.11	0.01
Z4 in %	4.73	0.03	7.78	0.09	10.91	0.17	1.38	0.06
Z5 in %	2.24	0.41	3.97	0.65	6.76	0.76	1.04	0.04
Z6 in %	0.12	0.03	0.35	0.06	1.12	0.15	0.06	0.00
Z7 in %	13.48	0.00	9.63	0.00	3.14	0.00	0.88	11.29
Z8 in %	14.36	0.01	13.86	0.53	8.45	2.20	12.99	37.60
Z9 in %	15.74	7.77	11.91	25.35	9.11	22.07	18.84	22.99
Z10 in %	22.46	59.66	22.87	42.38	19.68	34.33	20.22	11.47
Z11 in %	0.92	0.05	2.52	0.04	1.48	0.41	0.37	0.00
Z12 in %	0.00	9.45	0.07	6.55	0.00	3.04	0.09	7.56
Z13 in %	0.00	0.96	0.01	1.54	0.00	0.82	0.02	0.25
Z14 in %	0.01	48.65	0.12	34.69	0.00	21.30	0.01	23.20
Z15 in %	0.00	80.56	0.00	56.65	0.01	21.80	1.28	0.56
Z16 in %	5.02	17.23	10.68	15.87	9.41	14.49	8.10	6.34
Z17 in %	1.23	2.81	6.59	4.30	14.04	5.99	16.96	0.98
Z18 in %	0.01	1.03	0.19	2.20	2.52	4.11	16.99	0.43
Z19 in %	0.00	0.00	0.92	0.00	8.26	0.00	0.58	0.00

the decrease in the cold period of the year and favourable climatic conditions in spring and autumn (Table 2).

Central desert climate (warm to extremely hot). Stations located in the fifth cluster are known by the specific title of Warm to extremely hot central desert climate, and 11.48% of study stations are allocated to Stations in this cluster. Based on Figure 6, most of the focus of these stations is on deserts of Central Iran, although some stations in this cluster are distributed as small cores in the East and Southeast regions of Iran. In this cluster there is no need for cooling, the fifth cluster stations are located in the driest parts of Iran and can be described as continental climate. Therefore, cooling strategies of Zones 16 and 17, which are combined strategies of Natural ventilation, Thermal mass, Night ventilation and Evaporative cooling, are recommended for arid areas and appropriate for summer condition. On the one hand, the maximum strategy is related to the cold period of the year for the strategy of Z4 or Passive Solar Heating + Humidification with the frequency of 10.91%. On the other hand, the overall average of the occurrence of comfort conditions for stations of this cluster is 19.68% which has the maximum frequency of bioclimatic strategy zones. In fact, to provide comfort in cold winters desert areas, a set of passive strategies such as maintaining the heat generated inside the building (Internal Gains) and maximum absorption of direct sunlight (solar passive heating) with generating appropriate humidity for the environment (Humidification) is recommended to prevent dry winter air. Also, in areas where winter temperatures are less than 7°C, Active solar systems are recommended.

Coastal semi-humid climate (humid and warm). In this cluster, 3.4% of study stations are scattered in coastal strip of Persian Gulf and Oman Sea. In terms of geographical distribution, although this cluster is similar to clusters 2 and 4, the cluster is located on the southern border of the South, but some stations in the second and fourth clusters have been distributed in the Persian Gulf Islands. However, for the sixth cluster, no Southern Islands of Iran are located in this cluster. For the sixth cluster, despite the similarities in heating and cooling strategies with second and fourth clusters, there are significant differences in the frequency of cooling strategies used for several zones. First of all, no considerable heating strategy can be seen for the second and fourth clusters for the cold period of the year. However according to zone 9, for stations in cluster VI, one of the heating strategies with 22% frequencies is related to the strategy of using internal gain.

