COMPARATIVE STUDY OF URBAN RESIDENTIAL NEIGHBOURHOODS FOR ASSESSING
URBAN HEAT ISLAND EFFECTS USING ENVI-MET SIMULATION

BY

SARA SHABAHANG

A thesis submitted to the Victoria University of Wellington in fulfilment of the requirements
for the degree of Doctor of Philosophy

Victoria University of Wellington (2022)

Abstract

This study assessed the urban characteristics of residential neighbourhoods in Mashhad, Iran and the related urban heat island (UHI) characteristics. The aim was to find the influential and causative neighbourhood characteristics on metrological parameters such as air temperature and surface temperature and provide recommendations for urban policymakers and designers to reduce UHI in cities. The urban heat island effect is a product of urbanization and in certain climates, including climates like that of Mashhad, can lead to increased use of energy for cooling, and increased emissions of greenhouse gases (GHG). Global warming is also a product of human activities, and the climate change that comes with it poses a threat to both humankind and the planet. At the same time, Iran, as one of main global producers of greenhouse gasses, has witnessed rapid urbanization and a dramatic increase in energy use. In the past, urbanization did not produce this increase in energy use, suggesting modern urbanization is in complete contrast with traditional urban and architectural design principles. Climatic design has always been one of the most important principles of traditional architecture in Iran. Different climate zones have inspired traditional architecture, creating design solutions that made cities and buildings liveable for people. As this problem has at least in part been created by cities the solution should also be addressed there. Countermeasures against urban warming consist of mitigation and adaptation strategies, however, these two conflict with each other in many aspects, particularly in land use. Compact urban development has been proposed as a means of reducing greenhouse gas emissions by reducing car use, while expanding green spaces, and hence increasing distances between places, is a UHI adaptation strategy. Local adaptation and mitigation strategies based on available data, tools and resources in parallel with understanding the necessary level of intervention could be a valuable solution for reducing UHI effects in Iran.

In this study, the simulation method ENVI-met was examined as a way of modelling potential strategies to predict UHI. First, the sensitivity of the software needed to be examined. This was done through creating different scenarios for selected areas of the city of Mashhad. In order to assess ENVI-met simulation outputs the default inputs in both the modelled areas and simulation tool were manipulated. To see how much the simulation process could be simplified to suit the resources available in Iran, only ground surface temperature (T_s) was considered. The results revealed the difference in inputs for surface materials, topography, wind and tree size were captured by ENVI-met. However, ENVI-met did not show much sensitivity to start

time of simulation, simulation duration, nesting grid, empty cells and offset boundary. In the next step, different neighbourhoods with the same area (1600 m^2) in the coldest and warmest districts of Mashhad were chosen for more investigation. These districts were examined for their main urban patterns, then eleven areas of $400 \times 400 \text{ m}$ were chosen from the residential parts. The GIS map from the city council was used for the base model in ENVI-met. Other important factors which did not exist in the GIS map, such as trees, were modelled in GIS using google map. In ENVI-met, the Monde app used for creating models from vector-based GIS shapefiles to use them for simulation. Then, the Space app was used to define model domains. Using ENVIguide, metrological input was defined based on Mashhad weather station data from the city council. Finally, the ENVI-met simulations were run. Output data was created as T_a , T_s and SVF maps in the Leonardo app. As the T_a and T_s maps just showed the spatial temperature, two scripts were used to calculate the average temperature of each neighbourhood. The main urban characteristics of each neighbourhood were created as different excel tables, either using data in the attribute table of the Mashhad GIS map or by creating the necessary data using GIS tools. Quantities analysis was conducted by comparing outputs using scatter charts in excel and Pearson correlation coefficients from SPSS software. The urban and green characteristics of neighbourhoods were analysed.

The results indicated no significant relationship between T_a and T_s . Among the different urban characteristics, average plot size, average footprint size, average courtyard area and length, trees, and grass were factors more influential on T_s . Building density, street coverage, total footprint area, average street width, average SVF, H/W aspect ratio of street, courtyard, and canyon as well as trees influenced T_a . This study shows the significant role of trees among other factors, as they have a significant relationship with both T_a and T_s . Site coverage, average building height, courtyard coverage, average courtyard width and average canyon width affect neither T_a nor T_s . Based on the results, recommendations have been made for urban policymakers and urban designers. This study recommends neighbourhood-by-neighbourhood countermeasure policies for reducing UHI in existing neighbourhoods. Increasing building height as a long-term measure and changing surface materials and planting more trees as a short-term measure for existing neighbourhoods were suggested. For longer term measures, higher values of building density, and lower values for street coverage, H/W aspect ratio, average plot size, footprint size and courtyard size were recommended for new developments. It is important to note that these recommendations are based on simulation results at 15.00 in

summer in Mashhad. For a more reliable policy, more studies need to be done for different hours and different seasons in Mashhad.

Dedication

To my Mom as the most incredible person I have ever met in my entire life. Nothing in the world can compare to her kindness. She is the reason for any of my successes and persistence.

Acknowledgements

I would like to thank my supervisors who helped me to go through this journey, it would not have happened without their help. I would like to express my sincere appreciation to my supervisor Brenda Vale, for being affable, sympathetic and patient. Every single day of the last four years, I felt academically and emotionally supported by her. Brenda will be my best role model for the rest of my life as a knowledgeable scientist and special human being. Her continuous guidance and feedbacks had made me attentive and motivated throughout my study. I am most grateful to Morten Gjerde for leading me through my study by his comments and helping to fund the purchase of the ENVI-met license.

I would like to thank Victoria University of Wellington and especially Stewart Milne, IT team leader at the School of Architecture, for providing access to the latest version of ENVI-met and 10 other computers for simulations. I am also thankful to Lisa Woods (VUW statistical advisor), Dr. Mohammad Nekoie (School of Engineering and Computer science) for helping me write a script for average ground temperature in Leonardo, and the administration team of the university.

I gratefully acknowledge the assistance I have received from Mashhad city council during data collection, as they kindly gave me access to Mashhad GIS map and weather data.

I would also like to thank the ENVI-met team who patiently answered all my questions in the ENVI-met forum.

Last but not least, I have received great support from my family; my loving father, brother, sister and two uncles. Moreover, my lovely friends both in Iran and New Zealand have let me share my feelings and my thoughts with them and comfort me when I need them.

Sara Shabahang

29/11/2020

Table of Contents

1	INTRODUCTION	1
1.1	BACKGROUND	1
1.1.1	<i>Global Warming in Iran.....</i>	<i>3</i>
1.1.2	<i>Urban heat island in Iran.....</i>	<i>4</i>
1.1.3	<i>Global Warming countermeasures in Iran</i>	<i>5</i>
1.1.4	<i>Urban Heat Island countermeasures in Iran.....</i>	<i>6</i>
1.2	PROBLEM STATEMENTS, OBJECTIVE AND RESEARCH QUESTION.....	7
1.3	SCOPE OF THE RESEARCH	8
2	LITERATURE REVIEW.....	10
2.1	URBAN WARMING COUNTERMEASURES.....	10
2.1.1	<i>Global warming countermeasures.....</i>	<i>10</i>
2.1.2	<i>Urban Heat Island countermeasures</i>	<i>12</i>
2.1.3	<i>Contradictions between countermeasures.....</i>	<i>13</i>
2.2	URBAN DESIGN	13
2.2.1	<i>Sustainable urban design</i>	<i>14</i>
2.2.2	<i>Urban form.....</i>	<i>16</i>
2.2.3	<i>Neighborhood characteristics.....</i>	<i>17</i>
2.3	URBAN FORM AND URBAN WARMING	20
2.3.1	<i>Scale of measures</i>	<i>20</i>
2.3.2	<i>Translation of urban warming science into urban design</i>	<i>22</i>
2.4	URBAN HEAT ISLAND (UHI) EFFECTS	23
2.5	PARAMETERS THAT CONTRIBUTE TO UHI	24
2.5.1	<i>Urban form, energy use and GHG emissions.....</i>	<i>27</i>
2.5.2	<i>Urban microclimate</i>	<i>27</i>
2.5.3	<i>Urban characteristics.....</i>	<i>30</i>
2.6	METHODS OF STUDYING UHI	39
2.6.1	<i>Observational approach.....</i>	<i>39</i>
2.6.2	<i>Simulation approach.....</i>	<i>41</i>
2.7	SUMMARY	41
3	CASE STUDY BACKGROUND	43
3.1	IRAN	43
3.1.1	<i>General characteristics of Traditional Iranian Cities.....</i>	<i>44</i>
3.1.2	<i>Traditional sustainable Architecture in Iran</i>	<i>46</i>
3.1.3	<i>Traditional sustainable urban design in Iran</i>	<i>49</i>
3.1.4	<i>General Characteristics of Modern Iranian Cities</i>	<i>51</i>

3.1.5	<i>Urban planning and the urban design process in modern Iran.....</i>	52
3.2	MASHHAD	54
3.2.1	<i>Mashhad's urban growth.....</i>	54
3.2.2	<i>Land use changes and lack of green space in Mashhad.....</i>	55
3.2.3	<i>The relationship between UHI and green space in Mashhad</i>	56
3.3	MASHHAD DISTRICT PLAN	59
3.4	DISTRICT 1.....	59
3.4.1	<i>Major Routes and Places.....</i>	60
3.5	DISTRICT 10.....	63
3.5.1	<i>Major routes and places</i>	64
3.6	SELECTED NEIGHBOURHOODS	66
3.7	TYPICAL NEIGHBOURHOOD CHARACTERISTICS.....	72
3.8	SUMMARY	75
4	METHODOLOGY.....	76
4.1	REVIEW OF METHODS	76
4.2	METHODOLOGICAL APPROACH.....	81
4.3	ENVI-MET.....	81
4.3.1	<i>The ENVI-met concept.....</i>	82
4.3.2	<i>ENVI-met Model layout.....</i>	83
4.3.3	<i>ENVI-met 4 Updated model overview.....</i>	85
4.4	SIMULATION METHODS	88
4.5	INPUT DATA	92
4.5.1	GIS	92
4.5.2	Monde.....	94
4.5.3	SPACES	95
4.5.4	ENVIGuide	96
4.5.5	ENVI-met.....	100
4.6	OUTPUT DATA	100
4.6.1	<i>Validation of ENVI-met</i>	103
4.7	SUMMARY	104
5	PILOT STUDY.....	105
5.1	INTRODUCTION	105
5.1.1	<i>Case Study and Data.....</i>	106
5.1.2	<i>Simulation</i>	106
5.2	RESULTS.....	108
5.2.1	<i>Time, duration and material</i>	108
5.2.2	<i>Lateral boundary and DEM</i>	113

5.2.3	<i>Wind speed and offset boundary</i>	114
5.3	SUMMARY	116
6	RESULTS	117
6.1	GENERAL CHARACTERISTICS OF THE RESULTS	118
6.1.1	<i>Urban characteristics of District 1 (D1) and District 10 (D10)</i>	118
6.1.2	<i>Neighbourhood effects</i>	119
6.1.3	<i>Ta distribution map characteristics</i>	120
6.1.4	<i>Ts distribution map characteristics</i>	121
6.1.5	<i>The effect of wind speed</i>	122
6.2	LAND COVER	123
6.2.1	<i>Land use/surface materials</i>	123
6.2.2	<i>Building density (BD)</i>	124
6.2.1	<i>Street coverage (STC)</i>	125
6.2.2	<i>Asphalt pavement area/ dark concrete pavement</i>	125
6.2.3	<i>Bare land area/soil</i>	125
6.2.4	<i>Courtyard/concrete pavement</i>	126
6.3	URBAN FORM	127
6.3.1	<i>Orientation</i>	127
6.3.2	<i>Average Building Height (ABH)</i>	136
6.3.3	<i>Average Plot Size (APS)</i>	137
6.3.4	<i>Site Coverage (SC)</i>	138
6.3.5	<i>Average Footprint Size (AFS)</i>	139
6.3.6	<i>Average Sky View Factor (SVF)</i>	139
6.3.7	<i>Aspect Ratio (H/W)</i>	140
6.4	NEIGHBORHOOD COMPARISONS	147
6.4.1	<i>1-A (Sajad) and 10-C (Hesabi)</i>	147
6.4.2	<i>1-F (Ebnesina) and 10-A (Miad)</i>	150
6.4.3	<i>1-A (Sajad) and 10-A (Miad)</i>	152
6.4.4	<i>1-E1 (Majd) and 10-E (Hadi)</i>	154
6.5	THE EFFECT OF VEGETATION	156
6.5.1	<i>General characteristics</i>	156
6.5.2	<i>10-A (Miad) and 10-E (Hadi)</i>	158
6.5.3	<i>1-B (Ershad) and 10-D (Andishe)</i>	159
6.6	SUMMARY	163
7	DISCUSSION	164
7.1	ENVI-MET SENSITIVITY	164
7.2	CORRELATION BETWEEN URBAN CHARACTERISTICS AND UHI	165

7.2.1	<i>Ta and Ts correlations</i>	167
7.2.2	<i>Characteristics affecting both Ta and Ts</i>	168
7.2.3	<i>Characteristics affecting Ts</i>	169
7.2.4	<i>Characteristics affecting Ta</i>	171
7.2.5	<i>Characteristics not affecting Ta or Ts</i>	173
7.3	POLICY IMPLICATIONS (CLIMATE ACTION).....	173
7.3.1	<i>Existing neighbourhoods</i>	175
7.3.2	<i>Urban development</i>	179
7.4	SUMMARY	179
8	CONCLUSION	180
8.1	ANSWERING THE RESEARCH QUESTIONS	180
8.2	CONTRIBUTION TO KNOWLEDGE	180
8.3	STUDY LIMITATIONS	183
8.3.1	<i>Lack of data</i>	183
8.3.2	<i>Software limitation</i>	183
8.3.3	<i>Lack of time</i>	184
8.4	FUTURE WORK.....	184
	REFERENCES	186
	APPENDIX 1	206
	APPENDIX 2	222
	APPENDIX 3	226
	APPENDIX 4	230
	APPENDIX 5	234
	APPENDIX 6	238
	APPENDIX 7	242
	APPENDIX 8	246
	APPENDIX 9	248

Figures

Figure 1: Urban Warming: cause and effect	2
Figure 2: Trend of 10-year moving average normalized annual mean temperature index between 1955-2000 in arid and semi-arid regions of Iran (Kousari & Asadi Zarch, 2011)	3
Figure 3: Conflicts between UHI and global warming mitigation and adaptation strategies.	13
Figure 4: Different scales in urban design, Image google map	17
Figure 5: Five principal street patterns, source (Biddulph, 2007)	18
Figure 6: Density definitions, source : (Cheng, 2010).....	19
Figure 7: Space classification in an urban area, based on: (Swanwick et al. 2003)	20
Figure 8: Schematic of the climate boundary layers.....	23
Figure 9: Causative factors for UHI, source: (Kleerekoper et al., 2012)	25
Figure 10: Categorization of key factors responsible for UHI. The light grey boxes show the area of interest for this study.....	26
Figure 11: Schematic diagram for the scale of climate, source: (Yoshino & Yoshino, 1975)	28
Figure 12: Schematic diagram of the radiation and energy fluxes at the earth's surface, source: (Foken & Napo, 2008)	29
Figure 13: Airflow behaviour over an array of barriers, source: (Shishegar, 2013)	29
Figure 14: Left: Geometric street canyon. right: top view of wind directions approaching a street canyon. source : (Afiq et al., 2012).....	34
Figure 15: Schematic of the concept of SVF	36
Figure 16: Population by residence status based on 2016 census (Iran, 2014)	43
Figure 17: Number of cities: 1956-2016 (Iran, 2014).....	43
Figure 18: Schematic drawing of traditional Iranian city concept (Ehlers & Floor, 1993)	44
Figure 19: Traditional Iranian city structure in this case the traditional part of Isfahan city (Gharipour, 2003). As shown in the figure, spatial hierarchy is very important in the traditional urban form.	45
Figure 20: Traditional structure of Mashhad in 1971. All important activities are shaped around the Holy Shrine, the most important religious place in the whole country left (ARCHNET) right (reddit)	46
Figure 21: Inside pool (left) and windcatcher (right) for a dry and hot climate, Tabatabayi house Kashan, Iran (News, 2020)	47
Figure 22: Large windows towards the sun during the day and thermally heavy wall materials for a cold and snowy climate (Gasht, 2020).....	47
Figure 23: Ivan (a covered deck) to create shadow and ventilation for a hot and humid area (shargh, 2020)....	48
Figure 24: Pitched roofs for a humid and rainy region, Baghri house, Gorgon Iran (Order, 2020)	48
Figure 25: The typology of houses with a courtyard.....	48
Figure 26: The city of Ardakan: urban layout of modern district (left) and historical district (right), Image google map	52
Figure 27: Mashhad is located in the Northeast of Iran	54

Figure 28: Mashhad urban growth from 1891 to 2006 (Modiri et al., 2017)	55
Figure 29: Changes in green space and urban areas in Mashhad over 20 years (Reza Rafiee et al., 2009).	56
Figure 30 : Distribution of green space (parks) in the 13 districts of Mashhad. Green space per capita is green space area /population. Green space ratio is green space area/district area	57
Figure 31: Comparison between land use map and LST map of Mashhad in 2014 (Alavipanah et al., 2015)	58
Figure 32: District 1 plan (fava.mashhad, 2020)	60
Figure 33: Main routes around and in District 1, the district boundary is in purple. Selected areas for further study are in red. Image google map	61
Figure 34: Major routes and squares of District 1, photo 4,5 and 6 (Zone1.Mashhad, 2020), photo 1(Eghtesaonline, 2018), 3 and 8 (Pourab, 2020) and 7(Eligasht, 2019)	62
Figure 35: Major routes and places of District 1 (Zone1.Mashhad, 2020)	63
Figure 36: District 10 plan (fava.mashhad, 2020)	64
Figure 37: Main routes around District 10, the district boundary is in purple. Selected areas for further study are in red. Image google map	65
Figure 38: Major routes and squares of District 10, photo 1 (Farsnews, 2018), 2 and 3 (Zaernia, 2020), 4 (QasemAbad, 2020)	65
Figure 39: Major places in district 10, left (Irna, 2020), right (erasmusu, 2020)	66
Figure 40: Urban pattern classification in District 1	68
Figure 41: Urban pattern classification in District 10	68
Figure 42: selected neighbourhoods in District 1	70
Figure 43: Selected neighbourhoods in District 10	71
Figure 44: Typical Iranian building and street orientation. Streets are east-west orientated, and buildings are north-south oriented. aerial photo of case study 1-A	72
Figure 45: Schematic of the typical section of District 1	73
Figure 46: Schematic of the typical section of District 10	Error! Bookmark not defined.
Figure 47: The location of Mashhad airport with the only weather station and distance from the selected case study districts	77
Figure 48:ENVI-met concept, source (ENVI-met, 2019b)	82
Figure 49: Basic ENVI-met software model layout (ENVI-met, 2017a)	83
Figure 50: Different concepts for organizing the vertical grid layout: (A): Equidistant Grid, (B): Telescoping grid and (C): Telescoping grid with no extension factor (ENVI-met, 2018b)	84
Figure 51: Visualization of a raster DEM surface (esri, 2019)	85
Figure 52: Simulation method employed in this study. All activities in the orange rectangle were done in ENVI-met. GIS was used at the preparation stage.	89
Figure 53: Input data and settings examined in pilot study, and results used in the main simulation	90
Figure 54: Preparation stage for neighbourhood 1-A (Sajad), the process of completing GIS map obtained from Mashhad City Council. This process was done for all selected neighbourhoods. Street area in dark grey and	

trees added to original shapefiles. The smaller rectangle defines the selected area of 400m x400. The second and third rectangles show the buffer to the area selected for simulation.	93
Figure 55: Google Earth Aerial photo quality for digitizing trees in District 10 Hesabi neighbourhood.....	93
Figure 56: Steps taken in Monde application to create .monde file from shapefiles. Monde file was used in Space application.	94
Figure 57: The process of creating a local wall material based on database material in ENVI-met using database manger	95
Figure 58: Steps taken in the Spaces application to create the INX file to be used in ENVIGuide application.....	96
Figure 59: Average Annual Temperatures in Mashhad (Weather, 2020)	97
Figure 60: Seven different levels of ENVIGuide set up, from beginner to advanced. The path in dark grey is the setting chosen for this study.	99
Figure 61: Schematic of output considerations	100
Figure 62: Typical surface temperature map	101
Figure 63: typical air temperature map	101
Figure 64: typical SVF map.....	102
Figure 65: The main parts of the pilot study and related scenarios.....	106
Figure 66: Images of the selected areas: Aerial satellite views and GIS maps for Monde input. Left:1-D (Ahmadabad), right: 1-E1 (Majd)	106
Figure 67: Ground surface material maps obtained using Spaces, Ts maps and Bar charts obtained from Leonardo, Bar charts show surface temperature distribution in site 1-D	111
Figure 68: Ground surface material maps obtained using Spaces, Ts maps and Bar charts obtained from Leonardo, Bar charts show surface temperature distribution in site 2 (1-E1).....	112
Figure 69: from left to right Majd h and Majd j. Nesting grids are not shown in the maps, but empty cells are.	114
Figure 70: Ahmadabad d, the target boundary (400x400 sqm) is shown in color the offset boundary (580x580 sqm) is shown in grey.	116
Figure 71: Outline of results	117
Figure 72: Air temperature and ground surface temperature bar charts of selected neighbourhoods	120
Figure 73: Ta map of 1-B.....	121
Figure 74: Ta map of 1-A (left) and 10-A (right)	121
Figure 75: Ts map of 1-A (left) and 10-A (right).....	122
Figure 76 : the relationship between BD and average Ta and Ts in all selected neighbourhoods.....	124
Figure 77: The relationship between STC and average Ta and Ts in all selected neighbourhoods	125
Figure 78: The relationship between average courtyard area and average Ta and Ts in all selected neighbourhoods	127
Figure 79: Screenshot of Calculate Polygon Main Angle tool in GIS	127
Figure 80: The schematic of rotation methods in Calculate Polygon Main Angle in GIS.....	128
Figure 81: Main street orientations in D1 (left) and D10 (right) (111-120° and 51-60°) respectively.....	129

Figure 82: Main plot orientations in D1 (left) and D10 (right) of 21-30° and 171-180° respectively.....	130
Figure 83: Main building orientations in D1 and D10 of 21-30° and 141-150° respectively.....	131
Figure 84: The relationship between street orientation and average Ta and Ts in all selected neighbourhoods	134
Figure 85: The relationship between building orientation and average Ta and Ts in all selected neighbourhoods	134
Figure 86: The relationship between ABH and average Ta and Ts in all selected neighbourhoods.....	136
Figure 87: The relationship between APS and average Ta and Ts in all selected neighbourhoods.....	137
Figure 88: The relationship between SC and average Ta and Ts in all selected neighbourhoods.....	138
Figure 89: The relationship between AFS and average Ta and Ts in all selected neighbourhoods.....	139
Figure 90: the relationship between average SVF and average Ta and Ts in all selected neighbourhoods	140
Figure 91: Schematic drawing of H/W aspect ratio and typical urban pattern in Mashhad.....	141
Figure 92: Typical urban pattern in Mashhad. Light grey indicates streets, light yellow indicates courtyards and grey are building footprints. The white indicates streets that were not digitized.	142
Figure 93: Minimum Bounding Geometry tool setting in GIS map to create a polygon with width and length tag.	143
Figure 94: The streets are in grey, the CONVEX_HULL polygons created by GIS are in red.....	144
Figure 95: the process of calculating length of courtyards. First photo shows streets and plot, second photo shows building footprints on top of plots, third photo shows courtyards created using Erase tool in GIS and final photo shows purple rectangles corresponding to the courtyards created by Dice tool and then Minimum Bounding Geometry tool.....	144
Figure 96: Dice tool in GIS map to subdivide feature into smaller parts.	145
Figure 97: The relationship between H/W of streets and average Ta and Ts in all selected neighbourhoods ...	145
Figure 98: The relationship between H/W of courtyards and average Ta and Ts in all selected neighbourhoods	146
Figure 99: The relationship between H/W of canyon and average Ta and Ts in all selected neighbourhoods ..	146
Figure 100: the relationship between H/W of neighbourhood and average Ta and Ts in all selected neighbourhoods	147
Figure 101: Comparison maps of Ta, Ts and SVF for 1-A and 10-C.....	149
Figure 102: Comparison maps of Ta, Ts and SVF for 1-F and 10-A	152
Figure 103: Comparison maps of Ta, Ts and SVF for 1-A and 10-A.....	154
Figure 104: Comparison maps of Ta, Ts and SVF for 1-E1 and 10-E	156
Figure 105: The relationship between tree numbers and average Ta and Ts in all selected neighbourhoods ...	158
Figure 106: The relationship between tree numbers and average Ta and Ts difference in all selected neighbourhoods	158
Figure 107: Comparison maps of Ta, Ts and SVF for 1-F and 10-A	163
Figure 108: The three main urban characteristics investigated in this study. The blue rectangle indicates a strong correlation with Ta, and the orange rectangle a strong correlation with Ts. The characteristic in green is	

<i>the only one with a strong relationship to both T_a and T_s. The grey rectangles indicate no relationship with T_a or T_s.....</i>	<i>167</i>
<i>Figure 109: Relationships of urban characteristics to T_s.....</i>	<i>170</i>
<i>Figure 110: Two hypothetical scenarios. Neighbourhood A and neighbourhood B with same neighbourhood area, building density and street coverage but difference in average plot size, foot print size and courtyard size</i>	<i>170</i>
<i>Figure 111: Signification relationships.....</i>	<i>172</i>
<i>Figure 112: Policy hierarchy to counter UHI.....</i>	<i>175</i>
<i>Figure 113: Example of an area of grassland not supported by trees, which will tend to increase UHI (Wikipedia, 2016)</i>	<i>178</i>
<i>Figure 114: Vakilabad Boulevard: Example of area with less grassland which is supported by trees (Persiangig, 2020)</i>	<i>179</i>

Tables

<i>Table 1: Top ten CO₂ national emitters in the world. Iran is placed seventh in terms of GHG emissions but is much lower in terms of per capita CO₂ emissions (Scientists, 2020).....</i>	<i>4</i>
<i>Table 2: Types of mitigation and adaptation schemes by sector, based on:(Habitat, 2011)</i>	<i>11</i>
<i>Table 3: Approaches to residential urban design, based on :(Sheppard, 2015)</i>	<i>16</i>
<i>Table 4: Classification of street canyons relative to aspect ratio, source: (Afiq et al., 2012).....</i>	<i>34</i>
<i>Table 5: Four climate regions of Iran, based on (Eiraji & Namdar, 2011)</i>	<i>47</i>
<i>Table 6: Traditional climatic design features at the architectural and urban design scales for Bushehr (Motealleh et al., 2016)</i>	<i>49</i>
<i>Table 7: Climatic design strategies for Yazd, based on Keshtkaran (2011).....</i>	<i>50</i>
<i>Table 8: Comparison between modern and traditional urban and architectural characteristics, based on Marefat (1988).....</i>	<i>51</i>
<i>Table 9: Urban design legislation</i>	<i>52</i>
<i>Table 10: Comparison of UHI study approaches in Iran.....</i>	<i>78</i>
<i>Table 11: Comparison of two approaches to measuring surface temperature based on Mirzaei and Haghighat (2010)</i>	<i>79</i>
<i>Table 12: Different simulation approaches to studying urban climate characteristics.....</i>	<i>80</i>
<i>Table 13: Different vertical grid layouts in model area in ENVI-met</i>	<i>84</i>
<i>Table 14:Different types of lateral boundary condition in ENVI-met (ENVI-met, 2017b).....</i>	<i>87</i>
<i>Table 15: Shape files in GIS map or as created by author</i>	<i>93</i>
<i>Table 16: Material input data in Monde.....</i>	<i>95</i>
<i>Table 17: Model domain input in Spaces</i>	<i>96</i>
<i>Table 18: Meteorological requirements for advance setting in ENVIGuide</i>	<i>97</i>
<i>Table 19: Meteorological data from Mashhad City Council.....</i>	<i>98</i>
<i>Table 20:main meteorological input data.....</i>	<i>98</i>
<i>Table 21: Computer specification used for simulation.....</i>	<i>100</i>
<i>Table 22: Main Meteorological Input Data</i>	<i>107</i>
<i>Table 23: Material Input data: Ahmadabad and Majd.....</i>	<i>108</i>
<i>Table 24: Simulated Scenarios for time, duration, materials and Ts outputs.....</i>	<i>109</i>
<i>Table 25: Simulated Scenarios for lateral boundary and DEM and Ts outputs</i>	<i>114</i>
<i>Table 26: Simulated Scenarios for wind speed and offset boundary and Ts outputs.....</i>	<i>115</i>
<i>Table 27: UHI characteristics and urban characteristics—average values of selected area in D1 and D10.....</i>	<i>118</i>
<i>Table 28: The effect of different wind speeds on Ta and Ts</i>	<i>123</i>
<i>Table 29: Neighbourhood land use/surface materials and UHI characteristics</i>	<i>123</i>
<i>Table 30: Neighbourhood courtyard characteristics and UHI characteristics</i>	<i>126</i>
<i>Table 31: The frequency of all street orientations in all selected neighbourhoods.....</i>	<i>128</i>
<i>Table 32 : The frequency of plot orientations in all selected neighbourhoods</i>	<i>129</i>

<i>Table 33 : the frequency of building orientations in all selected neighbourhoods</i>	<i>131</i>
<i>Table 34: Main street, plot and building orientations in all neighbourhoods</i>	<i>132</i>
<i>Table 35: Code assigned to each orientation for Pearson correlation</i>	<i>133</i>
<i>Table 36: Street pattern and orientation comparison table. Average temperature in street orientation calculated from the same street orientation. For example, the average street orientation of E-W Street in a grid pattern is the mean of 1-A and 10-A. the average temperature of a street pattern is the mean temperature of all different orientations in that pattern. For example, the average temperature of an irregular street pattern is the mean of 1-D, 1-E2 and 10-B.</i>	<i>135</i>
<i>Table 37: Code assigned to each orientation for Pearson correlation</i>	<i>136</i>
<i>Table 38: Urban form characteristics and UHI characteristics</i>	<i>138</i>
<i>Table 39: UHI and urban characteristics of 1-A and 10-C</i>	<i>148</i>
<i>Table 40: UHI and urban characteristics of 1-F and 10-A</i>	<i>150</i>
<i>Table 41: UHI and urban characteristics of 1-A and 10-A</i>	<i>152</i>
<i>Table 42: UHI and urban characteristics of 1-E1 and 10-E</i>	<i>154</i>
<i>Table 43: The effect of vegetation on UHI</i>	<i>156</i>
<i>Table 44: UHI and urban characteristics of 10-A and 10-E</i>	<i>159</i>
<i>Table 45: UHI and urban characteristics of 1-B and 10-D</i>	<i>160</i>
<i>Table 46: The correlation between urban characteristics and UHI characteristics</i>	<i>166</i>
<i>Table 47: The correlation between trees, H/W aspect ratio and SVF</i>	<i>169</i>

Glossary

UHI	Urban heat island
GW	Global warming
IPCC	Intergovernmental panel on climate change
UTCI	Universal thermal climate index
VSHS	Very strong heat stress
EHS	Extreme heat stress
GHG	Greenhouse gases
T _{max}	Maximum air temperature
LST	Land surface temperature
LULC	Land use/land cover
TM	Thematic mapper images
UHII	Urban heat island intensity
UCL	Urban canopy layer
UBL	Urban boundary layer
SUHI	Surface urban heat island
IFOV	Instantaneous field of view
PV	Photovoltaic panel
T _{mrt}	Mean radiant temperature
PET	Physiological equivalent temperature
VMT	Vehicle miles travelled
HVAC	Heating, ventilation and air conditioning
SVF	Sky view factor
H/W	Height (building)/width (street)
L/W	Height (building)/length (street)
T _a	Air temperature
T _s	Ground surface temperature
N-S	North-south
E-W	East-west
CFD	Computational fluid dynamics
SET	Standard effective temperature
ABD	Average building density
STC	Street coverage
ABH	Average building height
APS	Average plot size
SC	Site coverage

1 Introduction

1.1 Background

Increasing urbanization is the new characteristic of our era and urban dwellers are predicted to increase to 70% of global population by 2050 (Bokaie et al., 2016). Urban areas and the people living in them are the main cause of increasing greenhouse gas emissions and approximately 70% of CO₂ emissions are created in cities (Canadell et al., 2009). Global Warming (GW), as a result of increased greenhouse gasses, leads to changes in climate. These changes include general changes to precipitation patterns and increasing storm intensity and frequency. Sea levels are also rising. The rise in atmospheric temperatures threatens human well-being, including human comfort and efficiency (Watkins et al., 2007) and is expected to lead to increased heat-related mortality (Dessai, 2003). Climate change is an international justice issue (Grasso, 2010) as the side-effects of global warming are strongly felt by vulnerable groups, often in developing countries (Thomas & Twyman, 2005). Stern and Stern (2007) state the following regarding the cost of climate change.

“Using the results from formal economic models, the Review estimates that if we don't act, the overall costs and risks of climate change will be equivalent to losing at least 5% of global GDP each year, now and forever. If a wider range of risks and impacts is taken into account, the estimates of damage could rise to 20% of GDP or more.

In contrast, the costs of action – reducing greenhouse gas emissions to avoid the worst impacts of climate change – can be limited to around 1% of global GDP each year”. (Stern & Stern, 2007)

Global Gross Domestic Product (GDP) in 2007 was US\$53 trillion (IMF, 2020), so 5% of this would be US\$2.65 trillion a year. Access to funding sufficient to take action on mitigation will not be affordable for many countries, including Iran (Fund, 2007).

Increasing urbanization also contributes to the Urban Heat Island (UHI) effect. This comes in part from the dry and dark nature of many construction materials in the built environment, as more heat absorption occurs downtown than in the countryside. As a result, urban areas become hotter than rural areas. This is a particular problem in modern Iranian cities where land is often left bare waiting for future development. These areas of bare land, generally next to buildings, form hot spots in the city. The UHI threatens both urban and rural inhabitants by raising energy consumption, increasing ground-level ozone, increasing human discomfort and related health

problems, and elevating mortality rates. Approximately 3 billion people are currently exposed to these problems and the number is estimated to become 5 billion by 2050 (Prospectus, 2003). Although GW and UHI come from two different sources, together both make cities warmer. GW is the result of greenhouse emissions caused by transportation and energy consumption in cities. UHI is the result of absorption of more solar energy due to the increase in impervious surfaces in cities. For this reason the term Urban Warming is used to refer to both problems together (Yumino et al., 2015). The relationship between the UHI effect and global warming is a matter of debate between scientists. However, the rise in the temperature of cities does not directly impact on global warming as less than 1% percent of world land is covered by cities. It is the social and economic activities of people that produce global warming, and the indirect influences are noticeable (Alcoforado & Andrade, 2008). High temperatures in cities lead to more use of air conditioners and consequently more energy consumption and greenhouse gas emissions (Figure 1).

Figure 1: Urban Warming: cause and effect

1.1.1 Global Warming in Iran

GW and the UHI effect are world-wide issues that also affect Iran. In the arid and semi-arid regions of Iran, minimum and mean temperatures have both changed dramatically during the last decades (Figure 2a & Figure 2b) (Kousari & Asadi Zarch, 2011), and annual rainfall has been measured as dropping by 67% (Modarres & Sarhadi, 2009).

Figure 2a: Spatial distribution of selected stations of Iran and its neighbouring countries (Kousari & Asadi Zarch, 2011)

Figure 2b: Trend of 10-year moving average normalized annual mean temperature index between 1955-2000 in arid and semi-arid regions of Iran (Kousari & Asadi Zarch, 2011)

Due to the harsh weather and cheap fossil fuels, the average use of energy is very high in Iran. As a developing country, Iran is highly dependent on energy, and 98% of Iran's energy consumption comes from carbon-based fuels (Hafeznia et al., 2017). In 2018 Iran was one of the top ten CO₂ national emitters in the world (Table 1) (Scientists, 2020).

Table 1: Top ten CO₂ national emitters in the world. Iran is placed seventh in terms of GHG emissions but is much lower in terms of per capita CO₂ emissions (Scientists, 2020)

Country	Total 2018 CO ₂ emissions Giga tonnes	Per capita 2018 CO ₂ emissions tonnes
China	10.06	7.05
United States	5.41	15.56
India	2.65	1.96
Russian Federation	1.71	11.74
Japan	1.16	9.13
Germany	0.75	9.12
Iran	0.72	8.82
South Korea	0.65	12.89
Saudi Arabia	0.62	18.48
Indonesia	0.61	2.30

These top ten countries together produce two-thirds of global CO₂ emissions (Nejat et al., 2015), although the situation does change when populations are taken into account. Soflaei et al. (2017) demonstrated that 34% of energy in Iran relates to building energy demand. The main energy consuming sectors in Iran are transportation, electricity generation, industry and the residential sector (Keyhani et al., 2010). Direct CO₂ emissions from residential activities increased 245% between 1990 and 2011 (Nejat et al., 2015). The Intergovernmental Panel on Climate Change (IPCC) has mapped how global surface temperatures have changed from 1901 to 2012, showing that many parts of Iran have demonstrated an increasing temperature trend, with surface temperatures increasing substantially in the centre and east of Iran (Stocker et al., 2013).

1.1.2 Urban heat island in Iran

Although there are studies on temperature trends in Iran, the study of UHI in its cities has remained neglected. This is partly due to the problems associated with studying surface temperature in Iran. Mirzaei and Haghighat (2010) have categorized the methods of studying UHI into “observational approaches” and “simulation approaches”. These two approaches are either expensive (observational approaches) or demand expert technical knowledge (simulation approaches). However, the importance of the UHI effect in Iran is undeniable. Recently, Roshan and Nastos (2017) assessed the Universal Thermal Climate Index (UTCI) in Iran. Their

findings were that 83.7% of meteorological stations reported UTCI classes of very strong heat stress (VSHS) and extreme heat stress (EHS). Moreover, 63.8% of the stations indicated there was long-term VSHS especially for the south of Iran. Mashhad which sits in the northwest of Iran suffers cold stress in winter and heat stress in summer. As a result, searching for thermal comfort and mitigation and adaptation strategies to GHG production in Mashhad is quite critical. In a study carried out by Kousari et al. (2013) the trends in measured maximum air temperatures in 32 synoptic stations over the whole of Iran were investigated. The results demonstrated a considerable upward trend for T max (maximum air temperature) in the hot months of April, June, July, August and September between 1960 and 2005. Cold seasons did not follow the same trend except in some parts in the west, north-east, south-east and central regions of the country. Bokaie et al. (2016) studied the association of Land Surface Temperature (LST) and Land Use/Land Cover (LULC) using Landsat Thematic Mapper Images (TM) satellite images in Tehran. The results revealed a negative relationship between LST and LULC. The lowest temperature was for water and green areas, and the highest temperatures were, in order from highest to lowest respectively, for paved areas, industrial areas, commercial areas, residential areas and transportation routes.

1.1.3 Global Warming countermeasures in Iran

Sadly, given the huge increases in greenhouse gas emissions the urban energy consumption, countermeasures undertaken by government have so far been unsuccessful. These policies either concern increasing the energy price or providing incentives for consumers to use more environmentally friendly products (Nejat et al., 2015). The same authors highlighted the weaknesses of this approach because it leads to less collaboration between responsible organizations, descriptive instructions rather than functional guidelines, continuing use of old construction methods related to false beliefs that energy efficiency would increase construction costs, no enthusiasm toward renovation, and no effort toward installing renewable energy systems (Nejat et al., 2015).

In Iran the Department of the Environment is officially responsible for environmental sustainability. The department consists of different sub-departments concentrating on different subjects, including environmental education, the natural environment, the marine environment, and the human environment. The mission of this department is focused on increasing green space, environmental conservation, control of waste, preserving existing natural and artificial green spaces with their flora and fauna, and producing less pollution (Environment, 2018). To

deal with climate change, in 2011 a national committee was established to keep up with international movements in this field. From 2011 to 2012, five meetings have been held to determine the national countermeasures and the related responsible organization or ministry to implement these. Despite the fact that the committee members have placed emphasis on national education, finding financial resources, and the urgent need for changes in technology, there have been no real outcomes in terms of policy instructions for reducing or preventing climate change. After 2012, no more meetings have been reported.

1.1.4 Urban Heat Island countermeasures in Iran

Providing more green space is a key factor in UHI mitigation as well as adaptation measures to deal with its effect. The idea of increasing green space will not be well received in Iran. Expanding green spaces in urban metropolitan areas has always faced big obstacles including land and water shortages, inappropriate soil, and financial problems (Nakhaei Moghaddam et al., 2008). These reasons can generally be divided in the two aspects of economic problems and environmental issues. Due to population growth and migration from rural areas into cities, the average land price in Iran increased by 828.73% from 2001 to 2011. Some provinces like Bushehr, Khorasan Razavi (Mashhad), and Hamedan have witnessed greater changes (Ghanbari et al., 2016). Meanwhile, due to a number of economic crises, land for commercial and residential use is in high demand while land for green space, education and sport uses is less sought after (Azimi & Pooyan 2014). Economic problems not only concern the land price but also the high cost of creating green space in Iran. Maintenance of these spaces has always imposed a financial burden on urban authorities (Beecham et al., 2008). As a hot and arid country, one of the main obstacles toward expansion of green spaces in Iran is the shortage of water (M. Amiri et al., 2009; Shooshtarian, 2010).

It appears that the important issue of UHI has not been considered a problem among urban designers and policy makers in Iran. Although pollution and climate change are issues for the human environment department, UHI is not yet seen as a significant problem by those involved (Environment, 2018). On the other hand, recently the number of environmental NGOs has increased remarkably. It is reported that there were around 550 environmental NGOs in 2003. However, they mostly focus on air pollution, environmental pollution, preserving animal species, vegetation, ecology, and the environment (Environment, 2018).

There is a lack of academic interest in studying urban heat islands, green space, and especially the relationship between them. From the literature (see chapter 2) it seems that to achieve a

more reliable LST analysis, researchers need to develop a specific urban heat island methodology. In terms of green space, researchers have concentrated more on the aesthetic-social and health aspects of green spaces in Mashhad. Three reasons could be considered as the main factors for this lack of research into the UHI effect. First is the lack of communication between the two disciplines of urban design and climate science. Secondly, there is also a lack of communication between Persian and international scholars due to political issues. Thirdly, universities in Iran would find it hard to afford the cost of the two main approaches described above of either observation or simulation. As a first step this thesis describes one effort to investigate UHI in a major city in Iran—Mashhad—using the simulation approach.

1.2 Problem statements, objective and research question

The increase in both CO₂ emissions and land surface temperatures in Iran is undeniable. Moreover, in both architecture and urban design, vernacular models like houses with a central courtyard or streets laid out in an organic form, have been replaced with modern designs like repeated rows of box-like buildings and wide, straight roads. In other words, due to the introduction of a modern lifestyle, traditional ways of living and consequently the morphology of cities have change dramatically in Iran. In addition, thanks to massive resources of oil and gas, petrol and gas are much cheaper in Iran than in other parts of the world. Given the often-harsh climate, cheap fossil fuels come as a relief for architects and urban designers, allowing them to build houses and cities that ignore climate. Since GW and UHI are contemporary problems created by modern cities the cure could be found in re-planning the built environment. The main objective of this study to find appropriate design and planning approaches in the city of Mashhad to diminish UHI effects.

In order to reduce the use of fossil fuels, Iranian cities need to be made more sustainable. Adaptation and mitigation strategies against global warming and UHI have been developed internationally but these may not be appropriate for Iran given its local climates, urban textures, and cultural, financial and political conditions. Current urban regulations in Iran do not deal with this and the reality is that there are no national guidelines to counter UHI. Given this situation the following research questions emerged.

1. Whether UHI countermeasures in Iran need to be localized?
2. For the city of Mashhad what is the effect of existing different neighbourhood patterns on UHI?
3. How are the urban characteristics of Mashhad correlated with UHI?

In addition, the research will also consider how any findings could be implemented in local planning, and what might be the best approach for doing this.

The research aims to develop a quantitative method with which to evaluate UHI effects, so as to provide climatic insights for urban designers and practical guidelines for policymakers and urban planners in the city of Mashhad.

1.3 Scope of the research

In order to address the research questions and aims, this thesis is divided into eight chapters.

Chapter 1 discusses the increasing concern about GW and UHI in Iran and the problems with finding national countermeasures against these issues. It introduces the research questions and aims of the research. It also provides an overview of the thesis organization.

Chapter 2 investigates the existing literature on urban warming and global countermeasures against it, including the cause and effect of UHI, different approaches to measuring UHI, and the relationship of UHI to urban design. It sets out the gap in knowledge addressed by this research.

Chapter 3 compares the urban characteristics of modern and traditional Iranian cities, then discusses the urban design process in Iran. Mashhad city, as the site of the investigation, is discussed in terms of urban growth, changes in land use, particularly the loss of green spaces and the effect of this on UHI. This chapter describes the two chosen case study districts in further detail.

Chapter 4 describes the research method used in this study and reasons for its choice. The simulation approach and the use of ENVI-met software are discussed. The validation of ENVI-met, data collection, and input and output data are explained.

Chapter 5 evaluates the sensitivity of the ENVI-met software by conducting different simulation scenarios. It includes scenarios with different start times, simulation periods, ground and building materials, different boundary sizes and wind speeds. The average Ts of the outputs are compared to discover an appropriate simulation approach for studying UHI in terms of speed and accuracy.

Chapter 6 presents a quantitative analysis of the outputs from investigating the relationship of urban characteristics and UHI characteristics. First the general characteristics of outputs are analysed, then each one is analysed individually.

Chapter 7 describes the significance of the correlation of neighbourhood characteristics to T_a and T_s . It also suggests some design and planning approaches for Mashhad city council to diminish UHI effects. Recommendations for dealing with UHI which would be suitable for the city council and urban design firms in Mashhad are made. Suggestions regarding using the simulation approach are discussed.

Chapter 8 summarizes the main achievements of the study. It reviews the research questions and aims. Limitations of the research are discussed and recommendations for future work are made.

Finally, appendices contain useful information that is not included in the main body of the thesis.

2 Literature Review

The existence of UHI and global warming and the damage imposed by them on the earth and human beings is undeniable. Many studies have pointed out cities are the main reason behind UHI effects (see 1.1) and in turn urban designers are in part the creators of the physical form of cities. It is important for urban designers to know what the main contributors to UHI are and how many of these they can control, so as to take measures against them. Therefore, in this literature review one goal was to find out what sort of countermeasures have been taken so far that are useful and practical. The other goal was to realize which urban characteristics are more important and effective than others. Answering these questions will help to prioritize the actions needed against UHI. To answer the research questions, knowing the different possible approaches to studying UHI that could be employed in this study of Mashhad was crucial. The method needs to be easy for urban design companies or the city council to use, and needs to be achievable within their budget and timeframe.

2.1 Urban warming countermeasures

Current urban warming is not only rooted in global warming but also in the UHI effect (Yumino et al., 2015). Actions against urban warming are generally divided into mitigation and adaptation strategies. Basically, mitigation is eliminating the reasons for a phenomenon while adaptation is reducing its side effects. In the following, GW and UHI countermeasures will be introduced separately, and then the importance of complementary actions will be discussed.

2.1.1 Global warming countermeasures

Technically, GW mitigation plans focus on minimizing existing and future greenhouse emissions, while adaptation attempts to make changes in the social and built environment to lessen the side effects of climate changes in the short term. Despite the fact that mitigation and adaptation strategies should be complementary, they are not always in harmony with each other (Biesbroek et al., 2009; Hamin & Gurran, 2009). Researchers have generally concentrated more on mitigation than adaptation. The sectors that captured more attention across the 100 cities studied by Broto and Bulkeley (2013) in a mitigation experiment were urban infrastructure (31.1% of cities), built environment (24.7% of cities), and transport (18.8% of cities). Adaptation strategies accounted for 12.1% of initiatives, followed by dealing with urban form (7%) and carbon sequestration (5%). Half of the strategies could not achieve mitigation while dealing with adaptation. Research conducted by Hamin and Gurran (2009) found 20 out of 50 actions for reducing global warming produced conflict between mitigation and

adaptation, but this was based on a business-as-usual scenario where work/education and home are separated by a journey. This perspective leads to the idea of the compact city as a means of achieving mitigation. However, for achieving adaptation, in many strategies, more land is needed in cities.

Conflict over land use is one reason for not being able to achieve mitigation and adaptation at the same time (Hamin & Gurran, 2009), although other work suggests conflicts could be avoided by making careful selection of both strategies (Laukkonen et al., 2009). Sprawling developments provide more green space, a necessary parameter for natural ventilation, natural light, urban cooling and storm water management (Hamin & Gurran, 2009). In contrast, compact cities seem to decrease vehicle travel, which consequently leads to reduced GHGs. Moreover, in some climates lower density and detached houses tend to consume more energy than higher density housing for heating and cooling (Ewing & Rong, 2008), while high-density areas limit tree cover, which is vital for cooling buildings and paving areas as well as capturing CO₂ emissions (Hamin & Gurran, 2009) (Table 2).

Table 2: Types of mitigation and adaptation schemes by sector (Habitat, 2011)

Climate change objective	Sector	Strategies
Mitigation	Urban infrastructure	<ul style="list-style-type: none"> -Alternative energy supply (renewable or low carbon) -Landfill gas capture -Alternative water supply -Collection of waste for recycling and reuse -Energy and water conservation measures -Network demand reduction measures
	Built environment	<ul style="list-style-type: none"> -Use of energy-efficient materials -Energy-efficient design -Building-integrated alternative energy supply -Building-integrated alternative water supply -New-build energy and water-efficient technologies -Retrofitting energy and water-efficient technologies -Energy and water-efficient appliances -Building-integrated demand reduction measures
	Urban form	<ul style="list-style-type: none"> -Urban expansion and suburban development -New urban development -Reuse of brownfield land -Neighbourhood and small-scale urban renewal
	Transport	<ul style="list-style-type: none"> -New low-carbon transport infrastructure -Low-carbon infrastructure renewal -Fleet replacement -Fuel switching -Enhancing energy efficiency -Mobility demand reduction measures (reducing travel) -Mobility demand enhancement measures (alternative means of travel)
	Carbon sequestration	<ul style="list-style-type: none"> -Urban capture and storage -Urban tree-planting programmes -Restoration of carbon sinks -Preservation and conservation of carbon sinks -Carbon offset schemes
Adaptation		<ul style="list-style-type: none"> -Cooling services and designs -Measures securing energy and water supply

		<ul style="list-style-type: none"> -Flood protection -Bushfire protection -Relocation and zoning policies -Blue and green infrastructure -Building codes for extreme weather -Early warning systems -Behaviour-based measures
--	--	--

2.1.2 Urban Heat Island countermeasures

Compacting the city as a mitigation strategy for GW (Jenks et al., 1996; Williams et al., 1996), increases temperatures in urban areas. Owing to the dry and dark feature of many construction materials in the built environment, more heat absorption occurs downtown than in the country. Cities and metropolises with more population suffer greatly as a result (Rizwan et al., 2008). Slower wind speeds, air pollution, and heat produced by human beings also aggravate the UHI (Gartland, 2012). The UHI threatens both urban and rural inhabitants by raising energy consumption (Konopacki & Akbari, 2002), increasing ground-level ozone (Rosenfeld et al., 1998), increasing human discomfort, and producing health problems and elevated mortality rates.

Much research into urban characteristics has been done to address mitigation of the UHI effect. Such mitigation can be divided into three different groups: (1) methods to reduce anthropogenic heat release (e.g. switching off air conditioners); (2) methods of different roof design (e.g. green roofs, white roofs, reflective roofs); (3) other design features (e.g. humidification, altering the albedo, photovoltaic canopies). In addition to the three groups, general planting to increase vegetation has become the most recommended mitigation method (Rizwan et al., 2008). For instance, parks are able to increase evaporation 300% more than their urban surroundings (Spronken-Smith et al., 2000). Green spaces are capable of producing a 10% reduction in cooling load (Yu & Hien, 2006). Street tree planting could decrease air temperatures by 4°C in the daytime (Y. Wang & Akbari, 2016), and each 0.6 km² park could decrease the temperature by 1.5°C (Ca et al., 1998). Similar to global warming, urban heat island mitigation and adaption strategies sometimes contradict each other. Although, green and highly reflective materials positively influence mitigation, highly reflective materials have a negative impact on adapting to urban warming and greening is also not as influential (Yumino et al., 2015).

2.1.3 Contradictions between countermeasures

To sum up, green mitigation strategies, due to their high land use rates, contradict other mitigation strategies against global warming, such as compact cities to reduce travel distances, although these, as stated earlier, are related to the organization of the local socio-economic system (Figure 3). Thus, these two phenomena together could increase the temperature in urban area. This research proposes a way of investigating both issues, as these can most commonly be influenced through urban design. This study will not propose new adaptation or mitigation strategies. The main purpose of this study is to evaluate and compare different urban design solutions that use both strategies in order to reduce heat in urban areas at the neighbourhood scale.

