Humboldt-Universität zu Berlin – Geographisches Institut

# Does The Third-Dimension Play A Role in Shaping Urban Thermal Conditions?

– Wie wirkt sich die dritte Dimension auf die urbane Hitzeinsel aus? –

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ZU BERLIN

*Dedicated to my parents, my wife and daughter.*

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# Summary

Among the studies on ecosystem services undertaken in urban areas, a dimension 'volume and height', i.e., the third-dimension of urban environment is largely ignored. More specific, three-dimensional spatial models will increase the knowledge of how complex environment shape the micro-climate in urban environment. The research objectives and questions of this dissertation is: i) the status of the current research addressing the third-dimension of ecosystem services in urban area, ii) assessing the association of urban multi-dimensional (two- and three- dimensional) indicators on urban surface temperature and iii) variation of indoor and outdoor urban temperature pattern. This dissertation is organized into four chapters. The first and second chapter explain the gaps in literature and the aim of this research. Chapter 3 holds the published articles. The last chapter discusses the results of the published articles. This dissertation emphasizes the importance of three-dimensional studies in urban ecosystems to advance the concept of sustainability in cities. Therefore, cross-continental studies that consider the three-dimensional structure of all the urban components and its impact on outdoor and indoor temperature is recommended for future research.

**Keywords:** Third dimension, urban morphology, 3D modeling, urban heat island, boosted regression tree analysis, indoor temperature.

# Zusammenfassung

Zahlreiche Studien den Stand der Forschung in Bezug auf die Ökosystemdienstleistungen untersucht. Dennoch wurde die Dimension „Volumen und Höhe“, d.h. die dritte Dimension städtischer Systeme, in den Studien zu Ökosystemdienstleistungen in städtischen Gebieten ignoriert. Die Forschungsziele und Fragestellungen dieser Dissertation lauten: i) Stand der aktuellen Forschung zur dritten Dimension von Ökosystemdienstleistungen im städtischen Raum, ii) Beurteilung des Zusammenhangs von urbanen mehrdimensionalen Indikatoren (zwei- und dreidimensionalen Indikatoren) für die Oberflächentemperatur in der Stadt und iii) Unterschiede zwischen Innen- und Außentemperaturen in urbanen Räumen. Diese Dissertation ist in vier Kapitel gegliedert. Im ersten und zweiten Kapitel werden die Forschungslücken und das Ziel der vorliegenden Untersuchung erläutert. Kapitel 3 enthält die veröffentlichten Artikel. Das letzte Kapitel behandelt die Ergebnisse der veröffentlichten Artikel. Diese Dissertation betont die Bedeutung von dreidimensionalen Studien in urbanen Ökosystemen, um das Konzept der Nachhaltigkeit in Städten voranzutreiben. Deshalb werden kontinentübergreifende Forschungen für weitere Studien empfohlen, die die dreidimensionale Struktur aller städtischen Komponenten und ihre Auswirkungen auf die Außen- und Innentemperatur berücksichtigen.

**Schlüsselwörter:** Dritte Dimension, Städtische Morphologie, 3D-Modellierung, Städtische Wärmeinsel, Verstärkte Regressionsbaumanalyse, Innentemperatur.

# چکیده[1]

به جرات می توان گفت که در مطالعات خدمات اکوسیستم، بخصوص خدمات اکوسیستم شهری[2]، بعد سوم[3] که شامل "ارتفاع و حجم" می باشد اصلا مورد توجه قرار نگرفته است. هدف از این پایان نامه، تلفیق مفهوم بعد سوم در خدمات اکوسیستم شهری و استفاده از فواید آن می باشد. مطالعه بعد سوم دانش ما را در نحوه شکل گیری اقلیم خُرد شهری افزایش می دهد. هدف این پروژه دکتری پاسخ به سوالات ذیل می باشد: ۱) سطح آگاهی تحقیقات از بعد سوم خدمات اکوسیستم شهری، ۲) ارزیابی ارتباط شاخص های چندبعدی (دو و سه بعدی) با دمای سطح و ۳) ارزیابی الگوی دمای درونی و بیرونی در شهر. جهت پاسخ دادن به سوال های مطرح شده، این پژوهش به چهار فصل تقسیم شده است. فصل اول و دوم، که جایگاه خدمات اکوسیستم را در مطالعات شهری بررسی و جای خالی مفهوم بعد سوم در مطالعات خدمات اکوسیستم شهری را جستجو می کند. فصل سوم، شامل سه مقاله چاپ شده در راستای این پروژه دکتری می باشد. فصل چهارم، که نتایج بدست آمده را تجزیه و تحلیل می کند. نتایج بدست آمده نشان می دهد که مطالعات خدمات اکوسیستم شهری از معنی کلی و بنیادی به سمت سازش پذیری شهرها با پدیده تغییر اقلیم در حال تغییر است. همچنین نتایج نشان می دهد که ساختار متفاوت شهری بر شکل گیری الگوی دمای بیرون و داخل ساختمان ها موثر می باشد. استنتاج نتایج بدست آمده از این پایان نامه دو مورد را پیشنهاد می کند. اول، بررسی نقش ساختار های دو بعدی و سه بعدی بر روی دیگر شهر ها و تاثیر آن بر شکل گیری دمای بیرون و درونی ساختمان ها.

**کلید واژه ها**: بعد سوم، مورفولوژی شهری، مدلسازی سه بعدی، جزایر حرارتی شهری، یادگیری ماشینی، دمای درون ساختمان.

[1] Summary in Farsi/Persian
[2] Urban ecosystem
[3] Third-dimension

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# List of Published Papers Included

This thesis consists of the following three appended papers. These are referred to in the text with the running titles provided below.

**A) Peer reviewed paper**

Alavipanah, S., Haase, D., Lakes, T., Qureshi, S., 2016. Integrating the third dimension into the concept of urban ecosystem services: A review. Ecological Indicators, 72, 374–398. DOI: http://dx.doi.org/10.1016/j.ecolind.2016.08.010.

**B) Peer reviewed paper**

Alavipanah, S., Schreyer, J., Haase, D., Lakes, T., Qureshi, S., 2017. The association of multi-dimensional indicators on urban thermal conditions. Journal of Cleaner Production, 115-123, ISSN 0959-6526. https://doi.org/10.1016/j.jclepro.2017.12.187.

**C) For peer reviewed paper (submitted)**

Alavipanah, S., Haase, D., Makki, M., Qureshi, S. On the spatial pattern of urban thermal condition using indoor and outdoor temperatures. PLOS ONE. *Submitted July 2018*.

# List of Abbreviations and Acronyms

| | |
|---|---|
| BRT | boosted regression tree |
| BWh | Hot desert climate |
| CAD | computer aided design |
| Z-score | critical value |
| GIS | geographic information systems |
| DLR | German aerospace center |
| HD | historic district |
| LWIR | long-wave infrared |
| ND | new district |
| OLI | operational land manager |
| P-value | significance level |
| SVF | sky view factor |
| SVF | support vector machines |
| TIRS | thermal infrared sensor |
| 3D | three-dimensional |
| 2D | two-dimensional |
| USGS | United States geological survey |
| UNESCO | United Nations educational, scientific and cultural organization |
| UES | urban ecosystem service |
| UHI | urban heat island |

# Chapter I

## Introduction: The multi-dimensional setting of urban environment


**Figure 1.1** A satellite image (Worldview-3) of Yazd showing the historic urban district (left) that is accompanied with the new urban structure (right). The character of the building morphology at both districts underlines the change of landscape from past to present.

## 1. Urbanization

Since the creation of Earth, the biophysical feature (e.g. forest, water) of its surface has been always the subject of continuous natural change (e.g. wildfire, landslide and soil erosion). However, since the presence of "modern" form of humans (about 200.000 years go) direct human activity (e.g. agriculture and built-up area) and indirect human activity (e.g. deforestation and water extractions) (Deilami, 2017) addition processes became responsible of continuous change. In particular, during the past 300 years - in response to the industrial revolution - humans have intensively changed the land use and the land cover to serve their wellbeing. Humans have replaced natural land cover with man-made settlement such as buildings, roads and generally grey spaces: The birth of urbanization.

Despite the fact that the human population has lived a rural lifestyle over the course of the human history, now, the world population is experiencing unprecedented urban growth, in particular over the past 200 years. The portion of world's population living in urban area increased progressively from 3 percent in 1800, 14 percent in 1900 to 30 percent in 1950 and 55% in 2018 (UN, 2014). Yet though living in urban environment has become the norm for most of us and all regions are expected to urbanize further over the coming decades. The intensity of landscape transformation into urban area is exemplified in Figure 1.1. It shows the extent of the City of Yazd, Iran, from Proto-Elamite period (3400-2500 BC) (historic district at left) to present (new district at right). At the moment, though the extent of cities comprises less than 3% of the world's surface (Millennium Ecosystem Assessment, 2005), there is an extraordinary concentration of population. There are growing evidence that shows the rapid changes in urban areas worldwide that reflect pronounced shifts in the form and structure of cities. For instance the results of Frokling et al. (2013) reveal that cities are expanding their material infrastructure stock in both height and extent. However, cities are more than just agglomeration of people. Although it is difficult to determine when a settlement becomes a city, but it can be admitted that urban dwellers are responsible for many existing environmental problems. In fact the ecological footprint of cities, due to human activities in cities, is far beyond their urban boundaries (Strohbach, 2011). Regardless of the causes, human-induced changes in land use and the land cover have significant impact on the environment and the wellbeing of humans itself. Especially the global environmental change has an impact on the regional and global climatic conditions. Both studies with field measurement and modelling documented the strong impact of land surface process on the *changing climate*.

## 2. Climate Change in the urban environment

Scientists around the world have reached an overwhelming consensus that climate change is real and caused primarily by human activity (Changnon et al., 2006; Bender et al., 2010; Allan, 2011; Cook et al., 2016). Human activity, explicitly in cities, is the major cause of the changing climate. Cities became also the first victims and early responders to climate challenge. Cities are exposed to the impacts of climate change due to their fixed geographic location, dense population and infrastructure. Climate change poses serious threats to entire urban system, specifically to the quality of life. It is likely that climate change will be the cause of more frequent occurrence of extreme events such as rising sea level, storm surges and heat waves. Among all the effects of climate change, exposure to excessive heat are the most damaging climate extremes to the quality of human life and wellbeing (Rizwan et al., 2008) on hand. On the one hand, excessive heat has been the most prominent hazard causing weather-related human fatalities. Just in 2003, a severe heat wave was blamed for the death of more than 70.000 people in Europe (World Bank 2005; Robine et al., 2008). The risk of excessive heat in urban areas are amplified by *urban heat island (UHI)* effect (Patz et al. 2005, Tan et al. 2010) – a phenomenon of higher temperatures in urban areas than in surrounding rural areas.

## 3. Urban heat island

The first documentation of urban heat occurs in 1818 (Howard, 1833). At this time Luke Howard's published his groundbreaking study of London's climate. Emilien Renou and Wilhelm Schmidt made similar researches about Paris during the second half of 19$^{th}$ century (Renou, 1855, 1862, 1868) and Vienna early in 20$^{th}$ century (Schmidt, 1917, 1929). In this regard, numerous studies have reported the higher urban temperature than the rural or surrounding temperature on average (e.g., Oke 1981; Morris et al. 2001; Bottyan and Unger 2003; Kim and Baik 2004; Grimmond 2007). In the United States only, the heat stress cause by the excessive temperature in urban area is known as the deadliest damaging environmental extremes (Klinenberg, 2015). Extreme heat stress has the potential to increase in human mortality (Patz et al. 2005; Anderson and Bell, 2011; Huang et al., 2011), morbidity (McGeehin and Mirabelli, 2001), energy demand (Sailor and Pavlova, 2003; van Vuuren, 2011) in urban area. A literature survey of papers on UHI shows that 411 papers has been published just from 2009 to 2013 (Aleksandrowicz et al., 2017). This shows the importance of this topic for the future urban dwellers. Currently, 10 factors are well known to play a major role in the formation of urban heat divided to "natural" and built-up related factors:

*Vegetation cover (1) and evapotranspiration (2):* An abundance of urban vegetation cover proved to be a simple and effective way in reducing UHI effect. Urban vegetation has a role in local and global climate change mitigation through several mechanisms of cooling simultaneously (shading, increasing albedo and evapotranspiration) (Kjelgren and Montague, 1998).

*Water (3):* In urban areas, water bodies have a positive effect upon microclimate of the surroundings with the relative cooling impact due to the evaporative procedure of water bodies. Therefore, this might be one of the pretty efficient methods for cooling urban spaces generally. Previous researches have also proven that water bodies are capable of reducing the urban temperature around 2-6°C. It could be concluded that raise of evapotranspiration, due to water bodies or vegetation, can efficiently mitigate the influence of the UHI (Hathway and Sharples, 2012).

*Wind flow (4):* UHI occurs both during the day and night. The maximum intensity of heat island occurs 3–5 h after sunset (Oke, 1987). One major reason is that man-made infrastructure may block the wind flow into the cities. Therefore, cities retain much of its heat in roads, buildings, and other structures that prevents them from cooling down (Rajagopalan et al., 2014).

*Building height (5) and urban geometry (6):* Building geometrical arrangements in cities are shown to play role in shaping the intensity of UHI. Geometry of buildings and blocks interacts with the exchanging radiation between the earth and sky by the phenomena of reflection, absorption and thermal storage. The geometric combination of horizontal and vertical intra-urban surfaces is often referred to as 'urban canyon'. The urban canyon is measured by the relationship between the average height of the building in an urban canyon and the street width where the building is located (Souza et al., 2009).

*Sky view factor (7):* In the cities the narrow streets and high buildings create deep canyons and this vertical geometry plays an important role in development of UHI. A sky view factor (SVF) represents the extent of sky observed from a point as a proportion of the total possible sky hemisphere (Oke, 1981). The sky view factor indicates the amount of solar radiation absorption onto the surface (Bottyan and Unger, 2003).

*Albedo (8), surface characteristics (9) and urban material (10):* Material used in the urban fabric play a very important role in the urban thermal balance. Urban material absorb the solar radiation, depending the type of material and its physical and chemical characteristics, and disperse the absorbed heat through convective and radiative process in the atmosphere. The impervious surface in urban area absorb and retain more of the sun’s heat due to the darker color. Therefore, the temperature of most of cities is higher than their surroundings.

These are some factors that play a role in forming the UHIs without making them the claim to be complete. Still, each city is in a way unique. Nevertheless, one thing could be agreed: the excessive human activity in cities has an impact on its *urban ecosystem* as well as the regional climate (Corumluoglu and Asri, 2015).

## 4. Urban ecosystem

It is the principal of ecology that living and abiotic components are inseparably linked in an ecosystem (Forman, 1995). Subsequently, the ecosystem approach in the urban environment, known as urban ecosystem, are implemented by researches. Urban ecosystems are dynamic ecosystems and are like all ecosystems composed of biological components (vegetation, animals, people) and the abiotic environments of cities (soil, water, air, climate, and topography) (Grove and Burch, 1997). In urban ecosystems, due to the presence of people, the interactions are affected not only by the natural environment, but also culture, personal behavior, politics, economics and social organization. Urban ecosystems are the result of human activity in building urban area. Urban areas are what Lambin et al. (2006) call *one-way land conversion*. In other words, once land has been converted into urban use, it is difficult for that land to be converted to a relative unmanaged use.

The urban ecosystem is consisted of several components such as urban atmosphere, biosphere, hydrosphere, built infrastructure, pedo- and lithosphere. All the components have influence on shaping the regional climate in urban area. However, among all the biophysical components of an urban ecosystem, the built infrastructure (grey spaces) is responsible for higher temperature in urban area (Weber et al., 2014) and the urban biosphere and hydrosphere are responsible for cooling the temperature. Among the previous studies, most of them are associated with two-dimensional data. However, the *third-dimension* of urban systems such as, volume and height, has been ignored. Advance in collection and digitization of urban data allows the urban planners to progress meaningful three-dimensional spatial models of urban environment. In addition, the creation of three-dimensional urban environment provides essential information for different aspects of urban life. Three-dimensional urban environment also increases the level of details with urban area on a regional scale, in particular, will increase the knowledge of how complex urban environment shapes the micro-climate in urban area. With this background in mind, the research questions are as follows next.

## 5. Research questions

The aim of this dissertation is to: i) understand the current status of reseach on urban three-dimensional ecosystem and ii) increasing the knowledge of three-dimensional geometry – height-related aspect – in urban context. In particular, how the three-dimensional enclosure of urban districts could shape its thermal conditions. To quantify and analyze the intensity of UHI, two spatially explicit measurements were taken in to the account: land surface temperature and air temperature. This topic has been chosen because the urban thermal condition has become an important and challenging topic of our time – increase in extreme events that could intensify the UHI effect has become a big challenge for human well-being in the urban environment. The thermal indoor and outdoor conditions are both linked by the intensification of UHI, first directly affected by the urban geometry and second due to the building material, which make them interesting to compare. The city of Yazd was chosen because on the one hand it is a compact city and on the other hand one of the cities holding the historic and the new district with very different urban geometry as well as building material. The main questions are:

I. **The status of the current research addressing the third-dimension of ecosystem services in urban area:** How can urban three dimensional studies close the existing knowledge gap about sustainability in cities?

II. **Assessing the association of urban multi-dimensional (two- and three-dimensional) indicators on urban surface temperature:** Based on the presence of two very different urban geometries in the city of Yazd, how does the surface temperature varies?

III. **Variation of indoor and outdoor urban temperature pattern:** How does different urban settlement, in particular the newly built-up area and the historic buildings behave in different thermal conditions?

Chapter III contains the three manuscripts that were published as part of this dissertation. Manuscript 1 aims the first research question, while manuscripts 2 and 3 have their emphasis on questions II and III. A synthesis of all three manuscripts is provided in chapter IV. The following flowchart provides an overview of this dissertation.

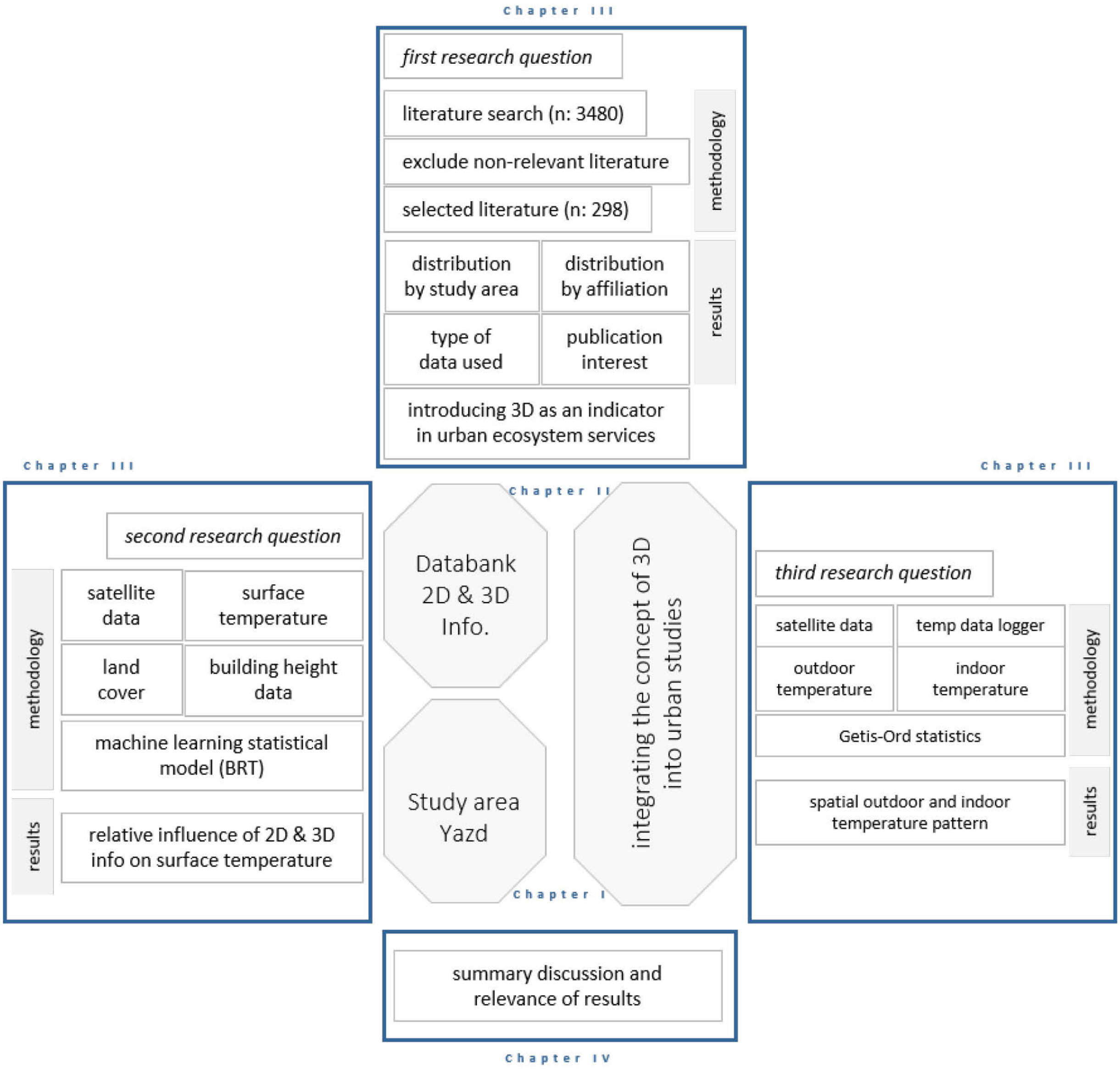


**Figure 1.2** Flowchart of this dissertation.

# Chapter II

## Concept and case study area

This chapter provides background information for a better understanding of the research papers of the thesis in chapter III. The focal point of the research papers underlines the current knowledge on three-dimension urban morphology in urban ecosystem, what is the role of two- and three-dimensional urban structure in shaping urban thermal conditions and finally the indoor and outdoor temperature pattern in the city of Yazd, Iran.