Also, for two strategies of zones 14 and 15, which include Indirect Evaporative Cooling and Air Conditioning + Conventional Dehumidification, the frequency percentage of occurrences for the sixth cluster is more than two other clusters. Regarding the three cooling strategies related to zones 17, 18 and 19, the frequencies in the second and fourth cluster are considerably higher than at stations in the cluster sixth. One of the other differences of stations, located in the sixth cluster with the second and fourth one, is the existence of frequency percentage of days located in the comfort zone. So that its average for the sixth cluster is 34.3% and it is less than 1% for two other clusters. Another feature of the sixth cluster, is the absence of any heating strategies of first to seventh bioclimatic strategy zones and also cooling strategies of zones 11, 13 and 19 (Table 2).

Semi-desert climate (warm). In the seventh cluster, only 14.18% of stations are located in this cluster. The main focus of this cluster's stations is related to the plain regions of South and South-West of the country. In the areas of this cluster that experience of warm and semi-humid climate condition in the warm seasons, there is no need to use strategies for zones 1, 2, 3, 6 and 11 to 14. Because these strategies are generally limited to areas where the humidity is very high or the temperature reaches more than 42°C. Meanwhile the strategies of zones Z16 and Z17 are limitedly required in stations of this group. Therefore, the set of passive cooling strategies can be considered. In these strategies, heat capacity of materials and daily Natural ventilation with heat loss through Night ventilation and also cooling capacity by evaporation are used. On the other hand, the strategies of Zones 18 and 9 with overall average of 17 and 18.84% are considered as the most important strategies in providing indoor comfort. Also, the maximum frequency of bioclimatic events with 20.22% belongs to the thermal comfort zone (Table 2).

Caspian coastal climate (humid). The eighth cluster or Caspian Coastal climate (humid) with a total of 6.2% of total study stations is deployed on the Southern Coast of the Caspian Sea. Climate characteristics of stations of this cluster are indicated in Table 2 using strategies of zones 2 to 6, 11, 13 and 19 does not work here. The main cause of this is high humidity of the air in these areas. In fact, all strategies that need humidification and also strategies which recommend Evaporative cooling are not used in the stations of this cluster, because it increases the humidity of the environment and causes discomfort conditions. On the other hand, heating strategies of Z9 and Z8 zones with an overall average of 22.9 and 37.6% and cooling strategies of Z14 with 23.2% were introduced as the main ways to ensure indoor comfort of houses in this cluster. Due to high humidity, high temperature fluctuations during the year are not experienced. Therefore, there is no need for active systems to provide cooling and heating. Heating passive strategies such as Internal Gains and Solar Passive Heating is enough. Frequency of thermal comfort for this cluster generally happens in early spring and early autumn.

Assessing characteristics of strategies

Clusters 1 to 8 stations of Orumiyeh, Chabahar, Saveh, Bandar Abbas, Tabas, Ahvaz and Rasht were examined respectively (see Figure 8). In Table 3, At the Orumiyeh station the representative of seventh cluster with values of 19.24 and 15.23% has had the maximum frequency for zone 1 and 7 (Figure 8(a)). For the second to sixth zones, which collectively suggest the need for indoor heating strategies combined with moisture injection, the maximum frequency of occurrences was in the third and fifth cluster including Saveh and Tabas stations (Figure 8(c) and (e)). This is because Tabas is located in the dry and hot desert climate and winter cold is accompanied with a sharp decrease in ambient humidity. Therefore, passive and active strategies along with humidification must be used. For this purpose, taking advantage of wet areas and water bodies (pond, pool, and fountain) and the vegetation consisting of broad-leaved plants and fruit trees in this region has been common in the past and still are used as strategies for increasing humidity.

On the one hand, stations located in Cluster 2, 4 and 6, which includes Chabahar, Bandar Abbas, Bushehr and even Ahvaz station, are representative of the fifth cluster. Due to the low latitude location and proximity to the equator and being affected by the Persian Gulf and Oman Sea they have the minimum need for the strategies of zones 1 to 6. In total, these clusters have the least need for direct sunlight and therefore, by measures such as reducing the glazing surface or window to wall ratio of the envelopes, shading devices and wide terraces and enjoying northern windows and the scattered light of sky can be used. Also reducing humidity inside the building and taking advantage of cross ventilation in the layout of interior spaces of the building can help to reduce ambient humidity.