Figure 3: Conflicts between UHI and global warming mitigation and adaptation strategies

2.2 Urban design

Despite the repetitive use of the word, there is no precise definition for urban design (Frey, 2003). It seems that urban design is placed on a scale between urban planning and architectural

design. It has been described as the design of public spaces or the practice of creating a single composition of many buildings (Moughtin, 2003). Urban planning is the science of environmental, transportation and land-use planning, and has a relationship with landscape architecture, policy recommendations, administration and urban design. There is much literature about the definition of urban design that discusses the process, scale and product of urban design as well as the profession involved in this practice (Dagenhart & Sawicki, 1994; Gosling & Maitland, 1984; Madanipour, 1996; Wheeler & Beatley, 2014). This literature also describes the different approaches in the field of urban design, including the political, social, physical, economic and environmental. (Carmona et al., 2010) categorized the traditional approaches toward urban design as the visual–artistic, social usage, and making places. The visual-artistic focuses more on the aesthetic point of view (Cullen, 1995; Rasmussen, 1964), while social usage tries to make a city more practical. The third approach of making places is quality oriented. It aims to mix diverse activities according to their aesthetic aspects and specific identity (Bentley, 1985; A. Jacobs & Appleyard, 1987; Lynch, 1984).

The philosophical point of view has always been very important in urban design and architecture (Alexander, 1977; Broadbent, 2003; Venturi et al., 1977). Historicism, modernism, new modernism, post-modernism and many diverse contemporary styles have different approaches to shaping cities. For instance, important factors in modernist urban design could be regarded as promoting healthier and practical spaces that are vehicle oriented, using a non-historic approach (Middleton, 1983). The complicated nature of urban design needs specialists from different disciplines, including planners, architects, urban designers, landscape architects, and traffic planners (Moughtin, 2003).

2.2.1 Sustainable urban design

Carmona et al. (2010) divided contemporary urban design trends into two main groups: smart cities as a reaction to the information era, and sustainable cities as a response to global warming. Sustainability is a broad concept with no accurate world-wide accepted definition. Since 1990, the concepts of sustainability and sustainable development have both been used in urban planning and design (Wheeler & Beatley, 2014). Sustainability is an interdisciplinary concept, involving disciplines from natural, social, applied and engineering science in the investigation of behavioural patterns in order to develop solutions for the complex problems associated with human well-being and resource availability (Bibri & Krogstie, 2017). Sustainable urban development pursues the creation of healthy environments for human beings

with minimal intervention of natural eco-systems and consumption of resources (energy, materials), so as to have a lesser effect on the environment (Bibri, 2013). Sustainable urban design is concerned with the relationships between the larger scale buildings, streets, neighbourhoods, districts, parks, public infrastructure and spaces with the initial goal of make them environmentally and functionally more sustainable and attractive (Boeing et al., 2014; Inam, 2013).

The procedure for designing cities is crucial for sustainable development. Sustainable development in urban areas needs to include the three main aspects of the social, environmental and economic, sometimes known as the pillars of sustainability (Biddulph, 2007; Carmona et al., 2010). Jabareen (2006) categorized sustainable urban forms into four models: (1) compact city, (2) eco-city, (3) neo-traditional development (new urbanism), and (4) urban containment. The first three are considered to be the most important in regard to sustainability. Moreover, to create a sustainable urban form, density, compactness, diversity, and mixed land use should be considered in parallel with advanced design and management systems. (Whitford et al., 2001) stated that the percentage of land cover, roads, different types of vegetation, and bare soil are vital items to consider in sustainable urban design.

While the meaning of sustainability has become the subject of heated debate between researchers, less effort has been put into introducing sustainable design principles in urban design books. Many urban design studies and books concentrate on the visual aspects of urban design. Although these include advice about greening the city, there are no practical solutions or guidelines for urban designers when it comes to minimizing surface temperature. Bentley (1985) in the book *Responsive Environments*, despite giving very clear and practical guidelines for starting the early stage of urban design, did not offer advice on sustainable development or the important role of the built environment in global warming. In fact, all the guidelines given only fulfil socio-economic, visual-aesthetic and accessibility needs. Another example is the later book *Essentials of Urban Design* (Sheppard, 2015), which is about teaching the practice of urban design to students. The tools and guides provided seem very practical. The design guidelines for residential neighbourhood development focus on transportation, visual aesthetics and the socio-economic characteristic of a neighbourhood. However, there is no obvious advice for addressing global warming. The writer argued the target of ecologically sustainable development is supported by encouraging more compact, mixed-use and walkable spaces. Biddulph (2007) in the book *Introduction to residential layout* developed practical advice for designing neighbourhoods based on current thinking in this field. He went one-step further and

suggested any residential layout should meet sustainable criteria in the three dimensions of the economic, social and environmental. To achieve the environmental goal, he addressed four main themes: minimizing greenhouse emissions, waste reduction, conserving water, and enhancing biodiversity. For addressing reduction of emissions and biodiversity, the writer pointed out that density and green infrastructure are critical. However, the advice given on what to do is very general and unclear. For example, the benefit of high density with the provision of enough urban green space is described, but the ideal proportions for these two is not. Table 3 sets out Sheppard's approaches to residential neighbourhood development.

Table 3: Approaches to residential urban design (Sheppard, 2015)

Approach to Residential Neighbourhood Development	Design Guidelines
Socio-economic Characteristic	<ul style="list-style-type: none"> -Community facilities (neighbourhood green, hubs) -Local park: location and shape -Housing type -Local centres
Visual-aesthetics Characteristic	<ul style="list-style-type: none"> -Community facilities -Street design: connector streets -Street design: local streets -Street design: shared surfaces and pedestrian streets -Street design: detail -Street design: rear lanes and car courts -Housing configuration -Mid block link -Lot layout -Local park: design -House and garden design
Transportation Characteristic	<ul style="list-style-type: none"> -Street network: grid -Street network: culs-de-sac -Street network: integration -Street network: legibility and place making -Street network: hilly sites

As a result, it seems there is a gap in the advice offered to urban designers when it comes to mitigating urban warming.

2.2.2 Urban form

Urban form is defined as the spatial layout of different land uses in cities (Anderson et al., 1996). Urban morphology refers to the arrangement of masses and spaces (Carmona et al., 2010). Land uses, building structures, plot patterns and street patterns are the four main elements that shape the urban morphology (Conzen, 1960). However, in modern times the elements that affect urban morphology have changed. The shape, pattern and size of these

elements have changed during the last century as a result of different styles and theories. There is much literature on how to design these elements artistically. Sitte (1986) described methods for the design and decoration of streets and squares based on the aesthetic aspects of design and Moughtin (2003) validated Sitte's design principals through analysing valued city streets and squares which are historically important. Moudon (1997) used the elements of buildings, gardens, streets, parks, and monuments to describe urban characteristics. Oliveira (2016) is less comprehensive, describing cities as an urban tissue composed of forms—streets, blocks, plots and buildings. The different combinations of these elements create different types of city patterns. Based on the literature the neighbourhood structure consists of street pattern, urban block, building plot, density, and green space. However, there have been fewer attempts at understanding how these important elements of streets, blocks and plots might be arranged so as to reduce urban warming, or even to reduce greenhouse gas emissions.

2.2.3 Neighborhood characteristics

Bentley (1985) explained how to start neighbourhood design. This is done by dividing a neighbourhood block into smaller blocks by inserting a route-street system. The best size for blocks and streets is explained in detail but without looking at urban warming. Four scales for urban design analysis are defined: district (1000-2000m), neighbourhood (500-1000m), street scape (100-500m) and site (Figure 4).

Figure 4: Different scales in urban design (Google, n.d.)

2.2.3.1 Street pattern

Street patterns shape urban neighbourhoods and define accessibility. Biddulph (2007) categorised street patterns into five principal forms: the grid, the tree, the closed loop, Radburn and Poundbury (Figure 5).

Figure 5: Five principal street patterns (Biddulph, 2007)

2.2.3.2 Urban block

The urban block refers to the application of the street pattern to a neighbourhood area. In a block “buildings are placed around the edge of the site facing onto surrounding streets” (Rudlin & Falk, 2009).

2.2.3.3 Density

The meaning of the term density varies in different subjects and concepts. Cheng (2009) divided the concept of physical density into four main groupings based on population, buildings, geography, and social matters. Each group has other subdivisions, which are illustrated in Figure 6. This research will concentrate on building density and the effects of this on urban warming. The definition of plot ratio (the ratio of total gross floor area of building to site area) is very close to the perception of density in this research.

Figure 6: Density definitions (Cheng, 2010)

2.2.3.4 Green space

Scarcity of green space is a main concern in many urban neighbourhoods. The benefits of green space have been extensively discussed (Maas et al., 2006; Wolch et al., 2014), although land use in terms of the balance between density and distribution of green space are a matter of debate between researchers. Green space distribution in cities generally follows a hierarchical pattern (Biddulph, 2007), with people travelling longer distances to large green areas and local green areas being much smaller in size. The area of green space, the scale of the urban area and the accessible distance for the individual are thus fundamental to green space distribution.

On the other hand green space is one of important mitigation measures for UHI. Kleerekoper et al. (2012) highlight the cooling role of green space in cities as it leads to evaporation, vegetation to provide shading, and heat transfer at night. Moreover, their study states the main types of green space in cities are urban forests (parks), street trees, private green areas in gardens, and green roofs and façades. Swanwick et al. (2003) also distinguish between different types of urban green and grey space (Figure 7).

Figure 7: Space classification in an urban area (Swanwick et al. 2003)

2.3 Urban Form and Urban Warming

Since the spatial characteristics of a city influence its microclimate, appropriate urban design could be a way of affecting that same microclimate. However, countermeasures against urban warming generally include policies and actions to be applied in different sectors. This means the collaboration of different disciplines, and knowledge of research from that discipline is needed for each strategy or the combination of the strategies, something which might be difficult to achieve. This research aims to find how urban design might decrease the effect of urban warming but rather than doing this through policy the research is aimed at urban design. In this section, an appropriate approach for such urban design will be investigated.

2.3.1 Scale of measures

With the aim of reducing the effects of global warming much research has been done in terms of municipal strategies, policies, and measures (Broto & Bulkeley, 2013; Prada et al., 2016; Roy, 2009) or adaptation strategies in buildings (Puurunen & Organschi, 2013). In other words, these countermeasures differ in scale and detail. Policies are very general suggestions for ministries or municipalities at the scale of a country or city, while the geometry, spacing or

orientation of building is the province of urban design. Urban design, generally as it shapes the city (Mills et al., 2010; Prasad & Samuels, 2013), and specifically at the mid-scale of the neighbourhood, has been neglected when it comes to research in this area. Global collaboration between municipalities around the world has demonstrated determination to address GW, with parties including the Federation of Canadian Municipalities Partners for Climate Protection (FCM, n.d.), the Global Cities Covenant on Climate (World Mayors Summit on Climate Change 2010), and the C40 Cities Climate Leadership Group (C40 Cities, n.d.) (Yee and Felske, 2013). However, this needs to be accompanied with design advice at the microscale.

2.3.1.1 Macro scale

Mitigation and adaptation measures both concern policy, which implies long-term change in attitudes at the large scale (Tol, 2005). In the other words, actions against climate change have concentrated more on energy policies (Carraro et al., 2012). Most interventions as a reaction to global warming are in the field of energy in both the urban infrastructure and built environment sectors (Broto & Bulkeley, 2013). These strategies consist of looking at energy and its uses (demand side) and at its generation and distribution (supply side) (Kemp et al., 2010). Energy policies mainly concern more use of renewable energy, increased energy efficiency, and lower consumption in the different sectors of society, particularly in urban areas (Parshall et al., 2010). As part of energy policy, moving to low carbon has become another area of focus for decision makers. Low carbon policies aim to reduce greenhouse gas emissions (Gomi et al., 2010; Lehmann, 2012; Y. Li et al., 2011; Ye et al., 2015) noting again that 70 % of energy use and greenhouse emissions concern cities (Tao, 2011). The common interface between urban design and a low carbon policy could be urban planning, in terms of form, transportation, and buildings (S. Cao & Li, 2011; Feliciano & Prosperi, 2011; Z. Liu et al., 2011), thus involving the macro urban scale. The compact city is one solution proposed for reducing carbon emissions related to urban form (Glaeser & Kahn, 2010; Kamal-Chaoui & Robert, 2009). However, little research has made quantitative estimates of the influence of urban form on CO₂ emissions (Fang et al., 2015).

2.3.1.2 Micro scale

The definition of sustainable building is very broad. Two aspects have been suggested, the first being to bring down the level of fossil fuel consumption in buildings, and the second to reduce the impact of buildings on the natural environment (Williamson et al., 2003). Many countries have changed their building codes in pursuit of energy efficiency (Energy, 2014; Puurunen & Organschi, 2013). Knudstrup et al. (2009) described how this legislative development has three

steps concerning buildings; use of insulation in exterior walls, a decrease in the total window area; and more detailed estimation of energy requirements at the design stage. Architectural action to minimize urban warming has been divided into four categories: adjusting building shape and layout, urban surface alteration, creating shade, and diminishing anthropogenic heat release (Yumino et al., 2015).

2.3.2 Translation of urban warming science into urban design

As designers, we must know the consequences of our design (Biddulph, 2007). Several studies have highlighted the important role of urban form, urban design and sustainable urban development in both UHI and global warming mitigation. Y. Wang and Akbari (2016) studied the effects of cooler surfaces for the pavement, roof and green areas through simulation using the software tool ENVI-met. They emphasized that urban form highly affects two important items for thermal comfort: how much direct sun is received and the mean radiant temperature. In another study Hamin and Gurran (2009) highlighted the land-use conflict between mitigation and adaptation strategies against global warming, and proposed that urban form solutions could minimize these conflicts. They argued linear green areas along transportation routes would work better than large area of vegetation. Moreover, they proposed medium density development with natural cooling and use of solar power for urban areas, but their suggestions for the type, size and shape of open space are vague, apart from the fact it should be designed to maintain a balance between density reduction and biodiversity conservation.

The goal of cooler urban areas is not achievable if global warming science cannot be translated into urban design practice. The absence of effective communication as well as no common language between scientists in both fields, could be key reasons for this problem (MacKillop, 2012). Moreover, implementing urban anti-warming measures in the planning process has emerged as another issue (Kleerekoper et al., 2012). The crucial question is when urban designers could utilize knowledge of countermeasures in the design process. From the design point of view, there are two different approaches for mitigation measures. These are those that can be applied during the design and planning stages (e.g. sky view factor and building material choice), and those that can be utilized after the design and planning stages (e.g. treeing green areas and roof spray cooling) (Rizwan et al., 2008). Whitford et al. (2001) believe appropriate urban design could help mitigation strategies. It seems the problems are well understood by planners and urban designers, but the results of most relevant research are not useful for those working in urban planning and design practice (Mills et al., 2010). Choosing the wrong kind

of vegetation for green roofs can lead to lessening the cooling effects. Similarly, urban designers often lack knowledge about materials in terms of their behaviour in a particular climate (MacKillop, 2012).

2.4 Urban Heat Island (UHI) effects

The main causes of UHI are anthropogenic heat production and re-radiation of absorbed solar radiation by hard surfaces, as both elevate the Urban Heat Island Intensity (UHII). UHII is the difference between urban temperature and rural temperature in the same location. Sometimes the temperature difference between the present and the past is also called UHI (Rizwan et al., 2008). The same authors also stated that re-radiation of energy absorbed by built environments has a significant effect on UHI.

UHI effects can be studied and measured in the three different layers of the atmosphere. These are the boundary layer heat island, canopy layer heat island, and surface urban heat island (SUHI) (R. Oke, 1997). As the underlying mechanism is different for each layer, it is vital to determine the target of the study. An atmospheric heat island refers to the Urban Canopy Layer (UCL) and Urban Boundary Layer (UBL). The UBL loosely occurs above roof level and makes changes in air flow, thermal turbulence, convective structure, mixed layer depth and local circulation systems (T. Oke, 1995). The UCL is located between the UBL and the surface/ground layer, thus between the base of the UBL and roof level. It is usually measured with a sensor at certain heights or by a vehicle traverse. The UBL heat island is measured differently, and needs more advance sensors installed in high-rise buildings, or via balloon flights or low flying aircraft. The best time for studying the atmospheric heat island is at night due to the difference in radiative cooling between rural and urban areas (Voogt & Oke, 2003). The SHUI needs to be observed using remote thermal sensors. Figure 8 shows the position of UBL, UCL and SUHI.

Figure 8: Schematic of the climate boundary layers

Researchers use different indicators for quantifying UHI such as air temperature and surface temperature. Since UHI is caused by many different heat sources, it is very difficult to define it with a single indicator. A useful approach is the Surface Energy Balance (SEB). This is the heat that has been produced and contained in one area. It is calculated using the SEB equation (Tim R Oke, 1988).

$$Q^* + QF = QH + QE + \Delta QS + \Delta QA$$

Q^* : net all-wave radiation: the difference between incoming and outgoing short and long-wave radiation

QF anthropogenic heat release

QE turbulent sensible heat flux

QH turbulent latent heat flux densities

ΔQS the sensible heat storage

ΔQA the net heat advection

The Urban Heat Island Intensity (UHII) is the air and/or surface temperature difference between an urban to rural area in the same locality. The mean and maximum temperatures are usually used in the comparison (Rizwan et al., 2008). The UHII is considered to be one of the urban warming indicators (Y.-H. Kim & Baik, 2005; Memon et al., 2009). The air temperature could be measured through weather stations, data collection using automobiles, and site survey data. The surface temperature could be collected through use of space technology with a clear sky. Space temperature has also been used to determine SEB. Numerical modelling has been employed to study UHI by prediction of air temperature (Takahashi et al., 2004) or anthropogenic heat release (Kato & Yamaguchi, 2005).

2.5 Parameters that contribute to UHI

The overall objective of this study is to examine the extent to which changes to urban characteristics can be used as a strategy to reduce the daytime heat in the city of Mashhad, in Iran. This section discusses these urban characteristics and their potential effect on UHI.

Causative factors for a UHI could be summarized as follows (Timothy R Oke, 2002; Santamouris, 2013) (Figure 9):

- 1- Increased short-wave radiation absorption due to low albedo materials in buildings. The effect increases when short-wave radiation is trapped in street canyons through multiple reflection
- 2- Increased GHG emissions absorb and re-emit long-wave radiation
- 3- Decreased long-wave radiant heat loss due to high H/W aspect ratio of canyons. Heat is absorbed by building materials before being release to the atmosphere

- 4- Increased anthropogenic heat through human activities
- 5- Increased heat storage by impervious surface materials which cover whole cities compared to rural areas
- 6- Decreased evaporation and cooling effect of vegetation by replacing this with hardscape
- 7- Decreased cooling effect of airflow in urban canyons when buildings block winds.

Figure 9: Causative factors for UHI (Kleerekoper et al., 2012)

Many studies focus on finding causative factors for UHI however, these causative factors need to be categorized and lead to clear recommendation for urban planners. In one of the earliest attempts to study the ranking of parameters, Oke et al. (1991) listed eight different causative factors for UHI and then used a surface heat island model (SHIM) to assess them. The setting of the simulation program was either the base set or a manual set by the researchers. Among the factors, canyon geometry was placed first, and then thermal properties. Perhaps, surprisingly, at the bottom of the list were greenhouse gas emissions and surface emissivity. Salvati et al. (2017) summarized the key parameters responsible for UHI in Barcelona and Rome and placed these into eight categories ranging from city size and urban form to wall material and anthropogenic heat. They also tried to assess the weighting of the parameters as contributors to UHI by comparing air temperature. Based on their study, urban morphology had the most significant effect by increasing annual mean UHI by 120%. In another study which was conducted as a literature review by Nuruzzaman (2015), the author highlighted the major role of green vegetation in affecting UHI among other factors like high albedo materials, urban planning and water bodies. Anthropogenic heat, impervious surfaces, and three-dimensional urban geometry, which was divided into three other subcategories including vertical walls, radiation trapping, and reduction in wind speed have been listed as affecting UHI by another researchers (Ryu & Baik, 2012). The same researchers simulated the air temperature of idealized urban scenarios in mid-latitude with manual meteorological settings. In another study vehicle temperature traverses measured air temperature in summertime afternoon hours in Portland, Oregon. Important factors for UHI included canopy cover, street

area, vehicular fuel combustion, HVAC (Heating, Ventilation and Air Conditioning) systems, and other anthropogenic producers which are not true urban characteristics (Hart & Sailor, 2009).

Figure 10 categorizes the important parameters responsible for UHI. Excessive levels of these could increase UHI. This study concentrates on the neighbourhood scale, and therefore the focus here is on urban characteristics as a background to the urban climate.

Figure 10: Categorization of key factors responsible for UHI. The light grey boxes show the area of interest for this study

2.5.1 Urban form, energy use and GHG emissions

GHG emissions store heat and enhance air temperature. Urban form has been claimed as having the potential to contribute to a decrease in the GHG emissions generated by transportation and building energy usage, although evidence of the precise influence of urban form is mixed. Anderson et al. (1996) argued the impact of urban form on energy and emissions is still unproven. Newman and Kenworthy (1989) in their book *Cities and automobile dependence* showed a high density city like Hong Kong consumes less transport energy per capita than Houston, a low density city. Y. Chen et al. (2011) investigated the relationship between urban form and energy use in cities. Their findings demonstrated the size of cities and irregularity of urban land use patterns increased energy consumption, while having a large urban density reduced it. Ewing et al. (1997) also investigated the relationship between urban form and greenhouse gas emissions. They found that if the density is doubled the vehicle miles travelled (VMT) diminish by 5 percent. On the other hand, C. Liu and Shen (2011) found that urban form characterized by density, diversity, street design, and accessibility, does not influence the total energy used by vehicles or VMT. However, a NASA study suggested road transportation is predicted to become the biggest contributor to global warming in the next half century (Burwell, 2010). The problem is that this is something that can only be controlled by policy makers rather than urban design.

X. Liu and Sweeney (2012) looked at compact city and sprawl scenarios in the Dublin region in Ireland, with the aim of measuring domestic heating energy consumption per household. Their investigation showed that compact city dwellers use 16.2% less energy to heat their buildings. They concluded a compact city decreases the use of energy-related CO₂ emissions. Byrd et al. (2013) studied the environmental benefit of utilizing PVs (photovoltaic panels) on both individual buildings and whole urban areas in Auckland, New Zealand. The outcome was that low density sprawl collects more solar energy. Such results are climate dependent but again the issue of generating energy from roof mounted PVs is an issue for policy makers rather than urban designers.

2.5.2 Urban microclimate

The climate of an area is influenced by its latitude, longitude, geographical characteristics and is usually assessed by physical parameters such as wind speed, temperature and precipitation (Erell et al., 2012). Yoshino and Yoshino (1975) categorized the climate into four levels based

on scale, these being microclimate, local climate, mesoclimate and macroclimate. Microclimate is the closest to the earth while macroclimate is the furthest away. Microclimate in an urban area also has three levels (UBL, UCL and urban surface layer), which were discussed earlier (see section 2.4) (Figure 11). The microclimate of a dense city in terms of building footprints is usually different from that of a less dense suburban area or rural hinterland. Temperature (or urban heat island), fog, wind and pollution levels are all affected by the nature of cities.

Figure 11: Schematic diagram for the scale of climate (Yoshino & Yoshino, 1975)

Studies have emphasized that UHI is highly impacted by local climate and geographical features (Mohajerani et al., 2017; L. Zhao et al., 2014). Debbage and Shepherd (2015) conducted research in fifty populated cities in the USA and found that the atmospheric condition, such as being a stable climate, or geography, such as distance from water bodies, have a great impact on UHI. Peng and Jim (2015) in their study on the thermal effects of green roofs in Hong Kong, indicated background climate parameters like “Air temperature, relative humidity, wind speed, solar radiation, and soil moisture” could vary the thermal effect by 83.6%–86%. X.-L. Chen et al. (2006) used thermal images for studying the LST of the Pearl River Delta and Shenzhen region in China. They found air temperature and humidity affect UHI intensity and predicted that the UHI effect was less in arid areas.

For atmospheric processes, land surface is the main area factor in energy activity (Foken & Napo, 2008). Surface temperature is the result of surface energy activities such as energy absorption and emission, energy translation and energy transmission. The physical properties of surfaces such as vegetation cover, imperviousness or other land cover affect surface temperature (Miaomiao et al., 2011). In turn, surface temperature modulates the air temperature

of the lower layers (Voogt & Oke, 2003). As can be seen in Figure 12, climate physics form a very complicated area for urban designers.

Figure 12: Schematic diagram of the radiation and energy fluxes at the earth's surface (Foken & Napo, 2008)

Air temperature is an important metrological parameter that shows the hotness or coldness of the weather measured in degrees. There are many different types of air temperature which usually relate to the different vertical layers. For urban designers the air temperature related to pedestrian level is important. Unlike warmed surfaces the air does not emit radiation efficiently. Mean radiant temperature is a physical quantity that shows the interaction between the human body and the outdoor climate. Another important influence on near-surface climate is evaporation. The transformation of liquid into vapour can cool the atmosphere around it. Such evaporation mostly happens around soil and vegetation. Wind flow can help in distributing this cooler air. When wind approaches an urban area, it creates an airflow pattern (Figure 13). The cooling effect of an airflow in summer or at night could decrease the UHI effects. Like UHI, airflow can be studied in different layers, such as the urban canopy layer and urban boundary layer. There are more obstacles to airflow in UCL than in UBL, due to the presence of buildings and trees.

Figure 13: Airflow behaviour over an array of barriers (Shishegar, 2013)

Wind velocity is an important parameter when it comes to the study of the relationship between canyon (a narrow street profile) orientation, wind direction and aspect ratio (the height to width of an open space like a street) (Chatzidimitriou & Yannas, 2017).

2.5.3 Urban characteristics

Knowledge about UHI is rooted in scientific studies which are more based on theory. Moreover, each research study tends to focus on one or two items. Street width, building height, and the portion of the plot occupied by buildings were used in a study of urban thermal comfort by (Johansson, 2006). Kleerekoper et al. (2012) emphasized that an urban area influences its climate at the small scale through its urban characteristics like geometry, orientation and spacing of buildings. The shape, orientation, height and density of buildings, and glazing ratio are mentioned as critical choices at the early stage of designing a master plan by MORELLO et al. (2009). Studies that have investigated the relationship between urban morphology and UHI have concentrated on building density (Adelia et al., 2019; Yuan & Chen, 2011), height to width (H/W) aspect ratio (Achour-Younsi & Kharrat, 2016; Chatzidimitriou & Axarli, 2017), and sky view factor (SVF) (Ahmadi Venhari et al., 2019; Svensson, 2004; Yuan & Chen, 2011). The important urban characteristics that can influence UHI effects are urban surface materials like asphalt and concrete pavements, the amount of vegetation both as grass and trees, building densities in terms of both the number of storeys and building volume, and the total number of buildings.

2.5.3.1 Land cover

For the purpose of UHI countermeasures, land cover can be studied in two different ways, by looking at land use and surface materials. In this study land use refers to the different usages of land such as for a residential area or a park. Most of the time land use and surface material are related to each other, but it is important to separate them for studying UHI. This is because while the different land uses show different UHI effects, material changes in the same land use area could affect UHI, such as the effect from having a green roof instead of a normal roof.

2.5.3.1.1 Land use

One approach in UHI studies is finding strategies which help to cool cities or reduce the energy being absorbed and then to try to implement these in urban design principles. There is strong relationship between land use and UHI, and change in land use is one of the main causative factors of UHI (X.-L. Chen et al., 2006; H. Zhang et al., 2013). Changing the pattern of natural land cover from a mixture of soil, vegetation and water to impervious surfaces in a built

environment diminishes evaporation and increases solar radiation absorption. A temperature difference is not only found for different land uses but can also occur in same one based on its specific urban characteristics (X.-L. Chen et al., 2006).

Research conducted by Kleerekoper et al. (2012) investigated urban characteristics like green space, water, built environment, and materials to understand their influence on reducing the UHI effect by a review of countermeasures against UHI. They made a number of general suggestions for UHI mitigation in the Netherlands like having street trees in urban areas, orientation of streets to reduce solar gain, and having green roofs, but they had no clear solution for planning the built environment. Bokaie et al. (2016) studied the association of land surface temperature (LST) and land use/land cover (LULC) using land sat TM satellite images in Tehran, Iran. Their results illustrated a negative relationship between LST and LULC. The lowest temperature was for water and green areas, and the highest temperatures were, respectively, for paved areas, industrial areas, commercial areas, residential areas and transportation routes. J. Li et al. (2011) studied the influence of landscape structure and layout in Shanghai, China by measuring land surface temperature using Landsat ETM+ images. Their results demonstrated that an impervious surface area raises LST. Although in this same study industrial spaces created more UHI, thanks to their lower proportion in the total urban area, residential areas were the main cause of high LST.

In a study of the Special Economic Zone of Shenzhen, X.-L. Chen et al. (2006) classified the urban area into eight land use types. These were "...road, vegetation (forest and grassland), water, residential area in low and high density, recreational area, and industrial area (High-tech area)." They found the highest temperature was in the road category, followed grassland and bushes, which were mainly found in the residential areas, and third were recreational areas "...because of lots of impervious surfaces and frequent human activities."

Commercial space and dense areas were ranked the hottest areas and open and green areas the coolest in Delhi, India in a study by Mohan et al. (2013). Most studies suggest that increasing the green area within cities will decrease the UHI effects (Jenerette et al., 2007; J.-P. Kim & Guldmann, 2014; Kotharkar & Surawar, 2016). However, these results are not always in total agreement. For example positive and negative relationships between urban vegetation and LST, have both been reported (J. Li et al., 2011; X. Li et al., 2012). This may have happened because the results from the special pattern of green spaces are highly dependent on the special resolution of images taken by different satellites (X. Li et al., 2012). Not only is the term green

space very general and in need of more explanation but the land for increasing green space is limited and in arid climates water shortage makes looking after such space more difficult. It thus seems that simply increasing green areas in cities will not necessarily reduce the UHI effect.

It is important to note that most studies on the relationship of land use to UHI have been done using satellite images and studying LST.

2.5.3.1.2 Building density

Since buildings absorb and store solar heat due to their often dark and non-reflective materials, building density is one of the main factors related to the UHI effect. A dense built environment, in parallel with building orientation, could control wind velocity in cities. A decrease in wind velocity leads less convection and consequently a higher air temperature. Early studies on UHI showed that having a compact core in cities increases the UHI effect. In contrast to this, Stone Jr and Rodgers (2001) showed that lower density and sprawl patterns increase the surface temperature due to the release of more radiant heat energy per parcel of land. They analysed high quality pictures from NASA to investigate the association of heat energy and single-family residential parcels. The results show lower density produces more radiant heat energy which aggravates the UHI. Alobaydi et al. (2016) investigated ground surface temperature, air temperature, and mean radiant temperature of three different urban layouts related to density (compact, detached, attached) in Baghdad using the Envi-met software. Green space, materials, and street shape were excluded from their investigation. The results showed increased density led to a lower UHI effect. Low density and low vegetation contribute to higher surface temperatures than high density and high vegetation (J. Li et al., 2011). Debbage and Shepherd (2015) argued neither high density nor sprawl are the influential factors on urban heat island but that spatial contiguity plays an important role. Palme et al. (2016) in their research into UHI contributing factors, indicated increased building density had increased the UHI in some cities while decreasing it in others. The negative effect of high density was mentioned in another study (Perini & Magliocco, 2014). It seems there could be an optimum value for building density to minimise UHI, although this might well be climate specific. There is a need to control heat gain in hard surfaces, and also to create shadows to effect solar absorption. However, density must not be such that it creates more CO₂ emissions from the use of air conditioners to control internal heat gains.

2.5.3.1.3 Surface materials

Urban surface materials influence solar radiation absorption according to their reflectivity. Their low permeability could also increase air temperature. Impervious surfaces have higher thermal conductivity than green spaces, and the heat stored in them during the day is released both at day and night. Therefore replacing hard materials with green surfaces could modify the built environment (Imran et al., 2019) and the UHI effect. As a result, studies have looked at green roofs (Costanzo et al., 2016; Sharma et al., 2016), green walls (H. Herath et al., 2018a, 2018b), albedo (Fahmy et al., 2018; Morini et al., 2016), and materials with special thermal properties, such as thermochromic coatings for buildings (Karlessi et al., 2009; Ma et al., 2002). These studies could be categorized into three main areas of focus: roof materials, wall materials and pavement materials. High albedo materials have attracted more attention (Taha, 1997), with a concentration on cool roofs (X.-X. Li & Norford, 2016; Roman et al., 2016). The main characteristic of a cool material is having a high albedo. Cool materials are considered to be a cost-effective and quick strategy to reduce UHI in comparison with adjusting the urban fabric (Y. Wang & Akbari, 2014). Cool pavements have not been fully explored and their influence on air temperature is unknown (Qin, 2015).

Impervious surfaces are usually made of asphalt and concrete. The albedo of fresh asphalt is 0.04 to 0.06 (H. Li et al., 2013; Taha et al., 1992), which increases with aging (Tran et al., 2009). The albedo of concrete is 0.2 to 0.3 (H. Li et al., 2013). However, the type of concrete and the aggregates used could increase the albedo. High albedo roof materials could also reduce the temperature (Susca, 2012). However, the effectiveness of a high albedo material depends on other factors like building characteristics, urban characteristics, and climate (J. Yang et al., 2015).

Most studies that have compared the influence of green spaces and impervious surfaces on LST have argued that green spaces have a negative impact and impervious surfaces a positive impact on LST (Estoque et al., 2017). Hendel et al. (2018) ranked pavement materials from coolest to warmest. Grass was top as the coolest material and asphalt was the warmest material. Granite sidewalks and asphalt roads were placed in between. Their results showed that surface albedo and the evapotranspiration characteristics of materials could predict surface temperature. On the other hand, Golden and Kaloush (2006) showed that rather than albedo, heat storage capacity and pavement thickness were the predominant material parameters for surface temperature prediction for roads. The reason behind these contradictions in results could come

from different study locations, a different definition of green space or/and different methods of measuring LST.

2.5.3.2 Urban form

2.5.3.2.1 H/W ratio

Street design is crucial element in climatic urban design (F Ali-Toudert & Bensalem, 2001). It is affected both by indoor and outdoor climate and has an important influence on pedestrians. The main problem with street design is the different thermal needs in different seasons. This is more complicated in a city like Mashhad which has hot summers when wind flow and shading are important and cold winters when wind deflection would be of benefit. A street canyon is usually described as a narrow street surrounded by buildings and defined by the aspect ratio (H/W), where H is the average height of buildings and W is the width of the street. This value together with the length of the canyon also defines the different classifications of an urban canyon as described in Table 4 (Afq et al., 2012). The effect of wind on a street canyon is illustrated in Figure 14. Wind could be parallel or perpendicular to the street orientation or be an oblique flow based on its direction to the street and buildings, and flow be upwind, or backwind based on the wind direction.

Table 4: Classification of street canyons relative to aspect ratio, source: (Afq et al., 2012)

Aspect ratio	Classification
$H/W < 0.5$	Avenue canyon
$H/W = 1$	Regular canyon
$H/W > 2$	Deep canyon
$L/H < 3$	Short canyon
$L/H = 5$	Medium canyon
$L/H > 7$	Long canyon

Figure 14: Left: Geometric street canyon. right: top view of wind directions approaching a street canyon (Afq et al., 2012)

The H/W ratio is an important factor in controlling solar access to the urban fabric (Arnfield, 1990). Generally, the H/W ratio is divided into two main categories; symmetrical where there is little variation in the proportion of height to width and asymmetrical when the opposite occurs. Researchers have investigated H/W and its impact on UHI in different climates. For example, in a tropical climate (Agapiou, 2006; Emmanuel & Johansson, 2006), a hot and dry climate (Fazia Ali-Toudert et al., 2005; Johansson & Emmanuel, 2006), and a Mediterranean climate (Andreou, 2013; Giannopoulou et al., 2010). Qaid and Ossen (2015) studied the impacts of both symmetrical and asymmetrical urban canyons in a tropical climate. Their results showed an asymmetrical canyon with an aspect ratio of 2-0.8 $((H_1-H_2)/W)$ where tall buildings blocked the wind and created afternoon shadows, was better than symmetrical one. In another study that was conducted with ENVI-met (Fazia Ali-Toudert & Mayer, 2006), a symmetrical street canyon was investigated for thermal comfort. Their findings showed that thermal comfort and heat stress strongly depended on H/W ratio and street orientation. Most studies have shown a lower surface temperature for shaded areas (Coronel & Alvarez, 2001; Yoshida et al., 1990). Nakata-Osaki et al. (2018) developed a GIS tool for investigating the maximum intensity of UHI (UHI max) based on the aspect ratio (H/W). Their findings revealed UHI_{max} tended to follow the H/W value. However, with the same H/W ratio, urban canyons with higher roughness relative to length had a UHI_{max} that was approximately two times smaller. In general, H/W ratio has a negative relationship with UHI (M. A. Bakarman & Chang, 2015).

2.5.3.2.2 Sky View Factor (SVF)

The sky view factor is a measure of the degree to which the sky is visible from a certain point on a surface in a built environment (Grimmond et al., 2001). Technically, SVF is the ratio of radiation received by the surface to the radiation emitted by the hemispheric environment (Watson & Johnson, 1987). It represents the density of the environment. In other words, if the SVF is equal to one it means the area is open to the sky without any obstacle to block the view and if it equals zero it means the area is indoor space (Figure 15). Trapping radiation in the built environment decreases surface cooling at night. SVF is thus an important urban geometry indicator which has been studied by researchers. For example, for investigating thermal comfort (Johansson, 2006; Lin et al., 2010), for urban climate modelling (Hämmerle et al., 2011; Middel et al., 2018), for urban planning (López et al., 2016; Rafieian et al., 2014) and for UHI effects (Tan et al., 2016; Yuan & Chen, 2011).

Figure 15: Schematic of the concept of SVF

There are different approaches to studying SVF, and like UHI these approaches can be divided into two main groups; the observational approach and simulation approach. Both approaches could employ different methods for calculating SVF. One method is the geometric (Chapman et al., 2001; Tim R Oke, 1981; Watson & Johnson, 1987), another is the fisheye lens method (Chapman et al., 2001), and a third through using GPS signals (Chapman & Thornes, 2004). Gál et al. (2009) noted there was little difference between simulation analysis (vector-based) and observational analysis (raster-based). While the numerical method created more accurate results, the raster-based needed less time. Researchers have employed a variety of platforms for simulating SVF, including TownScope (Matzarakis et al., 2010), RayMan (Matzarakis et al., 2010), SOLWEIG (Lindberg & Grimmond, 2011) and ENVI-met (Ahmadi Venhari et al., 2019; Rafieian et al., 2014). (Park & Tuller, 2014) used the raster based approach to study SVF using the HURES model. Their results showed the HURES model gave more accurate results than ENVI-met 3.1 or RayMan Pro, while all three models underestimated SVF.

Svensson (2004) showed there was a good relationship between SVF and T_a at night in different areas of Gothenburg, although not all researches are in agreement about the relationship between T_a and SVF. Yuan and Chen (2011) tested 18 different case study areas each 600x600m square in Hong Kong, and their results revealed that the T_a could drop by 0.4°C if the average SVF was elevated by 10%. They also found that the average SVF was correlated to the average building height and site coverage ratio. Therefore, to mitigate UHI effects, they suggested urban planners need to increase building height and decrease site coverage ratio to minimize SVF. As T_a in an urban area is continuous and changing, the calculation of the SVF also needs to be continuous to provide a logical base for comparison. If the SVF is obtained from separated points in a built area the T_a does not show a relationship to it (Yuan & Chen, 2011). In contrast, a larger sky view factor could be associated with a higher air temperature (F Bourbia & Boucheriba, 2010). Y. Wang and Akbari (2014) investigated SVF in more depth. They conducted simulation research utilizing ENVI-met in four case study areas each 300x300m over 24-h in both in summer and winter. All areas

included vegetation. Their study showed that the time and season of an urban climate study is very important. They found a higher SVF led to a lower T_a in both winter and summer at night time, but a higher T_a in day time in summer (Y. Wang & Akbari, 2014). Therefore, to come up with good urban planning suggestions, the duration of cold days and warm days and their effect on energy consumption for heating and cooling needs to be taken into account.

2.5.3.2.3 Street orientation

In a grid canyon the orientation of streets is usually defined by the long axis. Streets can affect and even control solar radiation and wind speed, which makes street orientation a challenging task for designers (Esch et al., 2007). Street characteristics affect the absorption, emission and ventilation characteristics of a neighbourhood. By absorbing more solar radiation north-south street canyons lead to lower ground irradiance in summer than those facing east-west (Arnfield, 1990). However, a study conducted by (Andreou, 2014) on the Island of Tinos, Greece found exactly the opposite. Three different air regimes could happen in an urban area, “(a) the isolated roughness regime; (b) the wake interference regime; and (c) the skimming regime. The conversion from one regime to another happens at critical combinations of H/W and L/W ” (Shishegar, 2013). Street orientation can be studied through its effects on wind direction and on solar exposure. E-W streets in a hot dry climate receive more solar radiation and have higher T_a and T_s (Fazia Ali-Toudert & Mayer, 2006). A NW-SE orientation in a hot arid climate leads to a lower temperature than NE-SW streets (M. Bakarman, 2017).

Fewer studies have been done on the orientation of buildings or streets and the effects of this on UHI. In a study in Tehran conducted by Farhadi et al. (2019) using ENVI-met, buildings in a selected area were rotated 30° towards east. The results showed the lowest T_a came from doing this in comparison with a green model and cool material model. In another study, perpendicular streets in two case studies in the Cycladic Islands were considered. The results showed that T_a did not have a significant relationship with street orientation but did with a combination of street axis and airflow (Andreou & Axarli, 2012). Their findings also showed that an E-W axis parallel to the wind had a higher T_s than a N-S axis street canyon. Other studies have suggested that T_a is more affected by regional climate than T_s or street orientation (Bärring et al., 1985; Pearlmutter et al., 1999; Shashua-Bar & Hoffman, 2003). However, other studies have indicated that street parameters like H/W aspect ratio and orientation have the most influence on canyon microclimate (Arnfield & Mills, 1994; Yoshida et al., 1990). It seems that street orientation is a matter of debate, although there is less doubt about the H/W aspect ratio effect.

2.5.3.3 Urban vegetation

Increasing urban vegetation is one of the most common strategies suggested for alleviating the effects of the UHI in urban areas (Z.-H. Wang et al., 2016; Q. Zhao et al., 2014). This can be achieved through increasing the number of trees, parks, gardens, green roofs and green walls. Vegetation protects ground surfaces from losing heat at night or absorbing heat during the day by blocking longwave radiation. In contrast to night time, the cooling effect of trees in daytime is higher than that of grasslands because of their shading effect. In general trees have more influence on reduction of T_a (H. Lee et al., 2016). However, the heat transfer between leaves in a tree canopy can increase T_a in the warm seasons (Y. Wang & Akbari, 2014). Another aspect of urban green areas is to increase the humidity in the air and decrease air temperature due to creating shadows (Honjo & Takakura, 1990). While the cooling effect of parks has been accepted by many researchers (Declet-Barreto et al., 2013; Simpson, 2002; Yu & Hien, 2006), this was excluded from this study because the purpose here is to investigate urban morphology.

2.5.3.3.1 Impact of vegetation type

When it comes to vegetation it is very important to determine the type because each has a different microclimate effect. Different climates will also need different types of vegetation for an optimum effect. For example, in studies of Melbourne grasslands provided a cooling surface that was more effective during the night than the morning (Imran et al., 2018; S. J. Jacobs et al., 2018). Melbourne day temperatures could also be reduced by green roofs and the effect could extend to night time by installing enough green roofs in a neighbourhood (S. J. Jacobs et al., 2018). Vegetation patches such as mixed forest and combination of mixed forest and grassland decreased UHI in Melbourne more than a combination of mixed shrubland and grassland (Imran et al., 2019). In a Tel-Aviv study, partial shading by trees in green wooded areas was the main factor for controlling air temperature (Shashua-Bar & Hoffman, 2000).

Trees slow down the wind speed but increase local turbulence around them (Robitu et al., 2006). Urban trees can decrease air-conditioner energy use by 10-35% (Raeissi & Taheri, 1999; Rosenfeld et al., 1993), and also decrease sky view factor and consequent solar radiation absorption by surface materials and human bodies (Robitu et al., 2006). Trees can block the exchange of long-wave radiation and produce evaporation with less water consumption compared to grasslands (Erell et al., 2012). Not only is the proportion and type of vegetation important in the reduction of UHI, but the background urban climate is also influential. Higher ambient temperatures with lower relative humidity make trees more effective in terms of temperature reduction (Perini & Magliocco, 2014).

Trees absorb CO₂ and block solar heat. The impact of tree shade has been studied mostly relative to energy saving in individual buildings. Planting trees to the west, east and southeast of buildings to block out the low angle sun have been recommended by different North American researchers (McPherson et al., 2004; Sawka et al., 2013; Simpson & McPherson, 1996). Cluster tree arrangements with enough open space between them for wind movement and planting in the central part of the south front yard of a building have been recommended for improving outdoor thermal comfort in a USA desert climate (Zhao, 2017).

2.6 Methods of studying UHI

Urban warming is a complex phenomenon of cities, although the features that cause urban warming will vary in different parts of the world. Owing to lack of knowledge in this area it is difficult to consider all features together. As a result, scientists simplify research case studies, which leads to diverse outcomes (Mirzaei & Haghighat, 2010). Consequently a better understanding of urban climate that is relevant to urban design is needed. Wamsler et al. (2013) listed precipitation, wind, temperature, air, humidity, and solar radiation as the factors which form the urban climate. The characteristics of an urban climate are that it is rainier, less windy, hotter, more contaminated, less humid, and cloudier in comparison with a rural area in the same climate. To understand UHI the first step is generally to measure land surface temperature (LST). Surface temperature depends on the surface thermal attributes. The correlation of surface temperature and air temperature changes based on the latitude (Carlson et al., 1977). Consequently, air temperature is not a reliable measure to indicate the UHI effect, while surface temperature is indirectly associated with air quality and thermal comfort (Stone and Rodgers, 2001).

Mirzaei and Haghighat (2010) categorized the methods of studying the UHI into “observational approaches” and “simulation approaches”. The observational approach relies on field measurements and utilizes thermal remote sensing or automobile data. The simulation approach can use either energy balance models or numerical studies using Computational Fluid Dynamics (CFD).

2.6.1 Observational approach

2.6.1.1 Remote thermal sensing

In recent years very good progress has been made in remote sensing approaches to observing UHI. It is possible to analyse thermal images that have been taken by satellite or aircraft. Voogt and Oke (2003) stated thermal remote sensing of urban surface temperature was a “special case

of observing land surface temperature which varies in response to the surface energy balance.” In fact, the surface radiative and thermodynamic properties shape existing surface temperature. Technically, what is measured is the instantaneous field of view (IFOV) of the effective radiometric source area of surfaces. In the first step, directional brightness temperatures are measured by an airborne thermal scanner and converted to a temperature. The second step includes revising this temperature for atmospheric effects by calculating the transmission and emission through the atmosphere between the surface and the sensors. Thirdly, the directional radiometric temperature series needs to be estimated. The emissivity of the different urban surface materials and vegetation makes the calculation possible. As a final stage, another correction is needed to add surfaces missed by the remote sensors (Voogt & Oke, 2003). In this way the temperature detected by the airborne thermal scanner can be converted into a surface temperature. Various platforms and sensors, such as Very High-Resolution Radiometer (VHRR), Heat Capacity Mapping Mission (HCMM), Landsat Themic Mapper (Landsat TM), have been used in different studies to investigate different aspects of the UHI, including the urban surface energy balance.

Some studies have highlighted the limitation of thermal image analysis. Y. Wang and Akbari (2015) mentioned spatial limitation as one factor. Remote sensing thermal images also ignore the complexity of urban areas such as building heights, and roof and vegetation shapes (Voogt & Oke, 2003). Spatial resolution is another important factor especially in terms of evaluating greenery in a built environment. The more accurate the images, the more it is possible to distinguish small patches of green space in urban areas (X. Li et al., 2012).

2.6.1.2 Automobile data collection

Automobile data collection is also called ground-based observation and uses a network of thermometers or traversing with thermometers mounted on vehicles. As noted above, Hart and Sailor (2009) investigated the role of land-use on UHI effects in Portland, Oregon by using vehicle temperature traverses to assess air temperature in the summer time. Their findings showed that industrial and commercial zones had a greater air temperature. Moreover, even in the same place, due to anthropogenic activities, weekdays experienced higher temperatures than weekends.

2.6.2 Simulation approach

2.6.2.1 Numerical modelling

Lindberg et al. (2008) conducted their research using a numerical tool called SOLWEIG 1.0. For assessing the validation of SOLWEIG 1.0. Matzarakis et al. (2007) used another numerical modelling tool called Rayman model to calculate mean radiant temperature (T_{mrt}). In another attempt, Matzarakis used the SkyHelios Model to estimate sky view factor (Matzarakis & Matuschek, 2011)

2.6.2.2 Numerical modelling with ENVI-met

Some studies have used air temperature (T_a) as the ENVI-met output for evaluating the UHI in a specific area (Crank et al., 2018; Emmanuel & Fernando, 2007; Middel et al., 2014; Roth & Lim, 2017). However, the accuracy of air temperature estimation by ENVI-met is debatable, as it is argued that ENVI-met either overestimates or underestimates T_a both in the day and night time (Emmanuel & Fernando, 2007).

The combination of two climatic factors like mean radiant temperature and air temperature as a way of determining the UHI effect has been recommended by other researchers, because these two factors are concerned with human comforts (Emmanuel & Fernando, 2007). Ambrosini et al. (2014) studied UHI mitigation strategies in historical places using ENVI-met, by studying atmospheric temperature, relative humidity and wind velocity. Other studies have concentrated on the Physiological Equivalent Temperature (PET) as an index for human thermal comfort (Juan A. Acero & Herranz-Pascual, 2015; F. Yang et al., 2011).

2.7 Summary

Countermeasures against global warming and UHI are needed to reduce warming in cities. Countermeasures against both problems can be divided into mitigation and adaptation strategies. These countermeasures have gained considerable attention at both the city management and architecture scale. The urban design scale remains neglected. However, the little advice which has been given by researchers is either contradictory, such as different land use recommendations, or very broad, such as the benefit of green space without determining the ratio of that in the district plan. It seems that, these conflicts apart, urban designers and climate scientists also need to find a common language so as to interact. Since urban design and global warming are both broad topics, which are made up of many factors, understanding their principles and how they can connect to each other is very important. Urban design is the art of laying out land in cities and establishing urban characteristics. Urban characteristics

include street pattern, urban block and orientation. Climatology is the science of the different layers of the atmosphere and how these interact with each other. To make this understandable it has to be represented by numbers such as air and surface temperature or humidity. UHI and global warming are defined by different characteristics like air temperature and surface temperature. In general, there are two different methods for the study of the urban heat island, the observational approach and the simulation approach. The observational approach is the technique of measuring air or surface temperature either by thermal imaging or by use of mechanical instruments. The simulation approach is the technique of predicting UHI by numerical modelling. The first technique is usually used to prove urban warming in cities. The second approach is usually used to study UHI in different cities and discover its causative factors. Different researchers have mentioned different factors which contribute to UHI. Land cover, urban form and vegetation are the main urban characteristics involved and these need further study in the city of Mashhad.

This review of the literature related to UHI has shown a lack of research that would be useful in showing urban designers what they should do in terms of issues like building density and street width and orientation to reduce UHI to its possible minimum. The literature also shows that such urban design recommendations need to relate to the local climate. This aims to fill this gap by looking at the relationship between urban characteristics and urban microclimate for the city of Mashhad in Iran.

3 Case Study Background

3.1 Iran

Iran is a country in the Middle East with an area of 1,648,195 km², six times the size of NZ and nearly seven times the size of the UK. Population growth increased 61% from 1986 to 2016 (Iran, 2014). According to the 2016 national census, Iran's population also rose significantly during the preceding two decades and Iran now accounts for 1.07% of global population. The average population density is 50 persons per km². Iran has hot dry weather and 54 out of 80 million Iranians lives in cities (Mollahosseini et al., 2017). In other words, approximately 70% of the population lives in urban areas. Population growth in Iran has led to large-scale urbanization leading to significant growth in big cities like Tehran, Mashhad, Tabriz, and Esfahan. This rapid change in population has raised the proportion of the urban population from 47% in 1976 (Fanni, 2006) to 74% in 2016 (Iran, 2014) (Figure 16). Iran has also witnessed a 519% growth in the number of towns and cities during last 60 years, moving from 201 towns in 1956 to 1245 towns in 2016 (Iran, 2014) (Figure 17).

Figure 16: Population by residence status based on 2016 census (Iran, 2014)

Figure 17: Number of cities: 1956-2016 (Iran, 2014)

3.1.1 General characteristics of Traditional Iranian Cities

Pirnia (2004) summarized traditional Iranian urban architecture as being based on five important principals;

- Human focus: pay attention to human size, standards and needs in urban and architectural design. In the other words, make spaces liveable for men, women and children
- Introversion: consider privacy in any design, leading to modest exterior facades and luxurious interior facades
- Self-sufficiency: use of local materials for buildings
- Avoid wastage: avoid adding any un-necessary details to buildings
- Building science: consider structure and suitability as part of architecture and not as a separate science.

Almost all these design principles address the cultural, climatic and structural needs of buildings. For example, for the aim of privacy, the traditional house is formed around an inner courtyard space.