### 1. Three-dimensional urban ecosystem services

Urban areas are centers of demand for ecosystem services (Elmqvist et al., 2015). Based on an expected increase of up to 66% by 2050 of the population living in urban areas (United Nations, 2014), concerns about the quality of life in cities have also increased. Therefore, the concept of ecosystem services in urban areas has increasingly drawn attention (Haase et al., 2014). In this regard, a large number of studies have examined the state of the art in research on ecosystem services (Haase et al., 2014; Seppelt et al., 2015). Especially there are studies that have examined the key role of urban ecosystem services, in particular green spaces, in contributing to the regulation of urban microclimate (Doick and Hutchings, 2013). Other recent studies concluded that natural landscapes at the local level have substantial direct and indirect impacts on the quality of life in urban areas (Derkzen et al., 2015; Ervin et al., 2012). Among the previous studies, the researches mainly focused on a linear relationship of urban ecosystem services and provided to improve the socio-environmental quality of life in urban areas.

In other words, there are few number of studies that takes the 'volume and height', i.e the third-dimension into consideration. Covering the third-dimension of the urban environment (volume) into ecological studies will increase the level of details associated with studies on urban structure-function relationships. In addition, it can also increase knowledge about the complex functioning of the urban area. With this background in mind, the main objective of the *first paper* (chapter III, section 1) is to find: "The status of the current research addressing the third-dimension of ecosystem services in urban area: How can urban three dimensional studies close the existing knowledge gap about sustainability in cities?"

To fulfill the existing gap for urban planners to overcome the gap in our understanding of the relationship between urban structure and ecosystem services is to analyze built environment and urban ecosystem both in volume and space. 3D information is necessary to analyze dense and complex urban shape for a better understanding of the formation and intensification of UHIs. How urban 3D structures are related with UHI is the subject of the *research paper 2*.

## 2. Three-dimensional urban heat island

Other than the climatological factors such as climatic region (incoming solar energy), season, time of the day and wind regimes, the bio-physical factors that are dependent of human presence and activities – such as the topography of the city, size of the urban area, population density, inhabitant activity, type of building materials, vegetation structure, and physical form of the urban landscape – play an important role in the formation and intensification of heat islands in urban areas. As mentioned previously (chapter III, section 2), there are several important factors that play a role in shaping the UHI. However, generally there are two shortcomings in previous UHI studies. First, most UHI research has been conducted in mid-latitude regions (Ana-Maria et al., 2016). The UHI effect has been rarely studied in arid and semi-arid regions. Second, the temperature intensity in UHI studies has been mainly associated with a single dimension, such as the effect of UHI on public health (Pantavou et al., 2011; Huang et al., 2013; O'Neill et all., 2003; Gosling et al., 2009), increased energy demand for cooling infrastructure (Arifwidodo and Chandrasiri, 2015), increased global temperature (Teuling et al., 2010), the cooling effect of urban vegetation (Weng et al., 2004), and the association of horizontal land cover classes with surface temperature (Alavipanah et al., 2016). Using individual dimensions usually leads to homogenous scaled outputs (Wong and Lau, 2013).

Previous studies have argued that it is difficult to measure diversity on a homogenous scale; therefore, to capture the complexity of the urban environment, we must engage with multidimensional information and respective indicators (Alavipanah et al., 2016). This is the subject of *research paper 2*.

## 3. Indoor and outdoor temperature variation

The urban structure is cited as one of the major contributors to the artificial temperature increase in cities by the UHI effect (Soltani and Sharifi, 2017). Whereas people spend most of their time indoors (Statistical center of Iran report, 2015), the predominantly remote sensing methods does not allow us to assess the crucial indoor temperature (Theunisse, 2015). In the study area due to the harsh climatic condition spend more time indoor during the hot daytime hours than other regions. Therefore, to reduce the impact of heat stress in the context of urban climate change strategies, indoor and outdoor temperature variations in different urban settlements are of special interest, not only during extreme situations but also during average days and nights. Thus, information about temperature variations during the day and night is valuable for urban planners to help them better understand the factors influencing temperature fluctuations (chapter III, section 3). Land surface temperature (Rosenfeld et al., 1995; Stathopoulou and cartalis, 2009; Xiaoma et al., 2017), the UHI effect (Yang et al., 2011; Gago et al., 2013; Rosa dos Santo et al., 2017) and indoor temperature measurements (Yoshino et al., 2004; Yousef Mousa et al., 2017) have been frequently studied. However, outdoor and indoor temperature pattern data on a city scale where remote sensing data and instrumental measurements have been used are still lacking. This is the subject of the *research paper 3*.

## 4. The Yazd case study area

The city of Yazd situated in the central Iran (31.8974° N, 54.3569° E) is the capital of the Yazd Province (chapter III, session 2, Figure 1). Yazd is one of the most ancient cities of Iran, known as the world's largest adobe brick city and has been continuously inhabited since the Proto-Elamite period (3400e2500 BC) (Carter and Mathew, 1984). In 2017 the city of Yazd has been added to the United Nations Educational, Scientific and Cultural Organization (UNESCO).

The city stretches of approximately 250 $Km^2$, 1200 m above sea level and home to almost half a million people in the year 2015. Yazd is adjacent to two natural phenomenon: I) mountains (Ku-e Kharanaq and SHir-Kuh) and deserts (Siah-koeh Kavir, Abarkhouh Kavir and Bafgh

Kavir) (chapter III, session 3, Figure 1). The climate of the city is dominated by its arid surrounding and is considered to have a hot desert climate (BWh) by the Köppen-Geiger climate classification. Over the course of the year, temperatures typically vary from 0.5° C in the cold season and during the hot season the temperature is frequently above 40° C. The city of Yazd is known to be driest city of Iran with an average annual precipitation of about 60 mm. Yazd has historical struggled with water scarcity and hot temperature as there is no water running nearby the region.

Human beings have long recognized the intelligence of the nature in shaping the environmental surrounding. Therefore, the connection between the environmental climatic conditions in the urban design process has been highly appreciated since centuries ago. The city of Yazd is not an exception to this fact either. The people in Yazd are known to be diligent and have historically compensated the harsh climatic condition of the region in several two main ways: i) bringing water from several kilometers far to the city by using simple tools. To bring the water they have constructed network of underground channels – known as Kariz or Qanat – with gentle slopes that transports water from aquifers in highlands to the surface at lower levels by gravity. ii) Constructing traditional and well-architectural buildings that are in harmony with the harsh climatic condition. The physical morphology of Yazd consists of two main of constructed areas: the historical and new districts. The new urban settlement started in the second half of the $19^{th}$ century to expand. The residential areas in the new district are finished with "modern" material such as cement and concrete. The buildings are mainly two to three and barely multi-story buildings. Wide streets, trees on the sidewalks and a "right" angle arrangement of buildings with the streets are some characteristics of this districts. Whereas, the historical district is situated in the middle of the new district and stretches to almost 10% of Yazd's surface area. Adobe bricks (a mixture of clay soil, water and straw) – also known as mud-brick – are the major material used to construct the buildings in the historical district. One-story buildings, arch-shaped roof, narrow alleys, thick walls, small windows and central yard (named Sahn) are some of the spatial characteristics of the historical district. Planting vegetation in public area such as the main roads was not usual due to the water scarcity in the region and the vegetation cover was mostly limited to single trees in the Sahn. The hot thermal condition of the city, presence of two very differently urban morphologies such as building three dimensional structure, texture, density and material and good data quality are the main reasons making Yazd an ideal case study for this dissertation.

# Chapter III

## Research papers

List of papers in this chapter:

**A) Peer reviewed paper**

Alavipanah, S., Haase, D., Lakes, T., Qureshi, S., 2016. Integrating the third dimension into the concept of urban ecosystem services: A review. Ecological Indicators, 72, 374–398.
DOI: http://dx.doi.org/10.1016/j.ecolind.2016.08.010.

**B) Peer reviewed paper**

Alavipanah, S., Schreyer, J., Haase, D., Lakes, T., Qureshi, S., 2017. The association of multi-dimensional indicators on urban thermal conditions. Journal of Cleaner Production, 115-123, ISSN 0959-6526. https://doi.org/10.1016/j.jclepro.2017.12.187.

**C) For peer reviewed paper (submitted)**

Alavipanah, S., Haase, D., Makki, M., Qureshi, S. On the spatial pattern of urban thermal condition using indoor and outdoor temperatures. PLOS ONE. *Submitted July 2018*.

# Paper A

## Integrating the third-dimension into the concept of urban ecosystem services: A review

Ecological Indicators 72 (2017) 374–398

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journal homepage: www.elsevier.com/locate/ecolind

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Review

# Integrating the third dimension into the concept of urban ecosystem services: A review

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A B S T R A C T

The spatial configuration of urban environments and its impact on local and global ecological functions were the subject of recent urban ecosystem service (UES) research projects. The outcomes of these projects with respect to the data they used, however, mainly consisted of two dimensions (2D). Studies that assess aspects of the third dimension (3D) of UES – such as height, volume and shadowing effects – were absent. The objective of this paper is to contribute to a better understanding of the local ecological functions based on knowledge of three-dimensional UES. 298 articles were selected for in-depth critical analyses. The technical and computational approaches for extracting urban 3D structures and 3D structures of vegetation were the focus of the reviewed literature. Authors' affiliations would be a better indicator for assessing the spatial distribution of articles. Uneven distribution of knowledge among countries is related to the technical and scientific advancement of countries. There was a shift in the subtheme of reviewed publications discussing the concept of ecosystem services in the first few years, while later researchers' interests moved towards UES and adaptation of cities to the changing climate. Further studies should progress in the development of both 3D data and results. Implementing 3D data and results helps to better understand the coupling of humans and their environs. It will be then a critically important step toward developing ecologically friendly cities.

## 1. Introduction

The spatial configuration of urban elements such as buildings and grey, blue and green spaces is one of the main characteristics of the urban form (Schwarz, 2010). On the one hand, its complexity influences both ecological functioning and human well-being in urban areas (Ahern, 2012; Ervin et al., 2012; Alberti and Marzluff, 2004). On the other hand, any change in the green and blue densities or area sizes significantly affects the performance of urban ecosystem service (UES) (Gomez-Baggethun and Barton, 2013).

Urban areas are centers of demand for ecosystem services (Elmqvist et al., 2015), which are dependent on nearby and distant resources (Kremer et al., 2015). Based on an expected increase of up to 66 % by 2050 of the population living in urban areas (United Nations, 2014), concerns about the quality of life in cities have also increased. In addition, climate change, particularly extreme events, has become another challenge for human well-being in the urban environment. Therefore, the concept of ecosystem services in urban areas has increasingly drawn attention (Haase et al., 2014).

In this regard, a large number of studies have examined the state of the art in research on ecosystem services (Haase et al., 2014; Seppelt et al., 2015). For example, Breuste at al. (2013) studied different services that provided green spaces in cities. Doick and Hutsching (2013) reported a key role of green spaces in contributing to the regulation of urban microclimate. Other recent studies concluded that natural landscapes at the local level have substantial direct and indirect impacts on the quality of life in urban areas (Derkzen et al., 2015; Ervin et al., 2012).

Nevertheless, the number of studies investigating ecosystem services in urban areas is less than 10 % of all ecosystem services publications (Gomez-Baggethum et al., 2010; Hubacek and Kronenberg, 2013; Haase et al. 2014). Among these, only a few covered more multiple ecosystem services (e.g., multiple services). These articles mainly focused on the benefits that ecosystem services provide to improve the socio-environmental quality of life in urban areas, such as the provision of food, regulation of the microclimate and storm water retention (Haase et al., 2014).

Yet, among the studies on ecosystem services undertaken in urban areas, the dimension ‘volume and height’, i.e., the third-dimension of urban systems was ignored. A publication by Larondelle et al. (2014), included as one of the first studies on regulating services, covered more than two-dimensions by using land cover data and building height. However, research that studies UES three dimensionally and takes the volume of urban ecosystem services and the urban built environment into consideration is sorely lacking.

Incorporating the third-dimension of the urban environment (volume) into ecological studies will increase the level of details associated with studies on urban structure-function relationships. In addition, it can also increase knowledge about the complex functioning of the urban area. With this background in mind, the main objectives of this paper are as follows:

i) to review the status of the current research and the geographic distribution of research projects since the first publication that addressed the third-dimension of ecosystem services in urban areas,
ii) to evaluate the articles most relevant to our first research objective by applying a set of criteria, and
iii) to highlight the role of urban three dimensional studies in closing existing knowledge gaps about sustainability in cities.

## 2. Methods

To address our research objectives, we conducted a comprehensive literature search to estimate how well the third-dimension of UES was reflected in scientific publications. From this first main pool of literature, we applied three systematic steps to address our research objectives (Figure 1).

First, we refined the pool of literature to meet the concept of our research (first research objective). Second, we cross-examined the pool of literature with several criteria (twelve) to select the most relevant articles (second research objective). Finally, we analyzed the frequency with which the selected literature's objective was to highlight the role of 3D data in closing the existing knowledge gap (third research objective).

### 2.1 Selection of articles

To refine the pool of searched literature that met our criteria, two pertinent search engines for scientific and academic research were used, i.e., Scopus and ISI Web of knowledge, which hold the world's largest citation databases of peer-reviewed research literature. The search was set from the date of the first relevant article until the end of the year 2014. The year 2015 was not considered because some of the literature found in 2015 was not yet published.

To find publications that investigated urban 3D ecosystem services, the following keywords were used at each query: (1) "three-dimensional urban ecosystem services", (2) "urban three-dimensional ", (3) " three-dimensional shape", (4) "urban three-dimensional modeling", (5) "urban three-dimensional function", and (6) “three-dimensional city model". Moreover, ‘3D’ was replaced with ‘three-dimensional’ to comprehensively review the current state of 3D in the literature on UES. Additionally, the following keywords were used: (7) "3D urban ecosystem services", (8) "urban 3D ", (9) "3D shape", (10) "urban 3D modeling", (11) "urban 3D function" and (12) "3D city model". During our literature search, we did not include books, grey literature, extended abstracts, reports and presentations.

The initial search returned 3,480 published articles between the years 1991 to 2014. These publications possessed at least one of the defined keywords. Afterward, to exclude non-relevant articles, several systematic criteria were implemented. For instance, duplicated literature found in both citation databases was excluded (n=1,473). English is the first and main language of academic publications. Therefore, we did not consider literature that was not fully published in English (n=355). For example, the language of published articles by Zhang et al. (2014) was Chinese; however, the abstract was published in English. Hence, such publications were not included in our analysis. We also excluded literature published in non-academic journals or those with no common scientific themes related to our research. For example, the Journal of Mining and Mineral Engineering, the Journal of Mining and Metallurgy, the Oil & Gas Journal, among others, were not included. Consequently, 1,652 articles were not included, and 298 scientific publications received further in-depth analysis. Figure 1 illustrates the systematic process of selecting articles, as well as the amount of literature excluded.

We are aware of the fact that the selected publications do not comprise the complete number of papers that mentioned the keywords related to 3D UES. There are also certain studies that might not use the term ‘ecosystem services’ but actually perform an ‘ecosystem services analysis’ simply because they are from a different academic background. However, the selected publications provided us with a broad overview of the most significant literature that drew relevant conclusions on the evolution of three dimensional ecosystem service research. To meet the research objectives, each of the selected publications (n=298) was validated with the following twelve criteria, which were in the form of questions:

- Date of the publication (year),
- Subject area of the journal,
- Which city has been chosen as a study case,
- Target group of the publication,
- Data used to publish the article,
- Methodology used,
- Main results of the publication,
- Focus and highlight of the study,
- Objective of the publication,
- Relevance of the publication with respect to our research,
- Relevance of the publication with respect to urban ecological indicators, and
- Country of affiliation.

Using an exemplary subset of papers, we tested these questions and collected data in a Table. We used information from 'year of publication', 'study area' and 'affiliation of the publication' to analyze the annual publication growth and spatial distribution of publications. This approach helped us derive the current state of publication with respect to 3D UES (first research objective).

2.2 Evaluation of relevant articles

To critically evaluate the relevant articles and the existing knowledge gap with respect to urban 3D ecosystem services, we prepared a Table. From this Table, we used the information in 'data used to publish the article' and 'objective of the publication'. Then, we presented the field of interest and country-wise trend of publication (growth rate).

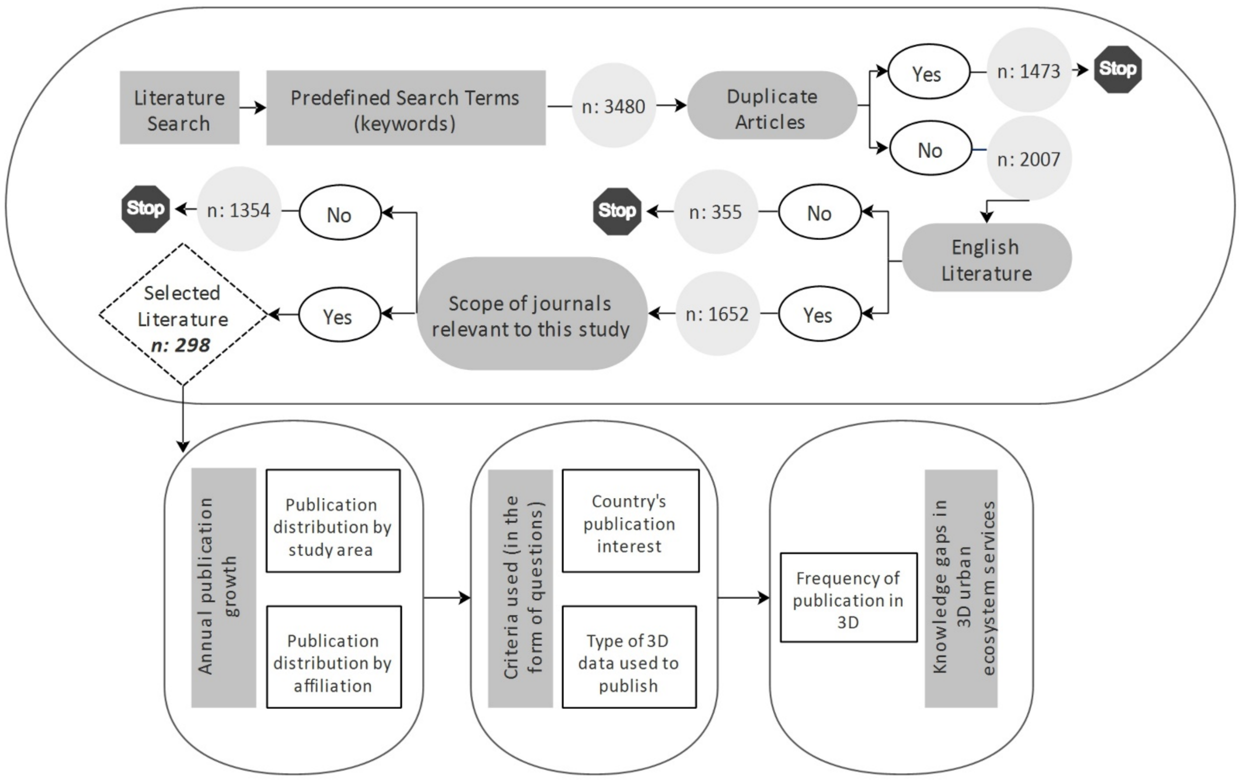



**Figure 1** Overview of the literature search. The upper Figure shows the literature selection process, and the lower graph illustrates the percentage of excluded literature as well as that of relevant literature.

## 3. Results

### 3.1 General pattern and spatial distribution

Of all the selected publications (*n=298*), we found approximately 19 % (*n=57*) of publications within the scope of the present study, and approximately 81 % (*n=241*) were generally within the scope of this study; however, they were not necessarily relevant. In other words, 57 of articles fit better with the scope of this study than the other 241 articles.

The 241 articles meet the criteria we set, i.e., they contained at least one of the twelve defined keywords, they were found in either Scopus or ISI Web of knowledge, they were published fully in English in academic and scientific journals and, finally, the scope of the literature was relevant to the objectives of our research. For instance, an article published by Lee (2007) contains one of our search keywords; however, the paper discusses “a three-dimensional navigable data model to support emergency response in micro-spatial built-environments”, which was not relevant to the scope of our research.

The other 57 publications meet the previous criteria, in addition to discussing UES to a certain extent, namely they possess at least one of the twelve keywords we defined. Nevertheless, this approach does not mean that the papers necessarily have three-dimensional results in ecosystem services as an outcome. For example, Aubrecht et al. (2009) investigated the urban land use function using 3D GIScience data; however, their results did not address UES. An overview of the selected literature (n= 298) shows an increase in the number of publications over time (Figure 2), from a single publication in 1991 by Rabie (1991) to 30 publications in 2014. This Figure represents a trend of increasing publications over the past 30 years.

While Figure 2 shows the annual publication trend, Figure 3 depicts the proportion of publications in each country, i.e., the spatial distribution of selected literature. It is clear that the number of publications in the northern hemisphere is higher than that in the southern hemisphere. A possible reason is the larger population size in the northern hemisphere. To better understand the spatial distribution of the selected literature, we analyzed the author affiliations (Figure 3) and the study area of the publication (Figure 3). This approach allows us to distinguish between countries interested in publishing and those that are the subject of the studies.