For zones 7 and 8, which include strategies of active solar heating and passive solar heating, at the Orumiyeh station, which is a representative of the first cluster with 15.23 and 17.48% frequencies of data, has had the maximum need to these heating strategies. In fact, in the first cluster that is located in high mountainous cities, the use of passive heating strategy alone is not sufficient and the use of solar-based installations like solar collectors for heating is required.

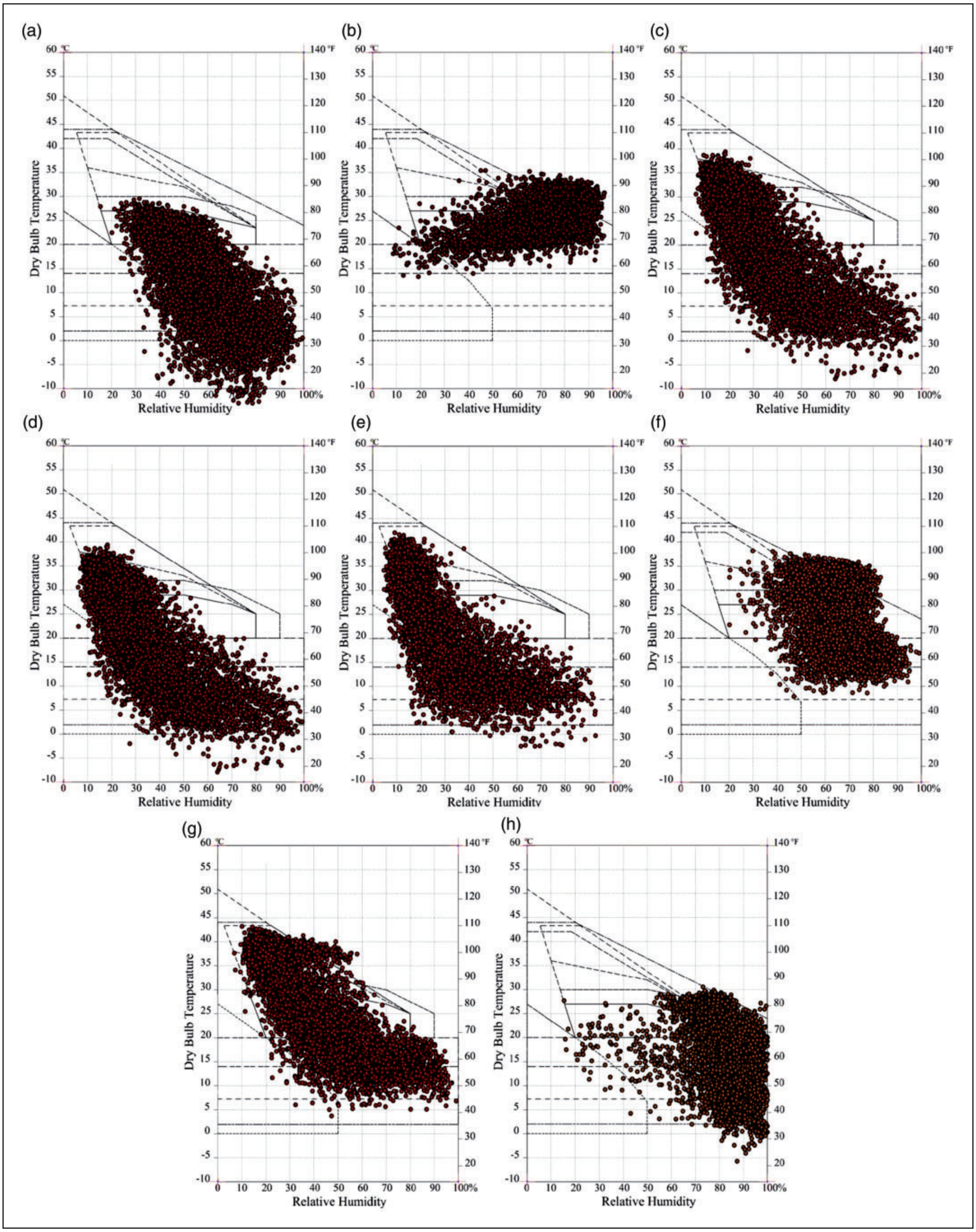

Figure 8. The distribution of bioclimatic conditions of selected study stations for the period of 1995–2014. (a) Orumiyeh, (b) Chabahar, (c) Saveh, (d) Bandarabbas, (e) Tabas, (f) Bushehr-airport, (g) Ahvaz, (h) Rasht.