Traditional urban spaces in Iran fall in two main categories, pre-Islamic and post-Islamic (Habibi, 2009). Many researchers have investigated the characteristics and structure of cities in the post-Islamic era. These studies have mostly concentrated on identifying different urban elements like the bazaar or mosque (Seelig, 2011; Sharifi & Murayama, 2013), although this approach does not provide a good perception of the physical shape and structure of these cities. Important elements found in traditional Iranian cities include the Great Mosque, Bazaar, Maidan (square or city centre), Mahalleh (neighbourhood), Zurkhanah (traditional fitness club), Hammam (Public Bathhouse), Persian Garden (Sharifi & Murayama, 2013), Castle, wall and fortifications, and cemetery (Ehlers & Floor, 1993) (Figure 18). Compact urban forms, and narrow streets and alleys with tall surrounding walls are other characteristics of traditional Iranian cities (Kheirabadi, 2000).

Figure 18: Schematic drawing of traditional Iranian city concept (Ehlers & Floor, 1993)

Great Mosques were important religious buildings. They are not only the places for praying to God, but are community buildings for housing many different social activities such as those related to politics and economics. Each city has one Great Mosque, a main Bazaar and a main Maidan but several smaller versions of these would be located in each neighbourhood (Figure 19 and Figure 20). Bazaars are long and wide organic streets used for commercial activities between residents and outsiders (K. Karimi, 1997). The linear characteristic of a Bazaar makes it possible to form a connection between all the important public and semi-public elements of the city. The Maidan is a large public place usually found at the end or beginning of the Bazaar. It is a place for social activities with green space and a fountain. The hierarchy of space in terms of access and privacy is one of important principles that shape traditional Iranian cities (Figure 19). A dense urban area, as well as a mixed-use pattern, are considered to be other characteristics.

Figure 19: Traditional Iranian city structure in this case the traditional part of Isfahan city (Gharipour, 2003). As shown in the figure, spatial hierarchy is very important in the traditional urban form.

In Mashhad, the main mosque is located next to the Holy Shrine, which is the second most important religious building in the Muslim world after Kaaba in Mecca. Figure 20 shows how the Bazaar and other public places are shaped around the Holy Shrine and the Great Mosque. The difference between public and private spaces is usually distinguishable from the size and the length of elements. Narrow organic streets not only provide privacy for private houses, but also create enough shade in warm seasons.

Figure 20: Traditional structure of Mashhad in 1971. All important activities are shaped around the Holy Shrine, the most important religious place in the whole country left (ARCHNET) right (reddit).

3.1.2 Traditional sustainable Architecture in Iran

Iran is an ancient country with many different climatic regions. Interestingly, each climate zone developed its own architectural solution adapted to the local conditions. Therefore, the different types of architecture in Iran are based on the different types of climate. Traditional Iranian architecture has changed considerably over time, responding to religious, cultural, social and political circumstances. Adaptation to climate and nature have also been important drivers for change. Architects in ancient times were forced to utilize natural energy to improve the interior condition of houses. Buildings were designed so they could use the sun, breeze, and vegetation in order to create a proper microclimate for human comfort, by highlighting the positive aspects of climate and diminishing its negative aspects (Varzaneh et al., 2014).

There is a significant body of literature addressing the climatic approach taken in traditional architecture and urban design in the Middle East (Eiraji & Namdar, 2011; Keshtkaran, 2011; Motealleh et al., 2016; Roaf, 1982; Soleymanpour et al., 2015; Varzaneh et al., 2014). However, some studies have concentrated on the building rather than the city scale (Arif Kamal, 2010). Eiraji and Namdar (2011) categorized Iran's climate into four regions and described the architectural characteristics of each (Table 5), mostly in terms of the architectural elements. As an example, they cited the use of the inside pool and windcatcher for a dry and hot climate (Figure 21), large windows facing towards the sun during the day and thermally heavy wall materials for a cold and snowy climate (Figure 22), an Ivan (a covered deck) to create shadow and ventilation for a hot and humid area (Figure 23), and pitched roofs for a humid and rainy region (Figure 24). However, they did not look at other aspects of traditional climatic design, such as urban layout.

Table 5: Four climate regions of Iran, based on (Eiraji & Namdar, 2011)

Region	Zone description	Location	Climate factors	Main strategy	Sustainable parameters	Main architectural elements
1	Dry and hot	Central parts of Iranian plateau	-No rain -Dry	Cooling	Wind and water	-Windcatcher (Badgir) -Inside pool (hozhaneh)
2	Cold and snowy	North and west of Iran	-Hot -Cold -Snow	Warming	Sun	-House orientation (south) -Large window (more sun) -Wall materials (store heat) -Yakhchals, ice Stores for preservation of Ice
3	Hot and humid	Northern shores of the Persian Gulf and the Sea of Oman	-Hot -Humid	Cooling	Shade and ventilation	-Ivan (coolness and shadow) -Kapar or reed hut (coolness and shadow)
4	Humid and rainy	Southern shores of the Caspian sea	-Rainy -Humid	Dryness	Roof	-Slope of roof -Local materials -Ivan (sheltered deck)

Figure 21: Inside pool (left) and windcatcher (right) for a dry and hot climate, Tabatabayi house Kashan, Iran (News, 2020)

Figure 22: Large windows towards the sun during the day and thermally heavy wall materials for a cold and snowy climate (Gasht, 2020)

Figure 23: Ivan (a covered deck) to create shadow and ventilation for a hot and humid area (shargh, 2020)

Figure 24: Pitched roofs for a humid and rainy region, Baghri house, Gorgan Iran (Order, 2020)

A central courtyard shaped both houses at the small scale and cities at the large scales. In a house, the courtyard is an open space surrounded with walls (Figure 25). The role of the domestic courtyard has been studied in its many different aspects of climate, geography of the area, and spatial and structural analysis (Amiriparyan & Kiani, 2016). Memarian (1993) summarized courtyard characteristics as privacy, being composed of different functions, bringing different spaces together, being a fresh environment, being an open space living room, and capturing wind and fresh air.

Figure 25: The typology of houses with a courtyard

Soleymanpour et al. (2015) investigated the different principles of design behind modern and vernacular architecture in Iran. To achieve this, a number of famous houses which represented the architecture styles of particular climatic regions were selected, both from ancient and modern times. The architectural design strategies with regard to climate were then compared. The results of these studies revealed that vernacular architecture was capable of providing more climate related comfort, and there was evidence to show that this comfort exceeded that provided by modern urban architecture.

3.1.3 Traditional sustainable urban design in Iran

A dense built environment and a narrow organic street pattern together form the most important climatic solution in most of Iran with a harsh climate. This urban form could reduce exposure to the sun, manage heat exchange during day and night, create shadows, reduce walking time, and control strong winds (Kheirabadi, 2000). Motealleh et al. (2016) investigated climatic design in Bushehr, a city that lies on the Persian Gulf, at two different scales. These were the urban design scale, which includes urban orientation and urban morphology, and the architectural scale, which includes architectural design and the architectural elements of buildings. The main purpose of vernacular design in Bushehr is adaptation to the hot and humid climate (Table 6).

Table 6: Traditional climatic design features at the architectural and urban design scales for Bushehr (Motealleh et al., 2016)

Scale	Aspect	Urban/Architectural Characteristics	Climate Reasons
Urban scale	Urban fabric	-Compact, dense and continuous: reducing surfaces of buildings which face sunlight -Narrow alleys with height: width of 10:1	-Hot and humid -Funnel cool sea breeze
	Structure of public spaces	-Minimal contiguous building boundaries -Organic hierarchical order	-Wind circulation -Temperature, humidity, orientation to wind flow, the earth's natural topography, socioeconomic characteristics
	Orientation of a building	-Passages exposed to dominant winds -Different orientations	-Dominant winds from north and north west -Based on the regional winds
	Utilizing passive systems by means of architectural elements	-Central courtyard -Opening windows toward the central courtyard and toward alleys	-Wind flow -Transverse ventilation to reduce the intensity of heat and dampness

Semi-open spaces in buildings	-Tall walls for shading central courtyard -Shenashir and large porches	-Create shadow -Faced toward wind -Reduce solar radiation -Reduce wall temperatures because of shading them -Cool breeze from the sea
Rooftop	-Provides cool part in house at night	-Cool breeze from the sea
Low heat capacity materials in buildings	-Wood -Straw, limestone, coral stone and sedimentary rock	-Will accumulate less heat

Keshtkaran (2011) used Yazd for another case study of vernacular architecture in Iran. Yazd is located in the central part of Iran and is surrounded by deserts. Traditional architects were obliged to deal with its hot and dry climate, with high temperatures during the day time and low temperatures at night. They also had to face having a hot summer and cold winter. Unlike previous studies, this study looked at both architectural features like materials, openings and roof coverings, and a number of urban features such as architectural texture, sidewalks, and facades (Table 7).

Table 7: Climatic design strategies for Yazd, based on Keshtkaran (2011)

Aspect	Design strategy	Goal
Architectural texture	-Dense mass of buildings	-Minimize exposure to sunlight
	-Organic pattern	-Create shadow -Protection from weather in winter
Sidewalks	-Narrow and curved with high walls on both side	-Create shadow -Block hot breeze
	-East-west orientation	-Protect from heat
	-Roofed sidewalk	-Create shadow
Openings	-Few windows in exterior facade	-Protect from unfavourable wind
	-More windows on interior elevation to courtyard	-Use of natural light in house
Materials	-Adobe and mud	-High thermal capacity to store heat in day and release it at night
Façade	-Light colour	-Absorb less solar energy
Courtyard	-Protected open space	-Decreasing exposure to harsh weather
Summer area and winter area	-Two separate parts in house located on different sides of the courtyard	-Integrated with winter and summer harsh weather conditions
Godalbaghche (sunken yard)	-Deep yard below ground level -Provide green space	-Create cold ground surface and cool air
Roof cover	-Arched or domed shape	-Accelerates the flow of air thus reducing the temperature
Air trap (wind tower)	-Tall element to capture wind	-Cooling

3.1.4 General Characteristics of Modern Iranian Cities

As an international movement, Modernism has also affected Iranian architecture and urban design. Rapid modernization in Iran started in 1920 when the ambitious Reza Shah aimed to transform Iran to be like a European country (Abrahamian, 2008). Ever since, urban Iran has been blessed with different styles and phases of domestic architecture, from low-cost housing in the 1950s to luxury houses and neighbourhoods in the 1960s (Habibi & De Meulder, 2015). Marefat (1988) demonstrated how walls and gates, the royal citadel, religious buildings, and residential neighbourhoods were replaced with the urban grid, public spaces, state institutions, and housing typologies of a modern character. These changes related to many opposites found in society: modern versus traditional, secular versus religious, public versus private, continuity versus discontinuity. From the urban point of view, and based on Marefat's study, the transformation undertaken to modernize Iranian cities could be divided into three categories (Table 8). These were changes to the street pattern, public open spaces, and public buildings. Architecturally, traditional houses with central courtyards changed to repeated row houses, apartments, and villas (Marefat, 1988).

Table 8: Comparison between modern and traditional urban and architectural characteristics, based on Marefat (1988)

	Type	Modern	Traditional
Urban	Street pattern	Wide boulevards, traffic routes	Organic street
	Public open spaces	Public park	Garden Square
	Public building	Ministries, banks, museums, universities and schools	Bazaar, Mosque
Architecture	Houses	Traditional houses with central courtyard	Row houses, Apartments, Villas

Streets were also widened to accommodate traffic, thereby making them less attractive to pedestrians, so the traditional city designed for walking became a modern one reliant on motorised transport. Streets were also straight rather than curved, so no longer provided the shade for pedestrians (Figure 26). These changes all affect the absorption of heat in the urban context.

Figure 26: The city of Ardakan: urban layout of modern district (left) and historical district (right), (Google, n.d.)

3.1.5 Urban planning and the urban design process in modern Iran

The first Iranian legislation in 1966 concerning urban design has been revised several times (in 1974, 1976, 1985 and 2007). This legislation, which is aimed at producing organized urban development, occurred due to population growth and rural–urban migration (Table 9) (Madanipour, 1998). The aim of some of this legislation was to permit the planning of new towns (enacted in 1974). This policy allowed the creation of new satellite towns within urban administrative boundaries as an alternative to rampant urban growth, with the intention it would help to reduce rural–urban migration (1979 legislation).

Table 9: Urban design legislation

Year	Goal
1966	Transferred more power to the Ministry of Interior to control the rampant development of urban settlements
1974,1976	Mandate granting permission for planning new towns
1979	Allowed creation of new satellite towns within urban administrative boundaries as an alternative to rampant urban growth and reducing the rural–urban migration
1985	“1- redistribution of the spill-over population in the designated areas of large cities 2- decentralisation and transfer of services to new towns to mediate between smaller and larger cities 3- aim was reducing the population density of large cities in order to improve their residents’ quality of life and service delivery 4- preventing the rampant increase of land and housing price, the formation of squatter settlements, and sprawl across the metropolitan areas” (Ziari, 2006)

Zamani and Arefi (2013) critically studied the urban planning process in Iran. Their study addressed issues in new town development including “fragmentation of responsibilities and roles, multiplicity of actors, and of inter-sectoral co-ordination and public participation.” Their study provided a picture of the complex bureaucratic structure of urban planning and management in Iran. They also defined key actors at both national level and city level. At the national level, although planning is covered by the Management and Planning Organisation

(MPO), there is no true regional planning. At the city level are the Ministry of Housing and Urban Development (MHUD), the Ministry of Interior (MOI), the Management and Planning Organisation (MPO) (which no longer exists, and in place of which there is a presidential deputy called Management and Evaluation), the Supreme (Higher) Council of Urban Development and Architecture (an inter-ministerial government body), the Article Five Committee of the City Planning Council, the Provincial Office of the Ministry of Housing and Urban Development, the Provincial Governor (including the provincial governor's Technical Office), the Provincial Development and Planning Council (Shora-e Tose'e va Barnamerizi), the Provincial City Planning Council, and the County Planning Committee (Komiteh Barnamerizi Shahrestan). This list illustrates the complexity of the urban design process in Iran. Although there are many organizations involved in decision making, the three most important are the Supreme Council, the MHUD and the MPO (Zamani & Arefi, 2013).

The Supreme Council of Urban Development and Architecture was established to cover both urban development and planning new towns. This organisation deals with site selection, production of a comprehensive plan, and planning at the neighbourhood scale. At the neighbourhood scale, master plans are prepared by consultant firms under the supervision of the MHUD (Zamani & Arefi, 2013). A master plan is a neighbourhood scale plan (approximately 1:20,000) that would be valid for a period of 10 years. Master plans must also consider population growth, employment, education, public health, infrastructure, traffic, housing, and building codes and ordinances related to neighbourhoods. The following need to be included:

“1-The land use map and the street network according to acceptable universal per capita standards.

2-Zoning and the spatial distribution of activities.

3-The appropriate population density, as well as the Floor Area Ratio (FAR).

4-The urban service delivery boundaries, the municipal administrative boundaries, and urban growth boundaries, even beyond the scope of master plans' time horizon” (Zamani & Arefi, 2013).

Studies into urban sprawl can be categorized in two main topics: anti-sprawl and pro-sprawl (Bagheri & Tousi, 2017). Most studies in Iran focus on the negative aspects of urban sprawl. These include the negative effects on the environment by destroying the landscape and natural resources, using farmlands around cities, threatening water resources, creating a rise in city travel, increased use of fossil fuels and the effect on the urban climate (Hosseini et al., 2010;

Mosammam et al., 2016; Shahraki et al., 2011; Soltani et al., 2017). Bagheri and Tousi (2017) illustrated the difference between Iranian and Western types of sprawl. Differences included the planning, street pattern, and type of development (horizontal or vertical). They concluded that unlike many successful urban developments in other countries, in Iran sprawl development was not successful, mainly because of the many political and economic crises that occurred after the revolution (Iran and Iraq war and population growth), which led to poor political and urban management.

3.2 Mashhad

Mashhad is the second largest city in Iran and is located in the northeast of the country (Figure 27). The metropolitan city, with an area of 320 km² is home for around 3 million people. Due to economic, social and religious attractions, the population has risen rapidly during last the two decades (R Rafiee, 2007). According to national censuses, Mashhad's population has increased from 668,000 in 1956 to 3 million in 2016 and at present its population comprises about 3.7% of Iran's total urban population (Iran, 2014). According to the Koppen Geiger climate classification, Mashhad's climate is categorized as an arid climate (Rubel & Kottek, 2010).

Figure 27: Mashhad is located in the Northeast of Iran (fava.mashhad, 2020)

3.2.1 Mashhad's urban growth

A study by Modiri et al. (2017), looked at the growth of Mashhad from 1891 to 2006 (Figure 28). The blue part is the first core of Mashhad where the Holy Shrine is located. For years the expansion of Mashhad followed a circular trend but after 1996 the path of development changed to a linear configuration to the north-west of Mashhad, mostly because of the milder weather of this part of the city, with a smaller linear development to the south east. District 1 developed between 1956 to 1976 while District 10 developed from 1976 to 1996, making a 20 year difference between the age of these two districts.

Figure 28: Mashhad urban growth from 1891 to 2006 (Modiri et al., 2017)

3.2.2 Land use changes and lack of green space in Mashhad

Globally, green space scarcity is a significant concern in urban neighbourhoods (Rudlin & Falk, 2009) and again this is a particular problem in Iran which has seen rapid urbanism. The benefits of green space have been extensively discussed (Maas et al., 2006; Wolch et al., 2014) and land use and the balance between density and the distribution of green space are a matter of debate for researchers. Green space distribution in cities generally follows a hierarchical pattern (Biddulph, 2007). On the other hand, green space is seen as one of the important mitigation measures for UHI. Kleerekoper et al. (2012) highlighted the cooling role of green spaces in cities as these provide evaporation, vegetation, shading, and heat transfer at night. Green space has the potential to lower temperatures by 4° - 6°C in different parts of a city (Wenting et al., 2012). In one study in the UK increasing the number of trees by 5% contributed to reducing mean hourly temperature by 1.0°C (Skelhorn et al., 2016).

Research into the purpose and use of green space in Mashhad has either focused on the social and cultural function of green spaces or the measurement of green space per capita. Salehifard et al. (2010) compared the different functions of municipal parks categorizing these into various aspects including the social, cultural, and recreational. Rahnema and Razzaghian (2012) evaluated the ecological sustainability of the three main parks of Mashhad called Mellat, Vahdat and Koohsangi. Their findings indicated all three parks were in a poor ecological condition. Razzaghian and Aghajani (2016) focused on enhancing the green quality of Mashhad by locating new urban parks within the city. Reza Rafiee et al. (2009) have also researched changes to green space in Mashhad and their results showed that during last 10

years the proportion of green spaces has dropped significantly. Figure 29 demonstrates how green areas were well distributed in 1987 and how by 2006 these had been affected by urban development. The problem is not only the increase in urban areas but also the conversion of green space to build environment.

Figure 29: Changes in green space and urban areas in Mashhad over 20 years (Reza Rafiee et al., 2009).

3.2.3 The relationship between UHI and green space in Mashhad

In a rare study undertaken by Mousavi Baigi et al. (2012) the TM images taken by the 5th Landsat satellite were compared with the Enhanced Thematic Mapper Plus Images (ETM+) taken by the 7th Landsat satellite, with a 10 year difference from 1992 to 2002. Moreover, for validation, data series from the climatology stations of the city of Mashhad were used for the same period. Overall analysis showed a positive trend in urban surface temperature particularly in residential areas. On the other hand, land-use city maps showed a remarkable decrease in green space for the same period. Thermal images for the years 1992 and 2002 were compared to the land-use map of the same time. The images illustrated that green space areas were less affected by the UHI phenomenon. The maps highlighted the Malekabad Garden. This is a major private garden in Mashhad, which in 2002 had an area of 28 km². Although this large green area has slightly reduced in size in the last decade, it is a good spot for tracking the changes. The map does not show the density of the built environment or the land cover of non-residential areas. As the residential area has grown around the Malekabad Garden, its temperature has slightly increased. Except for the green spaces that are full of trees and grass (from the author's observations of living in Mashhad) all other land cover types like bare land, non-irrigated horticulture, and pasture-mountain areas show a rise in temperature.

Recently, there has been a change as overall green space per capita in Mashhad has shown an upward trend from 2010 to 2014, rising from 10.12 to 12.15 m² per person (Council, 2018). However, this is still below the national standard of 25 m² per person, while the ratio in the US is 50.18 m² per capita (X.-J. Wang, 2009). The Park and Green Space Organization of Mashhad City Council is responsible for the creation and maintenance of green space in Mashhad. Green space here means parks, green squares, green boulevards and urban woods (Council, 2018). Figure 30 gives a better understanding of green space in Mashhad and its relation to district population and area. Green space per capita for each district means the total area of green space to the total population of that district. The green space per capita numbers were extracted from the Park and Green Space Organization of Mashhad City council website. The ratio of green space as calculated is based on the total green space area to the total area of the same district as provided by the city council. Figure 30 illustrates the considerable difference between the different zones. District 9 has remarkably more green space in comparison with other districts. This is mostly because it contains both Malekabad Garden and Ferdosi University, with the latter also acting as an urban park. Malekabad Garden is private property and Ferdosi University is semi-private property, so the high levels of green space do not indicate space which is accessible to all people, although this area of green space does affect LST as shown in Figure 31. The available green space in District 12 is 1 percent of its area, however the green space per capita here is not the worst. This is mainly because it is a new district with less built environment made up of compact neighbourhoods. The LST map of the two districts shown in Figure 31 indicates the differences in surface temperature resulting from bare land, built environment and green space.

Figure 30 : Distribution of green space (parks) in the 13 districts of Mashhad. Green space per capita is green space area /population. Green space ratio is green space area/district area

Comparing Figure 30 and Figure 31 reveals how complicated the relationship is between UHI and green space in Mashhad. The two maps in Figure 31 were extracted from a 2015 study by Alavipanah et al. (2015), and the approximate border of each district was overlaid digitally. Unfortunately, there is no mean LST for each district. Taking districts 1 and 10 for example, both districts were developed after the 1979 revolution. The LST map shows District 1 is cooler than District 10, however the green space per capita is less than that of District 10 (3.9m^2 compared to 6.38m^2 , with green space making 4.3% and 8.8% of all land uses). One reason for the cooler environment in District 1 could be the huge green spaces located in the south and west of this district. It seems the study of urban morphology as well as the type, size and distribution of green space might help in understanding the difference. The other notable issue is the importance of green space type. The land use map in Figure 31 reveals considerable green space in both the north of District 3 and the east of District 6. As these green spaces are farmland, they are not included in the green spaces of these districts. These green spaces have temperatures ranging from low to high. The type of farmland, whether being under harvest or not, and the type of products grown might affect the temperature. The findings of these comparisons indicate that to address the urban heat island problem in the city of Mashhad, mitigation and adaptation strategies should be localized with deep scrutiny of existing circumstances, potentials, and threats.

3.5

Figure 31: Comparison between land use map and LST map of Mashhad in 2014 (Alavipanah et al., 2015)

Because of similar levels of development but differences in LST District 1 and District 10 appeared to be good examples to investigate further. These districts are examined further in section 3.4 and 3.5.

3.3 Mashhad District Plan

The first district plan in Mashhad, which was approved in 1967, was called the Khazeni Plan. The second one, approved in 1996, was the Mehrazan Plan (Shahraraonline, 2015). Already Mashhad has seven different district plans which were created by urban design firms in Tehran. Different urban design and management plans in Mashhad usually contradict each other. For instance, the traffic plan which was prepared by the Traffic Department of Tehran Municipality is in conflict with the district plan prepared by the High Council for Urban Planning and Architecture of Iran. Apart from weak management, the second problem in Mashhad is misusing the district plan in order to meet financial goals set by the city council, which is called “selling density” (Shahraraonline, 2015). In other words, building density as defined and approved in the district plan, can be increased through the land owner’s application on condition of paying more money to the city council. In this business both parties, the city council and landlords, make profits but the city in general loses. The other problems with the Mashhad district plan are listed below.

- Different district plans (7 types)
- The process of approving the district plan is too long (the latest one took 7 years)
- Just 30% of existing buildings comply with the related district plan
- City management and planning contradict each other

3.4 District 1

District 1 is located at the heart of Mashhad (Figure 32), with area of 1,505 hectares and a population of 167,013. The district council was founded in 1984 (Zone1.Mashhad, 2020). In terms of urban design, District 1 is one of the best parts of the city. It provides enough facilities for modern life as well as preserving some of the traditional urban characteristics. In traditional Iranian cities, the form of each space explains its function. Also, the good combination of high-rise, low-rise buildings and open space together make the spaces very distinguishable for the residents. From my personal experience, even as a primary school student I never got lost during all times I walked back home. This is in contrast with District 10 in which as an architectural student I usually got lost when I needed to do something around that neighbourhood.

Figure 32: District 1 plan (fava.mashhad, 2020)

3.4.1 Major Routes and Places

In general, districts in Mashhad are defined by the boulevards and major streets. Most major routes of the city either surround District 1 or cross it (Figure 33). The Azadi Expressway, which is located to the west of district and which connects Esteghlal Square to Azadi Square, a multi-level intersection, is one of the main entrances to the city from the north. This square is multi-characteristic. It distributes traffic, and is also functionally and recreationally important. It is surrounded by Melat Park (72 hectares), Ferdosi University (243 hectares) and Malekabad Garden (283 hectares) (Council, 2018). It connects the old traditional part to the new modern part of the city.

Esteghlal Square is one of the first multi-level intersections of Mashhad, and connects the inter-city highway to the city. Both Ferdosi Boulevard and Shahid Gharani Boulevard by the north boundary are the main access ways to the Holy Shrine, which is the most important tourist attraction of the city. Ferdosi square is one of the main access points which connects the modern part to the traditional part of city and the Holy Shrine, these being the main destinations for tourists. Janbaz square used to be a simple intersection with traffic lights, however its character changed completely when the land use next to it changed to high-rise mixed-used office and commercial buildings. Recently Janbaz square has been considered to be the main commercial nexus of the city (Figure 33 and Figure 34).

Figure 33: Main routes around and in District 1, the district boundary is in purple. Selected areas for further study are in red (fava.mashhad, 2020)

Malaekabad Boulevard to the south-west of the district connects the most important non-level intersection of the city (Azadi Square) to Palestine Square. Palestine Square connects two important parts of the city, these being Ahmad Abad Boulevard (to the east), one of the main commercial parts of the city, and Kohsangi Park (to the south) the second tourist attraction of Mashhad. Kohsangi Avenue which is located to the south-east of the city connects Kohsangi Park through the oldest part of the city to Shohada Square, which is an old square and the second most important in the city. Shohada Square is within walking distance of the Holy Shrine (Figure 33 and Figure 34).

Figure 34: Major routes and squares of District 1, photo 4,5 and 6 (Zone1.Mashhad, 2020), photo 1(Eghtesaonline, 2018), 3 and 8 (Pourab, 2020) and 7(Eligasht, 2019)

Apart from all the major routes which surround District 1, some of the most important streets in Mashhad also pass through it, Sajad Boulevard being the main one. The importance of this boulevard is not only for the way it gives access to other parts of the city but also for the residential and commercial spaces next to it. In the 1980s this boulevard became the modern part of the city with commercial spaces called Pasaj. Pasaj is an innovative type of enclosed commercial space, which mixes up the traditional linear market (bazaar) with the new modern look. For three decades, the composition of Pasaj at ground level and high-rise office space or residential above made this part the most modern and expensive part of the whole city. The second important street within the district is Ahmad Abad Boulevard, which is older than Sajad Boulevard, but which has been revitalized with the same approach of modern commercial space at ground level and residential and office buildings above. The third important street is Khayyam Boulevard. This boulevard is one of the widest in the city with many high-rise government buildings along it, mostly to the west of the boulevard and big footprint buildings to the west (Figure 33 and Figure 35).

Sajad Boulevard

Ahmad Abad Boulevard

Figure 35: Major routes and places of District 1 (Zone1.Mashhad, 2020)

3.5 District 10

District 10 is located in the north-west of Mashhad (Figure 36). Its total area is 1,903 hectares and it has a population of 296,823. The population density is around 127 persons per hectare. The district council was founded in 1992 (usm.mashhad, 2020). It is a fairly new District most of which has been developed after the revolution (1979) to provide affordable housing for the middle classes.

Figure 36: District 10 plan (fava.mashhad, 2020)

3.5.1 Major routes and places

District 10 has an almost triangular shape and is surrounded by three expressways; to the north-west by the Ayatollah Hashemi Rafsanjani, to the north-east by the Azadi and to the south by the Imam Ali expressways (Figure 37). The Azadi expressway as mentioned before is one of main access routes to the city. The Azadi expressway meets the Imam Ali expressway at Qaem Square. Qaem Square is a multilevel junction with acts as a modern gate to the city. Two main routes pass through it (the Azadi and Cheraghchi expressways). Namayeshagah square is where the Ayatollah Hashemi Rafsanjany and Imam Ali expressways meet. It is a very important junction as it is one of two access points to the Mashhad International Exhibition (Figure 37 and Figure 38).

Figure 37: Main routes around District 10, the district boundary is in purple. Selected areas for further study are in red (fava.mashhad, 2020)

1- Ayatollah Hashemi Rafsanjani Expressway

3- Qaem Square

2- Azadi Expressway

4- Imam Ali Expressway

Figure 38: Major routes and squares of District 10, photo 1 (Farsnews, 2018), 2 and 3 (Zaernia, 2020), 4 (QasemAbad, 2020)

Unlike District 1, District 10 is not one of the major destinations for city activities. It does not have the central city type of commercial spaces or its nightlife. It is occupied by many residential complexes. Most of the latter belong to different governmental organizations such as the Ministries of Energy or Education. They provide affordable apartments for their employees. In this case a big cheap section bought from another governmental organization called the Urban, House Organization, changed the function of the land from farmland to residential. Doing this meant there were many big cheap sections that could be provided for other parts of government. The land and building construction costs would be subtracted from an employee's salary each month for a couple of years. In this way many employees could afford to buy a house. Therefore, this part of city is full of building with the same shape. However, some important areas do exist in this district. These are Azad University (Mashhad branch) which is located in the heart of the district, and Water Wave Land which is located in the north part of the district (Figure 39).

Figure 39: Major places in district 10, left (Irna, 2020), right (erasmusu, 2020)

3.6 Selected neighbourhoods

Since it is impossible to simulate the whole city to study UHI, specific neighbourhoods need to be chosen for investigation. Many studies (Juan A. Acero & Herranz-Pascual, 2015; Geletič et al., 2016; Middel et al., 2014; Ian D Stewart & Oke, 2012) have used a systematic method of neighbourhood selection called Local Climate Zones (LCZ) classification, which was invented by Stewart and Oke (Iain Douglas Stewart & Oke, 2010). It is done through three main steps: collecting metadata, matching chosen neighbourhoods with LCZ classes, and finally selecting the appropriate local climate zone (Ian D Stewart & Oke, 2012). Other researchers have selected their study area based on the variety of land cover and building height (Chow & Brazel, 2012; Chow et al., 2011; F. Yang et al., 2011). Most comparisons are between two different neighbourhoods, either with similar (F. Yang et al., 2011) or different urban characteristics, or between three neighbourhoods and their cooling scenarios (Chow & Brazel, 2012).

In this study, the idea of making a comparison of urban warming between District 1 and District 10 came from a study by Alavipanah et al. (2015). This study was conducted to investigate the urban heat island effect in the city of Mashhad by measuring LST through satellite thermal imaging (Alavipanah et al., 2015). After overlapping the district boundary on the city map, it appeared that District 1 was coldest, and District 10 was warmest district. Additionally, the age gap between design and construction of the two Districts and the different cultural, economic, and religious theories which supported this, could make a meaningful comparison. It was also not possible to make an LCZ classification due to the lack of data relating to the city of Mashhad.

To select appropriate neighbourhoods within each chosen district, different urban patterns in both districts need to be identified. Eight different main urban configurations could be found in District 1. They were named 1-A to 1-H (Figure 40). In District 10, five different patterns were found, named 10-A to 10-E (Figure 41). The neighbourhoods were chosen based on their different urban patterns, for example, different street orientations, organic patterns, traditional patterns, and different building footprint densities. In District 1, the area H is called Abkuh. It was an actually rural area in the middle of the Mashhad metropolitan area. For some reason, it remained untouched during the fast-paced urban development. Thus, it has rural area characteristics and was not appropriate to be included in this research since the main concern is urban characteristics. Area 1-G is a small area, and the orientation is only marginally different from that of area F. Because of this similarity and because it seemed useful to choose a similar number of neighbourhoods in both District 1 and District 10, area 1-G was also not chosen for simulation. In District 10 there are also many industrial areas located in the north which are not appropriate for this study.

The next step is to choose one neighbourhood representative of each urban pattern. The concentration of this study is on residential areas, and this became the main criteria for choosing neighbourhoods. The chosen neighbourhood needed to have a meaningful distance from district boundaries and large green spaces because boundary conditions and green space have a clear influence on UHI. For the same reason the chosen areas contain no large green spaces. Areas without main roads were preferred. Where this was not possible, main roads were either pushed to the boundaries or ignored as much as possible because they have an obvious effect on UHI due to their dark and solid nature.

Figure 40: Urban pattern classification in District 1 (fava.mashhad, 2020)

Figure 41: Urban pattern classification in District 10 (fava.mashhad, 2020)

The dimension of the areas to be simulated is very important. The neighbourhood is an important urban and social topic while its definition and the perception of its boundaries varies among both residents and experts, with definitions from one urban block to several urban blocks (Pebley & Sastry, 2009). However, these perceptions are different for city center and suburb. For example residents in the city centre see the neighbourhood as having smaller boundaries than suburban residents (Coulton et al., 2013). Bentley (1985) defined the scale of

the neighbourhood as an area with a radius from 500 to 1000m. Therefore, to meet the definition of neighbourhood and limitations of simulation (see section 4.3 and 8.3.2) the size of the selected neighbourhoods was set at 400m x400m. The selected neighbourhoods in Districts 1 and 10 are shown in Figure 42 and Figure 43.

Neighbourhod	Arial photo	Ground plan	Street photo
-Name: 1-A (Sajad) -Building density: % 55 -Street coverage: % 24.75 -Site coverage: % 44.72 -Aspect ratio: 0.31 -Tree number: 396
-Name: 1-B (Ershad) -Building density: % 13.64 -Street coverage: % 26.07 -Site coverage: % 1.95 -Aspect ratio: N/A -Tree number: 2836
-Name: 1-C (Sanabad) -Building density: % 56.79 -Street coverage: % 25.75 -Site coverage: % 57.41 -Aspect ratio: 0.31 -Tree number: 346
-Name: 1-D (Ahmadabad) -Building density: % 47.52 -Street coverage: % 29.74 -Site coverage: % 51.50 -Aspect ratio: 0.33 -Tree number: 436

Figure 42: selected neighbourhoods in District 1(fava.mashhad, 2020)

Neighbourhood	Arial photo	Ground plan	Street photo
-Name: 10-A (Miad) -Building density: % 38.63 -Street coverage: % 34.29 -Site coverage: % 43.13 -Aspect ratio: 0.21 -Tree number: 220
-Name: 10-B (Fallahi) -Building density: % 35.13 -Street coverage: % 36.96 -Site coverage: % 47.13 -Aspect ratio: 0.23 -Tree number: 350
-Name: 10-C (Hesabi) - Building density: % 38.39 -Street coverage: % 33.84 -Site coverage: % 57.21 -Aspect ratio: 0.30 -Tree number: 550
-Name: 10-D (Andishe) - Building density: % 29.34 -Street coverage: % 28.35 -Site coverage: % 15.89 -Aspect ratio: N/A -Tree number: 290
-Name: 10-E (Hadi) - Building density: % 50.39 -Street coverage: % 15.80 -Site coverage: % 49.53 -Aspect ratio: 0.26 -Tree number: 255

Figure 43: Selected neighbourhoods in District 10 (fava.mashhad, 2020)

3.7 Typical neighbourhood configurations

In the Iranian climate, street orientation is usually decided after determination of building orientation in residential areas. Traditionally, due to the harsh weather in most of the country, buildings need to block the cold wind in winter, welcome the gentle wind in summer, get as much natural light as possible during the day and create enough shade in the warm seasons. Not all of these goals can be accomplished by design, however facing the long side of buildings to the south is very common in the urban design of most cities with a hot arid climate such as Mashhad, Tehran and Yazd (Figure 44) because these will receive the smallest amount of radiation in summer and biggest amount of radiation in winter. The general Iranian urban design style is one in which buildings always need to be placed side by side in a row to avoid excess energy transfer outdoors in harsh weather and protect the lateral sides from receiving intense radiation in the morning or afternoon. Therefore, there are normally no openings or windows in the west or east sides of the buildings.

Figure 44: Typical Iranian building and street orientation. Streets are east-west orientated, and buildings are north-south oriented. aerial photo of case study 1-A (fava.mashhad, 2020)

In Mashhad, parks have many different types of vegetation but in urban areas, the vegetation is usually very simple. Streets predominately just have trees. It is very difficult to grow grass due to the lack of rain. In south oriented apartments, square boxes in front of the houses are used for trees, while in north facing apartments the squares become rectangles of the same width.

Figure 45 and **Error! Reference source not found.** represent the typical characteristics of each district. Each section of a street canyon is usually made of an asphalt street in the middle with concrete pavements on both sides. Both Districts share almost the same surface characteristics. Street trees are always between the street and sidewalk in the soil-filled boxes. It is worth mentioning that tree sizes in districts 10 and 1 are different. This is clear from both google images and site observations. This will need to be considered in the simulations.

Figure 45: Schematic of the typical section of District 1

Figure 46: Schematic of the typical section of District 10

3.8 Neighbourhood characteristics

Table 10 shows the land use /surface materials in the different neighbourhoods. Most neighbourhoods mainly consist of buildings, courtyards and streets. There are no ponds or water in any of the chosen areas. Almost 50% of the residential plots in both districts are courtyards which are finished with a light coloured concrete paving.

Table 10: Neighbourhood land use/surface materials

	Neighbourhood	Building density (%)	Sum of Courtyard areas (m ²)	Street coverage (%)	Sum of Grassland areas (m ²)	Sum of Bare land areas (m ²)	Sum of Asphalt pavement areas (m ²)
District 1	1-A (Sajad)	55.00	29351.33	24.75	3458.00	0	339.00
	1-C (Sanabad)	56.79	27963.58	25.75	0	0	79.49
	1-D (Ahmadabad)	47.52	36473.95	29.74	0	0	0
	1-E1 (Majd)	47.26	39076.52	27.48	73	0	0

District 10	1-E2 (Kolahdooz)	51.87	31044.61	27.18	0	2353.0	0
	1-F (Ebnesina)	50.65	32146.84	27.02	1215	0	0
	Average D1	51.52	39858.68	26.99	791.00	392.17	69.75
	10-A (Miad)	38.63	43102.18	34.29	7.78	0	0
	10-B (Fallahi)	35.13	42787.16	36.96	2666.00	0	0
	10-C (Hesabi)	38.39	26086.06	33.84	8600.00	0	19665.00
	10-E (Hadi)	50.39	47459.30	15.80	0	0	0
	Average D10	40.63	32676.14	30.22	2818.45	0	11065.00

In this study any orientation means the deviation of the long-axis from the north. In this way, wind direction and its relation to the orientation of a street, plot or footprint will be more logical. Table 11 summarizes the main orientation for streets, plots and buildings in each neighbourhood. All orientations with more than 10 percentage frequency have been reported in the table. Some neighbourhoods such as 1-A (Sajad) have a dominant street and building orientation but others such as 10-E (Hadi) and 1-D (Ahmadabad) have a mix of orientations, which mainly indicates non-grid patterns in these neighbourhoods.

Table 11: Street, plot and building orientation

Neighbourhood	Street		Plot		Building	
	degrees from North	Percentage (%)	degrees from North	Percentage (%)	degrees from North	Percentage (%)
1-A (Sajad)	91-100	53	0-10	87	0-10	79
	0-10	38	31-40	4	91-10	10
1-C (Sanabad)	111-120	64	21-30	69	21-30	64
	21-30	23	11-20	15	111-120	16
	11-20	9	111-120	8	0-10	12
1-D (Ahmadabad)	81-90	23	0-10	38	0-10	34
	91-100	19	171-180	27	171-18	23
	101-110	19	11-20	18	11-20	15
1-E1 (Majd)	0-10	16	81-90	10	-	-
	21-30	25	21-30	42	21-30	38
	111-120	25	111-120	18	111-120	22
	101-110	12	0-10	12	0-10	11
1-E2 (Kolahdooz)	111-120	41	21-30	47	21-30	44
	21-30	31	110-120	29	111-120	31
	101-110	15	11-20	10	11-20	10
1-F (Ebnesina)	141-150	59	51-60	69	51-60	54
	101-110	11	141-150	10	141-150	24
10-A (Miad)	81-90	68	171-180	94	171-180	75
	171-180	21	-	-	81-90	23
10-B (Fallahi)	141-150	29	51-60	39	51-60	33
	111-120	13	171-180	16	81-90	16

10-C (Hesabi)	81-90	13	81-90	13	171-180	14
	51-60	13	11-20	10	141-150	13
	51-60	60	141-150	84	141-150	79
	141-150	25	-	-	51-60	13
10-E (Hadi)	71-80	39	161-170	25	161-170	21
	151-160	19	151-160	18	71-80	20
	161-170	19	61-70	18	61-70	19
	141-150	10	71-80	16	151-160	18

Average building height, Average plot size, Average site coverage, Average foot print size, Average SVF in different neighbourhoods are reported in Table 12.

Table 12:urban form characteristics

	Neighbourhood	Average Building Height (m)	Average plot size(m ²)	Site coverage (%)	Average footprint size (m ²)	Average SVF
District 1	1-A (Sajad)	7.02	451.33	44.72	14.70	0.62
	1-C (Sanabad)	5.78	262.90	57.41	7.67	0.56
	1-D (Ahmadabad)	6.78	297.65	51.50	9.26	0.54
	1-E1 (Majd)	5.32	141.60	48.82	6.30	0.51
	1-E2 (Kolahdooz)	5.32	135.27	62.10	4.71	0.54
	1-F (Ebnesina)	6.72	244.08	48.90	8.58	0.52
	Average D1	6.16	255.47	50.79	129.76	0.66
District 10	10-A (Miad)	4.11	223.20	43.13	8.77	0.70
	10-B (Fallahi)	4.18	232.95	47.13	9.22	0.73
	10-C (Hesabi)	5.10	175.73	57.21	5.94	0.68
	10-E (Hadi)	3.89	113.74	49.53	5.08	0.52
	Average D10	4.32	186.41	48.68	90.73	0.55

3.9 Summary

This chapter has set the context of the research by first looking at urban design in Iran, both in the past and the present. The city of Mashhad, including its pattern of growth, was described and then the districts chosen for the case studies were described. The urban characteristics of these districts have been introduced. Chapter 4 discusses the method by which the UHI characteristics of the chosen case studies will be investigated.

4 Methodology

The Urban Heat Island (UHI) effect is a global issue that can aggravate global warming (GW), and is a major problem in cities in developing countries like Iran. Local adaptation and mitigation strategies based on available data, tools and resources in parallel with understanding the necessary level of intervention could be a valuable solution for reducing UHI effects in Iran. During the last decade, much research has been carried out on Urban Heat Islands (UHIs). Land Surface Temperature (LST) is the main factor in monitoring city climatology, and hence UHIs. Methods for studying UHIs can be categorized into two main groups: simulations and observations (Mirzaei & Haghighat, 2010). Each approach has benefits and drawbacks. Therefore, it is the responsibility of researchers and urban managers to find out which method would best suit the study aim and available resources. In addition, it is critical to have a localized methodology with regards to the accessibility of available data and tools and the level of intervention necessary (Shabahang, Gjerde, et al., 2018; Shabahang, Vale, et al., 2018). This research is thus trying to establish a method for estimating ground surface and air temperatures in developing countries like Iran where climatic and urban data are either not sufficient, not available, or very expensive to obtain.

4.1 Review of methods

In this section, the advantages and limitations of each approach will be reviewed and discussed in order to select the best technique for a comparative study of UHI based on available resources and the gap in knowledge in Iran, using the city of Mashhad as a case study.

The observational approach is the oldest technique for studying UHI. It needs to be done either by collecting weather data or by using thermal images. One way of collecting weather data is through weather stations. The city of Mashhad has only one weather station located far from the city in the airport (Figure 47). This station can only report the daily temperature of the surrounding area, which would not be useful for this study because this research aims to examine the temperature difference at the neighbourhood scale. The metrological data from this station can only be used for the initial metrological setup. The other method of metrological data collection is by vehicle temperature traverse. This approach is reliable but expensive especially for Iran which suffers from sanctions and an unstable currency. Other limitations could be machine or user error, a lack of a three-dimensional outcome, and difficulty in evaluating the data (Mirzaei & Haghighat, 2010).

Figure 47: The location of Mashhad airport with the only weather station and distance from the selected case study districts (fava.mashhad, 2020)

Satellites and airborne technologies could provide thermal images with which to study UHI. However, thermal images can only use for calculation of the surface temperature. Air temperature then needs to be assessed using mathematical methods. The thermal remote sensing approach was reviewed by Voogt and Oke (2003). Except for the cost, which was a big drawback, they especially highlighted the effect of low-resolution images on studies. In other words, valuable results could be derived for large scale areas such as the city-scale, but not for the neighbourhood scale. Much research in Iran has highlighted the importance of UHI in major cities (Table 13). Most of these studies were conducted at an urban scale using the observational approach to show the increase in urban temperatures in Iranian cities. These studies are very valuable for finding and highlighting the problem of UHI for urban designers and policymakers but do not suggest what needs to be changed to mitigate the UHI effect. To evaluate the effect of urban characteristics a different approach needs to be employed. Since the aim of this study is a comparative analysis of the existing distribution of UHI at the neighbourhood scale, remote sensing was not an option.

Table 13: Comparison of UHI study approaches in Iran

Authors and years	Parameter		scale		Method			Location
	Air Temperature	Land Surface Temperature	Urban scale	Neighbourhood scale	Weather data collection	Remote Sensing	CFD	
Ghazanfari et al. (2009)	√	-	√		√	-	-	Mashhad
Mousavi Baigi et al. (2012)	√	√	√		√	√	-	Mashhad
Bokaie et al. (2016)	-	√	√		-	√	-	Tehran
Soltanifard and Aliabadi (2019)		√	√			√		Mashhad
Sherafati et al. (2013)		√	√			√		Tehran
R. Amiri et al. (2009)		√	√			√		Tabriz
Ghobadi et al. (2018)	√				√			Karaj
Ramyar et al. (2019)		√	√	√			√	Tehran
Shirani-Bidabadi et al. (2019)		√	√			√		Isfahan
Naserikia et al. (2019)		√	√			√		Mashhad
Moghbel and Shamsipour (2019)	√	√	√		√			Tehran

The simulation approach is an empirical method for the study of urban climate. It can be done through several platforms such as Rayman model, SOLWEG model and ENVI-met. This approach was reviewed by Mirzaei and Haghighat (2010). The simulation approach can also be divided into two main subgroups; the urban canopy model (UCM) and computational fluid dynamics (CFD). The weakness of the UCM includes ignoring air velocity in temperature calculations as well as over-simplification of the urban structure. A CFD model can apply all necessary fluid mechanics equations in an urban model and should thus provide more accurate UHI outcomes. However, the accuracy level of the results follows the scale of the model. It means simulations at the street scale are different from those at the neighbourhood scale and the city scale. In fact, simulation models can operate at the various scales of indoors, the individual building, microscale and mesoscale models. Simulation requirements in terms of computer processing capacity and urban detail data along with currently incomplete theoretical

frameworks are big barriers to the success of these approaches. Major assumptions and simplifications could reduce cost but also accuracy. This approach depends on the study perspective and could be practical in a comparative analysis, at the early stage of urban design, or for a new urban development. It could be useful when the existing UHI distribution needs to be studied, evaluated and finally compared to the impact of proposed optimization scenarios. Table 14 compares the two approaches for studying the UHI effect and surface temperature.

Table 14: Comparison of two approaches to measuring surface temperature based on Mirzaei and Haghighat (2010)

approach	method	Function and strengths	Limitations
Observational approach	Thermal remote sensing	-Sensor technology measure the electromagnetic radiation emitted by the surface of the Earth -Collect data from macro scale part of city with the accuracy of one metre per pixel	-Very expensive -Not very accurate because of weather -Not very accurate because pictures are to 2 dimensional not 3 dimensional -Not directly measuring the surface temperature
	Computational fluid dynamic (CFD)	-More accurate than observational approach -Possibility of comparative analysis based on different scenarios -Simulations can provide results for any relevant variable in the whole computational domain.	-Cannot use the actual scale of city -Should be simplified thus they act under the rules of physics and the physics of microclimate are very complicated

Table 15 sets out the different CFD methods/platforms used for studying urban climate. The two main methods using CFD are Large Eddy Simulations (LES) and Reynolds Averaged Navier–Stokes (RANS). Each method has some other sub-method it uses. For example, among RANS simulation methods, standard k- ϵ turbulence models are very popular (Toparlar et al., 2017). These techniques are used for studying the validation of the software or for studying different aspect of urban climate, for instance thermal comfort or UHI in hypothetical scenarios or real urban areas. The application of CFD models was reviewed by Toparlar et al. (2017). They showed how, in recent years, the application of CFD models has changed from model development at the beginning to urban climate prediction. Among different platforms ENVI-met has been employed by half of the users for studying urban microclimate (Michael Bruse & Fleer, 1998; Toparlar et al., 2017). The second place is earned by the standard k- ϵ turbulence model. Although the LES model gained better results in terms of accuracy over RANS, the lack of guidelines for users and high computational requirements leads to its lesser popularity over RANS (96% of usage) (Toparlar et al., 2017).

Table 15: Different simulation approaches to studying urban climate characteristics

Authors and years	Method/Tool	Parameters studied	Study area/time
Lauwaet et al. (2016)	UrbClim	Air temperature at 2m above ground	Brussels, Belgium/ Summer months June, July and August
Matzarakis et al. (2007)	RayMan	Mean radiant Temperature	Freiburg, Germany/19.06.2005 at 22.30
Matzarakis and Matuschek (2011)	SkyHelios	Sky view factor (SVF)	Swabian Alps in south west Germany
Lindberg et al. (2008)	SOLWEIG 1.0	Mean radiant Temperature	Göteborg, Sweden/ 11 October 2005, 1 August 2006
N. Zhang et al. (2014)	Large Eddy Simulations (LES)/ Weather Research and Forecasting (WRF)	UHI intensity	Assumptions
Schrijvers et al. (2015)	Transient Reynolds Averaged Navier–Stokes (T-RANS)	Surface temperature	52° 22' N and 52° 22' N / 2012-06-10 00:00
Priyadarsini et al. (2008)	Reynolds Averaged Navier–Stokes / CFX-5.6 (2001)	Air temperature	Singapore, August 2002
Yasin Toparlar et al. (2015)	Reynolds-averaged Navier–Stokes (URANS)	Surface temperature	Rotterdam/ July 2006
Y. Wang et al. (2016)	ENVI-met	Surface temperature, air temperature, mean radiant temperature and PET	Toronto, Canada
Ambrosini et al. (2014)	ENVI-met	Atmospheric temperature, relative humidity and wind velocity	Teramo, Italy/20 July 2013
Crank et al. (2018)	ENVI-met	Air temperature at 2m above ground	Portland, Oregon (45.5° N, 122.7° W)
Roth and Lim (2017)	ENVI-met	Air temperature, mean radiant temperature	Singapore
Emmanuel and Fernando (2007)	ENVI-met	Air temperature, mean radiant temperature	Colombo, Sri Lanka
Middel et al. (2014)	ENVI-met	Air temperature distribution and variation, ventilation, surface temperatures, and shading	Phoenix, USA/ June 23, 2011
Chow et al. (2011)	ENVI-met		Phoenix, USA/ Oct 27–28, 200
F. Yang et al. (2011)	ENVI-met	Physiological equivalent temperature (PET) as the thermal comfort index	Shanghai, China/ 4–6 August 2008
Juan A. Acero and Herranz-Pascual (2015)	ENVI-met	Mean radiant temperature, wind speed, air temperature, PET values	Bilbao, Spain/ 6th-8th August
X. Yang et al. (2013)	ENVI-met	Soil temperature, soil heat flux, surface temperature, air temperature and humidity	Guangzhou, South China/ 29 August to 2 September in 2010

Choosing the right CFD application for this study was very important. The aim was to design an affordable methodological approach for urban design firms and city councils to enable them to evaluate UHI effects in different neighbourhoods easily and accurately. This way the whole

process of establishing countermeasures against UHI will be simpler. Therefore, the right platform for this study needed to be accurate, user friendly, cheap and not time-consuming. Among the different simulation approaches, ENVI-met seemed a good option. However, it needed further investigation.

4.2 Methodological approach

Based on the review of different methods, ENVI-met best served the aim of this research. In comparison to the other approaches, it is cheap and could be made available in many urban design firms. It also has a free version which could be very helpful for students. More importantly, it is user friendly. The ENVI-met website provides many valuable tutorials, fora and information for users. Nevertheless, the simulation method ENVI-met needed to be examined. A proper setting for the different applications in ENVI-met needed to be investigated to reduce time and cost. Part of this investigation is explained in this chapter. The sensitivity of different settings and inputs will be examined in the discussion of the pilot study (see chapter 5). This will be done through creating different scenarios for selected areas of the city of Mashhad. In order to assess ENVI-met simulation outputs the default inputs in both the modelled areas and simulation tool were manipulated. As the aim of this research was to see how much the simulation process could be simplified to suit the resources available in Iran, only ground surface temperature (Ts) was considered for the pilot study.