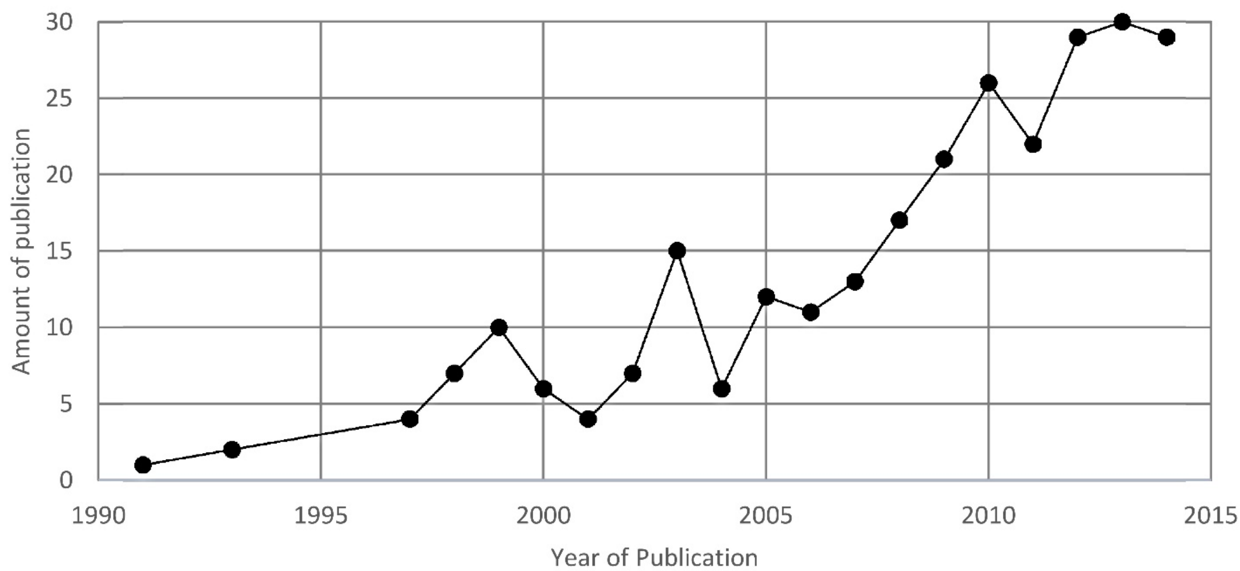



**Figure 2** Number of selected publications per year (n= 298).

Figure 3 presents an uneven distribution of knowledge, not only at a global scale, but also among countries within the same continent. Figure 4 depicts this uneven distribution of knowledge across continents. It is clear that Europe is the leader in the publication of literature on UES, followed by Asia and North America. Interestingly, we observed an uneven distribution of publications among countries of the same continent. As some countries are more advanced in science and technology, their contribution to the published literature is larger than those that are less advanced. For example, Germany is the leading country with respect to publishing articles concerning UES in Europe; China is the leader in Asia and USA in North America.

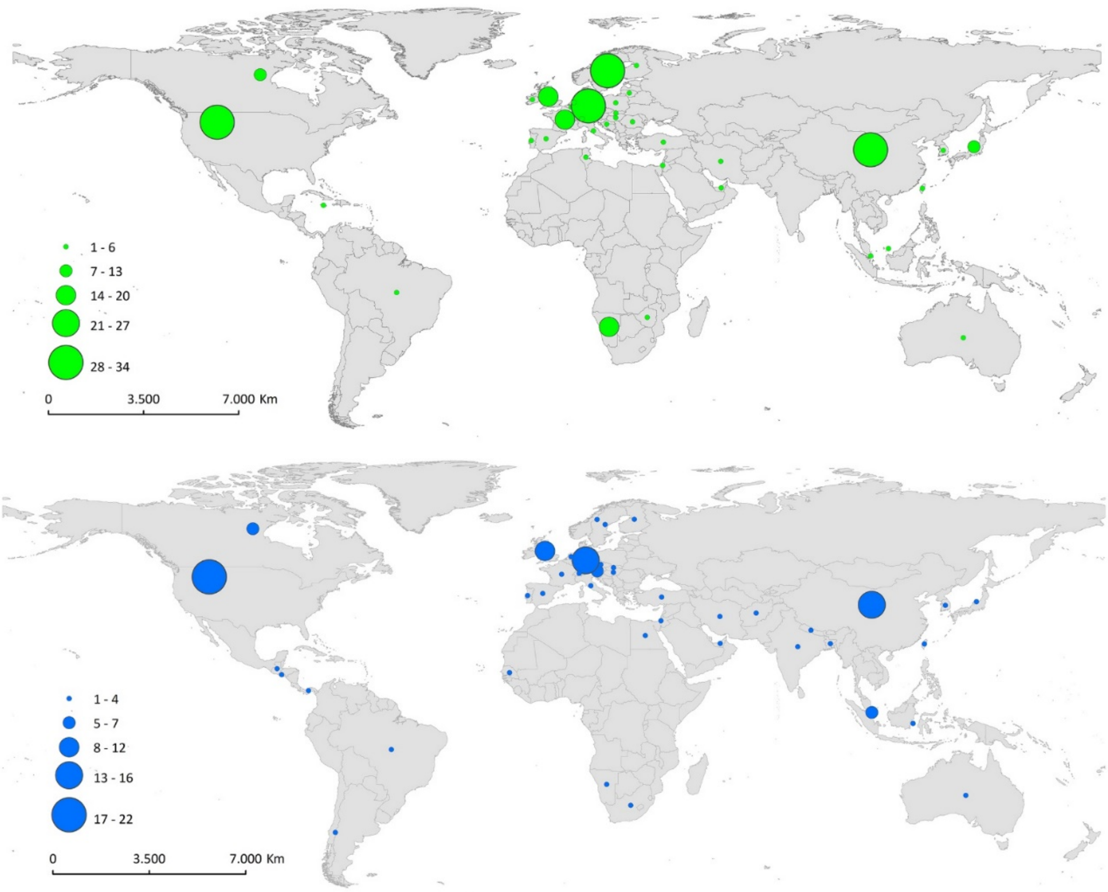



**Figure 3** Spatial distribution of the selected publications. The upper Figure shows the spatial distribution of publications based on their affiliation (n= 278). The affiliation of 20 publications was not clear. The lower Figure shows the spatial distribution of publications based on their study area (n= 258). 40 publications did not choose a specific study area.

Figures 3 and 4 show the overall proportion of countries that publish literature on UES. Likewise, these Figures show each country's publication growth rate in the field of UES. For instance, China has the highest number of publications (n= 34), followed by Germany (n= 33) and the United States (n= 32). China not only has the largest publication pool in the mentioned field but also shows a fast annual publication number.

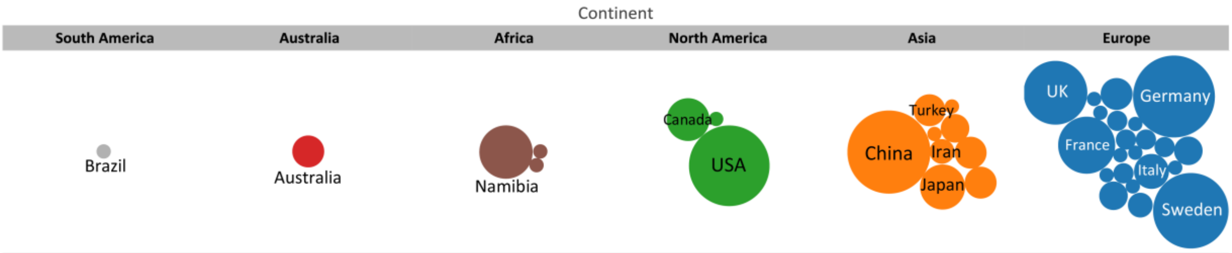



**Figure 4** Proportion of the total papers published on UES in each continent.

3.2 Data used in the publications on urban ecosystem services and 3D

For each of the publications, twelve questions associated with the objectives of our research were answered. One of the twelve questions asked what type of data was used in the study. The data used were categorized into four groups: i) sensor-based data, ii) ground-based data, iii) computer-based data and iv) aesthetic data. The first group included those publications that collected data from various sensors (sensor-based group): either airborne sensors, such as remote sensing, or terrestrial sensors, such as meteorological stations. These studies mainly focused on extracting the physical and 3D structure of urban infrastructure. They also used various methodologies to combine different types of sensors, which included active and passive sensors to extract the most accurate results from the 3D pattern of urban areas. In total, 141 articles were grouped as sensor-based. An article published by Tang et al. (2008) is an example of the implementation of 3D data derived from satellite imagery. They used linear laser source Lidar from different locations and angles of one object in order to generate a 3D data model for the entire objects.

For the second group, we applied land use/land cover or census data (ground-based-data). The use of Computer Aided Design (CAD), Geographic Information Systems (GIS) and surveying, among others, fell within this group. This group contained 118 articles. One of the examples is the publication by Jeager and Scwick (2014). They have used land use and land cover data in order to measure "urban sprawl" in Switzerland.

The focal point of their study was improving the measurement of urban sprawl with the application of land use and census data. A third group was comprised of those studies that obtained data from models and simulations (computer-based). The focal point of such articles was developing accurate and efficient algorithms to model the urban microclimate or developing a graphic code that consumed less computational resources. Twenty-four publications were considered in the computer-based group. For example, Suh and Shibasaki (2007) published an article that developed a navigation simulation in a complex urban environment. The final group was comprised of publications with an aesthetic background. These publications focused on the processes that reconstruct a virtual urban feature from camera pictures. Fifteen of the selected articles were in this group; for example, the article published by Liu and Stamos (2012) developed a systematic approach that used 2D texture mapping onto a 3D range model of a variety of urban scenes. Figure 5 illustrates the distribution of the type of data used among the mentioned categories.

Our results show that approximately 86 % of the selected articles focused on developing methods to extract the urban physical infrastructure and solid surfaces, to model urban structures and buildings, and to simulate urban microclimates. These publications have used at least one form of remotely sensed data. This pattern shows the important role of satellite data in urban studies.

### 3.3 Study objectives of the publications on UES and 3D

The information extracted from 'data used to publish the article' and 'objective of the publication' of the selected literature was used to present the incidence of studies with similar objectives. Figure 7 illustrates this frequency per country. These results were then used to establish the existing knowledge gap in the publications on urban 3D ecosystem services. The objective of most of the publications was city modeling (n= 49), urban extraction (n= 45), visualization (n= 36), urban planning (n= 31), Urban Heat Island (UHI) (n= 22), GIS (n= 20), energy exchange (n= 10), navigation (n= 10) and 3D cadastre (n= 5).

The objective of the first group was to accurately model the infrastructure by applying mathematical and geographical methods. These publications were categorized as 'city modelling'. For example, Nüchter et al. (2011) used panoramic 3D laser scans to model the historic German city of Bremen. This information was used to represent a 3D pattern of the study area. Gamba et al. (2002) discussed various airborne sensors that were used to retrieve the earth topology, such as the construction of a 3D shape at UCLA, USA.

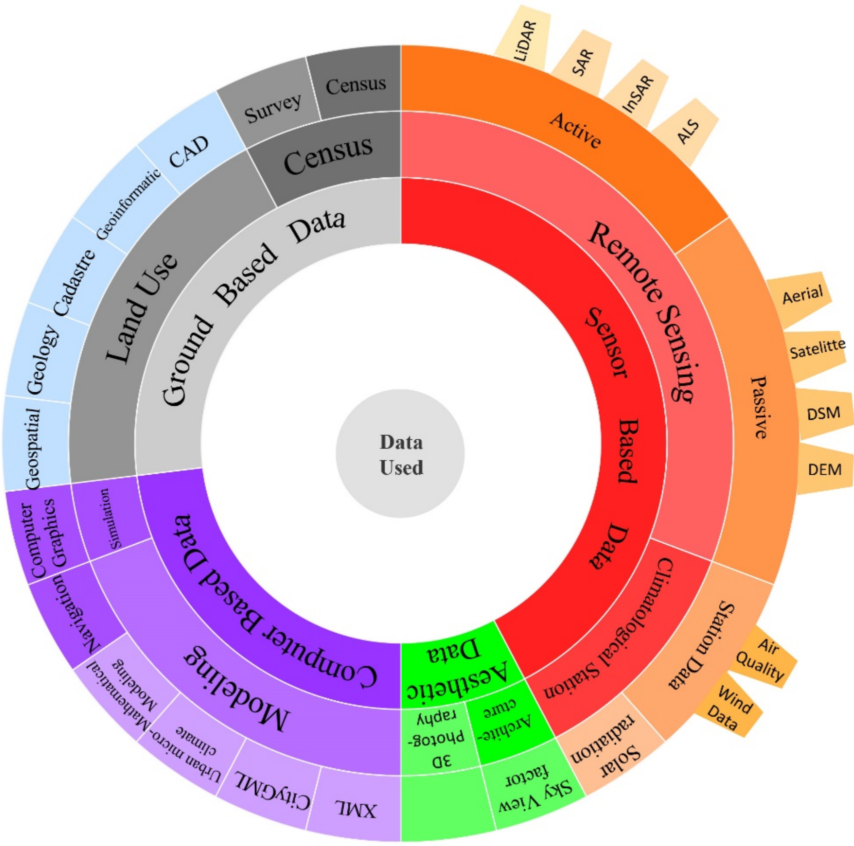



**Figure 5** Distribution of articles among the four categories based on the data used to publish their results.

The third group was focused on 'visualization'. These articles presented various mathematical and graphical approaches to improve the visual appearance of the urban infrastructure. Lu et al. (2011) presented a large volume of geometric urban models to reconstruct the virtual world. In their paper, they presented a framework that generates seamless 3D architectural models from 2D ground data that utilizes elevation and height information. The fourth group of publications is 'urban planning and management'. Wu et al. (2010) discussed the technical issues of developing a public virtual 3D urban planning platform. In their paper, they used web services and service-oriented architecture to support their visual planning.

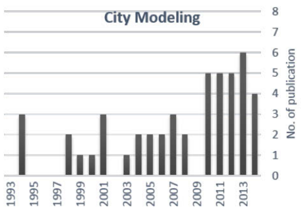
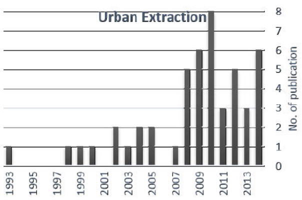
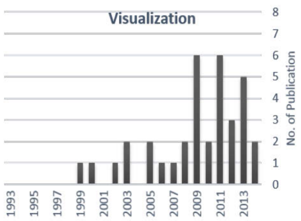
The focal point of the next group of articles was on UHI. The objective of those articles was to simulate UHI in 3D. Wong and Lau (2013) investigated the concentration of green roofs in the densely occupied old urban district of Mongkok, Hong Kong. Their results indicate that an adequate exposure to sunlight is considered as an enabling factor for green roofs. The focus of the sixth group was on Geographic Information Systems (GIS). These publications yielded cost-effective methods for producing accurate results. For instance, Alexander et al. (2009)

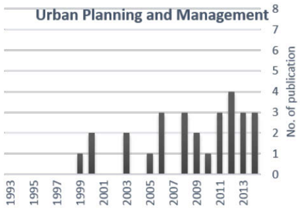
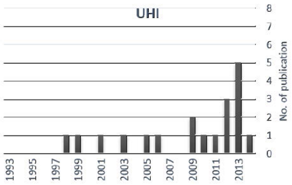
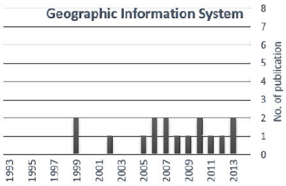
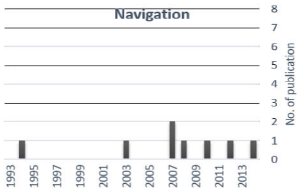
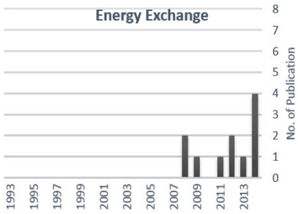
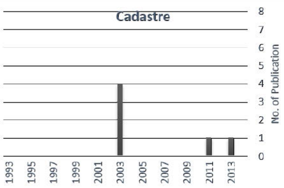
emphasized retaining a vector model that was suiTable for representing regular building structures.

The objective of the seventh group was to assess the flow of the exchanged energy (i.e., 'energy exchange'). For example, the study published by Jose et al. (2012) used a three-dimensional urban solar radiation model to explain the urban atmosphere and canopy energy exchange in Madrid, Spain. The eight group explored various methods to develop a navigating vacuum system for buildings and urban traffic systems. Garcia et al. (2014) used techniques and protocols incorporated into a web-based prototype for navigation and interaction in a virtual urban model. Such models facilitate an online navigation through cities.

The ninth group of publications concentrated on Cadastre. They presented the development of an automatic conversion of Cadastre data into digital formats and linked it with census data. For example Stoter and Salzmann (2003) fulfilled the need of a 3D Cadastre that was based in a planar map that portioned 2D space. They presented a 3D cadastre that showed infrastructure above and under the ground, i.e., cables and pipes.

**Table 1** Frequency of publication objectives per country.

| Objective of the study | Case study countries | Aim | Total publications |
|---|---|---|---|
|  | USA: 9; China: 6; UK, Germany: 5; Switzerland, Netherlands: 3; Singapore, Portugal, Japan: 2; Iran, Zimbabwe, Turkey, Taiwan, Spain, Lithuania, Japan, France, Croatia, Belgium, Austria, Australia. | Modeling and simulating the 3D shape of urban areas. | 49 |
|  | Germany: 10; France: 9; Italy: 5; USA: 4; Canada: 3; Switzerland, Turkey, UK: 2; Austria, Belgium, China, Ireland, Japan, South Korea, Spain, Sweden, Taiwan: 1. | Extracting the urban physical structure using mainly remote sensing data. | 47 |
|  | Germany: 6; China: 4; France, Japan, USA: 3; Iran, Canada, UK: 2; Belgium, Ireland, Italy, Israel, Namibia, Portugal, Singapore, South Kore, Spain, Turkey: 1. | Improving graphic algorithms for faster and better vision. | 36 |

| | | | |
|---|---|---|---|
|  | China: 6;<br>USA: 4;<br>Canada, UK: 3;<br>Germany: 2;<br>Australia, Finland, France, Italy, Malaysia, Netherlands, Singapore, South Korea, Switzerland, Taiwan, Turkey: 1. | Development of urban dynamic processes and impacts upon cities. | 31 |
|  | China: 6;<br>Germany, Hungary, Japan, Taiwan, USA: 2;<br>Australia, France, South Korea, UK, UAE: 1. | Mapping the heat island of different study areas. | 22 |
|  | China, UK: 3;<br>South Korea, Sweden, USA: 2;<br>Brazil, Canada, Check Republic, Singapore, Switzerland: 1 | Mapping | 18 |
|  | USA: 3;<br>Germany: 2;<br>China, France, Israel, Spain, UK: 1. | Improving navigation systems with 3D data | 10 |
|  | Germany: 2;<br>Slovakia, UK, Israel, Portugal, South Korea, Spain, USA: 1. | | 9 |
|  | Netherlands, Israel, Germany, Norway, China: 1. | Automatic digitizing hard copy cadastre data. | 5 |

## 4. Discussion

4.1 Current state of research on 3D urban ecosystem services

The number of results over the years shows that although the progress towards 3D research is relatively slow and in infant stages, it has received plenty of attention across different fields of studies. An overview of the results shows that the number of publications has increased over the years, even throughout the vicissitudes of different years. Our results show that the publications on 3D started in 1991 (Rabie, 1991), where the authors simulated an urban morphology. Then, 30 publications were produced in 2014, which discussed various forms of 3D patterns in urban areas and UES. Figure 2 shows an improvement in the published literature on 3D, which was initiated in the late 1990s.

Along with the temporal overview of the selected publications, the findings with respect to the spatial distribution of the publications are also interesting. Developed countries possess a considerable proportion of publications concerning urban 3D ecosystem services. In addition, most of the publications with study areas in developing countries were affiliated with institutes or organizations located in developed countries. In certain cases, the study area and the affiliations did not match. For instance, the study area of a publication by Tabib-Mahmoudi et al. (2013) was Rio de Janeiro, Brazil; however, the affiliations of the authors were the University of Tehran and the German Aerospace Center (DLR). Therefore, the distribution of the selected publications was assessed based on both the study area of the publications (*study area-spatial-distribution*) and the affiliations of the authors (*affiliation-spatial-distribution*). Figure 3 describes both spatial distributions.

However, there were also certain publications with no specified study area (n= 40). These publications were usually focused on the development of methodologies. Figure 3 shows that the spatial distribution of articles is denser in the northern hemisphere for both spatial distribution scenarios. Even some studies located in the southern hemisphere were affiliated with northern hemisphere academic institutions. There are possibly two reasons that can explain this pattern. First, approximately 90 % of the human population lives in the northern hemisphere, in comparison to the 740 million people who live in the southern hemisphere (Worldmeter, 2016). Second, several countries in the southern hemisphere suffer from poverty and a lack of experts and experience. Therefore, we suggest that the affiliation-spatial-distribution maps define a better spatial distribution of publications than the study-area-publications. This option may be effective especially for future review articles. This type of spatial distribution better represents the research investment from countries than the other method.

The results of the affiliation-spatial-distribution show a larger publication pool for certain continents and countries than others (Figure 4). Europe stands in first place with 137 publications. Asia, North America, Africa, Australia and South America follow. A closer look at the number of publications in each continent and country shows an unequal distribution of knowledge which is probably because of unequal distribution of research interest. Each continent has countries actively publishing literature. For instance, in Europe, countries such as Germany, France and the UK have higher publication number than Ireland, Hungary, Italy and Sweden. Alternatively, in Asia, several countries such as Iran, Turkey, and Japan contribute significantly to publishing articles; however, China publishes most of the literature.

Figure 4 presents the overall proportion of countries publishing studies on urban 3D ecosystem services. However, this Figure does not allow a complete understanding of the interest of those countries in publishing about urban 3D ecosystem services. With respect to the number of publication per year, certain countries have shown improved productivity, such as USA, Germany and China. Moreover, number of publications show that China seems to be more eager than any other country to publish on this topic. Conversely, other countries show no changes over time in their number of publications, such as Hungary and Belgium. Finally, the last group is comprised of those countries that seem to be losing interest in publishing about 3D UES. Australia and Japan are among these countries. Their annual number of publication has been reducing in recent years.

While certain countries are pioneers in publishing about a particular subject, others are more advanced in publishing on other themes. Our results explicitly show that the USA, China and Germany are pioneer countries in publishing articles on advanced airborne satellite imagery, LiDAR as well as intensive simulation algorithms and parameters in urban areas. For example, Kim and Medioni (2011) presented a study that detected large amounts of objects with 3D aerial scans and LiDAR (published in the USA). Longyu, from the Institute of Urban Environment of China, (Shi et al., 2009) published a study on the horizontal and vertical increase in Shanghai over time. Soergel et al. (2005) integrated SAR 3D data for image interpretation in urban areas. The mentioned countries are more progressive in terms of technology and applied sciences. This characteristic enables them to analyze larger data sets and run more complex simulations. Less developed countries try to focus on publishing mainly case studies. This pattern could be an indication of lower investment in research as well as restrictions on the availability of advanced technologies in less developed countries.