Determining the proper angle of these systems for receiving suitable solar irradiance, depends on the latitude of each station. According to the ninth zone that includes internal gains strategy for heating of indoor spaces, the Bandar Abbas station had 28.03% of maximum occurrence (Figure 8(d)). Therefore, in the coastal areas, due to high humidity, a sharp drop in winter temperatures is not observed and hence, there is no need for active systems and mechanical heating utilities. Only the use of insulated exterior envelopes and windows with roofs (which prevents the radiation in summer) can provide cold season's heating. One of the striking points in the assessment of each sample for a cluster is the occurrence of frequency percentage of comfort days. The results show that among the selected stations for each cluster, Chabahar station had 60.02% maximum thermal comfort occurrence as the sample station of second cluster (Figure 8(b)) and Bandar Abbas had 35.64% as the sample station of the fourth cluster is the second most thermally comfortable. In total, the stations of second and third cluster which are located in hot and humid areas only experience the crucial condition of summer while winters and springs have favourable temperatures. Consequently, comfort condition was experienced many times during not-hot seasons. As a result, predicting heating systems are rarely required in these areas. Also, findings of this section show that minimum days with comfort with 9.4 and 18% were found at Rasht and Tabas stations as the representative stations of fifth and eighth clusters (Figure 8(h) and (e)).

The fifth cluster due to locating in desert areas has the most difficult weather conditions in summer and winter. Low humidity on the one hand and high summer temperatures and low winter temperatures on the other hand has reduced the comfort conditions to a minimum. In these areas, architectural design should focus on the one hand on the heating strategies of cold seasons (Z2 to Z6) and on the other hand combined cooling strategies of warm seasons (Z16 to Z18). The lack of comfort in the climate at stations of eighth cluster is mostly due to high relative humidity. Therefore, cooling strategies are generally recommended far from increasing thermal inertia[52] and without evaporative cooling. Cooling of these areas only by the use of passive methods such as natural ventilation and in very difficult conditions with the help of air-conditioning systems is possible. Passive and active methods of heating without using humidification are recommended.

For zones 11, 12 and 14, which include indoor cooling strategies by using indirect evaporative cooling, Natural Ventilation and direct evaporative cooling, and Z15 which suggest the strategy of air conditioning + conventional dehumidification, the maximum values have occurred for the representative of the second cluster Chabahar station (Table 3) which is due to the hot and humid climate of the area. As Table 3 indicates, low percentages of frequencies was allocated to using the strategy of zone 13 for providing comfort, so that its maximum value of 2.34% occurred in Bandar Abbas. Regarding zones 16 and 18, a set of guidelines were followed so that mostly provide Indoor cooling and natural ventilation conditions, most occurrences can be seen in Bandar Abbas and Ahvaz. Undoubtedly in very hot conditions of coastal areas in the south of the country, a combination of cooling strategies such as daily natural ventilation, absorbing

Table 3. Comparison of frequency percentages of different bioclimatic strategies zones for sample stations of each cluster.