4.3 ENVI-met

Urban-Scale Energy Modelling (USEM) at the neighbourhood or urban level has begun to attract more attention (Sola et al., 2018). USEM is a new opportunity which enables urban designers to have a general overview of the microclimate of large areas and evaluate strategies (Sola et al., 2018). However, this opportunity is both expensive and time consuming. It is just possible with the help of powerful computers, which are able to work in parallel (ENVI-met, 2019d). For example, ENVI-met recommends using a computer with a 6-8 core CPU. However, this may not be feasible for developing countries whether the research is practice or university based. Although there are some comprehensive reviews of Urban-Scale Energy Modelling in terms of its classification and evaluation (Sola et al., 2018) fewer studies have been done for the software known as ENVI-met.

ENVI-met is a simulation tool that has been widely used for investigating urban micro climate and urban surface temperate. It has also been used to look at urban micro-climates and UHI mitigation (Juan A Acero & Arrizabalaga, 2018; Ambrosini et al., 2014; Crank et al., 2018;

Mohamed H Elnabawi et al., 2013). The numerical micro scale model is based on the interaction of urban materials and the climate. For instance, it takes account of solar radiation, including direct, diffuse and reflected radiation, along with airflow patterns and heat transfer from the urban surfaces to the air. By March 2018, some 280 ENVI-met related journal and conference papers were available in the Scopus database, 77% of these studies having been done from 2012 to 2017. Other areas of investigation with ENVI-met include air quality focusing on pollutants (S. Tsoka et al., 2018). Some of these studies have looked at local climate with different scenarios of urban greening (Mohamed H. Elnabawi et al., 2015; Morakinyo & Lam, 2016; Simon et al., 2018b), global warming effect (Huttner et al., 2008), or urban morphology (Stella Tsoka, 2017), concentrating on materials that will aid cooling and additional greening. Quantitative evaluation shows that the ENVI-met model is capable of predicting the microclimate in terms of its different variables with good accuracy (S. Tsoka et al., 2018). It seems ENVI-met is a reliable tool if users know its potential and weaknesses, and are able to interpret the outputs carefully (S. Tsoka et al., 2018). When it comes to the detail of using ENVI-met, Perini et al. examined a new method for simulating the microclimate of urban areas. They used ENVI-met and TRNSYS by means of Grasshopper. The study showed use of the pair of simulation tools enhanced the accuracy of the results (Perini et al., 2017).

4.3.1 The ENVI-met concept

To achieve good results, it is essential to understand the structure of the ENVI-met software. Each piece of software is limited in what actions it can undertake. Understanding the pros and cons of the software helps in realising how far and to what extent the results will be reliable. Figure 48 is the structure of ENVI-met 3.1 (M Bruse, 2009a). However, the concept ENVI-met 4 which was the software available for this research is slightly different.

Figure 48: ENVI-met concept, source (ENVI-met, 2019b)

4.3.2 ENVI-met Model layout

The ENVI-met model structure is made up of a model, the main 3d model and the soil model. There is also an area around the boundary which is called the nesting area (Figure 49). The boundary model is a 1d dimensional metrological parameter with a height of up to 2500m. The main 3d model is an area with all buildings, vegetation, surfaces, and atmosphere, and 3 the-dimensional soil model goes down to 5 metres below ground level (ENVI-met, 2017a).

Figure 49: Basic ENVI-met software model layout (ENVI-met, 2017a)

Smaller grid cells lead to better resolutions. Considering an area of 100m x100m, this could be modelled as an area of 100x100 grid of 1x1m cells, making 10,000 cells or a 100x100 grid of 5x5m cells, making 400 cells. The first one has a better resolution which needs considerable time and powerful a CPU. Generally, there is no limitation on 2d grid cells, and the size of the model area could be the size of the city. The limitation is simulation time. Higher resolution means more grid cells which consequently needs longer simulation times. For example, simulating 500x500 grid cells for the period of 24 hours takes roughly 3 times more than 250x250 grids cells in normal computers. The sufficient resolution for grid cells is two metres, however, the choice strongly depends on the goals of the study (ENVI-metBoard, 2019). In this study, the case study areas were 400m x 400m. This is quite a big area in terms of size, however the resolution of the results was also important. Therefore, the cell size considered was 2mx2m.

4.3.2.1 Vertical Grid Layout

Vertical grids work differently in 2.5D and full 3D models. In contrast to the full 3d model, settings in 2.5D are changeable. Figure 50 shows the different type of vertical grids in the main model. The usage of each type has been summarized in Table 16. As the chosen

neighbourhoods have almost the same height buildings, the Equidistant Grid was used as a vertical grid setting in this research.

Figure 50: Different concepts for organizing the vertical grid layout: (A): Equidistant Grid, (B): Telescoping grid and (C): Telescoping grid with no extension factor (ENVI-met, 2018b)

Table 16: Different vertical grid layouts in model area in ENVI-met

Vertical Grid Layout	Description
Grid Version A: Equidistant	A model with limited similar height
Grid Version B1 and B2: Telescoping	A model with notably different heights (like skyscrapers and low-rise buildings)
Grid Version C: Telescoping, but without Extending	A model with notably different heights (like skyscrapers and low-rise buildings)

4.3.2.2 Nesting grids

Basically, a nesting grid is the 2-dimensional horizontal area that starts at the border of the main domain and surrounds it (ENVI-met, 2017a) (Figure 49). In general, numerical models are not very reliable when it comes to the edge of the modelled area. ENVI-met creates different types of solution for this issue. Lateral boundary conditions and nesting grids are two of those. Using nesting grids takes the numerical border problem away from the main core. Nesting grids have certain features:

- They are not visible in output files, unless they are disabled in the project wizard.
- There are no buildings in this area and the soil profile is the combination of existing soil profiles.

- As there is no building in this area the surface temperature will be higher than for normal places with trees and buildings (ENVI-met, 2018a)
- The further they go from the core the bigger they get (ENVI-met, 2017a).

ENVI-met does not recommend using nesting grids because doing this time consuming and needs more powerful computers, instead, users are encouraged to add more grid cells at borders and then decide what is the core area of interest (ENVI-met, 2018a). Use of nesting grids highly depends on the power of the available computers which means they are not be applicable for all research. Since the difference between nesting grids, more empty cells around edge, and simulation of a bigger area depend on the research type and goal, these three options were examined, and the description of this is found in discussion of the pilot study section (section 5.2).

4.3.2.3 The Digital Elevation Models (DEM) setting

DEM represents the cell-based digital elevation of the earth's surface (esri, 2019) (Figure 51). In ENVI-met, it is achievable through the Monde application and Get Topography tool. Monde provides open access to different topographic sources like NASA and Japan AEA. The impact of DEM on the final outcomes, is also examined in the discussion of the pilot study.

Figure 51: Visualization of a raster DEM surface (esri, 2019)

4.3.3 ENVI-met 4 Updated model overview

ENVI-met 3 has been updated with the changes made mostly dealing with bug-fixing, numerical modelling improvements like flow calculation stability, 3d modelling improvements like adding a new option for telescoping grids, and some reviewing of the order and quality of actions like pollutant dispersion routines (M Bruse, 2009b). The ENVI-met 4 update could be

summarized as including new 3d editors, upgrading of the calculation of wall temperature and upgrading of the boundary conditions (Huttner & Bruse, 2009). The ENVI-met 4 winter-release 2018/2019 introduced new features such as the green facade model, full forcing, ENVI-net Monde, the potential to convert ENVI-met output to NETCDF, and finally a new plugin for working with Grasshopper (ENVI-met, 2019a). The new features of ENVI-met 4 are discussed in more detail below.

4.3.3.1 Green facade model

Both green roofs and green walls are considered as one of the main strategies for reducing urban warming, especially in existing sites (Costanzo et al., 2016; H. M. P. I. K. Herath et al., 2018; Razzaghmanesh et al., 2016; Zaid et al., 2018). ENVI-met provides the opportunity for users to study the interaction between vegetation, substrate layers, and fixing materials on facades or roofs (ENVI-met, 2019a). This cutting-edge potential could be very useful for creating optimized or adaptation scenarios, which were not an option in this study.

4.3.3.2 Full forcing

Since it is not feasible to simulate the whole city, boundary conditions emerge as a critical part of this type of simulation. Generally, Lateral boundary conditions (LBC) is a setting for temperature, humidity and turbulence variables at the borders of the model area. However, ENVI-met recommend either not to change the by default settings or to use the “Simple Forcing” options (ENVI-met, 2017b). The boundary conditions in ENVI-met were traditionally divided into three groups; open lateral boundary conditions, cyclic lateral boundary conditions, and simple forced lateral boundary conditions (Table 17). The first two simply either copied the value of the next grid point to the border at each time step (open lateral) or copied the value of downstream model border to the upstream model border (cyclic lateral). Thus, these two boundary conditions utilize very few initial parameters. This meant it is very difficult to create certain real-world conditions like sea or land breezes or in other words the real world. With simple forcing, a 24-hour cycle of air temperature and humidity are defined by the users. The limitations of simple forcing concern the time of 24 hours and humidity. The new full forcing option provides more accurate boundary conditions for different meteorological parameters for instance air temperature, humidity and wind directions and for a longer period of time (ENVI-met, 2019a). Although full forcing produces more accurate results, it was not an option for this study. Full forcing needs more detail methodological data such as an EPW file, which was not officially available for the city of Mashhad. Therefore, as recommended by ENVI-met simple forcing was chosen for the boundary condition settings.

Table 17: Different types of lateral boundary condition in ENVI-met (ENVI-met, 2017b)

Version	Type	Description
Old versions	Open LBC	The values of the next grid point close to the border are copied to the border for each time step
	Forced (or closed) LBC	The values of the 1-dimensional model or those from the forcing data are copied to the border
	Cyclic LBC	The values of the downstream model border are copied to the upstream model border.
New version	Full forcing	The predefine weather profile (temperature, humidity) copied to model
	Simple forcing	The predefine weather profile (temperature, humidity) copied to model

4.3.3.3 ENVI-net Monde

Considering more cities now provide their Vector data in Shape File or CAD-file, the Monde application in ENVI-met more than any other improvement paves a path for urban designers to study the urban micro-climate. This is because it changes the time-consuming grid-by-grid digitizing approach to a vector-based approach (ENVI-met, 2019a). Moreover, Monde has the option to import other open-source data like OpenStreetMap data and OpenTopography terrain data by. This option could shift microclimate study from universities and research centres to urban design firms. This application was exploited for the simulation because it saved time and increased the accuracy of the simulation.

4.3.3.4 Converting ENVI-met output to NetCDF

The binary format output which is produced by ENVI-met can only be visualized by Leonardo, while NetCDF is a machine-independent data format which can be visualized on MacOS or Linux (ENVI-met, 2019a). In this study only Leonardo was used for visualization.

4.3.3.5 Rhino Grasshopper plug-in

The Grasshopper plug-in provides a very quick tool, especially for architects, to run simulations in Rhino without even opening ENVI-met (ENVI-met, 2019a). It is also a good tool for creating and examining more scenarios both at the building and neighbourhood scale. In other words, optimizing any proposed scenarios can be done much faster with this improvement. This practical option will not be used in this study, as the objective is to simulate real neighbourhood conditions and not optimised scenarios.

4.3.4 ENVI-met limitations

ENVI-met is a cost-effective, user-friendly software for the study of the UHI. Therefore, most studies of the software have concentrated on validation of ENVI-met (4.6.1) and the benefits of employing it for UHI studies (4.3, Chapter 5.). There is a lack of research on sensitivity and the limitations of ENVI-met. Therefore, this study began with a pilot study to evaluate the sensitivity of the software to its own parameters, and this step is explained in chapter 5. In terms of ENVI-met limitations discovered by other researchers these are summarised below:

- air temperature and relative humidity are updated during the simulation time, while wind speed and direction remain the same for all processes. This limitation leads to hourly temperature differences between modelled and measure data (Acero, 2018).
- radiation fluxes have not been calculated accurately, also turbulent production k has been overestimated and this causes inaccuracy in wind speed estimations (Juan A. Acero & Herranz-Pascual, 2015; Huttner, 2012).
- Indoor temperature remains the same for the whole process and is considered to be the same value as the inner wall temperature (Huttner, 2012)
- The lack of information for accurate results occurs because of the grid resolution limitation (Acero, 2018), and the near wall calculation (Toparlar, 2017).
- The cloud is static rather than dynamic (Morakinyo, 2017).
- 3d Modelling is also limited because building shapes need to be simple and without any windows.

4.4 Simulation Methods

This research tested the effect of the existing urban characteristics on UHI, using ENVI-met simulations. This is thus a case-based comparative analysis. The goal was to understand the role of urban characteristics, with a focus on urban form, and air temperature and surface temperature as two characteristics of UHI. To run the simulations, different applications needed to be used either within an ENVI-met program like Monde, or outside ENVI-met like GIS. For accurate results, inputs need to be reliable.

Basically, the simulation approach consists of three main stages. These are the modelling stage, the CFD stage, and the translation stage. Establishing all the important settings and input data needs to happen at the modelling stage. The modelling output file is then imported to the CFD stage where the numerical modelling is run. The outputs of the simulation are saved in different folders which need to be translated or visualized using different applications. The detailed simulation method is shown in Figure 52. Fortunately, the GIS map was half prepared by the Mashhad City Council. However, more data needed to be added to the original map, such as a tree shapefile and a street shapefile. Moreover, the urban characteristics of each neighbourhood stored in the attribute table needed to be exported to Excel software for further analysis. After

the shapefiles were prepared, these were imported to the Monde application in the ENVI-met software. Material assignments and final modification were done in Monde. The output of Monde was imported to the Spaces application. In Spaces, the domain size and border conditions needed to be checked. The output of Spaces was then imported to the ENVIGuide application to define the lateral boundary condition and initial meteorological settings. To run the simulation, ENVI-met needed to import the output of the ENVIGuide. The processing time varied and once processing was finished all the atmospheric outputs could be found in the output folder. At this stage, the LEONARDO application could be used to visualize the simulation results. The whole process was first done for two selected neighbourhoods as a pilot study (see section 5), then the main simulations were conducted based on the pilot study results (Figure 53).

Figure 52: Simulation method employed in this study. All activities in the orange rectangle were done in ENVI-met. GIS was used at the preparation stage.

Figure 53: Input data and settings examined in pilot study, and results used in the main simulation

4.5 Data collection and limitations

Studying UHI at the neighbourhood scale is a gap in Iran in both in city planning area(1.1.3, 1.1.4) and the academic area (4.1). From the political point of view, it seems governments are underestimating the consequences of climate change. Therefore, they do not provide sufficient budget for universities and other research centres to investigate this and come up with solutions, despite the fact that data is available for such an investigation. For this reason, this study decided to run the investigation with all the available data. The data already exists and there is no need to ask for more investment from governments.

Input data for the ENVI-met simulation and for a statistically based urban comparison could be divided into two main groups; weather data and urban data. The researcher travelled back to Iran in 2019 with the aim of finding reliable data from reliable sources, because the official website of both the city council and the local weather station are not always up-to-date. The next goal was to explore the city to find suitable neighbourhoods for comparison.

As mentioned before, Mashhad is metropolitan city with an area of 320 km² and a population of around 3 million people. To manage this big city, the main city council has 13 district councils, 7 other sub-governmental organizations and 10 semi-governmental organizations. Some of the 13 district councils have good urban data about their district, but not all. The Mashhad GIS map formed the main data source for this study, as much detailed data could be extracted it, such as urban characteristics like site coverage or density. However, finding the Mashhad GIS map was not as easy as finding other GIS maps, as it could not be found on Open Street or the city council website. Moreover because of sanctions, many google map services like street view were not provided for Iran. The quality of aerial images were also very low. For access to the GIS map, the responsible organization needed to be found from among the 30 different organizations. As Mashhad has a big population, communication with the city council is a challenge. Although there are email addresses, and phone numbers or faxes on the websites, the best approach is visiting the related office and then finding the responsible person or section. Finding the responsible section for enquiring about data is another big mission, as employees not necessarily aware of the responsibilities of other sections. The researcher needed to interview different people to find out where the Mashhad GIS map was located. Fortunately, the independent office called the Mashhad Research and Information Technology Organization, which is responsible for both weather and urban data, was eventually located. However, this organisation stated that it is not possible to have access to these data because the researcher was studying abroad. The concerns was about publishing any urban information which could be used against the city in a possible war. After month of following up and discussing the issue of access with different people, and explaining that these types of data are not confidential and can be found publicly in other countries, the answer was still no. Finally on the last day of the visit, through an important connection, the principal of Mashhad Research and Information Technology Organization agreed to give access to the GIS map. Since then, communication with them has happened through email. Metrological data which includes temperature, humidity, participation, maximum wind and wind orientation during 12 months in Mashhad was emailed to the researcher. A main breakthrough was receiving the user name

and password so as to use GIS map. The Mashhad GIS map includes shapefiles regarding the district area, population, building heights, building area, and plot area. However, this was all the data obtained from local sources. There was no information about building and urban materials or about street vegetation. However, what was available was good basic information to start with. These were used to model the neighbourhoods and to run the simulations. Chapters 5 and 6 explain how the other input data was obtained or created.

The initial plan was to return to Iran after finishing the simulations. This would have enabled taking detailed photos of the selected neighbourhoods (which were not completely confirmed by the time of the first time), showing the study results and suggested improvements to the city council and asking for more detailed data on the urban characteristics. The hope was to build a connection and to ask for measured temperatures in neighbourhoods, data that could probably come from other governmental sections. All these plans were cancelled because of the Covid crisis all around the world. The only thing possible was to ask two of my friends Mona Safarzade and Mehrdad Chamani to take some photos in the selected neighbourhoods which are those that appear in this thesis.

4.6 Input data

Although the idea of simulating the whole city seemed very interesting and theoretically it is possible using ENVI-met, this would have needed a very powerful computer and a huge amount of time. Since this study aimed to create a methodological approach for urban designers at the scale of the neighbourhood, logically there was no need to model the whole city. The program inputs and outputs which were used to run simulations in this research are detailed below.

4.6.1 GIS

The GIS input data information for this research was obtained from Mashhad City Council. Except for preparing vector data for the modelling area, GIS was the main tool used for producing the necessary urban characteristics for neighbourhood analysis. The Mashhad GIS map contained a range of Vector data and attribute tables from population density to bare land. For the aim of this study, shapefiles which would help in simulating UHI were necessary. As can be seen from Table 18, the Mashhad GIS map contained some shapefiles and missed others that were needed. Consequently, the GIS base map was used to produce the missing shape files.

Table 18: Shape files in GIS map or as created by author

Urban characteristics needed for simulation	In Mashhad GIS map	Created by author
Footprints	✓	
Building heights	✓	
Plot areas	✓	
Bare land areas	✓	
Grassland areas		✓
Street areas		✓
Asphalt pavement areas		✓
Trees		✓

The background Google image showed some minor buildings were slightly different from the shape files, but this was ignored. Missing elements such as trees and streets were created one by one for the selected neighbourhoods following World imagery (Figure 54). As the quality of google image is not very good in Iran, these additional elements are approximate. It was difficult to guess whether a green volume is a tree or a bush. It was also difficult to guess objects in large shadows (Figure 55).

Figure 54: Preparation stage for neighbourhood 1-A (Sajad), the process of completing GIS map obtained from Mashhad City Council. This process was done for all selected neighbourhoods. Street area in dark grey and trees added to original shapefiles. The smaller rectangle defines the selected area of 400m x400. The second and third rectangles show the buffer to the area selected for simulation.

Figure 55: Google Earth Aerial photo quality for digitizing trees in District 10 Hesabi neighbourhood

4.6.2 Monde

A geo-reference is needed for the Monde application. In Monde geo-referencing could be done by tapping “World Set” and then using the Google search engine. In this study the metric UTM system was used for map geo-referencing to match the GIS geo-referencing. To have good resolution the map size remained at 5000mx 5000m. Open street map was not used for this study because the GIS map provided for Mashhad was very incomplete. However, Open street map was still useful because it visualizes the targeted area and make it easier to navigate in a model area. For building height and other important items, shape files have been imported into Monde (Figure 56).

Figure 56: Steps taken in Monde application to create .monde file from shapefiles. Monde file was used in Space application.

There are two ways to assign materials to the model area either through Spaces application or Monde application. At large scales, similar to the scale of this study, Monde is the better, faster option, because the Spaces concept is grid based while the Monde concept is vector based. After some manipulation of materials which are discussed in more detail in the pilot study (see section 5), Table 19 shows the final material assigned to each element. The assignment of materials was based on photos taken of the different neighbourhoods and the author’s knowledge of construction in Mashhad. Except for wall and roof materials, other materials were assigned from the ENVI-met database. The ENVI-met database does not have the profiles which are usually used for walls and roofs in Mashhad, therefore, these were created by the author from the Database Manager tab (Figure 57). The whole area is almost flat, so there was no need to import topography.

The Monde application in ENVI-met 4.4.4 crashed when it came to assigning the tree profile to the related shapefile. After communication with the ENVI-met group, this was found to be bug. As a result, ENVI-met 4.4.3 was used for the whole process of material assignment.

Table 19: Material input data in Monde

Layer name	element	Database ID	Profile
Buildings	Roof material	User profile	Concrete 15cm, concrete hollow block 30cm, plaster 3cm
	Wall material	User profile	Brick 2.5cm, brick 20cm, 1.5cm plaster
	Building foundation slab	0100PG	Concrete pavement grey, refer to ENVI-met database manager
Surfaces	Plot area (courtyard)	0000PL	Concrete pavement light, refer to ENVI-met database manager
	Bare land area	000000	Loamy soil, refer to ENVI-met database manager
	Street areas	0000ST	Asphalt, refer to ENVI-met database manager
	Asphalt pavement area	0100PD	Concrete pavement dark, refer to ENVI-met database manager
Vegetation	Grass lands	000000	Grass 50cm average, dense
	Grass soil profile	0100PP	Concrete pavement used/dirty, refer to ENVI-met database manager
	Trees (small)	010SDS	Cylindric, small trunk, dense, small (5m)
	Trees (medium)	010MDM	Cylindric, small trunk, dense, small (15m)

Figure 57: The process of creating a local wall material based on database material in ENVI-met using database manger

4.6.3 SPACES

Spaces used to be the main application for creating the model for simulation. All buildings, surfaces and vegetation could be created there. However, thanks to the new update all time-consuming grid base modelling can be done faster in the Monde application (Figure 58). Spaces is also the place to set the border conditions, whether using the nesting grid or empty cells. Another option for the border condition which is highly recommended by the ENVI-met support area is to simulate a bigger area and then to cut this to the area of interest in the Leonardo application. Because the difference between these different options was unknown,

all different possibilities were created and examined in the pilot study (section 5.2). Table 20 shows the final settings for Spaces which were used for the main simulation.

Figure 58: Steps taken in the Spaces application to create the INX file to be used in ENVIGuide application.

Since in the selected areas most of the buildings have a similar architecture, for example, they have a steel structure, brick exterior wall and similar window layouts, 2.5d mode was selected for the model area (ENVI-metBoard, 2018a).

Table 20: Model domain input in Spaces

Domain size (m)	Grid dimension (m)	resolution	Nesting grid	Empty cell	DEM
440x440x75	220x220x25	2x2x3	-	-	-

4.6.4 ENVIGuide

The initial meteorological data needs to be set up in ENVIGuide. This includes the start date, the start time, total simulation time, simulation level, forcing methods and other weather data such as air temperature, wind speed, humidity etc. The date was set to 23rd of July 2016 based on the following reasons. First, this study was inspired by another study that investigated UHI in Mashhad using remote sensing (Alavipanah et al., 2015). The authors used the Landsat thermal images for different dates (1987/5/1, 2000/5/28 and 2014/5/11). The time for the images was usually around 10am. Moreover, two other studies with the same approach in Mashhad have chosen summer time for their studies. Soltanifard & Aliabadi (2019) chose 2014/06/27 and Naserikia et al. (2019) chose 2017/07/06, 2001/07/10 and 1988/07/06. Second, the purpose was to investigate the UHI effects on the hottest date of the year. The graph below (Figure 59) summarizes Mashhad's yearly climate. July is the warmest month of the year, the second in terms of low precipitation, and also has the highest sunshine hours (Weather, 2020).

Figure 59: Average Annual Temperatures in Mashhad (Weather, 2020)

This study was interested in the hottest time of day in the hottest month of the year in Iran, which is usually between 2pm to 4 pm in July. The pilot study showed that ENVI-met was not very sensitive to start time. If the simulation begins a couple of hours before the target time, it is still sufficient (section 5.2.1). ENVI-met suggests sunrise as the start time for daytime simulation (ENVI-metBoard, 2018b). Since the target time is 15.00, 03.00 approximately two hours before sunrise, seemed a reasonable time to start the simulation.

The next step was to discover which level of ENVIGuide was needed, as these run from the three levels of beginner, intermediate, and advanced. In total, there are seven different options for setting up the levels (Figure 60). The setting for the beginner level seems very general. For example, the air temperature is defined as cold, mild, warm and hot. Since the purpose of this study is simulating real case studies, this was not a good option to choose. In the advance setting some expert data is needed (Table 21). This data is either not available for the city of Mashhad or beyond the knowledge for urban designers. Both intermediate and advanced options ask two more questions about measured data for the meteorological boundary condition. One of the main concerns of this research is localization. Therefore, it was very important to use local weather data. After choosing the level (which in this case was intermediate) then the type of forcing method needs to be chosen. As discussed earlier (see section 4.3.3.2), simple forcing was chosen.

Table 21: Meteorological requirements for advance setting in ENVIGuide

Project features include	Background concentration, Building indoor temperature, Cloud conditions, Pollutant conditions, Simulation time steps, Soil conditions, Solar adjustment factor, Update timing
Project features expert include	Many advance settings in threading, facades, SOR mode, average inflow, Turbulence Model
Full forcing setting	Load EPW file, time check, data to be forced (temperature, radiation/cloud, precipitation, wind, humidity)

This study had access to the limited meteorological data provided by Mashhad City Council. The metrological measurements for the different Districts did not exist. Therefore, for input data information collected by a weather station outside of the city close to the airport were used (Table 22). The height for the maximum wind speed measurement was unknown and there was no average wind speed. The average wind speed was taken as 5m/s from Spark (2020). For this level of weather data, the best option is highlighted in Figure 60. The final input for the main simulation can be found in Table 23.

Table 22: Meteorological data from Mashhad City Council

Mont h	Air temperature						Humidity						Days with rain	Sunny hours	Total evaporation (mm)	Maximum wind (m/s)	
	Absolut temperature (°C)		Temperature (°C)			Relative Humidity (%)			Absolut Humidity (%)			speed (m/s)				direction (°)	
	absolute min	absolute max	mean	min	max	6:30	12 : 30	18 :30	mean	min	max						
July	17. 1	40. 3	28. 7	20. 7	34. 7	28. 9	21. 1	19. 4	27. 0	13. 5	40. 6	4	374. 8	357. 3	14	80	

Table 23: Main meteorological input data

Meteorological Settings	Simulation date	Start-end time	Level	Forcing	Wind speed (m/s)	Wind direction	Min-Max Temperature (°C)	Min-Max Humidity
Input data	23 Jun 2018	3:00-15:00	Intermediate	Simple forcing	5	80°	20-30	13-40%

Figure 60: Seven different levels of ENVIGuide set up, from beginner to advanced. The path in dark grey is the setting chosen for this study.

4.6.5 ENVI-met

Both ENVI-met 4.4.3 and 4.4.4 were used both for modelling and simulations. Twelve computers with almost the same specification ran the simulations (Table 24). Except for the pilot study, the main simulation for the twelve selected neighbourhoods was run twice, the first time without trees, and the second time with trees. The total time needed for the simulation was different from one neighbourhood to another. However, overall when trees were included in a simulation it took more time. For example, the first part of the simulation was around 95 hours, but when trees were included, it was around 115 hours.

Table 24: Computer specification used for simulation

Processor	Intel(R) Core™ i7-6700 CPU @3.40GHz 3.41GHz
Installed RAM	32.0 GB (31.7GB usable)
System type	64-bit operating system, x64 processor

4.7 Output data

ENVI-met produces output folders for atmosphere, building, inflow, radiation, soil, solar access, surface and vegetation. In this research only folders at 15.00 for the atmosphere (for T_a), radiation (for SVF) and surface (for T_s) were used. It is helpful to note that an important limitation of ENVI-met is that building indoor temperature is assumed to be the same for all buildings. T_s only shows the state of the soil surface. A height of 1.5m is considered for T_a (Figure 61).

Figure 61: Schematic of output considerations

LEONARDO is the application in ENVI-met uses to help visualize the different outputs. The following graphic maps are typically used for representing ground surface temperature, air temperature and SVF (Figure 62, Figure 63 and Figure 64). The ground surface temperature map has a legend consisting of 15 colours. Each shade shows a 2°C temperature difference. The minimum temperature belongs to buildings, which are all blue. The plane cut for T_s maps is at a height of 0 m. In potential air temperature maps or T_a maps, buildings are shown in black. The legend consists of 10 different colours, each showing a 0.2°C temperature

difference. The small black arrows show wind directions. In SVF maps, all buildings are white. The legend consists of 10 different colours. Each colour represents a ratio. The bigger the ratio the more the space is open and less shaded.

Figure 62: Typical surface temperature map

Figure 63: typical air temperature map

Figure 64: typical SVF map

Except for the distribution of temperature, the average temperature of the outside area is very important for this research. Unlike min and max temperatures, this information could not be found in the Ta and Ts maps. The ENVI-met support team provided a script for average Ta. This script could be operated through the map script editor. Below is the script used for average Ta in a domain excluding buildings.

```
var
sum: Double;
i,j,counter: Integer;

Begin
{Edit your code here for the main routine}
sum := 0;
counter := 0;

for i := 0 to map_xgrids-1 do
for j := 0 to map_ygrids-1 do
if mapdata('Special2D',i,j) = 0 then
begin
sum := sum + mapdata('Data2D',i,j);
counter := counter + 1;
end;

Writeln(sum/counter);
```

However, this script was not working for Ts because the Ta map is at a height above ground of 1.5 m and Ts map is at 0 m. Therefore, the author with the help of a friend (Dr. Mohammad Nekooyi) came up with new script to address this issue. Below is the script used to produce average Ts in this research.

```
var
sum: Double;
i,j,counter: Integer;

Begin
{Edit your code here for the main routine}
  {AnalyseMap;
AnalyseMask(FALSE); }
  sum := 0;
  counter := 0;

  for i := 0 to map_xgrids-1 do
    for j := 0 to map_ygrids-1 do
      {Writeln(mapdata('Data2D',i,j)) }
      if mapdata('Data2D',i,j) > 22 then
        begin
          sum := sum + mapdata('Data2D',i,j);
          counter := counter + 1;
        end;

      Writeln(sum/counter);
    end;
```

4.7.1 Validation of ENVI-met

Toparlar et al. (2017) state that 58% of existing CFD studies do not have validation. Several researchers have compared ENVI-met results with observed or measured results (Mohamed H Elnabawi et al., 2013; Gusson & Duarte, 2016; Simon et al., 2018b), indicating that the results are very similar. The comparison of the spatial distribution of air temperature and humidity shows that the hotter/drier and cooler/wetter spots predicted by ENVI-met were generally consistent with the observations. Some studies have been conducted to compare the simulation approach with the observational approach (Takahashi et al., 2004; Y. Toparlar et al., 2015). Y. Toparlar et al. (2015) considered wind flow and heat transfer by conduction, convection, and radiation in their simulation. Their findings illustrate that CFD simulation is able to calculate urban surface temperatures at a confidence level of $\pm 7.9\%$.

Following the simulations, the Iran Metrological Organization website reported air temperature is very close to the air temperature found in this research. The air temperature at 15:00 on 23

July 2018 was reported as 30°C (IranMetrologicalOrganization, 2020). In this research the average Ta in D1 is 31.20 and in D10 is 32.14.

4.8 Summary

The methods used for investigating the UHI are introduced in this chapter. The reasons for using CFD for this study are discussed, and possible software introduced. The reasons for choosing ENVI-met are given. The ENVI-met features are introduced and the input data for this study are discussed along with the output data. Chapter 5 describes the pilot study which will be used to test aspects of ENVI-met in the context of this research.

5 Pilot study

5.1 Introduction

It seems ENVI-met is a reliable tool if users know its potential and weaknesses, and are able to interpret the outputs carefully (S. Tsoka et al., 2018). However, there has been less concentration on assessing model sensitivity to a variety of input data both for modelling and simulation parameters and how these affect the outputs (Arnfield, 2003). Crank et al. (2018) indicated that the grid size in the domain area plays an important role for air temperature. Research by Ambrosini et al. (2014) shows that although the UHI effects are quite visible in areas of 350x 350m, ENVI-met mitigation strategies like installing a green roof, have a small effect on the given area. It seems, therefore, that the size of the model area is an important thing to determine, as well as the simulation duration, in order to achieve reliable results, in other words, the number of hours that should be simulated, given ENVI-met recommends 24 hours, and how long it would take to run each simulation.

Policy makers need reliable outputs. The main aim of this pilot study was to explore how much simplification was needed in terms of simulation and the detail of urban areas to have both reliable results and save time and cost. This section tested material options not in terms of cooling effect but in terms of their effect on ground surface temperature (Ts). It also looked at simulation start time options and their effect on simulation processing time and Ts. Different case studies with slightly different input values were simulated and their results evaluated. The input differences concerned either simulation variables or material variables. The first case study dealt with two different simulation periods and some slight manipulation of materials. The second dealt with different surface, wall, and roof materials. The third evaluated the model domain and boundary condition. Finally, wind speed and offset boundary were examined (Figure 65). The results were compared with the aim of reducing the simulation process both in digitizing and computing times. For all simulations, Ts was the main output. In ENVI-met, Ts means the temperature of the top surface of the soil. For this reason, wherever buildings are located the Ts is minimum (ENVI-met, 2019c).

Each application in ENVI-met has variety of setting modes. One task is to find which setting in different applications will most suit each research goal. The goal of this study was to use a model that was as close to the real world as possible, while consuming the minimum time and computing resources. This led to the need to investigate data management in terms of the available data and the required input data. In some cases, city data were very detailed while in

others there was not enough data. For example, without a model of the existing trees to input into ENVI-met, which does not exist for Mashhad, it is too time consuming to enter each type of tree individually. To decide exactly what model to use for the main study, a small number of scenarios were simulated with ENVI-met V4.4.3 and V.4.4.4 and the results analysed.

Figure 65: The main parts of the pilot study and related scenarios

5.1.1 Case Study and Data

Two neighbourhoods were selected to assess the function and reliability of the ENVI-met software these being 1-D (Ahmadabad) and 1-E1 (Majd) (Figure 66). Each was first modelled and then simulated. Each area is 400m by 400m and is located in District 1.

Figure 66: Images of the selected areas: Aerial satellite views and GIS maps for Monde input. Left: 1-D (Ahmadabad), right: 1-E1 (Majd)

5.1.2 Simulation

More accurate model areas were created with the new ENVI-met application Monde, using the Universal Transverse Mercator (UTM) coordinate system for Georeferencing, and then imported shape files from GIS. The GIS shape files of buildings had a height tag. Digitizing was then carried out by importing topography from National Aeronautics and Space Administration (NASA) for some cases and finally generating ENVI-met model layers. For the pilot study, unlike the main simulation, trees were added in the Spaces application, using aerial

photos from Google Earth. This process helped to achieve almost accurate building height information.

5.1.2.1 Model Areas Setting

1-D (Ahmad Abad): The model area has 400x400x73.5 grids with a resolution of 2x2x3 metres per grid cell. Telescoping starts after 20.00m. There is no rotation in areas. The highest object in the model area is 14.00m. The majority of buildings are around 6.8m high. At this scale walls between separate buildings are removed automatically by ENVI-met. There are 470 buildings, and 121 Acers, 122 Pines, and 149 Fraxinuses were simulated as the tree cover. The types of tree were narrowed down from a list found in the Park and Green Space Organization of the Mashhad City Council website.

1-E1(Majd): The model area follows the same dimensions as 1-D. The highest object in the model area is 15.00m. The majority of buildings are 5.2m high. There are 943 buildings, and 172 Robinia Pseudoacacia and 113 Pines were simulated as tree cover. The types of tree were narrowed down from a list found in the Park and Green Space Organization of the Mashhad City Council website.

5.1.2.2 Meteorological Input Data

The profile for atmospheric boundary conditions was created with data from Mashhad city council, which in turn was extracted from metrological urban climate stations in Mashhad. In order to examine the effects of UHI, the hottest day was selected for simulation. The input data is found in Table 25 (M. Karimi, 2019).

Table 25: Main Meteorological Input Data

Meteorological Settings	Simulation date	Max wind speed (m/s)	Wind direction	Min-Max Temperature (°C)	Min-Max Humidity
Input data	23 Jun 2018	14	80°	20-30	13-40%

5.1.2.3 Simulation

Three alternative scenarios were created for checking time and duration and six alternatives for materials (Table 27). Additionally, there were nine scenarios for evaluation of lateral boundary and topography (

Table 28) and six scenarios for winds and offset boundary (Table 29). ENVI-met was run on an Intel(R) Core™ i7-6700 CPU @3.40GHz with 32.0 GB of Ram 64-bit operating system for both sites.

5.2 Results

5.2.1 Time, duration and material

When simulation needs to run at the scale of a city the question is whether the database (soils, plants, buildings and surface materials) needs to be generic or should follow local materials. The ENVI-met database provides a variety of materials for buildings, surfaces and vegetation. For the first model area the default building wall and roof of ENVI-met values were used. Asphalt was assigned to streets and the yard material was changed to light concrete pavement for the Ahmadabad b and c scenarios (Table 26 and Table 27). However, for the second model area not only were the surface materials changed from one scenario to another, but also the building roof and wall materials were changed. In order to localize materials, brick walls and concrete roofs were used as inputs in order to meet the general Iranian building wall and roof conditions for the last scenario (Table 26 and Table 27).

Table 26: Material Input data: Ahmadabad and Majd

Land cover	Material Name	Profile
Wall material (default)	Wc	Concrete18cm, insulation 12cm, 1cm plaster
Roof material (default)	R	Concrete18cm, insulation 12cm, 1cm plaster
Ground surface material (default)	Sl	Loamy soil
Surface material (default)	Sa	Asphalt
Surface material (default)	Sc	Concrete pavement light
Surface material (default)	Sp	Pavement (concrete), used/dirty
Roof material (custom settings)	Rc	Concrete 15cm, concrete hollow block 30cm, plaster 3cm
Wall material (custom settings)	Wb	Brick 2.5cm, brick 20cm, 1.5 plaster

Table 27: Simulated Scenarios for time, duration, materials and Ts outputs

Scenarios	Scenarios name	Start-end time	Computation time (hours)	Wall material	Roof material	Soil material	Street material	Yard material	Average Ts (°C)	Min-Max Ts (°C)
Time and duration	Ahmadabad a	10:00-15:00	79 h	Wc	R	Sl	Sa	Sl	26.24	18.7-52.1
	Ahmadabad b	9:00-15:00 next day	250 h	Wc	R	Sl	Sa	Sc	23.84	19.1-47.1
	Ahmadabad c	9:00-15:00	82 h	Wc	R	Sl	Sa	Sc	23.53	18.9-46.0
Material s	Majd a	7:00-15:00	77h	Wc	R	Sl	Sp	Sl	22.79	18.4-44.1
	Majd b	3:00-15:00	134h	Wc	R	Sl	Sp	Sl	22.84	18.7-44.2
	Majd c	3:00-15:00	133h	Wc	R	Sl	Sa	Sl	23.03	19.1-46.5
	Majd d	3:00-15:00	134h	Wc	R	Sl	Sa	Sc	23.97	19.1-47.8
	Majd e	3:00-15:00	137h	Wc	R	Sc	Sa	Sc	24.30	19.2-48.1
	Majd f	3:00-15:00	121h	Wb	Rc	Sc	Sa	Sc	24.32	19.2-48.1

Figure 67 includes the digital maps which show the ground surface materials, the ground surface temperature outputs, and the distribution of ground surface temperature as a bar chart for the first site (see Appendix 1). All Ts maps are at 15:00. The input data are slightly different (

Table 27). In all outputs building areas are the coldest part of the neighbourhood with temperatures mostly around 20°C. Trees create cooler areas in the streets. The difference between outputs a and b shows use of local materials just for surfaces leads to a drop in Ts (Table 27, Figure 66: Images of the selected areas: Aerial satellite views and GIS maps for Monde input. Left:1-D (Ahmadabad), right: 1-E1 (Majd)). Average Ts decreases from 26.24 °C to 23.84 °C. However, comparing output b with output c with the 24-hour simulation time difference does not show much difference in Ts (Table 27, Figure 67).

Scenarios Majd a and Majd b are similar in all materials, the only difference between them being the start time of the simulations. For a, the simulation starts at 07:00 while b starts at 03:00. Both outputs are at 15:00, which again does not show much difference. The differences between outputs start to be clearer when the material of the yards is changed from soil to light concrete, the latter being the general material used for those areas in Iran. Bar chart d shows there is a five degree gap between cool and warm areas. In other words, the temperature was not smoothly changing between areas. Changing surface materials to asphalt and light concrete (output e) is closer to reality, as most foundations in Iran are made of concrete and usually go some metres underground. The final model is the closet one to reality with building wall materials made of brick and roof material of hollow core concrete (Figure 68).

Figure 67: Ground surface material maps obtained using Spaces, Ts maps and Bar charts obtained from Leonardo, Bar charts show surface temperature distribution in site 1-D

Model area 2 (Majd) shows using more realistic materials in the simulation, means the gap between building temperatures and ground surface temperature has increased. The difference between average Ts in Majd a (22.79°C) and Majd f (24.32°C) is approximately 2°C. All simulations for the second study took almost the same time of around 130 hours. As a result, using materials similar to local materials shows a good surface temperature distribution in the neighbourhood. When, ENVI-met is used as tool to compare different urban layouts in parallel, using long simulation periods could be avoided and save time and computing resources.

Figure 68: Ground surface material maps obtained using Spaces, Ts maps and Bar charts obtained from Leonardo, Bar charts show surface temperature distribution in site 2 (I-E1)

5.2.2 Lateral boundary and DEM

In ENVI-met the condition of the domain border is very important because the numerical calculations of the edges are not very accurate. This will affect all UHI results. Four suggestions are offered by ENVI-met to solve this problem; using nesting grids, empty cells, simulation of a bigger area and then cutting it back to the target boundary, and using full forcing (see section 4.3). The first three options involve moving the boundary a bit further from the target boundary. However, the third one is highly recommended by ENVI-met. In this section, the first three options were tested with and without topography (DEM) and compared to previous scenarios without lateral boundary variables (Majd b). All simulations were in the simple force condition. For the first scenario, the influence of DEM was studied. Majd g showed a little difference in minimum and maximum temperature compared to Majd b, the biggest difference between them being in average T_s by 3.30°C. The second and third scenarios examined nesting grid and empty cells. The nesting grid scenario without DEM (Majd i) would never complete and sent errors multiple times. To have an accurate average temperature, empty cells need to be removed from the target boundary in the LEONARDO application. Without this action, simulation of the area with empty cells usually creates a warmer neighbourhood. Majd h (nesting grid with DEM) and Majd k (empty cells with DEM) showed only small differences to Majd b. The result of Majd m (empty cells without DEM) showed a rise in average T_s and both minimum and maximum temperatures similar to Majd g. The fourth scenario was created to examine the offset boundary solution. The aim was to simulate an area of 580mx580m and then cut that back to 400mx400m in the LEONARDO application. This scenario sent errors multiple times. After more than ten trials, finally, it was decided not to run another simulation for that scenario. Probably the bigger domain size (580m x 580m) and high wind speed (14m/s) made it impossible for ENVI-met to simulate the area. These results indicate that ENVI-met is more sensitive to topography than lateral boundary conditions.

Table 28: Simulated Scenarios for lateral boundary and DEM and Ts outputs

Scenarios	Scenarios name	Start-end time	Computation time (hours)	Domain size	Nesting grid	Empty cell	DEM	Trees	Material	Average Ts (°C)	Min-Max Ts (°C)
DEM Nesting grid (10 cells)	Majd b	3:00-15:00	134h	400x400	×	×	√	√	Default	22.84	18.7-44.2
	Majd g	3:00-15:00	107h	400x400	×	×	×	√	Default	26.14	19.9-43.3
	Majd h	3:00-15:00	125h	400x400	√	×	√	√	Default	23.29	19.1-44.4
	Majd i	3:00-15:00	4h	400x400	√	×	×	√	Default	Incomplete	Incomplete
	Majd j	3:00-15:00	120h	440x440	×	√	√	√	Default	24.12	19.2-44.4
	Majd k	-	-	400x400	×	√	√	√	Default	23.13	19.2-44.4
	Majd l	3:00-15:00	118h	440x440	×	√	×	√	Default	26.84	19.9-43.7
	Majd m	-	-	400x400	×	√	×	√	Default	26.28	19.9-43.7
	Majd n	3:00-18:00	10h	580x580	×	×	×	×	Local	Incomplete	Incomplete
Offset boundary without

Figure 69: from left to right Majd h and Majd j. Nesting grids are not shown in the maps, but empty cells are.

5.2.3 Wind speed and offset boundary

Since the maximum wind speed caused a malfunction in the offset boundary scenario (Majd n), site 1 Ahmadabad was chosen for continuing the testing. Three scenarios were simulated for this site with two different variables; wind speed and offset boundary. The maximum wind speed for the location is 14 m/s and average wind speed is 5 m/s. The target boundary is 400

x 400sqm, however, for the first two scenarios (Ahmadabad d and Ahmadabad g) the border boundary was offset 90m away and for the last one (Ahmadabad h) it was moved 20m away. The results are shown in (Table 29). Comparison between the offset boundary and target boundary shows little difference in average Ts. In all scenarios the target boundary is a bit warmer than the offset boundary with a difference lying between 0.30 to 0.40°C. However, computation time for the 580mx580m domain size was three times more than for 440m x 440m. Comparing Ahmadabad d and f indicated that the high wind speed made the simulation time greater even for same domain size. Except for computation time, wind speed affects both average Ts and maximum Ts. The reduction in average Ts is quite significant at around 4.25°C.

Table 29: Simulated Scenarios for wind speed and offset boundary and Ts outputs

Scenarios	Scenarios name	Start-end time	Computation time (hours)	Domain size	Nesting grid	Empty cell	DEM	Trees	Wind Speed (m/s)	Material	Average Ts (°C)	Min-Max Ts (°C)
Wind and offset boundary	Ahmadabad d	3:00-15:00	294h	580x580	×	×	×	×	14	local	37.10	19.9-51.3
	Ahmadabad e	3:00-15:00	-	400x400	×	×	×	×	14	local	37.50	19.9-50.8
	Ahmadabad f	3:00-15:00	212h	580x580	×	×	×	×	5	local	41.46	19.9-52.2
	Ahmadabad g	3:00-15:00	-	400x400	×	×	×	×	5	local	41.75	19.9-51.7
	Ahmadabad h	3:00-15:00	84h	440x440	×	×	×	×	5	local	41.34	19.9-52.2
	Ahmadabad i	3:00-15:00	-	400x400	×	×	×	×	5	local	41.77	19.9-52.2

Figure 70: Ahmadabad d, the target boundary (400 x 400 sqm) is shown in colour the offset boundary (580 x 580 sqm) is shown in grey.

5.3 Summary

The pilot study showed the importance of using materials that matched those found in Mashhad as closely as possible. It also reinforced the decision to model a 400 x 400m area using simple forcing. The next chapter sets out the results of the simulations on all the case study areas and the correlations that emerged between T_a , T_s and the urban characteristics.

6 Results

In this study a quantitative analysis was conducted on the relationship of the neighborhood characteristics with Ta and Ts. In this chapter, the general characteristics of all results are set out first and later the different urban form characteristics and their impacts on Ta and Ts are discussed. Cases 1-B and 10-B have not been considered in this because of their different patterns and morphology. These two are considered together in section 6.5.3. The outliers are also discussed in more detail (Figure 71).

Figure 71: Outline of results

6.1 General characteristics of the results

6.1.1 Urban characteristics of District 1 (D1) and District 10 (D10)

In general, the selected areas in D1 had a slightly lower average Ta and Ts than those of D10 (Table 30). The urban characteristics and UHI characteristics of the different neighbourhoods were calculated separately (see Appendix 8). For having an overall view of each district, the average value was calculated to represent the whole district. For example, in Table 30, the average Ta of D1 equals the mean temperature of neighbourhoods 1-A, 1-C, 1-D, 1-E1, 1-E2 and 1-F. The average Ta of D1 and D10 was 31.84°C and 32.22°C respectively and the average Ts was 41.57°C and 42.07°C respectively. This mirrors the results of the Landsat study where D1 was cooler than D10. District 1 has a bigger average plot size (see section 6.2 and 6.3 for the definitions of all the urban characteristics) than D10 (255.47 m² and 186.41 m² respectively), and a larger average footprint (129.76 m² and 90 m²). It also has a larger average site coverage (50.79% and 48.68%), average building density (51.52% and 40.63%), and average building height (6.16m and 4.32m) than District 10. District 1 has a lower street coverage than D10 (26.99% and 30.22%) and lower courtyard coverage (20.42% and 24.91%). These values show some urban characteristics varied considerably between D1 and D10, for example, average building density (ABD), average plot size (APS), average SVF and average aspect ratio, but that others were similar such as average building height (ABH).

At first glance, it seemed all D1 urban characteristics could lead to both lower Ta and Ts. This hypothesis was examined by studying the results of each neighbourhood.

Table 30: UHI characteristics and urban characteristics—average values of selected area in D1 and D10

UHI characteristic		District Name	
		D1	D10
Average Ta (°C)		31.84	32.22
Average Ts (°C)		41.57	42.07
Urban characteristics			
Land use/surface materials	Building density (%)/(brick, light concrete)	51.52	40.63
	Street coverage (%)/asphalt	26.99	30.22
	Asphalt pavement area (%)	0.38	0.1
	Bare land area (%)/soil	0.21	5.42

	Courtyard (%) / Light pavement	20.42	24.91
Urban form	Building orientation (°) percentage most prevalent orientation(s) (%)	21-30(30)	171-180 and 141-150 (19)
	Street orientation (°) percentage most prevalent orientation (%)	111-120 (26)	51-60 (28)
	Street pattern	-	-
	Average SVF	0.66	0.55
	H/W ratio of canyon	0.23	0.16
	Average plot (m ²)	255.47	186.41
	Average built footprint (m ²)	129.76	90.73
	Site coverage (%)	50.79	48.68
	Grassland area (%)	0	2
Vegetation	Trees (number)	389.33	343.75

6.1.2 Neighbourhood effects

Figure 72 shows the T_a and T_s of the different neighbourhoods in the two Districts. The range of T_s is greater than that of T_a . The T_a value ranged from 31.65°C (1-F) to 32.48°C (10-A) at pedestrian level (1.5 height from ground). Since every 0.6°C raise in air temperature could enhance the usage of cooling energy by 1.5-2% (Akbari, 2005), the 0.83°C temperature difference between the two neighbourhoods are important. The T_s value ranged from 40.27°C (1-A Sajad) to 42.67°C (10-C Hesabi), making a T_s difference of 2.4°C between these two neighbourhoods. Moreover, for the same neighbourhoods the air temperature did not follow the pattern of the surface temperature. In other words, the surface temperature is not representative of air temperature in the different case studies.

Figure 72: Air temperature and ground surface temperature bar charts of selected neighbourhoods

6.1.3 Ta distribution map characteristics

In most Ta maps the eastern part is warmer than the western part, with an average difference of around 2°C (Figure 73, Figure 74 , Appendix 2 and Appendix 3). Although overall the neighbourhoods gradually become cooler from east to west the extent of this trend mostly depends on street orientation and form. For example, case 1-B (Ershad) as an open midrise development allows more early morning sun-warmed air to penetrate the space (Figure 73). Other examples to show similar characteristics are 1-A (Sajad) and 10-A (Miad) (Figure 74). Both have E-W street orientations meaning the streets are open spaces that allow the sun warmed air to penetrate into the development, and this may be why these examples have the highest Ta in their respective districts. The reason why the eastern parts of all areas have a higher Ta relates to the sun direction and start time of the simulations. The sunrise on the selected day is around 5:15 am, which is 2 hours after the simulation start time. This means the eastern parts are exposed to more solar energy which is absorbed by the hard surfaces and thus heats up more than the western part. Given the Ta simulations include energy absorbed by buildings in the temperature calculation but Ts maps do not, this may explain the reason for the different patterns of Ta and Ts in the same neighbourhoods.

Figure 73: Ta map of 1-B

Figure 74: Ta map of 1-A (left) and 10-A (right)

6.1.4 Ts distribution map characteristics

The Ts maps show a different behaviour. In all the simulations the buildings in the western areas are the hottest part of the map (Figure 75). Unlike the Ta maps, the E-W orientations of examples like 1-A (Sajad) and 10-A (Miad) show fewer hot spots and a lower Ts. The reason for this is because at 15.00 the western parts of the areas are exposed to more sun while the eastern parts are in the shadow of the buildings. The taller the building the more shadows are created, meaning the H/W is crucial. It seems that the air temperature follows the ground surface temperature with a delay, as it takes a couple of hours for the air to warm up. However, for the air temperature, other factors particularly wind speed and direction also affect the results, and this is investigated later in this discussion.