4.2 Shift in publications over time and their scaling in urban areas

To address the second research question, we used the results of 'data used' and 'objective' of selected articles (Figures 6 and 7). 'Data-used' presents the form of the 3D data used in the literature. Furthermore, the 'objective' of the selected articles highlights the aim of each publication. Therefore, we considered the publications that used 3D data and, at the same time, those in which the objective and aim of their publication was closely related to our research. This method enabled us to follow the interest of researchers in UES.

Early ecological publications argued about the concept of ecosystem services. These articles were oriented towards ecosystem conservation at different spatial, service and functional scales (Breuste et al., 2013). They concentrated on how particular ecosystems provided services for humans and how humans affected those services (Chaudhary et al., 2015). Such publications reflect the idea of defining economic values for nature. While searching for the articles most relevant to our research, we found a range of authors concerned with putting a price on nature (Fairhead et al., 2012). According to their perspective, such valuation can ultimately lead to exploitation of the environment, as well as separation rather than a closer relationship to it (Chaudhary et al., 2015).

In recent years, several individual studies focused on implementing the knowledge of ecosystem services in urban areas rather than focusing on the basic unit of ecosystem services (Jim, 2012; Ahern et al., 2014; Wolch et al., 2014). As Breuste et al. (2013) mentioned, implementing the knowledge of ecosystem services in urban areas is a constant challenge, particularly in the megacities of developing countries. However, its benefits are well understood by urban planners and landscapers. Therefore, in recent years, remote sensing technologies have become popular and have provided useful data for mapping ecosystem services and performing cross-scale urban ecological research at various spatial, temporal, and spectral scales. The observation of patterns in human settlements and activities with Earth observation data is a key element in most of the selected papers. A major part of selected publications (86 %) used Earth observation data to some extent to establish their results, i.e., by using remotely sensed data. Remotely sensed data were used to extract information on the solid structure of urban areas. The purpose of such publications was to run more accurate and efficient models and simulations of urban areas (Chun and Guldmann, 2014). These publications used remotely sensed data through the application of advanced methodologies to extract more accurate and reliable urban structures, forms and patterns.

A review of the selected publications shows that there was a shift in the sub-theme of ecosystem services. While publications in the first few years discussed the concept of ecosystem services, later interest moved towards local studies, especially towards the role of ecosystem services in urban areas, i.e., UES.

Recent ecosystem service publications have shown greater interest in the integration and adaptation of cities to the changing climate. At a time when humans have been becoming increasingly urbanized it is projected that climate change increases the risks for people living in urban areas (IPCC, 2014). Thus, the role of UES in adaptation and mitigation is being recognized more ever than before (Alavipanah et al., 2015). Publications such as that of Zhaoyang et al. (2013) and Longyu et al. (2009) show the growing demand for the concept of ecologically friendly cities. In the meantime, we recognized that three-dimensional studies are increasing with improvements in the processing power of computers as well as improvements in satellite imagery resolution. Studies published by Heo et al. (2013) and Bartie et al. (2013) are good examples of this.

### 4.3 Research gaps and future prospects

Out of all the selected publications, ten articles provided new insights relevant to urban 3D ecosystem services. Moreover, out of these ten papers, six focused on the 3D aspect of UHI (Nichol et al., 2005; Matejicek et al., 2006; Unger, 2006; Noori-kakon and Mishima, 2009; Wu et al., 2013; Wong et al., 2013). The fact that these articles studied various cities worldwide, indicates the importance of this topic. However, the gap in number of published articles in 3D UHI can be seen. UHIs could directly and indirectly affect human thermal comfort and health of urban residents, particularly elderly people. 3D information is necessary to analyze dense and complex urban shape for a better understanding of the formation and intensification of UHIs. Therefore, future research in this field could fulfill the existing gap for urban planners.

The other four articles were dedicated more to the scope of this review than any other selected publications (Middle et al., 2014; Gret-Regamey et al., 2013; Chun and Guldmann, 2014; Chen, Xu and Devereux, 2014). These papers investigated UES and explicitly highlighted the 3D aspect of their results. However, only the combination of Gret-Ragamey et al. (2013) and

Middle et al. (2014) hits the importance of studying the third-dimension of ecosystem functions and services in urban area. Both publications have a specific focus on urban 3D configuration (Middle et al., 2014) and Gret-Ragamey et al. (2013) presents UES for sustainable urban planning. Middle et al. (2014) describes the impact from of urban areas and designs on the mid-afternoon microclimate in the Phoenix local climate zone. The goal of this paper was to find effective urban form and design strategies to ameliorate temperatures during the summer months. Their findings show that advection, solar radiation and local shading play an important role in the distribution of temperature in the 3D Figures of urban configurations. In contrast, Gret-Ragamey et al. (2013) describe UES as an important factor for sustainable urban development with the growing number of city dwellers. The approach of this study has been illustrated in the design of Abu Dhabi, United Arab Emirates from scratch. They approached an interactive 3D visualization of UES to report a sustainable urban development. Their approach developed knowledge and awareness of interactions between ecosystem services. Embedding three-dimensional data in UES is not only interesting for future inter/multi-disciplinary studies, but it can also assist in making sound decisions for sustainable urban planning.

Our review of selected literature indicates that the relationship between urban structure and ecosystems services is poorly understood. The absence of reliable 3D data was the major reason for this deficiency. However, the focus of scientists and urban planners in recent years is to use the concept of three-dimensional data to study the integration and adaptation of cities to the changing climate. With improvements in computer processing and higher resolutions of remote sensors, the academic community started publishing reliable results that are closer to real interactions. Furthermore, in recent years, climate change has become an important consideration for pollution and heat mitigation, citizen wellbeing and energy consumption at the urban scale. Many cities started to pay attention to providing adaptation and mitigation strategies. Therefore, measuring UES and built infrastructure both in volume (3D) and space is a promising way to overcome the gap in our understanding of the relationship between urban structure and ecosystem services.

## 5. Conclusions

Ecosystem services have not only raised attention in a wide variety of scientific publications but have also become a formal body of knowledge and policy. Considering the keywords applied for this review paper, based on the mentioned criteria, 298 articles were finally selected. From the selected publications, only 18.7 % fit the scope of this review. Moreover, within this percentage, only two articles refer to the three-dimensional concept. Three-dimensional study of urban areas improves our understanding of the interaction between fabricated areas and UES. In addition, it will also help to advance the concept of sustainability in cities, a sustainability based on the services that nature generously brings us free of charge.

Therefore, further investigations that consider urban infrastructure and UES in three dimensions are highly recommended. Such studies will ultimately allow cities to adapt to the changing climate under different scenarios. This way, such perspectives will generate principles to guide urban planning and design by considering the benefits of understanding the human environment, which will provide benefits with respect to the adaptation of cities to the changing climate. In other words, researchers that deal with the concept of sustainability and urban sustainability, in particular, are struggling to conceal the free service that nature has provided to humans. Therefore, as cities are growing around the world, knowledge about UES can improve our understanding and guide the development of more sustainable and resilient urban systems.

## Acknowledgment

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# Appendix A.

298 selected and reviewed articles.

| Authors | Title | Source titel | Year | Volume | Issue | P. Start | P. End | Doi |
|---|---|---|---|---|---|---|---|---|
| Ahern, j., cillers, s., and niemelä j. | The concept of ecosystem services in adaptive urban planning and design= a framework for supporting innovation | Landscape and urban planning | 2014 | | | 254 | 259 | |
| Al-douri f.a. | The impact of 3d modeling function usage on the design content of urban design plans in us cities | Environment and planning b: planning and design | 2010 | 37 | 1 | 75 | 98 | 10.1068/b35055 |
| Alexander c., smith-voysey s., jarvis c., tansey k. | Integrating building footprints and lidar elevation data to classify roof structures and visualise buildings | Computers, environment and urban systems | 2009 | 33 | 4 | 285 | 292 | 10.1016/j.compenvurbsys.2009.01.009 |
| Alkhoven p. | City map to virtual reality: 3d reconstruction models of cities | Gim international | 2005 | 19 | 10 | 84 | 85+87 | |
| Al-kodmany k. | Gis in the urban landscape: reconfiguring neighbourhood planning and design processes | Landscape research | 2000 | 25 | 1 | 5 | 28 | 10.1080/014263900113145 |
| Allani-bouhoula n., perrin j.-p. | Architectural knowledge for three dimensional reconstruction | International journal of design sciences and technology | 2010 | 17 | 1 | 23 | 38 | |
| Alobeid a., jacobsen k., heipke c. | Comparison of matching algorithms for dsm generation in urban areas from ikonos imagery | Photogrammetric engineering and remote sensing | 2010 | 76 | 9 | 1041 | 1050 | |
| An s.m., kim b.s., lee h.y., kim c.h., yi c.y., eum j.h., woo j.h. | Three-dimensional point cloud based sky view factor analysis in complex urban settings | International journal of climatology | 2014 | 34 | 8 | 2685 | 2701 | 10.1002/joc.3868 |
| Aneja, vp; kim, ds; das, m; hartsell, be | Measurements and analysis of reactive nitrogen species in the rural troposphere of southeast united states: southern oxidant study site sonia | Atmospheric environment | 1996 | 30 | 4 | | | 10.1016/1352-2310(95)00294-4 |
| Argany m., mostafavi m.a., akbarzadeh v., gagne c., yaagoubi r. | Impact of the quality of spatial 3d city models on sensor networks placement optimization | Geomatica | 2012 | 66 | 4 | 291 | 305 | 10.5623/cig2012-055 |
| Astier pena, m p; pueyo uson, m j; aza pascual-salcedo, m; vicente barra, a | [rational use of drugs. Viewpoint of the users in the 3d health area of saragossa]. | Atencion primaria / sociedad espanola de medicina de familia y comunitaria | 1995 | 16 | 6 | 344 | 350 | |
| Atkinson b.w. | Numerical modelling of urban heat-island intensity | Boundary-layer meteorology | 2003 | 109 | 3 | 285 | 310 | 10.1023/a:1025820326672 |

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| Aubrecht c., steinnocher k., hollaus m., wagner w. | Integrating earth observation and giscience for high resolution spatial and functional modeling of urban land use | Computers, environment and urban systems | 2009 | 33 | 1 | 15 | 25 | 10.1016/j.compenvurbsys.2008.09.007 |
| Auer s., balz t., becker s., bamler r. | 3d sar simulation of urban areas based on detailed building models | Photogrammetric engineering and remote sensing | 2010 | 76 | 12 | 1373 | 1384 | |
| Axelsson, pe | Processing of laser scanner data - algorithms and applications | Isprs journal of photogrammetry and remote sensing | 1999 | 54 | 02. Mrz | | | 10.1016/s0924-2716(99)00008-8 |
| Ayhan e., erden o., gormus e.t. | Three dimensional monitoring of urban development by means of ortho-rectified aerial photographs and high-resolution satellite images | Environmental monitoring and assessment | 2008 | 147 | 03. Jan | 413 | 421 | 10.1007/s10661-007-0129-x |
| Balz t., becker s., haala n., kada m. | Using real-time sar simulation to assist pattern recognition applications in urban areas | Pattern recognition and image analysis | 2008 | 18 | 3 | 412 | 416 | 10.1134/s1054661808030085 |
| Bamler r., eineder m., adam n., zhu x., gernhardt s. | Interferometric potential of high resolution spaceborne sar | Photogrammetrie, fernerkundung, geoinformation | 2009 | 2009 | 5 | 407 | 419 | 10.1127/1432-8364/2009/0029 |
| Bartie p., clementini e., reitsma f. | A qualitative model for describing the arrangement of visible cityscape objects from an egocentric viewpoint | Computers, environment and urban systems | 2013 | 38 | 1 | 21 | 34 | 10.1016/j.compenvurbsys.2012.11.003 |
| Barton j., plume j., parolin b. | Public participation in a spatial decision support system for public housing | Computers, environment and urban systems | 2005 | 29 | 6 spec. Iss. | 630 | 652 | 10.1016/j.compenvurbsys.2005.03.002 |
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| Benhamu m., doytsher y. | Toward a spatial 3d cadastre in israel | Computers, environment and urban systems | 2003 | 27 | 4 | 359 | 374 | 10.1016/s0198-9715(02)00036-4 |
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| Biljecki f., ledoux h., stoter j., zhao j. | Formalisation of the level of detail in 3d city modelling | Computers, environment and urban systems | 2014 | 48 | | 1 | 15 | 10.1016/j.compenvurbsys.2014.05.004 |
| Billen r., zlatanova s. | 3d spatial relationships model: a useful concept for 3d cadastre? | Computers, environment and urban systems | 2003 | 27 | 4 | 411 | 425 | 10.1016/s0198-9715(02)00040-6 |

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| Billen r., zlatanova s. | Moving into multi dimensional systems: a true revolution: conceptual issues in 3d urban gis | Gim international | 2003 | 17 | 1 | 33 | 35 | |
| Breunig m., zlatanova s. | 3d geo-database research: retrospective and future directions | Computers and geosciences | 2011 | 37 | 7 | 791 | 803 | 10.1016/j.cageo.2010.04.016 |
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| Buchroithner m. | A truly 3d cartographic future | Gim international | 2010 | 24 | 1 | 41 | | |
| Butkiewicz t., chang r., wartell z., ribarsky w. | Visual analysis and semantic exploration of urban lidar change detection | Computer graphics forum | 2008 | 27 | 3 | 903 | 910 | 10.1111/j.1467-8659.2008.01223.x |
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| Feng y., hu t., zhang l. | Impacts of structure characteristics on the thermal environment effect of city parks | Shengtai xuebao/ acta ecologica sinica | 2014 | 34 | 12 | 3179 | 3187 | 10.5846/stxb201306101641 |
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# Paper B

## The association of multi-dimensional indicators on urban thermal conditions

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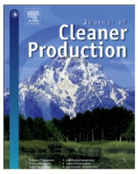


## The effect of multi-dimensional indicators on urban thermal conditions

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ABSTRACT

Urban heat island (UHI) studies have recognized ten factors as increasing the inner-city temperature compared with that of the surrounding suburbs. The UHI effect is a leading cause of heat-related diseases and mortality in many nations. However, there are still two main shortcomings. First, the effect of UHI is not well recognized in arid and semi-arid regions. Second, the association of multi-dimensional information with surface temperature in urban areas must be examined. This study focuses on the height-related aspects of urban geometry in an arid region. A range of multispectral and spatial vector data were used to derive the surface temperature and two-dimensional (2D) and three-dimensional (3D) information of the study area. All information was aggregated into a grid with common spatial resolution to create a homogeneous dataset. The machine learning statistical model of a boosted regression tree (BRT) was used to reflect the relative influence of 2D and 3D indicators with land surface temperature. Our results showed a cooler surface temperature in the city than in the surrounding area, leading to the question of whether the established UHI definition encompasses all types of cities. In addition, the thermal band was able to distinguish different spatial structures in the study area. The BRT analysis demonstrated that both multi-dimensional 2D and 3D indicators affect the surface temperature. In particular, the 3D indicators play a more important role than 2D indicators in shaping the surface temperature at different urban geometries of the study area. This new method can help urban planners identify the most influential 2D and 3D indicators that affect the surface temperature in different districts of a city.

## 1. Introduction

Human society is becoming increasingly urbanized. Projections by the United Nations suggest that the world's urban population is expected to increase by 66 percent by 2050 (United Nation, 2014). The associated expansion of urban area will also accelerate the destruction of the natural environment (Chun and Guldmann, 2014). Replacing natural environment with urban structures leads to significant higher temperatures, known as the urban heat island (UHI) effect (Weber et al., 2014). The UHI effect is a distinct micro-climate condition whereby temperatures in urban core areas are higher than in the surrounding suburban and rural areas (Oke, 1982). Generally, there are two main groups of factors that affect the formation and intensification of heat islands in urban areas. The first group includes climatological factors such as climatic region (incoming solar energy), season, time of the day and wind regimes (Tomlinson et al., 2010). This means bio-physical factors that are independent from human presence and activities. The second comprises factors related to the urban built environment, and thus human induced and influenced, such as the topography of the city, size of the urban area, population density, inhabitant activity, type of building materials, vegetation structure, and physical form of the urban landscape (Wienert and Kuttler, 2007). Both groups of factors act simultaneously and differ in terms of the possibility to influence them.

The human stress caused by UHI can directly (Harlan et al., 2006; Lafortezza et al., 2009) and indirectly (Stafoggia et al., 2008) affect city inhabitants' daily lives and individual health (Schuster et al., 2017). Currently, 10 factors are well known to play a major role in the formation of urban heat. An abundance of urban vegetation cover has been shown to decrease urban heat through leaf evapotranspiration (Kjelgren and Montague, 1998). Bodies of water in urban areas also cause a cooling island effect (Du et al., 2016). Surface characteristics and configuration also play a role (Amiri et al. 2009). Urbanized areas, in contrast to sprawling areas, affect the heat storage capability (Kato and Yamaguchi, 2007). Urban geometry (spacing between buildings) affects the heat distribution (Chun and Guldmann, 2014). The sky view factor indicates the amount of solar radiation absorption onto the surface (Bottyán and Unger, 2003). Wind flow and air circulation help reduce the temperature (Grimmond, 2007). Finally, a building's height and shape manipulate the surface albedo (Giridharan et al., 2004).

Generally, there are two shortcomings in previous UHI studies. First, most UHI research has been conducted in mid-latitude regions (Ana-Maria et al., 2016). The UHI effect has been rarely studied in arid and semi-arid regions. Second, the temperature intensity in UHI studies has been mainly associated with a single dimension, such as the effect of UHI on public health (Pantavou et al., 2011; Huang et al., 2013; O'Neill et all., 2003; Gosling et al., 2009), increased energy demand for cooling infrastructure (Arifwidodo and Chandrasiri, 2015), increased global temperature (Teuling et al., 2010), the cooling effect of urban vegetation (Weng et al., 2004), and the association of horizontal land cover classes with surface temperature (Alavipanah et al., 2016). Using individual dimensions usually leads to homogenous scaled outputs (Wong and Lau, 2000).

However, urban environments are multi-dimensional settings for which a multi-dimensional approach is undoubtedly needed to measure several horizontal (2D) and vertical (3D) dimensions in a city at the same time. UHI studies that assess several dimensions at once are largely absent, although there are a few exceptions (Nicholand Sing Wong, 2005; Matejicek et al., 2006; Unger, 2006; Noori-kakon and Mishima, 2009; Wu et al., 2013; Wong and Lau, 2013). Previous studies have argued that it is difficult to measure diversity on a homogenous scale; therefore, to capture the complexity of the urban environment, we must engage with multi-dimensional information and respective indicators (Alavipanah et al., 2016).

This study focuses on the spatial distribution of temperature in an urban context. In particular, the height-related aspects of urban geometry are addressed. The objective of this paper is to assess the association of urban multi-dimensional (two- and three-dimensional) indicators on urban surface temperature. Therefore, this study examines the city of Yazd due to the presence of two very different urban geometries in the city.

The remainder of the paper as organized as follows. Section 2 and 3 describes the study area and data source. Section 4 describes the method used to retrieve the surface temperature, mapping the land cover classes, modelling the three-dimensional structure of the built-up environment, data integration and statistical model of the study area. The results of the relative spatial effect of urban multi-dimensional indicators (2D and 3D) on surface temperature are shown in section 5. Section 6 discussed the remaining issues and areas to be studied in future research. Section 7 concludes the paper.

## 2. Study area

The study region is situated in central Iran (31.8974° N, 54.3569° E) (Figure 1, left panel). Continuously inhabited since the Proto-Elamite period (3400 to 2500 BC) (Carter and Stolper, 1984), Yazd is known as the world's largest adobe brick city and second-oldest city (Plotts, 1999). The city of Yazd is the capital and largest city of the province of Yazd. The United Nations Educational, Scientific and Cultural Organization (UNESCO) has added the city of Yazd to its list of world heritage since July 2017. As home to almost half a million inhabitants in 2015, Yazd stretches over a relatively flat area of approximately 240 $km^2$ at 1200 meters above sea level. With an average annual rainfall of only 60 mm and a summer temperature that is frequently above 40°C, Yazd is the driest major city in Iran. Yazd is clearly affected by its arid and dry surrounding and is considered to have a hot desert climate (BWh) by the Köppen-Geiger climate classification.

The physical morphology of Yazd consists of two main types of constructed areas: the historic and new districts. The historic district (approximately 10 $km^2$) is believed to have been established in the Elamite period. The traditional architecture in the historic district area evolved to produce buildings that are in harmony with the harsh climatic conditions. The spatial characteristics of the historic district consist primarily of by one-story buildings made of adobe bricks (also known as mudbricks), separated by narrow alleys (Figure 1, picture 1), and by closely built buildings with poor vegetation coverage that is mostly limited to single trees or small tree stocks in the courtyard, the so-called Sahn (Figure 1, picture 2). The clay soil in the surrounding environment was used to form the adobe bricks. The historic district is surrounded by a planned urban area, known as the new district, which started to expand in the second half of $19^{th}$ century (approximately 120 $km^2$). Further, the newly structured residential areas are finished with cement and concrete and contain multi-story buildings (mainly limited to two or three stories) (Figure 1, picture 3), with "right" angle arrangements and wide streets (Figure 1, picture 4).

The real impacts of urban heat, it's very differently shaped buildings and materials within the same city, its location in an arid region, the homogenous height of its buildings, its nearly flat terrain, an increase in its heat-related mortality and good data quality are the main reasons that make Yazd well-suited for this study.