Cluster	Cluster 1	Cluster 2	Cluster 3	Cluster 4	Cluster 5	Cluster 6	Cluster 7	Cluster 8
Stations	Orumiyeh	Chabahar	Saveh	Bandarabbas	Tabas	Bushehr-airport	Ahvaz	Rasht
Z1 in %	19.24	0.32	3.07	0.62	0.60	0.19	0.00	2.10
Z2 in %	0.22	0.00	0.33	0.00	0.12	0.00	0.00	0.00
Z3 in %	1.17	0.00	3.86	0.00	2.80	0.00	0.08	0.02
Z4 in %	1.42	0.07	9.65	0.32	9.91	0.05	0.66	0.14
Z5 in %	0.11	1.39	3.97	1.86	5.21	0.00	0.23	0.19
Z6 in %	0.00	0.11	0.26	0.25	0.70	0.00	0.01	0.00
Z7 in %	15.23	0.00	7.23	0.00	2.67	0.00	0.26	14.27
Z8 in %	17.48	0.00	11.54	1.17	11.32	4.87	11.49	36.62
Z9 in %	18.29	10.18	9.93	28.03	8.14	25.07	20.98	24.48
Z10 in %	26.12	60.02	21.89	35.64	18.08	22.88	20.31	9.36
Z11 in %	0.00	0.18	0.00	0.15	0.00	0.00	0.00	0.02
Z12 in %	0.00	13.50	0.00	5.96	0.00	3.16	0.05	8.54
Z13 in %	0.00	0.14	0.00	2.34	0.00	0.00	0.00	0.00
Z14 in %	0.00	69.27	0.00	33.52	0.00	0.00	0.00	26.56
Z15 in %	0.00	90.57	0.00	47.22	0.01	25.45	2.05	0.44
Z16 in %	0.73	13.47	10.81	15.16	7.92	12.22	7.84	4.28
Z17 in %	0.00	0.50	13.63	5.07	20.50	1.90	14.77	0.00
Z18 in %	0.00	0.11	0.63	3.43	5.90	4.21	21.19	0.00
Z19 in %	0.00	0.00	3.20	0.00	6.10	0.00	0.07	0.00

the heat inside the materials and disposing it through night ventilation and evaporative cooling techniques can improve only a part of environmental crisis and to do so, mechanical systems are required too. Finally, the outputs reflect the fact that the use of strategies of zones 17 and 19, with their maximum values of 20.5 and 6% occurred at Tabas station. In fact, using the strategy of Evaporative cooling is the mostly applicable in areas with dry summer climate and the aforementioned station is a good representative of this climate also the combination of day and night ventilation cooling strategies with High Thermal Mass only in such climates with large temperature difference between day and night works well. In fact, the use of materials with high thermal capacity that create decrement factor and time lag can transfer the heat of the day with a delay into inner spaces at night.

Discussion

Summary of main findings

Based on the findings of the present study, all the studied stations fall partially in Z10, the thermal comfort zone. Several stations have experienced bioclimatic comfort conditions for a certain period of the year with different frequencies. The results showed that the highest frequency of occurrence of days with comfort is in the Persian Gulf Coastline. Similar findings are found in similar studies,[29,53,54] and were observed by Daneshvar et al.[55] and Roshan et al.[56] These studies showed that the maximum occurrence of days with comfort during the cold period of the year are in the Iran's Southern Coastal Strip. For the Shores of the Sea of Oman and Persian Gulf, the combination of these bioclimatic strategies with Conventional Dehumidification is the most influential in 24% of study stations in providing comfort inside buildings. Moreover, using the strategy of (Z16) Natural Ventilation + High Thermal Mass + Night Ventilation + Direct and Indirect Evaporative Cooling, with an overall average of 8.51%, and the strategy of (Z17) Direct and Indirect Evaporative Cooling + High Thermal Mass + Night Ventilation, with an overall average of 6.65% for Iran, were introduced as the most important and widely used indoor cooling strategies. These two strategies are for the industrial countries' chart (Figure 3) but for stations that have been evaluated with non-industrial countries, the maximum need is for cooling strategy Z14 or Indirect Evaporative Cooling.

In total, the output given in Table 1 revealed that in Iran, the use of passive heating strategies has a higher priority than the passive cooling strategies. Several studies showed that the maximum energy demand for Iran is in the heating dominated areas based on the degree day index.[57,58] Figure 6 shows that this does not apply to all and each geographical area due to its specific characteristics and different priorities in the use of various heating and cooling strategies.[59] On the other hand, similarities and differences of study stations in using Z1 to Z19 has led to the division of Iran into 8 climatic clusters for simplification. Clustering diversity of Iran in other studies has been confirmed, which is in line with findings of other studies.[48,60] By evaluating these climatic clusters, the largest study cluster of 32.4% of frequencies occurred at stations in the first cluster. The second and fourth cluster, had 2.7% frequencies, and were introduced as the smallest clusters.