Figure 75: T_s map of 1-A (left) and 10-A (right)

6.1.5 The effect of wind speed

The simulation was first run with a wind speed 14m/s and then with wind speed 5m/s. The former is the maximum and the latter the average wind speed. Messages were sent twice for 1-E1 (Majd), 1-E2 (Kolahdooz) and 1-F (Ebnesina) when the wind speed was set to 14m/s. This means ENVI-met was not working well with the high wind speed. Table 31 indicates how different wind speeds affect both T_a and T_s . It was predictable that the higher wind speed would decrease both temperatures, however, the influence on T_s is more than on T_a . The effect on T_a with different wind speeds is shown in the table, and the same has been done for T_s . The highest T_a difference is in 1-C (Sanabad) and the lowest is in 10-E (Hadi) these being 0.58°C and 0.22°C respectively. The highest T_s difference is in 10-C (Hesabi) of 5.09°C and the lowest in 10-E (Hadi) of 3.27°C.

Table 31: The effect of different wind speeds on Ta and Ts

District	Neighbourhood name	Average Ta (°C) with wind speed 5m/s	Average Ta (°C) with wind speed 14m/s	The Ta difference	Average Ts (°C) with wind speed 5m/s	Average Ts (°C) with wind speed 14 m/s	The Ts difference
District 1	1-A (Sajad)	32.104	31.552	0.55	40.265	36.049	4.22
	1-C (Sanabad)	31.857	31.276	0.58	41.653	37.57	4.08
	1-D (Ahmadabad)	31.913	31.376	0.54	41.775	37.57	4.21
	1-E1 (Majd)	31.677	-	-	41.854	-	-
	1-E2 (Kolahdooz)	31.819	-	-	41.912	-	-
	1-F (Ebnesina)	31.653	-	-	41.947	-	-
	Average D1	31.837	-	-	41.568	-	-
District 10	10-A (Miad)	32.480	31.935	0.54	41.350	36.750	4.60
	10-B (Fallahi)	32.338	31.765	0.57	42.207	37.427	4.78
	10-C (Hesabi)	32.233	31.689	0.54	42.673	37.582	5.09
	10-E (Hadi)	31.839	31.620	0.22	42.052	38.783	3.27
	Average D10	32.223	-	-	42.071	-	-

6.2 Land Cover

Since much research has been conducted concerning the relationship of types of land use and UHI (section 2.5.3.1), this research set out to study only the effect of residential areas on UHI. Therefore, the case studies were chosen to be far from large parks, big highways, or other special land uses that might affect UHI. Consequently, the variety of surface materials is low in this study.

6.2.1 Land use/surface materials

Table 32 shows the land use /surface materials in the different neighbourhoods and their relation to Ta and Ts. It is a repeat of the table in section 3.8 but as it details the land use and surface materials of the neighbourhoods it seemed important to also have it in the section where the results are discussed.

Table 32: Neighbourhood land use/surface materials and UHI characteristics

	Neighbourhood	Building density (%)	Sum of Courtyard areas (m ²)	Street coverage (%)	Sum of Grassland areas (m ²)	Sum of Bare land areas (m ²)	Sum of Asphalt pavement areas (m ²)	Average Ta (°C)	Average Ts (°C)
District 1	1-A (Sajad)	55.00	29351.33	24.75	3458.00	0	339.00	32.10	40.27
	1-C (Sanabad)	56.79	27963.58	25.75	0	0	79.49	31.86	41.65
	1-D (Ahmadabad)	47.52	36473.95	29.74	0	0	0	31.91	41.78
	1-E1 (Majd)	47.26	39076.52	27.48	73	0	0	31.68	41.85

District 10	1-E2 (Kolahdooz)	51.87	31044.61	27.18	0	2353.0	0	31.82	41.91
	1-F (Ebnesina)	50.65	32146.84	27.02	1215	0	0	31.65	41.95
	Average D1	51.52	39858.68	26.99	791.00	392.17	69.75	31.84	41.57
	10-A (Miad)	38.63	43102.18	34.29	7.78	0	0	32.48	41.35
	10-B (Fallahi)	35.13	42787.16	36.96	2666.00	0	0	32.34	42.21
	10-C (Hesabi)	38.39	26086.06	33.84	8600.00	0	19665.00	32.23	42.67
	10-E (Hadi)	50.39	47459.30	15.80	0	0	0	31.84	42.05
	Average D10	40.63	32676.14	30.22	2818.45	0	11065.00	32.22	42.07

6.2.2 Building density (BD)

In this study, building density (BD) was defined as the ratio of the total building footprint area to the whole selected area, and is presented as a percentage. For example, 1-A has a total building footprint of 87,998.43m². The ratio of that value to the case study area of 160,000m² is considered to be the building density, which in this case is 55%. The aim was to find out how the built environment affected both Ta and Ts. For the simulation samples, BD varied from 47.26% to 56.79% in D1 and from 35.13% to 50.39% in D10 (Table 32). Average Ta and Ts are lower in D1. Figure 76 shows the relationship between BD and average Ta and Ts for all neighbourhoods in both districts. The left-hand graph suggests there is a significantly strong negative association between building density and Ta, $r = -.71$, $p = .02$, while the right-hand graph suggest a not significant but strong negative relationship between BD and Ts $r = -.48$, $p = .16$. This is mostly because the ground surface temperature is hugely influenced by ground materials, street pattern, and trees rather than buildings.

Figure 76 : the relationship between BD and average Ta and Ts in all selected neighbourhoods

6.2.1 Street coverage (STC)

Street coverage (STC) is defined as the ratio of the street area to the whole case study area. For example, 1-A has a total street area of 39593.00 m². The ratio of that value to the case study area of 160,000 m² is considered to be the average street coverage, which in this case is 24.75%. STC varied between 15.80% in 10-E to 32.48% in 10-A (Table 30). It is a very important factor, as due to the dark and solid nature of the streets they absorb a lot of solar energy. STC and Ta were found to be strongly positively correlated, $r = +.65$, $p = .04$. The Ta graph (Figure 77) demonstrates a slightly upward trend. It can be concluded that a greater street coverage leads to more heat in the case study areas. However, some areas with high street coverage have a lower Ta such as 1-F and 1-E1. The reason for this could be the street orientation and the H/W ratio. Although the relationship between STC and Ts is not significant, the scatter chart shows an upward linear trend, $r = +.23$, $p = .51$.

Figure 77: The relationship between STC and average Ta and Ts in all selected neighbourhoods

6.2.2 Asphalt pavement area/ dark concrete pavement

Asphalt/dark concrete pavement areas are places such as parking lots, sport areas, and school yards. Except for 1-A (Sajad), 1-C (Sanabad) and 10-C (Hesabi) which when taken together have a total of around 20,000m² such paved areas, other neighborhoods have none (Table 32). Thus, the sample size is very small for this variable, there is no significant relationship between asphalt/concrete pavement area and Ta or Ts.

6.2.3 Bare land area/soil

Bare land in a residential area usually signifies plots under construction or plots that will be under construction in the near future. 1-E2 (Kolahdooz) is the only neighbourhood which has

2,353m² of such bare land (Table 32). Thus, the sample size is very small for this variable. There is no significant relationship between bare land area and Ta or Ts.

6.2.4 Courtyard/concrete pavement

Courtyards are an essential part of urban design in Mashhad. If the plot is oriented N-S, the courtyard will be located on its south side. If the plot is oriented E-W the courtyard is usually located on the east side of the plot. Three different values were calculated for courtyard areas to study the relationship of these to Ta and Ts; Average Courtyard Area, Sum of Courtyard Areas and Courtyard Coverage (Table 33).

Table 33: Neighbourhood courtyard characteristics and UHI characteristics

	Neighbourhood	Average Courtyard Area (m ²)	Sum of Courtyard Area (m ²)	Courtyard Coverage (%)	Average Ta (°C)	Average Ts (°C)
District 1	1-A (Sajad)	249.51	29,351.33	18.34	32.10	40.27
	1-C (Sanabad)	111.96	27,963.58	17.48	31.86	41.65
	1-D (Ahmadabad)	144.35	36,473.95	22.80	31.91	41.78
	1-E1 (Majd)	72.48	39,076.52	24.42	31.68	41.85
	1-E2 (Kolahdooz)	51.27	31,044.61	19.40	31.82	41.91
	1-F (Ebnesina)	124.73	32,146.84	20.09	31.65	41.95
	Average D1	125.72	39,858.68	20.42	31.84	41.57
District 10	10-A (Miad)	126.94	43,102.18	26.94	32.48	41.35
	10-B (Fallahi)	123.15	42,787.16	26.74	32.34	42.21
	10-C (Hesabi)	75.19	26,086.06	16.30	32.23	42.67
	10-E (Hadi)	57.41	47,459.30	29.66	31.84	42.05
	Average D10	95.67	32,676.14	24.91	32.22	42.07

Average Courtyard area (AC) was the result of the subtraction of average footprint size from average plot size. 1-A (Sajad) has the highest AC value of 249.51 m² and 1-E2 (Kloahdooz) the lowest average value of 51.27 m². There is a significant negative relationship between average courtyard area and Ts, $r = -.81$, $p = .00$ (Figure 78). The sum of the courtyard areas is the difference between the sum of the total plot areas and the total footprint areas. Courtyard coverage was defined as the ratio of the sum of courtyard areas to the whole neighbourhood area. District 10-A (Miad) has the highest and 10-E (Hadi) the lowest total courtyard area and consequently courtyard coverage. Both courtyard coverage and total courtyard area have no significant relationship to Ta or Ts.

Figure 78: The relationship between average courtyard area and average Ta and Ts in all selected neighbourhoods

6.3 Urban form

6.3.1 Orientation

The shapefiles in GIS did not have an orientation tag, therefore, orientation was calculated using the Calculate Polygon Main Angle tool. This tool in GIS calculates the longest collection of segments with similar direction in three ways; the geographic, arithmetic and graphic methods (Figure 79 and Figure 80). The geographic has been chosen since the calculation measures the deviation of the short-axis from the north and sometimes shows as a negative value. At this stage, 90 degrees was added to each value to have the right deviation for the long-axis from north. In Figure 80, if the blue rectangle is the street, x is the angle calculated by the Calculate Polygon Main Angle tool in GIS and y is the angle calculated for this study by adding 90 to x.

Figure 79: Screenshot of Calculate Polygon Main Angle tool in GIS

Figure 80: The schematic of rotation methods in Calculate Polygon Main Angle in GIS

With the aim of simplicity, the street orientation was categorized into 18 groups. Each group covers ten degrees. Then the frequency of any degree within the related category was calculated in Excel (Table 34). Finally, the proportion of that category was represented by a percentage. For example, the frequency of the angle between 0-10 in 1-A (Sajad) is 12 which means 38% of all streets are in this category. All frequency values greater than 10% are shown as these represent the main street orientations.

Table 34: The frequency of all street orientations in all selected neighbourhoods

Deviation of long axis from North (°)	Frequency						Ratio (%) in D1	Frequency				Ratio (%) in D10
	1-A (Sajad)	1-C (Sanabad)	1-D (Ahmadabad)	1-E1 (Majid)	1-E2 (Kolahdooz)	1-F (Ehnesina)		10-A (Miad)	10-B (Fallahi)	10-C (Hesabi)	10-E (Hadi)	
0-10	12	1	7	6	0	0	9.42	0	1	1	0	1.21
11-20	0	4	3	2	4	1	5.07	0	0	0	0	0.00
21-30	0	11	0	15	21	1	17.39	0	0	0	0	0.00
31-40	0	0	0	2	0	0	0.72	0	1	0	0	0.61
41-50	0	0	0	2	0	0	0.72	1	0	1	1	1.82
51-60	0	0	0	0	0	2	0.72	0	5	41	0	27.88
61-70	0	0	0	0	0	0	0.00	1	1	0	1	1.82
71-80	0	0	1	0	0	0	0.36	0	0	0	12	7.27
81-90	1	0	10	1	2	2	5.80	19	5	2	0	15.76
91-100	17	0	8	5	0	0	10.87	0	0	0	0	0.00
101-110	0	1	8	7	10	3	16.02	0	4	0	0	2.42
111-120	0	30	3	15	28	1	27.90	1	5	0	0	3.64
121-130	1	0	0	3	1	1	2.17	0	0	2	0	1.21
131-140	0	0	0	1	1	0	0.80	0	1	1	0	1.21
141-150	0	0	0	0	0	16	5.80	0	11	17	3	18.79
151-160	0	0	0	0	0	0	0.00	0	0	0	6	3.64
161-170	0	0	0	0	0	0	0.00	0	0	0	6	3.64
171-180	1	0	3	0	1	0	1.81	6	4	3	2	9.09
Average Ta (°C)							31.84					41.57
Average Ts (°C)							32.22					41.37

6.3.1.1 Average Orientation comparisons D1 and D10

The dominant street orientation in D1 is between $111-120^\circ$ (27.90%), followed by the streets perpendicular this with a $21-30^\circ$ orientation (17.39%) (Table 34). The third main orientation is between $101-110^\circ$ (16.02%). This means that more streets in D1 are oriented E-W with a 10° to 20° deviation to the south. On the other hand, the main orientation in D10 is $51-60^\circ$ (27.88%) followed by the streets perpendicular to this orientation $141-150^\circ$ (18.79%). The third main orientation is $81-90^\circ$ (18.76%), which means that most streets in D10 are NE-SW oriented (Figure 81). The results show that E-W street orientations with a tilt toward south lead to lower Ta and Ts in both districts.

Figure 81: Main street orientations in D1 (left) and D10 (right) ($111-120^\circ$ and $51-60^\circ$) respectively

In D1 33.07% of plots are orientated $21-30^\circ$ and the next most common orientation of plots is $0-10^\circ$ (15.43%) (Table 35). In D10, the majority of plots are oriented $171-180^\circ$ followed by $141-150^\circ$ plots (21.87% and 19.81% respectively). It seems the majority of plots in D1 are NE-SW oriented, while plots in D10 are N-S oriented with a tilt towards the west (Figure 82). The results show that NE-SW plot orientations lead to both lower Ta and Ts.

Table 35 : The frequency of plot orientations in all selected neighbourhoods

Deviation of long axis from North ($^\circ$)	Frequency						Ratio (%) in D1	Frequency				Ratio (%) in D10
	I-A (Sajad)	I-C (Sanabad)	I-D (Ahmadabad)	I-E1 (Majid)	I-E2 (Kolahdoz)	I-F (Ebneshina)		I0-A (Miad)	I0-B (Fallahi)	I0-C (Hesabi)	I0-E (Hadi)	
0-10	225	8	143	94	16	11	15.43	9	11	10	17	1.87
11-20	1	67	69	49	81	23	9.01	0	43	0	0	1.71
21-30	1	312	0	339	393	20	33.07	0	34	0	0	1.35
31-40	10	0	2	26	33	0	2.20	1	6	0	0	0.28

41-50	0	0	0	11	2	4	0.53	1	4	0	11	0.64
51-60	0	0	0	0	0	330	10.25	0	164	29	99	11.59
61-70	0	0	0	0	0	1	0.03	1	0	0	20	8.22
71-80	0	0	0	0	0	0	0.00	0	0	0	18	7.23
81-90	8	11	38	25	21	15	3.66	13	56	15	29	4.49
91-100	4	0	15	45	1	0	2.02	0	0	0	0	0.00
101-110	0	5	5	45	33	3	2.83	0	3	0	0	0.12
111-120	0	36	3	144	244	12	13.63	1	4	0	0	0.20
121-130	0	0	0	16	8	1	0.78	0	0	14	0	0.56
131-140	0	0	0	3	1	0	1.90	0	1	4	19	0.95
141-150	1	0	0	0	0	48	1.52	0	31	41	49	19.81
151-160	0	0	0	0	0	0	0.00	0	0	0	19	7.86
161-170	2	0	0	0	0	0	0.06	0	0	0	28	11.27
171-180	8	13	103	13	10	9	4.84	444	68	7	32	21.87
Average Ta (°C)							31.84					41.57
Average Ts (°C)							32.22					41.37

Figure 82: Main plot orientations in D1 (left) and D10 (right) of 21-30° and 171-180° respectively

The main building orientation in D1 follows the main plot orientation of 21-30° (29.96%) (Table 36). The second and third most common building orientations are very close in frequency at 111-120° (15.59%) and 0-10° (15.03%). Like plot orientations, building orientations in D10 are very varied. The two most common building orientations are 141-150° (19.2%) and 171-180° (18.96%). The third most common building orientation is 51-90°. The dominant building orientation in D1 is NE-SW, however in D10 buildings with a NW-SE orientation are slightly more common than other building orientations (Figure 83). The results show that NE-SW building orientations lead to lower Ta and Ts in both districts.

Table 36 : the frequency of building orientations in all selected neighbourhoods

Deviation of long axis from North (°)	Frequency						Ratio (%) in D1	Frequency				Ratio (%) in D10
	I-A (Sajad)	I-C (Sanabad)	I-D (Ahmadabad)	I-E1 (Majd)	I-E2 (Kolahdooz)	I-F (Ehnesina)		I0-A (Mind)	I0-B (Fallahi)	I0-C (Hesabi)	I0-E (Hadi)	
0-10	330	9	168	117	9	10	15.03	5	16	14	15	1.56
11-20	0	70	76	77	101	24	8.13	0	29	0	0	0.91
21-30	1	387	0	413	434	35	29.69	0	47	0	1	1.50
31-40	8	0	1	34	43	0	2.01	0	3	0	0	0.09
41-50	2	0	0	15	3	8	0.65	3	1	4	21	0.91
51-60	0	0	1	1	0	370	8.70	0	171	80	10	11.17
61-70	0	0	0	0	0	3	0.07	0	0	2	26	8.48
71-80	0	0	3	0	0	0	0.07	0	0	0	29	9.17
81-90	9	14	50	22	23	20	3.23	148	81	15	46	9.07
91-100	43	0	36	51	1	0	3.06	2	3	0	0	0.16
101-110	1	14	35	74	47	13	4.30	0	11	0	0	0.34
111-120	0	96	6	245	304	16	15.59	0	8	0	1	0.28
121-130	9	0	5	24	12	1	1.19	0	2	1	0	0.09
131-140	0	0	0	2	1	5	0.19	0	0	2	26	1.56
141-150	4	0	0	1	0	163	3.93	0	69	48	59	19.12
151-160	0	0	0	0	0	2	0.05	0	0	0	25	7.98
161-170	1	0	0	0	0	0	0.02	1	0	0	29	9.32
171-180	11	12	115	18	10	9	4.09	483	71	10	42	18.96
Average Ta (°C)							31.84					41.57
Average Ts (°C)							32.22					41.37

Figure 83: Main building orientations in D1 and D10 of 21-30° and 141-150° respectively

6.3.1.2 Orientation comparison in D1 and D10

Table 37 summarizes the main orientation for streets, plots and buildings in each neighbourhood and the relation to Ta and Ts.

Table 37: Main street, plot and building orientations in all neighbourhoods

Neighbourhood	Street		Plot		Building		Average Ta (°C)	Average Ts (°C)
	degrees from North	Percentage (%)	degrees from North	Percentage (%)	degrees from North	Percentage (%)		
1-A (Sajad)	91-100	53	0-10	87	0-10	79	32.104	40.265
	0-10	38	31-40	4	91-10	10		
1-C (Sanabad)	111-120	64	21-30	69	21-30	64	31.857	41.653
	21-30	23	11-20	15	111-120	16		
	11-20	9	111-120	8	0-10	12		
1-D (Ahmadabad)	81-90	23	0-10	38	0-10	34	31.913	41.775
	91-100	19	171-180	27	171-18	23		
	101-110	19	11-20	18	11-20	15		
	0-10	16	81-90	10	-	-		
1-E1 (Majd)	21-30	25	21-30	42	21-30	38	31.677	41.854
	111-120	25	111-120	18	111-120	22		
	101-110	12	0-10	12	0-10	11		
1-E2 (Kolahdooz)	111-120	41	21-30	47	21-30	44	31.819	41.912
	21-30	31	110-120	29	111-120	31		
	101-110	15	11-20	10	11-20	10		
1-F (Ebnesina)	141-150	59	51-60	69	51-60	54	31.653	41.947
	101-110	11	141-150	10	141-150	24		
10-A (Miad)	81-90	68	171-180	94	171-180	75	32.480	41.350
	171-180	21	-	-	81-90	23		
10-B (Fallahi)	141-150	29	51-60	39	51-60	33	32.338	42.207
	111-120	13	171-180	16	81-90	16		
	81-90	13	81-90	13	171-180	14		
	51-60	13	11-20	10	141-150	13		
10-C (Hesabi)	51-60	60	141-150	84	141-150	79	32.233	42.673
	141-150	25	-	-	51-60	13		
10-E (Hadi)	71-80	39	161-170	25	161-170	21	31.839	42.052
	151-160	19	151-160	18	71-80	20		
	161-170	19	61-70	18	61-70	19		
	141-150	10	71-80	16	151-160	18		

1-A (Sajad) has a slightly higher Ta of 32.10°C than the other neighbourhoods in D1 (Table 37). In 1-A (Sajad) almost half the streets (53%) are oriented between 90-100° and most buildings (79%) and plots (87%) have a 0-10° orientation. On the other hand, 1-F (Ebnesina) with the lowest air temperature in both districts has a dominant street orientation of 141-150° (59%), building orientation of 51-60° (54%), and plots oriented the same as building (69%). 10-A (Miad) has the highest Ta of 32.48°C in both districts. Like 1-A, it has mainly E-W

oriented streets and N-S oriented buildings and plots (Table 37). 10-E (Hadi) has the lowest Ta of 31.84°C in D10. This neighbourhood has a very traditional pattern with many different orientations for streets, buildings and plots.

To understand the relationship between neighbourhood orientation and Ta and Ts, numbers were assigned to the main orientations of buildings and streets in excel. These numbers acted as a code and made it possible to run the Pearson correlation in SPSS (Table 38).

Table 38: Code assigned to each orientation for Pearson correlation

Neighbourhood name	Street orientation	Street orientation code	Building orientation	Building orientation code
1-A (Sajad)	E-W	1	N-S	1
1-C (Sanabad)	NW-SE	2	NE-SW	2
1-D (Ahmadabad)	E-W	1	N-S	1
1-E1 (Majd)	Irregular	3	NE-SW	2
1-E2 (Kolahdooz)	E-W	1	NE-SW	2
1-F (Ebnesina)	NW-SE	2	NE-SW	2
10-A (Miad)	E-W	1	N-S	1
10-B (Fallahi)	NW-SE	2	NE-SW	2
10-C (Hesabi)	NE-SW	4	NW-SE	3
10-E (Hadi)	Irregular	3	NW-SE	3

The scatter charts show the distribution of Ta and Ts in the existing street and building orientations. Based on SPSS data analysis there is no significant relationship between either Ta and street orientation or between Ta and building orientation. However, there is a relationship between Ts and street orientation, $r = .66$ $p = .04$ as well as Ts and building orientation, $r = .74$ $p = 0.01$. The positive relationship means the smaller numbers associate with smaller values (Figure 84 and Figure 85). In other words, E-W and NW-SE oriented streets are better than NE-SW and irregular streets regarding Ts, and N-S oriented buildings create a lower surface temperature than NW-SE buildings.

Figure 84: The relationship between street orientation and average Ta and Ts in all selected neighbourhoods

Figure 85: The relationship between building orientation and average Ta and Ts in all selected neighbourhoods

6.3.1.3 Street pattern comparison

Three street patterns can be distinguished in both districts, these being gridded, irregular and traditional (Table 39). In this study gridded neighbourhoods are either those which have two dominant street patterns or neighbourhoods in which one of the street orientations has a frequency of more than 50%, such as 1-F (Ebnesina) where 59% of its streets are oriented between 140-150°C (Table 39). Irregular and traditional street patterns do not have a dominant street pattern, and the range of orientations is more diverse. Irregular street patterns are those which have some distinguishable street orientation such as 1-D (Ahmadabad). In this neighbourhood 61% of streets are oriented between 80-110° (a 30 degree rather than a 10-degree difference). Traditional street patterns as are represented by 1-E1 (Majd) and 10-E

(Hadi) are difficult to categorise as their streets have no main orientations. The effect of these street patterns on temperature is discussed below.

Table 39: Street pattern and orientation comparison table. Average temperature in street orientation calculated from the same street orientation. For example, the average street orientation of E-W Street in a grid pattern is the mean of 1-A and 10-A. the average temperature of a street pattern is the mean temperature of all different orientations in that pattern. For example, the average temperature of an irregular street pattern is the mean of 1-D, 1-E2 and 10-B.

Street pattern	Average temperature in the street pattern		Main Street orientation	Average temperature in the street orientation		Neighbourhood	Main Building and plot orientation	Average temperature in the Neighbourhood	
	Ta (°C)	Ts (°C)		Ta (°C)	Ts (°C)			Ta (°C)	Ts (°C)
1.Grid	32.06	41.58	E-W	32.29	40.81	1-A (Sajad)	N-S	32.10	40.27
						10-A (Miad)	N-S	32.48	41.35
			NE-SW	32.23	42.67	10-C (Hesabi)	NW-SE	32.23	42.67
			NW-SE	31.76	41.80	1-F (Ebnesina)	NE-SW	31.65	41.95
						1-C (Sanabad)	NE-SW	31.86	41.65
2.Irregular	32.02	41.97	E-W	31.87	41.85	1-D (Ahmadabad)	N-S	31.91	41.78
						1-E2 (Kolahdooz)	NE-SW	31.82	41.91
			NW-SE	32.34	42.21	10-B (Fallahi)	NE-SW	32.34	42.21
3.Traditional	31.76	41.95	Irregular	32.16	41.70	1-E1 (Majd)	NE-SW	31.68	41.85
				31.84	42.05	10-E (Hadi)	NW-SE	31.84	42.05

Table 39 does not show a huge difference in temperature for the different street patterns. However, the traditional street pattern seems to have a slightly lower Ta and higher Ts (group 3). Among the different orientations, the NW-SE street orientation has the lowest Ta in a gridded street pattern at 31.76°C and the highest Ta in an irregular street pattern at 32.34°C. E-W oriented streets in a grid pattern had the lowest Ta at 40.81°C and NE-SW oriented streets in the same category had the highest Ts at 42.67°C.

In addition to the street pattern as described earlier, the urban pattern was also defined to give a better understanding of the neighbourhood characteristics. The urban pattern refers to both street pattern and orientation as one characteristic. For example, 1-A (Sajad) has an E-W orientation, a grid street pattern and a grid-E-W urban pattern. As mentioned earlier, some values were assigned to the urban characteristics and street pattern for Pearson correlation analysis (Table 40). However, neither street pattern nor urban pattern correlated with Ta or Ts.

Table 40: Code assigned to each orientation for Pearson correlation

Neighbourhood name	Street pattern	Street pattern code	Urban pattern	Urban pattern code
1-A (Sajad)	Grid	1	Grid-E-W	1
1-C (Sanabad)	Grid	1	Grid NE-SW	3
1-D (Ahmadabad)	Irregular	2	Irregular-E-W	4
1-E1 (Majd)	Traditional	3	Traditional-irregular	6
1-E2 (Kolahdooz)	Irregular	2	Irregular-E-W	4
1-F (Ebnesina)	Grid	1	Grid NW-SE	2
10-A (Miad)	Grid	1	Grid-E-W	1
10-B (Fallahi)	Irregular	2	Irregular-Nw-SE	5
10-C (Hesabi)	Grid	1	Grid NE-SW	3
10-E (Hadi)	Traditional	3	Traditional-irregular	6

6.3.2 Average Building Height (ABH)

There is little difference between average building heights in the different case study areas. The minimum belongs to 10-E at 3.89 m and maximum to 1-A at 7.02m (Table 41). Figure 86 illustrates ABH and shows that T_a was not correlated with ABH, $r = +.44$, $p = .21$, although there is a strong relationship between aspect ratio (H/W) and T_a (see section 6.3.7). This means the role of building heights in decreasing temperature strongly depends on the shadows they create, and not only the size of the shadow but also the length of time it will exist in the area. The latter depends on street orientation and width. Therefore, a study of building height needs to be combined with a study of street width and orientation when the average building height is more varied. ABH does not show any significant relationship with T_s , $r = -.45$, $p = .19$.

Figure 86: The relationship between ABH and average T_a and T_s in all selected neighbourhoods

6.3.3 Average Plot Size (APS)

Unlike ABH, average plot sizes varied considerably in the different case study areas, ranging from 113.74m² in 10-E to 451.33 m² in 1-A (Table 41). There is no significant relationship between average plot size and Ta, $r = +.23$, $p = .53$. Although greater APS in D1 goes with lower average Ta and Ts, each case individually does not follow this trend (Figure 87). For example, 1-A with the largest APS has an average Ta of 32.10°C which sits exactly in the middle of the scatter chart. Therefore, APS itself is probably not the main factor of influence on Ta. It seems it closely works with other factors. Except for 1-A which acts differently for both average Ta and Ts in the chart, the Ts scatter chart illustrates a significant strong opposite relationship to APS, $r = -.77$ $p = .00$. It means the bigger the plot size the lower the Ts.

Figure 87: The relationship between APS and average Ta and Ts in all selected neighbourhoods

Table 41: Urban form characteristics and UHI characteristics

	Neighbourhood	Average Building Height (m)	Average plot size(m ²)	Site coverage (%)	Average footprint size (m ²)	Average SVF	Average Ta (°C)	Average Ts (°C)
District 1	1-A (Sajad)	7.02	451.33	44.72	14.70	0.62	32.10	40.27
	1-C (Sanabad)	5.78	262.90	57.41	7.67	0.56	31.86	41.65
	1-D (Ahmadabad)	6.78	297.65	51.50	9.26	0.54	31.91	41.78
	1-E1 (Majd)	5.32	141.60	48.82	6.30	0.51	31.68	41.85
	1-E2 (Kolahdooz)	5.32	135.27	62.10	4.71	0.54	31.82	41.91
	1-F (Ebnesina)	6.72	244.08	48.90	8.58	0.52	31.65	41.95
	Average D1	6.16	255.47	50.79	129.76	0.66	31.84	41.57
District 10	10-A (Miad)	4.11	223.20	43.13	8.77	0.70	32.48	41.35
	10-B (Fallahi)	4.18	232.95	47.13	9.22	0.73	32.34	42.21
	10-C (Hesabi)	5.10	175.73	57.21	5.94	0.68	32.23	42.67
	10-E (Hadi)	3.89	113.74	49.53	5.08	0.52	31.84	42.05
	Average D10	4.32	186.41	48.68	90.73	0.55	32.22	42.07

6.3.4 Site Coverage (SC)

Site coverage was defined as the ratio of average footprint to average plot size. It lies between 43.13% in 10-A and 62.10% in 1-E2 (Table 41). Figure 88 shows there is an indicative negative relationship between site coverage and Ta, $r = -.36$, $p = .30$ but it is not significant. There is also a positive relationship between SC and Ts, $r = +.48$, $p = .16$ but again this is not significant.

Figure 88: The relationship between SC and average Ta and Ts in all selected neighbourhoods

6.3.5 Average Footprint Size (AFS)

Building footprints are usually 50% to 60% of plot sizes. Like plot sizes, they varied in size between the different districts and the selected case studies. The minimum belongs to 10-E at 56.34m² and the maximum to 1-A at 201.82m² (Table 41). There is no significant association between average footprint size and Ta, $r = -.13$, $p = .72$. However, there is a strong negative relationship between AFS and Ts, $r = -.66$, $p = .04$. It seems the bigger the footprint size the lower the Ts (Figure 89).

Figure 89: The relationship between AFS and average Ta and Ts in all selected neighbourhoods

6.3.6 Average Sky View Factor (SVF)

A low SVF is the result of tall buildings or high vegetation cover giving shade (see section 2.5.3.2.2). A higher SVF means there is open space in the area. If this open space leads to having more shading vegetation like trees it decreases daytime Ta in summer. A lower SVF means a higher average building height and high building density. When vegetation was included in the calculations the SVF became even lower. The average SVF varied between 0.51 in 1-E1 and 0.73 in 10-B (Table 41). In general, D1 had lower SVF values compared to D10 with averages of 0.55 and 0.66 respectively. This is probably because of there being more tall buildings, a higher building density and less street coverage in D1. Sky View Factors are very similar in four of the five case study areas in D1, ranging from 0.51 to 0.56 with the highest belonging to 1-A at 0.62. Although 1-A has the tallest buildings of all the areas at an average height of 7.02 m, the large level of exposed surfaces because of the way the buildings are laid out causes the higher SVF in 1-A. It seems the combination of short buildings of average height 4.18m and the low building density of 35.13%, which together provide a lot of exposed ground surface to solar heat are the reason for the highest D-10 SVF in 10-B.

Comparing 10-B to 10-A shows that SVF is more affected by the density of buildings than their height. While building density and building height are 35.13% and 4.18m in 10-B, these values are 50.39% and 3.83m in 10-A. However, this logic does not work for 1-E1 with the lowest SVF (Table 32 and Table 41), as it does not have the tallest buildings (average 5.32m) but it does have a high average BD (47.26%).

There is a significant strong positive relationship between SVF and T_a , $r = .96$, $p = .00$. The higher the SVF the warmer the areas are, although there is no significant relationship between T_s and average SVF, $r = -.02$, $p = .96$ (Figure 90).

Figure 90: the relationship between average SVF and average T_a and T_s in all selected neighbourhoods

6.3.7 Aspect Ratio (H/W)

Theoretically, the H/W aspect ratio means the ratio of the average height of buildings to the width of the relevant streets. The aim here is to analyse the geometry of the whole selected neighborhood. Therefore, choosing one or two main streets and dividing the average height of buildings along these to the average width of the streets would not be very helpful. This characteristic needs to be calculated based on the urban patterns in the selected areas in Mashhad. As a result, the aspect ratio was calculated in four different ways for this study. These were the aspect ratio of the street, aspect ratio of the yard, aspect ratio of the canyon and aspect ratio of neighbourhood. For the aspect ratio of the street the average height of buildings was divided by the average width of streets (Figure 91, sketch a). However, because the real distance between two buildings on either side of a street is not only defined by the width of the street, the aspect ratio of the canyon was also defined. In the aspect ratio of the canyon the average length of the courtyard was added to the width of the streets (Figure 91, sketch b). This

new characteristic was still not very accurate because the real pattern of the neighborhood is as found in sketch c in Figure 91. The space between two streets is usually occupied by two buildings and their own courtyards. In the other word, the aspect ratio of neighborhood means the average aspect ratio of canyon and courtyard.

Figure 91: Schematic drawing of H/W aspect ratio and typical urban pattern in Mashhad

Aspect ratio of street = H/W_s

Aspect ratio of courtyard = H/L

Aspect ratio of canyon = H/W_c

Aspect ratio of Neighbourhood = $H/W = ((\frac{H}{W_c}) + (\frac{H}{L}))/2$

Where H is the average height of buildings

W_s is the average width of the streets(Figure 92)

L is the average length of courtyards

W_c is the average distance between two buildings, which is equal to (W_s+L)

It is important to note that the street width might be narrower than as calculated. This is because the streets were digitized for the simulation. To face less error, streets with a width less than 5m were not digitized (Figure 92).

Figure 92: Typical urban pattern in Mashhad. Light grey indicates streets, light yellow indicates courtyards and grey are building footprints. The white indicates streets that were not digitized.

For calculation of the aspect ratio, the average building height was needed for each case. Since each building in a given area has a building height tag, it was easy to calculate average height. The next step was to consider the average distance between two buildings. Based on Mashhad's urban pattern, the distance between two buildings means the width of the street (W_s) plus the width of the courtyard between the building and the street edge (L). Since the purpose of study the was to save time in the process of studying UHI, measuring the streets and courtyard widths and lengths one by one in GIS was not logical. To overcome this, a new Tool for Heat Island Simulation (THIS) was tried. THIS is a tool for use in GIS to calculate the H/W parameter. After following all the steps and after several attempts the application was still not working and another approach needed to be tried. At this stage the average W_s and the average L_y needed to be calculated. Unfortunately, these values did not exist in the attribute table of the related shapefile in GIS. However, with another tool in GIS, which is called the Minimum Bounding Geometry, it is possible to determine the approximate length or width of polygon. As the existing streets are made of polygons, the input feature was polygon and for the geometry type CONVEX_HULL was chosen. Figure 93 shows the different settings and how it works. The one chosen for this study is marked in red.

Figure 93: Minimum Bounding Geometry tool setting in GIS map to create a polygon with width and length tag.

As can be seen in Figure 94 from GIS, the CONVEX_HULL polygons, which are in red, are slightly bigger than the streets in light grey. In some streets, like the one marked with an arrow it is much bigger. In this case the particular street was unselected, and the value entered manually into the relevant spreadsheet.

Figure 94: The streets are in grey, the CONVEX_HULL polygons created by GIS are in red.

The next step was to calculate the average courtyard length (L_y). The existing shapefile in GIS did not have this. The courtyard is the area between the building and its boundary and is usually surrounded by 2.5m high walls (Figure 91). First the courtyard areas needed to be acquired, and then their lengths. As the shapefiles of the plot and footprint of each building existed, the courtyard area could be achieved by subtracting the footprint from the building plot. For this purpose, the Erase Tool in GIS was used and the XY tolerance was considered to be 1m to create more rectangular courtyards (Figure 95).

Figure 95: the process of calculating length of courtyards. First photo shows streets and plot, second photo shows building footprints on top of plots, third photo shows courtyards created using Erase tool in GIS and final photo shows purple rectangles corresponding to the courtyards created by Dice tool and then Minimum Bounding Geometry tool

The new shapefile like the other existing files did not have the width or length attributes. Therefore, the Minimum Bounding Geometry tool was again used to create these. The only issue here was that some buildings had two courtyards, one in front of the building and the other at the back. The Minimum Bounding Geometry tool would have created the whole plot again in these cases. To avoid that another tool called Dice was used first to separate each courtyard (Figure 96). Now the required values could be transferred to the relevant spreadsheet to calculate the H/W ratio.

Figure 96: Dice tool in GIS map to subdivide feature into smaller parts.

6.3.7.1 H/W Aspect Ratio of Streets

There was a significantly strong negative relationship between the H/W Aspect Ratio of streets and Ta, $r = -.74$, $p = .01$ (

Figure 97). Neighbourhoods with higher aspect ratios experience lower Ta. However, there was not a significant relationship between the H/W Aspect Ratio of streets and Ts, $r = -.00$, p

=.98.

Figure 97: The relationship between H/W of streets and average Ta and Ts in all selected neighbourhoods

6.3.7.2 H/W Aspect Ratio of Courtyards

The effect of the H/W ratio of courtyards was very similar to that of streets. There is a significant strong negative relationship between the H/W Aspect Ratio of yards and Ta, $r = -$

.78, $p = .01$, but there is not a significant relationship between the H/W Aspect Ratio of yards and T_s $r = -.02$, $p = .96$ (Figure 98).

Figure 98: The relationship between H/W of courtyards and average T_a and T_s in all selected neighbourhoods

6.3.7.3 H/W Aspect ratio of canyon

The H/W ratio of the canyon is almost half that of the street and the trend is very similar. There is a significant strong negative relationship between the H/W aspect ratio of the canyon and T_a , $r = -.78$, $p = .01$. Neighbourhoods with lower aspect ratios experience higher T_a values. There is not a significant relationship between the H/W aspect ratio of the canyon and T_s , $r = -.00$, $p = .99$ (Figure 99)

Figure 99: The relationship between H/W of canyon and average T_a and T_s in all selected neighbourhoods

6.3.7.4 H/W aspect ratio of the Neighbourhood

There is a significantly strong negative relationship between the H/W aspect ratio of the neighbourhood and T_a , $r = -.78$, $p = .01$, but there is not a significant relationship between the H/W aspect ratio of the neighbourhood and T_s , $r = -.01$, $p = .98$ (Figure 100).

Figure 100: the relationship between H/W of neighbourhood and average T_a and T_s in all selected neighbourhoods

6.4 Neighbourhood comparisons

In this section different neighborhoods have been compared. Each selection for comparison was based on significant criteria, such neighbourhoods with the highest and lowest T_a and T_s or neighbourhoods that have the same urban pattern but where the T_a and T_s were different.

6.4.1 1-A (Sajad) and 10-C (Hesabi)

1-A (Sajad) and 10-C (Hesabi) have the respective lowest and highest T_s among all the neighborhoods. There is 2.41°C difference in T_s , although the deviation in T_a is only 0.13°C (see Table 32). Unlike T_a which could represent the behaviour of the local climate over a whole day, T_s only shows the reaction of surfaces to solar radiation in the last couple of hours of simulation. Comparing these two neighbourhoods could help to prioritise the factors that affect T_s . Meanwhile, it is also worthwhile to investigate why the big difference in T_s did not lead to a big difference in T_a .

In terms of land use, 1-A has a larger building density and consequently a lower street coverage (Table 42). The urban forms of the two neighbourhoods are also quite different. 1-A has a higher average plot size, footprint size, lower site coverage, and SVF. The difference between the average plot size, footprint size, site coverage and building density is significant.

Table 42: UHI and urban characteristics of 1-A and 10-C

UHI characteristic		Neighbourhood 1-A (Sajad)	10-C (Hesabi)
Average Ta (°C)		32.10	32.23
Average Ts (°C)		40.26	42.67
Urban characteristic			
Land use/surface materials	Building density (%) / (brick, light concrete)	55.00	38.39
	Street coverage (%) / asphalt	24.75	33.84
	Asphalt pavement area (%)	0.21	6.91
	Bare land area (%) / soil	0	0
Urban form	Courtyard (%) / Light pavement	18.34	16.30
	Building orientation	N-S	NW-SE
	Street orientation	E-W	NE-SW
	Street pattern	grid	grid
	Average SVF	0.62	0.68
	H/W ratio of canyon	0.21	0.20
	Average plot size (m ²)	451.33	175.73
	Average footprint size (m ²)	201.82	100.53
Vegetation	Site coverage (%)	44.72	57.21
	Grassland area (%)	2.16	5.37

Both neighbourhoods have a gridded street pattern, however, 1-A is oriented E-W and 10-C is oriented NE-SW (Figure 101). As can be seen from the Ts maps, high street coverage coupled with orientation, exposes 10-C to more solar energy than 1-A. The E-W oriented streets in 1-A absorb less solar radiation than the N-S oriented streets of 10-C. A large building mass seems very helpful in reducing Ts. However, in a sunny country like Iran, the orientation of a building needs to be considered not only for a day in summer but also over the year.

Figure 101: Comparison maps of Ta, Ts and SVF for 1-A and 10-C

6.4.2 1-F (Ebnesina) and 10-A (Miad)

1-F (Ebnesina) and 10-A (Miad) have the lowest and highest Ta respectively among all the neighbourhoods. The Ta difference is 0.83 °C. However, the Ts values are very close (see Table 32). Comparing these two neighbourhoods because they have very similar ground surface temperatures and different air temperatures, could help to prioritise the factors which affect Ta more. 1-F has a higher plot size, footprint size, site coverage, and building density and a lower street coverage and SVF (indicative of more shading) (Table 43). Except for building density and H/W aspect ratio, the differences between values are minor. Another distinguishable difference between the two neighbourhoods is the building and street orientations. 10-A has larger street areas exposed to solar radiation for most of the day and a lower building density which is orientated N-S. The orientation of the buildings in 10-A creates a shorter shadow during the day in comparison with 1-F (Figure 102). This comparison shows the importance of building density and H/W aspect ratio on average Ta.

Table 43: UHI and urban characteristics of 1-F and 10-A

UHI characteristic		Neighbourhood name	
		1-F (Ebnesina)	10-A (Miad)
Average Ta (°C)		31.65	32.48
Average Ts (°C)		41.95	41.35
Urban characteristic			
Land use/surface materials	Building density (%)/(brick, light concrete)	50.65	38.63
	Street coverage (%)/asphalt	27.02	34.29
	Asphalt pavement area (%)	0	0
	Bare land area (%)/soil	0	0
	Courtyard (%)/Light pavement	20.09	26.94
Urban form	Building orientation	NE-SW	N-S
	Street orientation	NW-SE	E-W
	Street pattern	grid	grid
	Average SVF	0.52	0.70
	H/W ratio of canyon	0.24	0.13
	Average plot size (m ²)	244.08	223.20
	Average footprint size (m ²)	119.35	96.27
	Site coverage (%)	48.90	43.13
Vegetation	Grassland area (%)	0.75	0.01

As can be seen from the Ta maps, both cases have warmer areas on the east side (Figure 102). However, where warmed air can penetrate 10-A, it is blocked in 1-F. The main reason for this could be the orientation of streets and buildings. It also shows the back courtyard creates cooler areas due to the light colour of the material and a higher H/W ratio. Although 10-A has the higher street coverage, the orientation of 1-F exposes more streets to direct solar radiation than in 10-A.

Figure 102: Comparison maps of T_a , T_s and SVF for 1-F and 10-A

6.4.3 1-A (Sajad) and 10-A (Miad)

1-A (Sajad) and 10-A (Miad) have similar urban characteristics such as street pattern and building orientation (Table 44). Except for building density, street coverage, light pavement, average plot size and footprint size, the differences in the other characteristics are minor. 1-A (Sajad) is 0.38 °C cooler in air temperature and 0.75 °C cooler in ground surface temperature. Comparing these two neighbourhoods could suggest how much difference in the urban characteristic values could lead to a difference in T_a or T_s . It seems building density and H/W aspect ratio negatively and street coverage positively affect T_a , while average plot size and footprint size negatively affect T_s .

Table 44: UHI and urban characteristics of 1-A and 10-A

UHI characteristic		Neighborhood name	
		1-A (Sajad)	10-A (Miad)
Average T_a (°C)		32.10	32.48
Average T_s (°C)		40.26	41.35
Urban characteristic			
Land use/surface materials	Building density (%) / (brick, light concrete)	55.00	38.63
	Street coverage (%) / asphalt	24.75	34.29
	Asphalt pavement area (%)	0.21	0
	Bare land area (%) / soil	0	0
	Courtyard (%) / Light pavement	18.34	26.94
Urban form	Building orientation	N-S	N-S
	Street orientation	E-W	E-W
	Street pattern	grid	grid
	Average SVF	0.62	0.70
	H/W ratio of canyon	0.21	0.13
	Average plot size (m ²)	451.33	223.20
	Average footprint size (m ²)	201.82	96.27

	Site coverage (%)	44.72	43.13
Vegetation	Grassland area (%)	2.16	0.01

The Ts maps suggest the courtyards have lower temperatures than other parts in both maps (Figure 103). This could be mainly because of the lower SVF and light pavements. However, a lower SVF would not by itself necessarily lead to a lower Ts. As can be seen from the Ts map and SVF maps, the grid pattern of 1-A (Sajad) is tilted toward east while that of 10-A (Miad) is tilted toward west. This tiny orientation difference exposes more streets in 10-A to solar radiation gain from the early hours. It also affects the Ta maps. More warmed air can penetrate 10-A as the street orientation is parallel to the wind direction. This lets more warmed air flow in 10-A, while the buildings in 1-A slightly block the wind.

Figure 103: Comparison maps of Ta, Ts and SVF for 1-A and 10-A

6.4.4 1-E1 (Majd) and 10-E (Hadi)

1-E1 (Majd) and 10-E (Hadi) were selected for comparison because both neighbourhoods have a traditional pattern. 1-E1 has both lower Ta and Ts, although the difference is not significant (Table 45). 1-E1 has a lower building density, street coverage, site coverage, and a lesser light pavement area, but a higher H/W ratio and lower site coverage. The SVFs are the same and the grassland area is very small and can be ignored. Except for street coverage, H/W aspect ratio and footprint size, other differences are minor. This comparison shows even with very high street coverage and almost the same urban pattern, it is still possible to have lower Ta and Ts. The bigger aspect ratio and NE-SW building orientation could be the key here. Table 45 suggests having exactly the same SVF does not lead to same H/W aspect ratio.

Table 45: UHI and urban characteristics of 1-E1 and 10-E

UHI characteristic		Neighbourhood name	
		1-E1 (Majd)	10-E (Hadi)
Average Ta (°C)		31.68	31.84
Average Ts (°C)		41.85	42.05
Urban characteristic			
Land use/surface materials	Building density (%)/(brick , light concrete)	47.26	50.39
	Street coverage (%)/asphalt	27.48	15.80
	Asphalt pavement area (%)	0	0
	Bare land area (%)/soil	0	0
	Courtyard (%)/Light pavement	24.42	29.66
Urban form	Building orientation	NE-SW	NW-SE
	Street orientation	Irregular	Irregular
	Street pattern	Irregular	Irregular
	Average SVF	0.51	0.51

	H/W ratio of canyon	0.24	0.17
	Average plot size (m ²)	141.60	113.74
	Average footprint size (m ²)	69.13	56.34
	Site coverage (%)	48.82	49.53
Vegetation	Grassland area (%)	0.04	0

Both neighbourhoods have a traditional irregular pattern, however 1-E1 has a slightly more traditional urban character in terms of lower street widths (Figure 104).

Figure 104: Comparison maps of Ta, Ts and SVF for 1-E1 and 10-E

6.5 The effect of vegetation

6.5.1 General characteristics

Table 46 shows the average Ta and Ts for each neighbourhood with and without trees. The number of trees and simulation method have been discussed in section 4.6. As mentioned before, District 10 has fewer and smaller trees than District 1. To make a better comparison between the two districts, another simulation was run for D10 with similar trees as found in D1. The results are shown in the last column of Table 46. Except for 10-E (Hadi) and 10-A (Miad) when simulated with small trees, in all cases, trees make the areas cooler. The average Ta in D1 dropped 0.64°C and in D10 dropped 0.08°C with small trees and by 0.64°C with average trees. The average Ts in D1 was reduced by 4.21°C and in D10 by 0.70°C with small trees and by 3.11°C with average trees. The results suggest that trees affected Ts more than Ta because of the cooling effect of shading. The reduction in air temperature in D10 with the same (average size) trees is the same as that of D1, noting D1 only has 45 more trees (0.64°C and 0.64°C). These results show the importance of tree size. However, other factors are still important. For example, 10-C (Hesabi) has the highest number of trees (550) but does not have a particularly low Ta and Ts. Another example is 1-E1 (Majd), which has the third lowest number of trees (319) but also has the third lowest Ta.

Table 46: The effect of vegetation on UHI

Neighbourhood name	Trees (numbers)	Average Ta (°C)	Average Ta (°C) with average	Difference Ta (°C)	Average Ts (°C)	Average Ts (°C) with average	Difference Ts (°C)		
1-A (Sajad)	396	32.10	31.37	0.74	40.27	36.53	3.74	-	-

1-C (Sanabad)	346	31.86	31.30	0.56	41.65	37.70	3.96	-	-
1-D (Ahmadabad)	436	31.91	31.02	0.89	41.78	37.19	4.59	-	-
1-E1 (Majd)	319	31.68	31.23	0.45	41.85	38.37	3.48	-	-
1-E2 (Kolahdooz)	356	31.82	31.25	0.57	41.91	37.98	3.93	-	-
1-F (Ebnesina)	483	31.65	31.02	0.63	41.95	36.36	5.58	-	-
Average D1	389	31.84	31.20	0.64	41.57	37.35	4.21	-	-
Neighbourhood name	Trees (numbers)	Average Ta (°C)	Average Ta (°C) with small trees	Difference Ta	Average Ts (°C)	Average Ts (°C) with small trees	Difference Ts	Average Ta (°C) with average	Average Ts (°C) with average
10-A (Miad)	220	32.48	32.40	0.08	41.35	41.41	-0.06	31.96	39.53
10-B (Fallahi)	350	32.34	32.25	0.09	42.21	41.65	0.56	31.67	39.21
10-C (Hesabi)	550	32.23	32.08	0.15	42.67	41.41	1.27	31.41	38.33
10-E (Hadi)	255	31.84	31.85	-0.01	42.05	41.02	1.03	31.51	39.59
Average D10	344	32.22	32.14	0.08	42.07	41.37	0.70	31.58	38.96

There is a significant strong negative relationship between the number of trees and Ta, $r = -.60$, $p = 0.03$ (Figure 105). Also, there is a significant strong positive relationship between the number of trees and difference in Ta with and without trees, $r = .78$, $p = .003$ (Figure 106). This means the higher the difference between Ta, the greater the number of trees. While 1-D (Ahmadabad) has the highest reduction in Ta (0.89°C) by having 436 trees, 10-C (Hesabi) with the highest number of trees only shows a 0.82°C air temperature reduction with trees. The least reduction in air temperature belongs to 10-E (Hadi) with the second-lowest number of trees (0.33°C , 255). 10-A (Miad) with the lowest number of trees (220) shows a 0.52°C drop in Ta. 1-F (Ebnesina) with the second-highest number of trees is located in the middle of Table 46 with a 0.63°C drop in Ta.

Ts shows a more logical trend in the relationship between the number of trees and the reduction in temperature. There is a significant strong negative relationship between the number of trees and Ts, $r = -.75$, $p = .00$ (Figure 105). There is a significant strong positive relationship between the number of trees and the difference in Ts with and without trees, $r = .85$, $p = .00$ (Figure 106). The reduction in temperature increases almost constantly with an increase in the number of trees, except for 10-C (Hesabi). Trees appear to form a major parameter regarding ground surface temperature. In terms of air temperature, the effect of trees is highly dependent on the shading effect, which in turn is related to the number of trees, the distance between them and their location in the street.