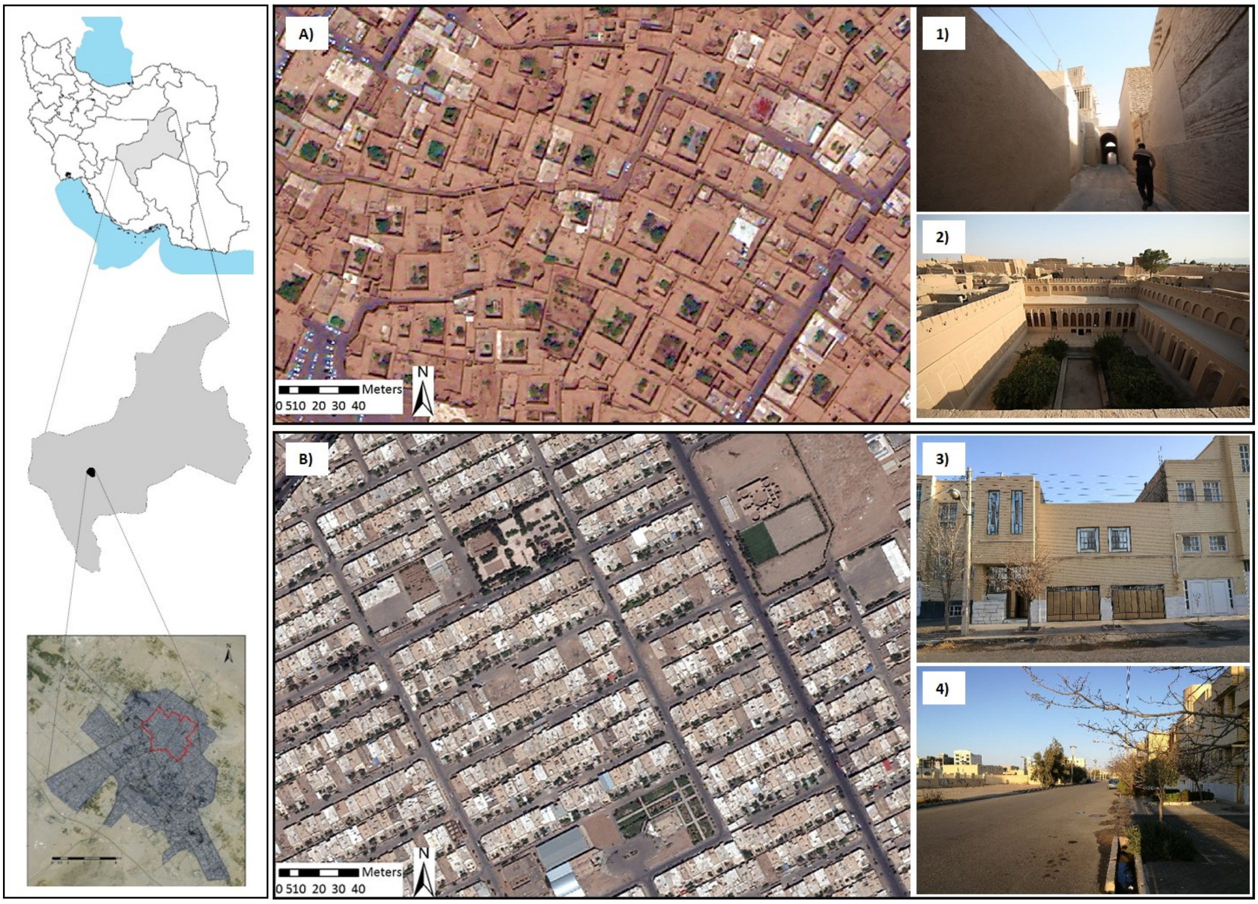


**Figure 1** The left panel shows the geographical location of the study area. The red border depicts the location and orientation of the historic district in the city of Yazd. A) The urban structure of the historic district (picture 1 and 2). B) Newly structured urban area (picture 3 and 4).

## 3. Data material

This study uses a range of multispectral and multiresolution remote sensing images (Landsat-8, WorldView-3) combined with spatial vector data (GIS building footprint). To derive the surface temperature (°C) of the study area, a cloud free Landsat 8 scene (path 162, row 38) was provided free of charge on the U.S. geological survey (USGS) website (www.earthexplorer.usgs.gov). The spatial resolution of Landsat 8 is 30 m for the operational land manager (OLI) bands. A spatial resolution of 100 m for the thermal infrared sensor (TIRS) was resampled to 30 m by the USGS to match the OLI bands (Table 1). In addition, Worldview-3 cloud free satellite images with 1.5 m multispectral spatial resolution were used to analyze the land cover of the study area. This geospatial data were prepared from high precision aerial images (less than 1 m resolution), including the height of each building

(Municipality of Yazd, 2016). The building layer was used for three-dimensional (3D) modeling of the entire study area.

**Table 1** Details of remote sensing image and spatial vector data.

| Sensor | Resolution (m) | Acquisition Date |
|---|---|---|
| Landsat 8 | 30 m (OLI) & 100 m (TIRS) | 9 August 2016 |
| Worldview-3 | 1.24 m (multispectral resolution) | 16 August 2016 |
| Building footprint vector | 1 m | 1 June 2016 |

## 4. Methods

To study the effect of urban 3D morphology on surface temperature, multiple 2D and 3D indicators were incorporated in a regular spatial grid (section 4.4). A 30-m grid size cell was considered to properly reflect multiple indicators with the resolution of surface temperature pixels over space. A machine learning algorithm was used to identify the association between the dependent variable (surface temperature) and independent variables (section 4.5). The following flowchart (Figure 2) illustrates the methodology.

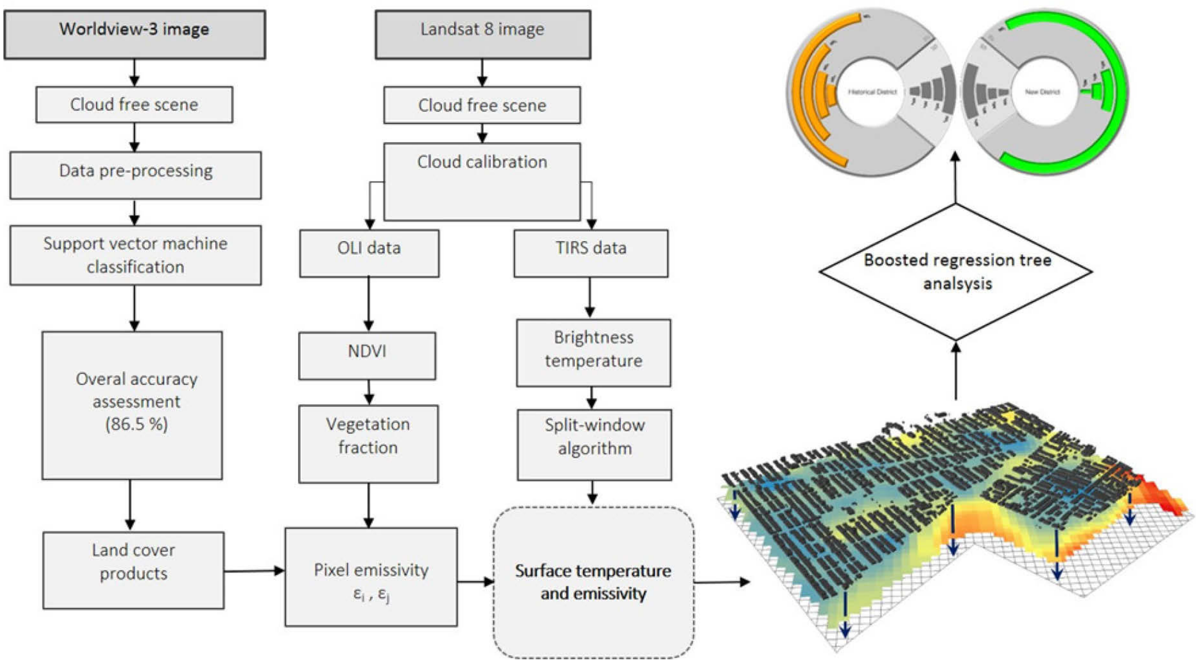


**Figure 2** Flowchart of the study framework.

4.1 Surface temperature

From a remote sensing point of view, the 'surface' is whatever the ground sees when it looks through the atmosphere. The surface could be a grassland, forest canopy or the roof of a building. Moreover, the surface temperature is the radiative skin temperature of the land surface that is measure in the direction of the airborne sensor (satellite). Surface temperature represents the average surface temperature in a given unit area at a certain time of day, instead of measuring the temperature of the air, like weather stations do. The surface temperature depends on the Albedo, the vegetation cover and the soil moisture.

To derive the surface temperature, the Landsat 8 TIRS bands (bands 10: 10.60 µm to 11.19 µ and band 11: 11.50 µm to 12.51 µm) were used to convert the digital numbers to space reaching radiance on top of the atmosphere measured by the instrument. The two bands in the long-wave infrared (LWIR) use Quantum Well Infrared Photodetector technology to detect long wavelengths of light emitted by the Earth surface at 100-meter resolution. A description of a step-by-step process proposed by the USGS (Landsat 8, Handbook, 2015) was used to create surface temperature maps.

The retrieval of surface temperature from satellite thermal bands can be broadly classified into three categories: single-channel method (mono-window algorithm), multi-channel methods (split-window algorithm) and multi-angle methods. The methodology suggested by Yuan and Bauer (2007) and Du et al. (2015) were used to estimate the surface temperature from Landsat 8 TIRS data by applying a split-windows algorithm. The split-window algorithm removes the atmospheric effect in accordance with the different absorptions of two TIRS bands, and the linear or nonlinear combination of the brightness temperatures is finally applied for the surface temperature.

4.2 Land cover classes

For mapping land cover classes in the city of Yazd, a supervised learning algorithm called support vector machines (SVM) was used. SVM are supervised non-parametric statistical learning techniques that improve classification and regression problems. Methods based on SVM have been particularly successful in applications with a large set of variables (Tax and Duin, 2004), such as remote sensing data. The methodology proposed by Okujeni et al., 2013 was implemented to classify the Worldview-3 image of the study area into vegetation, impervious surface, bare soil and water. First, three classes were used as the three main land cover types in the study area. The last class (water) was defined to ensure that the surface temperature of the study area was not affected by the water bodies. For validation of results, an accuracy assessment was conducted by measuring the overall accuracy with 255 randomly selected control points.

### 4.3 Three-dimensional city model

A 3D city model was required to determine the characteristics and geometry of the built-up environment. GIS geospatial data (building footprint) were used to shape the 3D form of the city. To do this, each individual building height was combined with the building footprint. Buildings are delineated as box-shaped 3D form. This is an accepTable approximation of the real building shape, considering the flat roofs in Yazd. To compute the 3D model of the urban environment of Yazd, ArcGIS 10.3 and ArcScene 10.3 were used.

To study the urban 3D environment, the following 3D indicators were considered: **the volume** of each individual building ($m^3$), **the surface area** of each individual building ($m^2$), the **building rooftop area** ($m^2$), the **shadow footprint** ($m^2$) of each building based on the height of the building at the time of satellite image acquisition, the **shadow volume** ($m^3$) of each building based on the height of building at the time of satellite image acquisition and the ratio of **building's height to its width** (H/W) (Figure 3).

The volume of each building in cubic meters ($m^3$) and the surface area of each building in square meters ($m^2$) are calculated using the following equations:

$$Volume = W \times D \times H \quad \text{equation 1)}$$

$$Building\ surface\ area = 2(H \times W) + 2(H \times D) + (W \times D) \quad \text{equation 2)}$$

where $W$ is the width of the building, $D$ is the depth of the building and $H$ is the height of the building. Then, the surface area of each individual building, i.e., the sum of the surface areas of all of the walls, including the rooftop area, was determined (Figure 3).

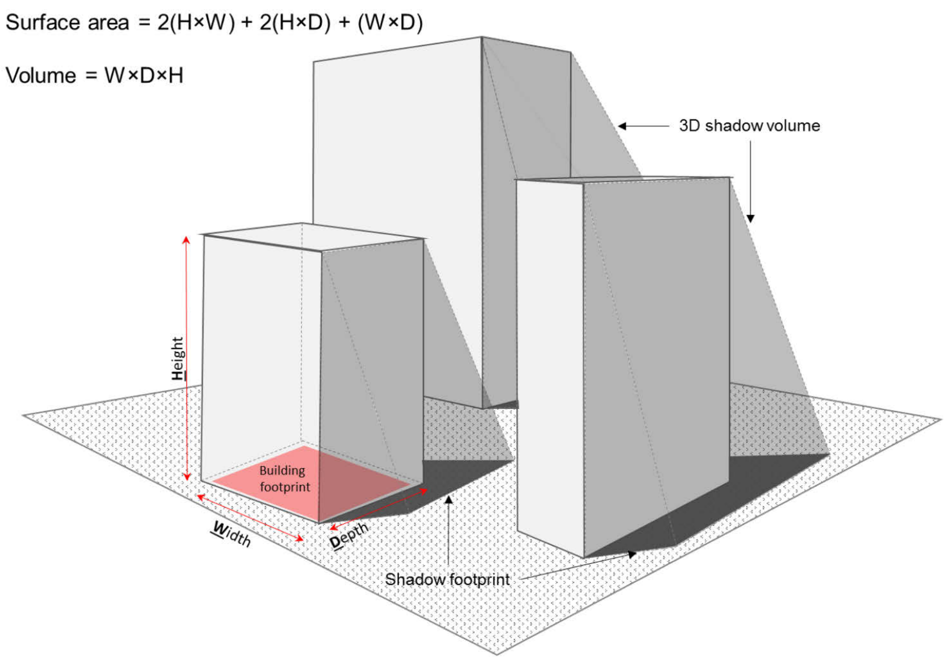


**Figure 3** The 2D shadow footprint and the 3D shadow volume.

4.4 Data integration and statistical modeling

The data sources used in this research have different spatial resolution. Therefore, an appropriate way to standardize data is to superimpose a grid with a common spatial resolution of 30 m × 30 m. This grid size is equal to the surface temperature pixel size and has proved to be an optimal size for aggregating 2D and 3D urban feature variables. A regular spatial grid was used to aggregate all of the 2D and 3D information into a homogeneous database. Table 2 shows the list of 2D and 3D indicators and their distribution ranges that were superimposed with the regular grid. The homogenous database offers a convenient structure for the subsequent boosted regression tree analysis. Due to the atmospheric flows and exchanges, the observed temperature at a given grid-cell is likely to be spatially correlated to the neighboring cells. Figure 4 shows the integration of the multi-dimensional indicators with the regular spatial grid.

4.5 Statistical model

A machine learning statistical model called a boosted regression tree (BRT), also known as boosted decision tree, was used to analyze the association of multi-dimensional indicators (2D and 3D) in the complex urban environment. The BRT approach differs fundamentally from conventional techniques that use a tool for quantifying the relationship between one variable and others upon which it depends. This models is advanced for analysis of the morphological relationships (Clarke & Johnston, 1999). The BRT combines the strengths of two algorithms, regression tree and boosting, in a single performance (Friedman, 2002). Regression trees are from the classification and regression trees (decision trees) group of models, and boosting builds and combines a collection of models. Boosting means that each tree is dependent on prior trees, and learns by fitting the residual of the trees, and the decisions respectively, that preceded it. The BRT method is a supervised learning method which requires a labeled dataset containing numerical values. The model can be trained by providing the model and the labeled as an input into the model. Thereafter, the trained model could be used to predict values for the new input examples. BRT could handle different types of predictor variables and accommodating missing data.

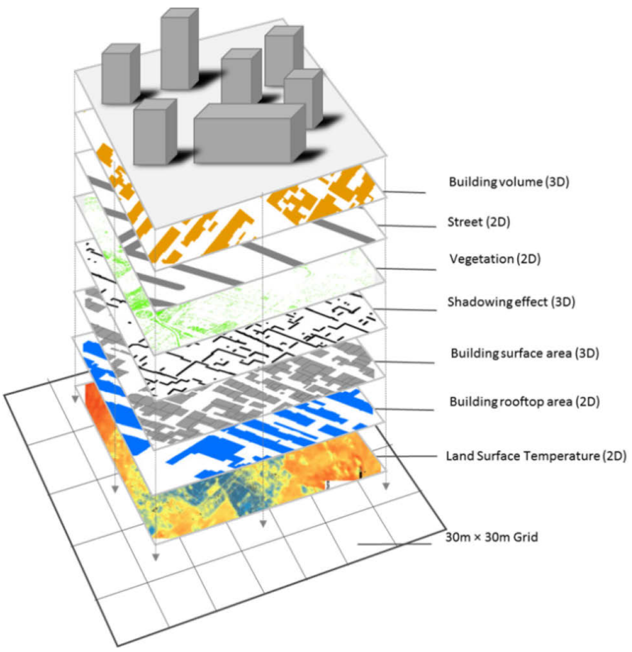


**Figure 4** Integrating the multi-dimensional indicators into a regular spatial grid with a common spatial resolution of 30 m × 30 m.

More specifically, the relative influence measure was scaled from 0 to 100%. The scale relies on the number of times an independent variable is selected for splitting during the decision tree process and weighted by the squared improvement to the model as a result of each split (Friedmann and Meulman, 2003). For our study, 50% of the data were used to fit our dependent variable and the surface temperature data as the first regression tree (bagging factor of 0.5). We included a “Laplace” distribution to fit our model because this kind of probability distribution can handle the non-binary surface temperature with multiple temperature values as dependent variables. Our independent variables consisted of several two- and three-dimensional indicators (see Table 2). Cells that did not hold information were designated not available (N/A). For instance, not all of the grid cells had vegetation cover (2D); therefore, they were designated N/A. The regression analysis was conducted on both districts separately to compare the association of their urban structure and geometry with the surface temperature. The results were evaluated using the scaled measures of the relative influence calculation. The statistical programming software R version 3.3.1 (2016-06-21) "Bug in your hair" with the main packages of "raster," "mmand," "rgdal", "gbm", and "dismo" (RCoreTeam 2015) was used to conduct the analysis on 24.978 Million entries. A notebook with Intel Core i5-6300U processor of 6th generation (2.4 GHz, 3 MB Cache) and 16 GB of DDR4 RAM (2.133 MHz) were used to process the R script in 6 hours.

**Table 2** Descriptive statistics for urban feature variables on the grid structure for historic and new structures of the study area.

| Urban feature variable | Indicator | Unit | New district | | Historic district | |
|---|---|---|---|---|---|---|
| | | | Min. value | Max. value | Min. value | Max. value |
| Building height | 3D | m | 0.0 | 36.0 | 0.0 | 5.9 |
| Building volume | 3D | $m^3$ | 0.0 | 13004.4 | 0.0 | 6523.18 |
| Building surface area | 3D | $m^2$ | 0.0 | 3324.1 | 0.0 | 3603.45 |
| Shadow footprint | 3D | $m^2$ | 0 | 7679.85 | 0 | 2174.54 |
| Shadow volume | 3D | $m^3$ | 0.0 | 1843.0 | 0.0 | 342.1 |
| H/W | --- | n/a | 0.0 | 11.6 | 0.0 | 1.7 |
| Surface temperature | 2D | °C | 29.3 | 50.4 | 34.4 | 45.1 |
| Building rooftop area | 2D | $m^2$ | 0.0 | 899.3 | 0.0 | 648.8 |
| Street | 2D | $m^2$ | 0.0 | 890.6 | 0.0 | 551.1 |
| Vegetation | 2D | $m^2$ | 0.0 | 900.0 | 0.0 | 850.0 |

Note: H/W: Height to width ratio of each building

## 5. Results

### 5.1 Land cover analysis and surface temperature

Cities have a complex environment that includes buildings, roads, and green and blue structures. Figure 5 illustrates the result for SVM classification with an overall accuracy assessment of 86.5%. Generated land cover data were overlaid with Landsat 8 thermal band data to retrieve the surface temperature of the study area.

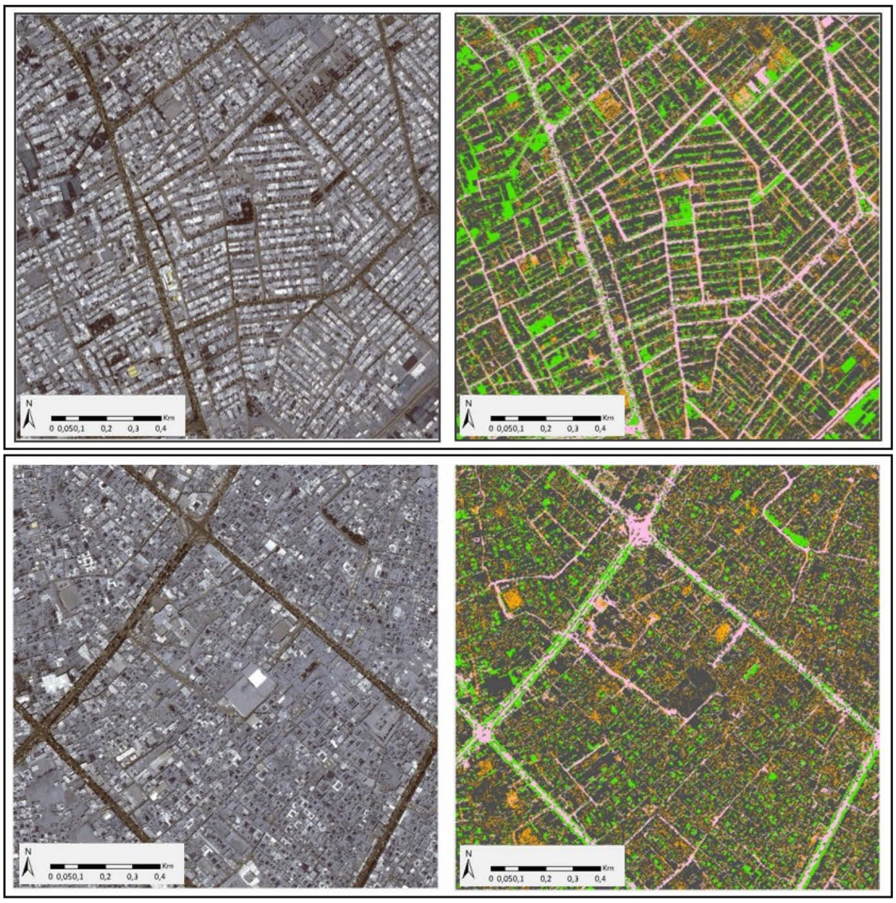

**Figure 5** SVM land cover classification with an overall accuracy assessment of 86.5%. The left image of the upper box shows the Worldview-3 image of the new structure, and the right-hand side shows the SVM classified image. The left image of the lower box shows the high resolution satellite image of the historic district, and the right-hand side shows the SVM classified image of the same area.