Strength and limitations

In this paper, different bioclimatic patterns of Iran were identified and evaluated by the use of long-term daily temperature and relative humidity data. The paper presents several significant contributions that were not published before in any similar studies, at least for Iran. The first contribution of this paper is related to using Givoni's BBCC. The second significant contribution of this study is providing different accurate climatic maps associated with various bioclimatic design recommendations and strategies for Iran. The third contribution presented in this study is the fact of clustering and grouping Iran's climate based different passive heating and cooling strategies for future building design and urban development. Two different techniques were used in this study and the combined resulting in novel atlas mapping and design guidance. Generation of climatic maps has been based on zoning technique which was carried out by using interpolation methods. Weather stations were divided into different clusters based on the clustering method and the frequency of 19 different bioclimatic conditions. The percentage of similarity within groups and the maximum difference between the identified clusters was the basis of this work. Although that in clusters 2, 4 and 6, many similarities and overlaps in the use of heating and cooling strategies exist, their differences have caused their distinction in the form of three separated climatic clusters. Therefore, the study outputs indicate a high sensitivity and precision of the clustering analysis. The output of this study emphasizes passive heating design strategies as the most important strategy for achieving comfort in buildings. The second most important bioclimatic design strategy is (Zone 9) the Internal Gains to provide comfort inside buildings.

On the other hand, the findings of this study are limited to daily temperature and relative humidity data and the distribution of bioclimatic conditions of the weather stations illustrated in Figure 7. There are other factors that influence the building performance and energy demand for cooling or heating including, the project site, building function and use, occupant density (occupant per square metre), expected comfort, sky cover, clothing etc. The climate characterization is more useful to understand the outdoor climate conditions before the design but does not represent the real performance of the building. Already, some strategies and design recommendation for the climatic zones, identified by this study, are conflicting with each other. This means that our clustering analysis should be mainly used during the pre-design phase and under any circumstances our results do not represent the real expected building performance or indoor comfort conditions. Moreover, the choice of the thermal comfort model and indoor environmental quality expectations have a significant impact on the bioclimatic design recommendation and strategies that needs to be undertaken.[61] According to the EU Directive, the concept of bioclimatic design and construction can reduce energy demand even by up to 60%, assuming that all traditional thermal standards are met, improving heating, cooling, ventilation and lighting.[62] Therefore, our assessment of cooling and heating characteristics should be carefully considered as recommendations that provide guidance during early design phases. Thus, our study results can be used initially and must be amends and followed by building performance simulation to determine the interaction between the microclimate, topography, altitude, solar access, landscape, occupant behaviour and the building.[10]

Implications on practice and future research

Climatic zoning is an essential element for bioclimatic design and building energy efficiency in Iran. Climate zoning plays an important role in humans' living and working activities, one of which is well-being and buildings energy efficiency. One of the basics of sustainable buildings design and cities development depends on the knowledge and understanding of the natural environments' potential and climatic conditions. This study is a starting point to provide guidance for design decisions to deliver climate responsive and bioclimatic architecture. As a direct implication of this study, a future tool or a visual guide can be developed to incorporate design recommendations to achieve sustainable building design effectively. This can be of interest for designers and contractors. Moreover, we recommend integrating the new atlas maps and climatic zoning results in the building energy efficiency standard of Iran. The outputs of this research can be used by energy legislators, policy makers and planners as an effective step in Iran's land use planning, energy supply management and energy risk management. The results of this study provide the means to revise the existing climatic zoning, to apply bioclimatic design strategies and support evidence-based decision making energy policy.