Figure 105: The relationship between tree numbers and average Ta and Ts in all selected neighbourhoods

Figure 106: The relationship between tree numbers and average Ta and Ts difference in all selected neighbourhoods

6.5.2 10-A (Miad) and 10-E (Hadi)

10-A (Miad) and 10-E (Hadi) were the only neighbourhoods with an increase in Ts (10-A) and in Ta (10-E) when both districts were simulated with small trees. While the average drop in Ta in all other neighbourhoods was 0.46°C the Ta in 10-E increased by a marginal 0.01°C and Ts in 10-A by 0.06°C (Table 46). This could be due to the low numbers of trees in these neighbourhoods and an increase leaf temperature. In case of insufficient water access or soil moisture, the plant starts to prevent water loss by operating stomatal conductance. As a consequence, leaf temperature increases (May et al., 2013; Savi et al., 2015). At midday, when heat stress increases, the water saving strategy used by plants increases the leaf temperature and consequently the air temperature (Simon et al., 2018a). If trees are bigger in size or close

to each other, then this phenomenon is less likely to happen, because the shading effect of trees prevents heat stress in the first place. The UHI and urban characteristics of 10-A (Miad) and 10-E (Hadi) are set out in Table 47.

Table 47: UHI and urban characteristics of 10-A and 10-E

UHI characteristic		Neighbourhood name	
		10-A (Miad)	10-E (Hadi)
	Average Ta (°C)	32.48	31.84
	Average Ts (°C)	41.35	42.05
Urban characteristic			
Land use/surface materials	Building density (%)/(brick, light concrete)	38.63	50.39
	Street coverage (%)/asphalt	34.29	15.80
	Asphalt pavement area (%)	0	0
	Bare land area (%)/soil	0	0
	Courtyard (%)/Light pavement	26.94	29.66
Urban form	Building orientation	N-S	NW-SE
	Street orientation	E-W	Irregular
	Street pattern	grid	Irregular
	Average SVF	0.70	0.51
	H/W ratio of canyon	0.13	0.17
	Average plot size(m ²)	223.20	113.74
	Average footprint size(m ²)	96.27	56.34
	Site coverage (%)	43.13	49.53
Vegetation	Grassland area (%)	0.01	0
	Tree numbers	220	255

6.5.3 1-B (Ershad) and 10-D (Andishe)

1-B (Ershad) and 10-A (Andishe) were excluded from the main neighbourhood comparison because of their different urban patterns. These two neighbourhoods could be considered as open midrise. Each belongs to two different periods of urban development with a different view

on urban planning and urban design (see section 3.2.1). It could be worthwhile investigating how different views on urban design could affect urban microclimate. Table 48 presents the comparison of the different criteria in the two neighbourhoods. 1-B (Ershad) is comprised of 13.64% building area, 33.74% asphalt area (street and asphalt pavement area together) and 39.37% grassland. The remaining areas are mostly pavement area. This proportion of grassland is the highest in all the chosen neighbourhoods. 10-D (Andishe) is made up of 29.34% building area, 40.03% asphalt area (street and asphalt pavement area together) and 4.21% bare land, with the remaining areas mostly pavement areas.

Table 48: UHI and urban characteristics of 1-B and 10-D

UHI characteristic		Neighbourhood name	
		1-B (Ershad)	10-D (Andishe)
	Average Ta (°C)	32.51	31.65
	Average Ta (°C) with trees	30.162	31.37
	Average Ts (°C)	41.19	41.08
	Average Ts (°C) with trees	32.54	38.14
Urban characteristic			
Land use/surface materials	Building density (%)/(brick, light concrete)	13.64	29.34
	Street coverage (%)/asphalt	26.06	28.35
	Asphalt pavement area (%)	20.10	11.68
	Bare land area (%)/soil	0	4.21
	Courtyard (%)/light pavement		
Urban form	Building orientation	N-S	NE-SW
	Street orientation	-	-
	Street pattern	-	-
	Average SVF	0.66	0.56
	Average SVF with trees	0.13	0.38
	H/W ratio		
	Average plot size (m ²)	9,008.63	1,349.03
	Average footprint size (m ²)	176.02	214.33
	Site coverage (%)	1.95	15.89
Vegetation	Trees (number)	2836	290
	Grassland area (%)	39.37	1.45

Although 1-B (Ershad) has the highest ratio of grass land, both Ta and Ts are higher than 10-A which is mostly covered by asphalt area and pavement (Table 48). This result contradicts studies have which highlighted the importance of green space (parks) (Bowler et al., 2010; X.

Cao et al., 2010; S.-H. Lee et al., 2009). It means when it comes to green space, it is very important to distinguish between surface level green space such as grass and taller green space such as trees. In most studies grass has a lower temperature than impervious areas like concert pavements and asphalt (Bokaie et al., 2016; X. Cao et al., 2010). In a study that related the cooling effect of grass to the size of the area, big parks (7.8 ha) with a large area of grassland were warmer than small parks (0.1 ha) (Armson et al., 2012). This happens because large areas of grassland convert solar energy to sensible heat (Monteith & Unsworth, 2013). This suggested that small patches of grassland could be more effective than large grass areas (Monteith & Unsworth, 2013).

From the Ta maps, it seems a lower building density in the area allows more warm air to penetrate the urban environment. In some areas, grassland is as hot as the asphalt areas (Figure 107), 1-B (Ershad), Ta map). A noticeable change occurs when existing trees are involved. Trees dropped Ta in 1-B (Ershad) by 2.35°C and in 10-D (Andishe) by 0.28°C and Ts dropped by 8.56°C and 2.94 °C respectively (Table 48). The reason for the higher reduction in air temperature and ground surface temperature in 1-B is that the number of trees is 9.7 times more than that of 10-D. Although 1-B has taller buildings than 10-D, due to more open space and a lower building density, it has a lower SVF than 10-D (Table 48). However, with trees, 1-B has much lower SVF than 10-D. The SVF map reveals to what extent SVF as an urban characteristic can predict both Ta and Ts. Open space (high SVF) is hotter than shaded space (low SVF). Therefore, with the existing urban characteristics, dense areas are cooler than open spaces, unless the open space is shaded by a reasonable number of trees.

Case study	1-B (Ershad)	10-D (Andishe)
Aerial photo

Figure 107: Comparison maps of T_a , T_s and SVF for 1-F and 10-A

6.6 Summary

Chapter 6 sets out the results of the simulation of the case study districts for T_a , T_s , and SVF. All results are correlated with the urban characteristics to discover which are the most relevant. Orientation is important, as is SVF and the H/W ratio, but these need to be considered together and shading of hard surfaces is important in reducing the UHI effect. Trees are also important for the shade they provide. The implications of the results for urban designers are discussed in chapter 7.

7 Discussion

As a result of the complexity of dealing with existing conditions, it is important to note that these findings and the proposed recommendations are based on comparing simulations at 15.00 in the middle of the summer. Reliable recommendations need to be based on different hours in the day and in different seasons, and also consider building and human energy exchange to surrounding environments. Only then, can urban designers choose a sustainable approach to reducing UHI. This research is, therefore, a first step into this complex problem.

7.1 ENVI-met sensitivity

Since the discussion of the results relies on their accuracy, it seems appropriate to start such a discussion with some reflections on aspects of using ENVI-met. As explained in 2.64.1, among the UHI study approaches, simulation gives urban designers and city planners a chance to examine urban microclimate at the early stages of design. Considering all the complexities found in the urban texture and urban climate, simplification in simulation seems inevitable. However, changing a single input, either metrological or material, can affect the final results. While previous studies have placed more emphasis on validation of ENVI-met by comparing simulation outputs to measured data, a pilot study was run to assess the sensitivity of ENVI-met to input data, in particular input surface materials (chapter 5). As part of this pilot study, two typical residential neighbourhoods (mid-rise areas) were selected for studying Ts. The findings and recommendations were as follows:

- ENVI-met shows sensitivity to input surface material therefore using materials close to local materials should result in more realistic outputs.
- ENVI-met does not show sensitivity to the simulation start time and duration of simulation. It means starting the simulation only a couple hours before the target time could be enough.
- Topography affects Ts, therefore it is better to include DEM in modelling. However, for saving time, and because of the flat nature of Mashhad, this study did not use this option.
- ENVI-met shows sensitivity to metrological input, especially wind, so using local metrological data is recommended. High wind speed affected both Ts and computation time. Therefore, it is better to use average wind speed to reduce computation time and increase the chance of obtaining reliable ground surface temperature results.
- ENVI-met shows sensitivity to the size of street trees, which is in agreement with a previous study (Simon et al., 2018a).
- ENVI-met does not show sensitivity to nesting grid, empty cells and offset boundary. When the aim of the study is to compare different scenarios at the urban scale, using these is not recommended.

Consistency is very important in modelling when different case studies are involved. Since Ts maps are only concerned with the top surface of the soil, using local building materials did not show much difference. To understand the role of building materials, studying air temperature is essential. Future studies could consider other aspects of ENVI-met input data, for example, the role of both surface and building materials on air temperature and the role of lateral borders around case studies to help reduce computing time but still give reliable results for comparing scenarios.

7.2 Correlation between Urban characteristics and UHI

This section deals with correlations for the factors that contribute to UHI (Table 49). In most studies, UHI causative factors are usually listed based on their influences on UHI. Both causative factors and UHI terms are very broad. For finding the effect of urban characteristics on UHI, studies need to categorize them more accurately. Instead of using general terms such as UHI, it is better to note the UHI characteristic which is being studied, such as Ts or Ta. The time of the day as well as the season are both very important. However, how and when Ta and Ts could affect each other is also crucial.

Factors contributing to UHI were studied in section 2.5, and then analysed in section 6.1 and 6.2. Since the original GIS map from Mashhad city council did not have all required data, some characteristics such as courtyard area, street width and H/W aspect ratio have been calculated and saved in the same spreadsheet with the main characteristics (Appendix 8). To obtain Pearson correlations, values of the urban characteristic needed to be imported into SPSS. To save time, instead of selecting the main parameters, the whole spreadsheet was imported. The outcome was both interesting and sometimes confusing (Table 49 and Appendix 9). At first only average plot size was considered as an urban form characteristic among other related alternatives such as sum of plot size area (m^2) or plot area coverage (%) to represent plot area. Although the results showed a strong correlation between average plot size and Ts, they also showed the strong correlation between the sum of plot size area and Ta. This means different urban characteristics could affect UHI in different ways, therefore it is helpful to study them more deeply and in more detail.

Table 49: The correlation between urban characteristics and UHI characteristics

UHI characteristic Statistical relationship		Average Ta correlation coefficient	P value	Average Ts correlation coefficient	P value
Local climate	Wind				
	Average Ta	-	-	-.09	.81
	Average Ts	-.09	.81	-	-
Urban characteristic					
Land use/surface materials	Building density (%)/(brick , light concrete)	-.712*	.021	-.482	.159
	Street coverage(%)/asphalt	.648*	.043	.233	.517
	Sum of street area	.649*	.043	.233	.517
	Average Courtyard area (Light pavement)	.286	.422	-.811**	.004
	Average courtyard length	.267	.456	-.664*	.036
Urban form	Building orientation	-.231	.521	.739*	.015
	Street orientation	-.124	.732	.658*	.038
	Average street width	.706*	.023	-.402	.250
	Average SVF	.958**	.000	.019	.958
	H/W ratio of streets	-.740*	.014	-.008	.982
	H/W ratio of yard	-.779**	.008	.017	.964
	H/W ratio of canyon	-.779**	.008	-.003	.993
	H/W ratio of neighbourhood	-.783**	.007	.009	.981
	Average plot size (m ²)	.226	.531	-.768**	.009
	Sum of plot size	-.634*	.049	-.440	.203
	Average footprint size (m ²)	.132	.717	-.664*	.036
	Sum of foot print size	-.712*	.021	-.482	.159
Vegetation	Trees	-.603*	.038	-.637*	.026
	Average SVF with trees	.878**	.001	.201	.578
	Trees and temperature difference	.756**	.004	.851**	.000

** . Correlation is significant at the 0.01 level (2-tailed).

* . Correlation is significant at the 0.05 level (2-tailed).

Figure 108 shows the urban characteristics which were studied in this research. The urban characteristics were divided into the three main groups of land use/surface material, urban form and vegetation. The colour of the rectangle represents either a significant correlation with Ta or Ts or no relationship with them.

Figure 108: The three main urban characteristics investigated in this study. The blue rectangle indicates a strong correlation with Ta, and the orange rectangle a strong correlation with Ts. The characteristic in green is the only one with a strong relationship to both Ta and Ts. The grey rectangles indicate no relationship with Ta or Ts.

7.2.1 Ta and Ts correlations

Table 49 shows only the urban characteristics with a strong relationship to Ta or Ts. This shows that Ts (ground surface temperature) and Ta (air temperature at 1.5m height) are not correlated with each other. In most studies regarding UHI, surface temperature is derived from thermal images and air temperature is either based on recordings from metrological stations or

extraction of surface temperature data (Prihodko & Goward, 1997; Vancutsem et al., 2010; Zhu et al., 2013). However, less research has concentrated on the relationship between Ta and Ts. Studies that have investigated this correlation have usually been conducted during the night because the calculation process of estimating Ta from Ts is easier at night (Jones et al., 2004; Mostovoy et al., 2006). Kawashima et al. (2000) showed that Ta and Ts have a strong correlation coefficient during winter nights in Japan, which is in disagreement with these research findings. This could be because of the different method or different time of study.

7.2.2 Characteristics affecting both Ta and Ts

The literature review revealed the importance of green space. However, finding an empty space in a dense residential area in Mashhad to create new parks seems impossible. The benefits of trees in urban areas are obvious due to their shading and transpiration effects. Skelhorn et al (2016) showed that just adding 5% medium-size trees to an urban area in Manchester in the UK could decrease the air temperature by 1% and consequently reduce the energy used by air conditioners. Although at first, street trees seemed to have low effect on UHI, the results revealed that they are only urban parameter that affects both Ta and Ts. Other characteristics only effect Ta or Ts but not both. The results showed the great effect trees have, especially on reducing air temperature. However, the role of trees depends on their size and number.

Most studies have concentrated on the relationship between trees and Ta (A. Rafiee et al., 2016; Y. Wang & Akbari, 2016) and there are fewer studies about Ts and trees. In this study the number of trees had a significant effect on reducing Ts. This result is in agreement with Loughner et al (2012). The number of trees also had a significant effect on reducing Ta. This result is in agreement with many other studies (Aboelata, 2020; Aboelata & Sodoudi, 2020; O'Malley et al., 2015; A. Rafiee et al., 2016; Y. Wang & Akbari, 2016). Aboelata & Sodoudi, (2020) emphasized that the impact of tree coverage on Ta is also related to other neighbourhood characteristics especially urban density. Increased tree numbers lower Ta in higher building density neighbourhoods while they increase Ta in lower building density neighbourhoods.

Table 50 suggests that trees are more effective when the case study neighbourhoods have a higher aspect ratio and lower SVF. Because a high aspect ratio has strong correlation with Ta, adding trees make this stronger. In other words, the influence of trees on Ta increases when the canyon is deeper. This will enhance the shading effect of both buildings and trees.

Table 50: The correlation between trees, H/W aspect ratio and SVF

		H/W ratio of Streets	H/W ratio of Yard	H/W ratio of Canyon(Street and courtyard length	H/W ratio of Neighbourhood	Average SVF	Average SVF with trees	difference SVF
Average Ta (°C)	Pearson Correlation	-.740*	-.779**	-.779**	-.783**	.958**	.878**	-0.470
	Sig. (2- tailed)	0.014	0.008	0.008	0.007	0.000	0.001	0.171
Average Ta (°C) with trees	Pearson Correlation	-.795**	-.887**	-.856**	-.880**	.747*	.932**	-.808**
	Sig. (2- tailed)	0.006	0.001	0.002	0.001	0.013	0.000	0.005
Difference Ta	Pearson Correlation	0.109	0.201	0.149	0.181	0.331	-0.112	0.579
	Sig. (2- tailed)	0.764	0.577	0.682	0.617	0.350	0.758	0.080
Average Ts (°C)	Pearson Correlation	-0.008	0.017	-0.003	0.009	0.019	0.201	-0.337
	Sig. (2- tailed)	0.982	0.964	0.993	0.981	0.958	0.578	0.341
Average Ts (°C) with trees	Pearson Correlation	-0.584	-.705*	-.653*	-.688*	0.394	.789**	-.957**
	Sig. (2- tailed)	0.076	0.023	0.041	0.028	0.260	0.007	0.000
Difference Ts	Pearson Correlation	0.624	.769**	.700*	.745*	-0.413	-.731*	.831**
	Sig. (2- tailed)	0.054	0.009	0.024	0.013	0.236	0.016	0.003
Tree Numbers	Pearson Correlation	0.328	0.517	0.415	0.478	0.008	-0.348	0.631
	Sig. (2- tailed)	0.355	0.126	0.233	0.162	0.982	0.324	0.050

7.2.3 Characteristics affecting Ts

In most studies Ts is related to land-cover/surface materials and particularly to impervious surfaces and vegetation. In this study, the neighbourhoods have been chosen from residential areas, so there is not much diversity in land cover. The focus given here to urban characteristics, however, has revealed some new findings about surface materials. Characteristics related to urban form, trees and land use are based on Pearson correlation findings. Others such as grassland are based on Ts maps (Table 49 and Figure 109).

Figure 109: Relationships of urban characteristics to T_s

Average plot size and average courtyard size have a significant negative relationship with T_s at the 0.01 level. Average footprint size and average courtyard length have a significant negative relationship with T_s at the 0.05 level. This means that in Figure 110, neighbourhood B would have lower T_s than neighbourhood A due to the higher value for the average plot size and average foot print size.

Figure 110: Two hypothetical scenarios. Neighbourhood A and neighbourhood B with same neighbourhood area, building density and street coverage but difference in average plot size, foot print size and courtyard size

The courtyard width has no correlation with T_s but a higher value for the average courtyard length is desirable for a lower T_s . This criterion could be related to material colour and albedo in comparison with the street material. However, there is contradiction here which needs more investigation in future research. If all the plot areas have the same size, then the lower value

for footprint size leads to a higher value for courtyard size and length. Since courtyards have a stronger relationship with T_s than footprint the priority could be courtyard size and length. Finding the optimal size for each criterion could be investigated in future research.

In most of studies green space means a park which generally consists of different types of vegetation such as trees, grasslands and shrubby patches. An urban area park is one type of green space which is not always affordable. Instead, urban trees, urban grasslands and other landscapes could be located individually rather than being mixed in a park, especially when there is a shortage of land or water resources. Green spaces generally show low surface temperatures (Jenerette et al., 2007; J.-P. Kim & Guldmann, 2014; Kotharkar & Surawar, 2016). The cooling effect of grassland is usually reported in UHI studies using thermal images (Su et al., 2010). In this study, the effect of grassland in increasing T_s is in contradiction with some research (Hendel et al., 2018; Su et al., 2010), but in agreement with other studies (X.-L. Chen et al., 2006; Murphy et al., 2011).

In this study orientation only affected T_s and not T_a . This conclusion is confirmed by other studies (Andreou & Axarli, 2012; Fatiha Bourbia & Awbi, 2004; de La Flor & Dominguez, 2004). E-W and NW-SE street orientations with buildings-oriented N-S and NW-SE created a lower T_s in the case study neighbourhoods. Although the orientation results could be very localised and dependent on geographic location, wind regime, and aspect ratio, a study in Stuttgart, Germany found that NW-SE oriented street created a cooler environment (Ketterer & Matzarakis, 2014).

H/W aspect ratios, SVF and building height did not affect T_s . All these characteristics are related to each other and are canyon characteristics. This outcome does not align with other research about the relationship of building height, street canyon and T_s (Loughner et al., 2012). This study showed how the shadow created by higher buildings decreased surface temperature.

7.2.4 Characteristics affecting T_a

Building density, total footprint area, average street width, average SVF, and H/W aspect ratio of street, yard and canyon have a significant correlation with T_a at the level of 0.01. Street coverage and number of trees have a significant correlation with T_a at the level of 0.05 (Table 49 and Figure 111).

In terms of building density, it is also important to consider human activity. Although building density decreased T_a in this study, population density, which is more important than building density, was not considered.

Figure 111: Signification relationships

There are mixed opinions about the effect of density on UHI (see section 2.5.3.1.2). Different definitions of density could be one reason for this. In some studies a dense environment is negatively correlated with land surface temperature (Stone Jr & Rodgers, 2001), however, no such relationship was found in this study. In terms of T_a , the results of this study suggest the denser environment would create a lower air temperature. This is in contradiction with some studies ((Mohan et al., 2013) in India) and in agreement with others (Alobaydi et al., 2016). However, in this study it is important to note the comparison is between buildings and impervious surfaces, especially street area, and not buildings and green spaces. This means in a residential area it is preferred that area is covered with buildings rather than impervious surfaces. This means if designers go for a dense neighbourhood, then the denser is the better.

The relationship between a very dense neighbourhood with some green space remains to be explored.

This study unlike others (Nasir et al., 2017) did not find any correlation between H/W aspect ratio and Ts, but did find a strong relationship with Ta. This is in agreement with other studies (Fazia Ali-Toudert & Mayer, 2006; M. A. Bakarman & Chang, 2015; Deng & Wong, 2020). A high H/W aspect ratio creates more shade and reduces solar access resulting in a lower temperature. The H/W aspect ratio could act as a very good controlling variable in neighbourhood design, where due to a neighbourhood situation where the streets need to be wider, then the buildings could be taller. This study could be categorized as symmetrical aspect ratio study, because the differences between building heights in the simulated neighbourhoods are very low.

A higher SVF (more open space) leads to a higher Ta as result of more exposure to solar radiation. This is in contradiction with a study of Montreal at midday in summer (Y. Wang & Akbari, 2014) but in agreement with studies undertaken in Beijing, China (He et al., 2015) and in Tehran (Baghaeipoor & Nasrollahi, 2019). When trees exist, in the SVF calculation the SVF decreases and consequently Ta decreases. This is in agreement with other studies (Y. Wang et al., 2016).

In many studies roads have the highest surface temperature (X.-L. Chen et al., 2006), however in this study there is no correlation between street area and Ts, although street coverage and sum of street area are correlated with Ta.

7.2.5 Characteristics not affecting Ta or Ts

Site coverage, average building height, sum of courtyards, courtyard coverage, average courtyard width, average canyon width, sum of concrete pavement area, sum of grassland area, and sum of bare land area have no effect either on Ta or Ts.

7.3 Policy implications (climate action)

Climate countermeasures can only be achieved when they address the social, economic and political status of urban areas (Kleerekoper et al., 2012). The idea of having different urban variables which are capable of reducing heat in cities could help urban designers to consider climate design more creatively.

A compact urban form is the traditional urban design solution in a harsh climate like Iran. This design solution usually involves narrow, irregular street patterns to create more shadows and enough privacy for neighbours. Contemporary Iranian cities tend to have grid patterns which are usually oriented E-W, with buildings which are usually oriented N-S. Although modern urban design in Iran has preserved some climatic design solutions such as compactness, it has also served more modern urban characteristics, such as car-orientation or political views, such as religious orientation toward Mecca. There are no countermeasure policies against UHI in Iran. Countermeasures against UHI not only decrease temperature within cities and increase thermal comfort but also help reduce energy consumption in Iran. One aim of this study was to support the development of such policies. To convert climatic findings into applicable planning strategies some recommendations will be proposed based on the existing situation in Mashhad (Figure 112). Some researchers have suggested “city-by-city” countermeasures against UHI (J. Yang et al., 2015), while this research recommends that any solution needs to be considered neighbourhood by neighbourhood. Two approaches could be considered for the UHI problem in Iran, these being countermeasures for existing urban areas and those for new urban developments. Since the existing urban warming problem came from existing urban design, the first approach seems more useful, although both approaches are explained further below. However, before initiating any changes in the strategic plan of Mashhad two important things need to be considered. First, the existing urban characteristics of neighbourhoods need to be studied. To achieve this, different urban patterns and urban microclimates in Mashhad need to be determined and categorized. Then, suitable indices need to be created for each urban characteristic, such as SVF and H/W ratio. It is important to note that such detailed study needs to be done in conjunction with the study of population and anthropogenic activities in that area.

However, similar to other studies, the actions suggested will probably not have a significant effect on UHI if they are only treated as individual changes.

Figure 112: Policy hierarchy to counter UHI

7.3.1 Existing neighbourhoods

Responses in existing neighbourhoods can be broken down into long-term and short-term strategies.

7.3.1.1 Long-term planning

Long-term planning means reshaping urban form over a long period, for example 50 years. Depending on the situation, it could include increasing building density, building height (and SVF and H/W ratio), plot size, foot print sizes, courtyard area, courtyard length and decreasing street coverage and average street width. Changing any of above characteristics needs to be in conjunction with the effect of any rise in population density and anthropogenic activities in that area. Considering building life span in Iran is between 25 to 35 years (Persia, 2017), if the city council allows residential design to stretch plot length and increase site coverage and height density, the street width decreases and all goals mentioned above will achievable. However, further research needs to be conducted in order to find the optimal values for increasing the characteristics mentioned. For example, site coverage ratio and building height have different impacts on SVF when land use densities are varied (Yuan & Chen, 2011). Additionally, raising the H/W ratio is more effective in N-S streets than E-W streets (Venhari et al., 2019). Building

density and street coverage have a strong negative relationship with each other. This means that more built environment leads to less street area and a potentially lower T_a . However, in the case of an existing neighbourhood, narrowing streets would bring concerns about car circulation, public transportation and car parking areas. Instead of that, the city council could allow increases in height. Higher buildings increase the H/W ratio and decrease SVF. In this case, research would be needed to determine the optimal SVF and H/W ratio. On the other hand, high-rise buildings mean more people, more anthropogenic activities and more demand for car parks in the neighbourhood. Considering a shared underground parking area for two or three residential plots or a separate car park building in the neighbourhood are possible solutions. To solve street coverage area, underground streets could also be considered.

7.3.1.2 Short-term planning

The short-term plan could include planting vegetation and changing pavement materials, which would need slight manipulation of the existing regulations. Increasing shading in streets by using pergolas could be useful. In comparison with long-term planning, short-term planning is more cost-effective and quickly achievable.

7.3.1.2.1 Planning land use/surface material

Land use planning has different levels, all of which are bigger than the neighbourhood scale. Existing neighbourhoods have been built based on a strategic or master plan. At the scale of this study, changing the surface material could be very beneficial and achievable. Although, changing the roof surface and building vertical surface materials are a very important strategy, they have not been investigated in this study. The focus of this study has been more on ground surface materials. A light concrete pavement showed less temperature increase than dark asphalt areas. Although, asphalt is inevitable for streets and roads, the city council could change the pavements in public places like car parks or pavements in parks to any sort of cooling pavement with a high albedo.

7.3.1.2.2 Planning Vegetation

Green infrastructure has several effects on lessening the UHI effect by casting shadows on building walls and ground surfaces. This decreases the heat stored in surface materials during the day, which leads to cooler nights as less heat is released from storage to the air (Imran et al., 2019).

Trees

Planting trees could be used as a quick strategy for reducing the UHI effect. However, there needs to be a balance in a city like Mashhad where water is scarce. An efficient number of trees in the Mashhad climate would mean minimum water consumption and maximum increased cooling effect, although calculation of this was beyond the scope of this study. Some studies have suggested that examination of species needs to be done in different climates to find the best-adapted species to be beneficial both in summer and winter (Massetti et al., 2019; Stanley et al., 2019). Because a main concern about trees is wind reduction, the distance between them to allow air movement is very important (Müller et al., 2014).

Therefore, some consideration is needed for expanding shade coverage on impervious surfaces and the vertical walls of buildings to achieve spatial optimization of tree locations.

- **Size:** the results of simulating with and without trees show the size of trees is very important. Trees need to be big enough to prevent solar radiation penetration. Therefore, instead of planting seeds and waiting for a long time for trees to grow, it is better to use suitable areas outside of the city to grow trees and then, when the trees have grown to a suitable size move them to the selected locations.
- **Arrangement and spacing:** the most important role of trees in an urban area in reducing UHI is through creating shadows and preventing solar radiation penetration. Due to water shortages in Iran, it is not a good idea to plant many trees in urban areas. Therefore, the distance between trees is very important.
- **Location:** currently in Mashhad, trees are mostly located in the sidewalks between apartments and the streets, which works well for decreasing UHI. Few buildings have trees in their courtyards, mostly because building users prefer to use their courtyards for an extra parking area or as a playground for children. However, planting trees in courtyards would be very beneficial for casting shadows both on the vertical walls of buildings and the courtyard floor. If trees are not planted in a proper location the shading area could be minimized to zero (Zhao, 2017). This indicates that randomly planting trees in courtyards could lead to zero shading results. Therefore, green locations need to be determined based on the different orientations and plot sizes in the different neighbourhoods. It seems it would be good if the city council could encourage people to plant trees in courtyards by allowing them to have parking spaces underground or in the streets. The second place which could be very suitable for trees is in the green islands that are formed in the centres of wide boulevards. Any big asphalt area such as a playground or school yard, ideally needs to be surrounded by trees to reduce T_a . Another important factor for tree location is consideration of the wind. Trees should not be sited so as to block a cooling wind in summer.
- **Type:** tree selections is usually made based on appearance, screening ability, water resistance, flower and fruit capability, or shadows. For reducing UHI, not only does this list of criteria need to be considered, with shading being the vital factor, but a

new criterion also needs to be added to the list. For example, the ability to decrease SVF in a neighbourhood is connected to the size of trees and their leafage, so this should be considered. It is also important to note that the type of tree needs to be chosen based on both summer and winter behaviour. In winter, urban areas need more solar radiation to warm up neighbourhoods. Therefore, deciduous trees would work better.

Without considering the above recommendations, unplanned tree planting in cities may not only not help in reducing UHI but could increase it. Given the importance of trees, Mashhad City Council would need to do more research and provide a strategic tree planting plan for residents.

Grasslands

The results showed that grassland had strong positive effect on Ts. This result contradicts other studies which suggest increasing green surfaces will modify the high conductivity effect of impervious surfaces (Imran et al., 2019). In some areas in this study, the grassland areas are as hot as asphalt areas. Due to the high cost and difficulty of the maintenance of grassland, it is not recommended to increase the grassland area in the city unless the grassland is supported by trees (Figure 114). Therefore, green walls, green roofs and green islands in wide highways (Figure 113) are not a good location for grass.

Figure 113: Example of an area of grassland not supported by trees, which will tend to increase UHI (Wikipedia, 2016)

Figure 114: Vakilabad Boulevard: Example of an area with less grassland which is supported by trees (Persiangig, 2020)

7.3.2 Urban development

The urban development recommendations made here are more based on the urban characteristics rather than suggesting urban policies. The results do not lead to recommending any specific street pattern or building, plot or street orientation. However, whatever street orientation is chosen, a higher building density with less street coverage and with a high aspect ratio is recommended. If based on population density wider streets are needed, then the aspect ratio needs to be higher. The average plot size, foot print size and courtyard size also need to be high. The simulation method as tested in this study could be an easy and relatively quick way to evaluate different scenarios and find the optimal mix for any of these variables.

7.4 Summary

Based on the results a number of recommendations have been made for urban design in Mashhad. The results have also been compared with similar studies in the literature. Simulations similar to those carried out in this study could be a way forward for urban design through testing for the optimal combination of the urban characteristics that affect UHI. Chapter 8 concludes the thesis.

8 Conclusion

8.1 Answering the research questions

This research was motivated by the lack of countermeasures against urban warming, noting this as a growing problem in the city of Mashhad. It proposed use of a simulation approach for investigating the UHI effect in existing residential neighbourhoods, using Mashhad as a case study. It did this through investigating a series of 400x400 areas representative of the same urban pattern in each of 2 districts from the 13 different districts in Mashhad. Districts 1 and 10 were chosen as the coolest and warmest districts based on previous research on the urban heat island in Mashhad (Alavipanah et al., 2015). Among the different approaches to studying urban heat islands, simulation using ENVI-met was chosen based on the social, academic and political situation in Iran.

One problem in using the simulation approach is knowing what it is critical to simulate. To examine the sensitivity of ENVI-met, two different case studies in District 1 were chosen. Start time, computation time, materials, lateral boundary conditions, topography and wind speed were tested to see which had most effect on the final results. This was done to enhance accuracy and reduce simulation processing time. This process has been described in detail in chapter 5. However, as a result of this investigation it has been possible to make a number of recommendations regarding ENVI-met sensitivity in discussion chapter (see section 7.1). Studying the relationship between urban characteristics and T_a and T_s was the next step in the investigation (see chapter 6). Based on the results, a number of recommendations have been made, which are set out in chapter 7.

The first research question to be answered by this study was

Whether UHI countermeasures in Iran need to be localized?

The results show that rather than a whole country or a city by city approach to dealing with UHI, as has been suggested, the approach needs to be neighbourhood by neighbourhood, as the urban characteristics at this level will affect both air and surface temperatures. This means that the decisions of both urban and building designers will have an affect on UHI.

The second research question to be answered by this study was

-For the city of Mashhad what is the effect of existing different neighbourhood patterns on UHI?

This question was answered by comparing the T_a and T_s results for the different neighbourhoods with their urban characteristics. The results indicated the different existing neighbourhood patterns could affect both T_a and T_s . Generally, it can be concluded that although District 1 is older than District 10, has more positive urban characteristics which lead to lower air and surface temperature. The highest average air temperature difference was 0.83°C and the highest average ground surface temperature difference was 2.4°C . The selected neighbourhoods are very different regarding some urban characteristics and very similar regarding others. For example, the highest difference between average height of buildings is 3.31m which is just one story, while the highest difference between average courtyard areas is 192.10 m^2 . It means even with no huge difference in urban characteristics the UHI effect is completely obvious in different neighbourhood patterns.

Urban and street pattern did not show any relation to T_a and T_s , however street and building orientation did. E-W orientated street and N-S orientated building create colder surface temperature. This result, on the one hand gives the urban designers the flexibility of choosing urban pattern (grid or none-grid), and on the other hand the possibility of lowering surface temperature by choosing right street and building orientation.

The third research question was

-How are the urban characteristics of Mashhad correlated with UHI?

This question was answered by using the Pearson correlation coefficient to measure the association between either T_a and T_s and the urban characteristics. The results failed to show any strong relationship between T_a and T_s . T_a has a strong significant relationship at level 0.01 to the H/W aspect ratio of yards, the H/W aspect ratio of canyons, the H/W aspect ratio of neighbourhoods, and average SVF, and significant relationship at level 0.05 to building density, total footprint area, average street width, the H/W aspect ratio of streets, street coverage, total street area and total plot size. The highest difference in the H/W aspect ratio of yards is 0.20, of canyons is 0.15, of neighbourhoods is 0.18, and in average SVF is 0.22. Although the magnitude of these changes in value is not very high, there is a great impact on T_a . The comparison between these urban characteristics and their relationship to T_a , highlighted the role of building height and street width in urban form. T_s has a strong significant relationship at level 0.01 to average plot size, average courtyard area, and a significant relationship at level 0.05 to average footprint size and average courtyard length. The

highest difference between average plot size is 114.07 m² and of average courtyard area is 192.10 m². These results show the role of the exposure of surface material on Ts.

8.2 Contribution to knowledge

This study does not prove any major causal mechanisms between UHI and urban characteristics, but rather concludes that the literature regarding UHI and urban form should be localized and expanded in terms of sample sizes. It is essential to investigate the main causes of UHI in existing situations rather than attempt to generalise. Urban form consists of many different aspects such as orientation and building density. Research studies with the aim of studying the relationship between urban forms and UHI either create hypothetical scenarios or use case studies. Hypothetical scenarios are usually created to examine one aspect of urban form. In this approach except for one variable, other characteristics remain constant to enable researchers to find the relationship between that characteristic and UHI. Although the results of this approach could provide an environmental perspective for designing new neighbourhoods, they are not applicable in an existing situation.

This is firstly because of local and global climate differences, and secondly, because of urban form differences. For example, results came from one street orientation might not apply to other urban orientations. On the other hand, the results from existing case studies usually come from small sample sizes which makes it difficult to generalize and apply the results to the whole city or even other neighbourhoods in the same city. In fact, the thousand different types of urban form in different countries might not follow those from a small sample size or imaginary scenarios. To overcome these issues, this research contributes to a better understanding of urban warming in a hot arid climate in a developing city such as Mashhad by statistically evaluating the detailed effect of local neighbourhood characteristics on UHI parameters. The main contribution of this study has been to try to find a practical method for studying the UHI effect in the city of Mashhad, by choosing larger size samples to achieve more reliable results. In this study an area of 1,920,000m² containing 5831 buildings has been simulated.

Moreover, a simulation method has been designed that is not too costly in simulation time. As a result, it can be recommended for city councils and small urban design companies as a mean of easily and frequently monitoring changes in urban characteristics and impact of this on the surface temperature of different neighbourhoods. It is suggested that ENVI-met could be a useful tool for a comparison study of UHI, especially if the city council also updates and enhances the GIS maps more often.

8.3 Study Limitations

There are several limitations regarding this study. They can be divided into two main groups of lack of up-to-date data and the limitations of the software.

8.3.1 Lack of data

There is insufficient data for the details of the urban form and for the metrological information. The only available GIS map of Mashhad used for this study is at least 20 years old, and during this time many parts of the city have been changed, especially in terms of building heights. Even so, it does not have all data which was needed for this study. For example, the GIS map has no trees, streets and sidewalks shapefiles. In this study, the first two were modelled based on inspection of recent google map images for the selected neighbourhoods and the last one was ignored. There is also no database of building and surface materials. Material assignments were based on the author's knowledge of the local building industry and photos taken in Mashhad.

Regarding metrological data, the only available information is from the airport weather station, which is far from two selected neighbourhoods. There is not enough detailed metrological information in the form of average data for each district or neighbourhood. For example, the wind speed data from the city council was only maximum wind rather than average wind speed.

8.3.2 Software limitation

The ENVI-met validation investigated through literature review and Mashhad mythological data for the same date. The weather data only shows air temperature which is close to simulated T_a (see chapter 4). The research is limited to summer-time only and was conducted for one period of 12 hours from 3.00 to 15.00, and the results are based on one hour. This is because the duration of calculation is too long in ENVI-met. For the same reason, the scale of the model area could not be bigger than 400x400m². Building heat capacity, and anthropogenic heat are not considered in the simulation.

The other limitations regarding ENVI-met are listed below.

- indoor building temperature is assumed to be the same for all buildings
- in the 2.5 model buildings could not have windows

8.3.3 Lack of time

At the beginning this research designed to evaluate the UHI characteristics of existing neighbourhood in order to find out the optimal characteristics in urban design. In the other word, after statistical analysing of the relationship between urban heat island parameters and neighbourhood parameters, these outcomes would use to design new scenarios based on existing neighbourhood pattern. At the final step the results of new scenarios would compare to existing ones. However, due to software limitation and lack of time this part of study was cancelled.

8.4 Future work

This study suggests that future research should focus on short-term and cost-effective solutions rather than long-term and expensive urban change solutions. This research explored the importance of urban form and materials in two hot arid residential neighbourhoods of Mashhad. Future work could start by investigation of the urban characteristics of Mashhad. Existing urban patterns, vegetation patterns and species, and surface and building materials need to be studied to provide a suitable database for other researchers to follow, especially those involving simulations. This information would allow a comprehensive evaluation of the existing situation in the city. Other future studies could be in the three main areas of vegetation, materials and ENVI-met simulations.

In addition to expanding research on existing vegetation, researchers need to do more study on the optimal types, size, location and planting distances of vegetation, especially trees. Tree research should include tree size, shadow size, water resistance, and how far apart they need to be in the street or around building, as well as where to put trees when developing residential urban design plans, including where they should be in side-walks, in boulevards, and in parking lots or other big asphalt areas.

The study of materials is another mitigation approach which could have a quick influence on changing the UHI effect. Research is needed into finding materials that could work as thermal insulation in the hot-arid climate of Mashhad while also reducing solar energy absorption. Optimal colour and albedo also need to be examined.

This study did not investigate the sensitivity of ENVI-met for any other atmospheric variable except for T_s . More study needs to be done to assess to what extend the ENVI-met simulations

are reliable. This could include lateral boundary studies and input material studies. In other words, there is a need to examine how accurate and close to reality each input profile is regarding soil, walls, roof and surface materials. The problem for a city like Mashhad is that it is hard to find the money to validate the simulated results. Paying more attention to the inputs in places where there is the money for such validation could help in developing country situations like Mashhad.

8.5 Recommendations to urban designers in Mashhad

Although detailed recommendations have already been given in section 7.3 it may be useful to reflect on the role of both policy makers and urban design in avoiding the creation of UHIs. If cities continue to grow outwards this will tend to create UHIs unless great care is taken in the design to counter the creation of more built environment with appropriate tree cover. The materials and form should also be selected to minimise the build up of heat. This can only be achieved by modelling the proposals at the design stage in a way similar to that described in this thesis. The alternative is to grow through regional development and the creation of smaller, dispersed settlements but this topic is beyond the remit of this thesis.

References

- Aboelata, A. (2020). Vegetation in different street orientations of aspect ratio (H/W 1: 1) to mitigate UHI and reduce buildings' energy in arid climate. *Building and environment*, 172, 106712.
- Aboelata, A., & Sodoudi, S. (2020). Evaluating the effect of trees on UHI mitigation and reduction of energy usage in different built up areas in Cairo. *Building and environment*, 168, 106490.
- Abrahamian, E. (2008). *A history of modern Iran*: Cambridge University Press.
- Acero, J. A., & Arrizabalaga, J. (2018). Evaluating the performance of ENVI-met model in diurnal cycles for different meteorological conditions. *Theoretical and applied climatology*, 131(1-2), 455-469.
- Acero, J. A., & Herranz-Pascual, K. (2015). A comparison of thermal comfort conditions in four urban spaces by means of measurements and modelling techniques. *Building and environment*, 93, 245-257. doi:<https://doi.org/10.1016/j.buildenv.2015.06.028>
- Achour-Younsi, S., & Kharrat, F. (2016). Outdoor Thermal Comfort: Impact of the Geometry of an Urban Street Canyon in a Mediterranean Subtropical Climate – Case Study Tunis, Tunisia. *Procedia - Social and Behavioral Sciences*, 216, 689-700. doi:<https://doi.org/10.1016/j.sbspro.2015.12.062>
- Adelia, A. S., Yuan, C., Liu, L., & Shan, R. Q. (2019). Effects of urban morphology on anthropogenic heat dispersion in tropical high-density residential areas. *Energy and buildings*, 186, 368-383. doi:<https://doi.org/10.1016/j.enbuild.2019.01.026>
- Afiq, W., Azwadi, C. N., & Saqr, K. (2012). Effects of buildings aspect ratio, wind speed and wind direction on flow structure and pollutant dispersion in symmetric street canyons: a review. *International Journal of Mechanical and Materials Engineering*, 7(2), 158-165.
- Agapiou, A. (2006). Tropical sustainable architecture: social and environmental dimensions. *Building Engineer*, 42.
- Ahmadi Venhari, A., Tenpierik, M., & Taleghani, M. (2019). The role of sky view factor and urban street greenery in human thermal comfort and heat stress in a desert climate. *Journal of Arid Environments*, 166, 68-76. doi:<https://doi.org/10.1016/j.jaridenv.2019.04.009>
- Alavipanah, S. K., Darrehbadami, S. H., & Kazemzadeh, A. (2015). Spatial-Temporal Analysis of Urban Heat-Island of Mashhad City due to Land Use/Cover Change and Expansion.
- Alcoforado, M. J., & Andrade, H. (2008). Global warming and the urban heat island. *Urban ecology*, 249-262.
- Alexander, C. (1977). *A pattern language: towns, buildings, construction*: Oxford university press.
- Ali-Toudert, F., & Bensalem, R. (2001). *A methodology for a climatic urban design*. Paper presented at the Proc. 18th Int. Conf. on PLEA, Florianopolis, Brazil.
- Ali-Toudert, F., Djenane, M., Bensalem, R., & Mayer, H. (2005). Outdoor thermal comfort in the old desert city of Beni-Isguen, Algeria. *Climate research*, 28(3), 243-256.
- Ali-Toudert, F., & Mayer, H. (2006). Numerical study on the effects of aspect ratio and orientation of an urban street canyon on outdoor thermal comfort in hot and dry climate. *Building and environment*, 41(2), 94-108.
- Alobaydi, D., Bakarman, M. A., & Obeidat, B. (2016). The Impact of Urban Form Configuration on the Urban Heat Island: The Case Study of Baghdad, Iraq. *Procedia Engineering*, 145, 820-827. doi:<https://doi.org/10.1016/j.proeng.2016.04.107>
- Ambrosini, D., Galli, G., Mancini, B., Nardi, I., & Sfarra, S. (2014). Evaluating mitigation effects of urban heat islands in a historical small center with the ENVI-Met® climate model. *Sustainability*, 6(10), 7013-7029.
- Amiri, M., Abedi-Kuopai, J., & EbrahimZadeh, A. (2009). *Using aridity management in reduction of water requirement in green space*. Paper presented at the The 1st International Congress on Water Crisis. Zabol University. Zabol.

- Amiri, R., Weng, Q., Alimohammadi, A., & Alavipanah, S. K. (2009). Spatial–temporal dynamics of land surface temperature in relation to fractional vegetation cover and land use/cover in the Tabriz urban area, Iran. *Remote sensing of environment*, 113(12), 2606-2617.
- Amiriparyan, P., & Kiani, Z. (2016). Analyzing the Homogenous Nature of Central Courtyard Structure in Formation of Iranian Traditional Houses. *Procedia-Social and Behavioral Sciences*, 216, 905-915.
- Anderson, W. P., Kanaroglou, P. S., & Miller, E. J. (1996). Urban form, energy and the environment: a review of issues, evidence and policy. *Urban studies*, 33(1), 7-35.
- Andreou, E. (2013). Thermal comfort in outdoor spaces and urban canyon microclimate. *Renewable Energy*, 55, 182-188.
- Andreou, E. (2014). The effect of urban layout, street geometry and orientation on shading conditions in urban canyons in the Mediterranean. *Renewable Energy*, 63, 587-596.
- Andreou, E., & Axarli, K. (2012). Investigation of urban canyon microclimate in traditional and contemporary environment. Experimental investigation and parametric analysis. *Renewable Energy*, 43, 354-363.
- ARCHNET. Imam Riza Shrine Complex. Retrieved from https://archnet.org/sites/1642/media_contents/134619
- Arif Kamal, M. (2010). Climatic Responsiveness In Traditional Built Form Of Lucknow. In *New Architecture and Urbanism: Development of Indian Traditions* (Vol. 201, pp. 201-209): Cambridge Scholars Publishing in association with GSE Research.
- Armson, D., Stringer, P., & Ennos, A. (2012). The effect of tree shade and grass on surface and globe temperatures in an urban area. *Urban Forestry & Urban Greening*, 11(3), 245-255.
- Arnfield, A. J. (1990). Street design and urban canyon solar access. *Energy and buildings*, 14(2), 117-131.
- Arnfield, A. J. (2003). Two decades of urban climate research: a review of turbulence, exchanges of energy and water, and the urban heat island. *International Journal of Climatology: a Journal of the Royal Meteorological Society*, 23(1), 1-26.
- Arnfield, A. J., & Mills, G. M. (1994). An analysis of the circulation characteristics and energy budget of a dry, asymmetric, east-west urban canyon. II. Energy budget. *International journal of climatology*, 14(3), 239-261.
- Azimi, N., & Pooyan, S. (2014). Investigating the urban land use changes through the approval of Article 5 Commission (Case study of Rasht city). *Planning and Geography Journal*, 18(47), 171-195.
- Baghaeipoor, G., & Nasrollahi, N. (2019). The Effect of Sky View Factor on Air temperature in High-rise Urban Residential Environments. *Journal of Daylighting*, 6(2), 42-51.
- Bagheri, B., & Tousi, S. N. (2017). An explanation of urban sprawl phenomenon in Shiraz Metropolitan Area (SMA). *Cities*.
- Bakarman, M. (2017). Evaluating the Influence of Urban Canyon Geometry on Air and Surface Temperatures inside Modern Residential Neighborhoods in Hot-arid Climates: A Case Study of Riyadh, Saudi Arabia. In J. D. Chang, H. Cai, M. Medina, M. Rashid, & S. White (Eds.): ProQuest Dissertations Publishing.
- Bakarman, M. A., & Chang, J. D. (2015). The influence of height/width ratio on urban heat island in hot-arid climates. *Procedia Engineering*, 118, 101-108.
- Bärring, L., Mattsson, J. O., & Lindqvist, S. (1985). Canyon geometry, street temperatures and urban heat island in Malmö, Sweden. *Journal of Climatology*, 5(4), 433-444.
- Beecham, S., Kazemi, F., & Kish Island, I. (2008). Strategies for sustainable arid landscape design: a perspective from Australia.
- Bentley, I. (1985). *Responsive environments: A manual for designers*: Routledge.
- Bibri, S. E. (2013). ICT for sustainable urban development in the European information society: A discursive investigation of energy efficiency technology. *School of Culture and Society, Malmö University*.