Figure 6 (A) shows the daytime surface temperature of the city of Yazd and its surrounding on 9 August 2016 at 10.30 A.M. local time. The number of blue boxes in Figure 6 (A) shows the association of different land cover types with the surface temperature. The land cover type of these boxes are as follows: 1, historic district; 2, central rail way and open field; 3, bare field; 4, 5, and 6, newly structured district. The overall inner surface temperature of the city of Yazd is cooler than the surrounding suburb. This result contradicts the current definition of UHI that argues that cities have warmer temperatures than the surrounding areas due to human activity. Figure 6 (B) shows that the thermal band of Landsat 8 distinguishes the historic district from the new district. Figure 6 (A,B) shows a warmer surface temperature in the historic district than in the newly built district. The highest surface temperature recorded in the historic district was 45 °C, whereas that in the new district was 39 °C.

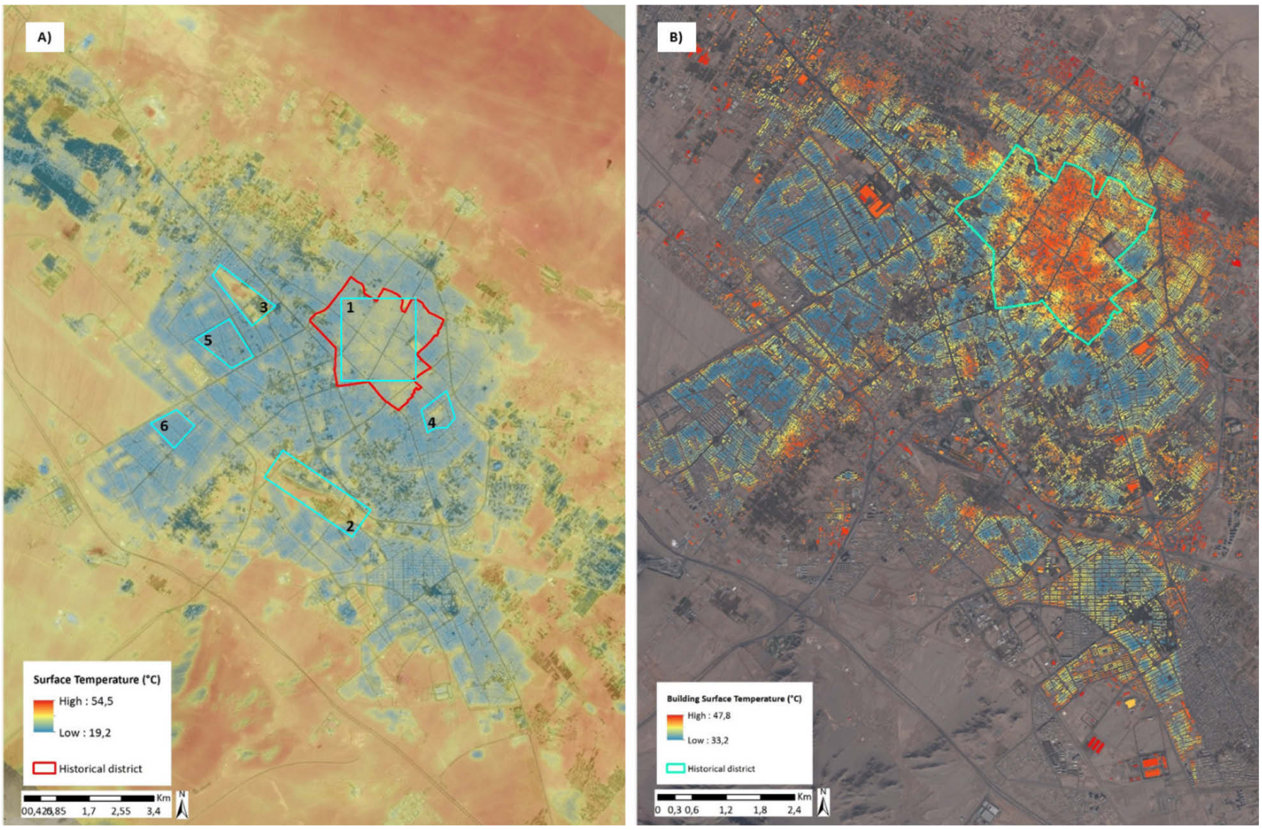


Figure 6 Surface temperature of Yazd on 9 August 2016 at 10.30 A.M. local time. A) The inner urban area shows a lower surface temperature in contrast to its suburban area. The land cover of the numbered blue boxes is as follows: 1, historic district; 2, central rail way and open field; 3, bare field; 4, 5, and 6, newly structured district. B) Infrastructure in the historic district is more affected by heat. The average surface temperatures of the historic and new districts are 40 °C and 37 °C, respectively.

5.2 3D city model

The 3D spatial models of both the new and historic districts of Yazd are shown in Figure 7. The well-aligned structure of the new district has abundant urban vegetation, and the compact and dense structure of the historic district has bare vegetation cover.

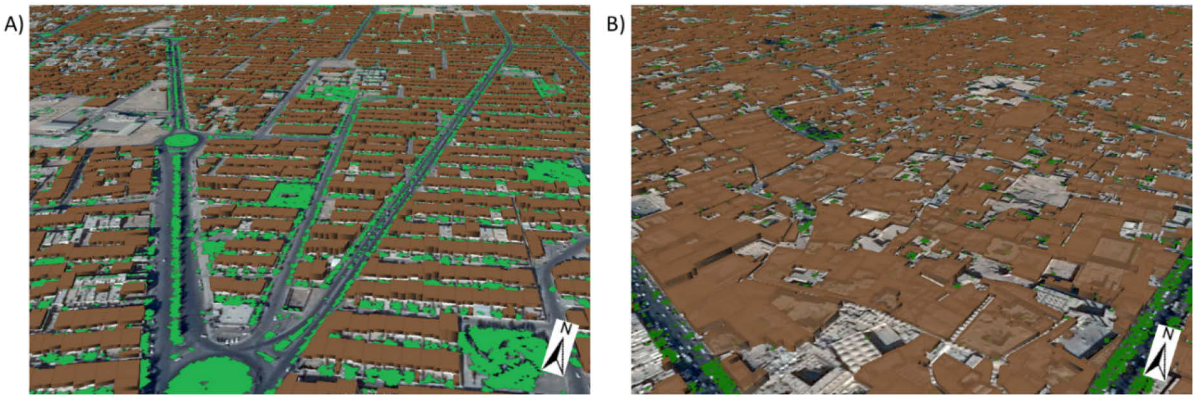


**Figure 7** Yazd 3D model including the shadowing effect of each individual building. A) 3D model of the new district; B) 3D model of the historic district.

5.3 Boosted regression tree analysis

The BRT was processed independently for both districts to understand the relative spatial effect of urban multi-dimensional indicators (2D and 3D) on surface temperature. Figure 8 illustrates the BRT analysis of the 2D and 3D indicators for both districts in separate graphs. The left-hand graph shows the percentage of the relative influence of the 2D and 3D indicators on the surface temperature for the historic district (HD). The right-hand graph illustrates the same information for the new district (ND). $HD_{1-5}$ depicts the percentage of different 3D indicators for the historic district. $HD_{6-9}$ shows the percentage for different 2D indicators of the historic district. $ND_{1-5}$ illustrates the percentage of different 3D indicators in the new district, and $HD_{6-9}$ illustrates the percentage of the different 2D indicators of the new district.

The results show that all of the 2D and 3D indicators play a role in defining the surface temperature. However, some indicators have a greater effect than others. The overall relative influence on surface temperature in the historic district ($HD_{6-9}$) was 30% and that for 3D indicators in the same district ($HD_{1-5}$) was 70%. The overall relative influence on surface temperature for the new district were 23.5% for the 2D indicators ($ND_{6-9}$) and 76.5% for the 3D indicators ($ND_{1-5}$). In other words, 3D indicators have a much stronger relative influence on the surface temperature in both districts.

The relative influences on surface temperature for 3D indicators of the historic district are as follows. Building height has the strongest relative influence ($HD_1$), with 21%. This is followed by the building H/W ratio ($HD_2$), with 14%; building shadowing effect ($HD_3$), with 13%; building surface area ($HD_4$), with 12%; and building volume ($HD_5$), with 10% of relative influence on the surface temperature. The relative influence of 2D indicators on surface temperature in the historic district is weaker. The strongest relative influence among 2D indicators on surface temperature is from the street area ($HD_6$), with 14%. This is followed by vegetation cover ($HD_7$), with 9%; building rooftop area ($HD_8$), with 4%; and land cover type ($HD_9$), with 3%.


**Figure 8** The relative influence of urban multi-dimensional indicators on the surface temperature of the city of Yazd. The left-hand graph shows the analysis for the historic district (HD). $HD_1$: building height with 21%, $HD_2$: building H/W ratio with 14%, $HD_3$: building shadow with 13%, $HD_4$: building surface area with 12%, $HD_5$: building volume with 10%, $HD_6$: Building street area with 14%, $HD_7$: vegetation cover with 4%, $HD_8$: building rooftop area with 4%, and $HD_9$: urban land cover type with 3%. The right-hand graph illustrates it for the new district (ND). $ND_1$: building surface area with 30%, $ND_2$: building height with 24.5%, $ND_3$: building shadow with 18%, $ND_4$: building H/W ratio with 2%, $ND_5$: building volume with 2%; $ND_6$: building rooftop area with 18.5%, $ND_7$: street area with 3%, $ND_8$: vegetated area with 2% and $ND_9$: urban land cover type with 0.01%.

The relative influence of 3D indicators in the new district ($ND_{1-5}$) also shows a stronger association with surface temperature than the 2D indicators. With 30%, building surface area ($ND_1$) is the strongest relative influential 3D indicator associated with surface temperature in the new district. This is followed by building height ($ND_2$), with 24.5%; building shadow ($ND_3$), with 18%; building H/W ($ND_4$), with 2%; and building volume ($ND_5$), with 2%. The relative influence of 2D indicators on surface temperature in the new district ($ND_{6-9}$) are as follows: building rooftop area ($ND_6$), with 18.5%; street area ($ND_7$) and ($ND_8$), with 3%; and vegetated area ($ND_9$), with 2%.

## 6. Discussion

3D studies across different fields have received great attention, but this technique is still in its infancy (Alavipanah et al., 2016). The focus of this research was to understand the variation in surface temperature caused by different urban multi-dimensional environment. A machine learning algorithm was used to understand the relative influence of 2D and 3D indicators on surface temperature.

Many previous UHI studies have confirmed that UHI is characterized by higher temperature in the urban area than in its surroundings. For example, the temporal and spatial characteristics of UHI were published by Cui et al. (2017); remote sensing of UHI across the continental USA was reported by Imhoff et al. (2010); and Deosthali (2000) studied the impact of rapid urban growth on UHI. However, our results show a cooler surface temperature for the inner urban area of Yazd compared to the surrounding suburbs. Another study in the semi-arid city of Erbil, Iraq, showed similar behavior (Rasul et al., 2015). This finding contradicts the current definition of UHI. The current definition is suiTable for cities in mid-latitude (Ward et al., 2016), as well as in tropical (Qaid et al., 2016) and sub-tropical (Lau et al., 2016; Goldreich, 1992) regions. The question that arises is whether the traditional and established definition of UHI is adequate to encompass all types of cities. Therefore, it is recommended to use the term 'urban cooling island' in studies when the heat pattern of the inner city is less than that of the surrounding suburb, particularly in arid and semi-arid cities.

Several factors play a role in shaping the cooler inner city temperature in Yazd. First, the geographical position of Yazd is located in an arid region surrounded by bare and dry soil. Based on the findings of Larson & Carnahan (1997), dry soil heats up very fast in the direct sun light and can be linked to high surface temperatures. Second, the presence of vegetation in the urban area is responsible for several mechanisms of simultaneously cooling, similar to the evapotranspiration process and shading effect. Furthermore, regular irrigation of parks and gardens in the city, especially during the hot season, could reduce the temperature in the urban area. Shadowing effects are also additional factors. Based on solar position and the urban 3D geometry (buildings and vegetation), various angles of a building or vegetation receive light, and the other side remains comparatively dark. As the penetration of sunlight and energy storage in the soil is less for shaded areas, the temperature is also cooler. Therefore, shadowing could possibly lead to lower surface temperature within the cities.

In addition, the findings show that dissimilar urban structures, historic and newly built, lead to different spatial heat patterns. From the results, it is interesting to see that thermal data distinguished the historic district from the new district. In other words, the historic district and newly built district have different heat patterns. This difference may result from the different building materials and 3D spatial orientation of the buildings in both districts. The material used in the historic district is mainly adobe bricks (a mixture of clay soil, water and straw), whereas the material of the newly built district consists of cement and concrete. The thermal conductivity for adobe bricks (1.0 W/mK) is greater than the thermal conductivity of concrete (0.3 W/mK) at the room temperature (25 °C). It was probably due to this fact that ancient architects used two methods to avoid the penetration of sunlight into the buildings: building thick walls (from 1 to 1.5 meters) and mixing straw with mud when molding the bricks. Experience has shown that the existence of straw reduces solar penetration by reflecting solar radiation (Bahadori-nejad and Yaghoebi, 2006), so this could be a reason for the warmer heat pattern in the historic district.

The results of this research also depict the critical role that the 3D spatial orientation of the urban environment plays in shaping the heat pattern of the study area. The newly structured residential areas have a regular urban structure with aligned, multistoried buildings, wide streets and a relatively large amount of street vegetation. Wide streets and a regular urban structure facilitate better wind flow and air convection, as Wang and Akbari (2016) reported. In contrast, the 3D spatial configuration of the historic district is quite compact, with one-story buildings, narrow streets with continuous walls where the vegetation is limited to the central garden of each house. One should bear in mind that the high density of constructed buildings and streets was a strategy to avoid the penetration of hot solar radiation. The urban physical form, in particular the 3D building shape, plays a critical role in determining the amount of incoming solar radiation (source and sink). Solar radiation increases the surface temperature of areas without any obstructions (building or vegetation cover). Nearby structures, including the Sahn, could benefit from building shadows during different times of the day, providing great relief from the hot sunlight and dry climate. However, perhaps the ancient architects were not aware of the phenomenon known as the urban street canyon, which intensifies the UHI effect by trapping the heat inside compact structures and blocking the wind. The focal point of this research was to study how different urban geometry (2D and 3D) could affect surface temperature. BRT analysis was very useful to study the association of multi-dimensional indicators with surface temperature.

The results showed that although both districts had very different 3D spatial structure and configuration, the 3D structure plays a critical role in defining the surface temperature of the study area, approximately 70% for each district individually. Because all interactions in the real world occur in a multi-dimensional environment, it is clear that studying a sustainable urban area without considering 3D indicators would not be possible. Building height, which is key to other 3D indicators, has a very strong influence on surface temperature in the city of Yazd. The average influence of height on surface temperature for both districts ($HD_1$ and $ND_2$) was approximately 23%. The findings of Resch and his colleague's (2016) confirmed that the role of height in energy use is an important aspect for urban sustainability. H/W is another representative 3D indicator that is associated with the surface temperature in the historic district ($HD_2$). A lower H/W ratio is associated with a warmer relative surface temperature. For example, the average surface temperature for grid-cells with a H/W ratio between 1 and 2 is 38.05 °C, that for grid-cells with a H/W ratio between 3 and 4 is 37.85 °C, and that for grid-cells with a H/W ratio between 4 and 5 is 37.76 °C. In other words, lower H/W ratios indicate buildings that are wider than they are tall, which are more exposed to solar radiation. Chun and Guldman (2014) also supported the association of H/W with surface temperature.

Furthermore, BRT recognized shading ($ND_3$ and $HD_3$) as another factor that influences surface temperature. The findings of Middle et al. (2014) showed the important role of shading on the distribution of heat by considering the 3D urban configuration. It could be understood that surface temperature is relatively cooler in shaded areas due to less penetration of sunlight, as mentioned above. Moreover, the volume and surface area of each building were found to be influential factors in the BRT analysis ($HD_4$, $HD_5$, $ND_1$ and $ND_5$). Objects with a larger area have a larger surface to conduct heat. In urban areas, the solar energy is absorbed by building walls. Thus, in compact districts (such as the historic district), a larger wall surface and a lack of open space probably traps hot air, which might lead to warmer surface temperature. However, a problem with a less compact urban structure (such as the new districts) is that the building surface area is more exposed to solar radiation than are buildings in the historic district. The findings of Deng et al. (2016) also state the importance of building arrangements to both the microclimate and energy demand. The building volume and surface area are relatively novel 3D indicators that were absent in previous studies. These could be used to represent the urban 3D roughness and to analyze the relationship between a building's 3D geometry with urban sustainability, in terms of energy consumption. In contrast to 3D indicators, previous studies have studied the relative influence of 2D information, such as street area ($HD_9$), vegetation area ($HD_7$), building rooftop area and different urban structures ($HD_9$). Bourbia and Boucheriba (2010) reported the association of street design with urban microclimate, specifically on UHI. Zhao et al. (2015) confirmed our findings on rooftop surface temperature analysis. Further, there are also many studies on the cooling effect of vegetation in urban areas (Honjo et al., 1986; Gallo et al., 1993; Weng, 2009, Alavipanah et al., 2015). It is interesting to see that vegetation has a stronger influence in the historic district ($HD_7$) than in the new district ($ND_8$). The isolated microclimate shaped by vegetation in the courtyard (Sahn) might be the cause.

This study uses a multidisciplinary approach to analyze the association of multi-dimensional indicators (2D and 3D) with the intensity of surface temperature in the city of Yazd. The methodology can also be tested for different cities with different morphology and land-use structure, as long as data are available. Research on multi-dimensional indicators could help urban planners assess the most influential 2D and 3D indicators in shaping the urban temperature and heat pattern. However, there are several limitations to the present study. First, we were not able to include all factors that are known to influence urban heat and surface temperature other than those noted in the introduction. Second, at the present time, there are technical limitations for better resolution (spatial and temporal) by thermal sensors. Improved sensor resolution could provide more detailed information. Third, there were no data on vegetation height for the present study area. Vegetation height could be used to improve the current methodology by understanding the role of different vegetation shape and height in cooling the surface temperature. Fourth, to the best of our knowledge this is the first paper of its kind to analyze the effect of multi-dimensional indicators on surface temperature. Especially in arid and semi-arid regions. Therefore, the results of this publication would be valid for the city of Yazd during the warm season and very probably also for comparable cities in comparable climate zones.

## 7. Conclusions

Most previous UHI studies have a linear view of point towards the formation of the urban surface temperature. This study aggregated the results of previous studies into a single analysis. The results of this study confirm that all urban characteristics play a role in shaping the urban heat pattern at the same time. However, some factors have a greater effect than others. The 3D urban infrastructure, regardless of the spatial configuration, affects the surface temperature more than the 2D indicators do. However, due to a limitation in the availability of 3D data, there are counteracting factors for which the statistical model does not account, such as vegetation height, when analyzing its effect on shaping the surface temperature. The proposed methodology allow identifying districts sensitive to increasing heat-stress in the arid city of Yazd during the warm period. By considering the 2D and 3D urban infrastructure of the study area we argue that the vegetation density should be improved to increase the cooling effect across different urban districts. Specifically increasing the vegetation cover in more dense urban districts such as the historical district without declining the air ventilation by allowing tree canopies to spread in an unlimited way. In addition, improving the ground vegetation cover in the bare soil of the inner-city to decrease the albedo. The critical districts at risk of potential heat-stress must become crucial for resilient urban design and be addressed by urban planners to mitigate both heat-related death and heat stress (of the working population) rate during the warm period. For future studies, it is recommended that the 3D shape of vegetation be considered in shaping the land surface temperature. Any improvement to understand the complex multi-dimensional urban environment will guide the development of more sustainable and resilient urban systems.

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# Paper C

## On the spatial patterns of urban thermal conditions using indoor and outdoor temperature

# *On the spatial patterns of urban thermal conditions using indoor and outdoor temperatures*

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## Abstract

The changing climate has introduced new and unique challenges and threats to humans and their environment. Urban dwellers in particular have suffered from increased levels of heat stress, and the situation is predicted to continue worsening in the future. Attention toward urban climate change adaptation has increased more than ever before, but previous studies have focused on indoor and outdoor temperature patterns separately. The objective of this research is to assess the indoor and outdoor temperature patterns of different urban settlements. Remote sensing data, together with air temperature data collected with temperature data loggers, were used to analyze land surface temperature (outdoor temperature) and air temperature (indoor temperature). A hot and cold spot analysis was performed to identify the statistically significant clusters of high and low temperature data. The results showed a distinct temperature pattern across different residential units. Districts with dense urban settlements show a warmer outdoor temperature than do more sparsely developed districts. Dense urban settlements show cooler indoor temperatures during the day and night, while newly built districts show cooler indoor temperatures during the warm season. Understanding indoor and outdoor temperature patterns simultaneously could help to better identify districts vulnerable to heat stress in each city. Recognizing vulnerable districts could minimize the impact of heat stress on inhabitants.

**Keywords:** Outdoor temperature, indoor temperature, temperature data logger, spatial analysis, hot spot and cold spot.