Future research should address clustering the climate in Iran's different regions based on more parameters beyond temperature, degree days, altitude and relative humidity. Also, a combination of building performance simulation and climatic zoning should be the next scientific step to explore bioclimatic design scenarios and building construction technologies. Also investigating thermal comfort in Iran is an important step forward to provide more robust recommendations to tackle the complex relation between the changing climate and building energy performance.

Conclusion

A clustering analysis for data from 48 weather stations in Iran was conducted. 19 major passive design strategies were identified and were assessed regarding their effectiveness. With the help of Givoni's building bioclimatic chart and Brown and Dekay's chart, the weather dataset from 1995–2014 was plotted and quantified to rank and distinguish the different climatic regions and cities. 19 atlas maps were generated to map and visualize the 19 climatic design strategies. For simplification purposes, the cluster analysis grouped the 48 climatic locations under 8 major regions to facilitate the guidance and the classification of the most effective design strategies in Iran with a high accuracy. The study findings indicate that the built environment in Iran is mainly heating dominated areas due to high latitudes and altitude. Passive heating and energy efficiency measures such as solar heating, insulation and buildings airtightness should be used in the architectural and building construction practice. At the same time, the data analysis shows a significant climate variety and presence of hot climate conditions in Southern and Coastal Area, which requires different urban planning approaches in relation to socio-economic activities. The three major contributions of the paper relate to (1) the innovative use of the Dekay and Brown's chart with relatively recent climatic data, (2) the creation of accurate and visual climatic atlas maps for designers and (3) the classification of Iran's large number of cities under 8 major climatic regions associated with bioclimatic design recommendation. The study results are beneficial to quantify and identify the most influential bioclimatic design strategies and provide a new climatic zoning for Iran.

The following design recommendations summarize the quantified bioclimatic design recommendations. The recommendations characterize the bioclimatic conditions of each investigated city and provide guidance regarding the most effective passive design strategies based on Figure 6, Figure 8, Tables 1 to 3:

1. Iran's mountain climate zone (Cluster 1) is cold with warm and dry summers. Passive solar heating, thermal control and thermal heat storage are the most effective during winter. Natural ventilation is the most effective during summer.
2. Represented by Chabahar, the coastal climate zone (Custer 2) is very humid and warm with the largest number of hours falling in the thermal comfort zone. Shading, natural ventilation and porous envelopes are effective in summer. Passive solar heating is effective during winter.
3. Saveh has a foothill and semi-desert dry climate representing Cluster 3. The climate is hot and dry with cold winters and hot summers. Thermal control of envelopes and natural ventilation are the most effective strategy during summer. In some cities in this cluster, humidification through evaporative cooling can be required.
4. Bandarabbas (Cluster 4) has a coastal humid and warm climate. Natural ventilation and night cooling are the most effective strategies. Shading, natural ventilation and porous envelopes are recommended and during winter, passive solar heating is the most effective.
5. Tabas, is falling in the central desert climate (Cluster 5) and has an arid climate with the high temperature disparity between day and night as well as between summer and winter. Solar shading and direct evaporative cooling are the most effective strategy in the summer, followed by natural ventilation. Passive solar heating and thermal mass are the most effective strategies in the winter.
6. Bushehr has a humid and warm climate in a coastal semi-humid and warm zone (Cluster 6). Despite the similarity with Cluster 2 and 4, the climate of Cluster 6 is significantly different. Indirect evaporative cooling and shading are the most effective strategy in summer, followed by natural ventilation.
7. Ahvaz has a warm semi-desert climate with dry and warm summers and mild winters. Direct evaporative cooling is the most effective strategy in summer, followed by natural ventilation. However, passive solar heating is needed in winter. Cluster 7 falls in the thermal comfort boundaries and accounts for 20% of the annual hours.
8. Rasht falls in the Capsian Coastal zone (Cluster 8) and has a humid and sunny climate all year round. Solar shading, natural ventilation and indirect passive cooling are the most effective strategies. Passive solar heating is effective in winter.

Authors' contribution

Gholamreza Roshan wrote the majority of the paper. Mohammad Farrokhzad and Shady Attia provided support with some paragraphs as well as comments and corrections.

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