- Bibri, S. E., & Krogstie, J. (2017). Smart sustainable cities of the future: An extensive interdisciplinary literature review. *Sustainable Cities and Society*, 31, 183-212.
- Biddulph, M. (2007). *Introduction to residential layout*: Routledge.
- Biesbroek, G. R., Swart, R. J., & Van der Knaap, W. G. (2009). The mitigation–adaptation dichotomy and the role of spatial planning. *Habitat international*, 33(3), 230-237.
- Boeing, G., Church, D., Hubbard, H., Mickens, J., & Rudis, L. (2014). LEED-ND and livability revisited. *Berkeley Planning Journal*, 27(1), 31-55.
- Bokaie, M., Zarkesh, M. K., Arasteh, P. D., & Hosseini, A. (2016). Assessment of Urban Heat Island based on the relationship between land surface temperature and land use/land cover in Tehran. *Sustainable Cities and Society*, 23, 94-104.
- Bourbia, F., & Awbi, H. (2004). Building cluster and shading in urban canyon for hot dry climate: Part 1: Air and surface temperature measurements. *Renewable Energy*, 29(2), 249-262.
- Bourbia, F., & Boucheriba, F. (2010). Impact of street design on urban microclimate for semi arid climate (Constantine). *Renewable Energy*, 35(2), 343-347.
- Bowler, D. E., Buyung-Ali, L., Knight, T. M., & Pullin, A. S. (2010). Urban greening to cool towns and cities: A systematic review of the empirical evidence. *Landscape and Urban Planning*, 97(3), 147-155.
- Broadbent, G. (2003). *Emerging concepts in urban space design*: Taylor & Francis.
- Broto, V. C., & Bulkeley, H. (2013). A survey of urban climate change experiments in 100 cities. *Global environmental change*, 23(1), 92-102.
- Bruse, M. (2009a). Overview Data/File Structure. *ENVI-met 3.1 online manual*. Retrieved from <http://www.envi-met.info/documents/onlinehelpv3/hs30.htm>
- Bruse, M. (2009b). What's new in Version 3.1 compared to 3.0... *ENVI-met 3.1 online manual*. Retrieved from <http://www.envi-met.info/documents/onlinehelpv3/hs25.htm>
- Bruse, M., & Fleer, H. (1998). Simulating surface–plant–air interactions inside urban environments with a three dimensional numerical model. *Environmental modelling & software*, 13(3-4), 373-384.
- Byrd, H., Ho, A., Sharp, B., & Kumar-Nair, N. (2013). Measuring the solar potential of a city and its implications for energy policy. *Energy policy*, 61, 944-952.
- Ca, V. T., Asaeda, T., & Abu, E. M. (1998). Reductions in air conditioning energy caused by a nearby park. *Energy and buildings*, 29(1), 83-92.
- Canadell, J., Ciais, P., Dhakal, S., Le Quéré, C., Patwardhan, A., & Raupach, M. (2009). The human perturbation of the carbon cycle. *The Global Carbon Cycle-2*.
- Cao, S., & Li, C. (2011). The exploration of concepts and methods for low-carbon eco-city planning. *Procedia Environmental Sciences*, 5, 199-207.
- Cao, X., Onishi, A., Chen, J., & Imura, H. (2010). Quantifying the cool island intensity of urban parks using ASTER and IKONOS data. *Landscape and Urban Planning*, 96(4), 224-231.
- Carlson, T., Augustine, J., & Boland, F. (1977). Potential application of satellite temperature measurements in the analysis of land use over urban areas. *Bulletin of the American Meteorological Society*, 1301-1303.
- Carmona, M., Heath, T., Tiesdell, S., & Oc, T. (2010). *Public places, urban spaces: the dimensions of urban design*: Routledge.
- Carraro, C., Favero, A., & Massetti, E. (2012). Investments and public finance in a green, low carbon, economy. *Energy Economics*, 34, S15-S28.
- Chapman, L., & Thornes, J. (2004). Real-time sky-view factor calculation and approximation. *Journal of Atmospheric and Oceanic Technology*, 21(5), 730-741.
- Chapman, L., Thornes, J., & Bradley, A. (2001). Rapid determination of canyon geometry parameters for use in surface radiation budgets. *Theoretical and applied climatology*, 69(1-2), 81-89.
- Chatzidimitriou, A., & Axarli, K. (2017). Street Canyon Geometry Effects on Microclimate and Comfort; A Case Study in Thessaloniki. *Procedia Environmental Sciences*, 38, 643-650. doi:<https://doi.org/10.1016/j.proenv.2017.03.144>

- Chatzidimitriou, A., & Yannas, S. (2017). Street canyon design and improvement potential for urban open spaces; the influence of canyon aspect ratio and orientation on microclimate and outdoor comfort. *Sustainable Cities and Society*, 33, 85-101.
- Chen, X.-L., Zhao, H.-M., Li, P.-X., & Yin, Z.-Y. (2006). Remote sensing image-based analysis of the relationship between urban heat island and land use/cover changes. *Remote sensing of environment*, 104(2), 133-146.
- Chen, Y., Li, X., Zheng, Y., Guan, Y., & Liu, X. (2011). Estimating the relationship between urban forms and energy consumption: A case study in the Pearl River Delta, 2005–2008. *Landscape and Urban Planning*, 102(1), 33-42.
- Cheng, V. (2009). Understanding density and high density. In *Designing high-density cities* (pp. 37-51): Routledge.
- Chow, W. T., & Brazel, A. J. (2012). Assessing xeriscaping as a sustainable heat island mitigation approach for a desert city. *Building and environment*, 47, 170-181.
- Chow, W. T., Pope, R. L., Martin, C. A., & Brazel, A. J. (2011). Observing and modeling the nocturnal park cool island of an arid city: horizontal and vertical impacts. *Theoretical and applied climatology*, 103(1-2), 197-211.
- Conzen, M. R. G. (1960). Alnwick, Northumberland: a study in town-plan analysis. *Transactions and Papers (Institute of British Geographers)*(27), iii-122.
- Coronel, J., & Alvarez, S. (2001). Experimental work and analysis of confined urban spaces. *Solar Energy*, 70(3), 263-273.
- Costanzo, V., Evola, G., & Marletta, L. (2016). Energy savings in buildings or UHI mitigation? Comparison between green roofs and cool roofs. *Energy and buildings*, 114, 247-255.
- Coulton, C. J., Jennings, M. Z., & Chan, T. (2013). How big is my neighborhood? Individual and contextual effects on perceptions of neighborhood scale. *American journal of community psychology*, 51(1-2), 140-150.
- Council, C. (2018). The Park and Green Space Organization of Mashhad City Council www.parks.mashhad.ir.
- Crank, P. J., Sailor, D. J., Ban-Weiss, G., & Taleghani, M. (2018). Evaluating the ENVI-met microscale model for suitability in analysis of targeted urban heat mitigation strategies. *Urban Climate*, 26, 188-197. doi:<https://doi.org/10.1016/j.uclim.2018.09.002>
- Cullen, G. (1995). *The concise townscape*: Routledge.
- Dagenhart, R., & Sawicki, D. (1994). If (Urban) Design is Everything, Maybe It's Nothing. *Journal of Planning Education and Research*, 13(2), 146-148.
- de La Flor, F. S., & Dominguez, S. A. (2004). Modelling microclimate in urban environments and assessing its influence on the performance of surrounding buildings. *Energy and buildings*, 36(5), 403-413.
- Debbage, N., & Shepherd, J. M. (2015). The urban heat island effect and city contiguity. *Computers, Environment and Urban Systems*, 54, 181-194. doi:<https://doi.org/10.1016/j.compenvurbsys.2015.08.002>
- Declet-Barreto, J., Brazel, A. J., Martin, C. A., Chow, W. T., & Harlan, S. L. (2013). Creating the park cool island in an inner-city neighborhood: heat mitigation strategy for Phoenix, AZ. *Urban Ecosystems*, 16(3), 617-635.
- Deng, J.-Y., & Wong, N. H. (2020). Impact of urban canyon geometries on outdoor thermal comfort in central business districts. *Sustainable Cities and Society*, 53, 101966.
- Dessai, S. (2003). Heat stress and mortality in Lisbon Part II. An assessment of the potential impacts of climate change. *International journal of biometeorology*, 48(1), 37-44.
- Eghtesaonline. (2018). House price in Mashhad. Retrieved from <https://www.eghtesaonline.com/%D8%A8%D8%AE%D8%B4-%D9%85%D8%B3%DA%A9%D9%86-10/369464-%D8%A7%DB%8C%D9%86%D8%AC%D8%A7-%D8%AE%D8%A7%D9%86%D9%87-%D8%A8%D9%87-%D9%85%D8%AA%D8%B1%DB%8C->

- [%D9%85%DB%8C%D9%84%DB%8C%D9%88%D9%86-%D8%AA%D9%88%D9%85%D8%A7%D9%86-%D8%B1%D8%B3%DB%8C%D8%AF%D9%87-%D8%A7%D8%B3%D8%AA](#)
- Ehlers, E., & Floor, W. (1993). Urban change in Iran, 1920–1941. *Iranian Studies*, 26(3-4), 251-275.
- Eiraji, J., & Namdar, S. A. (2011). Sustainable systems in Iranian traditional architecture. *Procedia Engineering*, 21(Supplement C), 553-559. doi:<https://doi.org/10.1016/j.proeng.2011.11.2050>
- Eligasht. (2019). Watch Mashhad from Kolsangi. Retrieved from <https://www.eligasht.com/Blog/travelguide/%D9%85%D8%AC%D9%85%D9%88%D8%B9%D9%87-%D8%AA%D9%81%D8%B1%DB%8C%D8%AD%DB%8C-%DA%A9%D9%88%D9%87%D8%B3%D9%86%DA%AF%DB%8C/>
- Elnabawi, M. H., Hamza, N., & Dudek, S. (2013). *Use and evaluation of the ENVI-met model for two different urban forms in Cairo, Egypt: measurements and model simulations*. Paper presented at the 13th Conference of International Building Performance Simulation Association, Chambéry, France.
- Elnabawi, M. H., Hamza, N., & Dudek, S. (2015). Numerical modelling evaluation for the microclimate of an outdoor urban form in Cairo, Egypt. *HBRC Journal*, 11(2), 246-251. doi:<https://doi.org/10.1016/j.hbrj.2014.03.004>
- Emmanuel, R., & Fernando, H. J. (2007). Urban heat islands in humid and arid climates: role of urban form and thermal properties in Colombo, Sri Lanka and Phoenix, USA. *Climate Research*, 34(3), 241-251.
- Emmanuel, R., & Johansson, E. (2006). Influence of urban morphology and sea breeze on hot humid microclimate: the case of Colombo, Sri Lanka. *Climate research*, 30(3), 189-200.
- Energy, U. S. D. o. (2014). Building Energy Codes Program. Retrieved from www.energycodes.gov/adoption/states
- ENVI-met. (2017a). Knowledge Base: Model Layout. Retrieved from <http://www.botworld.info/doku.php?id=kb:modellayout>
- ENVI-met. (2017b). Lateral Boundary Conditions. Retrieved from <http://www.envi-met.info/doku.php?id=kb:lbc>
- ENVI-met. (2018a). Nesting Grids. Retrieved from <http://www.envi-met.info/doku.php?id=kb:nesting>
- ENVI-met. (2018b). Vertical Grid Layout. Retrieved from <http://www.botworld.info/doku.php?id=kb:verticalgrid>
- ENVI-met. (2019a). Brochures. Winter 2018/ 2019. Retrieved from <https://www.envi-met.com/brochures/>
- ENVI-met. (2019b). ENVI-met Model Architecture. Retrieved from <http://www.botworld.info/doku.php?id=intro:modelconcept>
- ENVI-met. (2019c). ENVI-met Output Files. Retrieved from <http://envi-met.info/doku.php?id=filereference:output:start>
- ENVI-met. (2019d). What are the minimum system requirements to run ENVI-met? Retrieved from <https://www.envi-met.com/buy-now/>
- ENVI-metBoard. (2018a). 2.5D or 3D? *ENVI-met 4 (Beginner's Corner)*. Retrieved from <http://www.envi-hq.com/viewtopic.php?f=31&t=2540&sid=2e0b60c38f4a16fa29a12de38e206d6a>
- ENVI-metBoard. (2018b). Optimal Start Time for a 24 Hour Model. *ENVI-met 4 (Beginner's Corner)*. Retrieved from <http://www.envi-hq.com/viewtopic.php?f=31&t=2578&sid=d981c855c7609898456d64c7d85bf10d>
- ENVI-metBoard. (2019). Domain Extended in Winter Version 4.1.2. *ENVI-met 4 (Main Simulation Model)*. Retrieved from <http://www.envi-hq.com/viewforum.php?f=3&sid=87ab16c18c0ca33fd48f564265ba5887>
- Environment, D. o. (2018). www.doe.ir.
- erasmus. (2020). water waves land. Retrieved from <https://erasmusu.com/en/erasmus-mashhad/what-to-do/water-waves-land-12377>

- Erell, E., Pearlmutter, D., & Williamson, T. (2012). *Urban microclimate: designing the spaces between buildings*: Routledge.
- Esch, M., van Bruin-Hordijk, T., & de Duijvestein, K. (2007). *The influence of building geometry on the physical urban climate: a revival of 'light, air and space'*. Paper presented at the PLEA2007–24th Conference on Passive and Low Energy Architecture.
- esri. (2019). Exploring digital elevation models. Retrieved from <https://pro.arcgis.com/en/pro-app/tool-reference/spatial-analyst/exploring-digital-elevation-models.htm>
- Estoque, R. C., Murayama, Y., & Myint, S. W. (2017). Effects of landscape composition and pattern on land surface temperature: An urban heat island study in the megacities of Southeast Asia. *Science of the Total Environment*, 577, 349-359.
- Ewing, R., Bartholomew, K., Winkelman, S., Walters, J., Chen, D., McCann, B., & Goldberg, D. (1997). *Growing cooler: The evidence on urban development and climate change*: Urban Land Institute.
- Ewing, R., & Rong, F. (2008). The impact of urban form on US residential energy use. *Housing policy debate*, 19(1), 1-30.
- Fahmy, M., Ibrahim, Y., Hanafi, E., & Barakat, M. (2018). *Would LEED-UHI greenery and high albedo strategies mitigate climate change at neighborhood scale in Cairo, Egypt?* Paper presented at the Building Simulation.
- Fang, C., Wang, S., & Li, G. (2015). Changing urban forms and carbon dioxide emissions in China: A case study of 30 provincial capital cities. *Applied energy*, 158, 519-531.
- Fanni, Z. (2006). Cities and urbanization in Iran after the Islamic revolution. *Cities*, 23(6), 407-411.
- Farhadi, H., Faizi, M., & Sanaieian, H. (2019). Mitigating the urban heat island in a residential area in Tehran: Investigating the role of vegetation, materials, and orientation of buildings. *Sustainable Cities and Society*, 46, 101448. doi:<https://doi.org/10.1016/j.scs.2019.101448>
- Farsnews. (2018). Change of name. Retrieved from <https://www.farsnews.ir/razavi/news/13980926000627/%D9%81%D8%A7%D8%B1%D8%B3-%D9%85%D9%86%7C-%D8%AA%D8%BA%DB%8C%DB%8C%D8%B1-%D9%86%D8%A7%D9%85-%D8%A8%D8%B2%D8%B1%DA%AF%D8%B1%D8%A7%D9%87-%D9%85%DB%8C%D8%AB%D8%A7%D9%82-%D8%A8%D9%87-%D8%A2%DB%8C%D8%AA-%D8%A7%D9%84%D9%84%D9%87-%D9%87%D8%A7%D8%B4%D9%85%DB%8C%E2%80%8C%D8%B1%D9%81%D8%B3%D9%86%D8%AC%D8%A7%D9%86%DB%8C-%D8%A8%D8%B1%D8%A7%DB%8C-%D9%85%D8%B1%D8%AF%D9%85>
- fava.mashhad. (2020). Amarnam Mashhad. Retrieved from <https://fava.mashhad.ir/index.php>
- Feliciano, M., & Prosperi, D. C. (2011). Planning for low carbon cities: Reflection on the case of Broward County, Florida, USA. *Cities*, 28(6), 505-516.
- Foken, T., & Napo, C. J. (2008). *Micrometeorology* (Vol. 2): Springer.
- Frey, H. (2003). *Designing the city: Towards a more sustainable urban form*: Taylor & Francis.
- Fund, I. M. (2007). World Economic Outlook Database, October 2007. Retrieved from <https://www.imf.org/external/pubs/ft/weo/2007/02/weodata/weorept.aspx?sy=2007&ey=2007&scsm=1&ssd=1&sort=country&ds=.&br=1&c=001&s=NGDPD&grp=1&a=1&pr1.x=57&pr1.y=10>
- Gál, T., Lindberg, F., & Unger, J. (2009). Computing continuous sky view factors using 3D urban raster and vector databases: comparison and application to urban climate. *Theoretical and applied climatology*, 95(1-2), 111-123.
- Gartland, L. M. (2012). *Heat islands: understanding and mitigating heat in urban areas*: Routledge.
- Gasht, E. (2020). Behnam House Tabriz. Retrieved from <https://ealiya.com/attraction/behnam-house/>
- Geletič, J., Lehnert, M., & Dobrovolný, P. (2016). Land surface temperature differences within local climate zones, based on two central European cities. *Remote Sensing*, 8(10), 788.

- Ghanbari, M., Ajza Shokuhi, M., Rahnama, M. R., & Kharazmi, O. A. (2016). An analysis on the price of urban land in Iran's provinces during 2001 to 2011. *Journal of Urban Economics and Management*, 4(14), 77-99. Retrieved from <http://iueam.ir/article-1-397-fa.html>
- Gharipour, M. (2003). Iranian Architecture & Monuments; Bazaar of Isfahan. *Iranian chamber society*. Retrieved from http://www.iranchamber.com/architecture/articles/bazaar_of_isfahan2.php
- Ghazanfari, S., Naseri, M., Faridani, F., Aboutorabi, H., & Farid, A. (2009). Evaluating the effects of UHI on climate parameters (A case study for Mashhad, Khorrasan). *International Journal of Energy and Environment*, 3(2), 94-101.
- Ghobadi, A., Khosravi, M., & Tavousi, T. (2018). Surveying of heat waves impact on the urban heat islands: Case study, the Karaj City in Iran. *Urban climate*, 24, 600-615.
- Giannopoulou, K., Santamouris, M., Livada, I., Georgakis, C., & Caouris, Y. (2010). The impact of canyon geometry on intra urban and urban: suburban night temperature differences under warm weather conditions. *Pure and applied geophysics*, 167(11), 1433-1449.
- Glaeser, E. L., & Kahn, M. E. (2010). The greenness of cities: carbon dioxide emissions and urban development. *Journal of urban economics*, 67(3), 404-418.
- Golden, J. S., & Kaloush, K. E. (2006). Mesoscale and microscale evaluation of surface pavement impacts on the urban heat island effects. *The international journal of pavement engineering*, 7(1), 37-52.
- Gomi, K., Shimada, K., & Matsuoka, Y. (2010). A low-carbon scenario creation method for a local-scale economy and its application in Kyoto city. *Energy policy*, 38(9), 4783-4796.
- Gosling, D., & Maitland, B. (1984). *Concepts of urban design*.
- Grasso, M. (2010). An ethical approach to climate adaptation finance. *Global Environmental Change*, 20(1), 74-81.
- Grimmond, C., Potter, S., Zutter, H., & Souch, C. (2001). Rapid methods to estimate sky-view factors applied to urban areas. *International Journal of Climatology: A Journal of the Royal Meteorological Society*, 21(7), 903-913.
- Gusson, C. S., & Duarte, D. H. S. (2016). Effects of Built Density and Urban Morphology on Urban Microclimate - Calibration of the Model ENVI-met V4 for the Subtropical Sao Paulo, Brazil. *Procedia Engineering*, 169, 2-10. doi:<https://doi.org/10.1016/j.proeng.2016.10.001>
- Habibi, R., & De Meulder, B. (2015). Architects and 'architecture without architects': modernization of Iranian housing and the birth of a new urban form Narmak (Tehran, 1952). *Cities*, 45, 29-40.
- Habitat, U. (2011). Cities and climate change: Global report on human settlements 2011. *London: Earthscan*.
- Hafeznia, H., Pourfayaz, F., & Maleki, A. (2017). An assessment of Iran's natural gas potential for transition toward low-carbon economy. *Renewable and Sustainable Energy Reviews*, 79(Supplement C), 71-81. doi:<https://doi.org/10.1016/j.rser.2017.05.042>
- Hamin, E. M., & Gurran, N. (2009). Urban form and climate change: Balancing adaptation and mitigation in the US and Australia. *Habitat international*, 33(3), 238-245.
- Hämmerle, M., Gál, T., Unger, J., & Matzarakis, A. (2011). Comparison of models calculating the sky view factor used for urban climate investigations. *Theoretical and applied climatology*, 105(3-4), 521-527.
- Hart, M. A., & Sailor, D. J. (2009). Quantifying the influence of land-use and surface characteristics on spatial variability in the urban heat island. *Theoretical and applied climatology*, 95(3-4), 397-406.
- He, X., Miao, S., Shen, S., Li, J., Zhang, B., Zhang, Z., & Chen, X. (2015). Influence of sky view factor on outdoor thermal environment and physiological equivalent temperature. *International journal of biometeorology*, 59(3), 285-297.
- Hendel, M., Parison, S., Grados, A., & Royon, L. (2018). Which pavement structures are best suited to limiting the UHI effect? A laboratory-scale study of Parisian pavement structures. *Building and environment*, 144, 216-229.

- Herath, H., Halwatura, R., & Jayasinghe, G. (2018a). Evaluation of green infrastructure effects on tropical Sri Lankan urban context as an urban heat island adaptation strategy. *Urban Forestry & Urban Greening*, 29, 212-222.
- Herath, H., Halwatura, R., & Jayasinghe, G. (2018b). Modeling a tropical urban context with green walls and green roofs as an urban heat island adaptation strategy. *Procedia Engineering*, 212, 691-698.
- Herath, H. M. P. I. K., Halwatura, R. U., & Jayasinghe, G. Y. (2018). Modeling a Tropical Urban Context with Green Walls and Green Roofs as an Urban Heat Island Adaptation Strategy. *Procedia Engineering*, 212, 691-698. doi:<https://doi.org/10.1016/j.proeng.2018.01.089>
- Honjo, T., & Takakura, T. (1990). Simulation of thermal effects of urban green areas on their surrounding areas. *Energy and buildings*, 15(3-4), 443-446.
- Hosseini, S. A., Shahraki, S. Z., Farhudi, R., Hosseini, S. M., Salari, M., & Pourahmad, A. (2010). Effect of urban sprawl on a traditional water system (Qanat) in the City of Mashhad, NE Iran. *Urban Water Journal*, 7(5), 309-320.
- Huttner, S. (2012). Further development and application of the 3D microclimate simulation ENVI-met. *Mainz University, Germany*.
- Huttner, S., & Bruse, M. (2009). *Numerical modeling of the urban climate—a preview on ENVI-met 4.0*. Paper presented at the 7th international conference on urban climate ICUC-7, Yokohama, Japan.
- Huttner, S., Bruse, M., & Dostal, P. (2008). *Using ENVI-met to simulate the impact of global warming on the microclimate in central European cities*. Paper presented at the 5th Japanese-German Meeting on Urban Climatology.
- Imran, H. M., Kala, J., Ng, A., & Muthukumaran, S. (2018). Effectiveness of green and cool roofs in mitigating urban heat island effects during a heatwave event in the city of Melbourne in southeast Australia. *Journal of Cleaner Production*, 197, 393-405.
- Imran, H. M., Kala, J., Ng, A., & Muthukumaran, S. (2019). Effectiveness of vegetated patches as Green Infrastructure in mitigating Urban Heat Island effects during a heatwave event in the city of Melbourne. *Weather and Climate Extremes*, 25, 100217.
- Inam, A. (2013). *Designing urban transformation*: Routledge.
- Iran, S. C. o. (2014). <https://www.amar.org.ir/english/Databases-Systems/ICPD>.
- IranMetrologicalOrganization. (2020). Services and Resources. *search based on metrological stations*. Retrieved from http://www.irimo.ir/far/wd/720-%D9%85%D8%AD%D8%B5%D9%88%D9%84%D8%A7%D8%AA-%D8%AE%D8%AF%D9%85%D8%A7%D8%AA.html#report_builder_form
- Irna. (2020). the name of the cultural complex of Azada University Changed. *The Islamic Republic News Agency*. Retrieved from <https://www.irna.ir/news/82391182/%D9%85%D8%AC%D9%85%D9%88%D8%B9%D9%87-%D9%81%D8%B1%D9%87%D9%86%DA%AF%D9%8A-%D8%AF%D8%A7%D9%86%D8%B4%DA%AF%D8%A7%D9%87-%D8%A2%D8%B2%D8%A7%D8%AF-%D8%A7%D8%B3%D9%84%D8%A7%D9%85%D9%8A-%D9%85%D8%B4%D9%87%D8%AF-%D8%A8%D9%87-%D9%86%D8%A7%D9%85-%D8%A2%D9%8A%D8%AA-%D8%A7%D9%84%D9%84%D9%87-%D9%87%D8%A7%D8%B4%D9%85%D9%8A>
- Jabareen, Y. R. (2006). Sustainable urban forms: Their typologies, models, and concepts. *Journal of planning education and research*, 26(1), 38-52.
- Jacobs, A., & Appleyard, D. (1987). Toward an urban design manifesto. *Journal of the American Planning Association*, 53(1), 112-120.
- Jacobs, S. J., Gallant, A. J., Tapper, N. J., & Li, D. (2018). Use of cool roofs and vegetation to mitigate urban heat and improve human thermal stress in Melbourne, Australia. *Journal of Applied Meteorology and Climatology*, 57(8), 1747-1764.

- Jenerette, G. D., Harlan, S. L., Brazel, A., Jones, N., Larsen, L., & Stefanov, W. L. (2007). Regional relationships between surface temperature, vegetation, and human settlement in a rapidly urbanizing ecosystem. *Landscape ecology*, 22(3), 353-365.
- Jenks, M., Burton, E., & Williams, K. (1996). Compact cities and sustainability: an introduction. *The Compact City: a sustainable urban form*, 11-12.
- Johansson, E. (2006). Influence of urban geometry on outdoor thermal comfort in a hot dry climate: A study in Fez, Morocco. *Building and environment*, 41(10), 1326-1338.
- Johansson, E., & Emmanuel, R. (2006). The influence of urban design on outdoor thermal comfort in the hot, humid city of Colombo, Sri Lanka. *International journal of biometeorology*, 51(2), 119-133.
- Jones, P., Jedlovec, G., Suggs, R., & Haines, S. (2004). *Using MODIS LST to estimate minimum air temperatures at night*. Paper presented at the 13th Conference on Satellite Meteorology and Oceanography.
- Kamal-Chaoui, L., & Robert, A. (2009). Competitive cities and climate change.
- Karimi, K. (1997). *The spatial logic of organic cities in Iran and the United Kingdom*. Paper presented at the 1st International Space Syntax Symposium.
- Karimi, M. (2019). [personal communication].
- Karlessi, T., Santamouris, M., Apostolakis, K., Synnefa, A., & Livada, I. (2009). Development and testing of thermochromic coatings for buildings and urban structures. *Solar Energy*, 83(4), 538-551.
- Kato, S., & Yamaguchi, Y. (2005). Analysis of urban heat-island effect using ASTER and ETM+ Data: Separation of anthropogenic heat discharge and natural heat radiation from sensible heat flux. *Remote Sensing of Environment*, 99(1-2), 44-54.
- Kawashima, S., Ishida, T., Minomura, M., & Miwa, T. (2000). Relations between surface temperature and air temperature on a local scale during winter nights. *Journal of Applied Meteorology*, 39(9), 1570-1579.
- Kemp, R., Ion, S., Cumpsty, N., Fisk, D., Jenkins, N., Kelly, M., . . . Roberts, J. (2010). Generating the future: UK energy systems fit for 2050. In: Royal Academy of Engineering.
- Keshtkaran, P. (2011). Harmonization between climate and architecture in vernacular heritage: A case study in Yazd, Iran. *Procedia Engineering*, 21, 428-438.
- Ketterer, C., & Matzarakis, A. (2014). Human-biometeorological assessment of heat stress reduction by replanning measures in Stuttgart, Germany. *Landscape and Urban Planning*, 122, 78-88.
- Keyhani, A., Ghasemi-Varnamkhasti, M., Khanali, M., & Abbaszadeh, R. (2010). An assessment of wind energy potential as a power generation source in the capital of Iran, Tehran. *Energy*, 35(1), 188-201. doi:<https://doi.org/10.1016/j.energy.2009.09.009>
- Kheirabadi, M. (2000). *Iranian cities: formation and development*: Syracuse University Press.
- Kim, J.-P., & Guldmann, J.-M. (2014). Land-use planning and the urban heat island. *Environment and Planning B: Planning and Design*, 41(6), 1077-1099.
- Kim, Y.-H., & Baik, J.-J. (2005). Spatial and temporal structure of the urban heat island in Seoul. *Journal of Applied Meteorology*, 44(5), 591-605.
- Kleerekoper, L., van Esch, M., & Salcedo, T. B. (2012). How to make a city climate-proof, addressing the urban heat island effect. *Resources, Conservation and Recycling*, 64, 30-38.
- Knudstrup, M.-A., Hansen, H. T. R., & Brunsgaard, C. (2009). Approaches to the design of sustainable housing with low CO2 emission in Denmark. *Renewable Energy*, 34(9), 2007-2015.
- Konopacki, S., & Akbari, H. (2002). Energy savings for heat-island reduction strategies in Chicago and Houston (including updates for Baton Rouge, Sacramento, and Salt Lake City).
- Kotharkar, R., & Surawar, M. (2016). Land use, land cover, and population density impact on the formation of canopy urban heat islands through traverse survey in the Nagpur urban area, India. *Journal of Urban Planning and Development*, 142(1), 04015003.
- Kousari, M. R., Ahani, H., & Hendi-zadeh, R. (2013). Temporal and spatial trend detection of maximum air temperature in Iran during 1960–2005. *Global and planetary change*, 111, 97-110.

- Kousari, M. R., & Asadi Zarch, M. A. (2011). Minimum, maximum, and mean annual temperatures, relative humidity, and precipitation trends in arid and semi-arid regions of Iran. *Arabian Journal of Geosciences*, 4(5), 907-914. doi:10.1007/s12517-009-0113-6
- Laukkonen, J., Blanco, P. K., Lenhart, J., Keiner, M., Cavric, B., & Kinuthia-Njenga, C. (2009). Combining climate change adaptation and mitigation measures at the local level. *Habitat international*, 33(3), 287-292.
- Lauwaet, D., De Ridder, K., Saeed, S., Brisson, E., Chatterjee, F., van Lipzig, N. P., . . . Hooyberghs, H. (2016). Assessing the current and future urban heat island of Brussels. *Urban Climate*, 15, 1-15.
- Lee, H., Mayer, H., & Chen, L. (2016). Contribution of trees and grasslands to the mitigation of human heat stress in a residential district of Freiburg, Southwest Germany. *Landscape and Urban Planning*, 148, 37-50.
- Lee, S.-H., Lee, K.-S., Jin, W.-C., & Song, H.-K. (2009). Effect of an urban park on air temperature differences in a central business district area. *Landscape and Ecological Engineering*, 5(2), 183-191.
- Lehmann, S. (2012). Can rapid urbanisation ever lead to low carbon cities? The case of Shanghai in comparison to Potsdamer Platz Berlin. *Sustainable Cities and Society*, 3, 1-12.
- Li, H., Harvey, J., & Kendall, A. (2013). Field measurement of albedo for different land cover materials and effects on thermal performance. *Building and environment*, 59, 536-546.
- Li, J., Song, C., Cao, L., Zhu, F., Meng, X., & Wu, J. (2011). Impacts of landscape structure on surface urban heat islands: A case study of Shanghai, China. *Remote sensing of environment*, 115(12), 3249-3263.
- Li, X.-X., & Norford, L. K. (2016). Evaluation of cool roof and vegetations in mitigating urban heat island in a tropical city, Singapore. *Urban Climate*, 16, 59-74.
- Li, X., Zhou, W., Ouyang, Z., Xu, W., & Zheng, H. (2012). Spatial pattern of greenspace affects land surface temperature: evidence from the heavily urbanized Beijing metropolitan area, China. *Landscape ecology*, 27(6), 887-898.
- Li, Y., Li, Y., Zhang, H., Liu, Y., Xu, W., & Zhu, X. (2011). Canadian experience in low carbon eco-city development and the implications for China. *Energy Procedia*, 5, 1791-1795.
- Lin, T.-P., Matzarakis, A., & Hwang, R.-L. (2010). Shading effect on long-term outdoor thermal comfort. *Building and environment*, 45(1), 213-221.
- Lindberg, F., & Grimmond, C. (2011). The influence of vegetation and building morphology on shadow patterns and mean radiant temperatures in urban areas: model development and evaluation. *Theoretical and applied climatology*, 105(3-4), 311-323.
- Lindberg, F., Holmer, B., & Thorsson, S. (2008). SOLWEIG 1.0—Modelling spatial variations of 3D radiant fluxes and mean radiant temperature in complex urban settings. *International journal of biometeorology*, 52(7), 697-713.
- Liu, C., & Shen, Q. (2011). An empirical analysis of the influence of urban form on household travel and energy consumption. *Computers, Environment and Urban Systems*, 35(5), 347-357.
- Liu, X., & Sweeney, J. (2012). Modelling the impact of urban form on household energy demand and related CO2 emissions in the Greater Dublin Region. *Energy Policy*, 46, 359-369.
- Liu, Z., Yu, J., & Zhang, D. (2011). Study on low-carbon building ecological city construction in harmonious Beibu Gulf culture. *Procedia Environmental Sciences*, 10(Part C), 1881-1886.
- López, C. S. P., Sala, M., Tagliabue, L. C., Frontini, F., & Bouziri, S. (2016). Solar radiation and daylighting assessment using the sky-view factor (SVF) analysis as method to evaluate urban planning densification policies impacts. *Energy Procedia*, 91, 989-996.
- Loughner, C. P., Allen, D. J., Zhang, D.-L., Pickering, K. E., Dickerson, R. R., & Landry, L. (2012). Roles of urban tree canopy and buildings in urban heat island effects: Parameterization and preliminary results. *Journal of Applied Meteorology and Climatology*, 51(10), 1775-1793.
- Lynch, K. (1984). *Good city form*: MIT press.

- Ma, Y., Zhang, X., Zhu, B., & Wu, K. (2002). Research on reversible effects and mechanism between the energy-absorbing and energy-reflecting states of chameleon-type building coatings. *Solar Energy*, 72(6), 511-520.
- Maas, J., Verheij, R. A., Groenewegen, P. P., De Vries, S., & Spreeuwenberg, P. (2006). Green space, urbanity, and health: how strong is the relation? *Journal of Epidemiology & Community Health*, 60(7), 587-592.
- MacKillop, F. (2012). Climatic city: Two centuries of urban planning and climate science in Manchester (UK) and its region. *Cities*, 29(4), 244-251.
- Madanipour, A. (1996). Urban design and dilemmas of space. *Environment and planning D: Society and Space*, 14(3), 331-355.
- Madanipour, A. (1998). *Tehran: the making of a metropolis*: Academy Press.
- Marefat, M. (1988). *Building to power: architecture of Tehran 1921-1941*. Massachusetts Institute of Technology,
- Massetti, L., Petralli, M., Napoli, M., Brandani, G., Orlandini, S., & Pearlmutter, D. (2019). Effects of deciduous shade trees on surface temperature and pedestrian thermal stress during summer and autumn. *International journal of biometeorology*, 63(4), 467-479.
- Matzarakis, A., & Matuschek, O. (2011). Sky View Factor as a parameter in applied climatology—Rapid estimation by the SkyHelios Model. *Meteorologische Zeitschrift*, 20(1), 39-45.
- Matzarakis, A., Rutz, F., & Mayer, H. (2007). Modelling radiation fluxes in simple and complex environments—application of the RayMan model. *International journal of biometeorology*, 51(4), 323-334.
- Matzarakis, A., Rutz, F., & Mayer, H. (2010). Modelling radiation fluxes in simple and complex environments: basics of the RayMan model. *International journal of biometeorology*, 54(2), 131-139.
- May, P. B., Livesley, S. J., & Shears, I. (2013). Managing and monitoring tree health and soil water status during extreme drought in Melbourne, Victoria. *Arboricult Urban For*, 39, 136-145.
- McPherson, G., Simpson, J. R., Peper, P. J., Maco, S. E., Xiao, Q., & Mulrean, E. (2004). Desert southwest community tree guide: benefits, costs and strategic planting. *Arizona Community Tree Council, Inc. Phoenix, AZ*.
- Memarian, G. (1993). An introduction to house typology in Iran: Courtyard houses. *Tehran: Iran University of Science and Technology*.
- Memon, R. A., Leung, D. Y., & Liu, C.-H. (2009). An investigation of urban heat island intensity (UHII) as an indicator of urban heating. *Atmospheric Research*, 94(3), 491-500.
- Miaomiao, X., Yanglin, W., & Meichen, F. (2011). An overview and perspective about causative factors of surface urban heat island effects. *Progress in Geography*, 30(1), 35-41.
- Middel, A., Häb, K., Brazel, A. J., Martin, C. A., & Guhathakurta, S. (2014). Impact of urban form and design on mid-afternoon microclimate in Phoenix Local Climate Zones. *Landscape and Urban Planning*, 122, 16-28.
- Middel, A., Lukasczyk, J., Maciejewski, R., Demuzere, M., & Roth, M. (2018). Sky view factor footprints for urban climate modeling. *Urban climate*, 25, 120-134.
- Middleton, R. (1983). I. THE USE AND ABUSE OF TRADITION IN ARCHITECTURE. *Journal of the royal society of arts*, 131(5328), 729-739.
- Mills, G., Cleugh, H., Emmanuel, R., Endlicher, W., Erell, E., McGranahan, G., . . . Steemer, K. (2010). Climate information for improved planning and management of mega cities (needs perspective). *Procedia Environmental Sciences*, 1, 228-246.
- Mirzaei, P. A., & Haghighat, F. (2010). Approaches to study urban heat island—abilities and limitations. *Building and environment*, 45(10), 2192-2201.
- Modarres, R., & Sarhadi, A. (2009). Rainfall trends analysis of Iran in the last half of the twentieth century. *Journal of Geophysical Research: Atmospheres*, 114(D3), n/a-n/a. doi:10.1029/2008JD010707
- Modiri, Hayati, Salman, & Moghdam, R. (2017). Metropolitan spatial development pattern analysis

- and risk factors in Mashhad. *Urban Management*, 16(46), 7-22.
- Moghbel, M., & Shamsipour, A. (2019). Spatiotemporal characteristics of urban land surface temperature and UHI formation: a case study of Tehran, Iran. *Theoretical and applied climatology*, 137(3-4), 2463-2476.
- Mohajerani, A., Bakaric, J., & Jeffrey-Bailey, T. (2017). The urban heat island effect, its causes, and mitigation, with reference to the thermal properties of asphalt concrete. *Journal of environmental management*, 197, 522-538.
- Mohan, M., Kikegawa, Y., Gurjar, B., Bhati, S., & Kolli, N. R. (2013). Assessment of urban heat island effect for different land use–land cover from micrometeorological measurements and remote sensing data for megacity Delhi. *Theoretical and applied climatology*, 112(3-4), 647-658.
- Mollahosseini, A., Hosseini, S. A., Jabbari, M., Figoli, A., & Rahimpour, A. (2017). Renewable energy management and market in Iran: A holistic review on current state and future demands. *Renewable and Sustainable Energy Reviews*, 80(Supplement C), 774-788. doi:<https://doi.org/10.1016/j.rser.2017.05.236>
- Monteith, J., & Unsworth, M. (2013). *Principles of environmental physics: plants, animals, and the atmosphere*: Academic Press.
- Morakinyo, T. E., & Lam, Y. F. (2016). Simulation study on the impact of tree-configuration, planting pattern and wind condition on street-canyon's micro-climate and thermal comfort. *Building and environment*, 103, 262-275. doi:<https://doi.org/10.1016/j.buildenv.2016.04.025>
- MORELLO, E., Gori, V., Balocco, C., & Ratti, C. (2009). *Sustainable urban block design through passive architecture: A tool that uses urban geometry optimization to compute energy savings*. Paper presented at the PLEA 2009.
- Morini, E., Touchaei, A. G., Castellani, B., Rossi, F., & Cotana, F. (2016). The impact of albedo increase to mitigate the urban heat island in Terni (Italy) using the WRF model. *Sustainability*, 8(10), 999.
- Mosammam, H. M., Nia, J. T., Khani, H., Teymouri, A., & Kazemi, M. (2016). Monitoring land use change and measuring urban sprawl based on its spatial forms: The case of Qom city. *The Egyptian Journal of Remote Sensing and Space Science*.
- Mostovoy, G. V., King, R. L., Reddy, K. R., Kakani, V. G., & Filippova, M. G. (2006). Statistical estimation of daily maximum and minimum air temperatures from MODIS LST data over the state of Mississippi. *GIScience & Remote Sensing*, 43(1), 78-110.
- Motealleh, P., Zolfaghari, M., & Parsaee, M. (2016). Investigating climate responsive solutions in vernacular architecture of Bushehr city. *HBRC Journal*.
- Moudon, A. V. (1997). Urban morphology as an emerging interdisciplinary field. *Urban morphology*, 1(1), 3-10.
- Moughtin, C. (2003). *Urban design: street and square*: Routledge.
- Mousavi Baigi, S., Ashraf, f., Farid Hoseini, A., & Mianabadi, A. (2012). Study of Urban Heat Island of Mashhad using Satellite Images and Fractal Theory). *Geography and environmental hazards*, 1(1), 35-49.
- Müller, N., Kuttler, W., & Barlag, A.-B. (2014). Counteracting urban climate change: adaptation measures and their effect on thermal comfort. *Theoretical and applied climatology*, 115(1-2), 243-257.
- Murphy, D. J., Hall, M. H., Hall, C. A., Heisler, G. M., Stehman, S. V., & Anselmi-Molina, C. (2011). The relationship between land cover and the urban heat island in northeastern Puerto Rico. *International Journal of Climatology*, 31(8), 1222-1239.
- Nakata-Osaki, C. M., Souza, L. C. L., & Rodrigues, D. S. (2018). THIS–Tool for Heat Island Simulation: A GIS extension model to calculate urban heat island intensity based on urban geometry. *Computers, Environment and Urban Systems*, 67, 157-168.
- Nakhaei Moghaddam, M., Sargazi, S., & Malek, H. (2008). *Study of limiting factors in urban landscape expansion of Sistan*. Paper presented at the The 3rd National Congress on Urban Landscape and Green Space. Kish Island.

- Naserikia, M., Asadi Shamsabadi, E., Rafieian, M., & Leal Filho, W. (2019). The urban heat island in an urban context: A case study of Mashhad, Iran. *International journal of environmental research and public health*, 16(3), 313.
- Nasir, D. S., Hughes, B. R., Calautit, J. K., Aquino, A. I., & Shahzad, S. (2017). Effect of urban street canyon aspect ratio on thermal performance of road pavement solar collectors (RPSC). *Energy Procedia*, 105, 4414-4419.
- Nejat, P., Jomehzadeh, F., Taheri, M. M., Gohari, M., & Abd. Majid, M. Z. (2015). A global review of energy consumption, CO2 emissions and policy in the residential sector (with an overview of the top ten CO2 emitting countries). *Renewable and Sustainable Energy Reviews*, 43(Supplement C), 843-862. doi:<https://doi.org/10.1016/j.rser.2014.11.066>
- Newman, P. G., & Kenworthy, J. R. (1989). *Cities and automobile dependence: An international sourcebook*.
- News, T. (2020). Historical buildings in Kashan. Retrieved from <https://www.tasnimnews.com/fa/news/1399/05/11/2318376/%DA%A9%D8%A7%D8%B4%D8%A7%D9%86-%D8%A8%DB%8C%D8%B4-%D8%A7%D8%B2-1000-%D8%A7%D8%AB%D8%B1-%D8%AA%D8%A7%D8%B1%DB%8C%D8%AE%DB%8C-%D8%AF%D8%A7%D8%B1%D8%AF-%D8%A7%D8%B9%D8%AA%D8%A8%D8%A7%D8%B1%D8%A7%D8%AA-%D9%88%D8%B2%D8%A7%D8%B1%D8%AA%D8%AE%D8%A7%D9%86%D9%87-%D8%A7%DB%8C-%D8%A8%D8%B1%D8%A7%DB%8C-%D8%A2%D8%AB%D8%A7%D8%B1-%D8%AA%D8%A7%D8%B1%DB%8C%D8%AE%DB%8C-%DA%A9%D8%A7%D8%B4%D8%A7%D9%86-%D9%85%DA%A9%D9%81%DB%8C-%D9%86%DB%8C%D8%B3%D8%AA>
- Nuruzzaman, M. (2015). Urban heat island: causes, effects and mitigation measures-a review. *International Journal of Environmental Monitoring and Analysis*, 3(2), 67-73.
- O'Malley, C., Piroozfar, P., Farr, E. R., & Pomponi, F. (2015). Urban Heat Island (UHI) mitigating strategies: A case-based comparative analysis. *Sustainable Cities and Society*, 19, 222-235.
- Oke, R. (1997). Urban climate and global environmental change. *Applied climatology*, 273-287.
- Oke, T. (1995). The heat island of the urban boundary layer: characteristics, causes and effects. In *Wind climate in cities* (pp. 81-107): Springer.
- Oke, T. R. (1981). Canyon geometry and the nocturnal urban heat island: comparison of scale model and field observations. *Journal of climatology*, 1(3), 237-254.
- Oke, T. R. (1988). The urban energy balance. *Progress in Physical geography*, 12(4), 471-508.
- Oke, T. R. (2002). *Boundary layer climates*: Routledge.
- Oliveira, V. (2016). *Urban morphology: an introduction to the study of the physical form of cities*: Springer.
- Order, F. S. (2020). Bagheri House. Retrieved from <http://orc.sellfile.ir/prod-2012246-%D9%BE%D8%A7%D9%88%D8%B1%D9%BE%D9%88%DB%8C%D9%86%D8%AA+%D8%AE%D8%A7%D9%86%D9%87+%D8%A8%D8%A7%D9%82%D8%B1%DB%8C+%D9%87%D8%A7+%DA%AF%D8%B1%DA%AF%D8%A7%D9%86+%D8%A8%D9%87+%D9%87%D9%85%D8%B1%D8%A7%D9%87+%D9%86%D9%82%D8%B4%D9%87+%DA%A9%D8%A7%D9%85%D9%84++%D8%A7%D8%AA%D9%88%DA%A9%D8%AF+%D8%A8%D9%86%D8%A7.html>
- Palme, M., Lobato, A., & Carrasco, C. (2016). Quantitative analysis of factors contributing to urban heat island effect in cities of latin-American Pacific coast. *Procedia Engineering*, 169, 199-206.
- Park, S., & Tuller, S. E. (2014). Advanced view factor analysis method for radiation exchange. *International journal of biometeorology*, 58(2), 161-178.
- Parshall, L., Gurney, K., Hammer, S. A., Mendoza, D., Zhou, Y., & Geethakumar, S. (2010). Modeling energy consumption and CO2 emissions at the urban scale: Methodological challenges and insights from the United States. *Energy Policy*, 38(9), 4765-4782.
- Pearlmutter, D., Bitan, A., & Berliner, P. (1999). Microclimatic analysis of "compact" urban canyons in an arid zone. *Atmospheric Environment*, 33(24-25), 4143-4150.

- Pebbley, A., & Sastry, N. (2009). Our place: perceived neighborhood size and names in Los Angeles. *UCLA CCPR Population Working Papers*.
- Peng, L. L., & Jim, C. Y. (2015). Seasonal and diurnal thermal performance of a subtropical extensive green roof: The impacts of background weather parameters. *Sustainability*, 7(8), 11098-11113.
- Perini, K., Chokhachian, A., Dong, S., & Auer, T. (2017). Modeling and simulating urban outdoor comfort: Coupling ENVI-Met and TRNSYS by grasshopper. *Energy and buildings*, 152, 373-384. doi:<https://doi.org/10.1016/j.enbuild.2017.07.061>
- Perini, K., & Magliocco, A. (2014). Effects of vegetation, urban density, building height, and atmospheric conditions on local temperatures and thermal comfort. *Urban Forestry & Urban Greening*, 13(3), 495-506.
- Persia, T. (2017). The average life span of a building is 25 years in Iran; one-third of the global standard. Retrieved from <https://www.trackpersia.com/average-life-span-building-25-years-iran-one-third-global-standard/>
- Persianguig. (2020). Retrieved from <http://idetak.persianguig.com/image/%D8%B9%DA%A9%D8%B3%D9%87%D8%A7%DB%8C%20%D9%87%D9%88%D8%A7%DB%8C%DB%8C%20%D9%85%D8%B4%D9%87%D8%AF/%d8%a8%d9%84%d9%88%d8%a7%d8%b1%20%D9%88%D9%83%D9%8a%D9%84%20%D8%a2%D8%a8%D8%a7%D8%af.jpg>
- Pirnia, M. K. (2004). Stylistics of Iranian architecture. *Memar Publication, Tehran*.
- Pourab, M. (2020). Mashhad Parnoma. Retrieved from <https://cdn.isna.ir/d/off-old/Khorasan-Razavi/Files/News/Image/13978/210061.jpg>
- Prada, S., Cruz, J. V., & Figueira, C. (2016). Using stable isotopes to characterize groundwater recharge sources in the volcanic island of Madeira, Portugal. *Journal of Hydrology*, 536, 409-425. doi:<https://doi.org/10.1016/j.jhydrol.2016.03.009>
- Prasad, D. K., & Samuels, R. (2013). *Global warming and the built environment*: Spon Press.
- Prihodko, L., & Goward, S. N. (1997). Estimation of air temperature from remotely sensed surface observations. *Remote Sensing of Environment*, 60(3), 335-346.
- Priyadarsini, R., Hien, W. N., & David, C. K. W. (2008). Microclimatic modeling of the urban thermal environment of Singapore to mitigate urban heat island. *Solar energy*, 82(8), 727-745.
- Prospectus, W. U. (2003, 2008). <http://www.un.org/esa/population/publications/wup2003/2003WUPHighlights.pdf>.
- Puurunen, E., & Organschi, A. (2013). Multiplier Effect: High Performance Construction Assemblies and Urban Density in US Housing. In *Mitigating Climate Change* (pp. 183-206): Springer.
- Qaid, A., & Ossen, D. R. (2015). Effect of asymmetrical street aspect ratios on microclimates in hot, humid regions. *International journal of biometeorology*, 59(6), 657-677.
- QasemAbad. (2020). QasemAbad photos. *Facebook*. Retrieved from https://www.facebook.com/QasmAbad/about/?ref=page_internal
- Qin, Y. (2015). A review on the development of cool pavements to mitigate urban heat island effect. *Renewable and sustainable energy reviews*, 52, 445-459.
- Raeissi, S., & Taheri, M. (1999). Energy saving by proper tree plantation. *Building and environment*, 34(5), 565-570.
- Rafiee, A., Dias, E., & Koomen, E. (2016). Local impact of tree volume on nocturnal urban heat island: A case study in Amsterdam. *Urban forestry & urban greening*, 16, 50-61.
- Rafiee, R. (2007). Site selection for waste transfer station with regard to urban growth trend (Mashad Case Study). *Unpublished M. Sc. Thesis, University of Tehran*.
- Rafiee, R., Mahiny, A. S., & Khorasani, N. (2009). Assessment of changes in urban green spaces of Mashad city using satellite data. *International Journal of Applied Earth Observation and Geoinformation*, 11(6), 431-438.

- Rafieian, M., Rad, H. R., & Sharifi, A. (2014). *The necessity of using Sky View Factor in urban planning: A case study of Narmak neighborhood, Tehran*. Paper presented at the 2014 International Conference and Utility Exhibition on Green Energy for Sustainable Development (ICUE).
- Rahnama, M. R., & Razzaghian, F. (2012). Ecological analysis of urban parks; case study: Mashhad Metropolitan. *International Journal of Applied Science and Technology*, 2.
- Ramyar, R., Zarghami, E., & Bryant, M. (2019). Spatio-temporal planning of urban neighborhoods in the context of global climate change: Lessons for urban form design in Tehran, Iran. *Sustainable Cities and Society*, 51, 101554.
- Rasmussen, S. E. (1964). *Experiencing architecture* (Vol. 2): MIT press.
- Razzaghian, F., & Aghajani, H. (2016). Evaluating and land-use locating of city parks using network analysis (Case study: Mashhad Metropolis, Iran). *International Journal of Applied*, 6(4).
- Razzaghmanesh, M., Beecham, S., & Salemi, T. (2016). The role of green roofs in mitigating Urban Heat Island effects in the metropolitan area of Adelaide, South Australia. *Urban Forestry & Urban Greening*, 15, 89-102. doi:<https://doi.org/10.1016/j.ufug.2015.11.013>
- reddit. Imam Reza Shrine, Mashhad, Iran. Retrieved from https://www.reddit.com/r/CityPorn/comments/4nacba/1100x1043_imam_reza_shrine_mashhad_iran/?utm_source=ifttt
- Rizwan, A. M., Dennis, L. Y., & Chunho, L. (2008). A review on the generation, determination and mitigation of Urban Heat Island. *Journal of Environmental Sciences*, 20(1), 120-128.
- Roaf, S. (1982). Wind catchers, living with the desert. *Airs & Philips, London*.
- Robitu, M., Musy, M., Inard, C., & Groleau, D. (2006). Modeling the influence of vegetation and water pond on urban microclimate. *Solar energy*, 80(4), 435-447.
- Roman, K. K., O'Brien, T., Alvey, J. B., & Woo, O. (2016). Simulating the effects of cool roof and PCM (phase change materials) based roof to mitigate UHI (urban heat island) in prominent US cities. *Energy*, 96, 103-117.
- Rosenfeld, A. H., Akbari, H., Bretz, S., Sailor, D., & Taha, H. (1993). Mitigation of urban heat islands: materials, utility programs: update. *Journal of Energy efficiency*, 1(1), 1-20.
- Rosenfeld, A. H., Akbari, H., Romm, J. J., & Pomerantz, M. (1998). Cool communities: strategies for heat island mitigation and smog reduction. *Energ. Build.* 1998, 28, 51, 62.
- Roshan, G., & Nastos, P. T. (2017). Assessment of extreme heat stress probabilities in Iran's urban settlements, using first order Markov chain model. *Sustainable Cities and Society*.
- Roth, M., & Lim, V. H. (2017). Evaluation of canopy-layer air and mean radiant temperature simulations by a microclimate model over a tropical residential neighbourhood. *Building and environment*, 112, 177-189.
- Roy, M. (2009). Planning for sustainable urbanisation in fast growing cities: Mitigation and adaptation issues addressed in Dhaka, Bangladesh. *Habitat International*, 33(3), 276-286.
- Rubel, F., & Kottek, M. (2010). Observed and projected climate shifts 1901–2100 depicted by world maps of the Köppen-Geiger climate classification. *Meteorologische Zeitschrift*, 19(2), 135-141.
- Rudlin, D., & Falk, N. (2009). *Sustainable Urban Neighbourhood: building the 21st century home*: Routledge.
- Ryu, Y.-H., & Baik, J.-J. (2012). Quantitative analysis of factors contributing to urban heat island intensity. *Journal of Applied Meteorology and Climatology*, 51(5), 842-854.
- Salehifard, M., Khakpour, B., Rafiei, H., & Tavangar, M. (2010). The analysis of social dimension of municipal parks with an emphasis on citizens' opinions (case study: Mashhad metropolis).
- Salvati, A., Palme, M., & Inostroza, L. (2017). Key parameters for urban heat island assessment in a Mediterranean context: A sensitivity analysis using the Urban Weather Generator model.
- Santamouris, M. (2013). *Energy and climate in the urban built environment*: Routledge.
- Savi, T., Bertuzzi, S., Branca, S., Tretiach, M., & Nardini, A. (2015). Drought-induced xylem cavitation and hydraulic deterioration: risk factors for urban trees under climate change? *New Phytologist*, 205(3), 1106-1116.