## 1. Introduction

Human beings have long recognized that cities designed with nature in mind are beneficial, practical and aesthetically pleasing (Pressman, 1994). Therefore, the harmonious integration of settlements into the natural environment is highly desired. The tradition of considering environmental climatic conditions in the urban design process dates back approximately 2000 years (Morgan, 1960). The population of urban inhabitants is expected to reach 6.4 billion out of a total population of 9.7 billion (66 percent) by 2050 (United Nation, 2014). This brings urban areas and cities to the center of attention more than ever before. In addition, climate change has emerged as one of the most urgent and complicated issues of the early 21st century. Increases in surface temperature (known as global warming) and more frequent and intensive heatwaves in urban areas, coupled with the urban heat island (UHI) effect, can dramatically increase the risk of heat stress for inhabitants in cities (Howard, 1833; Detwiller, 1970; Fukui, 1970, Katsoulis and Theoharatos, 1985, Wang et al., 1990, Kim 1992; Lee, 1993; Johnson et al., 1994; Tso, 1996, Camilloni and Barros, 1997). Heat stress caused by the UHI effect has been shown to have a dramatic impact on human health (Revich and Shaposhnikov, 2012; Robbin et al., 2008), and urban citizens in particular are likely to suffer more in the future (Beniston et al., 2007; Oke, 1973; Patz et al., 2005; Revi et al., 2014). It is also expected that an increase in heat stress could result in the average global income being reduced by 23% by 2100 (Burke et al., 2015) due to loss of labor capacity during the warmer months (Dunne et al., 2013). Therefore, better understanding the indoor and outdoor temperature patterns in each city is crucial to reducing the impact of heat stress.

To reduce the impact of heat stress in the context of urban climate change strategies, indoor and outdoor temperature variations in different urban settlements are of special interest, not only during extreme situations but also during average days and nights. Thus, information about temperature variations during the day and night is valuable for urban planners to help them better understand the factors influencing temperature fluctuations. Land surface temperature (Rosenfeld et al., 1995; Stathopoulou and cartalis, 2009; Xiaoma et al., 2017), the UHI effect (Yang et al., 2009; Gago et al., 2013; Rosa dos Santo et al., 2017) and indoor temperature measurements (Yoshino et al., 2004; Yousef Mousa et al., 2017) have been frequently studied. However, outdoor and indoor temperature pattern data on a city scale where remote sensing data and instrumental measurements have been used are still lacking. This study could be important because of its strong implications for urban planners and risk managers.

This study focuses on the spatial patterns of temperature in an urban context particularly the indoor and outdoor temperature patterns of urban settlements. The overarching aim of this research is to assess the variation of indoor and outdoor urban temperature patterns. This study examines the city of Yazd due to the presence of two very different urban geometries, materials and structures in the city.

## 2. Materials and Methods

### 2.1 Study Area

The study area is situated in central Iran (31.8974° N, 54.3569° E) adjacent to the Siah-koeh Kavir, Abarkouh Kavir and Bafgh Kavir deserts, as well as the Kuh-e Kharanaq and Shir-Kuh mountains (Figure 1). Yazd is located 1200 meters above sea level on relatively flat terrain. The topography within a two-mile radius of Yazd shows modest variations in elevation, with a maximum elevation change of approximately 50 meters. The city of Yazd is approximately 240 $km^2$ in size and was home to approximately half a million people in 2015. The climate in Yazd is categorized as a hot desert climate (BWh) by the Köppen-Geiger climate classification scheme. Summers in Yazd are hot and dry, and winters are cold and dry. The warm season lasts from mid-April to mid-October (May–October are hot months). Over the course of the year, temperatures typically vary from 0.5°C (3.2 of the cool season) to 42°C (3.8 of the hot season). The average annual rainfall in Yazd is only 60 mm.

Since July 2017, the city of Yazd has been added to the list of world heritage UNESCO sites (The United Nations Educational, Scientific and Cultural Organization, 2017). Characteristics of the inner city are strongly influenced by historical legacies and consist of two main types of housing estates: The historical district (built in approximately 2500 BC) (Carter and Mathew, 1984), and newly built districts (developed in the second half of the 19$^{th}$ century). Containing 7.5% of the infrastructure, the historical district stretches to almost 10% of Yazd's surface area. The historical district is believed to have been established in the Elamit period (2500 BC). The physical morphology of the buildings in the historical district is adapted to the hot and dry climatic conditions of the region: Buildings are made of adobe bricks (also known as mudbricks) and are separated by narrow alleys (Figure 1, pictures 1 to 3). The newly built residential areas, known as the new district, contain 20% of the city's infrastructure and cover over 90% of the study area. Multi-stored blocks (mainly limited to two or three stories) in the new district are finished with “modern materials” such as cement and concrete, and wide streets separate the buildings (Figure 1, pictures 4 to 6).

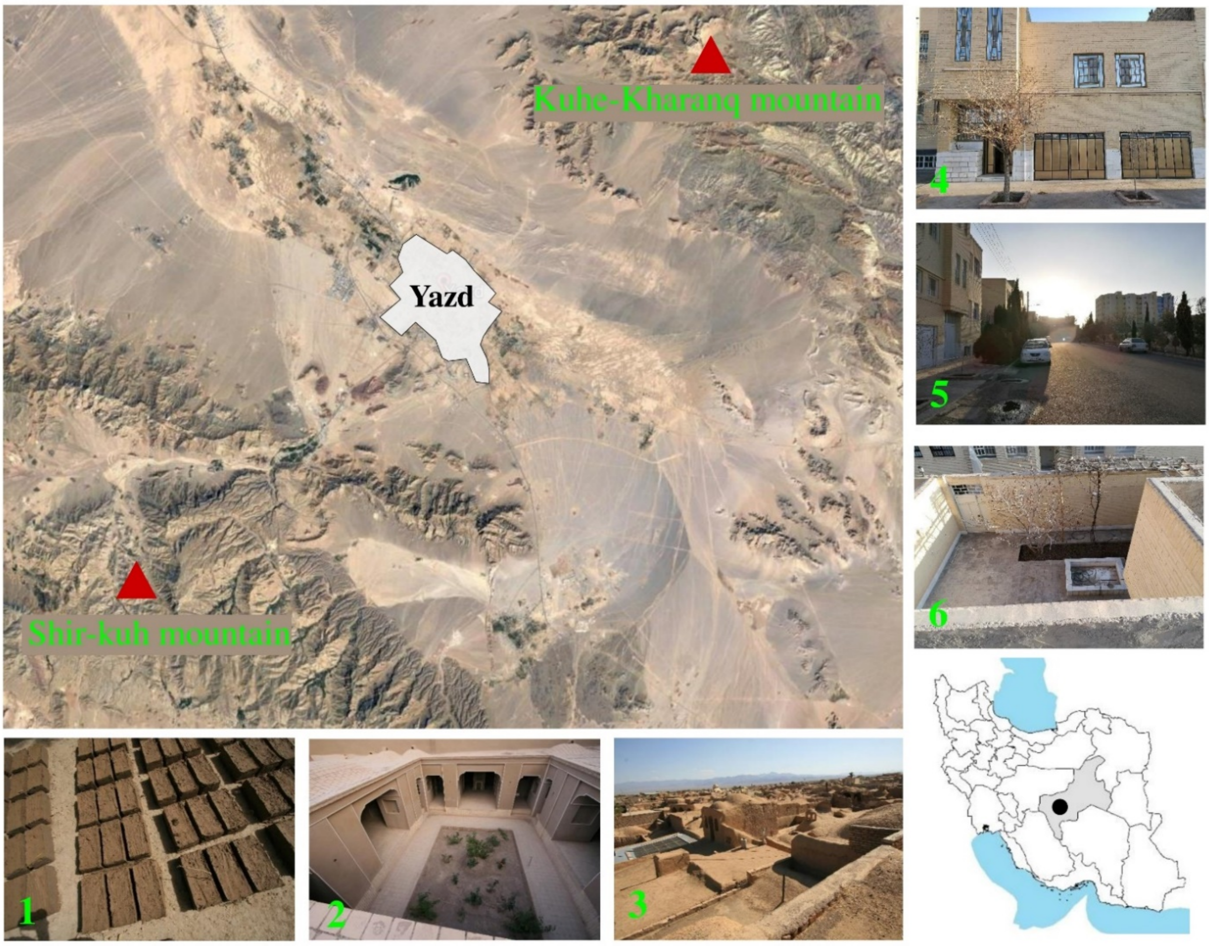


**Figure 1** The main picture in the center shows the location of the study area in central Iran, adjacent to the Kuhe-Karanaq and Shir-kuh mountains. Pictures 1-3 show the historical district, and pictures 4 to 6 show the new district of the city of Yazd. Pictures 1, 2 and 3 were taken by Mohsen Maki, and pictures 4, 5 and 6 were taken by Amirmasoud Zarrabi.

2.2 Indoor measurements of air temperature data

Temperature data were collected every hour during a 6-month period from 25 March to 20 September 2017 using the temperature data logger RC-5 at 70 locations chosen in the city of Yazd (Figure 2). In the historical district, 10 temperature data loggers were installed

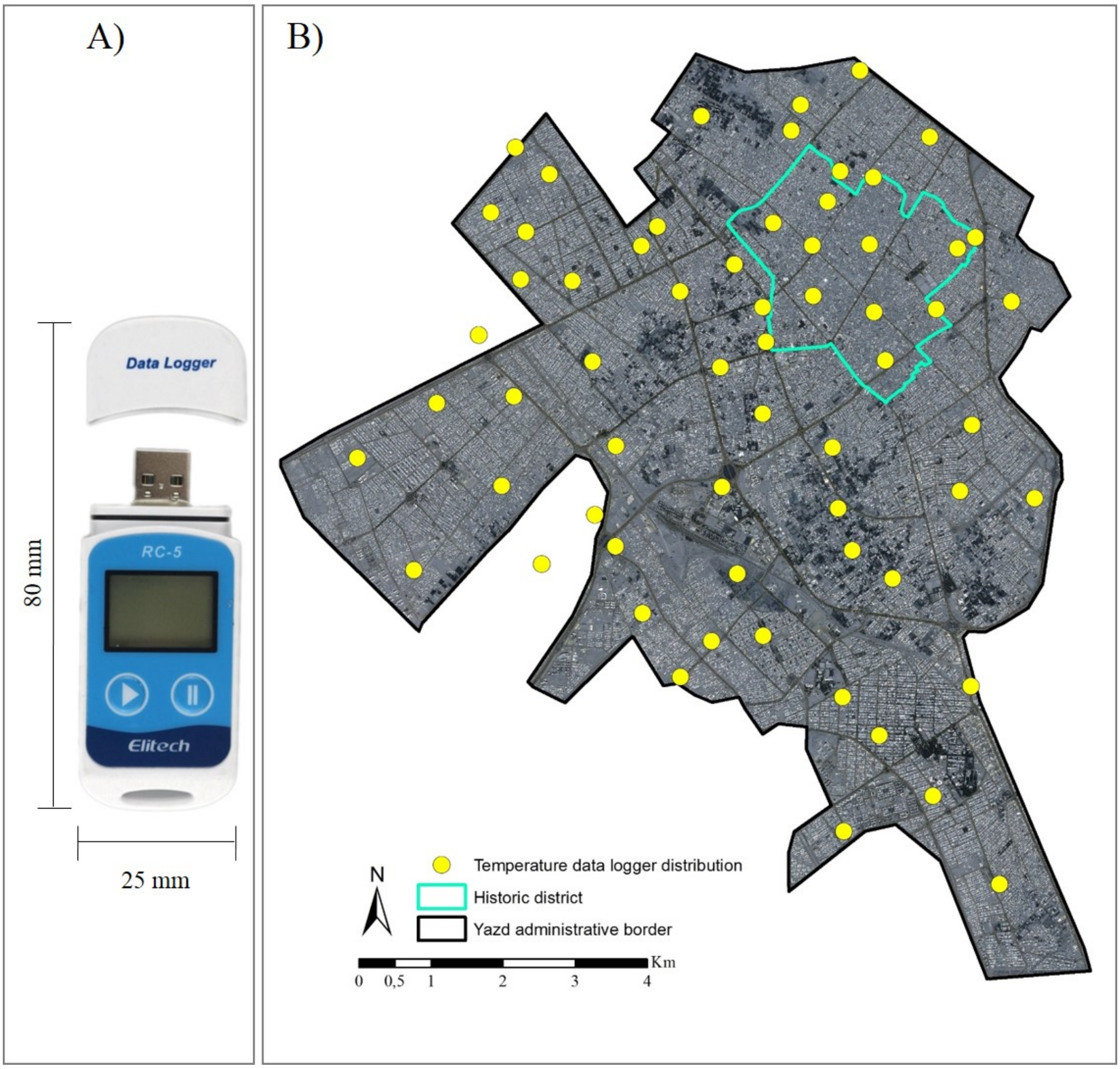


**Figure 2** The left-hand panel (A) shows the temperature data logger. The right-hand panel (B) shows the distribution of the temperature data loggers for the entire city of Yazd (10 devices in the historical district and 60 devices in the newly built district).

and in the newly built district, 60 temperature data loggers were installed; thus, each square kilometer in the historical district and every two square kilometers in the newly built district contained one temperature data logger. The RC-5 temperature data loggers from the Elitech Company (approximate dimension 80(L) × 34 (W) × 14(H) mm measure a temperature range of -30°C to +70°C at a resolution of +0.1°C. The accuracy of the RC-5 is +0.5°C, and the measurements range from -20°C to +40°C. Each temperature data logger was regulated to record the temperature in a 60-minute interval. All temperature data loggers recorded temperature values from March 25 to September 20, 2017. The exact locations of the loggers were identified using a GPS device.

The temperature data loggers were calibrated by direct comparison to a reference digital thermometer at a level of 0°C. For the installation of the temperature loggers, two major criteria were strictly observed: first, they must be installed indoors in a non-closed room with sufficient air convection and at a height of 2 meters on a wall, and second, the devices were kept out of direct sun exposure and were positioned where the indoor temperature was not directly affected by artificial air conditioning.

On 21 September, all temperature data loggers were collected. Using the USB port included in each temperature logger, the temperature data from the 25 March to 20 September were transferred to a single Excel spreadsheet. Temperature loggers were installed and collected at different times (early in the morning until late in the evening) on 25 March and 20 September. To ensure that the data loggers started recording temperature at the same time, only the time from the last installation of temperature data loggers to the time of the first collection of temperature data loggers were considered in the statistical analysis. For instance, if all temperature loggers were installed between 8.00 and 16.00 on the same day, we only considered the temperature records after 16.00 in the statistical analysis. Additionally, if the collection of the temperature loggers occurred between 8.00 and 16.00 on the same day, we did not consider temperature records after 8.00 in the statistical analysis. To cross-check whether the devices functioned properly during data collection and storage, the temperature data were compared with the daily temperature data recorded by the weather station in Yazd.

### 2.3 Outdoor measurements of surface temperature data

Measuring the land surface temperature using satellite data is one of the key steps in evaluating the physical process of surface energy exchange at local and global scales. Surface temperature characterizes the average temperature of the surface in a given areal unit, for instance, 30×30 meters, at a certain time during the local day or night. For this study, data were collected during the day (local time 10:30 AM) using a thermal infrared sensor (TIRS) on a Landsat-8 satellite. A cloud-free satellite image (less than 5%) was freely available from the United States Geological Survey (USGS) website (www.earthexplorer.usgs.gov) for

August 9, 2016. The spatial resolution of TIRS bands is 100 meters. A detailed description proposed by the USGS Landsat 8 Handbook was used to create land surface temperature maps.

2.4 Statistical Analysis

A statistical analysis termed the hot and cold spot analysis, a spatial statistics measure, was performed using temperature data from the 70 aforementioned temperature data loggers. The statistical analysis tests the null hypothesis and determines whether there is any spatial pattern among the detected features or among values associated with those features. To analyze the spatial temperature pattern, daytime temperature data were separated from nighttime temperature data (Ruiz et al., 2017; Zhang et al., 2017). Sunrise and sunset data from Yazd were included for each month (from March to September) to calculate day length hours and night length hours, respectively. Table 1 shows the average sunrise and sunset times and the average day and night length hours for the months of the temperature records (from March 25 to September 20, 2017) in Yazd. The average day and night-time temperatures were then calculated considering the day and night length hours.

**Table 1** Average day length hours during the months of temperature logger records in the city of Yazd.

| Months of temperature record | Average sunrise | Average sunset | Day length hours |
|---|---|---|---|
| March | 06:47:30 | 19:08:00 | 11:55:00 |
| April | 06:24:00 | 19:22:00 | 12:55:00 |
| May | 05:56:30 | 19:42:00 | 13:46:00 |
| June | 05:48:30 | 19:57:30 | 14:11:00 |
| July | 05:58:30 | 19:56:00 | 14:00:00 |
| August | 06:17:00 | 19:32:00 | 13:17:00 |
| September | 06:35:00 | 19:33:00 | 12:19:00 |

The hot and cold spot analysis identifies statistically significant spatial clusters of high values (hot spots) and low values (cold spots) using Getis-Ord (Gi-star) statistics. In the standard normal distribution of temperature data, the z-score is a test of statistical significance that tells whether one can reject the null hypothesis. The p-value is the probability of a falsely rejected null hypothesis. When the absolute value of the z-score falls in one of the two tails (larger than

1.65 and smaller than -1.65) of the normal distribution and the probability is lower than 0.05, the confidence level is greater than 90% (Table 2).

**Table 2** Critical p-value and z-scores for different confidence levels.

| Critical value (z-score) | Significance level (p-value) | Confidence level |
|---|---|---|
| < -1.65 or > +1.65 | < 0.10 | 90% |
| < -1.96 or > +1.96 | < 0.05 | 95% |
| < -2.58 or > +2.58 | < 0.01 | 99% |

In this case, the null hypothesis can be rejected, and it is very unlikely that the observed spatial pattern is the result of random processes (Figure 3).

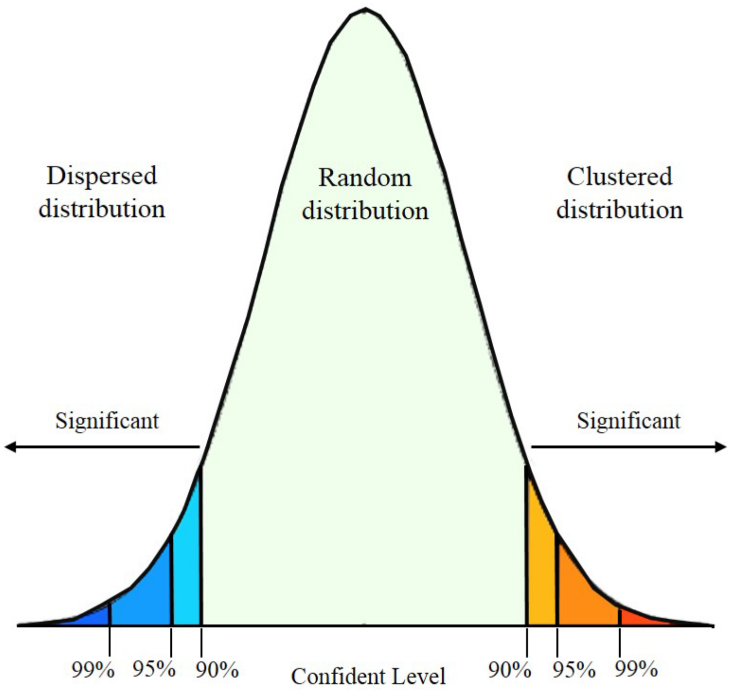


**Figure 3** P-value and z-score values are associated with the standard normal distribution.

Higher z-scores (> +1.65) of some features not only indicate a significant hot-spot but also intensive clustering within the data. Lower z-scores (< -1.65), on the other hand, indicate the statistical significance of a feature as well as a more dispersed pattern. Values close to zero are randomly distributed.

## 3. Results

### 3.1 Air temperature

The hourly day-time and night-time temperatures were separated for every temperature data logger. Then, the average day-time temperature and the average night-time temperature of each temperature data logger were calculated for every day between March 25 and September 20, 2017. Thus, for every temperature data logger, there is an average day-time and night-time temperature for every single day in the recording period. The statistical analysis used for this study was done separately for the historical and new districts in order to present the temperature patterns of both districts individually.

Figure 4 A depicts the average day-time and night-time temperatures during the recording period. The result shows lower night-time temperatures than the day-time temperatures in both districts. Interestingly, both the daytime and night-time inner-building temperatures of the historical district are lower than those of the new district. The results from the analysis of variance test, performed on the variation in indoor temperature between the historical and the new districts during the study, are shown in Figure 4 B. The variance is larger for the new district than for the historical district. This indicates that over the course of the day, the indoor temperature variation in the historical district is lower than that of the newly built housing stock. The temperature variance for the historical district is 7.3 during the day and 5.9 during the night, compared to 20 during the day and 17.40 during the night for the newly built district. Thus, the temperature is more constant and sTable in the historical district than the newly built.

Subsequently, to determine whether the temperature data are associated with the spatial patterns of building structures, the hot spot and cold spot statistical analysis was performed using temperature data from the temperature data loggers. The upper graph in Figure 5 illustrates the hot-spots and cold-spots during the day-time, and the lower graph in Figure 5 illustrates the hot and cold spots during the night-time for both historical and newly built districts for the period of the recorded temperature. Figure 5 shows the hot-spots and cold-spots over the course of the indoor temperature recording period. The distribution of hot-spots and cold-spots in the study area in Figure 6 has been illustrated. Figure 6 shows the frequency of hot-spots and cold-spots counted for each temperature data logger from March 25 to September 20, 2017. The frequency shows the hot-spots and cold-spots for days and nights separately. Figure 6 shows the historical district as a hot-spot during the temperature recording period for both days and nights. Thus, the probability that the indoor temperature in the historical district creates a cluster and is spatially related seems higher than the same probability for the newly built districts, which, even when the analysis is statistically significant, acts as a dispersed distribution.