- Sawka, M., Millward, A. A., McKay, J., & Sarkovich, M. (2013). Growing summer energy conservation through residential tree planting. *Landscape and Urban Planning*, 113, 1-9.
- Schrijvers, P., Jonker, H., Kenjereš, S., & de Roode, S. (2015). Breakdown of the night time urban heat island energy budget. *Building and environment*, 83, 50-64.
- Scientists, U. o. C. (2020, 12/08/2020). Each Country's Share of CO2 Emissions. Retrieved from <https://www.ucsusa.org/resources/each-countrys-share-co2-emissions>
- Seelig, S. (2011). A master plan for low carbon and resilient housing: The 35ha area in Hashtgerd New Town, Iran. *Cities*, 28(6), 545-556.
- Shabahang, S., Gjerde, M., Vale, B., & Balador, Z. (2018). *The Problem of Lack of Green Space and Rise in Surface Temperature in the City of Mashhad*. Paper presented at the International Conference on Sustainability in Energy and Buildings.
- Shabahang, S., Vale, B., & Gjerde, M. (2018). *The Problem of the Modern Built Environment and Enhanced Urban Warming in Iran*. Paper presented at the International Conference on Sustainability in Energy and Buildings.
- Shahraki, S. Z., Sauri, D., Serra, P., Modugno, S., Seifolddini, F., & Pourahmad, A. (2011). Urban sprawl pattern and land-use change detection in Yazd, Iran. *Habitat International*, 35(4), 521-528.
- Shahraraonline. (2015). only 30% of district plan goals will fulfill best case scenarios. Retrieved from <http://shahraraonline.ir/final/site/news-content.php/52873?id=52873>
- shargh, N. (2020). What is the difference between balcony and Ivan. Retrieved from <https://neginshargh.com/%D8%AA%D9%81%D8%A7%D9%88%D8%AA-%D8%A8%D8%A7%D9%84%DA%A9%D9%86-%D9%88-%D8%AA%D8%B1%D8%A7%D8%B3-%DA%86%DB%8C%D8%B3%D8%AA-%D8%9F/>
- Sharifi, A., & Murayama, A. (2013). Changes in the traditional urban form and the social sustainability of contemporary cities: A case study of Iranian cities. *Habitat International*, 38, 126-134.
- Sharma, A., Conry, P., Fernando, H., Hamlet, A. F., Hellmann, J., & Chen, F. (2016). Green and cool roofs to mitigate urban heat island effects in the Chicago metropolitan area: Evaluation with a regional climate model. *Environmental Research Letters*, 11(6), 064004.
- Shashua-Bar, L., & Hoffman, M. E. (2000). Vegetation as a climatic component in the design of an urban street: An empirical model for predicting the cooling effect of urban green areas with trees. *Energy and buildings*, 31(3), 221-235.
- Shashua-Bar, L., & Hoffman, M. E. (2003). Geometry and orientation aspects in passive cooling of canyon streets with trees. *Energy and buildings*, 35(1), 61-68.
- Sheppard, M. (2015). *Essentials of urban design*: Csiro Publishing.
- Sherafati, S., Saradjian, M., & Niazmardi, S. (2013). Urban heat island growth modeling using artificial neural networks and support vector regression: a case study of Tehran, Iran. *ISPRS-International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, XL-1/W3, 399-403.
- Shirani-Bidabadi, N., Nasrabadi, T., Faryadi, S., Larijani, A., & Roodposhti, M. S. (2019). Evaluating the spatial distribution and the intensity of urban heat island using remote sensing, case study of Isfahan city in Iran. *Sustainable Cities and Society*, 45, 686-692.
- Shishegar, N. (2013). Street design and urban microclimate: analyzing the effects of street geometry and orientation on airflow and solar access in urban canyons. *Journal of clean energy technologies*, 1(1).
- Shooshtarian, S. (2010). *Physiological and ecological investigation of some groundcover plants in green space of Kish Island*. Msc Thesis, Shiraz University. 168p,
- Simon, H., Lindén, J., Hoffmann, D., Braun, P., Bruse, M., & Esper, J. (2018a). Modeling transpiration and leaf temperature of urban trees—a case study evaluating the microclimate model ENVI-met against measurement data. *Landscape and Urban Planning*, 174, 33-40.
- Simon, H., Lindén, J., Hoffmann, D., Braun, P., Bruse, M., & Esper, J. (2018b). Modeling transpiration and leaf temperature of urban trees – A case study evaluating the microclimate model ENVI-

- met against measurement data. *Landscape and Urban Planning*, 174, 33-40. doi:<https://doi.org/10.1016/j.landurbplan.2018.03.003>
- Simpson, J. R. (2002). Improved estimates of tree-shade effects on residential energy use. *Energy and buildings*, 34(10), 1067-1076.
- Simpson, J. R., & McPherson, E. G. (1996). Potential of tree shade for reducing residential energy use in California. *Journal of Arboriculture*, 22, 10-18.
- Sitte, C. (1986). *City planning according to artistic principles*.
- Skelhorn, C. P., Levermore, G., & Lindley, S. J. (2016). Impacts on cooling energy consumption due to the UHI and vegetation changes in Manchester, UK. *Energy and buildings*, 122, 150-159.
- Soflaei, F., Shokouhian, M., & Zhu, W. (2017). Socio-environmental sustainability in traditional courtyard houses of Iran and China. *Renewable and Sustainable Energy Reviews*, 69(Supplement C), 1147-1169. doi:<https://doi.org/10.1016/j.rser.2016.09.130>
- Sola, A., Corchero, C., Salom, J., & Sanmarti, M. (2018). Simulation tools to build urban-scale energy models: A review. *Energies*, 11(12), 3269.
- Soleymanpour, R., Parsaee, N., & Banaei, M. (2015). Climate comfort comparison of vernacular and contemporary houses of Iran. *Procedia-Social and Behavioral Sciences*, 201, 49-61.
- Soltani, A., Hosseinpour, M., & Hajizadeh, A. (2017). Urban Sprawl in Iranian Medium-sized Cities; Investigating the Role of Masterplans. *Journal of Sustainable Development*, 10(1), 122.
- Soltanifard, H., & Aliabadi, K. (2019). Impact of urban spatial configuration on land surface temperature and urban heat islands: a case study of Mashhad, Iran. *Theoretical and applied climatology*, 137(3-4), 2889-2903.
- Spark, W. (2020). Average Weather in July in Mashhad Iran. Retrieved from <https://weatherspark.com/m/105881/7/Average-Weather-in-July-in-Mashhad-Iran>
- Spronken-Smith, R. A., Oke, T. R., & Lowry, W. P. (2000). Advection and the surface energy balance across an irrigated urban park. *International Journal of Climatology: A Journal of the Royal Meteorological Society*, 20(9), 1033-1047.
- Stanley, C. H., Helletsgruber, C., & Hof, A. (2019). Mutual Influences of Urban Microclimate and Urban Trees: An Investigation of Phenology and Cooling Capacity. *Forests*, 10(7), 533.
- Stern, N., & Stern, N. H. (2007). *The economics of climate change: the Stern review*: cambridge University press.
- Stewart, I. D., & Oke, T. R. (2010). *Thermal differentiation of local climate zones using temperature observations from urban and rural field sites*. Paper presented at the Ninth symposium on urban environment, Keystone, CO.
- Stewart, I. D., & Oke, T. R. (2012). Local climate zones for urban temperature studies. *Bulletin of the American Meteorological Society*, 93(12), 1879-1900.
- Stocker, T., Qin, D., Plattner, G., Tignor, M., Allen, S., Boschung, J., . . . Midgley, P. (2013). IPCC, 2013: summary for policymakers in climate change 2013: the physical science basis, contribution of working group I to the fifth assessment report of the intergovernmental panel on climate change. In: Cambridge University Press, Cambridge, New York, USA.
- Stone Jr, B., & Rodgers, M. O. (2001). Urban form and thermal efficiency: how the design of cities influences the urban heat island effect. *American Planning Association. Journal of the American Planning Association*, 67(2), 186.
- Su, W., Gu, C., & Yang, G. (2010). Assessing the impact of land use/land cover on urban heat island pattern in Nanjing City, China. *Journal of Urban Planning and Development*, 136(4), 365-372.
- Susca, T. (2012). Multiscale Approach to Life Cycle Assessment: Evaluation of the Effect of an Increase in New York City's Rooftop Albedo on Human Health. *Journal of Industrial Ecology*, 16(6), 951-962.
- Svensson, M. K. (2004). Sky view factor analysis—implications for urban air temperature differences. *Meteorological applications*, 11(3), 201-211.
- Swanwick, C., Dunnett, N., & Woolley, H. (2003). Nature, role and value of green space in towns and cities: An overview. *Built Environment (1978-)*, 94-106.

- Taha, H. (1997). Urban climates and heat islands: albedo, evapotranspiration, and anthropogenic heat. *Energy and buildings*, 25(2), 99-103.
- Taha, H., Sailor, D. J., & Akbari, H. (1992). High-albedo materials for reducing building cooling energy use.
- Takahashi, K., Yoshida, H., Tanaka, Y., Aotake, N., & Wang, F. (2004). Measurement of thermal environment in Kyoto city and its prediction by CFD simulation. *Energy and buildings*, 36(8), 771-779.
- Tan, Z., Lau, K. K.-L., & Ng, E. (2016). Urban tree design approaches for mitigating daytime urban heat island effects in a high-density urban environment. *Energy and buildings*, 114, 265-274.
- Tao, Z. (2011). Strategy of city development in low-carbon economic mode-a case study on Qingdao. *Energy Procedia*, 5, 926-932.
- Thomas, D. S., & Twyman, C. (2005). Equity and justice in climate change adaptation amongst natural-resource-dependent societies. *Global environmental change*, 15(2), 115-124.
- Tol, R. S. (2005). Adaptation and mitigation: trade-offs in substance and methods. *Environmental Science & Policy*, 8(6), 572-578.
- Toparlar, Y., Blocken, B., Maiheu, B., & Van Heijst, G. (2017). A review on the CFD analysis of urban microclimate. *Renewable and Sustainable Energy Reviews*, 80, 1613-1640.
- Toparlar, Y., Blocken, B., Vos, P., van Heijst, G. J. F., Janssen, W. D., van Hooff, T., . . . Timmermans, H. J. P. (2015). CFD simulation and validation of urban microclimate: A case study for Bergpolder Zuid, Rotterdam. *Building and environment*, 83, 79-90.
doi:<https://doi.org/10.1016/j.buildenv.2014.08.004>

- Wang, X.-J. (2009). Analysis of problems in urban green space system planning in China. *Journal of Forestry Research*, 20(1), 79-82. doi:10.1007/s11676-009-0014-2
- Wang, Y., & Akbari, H. (2014). Effect of sky view factor on outdoor temperature and comfort in Montreal. *Environmental Engineering Science*, 31(6), 272-287.
- Wang, Y., & Akbari, H. (2015). Development and application of 'thermal radiative power' for urban environmental evaluation. *Sustainable Cities and Society*, 14, 316-322. doi:<https://doi.org/10.1016/j.scs.2014.07.003>
- Wang, Y., & Akbari, H. (2016). The effects of street tree planting on Urban Heat Island mitigation in Montreal. *Sustainable Cities and Society*, 27, 122-128. doi:<https://doi.org/10.1016/j.scs.2016.04.013>
- Wang, Y., Berardi, U., & Akbari, H. (2016). Comparing the effects of urban heat island mitigation strategies for Toronto, Canada. *Energy and buildings*, 114, 2-19. doi:<https://doi.org/10.1016/j.enbuild.2015.06.046>
- Wang, Z.-H., Zhao, X., Yang, J., & Song, J. (2016). Cooling and energy saving potentials of shade trees and urban lawns in a desert city. *Applied Energy*, 161, 437-444.
- Watkins, R., Palmer, J., & Kolokotroni, M. (2007). Increased temperature and intensification of the urban heat island: implications for human comfort and urban design. *Built Environment*, 33(1), 85-96.
- Watson, I., & Johnson, G. (1987). Graphical estimation of sky view-factors in urban environments. *Journal of climatology*, 7(2), 193-197.
- Weather, E. D. (2020). Mashhad Iran Yearly Climate Temperature and Precipitation. Retrieved from <https://www.eldoradoweather.com/climate/iran/Mashhad.html>
- Wenting, W., Yi, R., & Hengyu, Z. (2012). Investigation on temperature dropping effect of urban green space in summer in Hangzhou. *Energy Procedia*, 14, 217-222.
- Wheeler, S. M., & Beatley, T. (2014). *Sustainable urban development reader*: Routledge.
- Whitford, V., Ennos, A. R., & Handley, J. F. (2001). "City form and natural process"—indicators for the ecological performance of urban areas and their application to Merseyside, UK. *Landscape and Urban Planning*, 57(2), 91-103.
- Wikipedia. (2016). Retrieved from https://en.wikipedia.org/wiki/Mashhad#/media/File:Mashhad_entrance_at_the_end_of_Noruz_holidays_03.jpg
- Williams, K., Burton, E., & Jenks, M. (1996). Achieving the compact city through intensification: An acceptable option. *The Compact City: a sustainable urban form*, 83-96.
- Williamson, T. J., Williamson, T., Radford, A., & Bennetts, H. (2003). *Understanding sustainable architecture*: Taylor & Francis.
- Wolch, J. R., Byrne, J., & Newell, J. P. (2014). Urban green space, public health, and environmental justice: The challenge of making cities 'just green enough'. *Landscape and Urban Planning*, 125, 234-244.
- Yang, F., Lau, S. S., & Qian, F. (2011). Thermal comfort effects of urban design strategies in high-rise urban environments in a sub-tropical climate. *Architectural Science Review*, 54(4), 285-304.
- Yang, J., Wang, Z.-H., & Kaloush, K. E. (2015). Environmental impacts of reflective materials: Is high albedo a 'silver bullet' for mitigating urban heat island? *Renewable and Sustainable Energy Reviews*, 47, 830-843.
- Yang, X., Zhao, L., Bruse, M., & Meng, Q. (2013). Evaluation of a microclimate model for predicting the thermal behavior of different ground surfaces. *Building and environment*, 60, 93-104.
- Ye, H., He, X., Song, Y., Li, X., Zhang, G., Lin, T., & Xiao, L. (2015). A sustainable urban form: The challenges of compactness from the viewpoint of energy consumption and carbon emission. *Energy and buildings*, 93, 90-98.
- Yoshida, A., Tominaga, K., & Watatani, S. (1990). Field measurements on energy balance of an urban canyon in the summer season. *Energy and buildings*, 15(3-4), 417-423.

- Yoshino, M. M., & Yoshino, M. (1975). *Climate in a small area: an introduction to local meteorology*: University of Tokyo press.
- Yu, C., & Hien, W. N. (2006). Thermal benefits of city parks. *Energy and buildings*, 38(2), 105-120.
- Yuan, C., & Chen, L. (2011). Mitigating urban heat island effects in high-density cities based on sky view factor and urban morphological understanding: a study of Hong Kong. *Architectural Science Review*, 54(4), 305-315.
- Yumino, S., Uchida, T., Sasaki, K., Kobayashi, H., & Mochida, A. (2015). Total assessment for various environmentally conscious techniques from three perspectives: Mitigation of global warming, mitigation of UHIs, and adaptation to urban warming. *Sustainable Cities and Society*, 19, 236-249. doi:<https://doi.org/10.1016/j.scs.2015.05.010>
- Zaernia, M. (2020). Arial photo of City. Retrieved from https://photo.mashhad.ir/media_gallery/1611992-%D8%AA%D8%B5%D8%A7%D9%88%DB%8C%D8%B1-%D9%87%D9%88%D8%A7%DB%8C%DB%8C-%D8%B3%D8%B7%D8%AD-%D8%B4%D9%87%D8%B1-1.html
- Zaid, S. M., Perisamy, E., Hussein, H., Myeda, N. E., & Zainon, N. (2018). Vertical Greenery System in urban tropical climate and its carbon sequestration potential: A review. *Ecological Indicators*, 91, 57-70. doi:<https://doi.org/10.1016/j.ecolind.2018.03.086>
- Zamani, B., & Arefi, M. (2013). Iranian new towns and their urban management issues: A critical review of influential actors and factors. *Cities*, 30, 105-112.
- Zhang, H., Qi, Z.-f., Ye, X.-y., Cai, Y.-b., Ma, W.-c., & Chen, M.-n. (2013). Analysis of land use/land cover change, population shift, and their effects on spatiotemporal patterns of urban heat islands in metropolitan Shanghai, China. *Applied Geography*, 44, 121-133.
- Zhang, N., Wang, X., & Peng, Z. (2014). Large-eddy simulation of mesoscale circulations forced by inhomogeneous urban heat island. *Boundary-layer meteorology*, 151(1), 179-194.
- Zhao, L., Lee, X., Smith, R. B., & Oleson, K. (2014). Strong contributions of local background climate to urban heat islands. *Nature*, 511(7508), 216-219.
- Zhao, Q. (2017). *Evaluating the effectiveness of tree locations and arrangements for improving urban thermal environment*: Arizona State University.
- Zhao, Q., Wentz, E. A., & Murray, A. T. (2014). Shade Optimization in a Desert Environment. *Extended Abstract Proceedings of the GIScience 2014*, 118-121.
- Zhu, W., Lü, A., & Jia, S. (2013). Estimation of daily maximum and minimum air temperature using MODIS land surface temperature products. *Remote Sensing of Environment*, 130, 62-73.
- Ziari, K. (2006). The planning and functioning of new towns in Iran. *Cities*, 23(6), 412-422.
- Zone1.Mashhad. (2020). District 1 Retrieved from https://zone1.mashhad.ir/org_units/8470-%D8%B4%D9%87%D8%B1%D8%AF%D8%A7%D8%B1%DB%8C-%D9%85%D9%86%D8%B7%D9%82%D9%87-%D9%85%D8%B4%D9%87%D8%AF.html

Appendix 1

The pilot study Ts map and distribution barchart generated with LEONARDO application.

Ahmadabad a

Ahmadabad b

Ahmadabad c

Majd a

Majd b

Majd c

Majd d

Majd e

Majd f

Majd g

Majd h

Majd j

Majd k

Majd 1

Majd m

Ahmadabad d

Ahmadabad e

Appendix 2

Ta maps, wind speed 5m/s, without trees

1-A (Sajad)

1-B (Ershad)

1-C (Sanabad)

1-D (Ahmadabad)

1-E1 (Majd)

1-E2 (Kolahdooz)

1-F (Ebnesina)

ENVI_met

<Right foot>

Appendix 3

Ts maps, wind speed 5m/s, without trees

1-A (Sajad)

1-B (Ershad)

1-C (Sanabad)

1-D (Ahmadabad)

1-E1 (Majd)

1-E2 (Kolahdooz)

1-F (Ebnesina)

ENVi_met

<Right foot>

Appendix 4

SVF maps, wind speed 5m/s, without trees

1-A (Sajad)

1-B (Ershad)

1-C (Sanabad)

1-D

(Ahmadabad)

1-E1 (Majd)

1-E2 (Kolahdooz)

1-F (Ebnesina)

Appendix 5

Ta maps, wind speed 5m/s, with trees

1-A (Sajad)

1-B (Ershad)

1-C (Sanabad)

1-D (Ahmadabad)

1-E1 (Majd)

1-E2

(Kolahdooz)

1-F (Ebnesina)

ENV1_met

<Right foot>

Appendix 6

Ts maps, wind speed 5m/s, with trees

1-A (Sajad)

1-B (Ershad)

1-C (Sanabad)

1-D (Ahmadabad)

1-E1 (Majd)

1-E2 (Kolahdooz)

1-F (Ebnesina)

Appendix 7

SVF maps, wind speed 5m/s, with trees

1-A (Sajad)

1-B (Ershad)

1-C (Sanabad)

1-D (Ahmadabad)

1-E1 (Majd)

1-E2 (Kolahdooz)

1-F (Ebnesina)

Appendix 8

UHI characteristics and urban characteristics—average values of selected area in D1 and D10

Neighbourhood name	Average Ta (°C)	Average Ta (°C) with trees	Difference Ta	Average Ts (°C)	Average Ts (°C) with trees	Difference Ts	Average plot size(m2)	Average plot length(m)	Average plot width(m)	Average footprint size(m2)	Average footprint length(m)	Average footprint width (m)	Site coverage (%)	Building density (%)	Average building height(m)	Sum of foot print (m2)	trees (numbers)	divent of trees(tree number-220	average courtyard area	sum of courtyards (m2)
1-A (Sajad)	32.10	31.37	0.74	40.27	36.53	3.74	451.33	30.70	14.70	201.82	13.73	14.70	44.72	55.00	7.02	87995.43	396	176.00	249.51	29,351.33
1-C (Sanabad)	31.86	31.30	0.56	41.65	37.70	3.96	262.90	34.28	7.67	150.94	19.68	7.67	57.41	56.79	5.78	90865.33	346	126.00	111.96	27,963.58
1-D (Ahmadabad)	31.91	31.02	0.89	41.78	37.19	4.59	297.65	32.13	9.26	153.30	16.55	9.26	51.50	47.52	6.78	76037.95	436	216.00	144.35	36473.95
1-E1 (Majd)	31.68	31.23	0.45	41.85	38.37	3.48	141.60	22.47	6.30	69.13	10.97	6.30	48.82	47.26	5.32	75622.78	319	99.00	72.48	39076.52
1-E2 (Kolahdooz)	31.82	31.25	0.57	41.91	37.98	3.93	135.27	28.73	4.71	84.00	17.84	4.71	62.10	51.87	5.32	82992.63	356	136.00	51.27	31044.61
1-F (Ebnesina)	31.65	31.02	0.63	41.95	36.36	5.58	244.08	28.45	8.58	119.35	13.91	8.58	48.90	50.65	6.72	81045.25	483	263.00	124.73	32146.84
10-A (Miad)	32.48	32.40	0.08	41.35	41.41	-0.06	223.20	25.44	8.77	96.27	10.97	8.77	43.13	38.63	4.11	61802.30	220	0.00	126.94	43102.18
10-B (Fallahi)	32.34	32.25	0.09	42.21	41.65	0.56	232.95	25.25	9.22	109.80	11.90	9.22	47.13	35.13	4.18	56215.53	350	130.00	123.15	42787.16
10-C (Hesabi)	32.23	32.08	0.15	42.67	41.41	1.27	175.73	29.56	5.94	100.53	16.91	5.94	57.21	38.39	5.10	61426.24	550	330.00	75.19	26086.06
10-E (Hadi)	31.84	31.85	-0.01	42.05	41.02	1.03	113.74	22.39	5.08	56.34	11.09	5.08	49.53	50.39	3.89	80616.90	255	35.00	57.41	47459.30
Average D10	32.22	32.14	0.08	42.07	41.37	0.70	186.41	25.22	7.39	90.73	12.27	7.39	48.68	40.63	4.32	65015.24	344	123.75	95.67	32676.14
Average D1	31.84	31.20	0.64	41.57	37.35	4.21	255.47	28.48	8.97	129.76	14.46	8.97	50.79	51.52	6.16	82426.56	389	169.33	125.72	39858.68

UHI characteristics and urban characteristics—average values of selected area in D1 and D10

Neighbourhood name	Courtyard coverage (%)	average street Width	average courtyard area	average courtyard Length	average canyon Width	H/W ratio of Streets	H/W ratio of Yard	H/W ratio of Canyon	H/W ratio of Alley	Average SVF	Average SVF with trees	difference SVF	Street coverage (%)	Sum street area (m2)	plot number	foot print number	Sum concrete pavement area (m2)	Sum grassland area (m2)	Sum bare land area (m2)	Sum of plot size (m2)	street orientation	street orientation code	Building orientation	Building orientation	Street pattern	Street pattern code	Urban pattern	Urban pattern code
1-A (Sajad)	18.34	16.47	8.61	16.97	33.44	0.43	0.41	0.21	0.31	0.62	0.33	0.29	24.75	39,593.00	260	436	339.00	3,458.00	0	117,346.76	E-W	1	N-S	1	Grid	1	grid-E-W	1
1-C (Sanabad)	17.48	12.34	8.44	14.60	26.94	0.47	0.40	0.21	0.31	0.56	0.31	0.25	25.75	41,207.00	452	602	79.49	0	0	118,828.91	NW-SE	2	NE-SW	2	Grid	1	grid NE-SW	3
1-D (Ahmadabad)	22.80	13.52	8.54	15.58	29.10	0.50	0.43	0.23	0.33	0.54	0.26	0.28	29.74	47,576.00	378	496	0	0	0	112,511.91	E-W	1	N-S	1	Irregular	2	irregular-E-W	4
1-E1 (Majd)	24.42	11.07	6.48	11.50	22.57	0.48	0.46	0.24	0.35	0.51	0.29	0.22	27.48	43,963.00	810	1094	0	73	0	114,699.30	Irregular	3	NE-SW	2	traditional	3	traditional-irregular	6
1-E2 (Kolahdooz)	19.40	7.94	5.90	10.89	18.83	0.67	0.49	0.28	0.39	0.54	0.32	0.22	27.18	43,491.00	843	988	0	0	2,353.00	114,037.24	E-W	1	NE-SW	2	Irregular	2	irregular-E-W	4
1-F (Ebnesina)	20.09	13.99	8.25	14.54	28.53	0.48	0.46	0.24	0.35	0.52	0.24	0.28	27.02	43,225.00	475	679	0	1215	0	113,192.09	NW-SE	2	NE-SW	2	Grid	1	grid NW-SE	2
10-A (Miad)	26.94	17.46	8.40	14.47	31.93	0.24	0.28	0.13	0.21	0.70	0.59	0.11	34.29	54,858.00	470	642	0	7.78	0	104,904.48	E-W	1	N-S	1	Grid	1	grid-E-W	1
10-B (Fallahi)	26.74	16.32	7.93	13.35	29.67	0.26	0.31	0.14	0.23	0.73	0.57	0.16	36.96	59,136.00	425	512	0	2,666.00	0	99,002.68	NW-SE	2	NE-SW	2	Irregular	2	irregular-Nw-SE	5
10-C (Hesabi)	16.30	13.15	6.29	12.65	25.80	0.39	0.40	0.20	0.30	0.68	0.49	0.20	33.84	54,139.00	498	611	19,665.00	8,600.00	0	87,512.29	NE-SW	4	NW-SE	3	Grid	1	grid NE-SW	3
10-E (Hadi)	29.66	11.03	6.08	11.30	22.33	0.35	0.34	0.17	0.26	0.52	0.43	0.09	15.80	25,280.00	1126	1431	0	0	0	128,076.20	Irregular	3	NW-SE	3	traditional	3	traditional-irregular	6
Average D10	24.91	14.49	7.18	12.94	27.43	0.30	0.33	0.16	0.25	0.55	0.29	0.26	30.22	48353.25	2519.00	3196.00	19665.00	2818.45	0.00	104873.91								
Average D1	20.42	12.55	7.70	14.01	26.57	0.49	0.44	0.23	0.34	0.66	0.52	0.14	26.99	43175.83	3218.00	4295.00	69.75	791.00	392.17	115102.70								

Appendix 9

The correlation between urban characteristics and UHI characteristics

		street coverage (%)	difference SVF	Average SVF with trees	Average SVF	H/W ratio of Neighborhood	H/W ratio of Canyon/Street and Yard	H/W ratio of Streets	average canyon Width	average courtyard Length	average courtyard Width	average street Width	courtyard coverage (%)	sum of courtyards (m2)	average courtyard area	divent of trees(tree number-trees (numbers)	Sum of foot print	Average building height(m)	Building density(%)	Site coverage(%)	Average footprint size(m2)	Average plot size(m2)	Difference Ts	Average Ts (°C) with trees	Average Ts (°C)	Difference Ta	Average Ta (°C) with trees	Average Ta (°C)
Average Ta (°C)	Pears on Correlation	.651*	- 0.306	.654*	.782**	-.806**	-.802**	-.767**	.0004	.0008	.0500	.0009	.0170	.0170	.032	-.0175	-.741**	-.0499	-.741**	-.0371	.0058	.0160	-.800**	.705*	-.0025	-.0562	.866**	1
	Sig. (2-tailed)	.0022	.0333	.0021	.0003	.0002	.0002	.0004	.0002	.0008	.0000	.0009	.0039	.0039	.0068	.0086	.0006	.0099	.0006	.0235	.0058	.0018	.0002	.0010	.0038	.0057	.0000	
	N	12	12	12	12	12	12	12	12	12	12	12	12	10	10	12	12	12	12	12	12	12	12	12	12	12	12	12
Average Ta (°C) with trees	Pears on Correlation	.0447	-.0559	.690*	.614*	-.890**	-.887**	-.853**	.0000	.0028	.0482	.0109	.0427	.0427	.0164	-.0343	-.801**	-.833**	-.801**	.0322	-.0381	.0266	-.977**	.944**	.0273	-.900**	.866**	1
	Sig. (2-tailed)	.0145	.0059	.0013	.0034	.0000	.0000	.0000	.0000	.0028	.0058	.0009	.0019	.0019	.0011	.0075	.0002	.0001	.0001	.0307	.0222	.0004	.0000	.0000	.0090	.0000	.0000	
	N	12	12	12	12	12	12	12	12	12	12	12	12	10	10	12	12	12	12	12	12	12	12	12	12	12	12	12
Difference Ta	Pears on Correlation	-.0172	.658*	-.0572	-.0333	-.890**	.769**	.764**	.743**	.0110	.0521	.0126	.0185	-.0551	-.0551	.0474	.0415	.679*	.944**	.679*	.0209	.681*	.580*	.920**	-.948**	-.0475	-.900**	1
	Sig. (2-tailed)	.0594	.0020	.0052	.0090	.0003	.0003	.0004	.0006	.0035	.0082	.0168	.0066	.0099	.0099	.0119	.0180	.0015	.0000	.0015	.0014	.0015	.0048	.0000	.0000	.0119	.0000	
	N	12	12	12	12	12	12	12	12	12	12	12	12	10	10	12	12	12	12	12	12	12	12	12	12	12	12	12
Average Ts (°C)	Pears on Correlation	.0251	-.0242	.0113	-.0034	-.0059	-.0059	-.0072	-.0027	-.0017	-.0065	-.0061	.0098	.0098	-.813**	.0258	-.0509	-.0480	-.0509	.0449	-.677*	-.775**	-.0279	.0520	-.0475	.0273	1	
	Sig. (2-tailed)	.0025	.0042	.0013	.0034	.0003	.0003	.0005	.0001	.0027	.0017	.0065	.0061	.0008	.0008	.0003	.0058	.0009	.0080	.0009	.0049	.0077	.0055	.0029	.0020	.0075	.0073	
	N	12	12	12	12	12	12	12	12	12	12	12	12	10	10	12	12	12	12	12	12	12	12	12	12	12	12	12

	Sig. (2-tailed)	0.938	0.390	0.119		0.083	0.380	0.003	0.016	0.143	0.091	0.114	0.091	0.418	0.418	0.001	0.788	0.788	0.250	0.056	0.017	0.078	0.823	0.875	0.828	0.855	0.916	0.726	0.449	0.431
	N	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	10	10	12	12	12	12	12	12	12	12	12	12	12	12
Average Ts (°C) with trees	Pearson Correlation	.705*	.944**	-.948**	0.520	1	-.965**	-.0522	-.601*	-.0157	-.814**	-.923**	-.814**	-.0332	-.0332	-.0436	0.516	0.516	0.241	-.0372	-.0451	-.043	-.754**	-.793**	-.789**	-.795**	0.451	.622*	-.618*	0.362
	Sig. (2-tailed)	0.010	0.000	0.000	0.083		0.000	0.082	0.039	0.625	0.001	0.000	0.001	0.291	0.291	0.157	0.127	0.127	0.451	0.234	0.142	0.895	0.005	0.002	0.002	0.002	0.142	0.031	0.032	0.247
	N	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	10	10	12	12	12	12	12	12	12	12	12	12	12	12
Difference Ts	Pearson Correlation	-.800**	-.977**	.920**	-.0279	-.965**	1	0.350	0.468	0.314	.760**	.891**	.760**	0.453	0.453	0.241	-0.546	-0.546	-0.381	0.245	0.301	-0.113	.825**	.876**	.866**	.876**	-0.517	-.665*	.621*	-0.330
	Sig. (2-tailed)	0.002	0.000	0.000	0.380	0.000		0.265	0.125	0.320	0.004	0.000	0.004	0.140	0.140	0.450	0.102	0.102	0.222	0.443	0.341	0.727	0.001	0.000	0.000	0.000	0.085	0.018	0.031	0.294
	N	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	10	10	12	12	12	12	12	12	12	12	12	12	12	12
Average plot size(m2)	Pearson Correlation	0.160	-.0266	.580*	-.775**	-.0522	0.350	1	.964**	-.0375	0.308	.683*	0.308	0.254	0.254	.979**	-0.367	-0.367	.593*	.810**	.945**	.797**	-0.018	0.045	0.015	0.033	0.245	-0.119	0.488	0.075
	Sig. (2-tailed)	0.618	0.404	0.048	0.003	0.082	0.265		0.000	0.230	0.330	0.014	0.330	0.425	0.425	0.000	0.297	0.297	0.042	0.001	0.000	0.002	0.956	0.891	0.963	0.920	0.443	0.712	0.108	0.817
	N	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	10	10	12	12	12	12	12	12	12	12	12	12	12	12
Average footprint size(m2)	Pearson Correlation	0.058	-.0381	.681*	-.677*	-.601*	0.468	.964**	1	-.0135	0.404	.761**	0.404	0.373	0.373	.889**	-0.536	-0.536	0.437	.775**	.913**	.682*	0.144	0.173	0.166	0.171	0.182	-0.202	0.567	0.062
	Sig. (2-tailed)	0.858	0.222	0.015	0.016	0.039	0.125	0.000		0.675	0.192	0.004	0.192	0.232	0.232	0.000	0.110	0.110	0.155	0.003	0.000	0.015	0.656	0.591	0.607	0.596	0.571	0.529	0.055	0.847
	N	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	10	10	12	12	12	12	12	12	12	12	12	12	12	12

Site coverage (%)	Pears on Correlation	- 0.371	- 0.322	0.209	0.449	- 0.157	0.314	- 0.375	- 0.135	1	0.291	0.104	0.291	0.369	0.369	- 0.542	- 0.560	- 0.560	- .778**	- 0.489	- 0.436	- .693*	.682*	0.531	.624*	0.572	- 0.260	- 0.258	0.175	- 0.100
	Sig. (2-tailed)	0.235	0.307	0.514	0.143	0.625	0.320	0.230	0.675		0.358	0.748	0.358	0.238	0.238	0.069	0.092	0.092	0.003	0.107	0.157	0.013	0.014	0.076	0.030	0.052	0.414	0.418	0.587	0.758
	N	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	10	10	12	12	12	12	12	12	12	12	12	12	12	12
Building density (%)	Pears on Correlation	- .741**	- .801**	.679*	- 0.509	- .814**	.760**	0.308	0.404	0.291	1	.630*	1.000*	0.021	0.021	0.218	- 0.378	- 0.378	- 0.460	0.114	0.208	- 0.205	.695*	.616*	.685*	.648*	- .588*	- 0.566	0.364	- .760**
	Sig. (2-tailed)	0.006	0.002	0.015	0.091	0.001	0.004	0.330	0.192	0.358		0.028	0.000	0.949	0.949	0.496	0.282	0.282	0.132	0.725	0.517	0.522	0.012	0.033	0.014	0.023	0.044	0.055	0.245	0.004
	N	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	10	10	12	12	12	12	12	12	12	12	12	12	12	12
Average building height (m)	Pears on Correlation	- 0.499	- .833**	.944**	- 0.480	- .923**	.891**	.683*	.761**	0.104	.630*	1	.630*	.591*	.591*	.590*	- .656*	- .656*	- 0.026	0.478	.633*	0.261	.619*	.722**	.680*	.708**	- 0.257	- 0.555	.713**	- 0.155
	Sig. (2-tailed)	0.099	0.001	0.000	0.114	0.000	0.000	0.014	0.004	0.748	0.028		0.028	0.043	0.043	0.044	0.039	0.039	0.937	0.116	0.027	0.412	0.032	0.008	0.015	0.010	0.420	0.061	0.009	0.630
	N	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	10	10	12	12	12	12	12	12	12	12	12	12	12	12
Sum of footprint	Pears on Correlation	- .741**	- .801**	.679*	- 0.509	- .814**	.760**	0.308	0.404	0.291	1.000*	.630*	1	0.021	0.021	0.218	- 0.378	- 0.378	- 0.460	0.114	0.208	- 0.205	.695*	.616*	.685*	.648*	- .588*	- 0.566	0.364	- .760**
	Sig. (2-tailed)	0.006	0.002	0.015	0.091	0.001	0.004	0.330	0.192	0.358	0.000	0.028		0.949	0.949	0.496	0.282	0.282	0.132	0.725	0.517	0.522	0.012	0.033	0.014	0.023	0.044	0.055	0.245	0.004
	N	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	10	10	12	12	12	12	12	12	12	12	12	12	12	12
trees (numbers)	Pears on Correlation	- 0.175	- 0.343	0.415	0.258	- 0.332	0.453	0.254	0.373	0.369	0.021	.591*	0.021	1	1.000*	0.150	- .726*	- .726*	- 0.041	0.047	0.241	0.079	0.343	0.519	0.424	0.483	0.038	- 0.279	0.545	0.232
	Sig. (2-tailed)	0.586	0.275	0.180	0.418	0.291	0.140	0.425	0.232	0.238	0.949	0.043	0.949		0.000	0.642	0.018	0.018	0.900	0.886	0.450	0.806	0.275	0.084	0.170	0.112	0.906	0.380	0.067	0.469

	N	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	10	10	12	12	12	12	12	12	12	12	12	12	12	12	12
divent of trees(tr ee number -220	Pears on Correlation	- 0.175	- 0.343	0.415	0.258	- 0.332	0.453	0.254	0.373	0.369	0.021	.591*	0.021	1.000*	1	0.150	- .726*	- .726*	- 0.041	0.047	0.241	0.079	0.343	0.519	0.424	0.483	0.038	- 0.279	0.545	0.232	
	Sig. (2-tailed)	0.586	0.275	0.180	0.418	0.291	0.140	0.425	0.232	0.238	0.949	0.043	0.949	0.000		0.642	0.018	0.018	0.900	0.886	0.450	0.806	0.275	0.084	0.170	0.112	0.906	0.380	0.067	0.469	
	N	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	10	10	12	12	12	12	12	12	12	12	12	12	12	12
average courtya rd area	Pears on Correlation	0.232	- 0.164	0.474	- .813**	- 0.436	0.241	.979**	.889**	- 0.542	0.218	.590*	0.218	0.150	0.150	1	- 0.221	- 0.221	.684*	.798**	.924**	.846**	- 0.142	- 0.057	- 0.102	- 0.076	0.281	- 0.050	0.402	0.081	
	Sig. (2-tailed)	0.468	0.611	0.119	0.001	0.157	0.450	0.000	0.000	0.069	0.496	0.044	0.496	0.642	0.642		0.540	0.540	0.014	0.002	0.000	0.001	0.659	0.861	0.752	0.815	0.376	0.878	0.195	0.802	
	N	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	10	10	12	12	12	12	12	12	12	12	12	12	12	12
sum of courtya rds (m2)	Pears on Correlation	0.170	0.427	- 0.551	0.098	0.516	- 0.546	- 0.367	- 0.536	- 0.560	- 0.378	- .656*	- 0.378	- .726*	- .726*	- 0.221	1	1.000*	0.153	- 0.100	- 0.294	- 0.031	- 0.542	- 0.586	- 0.571	- 0.583	0.053	0.442	- .729*	- 0.112	
	Sig. (2-tailed)	0.639	0.219	0.099	0.788	0.127	0.102	0.297	0.110	0.092	0.282	0.039	0.282	0.018	0.018	0.540		0.000	0.673	0.784	0.410	0.933	0.106	0.075	0.085	0.077	0.885	0.201	0.017	0.758	
	N	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10
courtya rd coverag e (%)	Pears on Correlation	0.170	0.427	- 0.551	0.098	0.516	- 0.546	- 0.367	- 0.536	- 0.560	- 0.378	- .656*	- 0.378	- .726*	- .726*	- 0.221	1	1.000*	0.153	- 0.100	- 0.294	- 0.031	- 0.542	- 0.586	- 0.571	- 0.583	0.053	0.442	- .729*	- 0.112	
	Sig. (2-tailed)	0.639	0.219	0.099	0.788	0.127	0.102	0.297	0.110	0.092	0.282	0.039	0.282	0.018	0.018	0.540		0.000	0.673	0.784	0.410	0.933	0.106	0.075	0.085	0.077	0.885	0.201	0.017	0.758	
	N	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10
average street Width	Pears on Correlation	.711**	0.487	- 0.185	- 0.361	0.241	- 0.381	.593*	0.437	- .778**	- 0.460	- 0.026	- 0.460	- 0.041	- 0.041	.684*	0.153	0.153	1	.721**	.693*	.949**	- .761**	- .645*	- .723**	- .680*	.607*	0.379	- 0.005	0.500	
	Sig. (2-tailed)	0.009	0.109	0.566	0.250	0.451	0.222	0.042	0.155	0.003	0.132	0.937	0.132	0.900	0.900	0.014	0.673	0.673		0.008	0.012	0.000	0.004	0.024	0.008	0.015	0.036	0.225	0.987	0.098	
	N	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12

[illegible]

	Sig. (2-tailed)	0.002	0.000	0.004	0.875	0.002	0.000	0.891	0.591	0.076	0.033	0.008	0.033	0.084	0.084	0.861	0.075	0.075	0.024	0.540	0.821	0.145	0.000		0.000	0.000	0.083	0.033	0.076	0.367
	N	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	10	10	12	12	12	12	12	12	12	12	12	12	12	12
H/W ratio of Canyon (Street and courtyard length)	Pearson Correlation	-.802**	-.887**	.769**	-.0070	-.789**	.866**	0.015	0.166	.624*	.685*	.680*	.685*	0.424	0.424	-.0102	-.0571	-.0571	-.723**	-.0214	-.0104	-.0512	.988**	.979**	1	.993**	-.0547	-.609*	0.486	-.0347
	Sig. (2-tailed)	0.002	0.000	0.003	0.828	0.002	0.000	0.963	0.607	0.030	0.014	0.015	0.014	0.170	0.170	0.752	0.085	0.085	0.008	0.503	0.747	0.089	0.000	0.000		0.000	0.066	0.036	0.109	0.270
	N	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	10	10	12	12	12	12	12	12	12	12	12	12	12	12
H/W ratio of Neighbourhood	Pearson Correlation	-.806**	-.890**	.770**	-.0059	-.795**	.876**	0.033	0.171	0.572	.648*	.708**	.648*	0.483	0.483	-.0076	-.0583	-.0583	-.680*	-.0205	-.0086	-.0476	.963**	.996**	.993**	1	-.0534	-.617*	0.515	-.0313
	Sig. (2-tailed)	0.002	0.000	0.003	0.855	0.002	0.000	0.920	0.596	0.052	0.023	0.010	0.023	0.112	0.112	0.815	0.077	0.077	0.015	0.523	0.789	0.118	0.000	0.000	0.000		0.074	0.033	0.087	0.322
	N	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	10	10	12	12	12	12	12	12	12	12	12	12	12	12
Average SVF	Pearson Correlation	.782**	.614*	-.0333	-.0034	0.451	-.0517	0.245	0.182	-.0260	-.588*	-.0257	-.588*	0.038	0.038	0.281	0.053	0.053	.607*	0.250	0.247	0.500	-.0538	-.0521	-.0547	-.0534	1	.868**	-.0449	.670*
	Sig. (2-tailed)	0.003	0.034	0.290	0.916	0.142	0.085	0.443	0.571	0.414	0.044	0.420	0.044	0.906	0.906	0.376	0.885	0.885	0.036	0.433	0.440	0.098	0.071	0.083	0.066	0.074		0.000	0.143	0.017
	N	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	10	10	12	12	12	12	12	12	12	12	12	12	12	12
Average SVF with trees	Pearson Correlation	.654*	.690*	-.0572	0.113	.622*	-.665*	-.0119	-.0202	0.258	0.566	0.555	0.566	-.0279	-.0279	-.0050	0.442	0.442	0.379	-.0028	-.0091	0.204	-.577*	-.617*	-.609*	-.617*	.868**	1	-.833**	0.400
	Sig. (2-tailed)	0.021	0.013	0.052	0.726	0.031	0.018	0.712	0.529	0.418	0.055	0.061	0.055	0.380	0.380	0.878	0.201	0.201	0.225	0.931	0.779	0.524	0.049	0.033	0.036	0.033	0.000		0.001	0.197
	N	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	10	10	12	12	12	12	12	12	12	12	12	12	12	12

difference SVF	Pearson Correlation	-0.306	-0.559	.658*	-0.242	-.618*	.621*	0.488	0.567	0.175	0.364	.713**	0.364	0.545	0.545	0.402	-.729*	-.729*	-0.005	0.330	0.438	0.189	0.439	0.531	0.486	0.515	-.0449	-.833**	1	0.026
	Sig. (2-tailed)	0.333	0.059	0.020	0.449	0.032	0.031	0.108	0.055	0.587	0.245	0.009	0.245	0.067	0.067	0.195	0.017	0.017	0.987	0.295	0.154	0.557	0.153	0.076	0.109	0.087	0.143	0.001		0.935
	N	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	10	10	12	12	12	12	12	12	12	12	12	12	12	12
street coverage (%)	Pearson Correlation	.651*	0.447	-0.172	0.251	0.362	-.0330	0.075	0.062	-0.100	-.760**	-0.155	-.760**	0.232	0.232	0.081	-0.112	-0.112	0.500	0.257	0.152	0.389	-0.356	-0.286	-0.347	-0.313	.670*	0.400	0.026	1
	Sig. (2-tailed)	0.022	0.145	0.594	0.431	0.247	0.294	0.817	0.847	0.758	0.004	0.630	0.004	0.469	0.469	0.802	0.758	0.758	0.098	0.420	0.638	0.212	0.256	0.367	0.270	0.322	0.017	0.197	0.935	
	N	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	10	10	12	12	12	12	12	12	12	12	12	12	12	12

** . Correlation is significant at the 0.01 level (2-tailed).

* . Correlation is significant at the 0.05 level (2-tailed).

The correlation between tree characteristics and UHI characteristics

		Average Ta (°C)	Average Ta (°C) with trees	Difference Ta	Average Ts (°C)	Average Ts (°C) with trees	Difference Ts	Tree Numbers
Average Ta (°C)	Pearson Correlation	1	.836**	0.268	-0.025	0.519	-.586*	-0.175
	Sig. (2-tailed)		0.001	0.399	0.938	0.084	0.045	0.587
	N	12	12	12	12	12	12	12
Average Ta (°C) with trees	Pearson Correlation	.836**	1	-0.304	-0.013	.798**	-.885**	-.603*
	Sig. (2-tailed)	0.001		0.336	0.968	0.002	0.000	0.038
	N	12	12	12	12	12	12	12
Difference Ta	Pearson Correlation	0.268	-0.304	1	-0.021	-0.499	0.537	.756**
	Sig. (2-tailed)	0.399	0.336		0.948	0.098	0.072	0.004
	N	12	12	12	12	12	12	12
Average Ts (°C)	Pearson Correlation	-0.025	-0.013	-0.021	1	0.429	0.109	0.259
	Sig. (2-tailed)	0.938	0.968	0.948		0.164	0.737	0.417
	N	12	12	12	12	12	12	12
Average Ts (°C) with trees	Pearson Correlation	0.519	.798**	-0.499	0.429	1	-.852**	-.637*
	Sig. (2-tailed)	0.084	0.002	0.098	0.164		0.000	0.026
	N	12	12	12	12	12	12	12
Difference Ts	Pearson Correlation	-.586*	-.885**	0.537	0.109	-.852**	1	.851**
	Sig. (2-tailed)	0.045	0.000	0.072	0.737	0.000		0.000
	N	12	12	12	12	12	12	12
Tree Numbers	Pearson Correlation	-0.175	-.603*	.756**	0.259	-.637*	.851**	1
	Sig. (2-tailed)	0.587	0.038	0.004	0.417	0.026	0.000	
	N	12	12	12	12	12	12	12

** . Correlation is significant at the 0.01 level (2-tailed).

*. Correlation is significant at the 0.05 level (2-tailed).

The correlation between urban pattern and UHI characteristics

		Average Ta (°C)	Average Ts (°C)	street orientation code	Building orientation code	Street pattern code	Urban pattern code
Average Ta (°C)	Pearson Correlation	1	-0.089	-0.124	-0.231	-0.399	-0.389
	Sig. (2-tailed)		0.807	0.732	0.521	0.253	0.267
	N	10	10	10	10	10	10
Average Ts (°C)	Pearson Correlation	-0.089	1	.658*	.739*	0.283	0.553
	Sig. (2-tailed)	0.807		0.038	0.015	0.429	0.097
	N	10	10	10	10	10	10
street orientation code	Pearson Correlation	-0.124	.658*	1	.857**	0.256	0.458
	Sig. (2-tailed)	0.732	0.038		0.002	0.475	0.183
	N	10	10	10	10	10	10
Building orientation code	Pearson Correlation	-0.231	.739*	.857**	1	0.311	0.532
	Sig. (2-tailed)	0.521	0.015	0.002		0.382	0.114
	N	10	10	10	10	10	10
Street pattern code	Pearson Correlation	-0.399	0.283	0.256	0.311	1	.916**
	Sig. (2-tailed)	0.253	0.429	0.475	0.382		0.000
	N	10	10	10	10	10	10
Urban pattern code	Pearson Correlation	-0.389	0.553	0.458	0.532	.916**	1
	Sig. (2-tailed)	0.267	0.097	0.183	0.114	0.000	
	N	10	10	10	10	10	10

** . Correlation is significant at the 0.01 level (2-tailed).

* . Correlation is significant at the 0.05 level (2-tailed).

The correlation between urban characteristics (H/W aspect ratio, SVF and trees) and UHI characteristics

		Average Ta (°C)	Average Ta (°C) with trees	Difference Ta	Average Ts (°C)	Average Ts (°C) with trees	Difference Ts	Tree Numbers	H/W ratio of Yard	H/W ratio of Canyon(Street and courtyard length	H/W ratio of Neighborhood	Average SVF	Average SVF with trees	difference SVF
Average Ta (°C)	Pearson Correlation	1	.836**	0.268	-0.025	0.519	-.586*	-0.175	-.802**	-.802**	-.806**	.782**	.654*	-0.306
	Sig. (2-tailed)		0.001	0.399	0.938	0.084	0.045	0.587	0.002	0.002	0.002	0.003	0.021	0.333
	N	12	12	12	12	12	12	12	12	12	12	12	12	12
Average Ta (°C) with trees	Pearson Correlation	.836**	1	-0.304	-0.013	.798**	-.885**	-.603*	-.896**	-.868**	-.889**	.593*	.704*	-.607*
	Sig. (2-tailed)	0.001		0.336	0.968	0.002	0.000	0.038	0.000	0.000	0.000	0.042	0.011	0.036
	N	12	12	12	12	12	12	12	12	12	12	12	12	12
Difference Ta	Pearson Correlation	0.268	-0.304	1	-0.021	-0.499	0.537	.756**	0.182	0.132	0.162	0.317	-0.100	0.534
	Sig. (2-tailed)	0.399	0.336		0.948	0.098	0.072	0.004	0.572	0.683	0.615	0.315	0.757	0.074
	N	12	12	12	12	12	12	12	12	12	12	12	12	12
Average Ts (°C)	Pearson Correlation	-0.025	-0.013	-0.021	1	0.429	0.109	0.259	-0.051	-0.070	-0.059	-0.034	0.113	-0.242
	Sig. (2-tailed)	0.938	0.968	0.948		0.164	0.737	0.417	0.875	0.828	0.855	0.916	0.726	0.449
	N	12	12	12	12	12	12	12	12	12	12	12	12	12
Average Ts (°C) with trees	Pearson Correlation	0.519	.798**	-0.499	0.429	1	-.852**	-.637*	-.736**	-.689*	-.721**	0.268	0.572	-.732**
	Sig. (2-tailed)	0.084	0.002	0.098	0.164		0.000	0.026	0.006	0.013	0.008	0.400	0.052	0.007
	N	12	12	12	12	12	12	12	12	12	12	12	12	12
Difference Ts	Pearson Correlation	-.586*	-.885**	0.537	0.109	-.852**	1	.851**	.780**	.718**	.758**	-0.314	-0.564	.665*
	Sig. (2-tailed)	0.045	0.000	0.072	0.737	0.000		0.000	0.003	0.009	0.004	0.320	0.056	0.018
	N	12	12	12	12	12	12	12	12	12	12	12	12	12
Tree Numbers	Pearson Correlation	-0.175	-.603*	.756**	0.259	-.637*	.851**	1	0.519	0.424	0.482	0.038	-0.279	0.545

	Sig. (2-tailed)	0.587	0.038	0.004	0.417	0.026	0.000		0.084	0.170	0.112	0.907	0.379	0.067
	N	12	12	12	12	12	12	12	12	12	12	12	12	12
H/W ratio of Yard	Pearson Correlation	-.802**	-.896**	0.182	-0.051	-.736**	.780**	0.519	1	.979**	.996**	-0.521	-.617*	0.531
	Sig. (2-tailed)	0.002	0.000	0.572	0.875	0.006	0.003	0.084		0.000	0.000	0.083	0.033	0.076
	N	12	12	12	12	12	12	12	12	12	12	12	12	12
H/W ratio of Canyon(Street and courtyard length	Pearson Correlation	-.802**	-.868**	0.132	-0.070	-.689*	.718**	0.424	.979**	1	.993**	-0.547	-.609*	0.486
	Sig. (2-tailed)	0.002	0.000	0.683	0.828	0.013	0.009	0.170	0.000		0.000	0.066	0.036	0.109
	N	12	12	12	12	12	12	12	12	12	12	12	12	12
H/W ratio of Neighborhood	Pearson Correlation	-.806**	-.889**	0.162	-0.059	-.721**	.758**	0.482	.996**	.993**	1	-0.534	-.617*	0.515
	Sig. (2-tailed)	0.002	0.000	0.615	0.855	0.008	0.004	0.112	0.000	0.000		0.074	0.033	0.087
	N	12	12	12	12	12	12	12	12	12	12	12	12	12
Average SVF	Pearson Correlation	.782**	.593*	0.317	-0.034	0.268	-0.314	0.038	-0.521	-0.547	-0.534	1	.868**	-0.449
	Sig. (2-tailed)	0.003	0.042	0.315	0.916	0.400	0.320	0.907	0.083	0.066	0.074		0.000	0.143
	N	12	12	12	12	12	12	12	12	12	12	12	12	12
Average SVF with trees	Pearson Correlation	.654*	.704*	-0.100	0.113	0.572	-0.564	-0.279	-.617*	-.609*	-.617*	.868**	1	-.833**
	Sig. (2-tailed)	0.021	0.011	0.757	0.726	0.052	0.056	0.379	0.033	0.036	0.033	0.000		0.001
	N	12	12	12	12	12	12	12	12	12	12	12	12	12
difference SVF	Pearson Correlation	-0.306	-.607*	0.534	-0.242	-.732**	.665*	0.545	0.531	0.486	0.515	-0.449	-.833**	1
	Sig. (2-tailed)	0.333	0.036	0.074	0.449	0.007	0.018	0.067	0.076	0.109	0.087	0.143	0.001	
	N	12	12	12	12	12	12	12	12	12	12	12	12	12

** . Correlation is significant at the 0.01 level (2-tailed).

* . Correlation is significant at the 0.05 level (2-tailed).