A)

B)

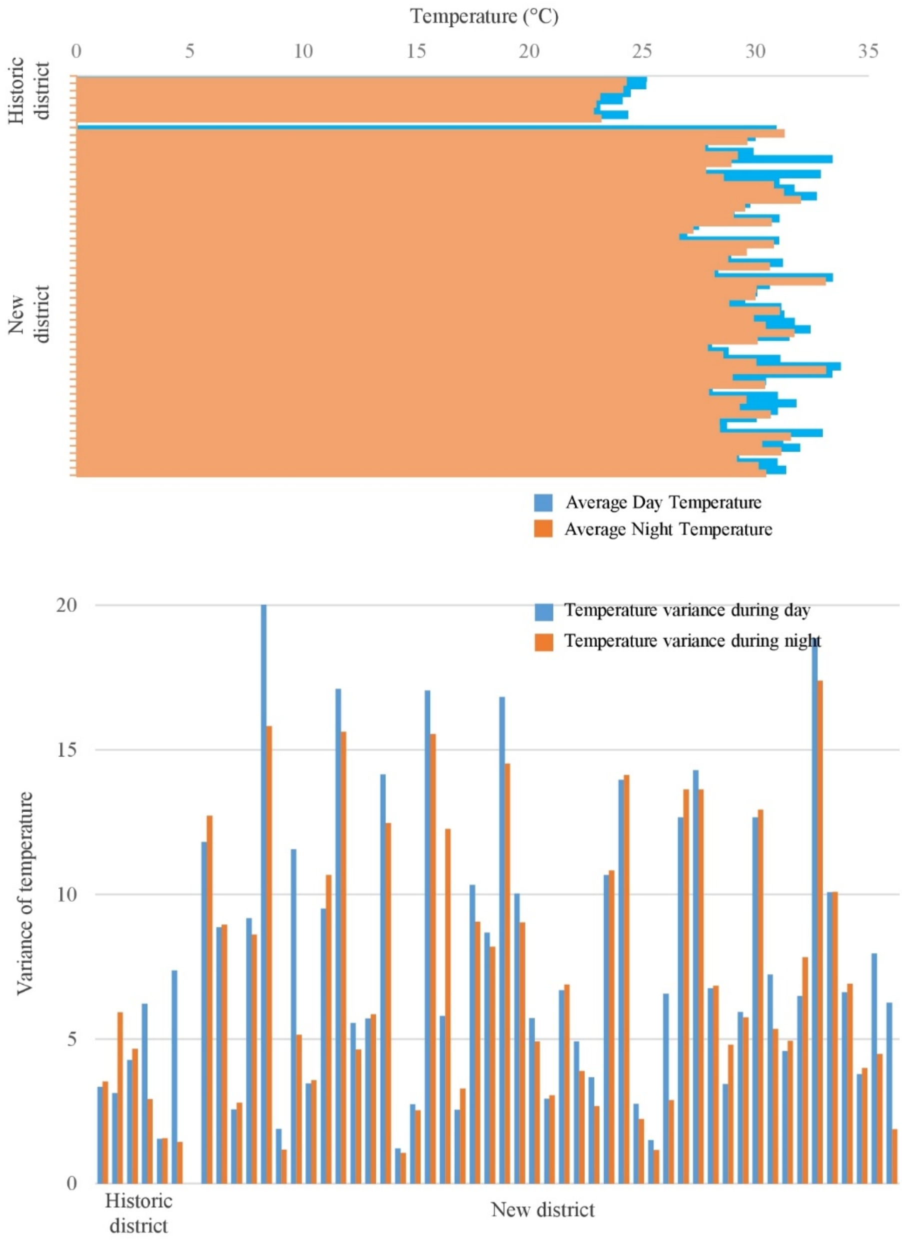


**Figure 4** A) Average day-time and night-time temperatures of historical and new districts of the city of Yazd based on 10 temperature loggers in the historical district and 60 temperatures in the newly built district. B) Variance of indoor temperature during the recording period in both historical and newly built districts.

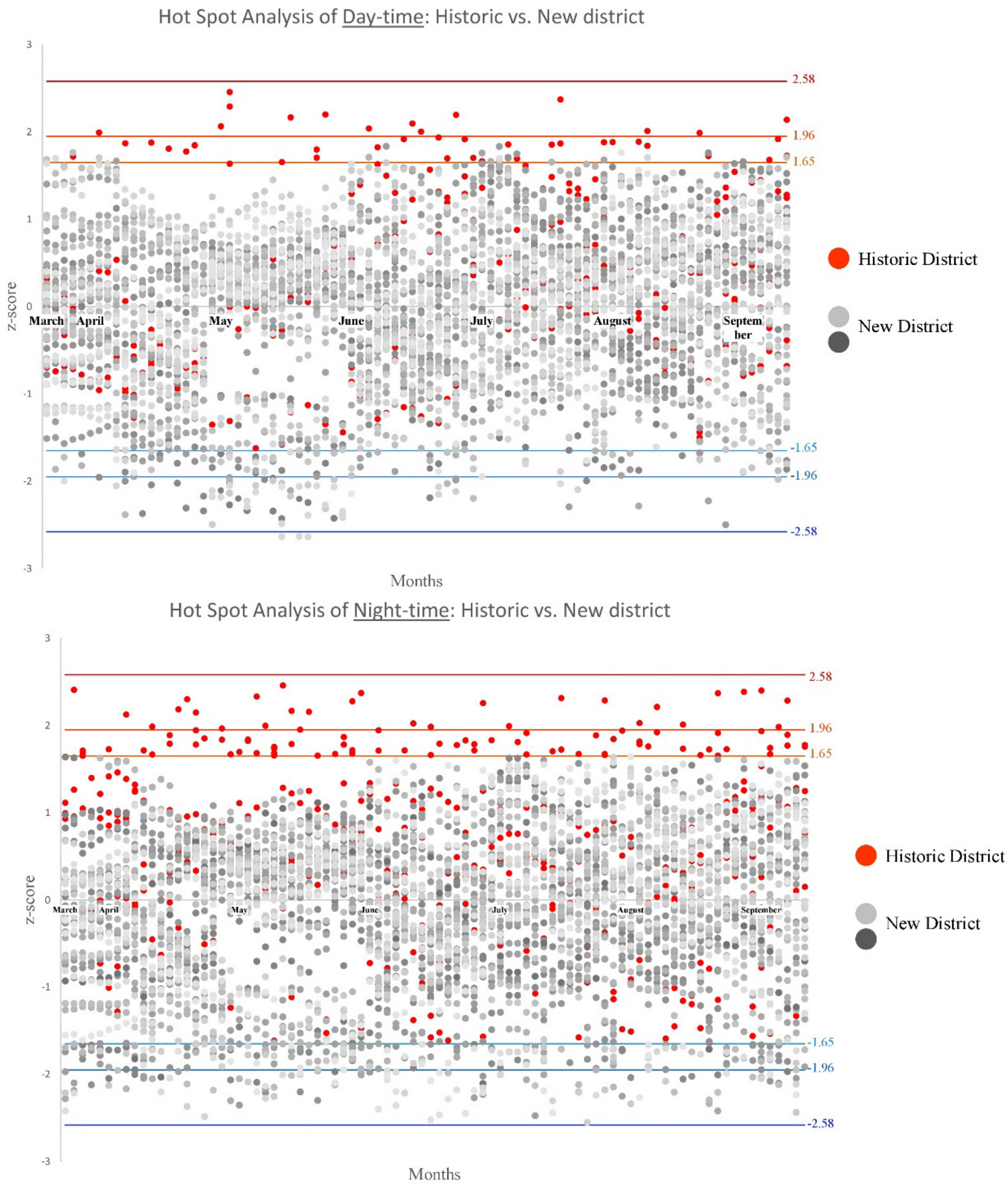


**Figure 5** The hot-spots and cold-spots of both historical and newly built districts of Yazd during day-time and night-time (from March 25 to September 20, 2017).

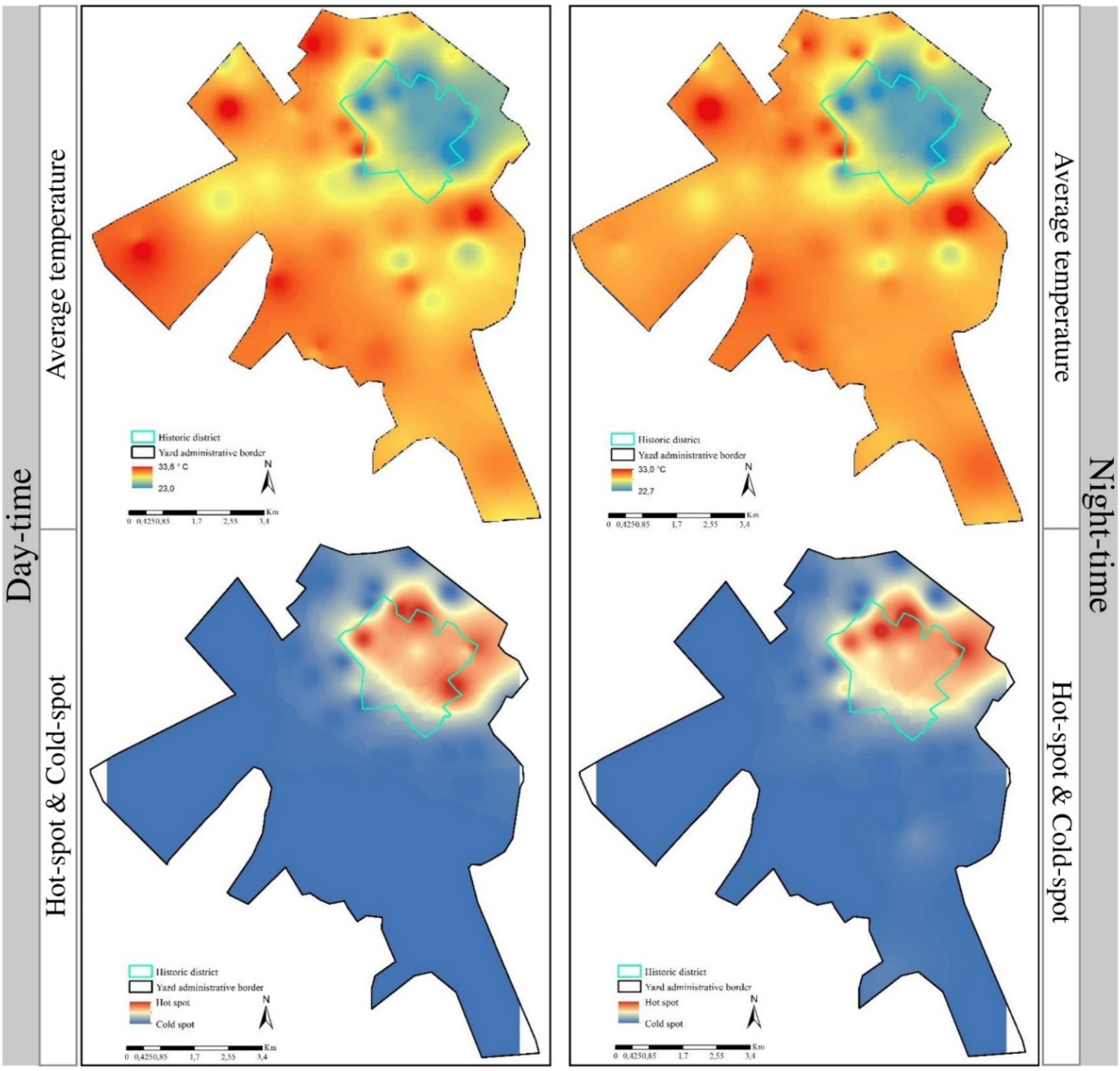


**Figure 6** Both upper Figures show the average indoor temperature recorded by loggers during days and nights. Both lower Figures illustrate the number of hot-spots and cold-spots repeated (frequency) for the temperature loggers during the day and night indoor temperature recording period.

3.2 Surface temperature

Figure 7 shows the structure and the surface temperature of the city of Yazd at 10:30 A.M. local time on 9 August 2016.

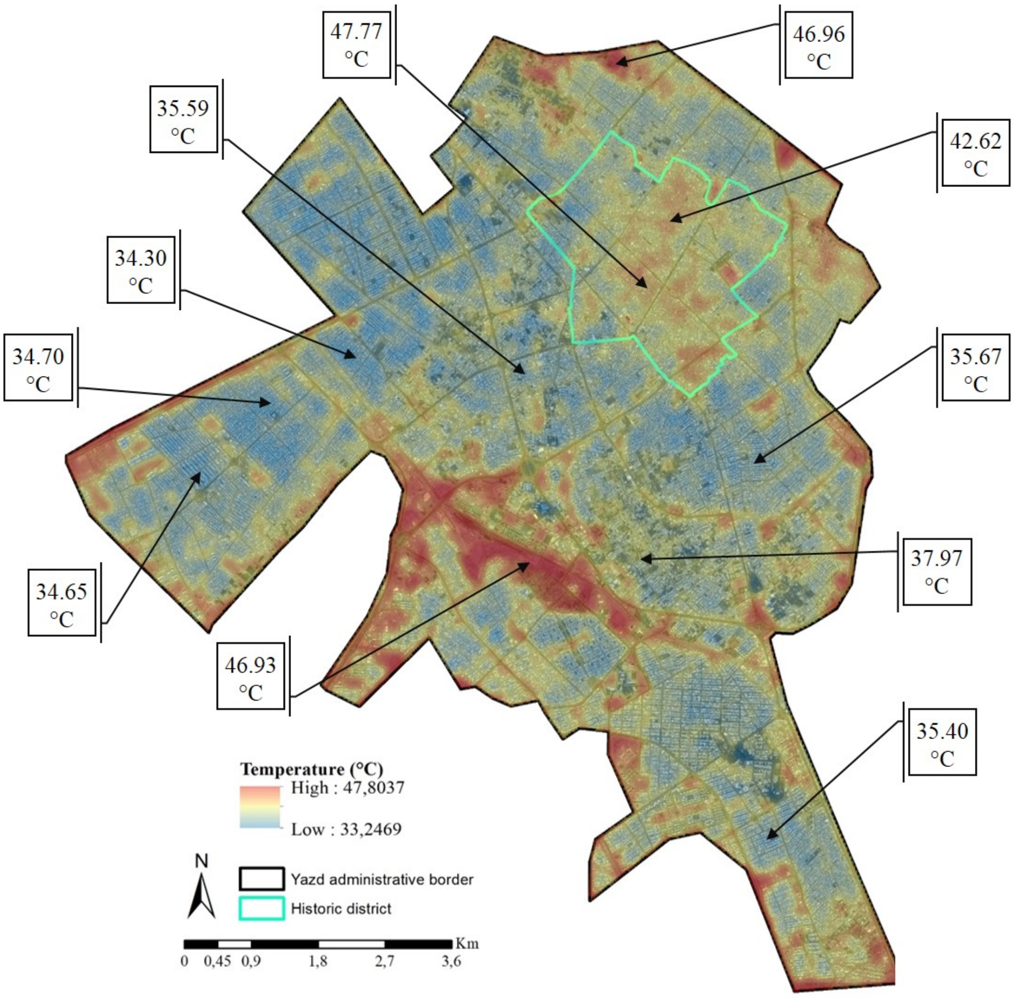


**Figure 7** Surface temperature for the city of Yazd, including both the historical and the new districts.

The surface temperature shows various behaviors in different districts as well as different land covers. Table 3 shows the temperature variations for different districts and land covers.

The results show a lower maximum, minimum and average temperature for the new district compared to the historical district. Among the different land covers, the surface temperatures of open and bare soil represent the highest minimum, maximum and average temperatures.

**Table 3** Distribution of surface temperatures in different districts and land cover types of Yazd.

| Surface temperature | Minimum record (°C) | Maximum record (°C) | Average (°C) | Standard deviation |
|---|---|---|---|---|
| Entire study area | 33.2 | 47.8 | 39.2 | 2.6 |
| Built-up in new district | 32.2 | 45.2 | 38.2 | 1.9 |
| Built-up in historical district | 34.4 | 46.9 | 39.2 | 1.7 |
| Open and bare soil | 37.0 | 47.8 | 42.8 | 1.9 |

## 4. Discussion

Previous UHI studies have either used remote sensing thermal data to report land surface temperatures (de Faria Peres et al., 2008; Mathew et al., 2018; Bonafoni et al., 2017; Chen et al., 2016) or have measured the heat fluxes using instrumental measurements to represent air temperatures (Shiflett et al., 2017; Jamei et al., 2017; Shojaei et al., 2017). Meteorological ground measurements of air temperature are the classic method used to measure the fluxes and air temperature. In the past few years, thermal remote sensing data have received renewed attention for their ability to retrieve land surface temperatures (Schwarz et al., 2011). Retrieving land surface temperature is still a challenging task, but it provides very useful knowledge of temporal, as well as spatial, variations in the surface equilibrium state.

The surface temperature in cities is associated with outdoor weather and human health (Weber et al., 2014). In Yazd, due to the desert-like conditions and the high heat during daytime hours, people spend most of their time indoors (Statistical center of Iran report, 2015). Therefore, the focus of this research was to associate the strength of satellite and on-ground in situ measurements to provide a better understanding of the indoor and outdoor temperature patterns during the day and night. Indoor and outdoor measurements occurred in both the historical and the newly built areas of the study area.

Although retrieving land surface temperature is still a challenging task, it provides very useful knowledge of temporal, as well as spatial, variations of the surface equilibrium state. In the context of UHI, thermal remote sensing information was used to retrieve surface and outdoor temperatures. The findings of this study indicate that two districts are exposed to higher temperatures than the others: the historical district located in the center of the study area and the bare grounds (open soils), which are spread among the newly built district of the city. The values of randomly selected pixels in Figure 5 represent both these districts with the red color, representing high surface temperature. In addition, the average surface temperature reflected in Table 3 confirms that open and bare soil show the highest average outdoor surface temperature, followed by the historical district of the study area.

The surrounding soil of Yazd (mainly sandy) is very dry, with almost no vegetation cover due to the dry climatic conditions of that geographical location. This is why the dry soil heats up so rapidly in the direct sunlight, producing high surface temperatures as demonstrated by Larson & Carnahan (1997). In addition, several factors play a key role in shaping the high surface temperatures of the historical district. The building material in the historical district (adobe brick) is made from the surrounding soil, which is replaced with newly built district building materials currently. The dense urban structure with houses built close together and with narrow alleys may be another reason for the high rooftop temperatures of the historical district. However, the historical district has a lower average surface temperature compared with the open and bare soil. The shadow effect produced by buildings and the small tree stock in the courtyards, the so-called ‘Sahn’, is presumed to be the main reason for the lower surface temperatures.

The air temperature recorded by the mobile temperature loggers tells a different story in terms of the indoor room temperatures of the study area, with a focus on the two different districts. The results indicate that indoor temperature data (air temperature) show different temperature behavior than outdoor temperature data (surface temperature). In addition, it is surprising that the indoor temperatures of the historical area show cooler temperatures than those of the new district. This is in direct contrast with the outdoor temperature data. Wael et al. (2017) and Adewale Oluseyi Adunola (2014) also reported similar contrasts in temperature results for their study areas. Figure 3 explains this contrast in a straightforward way by showing that the average indoor temperature of all 10 temperature loggers installed in the historical district is cooler than the average indoor temperature of all 60 temperature loggers installed in the new district. The indoor temperature of the historical district is cooler during the day and the night for the entire warm period.

Several factors play a role in shaping the difference between the indoor and outdoor temperatures. The outdoor spaces are exposed to a high intensity of solar radiation. The dense and often continuous developments of man-made infrastructure such as buildings, roads, railways, and minimal vegetation cover characterize the contemporary urban environment. Moreover, the use of dark-colored materials with high thermal storage properties leads to the high thermal accumulation of impervious surfaces. The vegetation cover of the Yazd urban environment is sparse. The dry climate and the high maintenance costs of irrigating trees due to water scarcity are the main reasons for this. Both facts are among other reasons for the weak evapotranspiration and the fragile cooling effect of urban vegetation. However, the vegetation cover in Yazd plays a different role in terms of cooling its surroundings in different physical morphological urban structures (new and historical districts). The findings of the statistical analysis presented in Figure 4 confirm the differences in the spatial patterns for the indoor temperatures of both districts. The Getis-Ord (Gi-star) statistical analysis identified the indoor temperatures of the historical district as constituting a statistically significant spatial cluster of hot spots. These findings are valid both for day-time and night-time indoor temperatures. Over the course of the temperature recording period during the days and nights of the warm months, the indoor temperature of the historical district frequently has a confidence level greater than 90 percent. Thus, it is very likely that the indoor temperature spatial pattern is statistically significant for the historical district. On the other hand, the observed spatial patterns of the new district are the result of random processes.

A previous study on human activity patterns published by Klepeis et al. (2001) indicated that humans spend, on average, 87% of their time in enclosed buildings, such as at home, in school, at work or during leisure time and approximately 6% of their time in enclosed vehicles. This pattern may vary by country, culture, climatic conditions, geographical conditions, urban infrastructure and accessibility, etc. However, there is no doubt that both indoor and outdoor temperatures are essential factors determining human thermal comfort. Comparing the outdoor and the indoor temperatures of different urban geometries (new and the historical district) indicates that urban physical morphologies and impervious surfaces are principle factors determining temperature in urban areas. Previous studies published by Wang et al. (2016) and Palme et al. (2016) also confirm this. In addition, a study published by Pasanen et al. (2014) shows that outdoor temperature and exposure to urban greening are connected to improved general and mental health. Therefore, combining and monitoring outdoor and indoor temperatures could aid our understanding of human thermal comfort.

The results of this study indicate a cooler outdoor temperature for the new urban district compared to the historical district. The planned structure of the new district with wide streets, plenty of space between buildings and open fields allows the wind to flow unhindered to cool down the surfaces during day and night. The geometry of the streets, especially the length-to-width ratio, could directly influence the airflow and solar access, which leads to less of a canyon effect as reported by Shishegar (2013). The vegetation cover in the new district is also more abundant compared to the historical district. More planted vegetation along the streets, in the middle of boulevards and in the backyards of houses in the new district aids the cooling effect. The cooling effect is shaped by the evapotranspiration of tress, and the resulting shadowing effect significantly decreases heat stress during the warm season. While the temperature is lower in the new district, the outdoor temperature of the historical district is higher. The dense architecture of the buildings and narrow alleys not only make wind flow more difficult, especially in the core of the district, but also increases the trapping of thermal energy and intensifies the overall canyon effect. Due to the dense urban structures and narrow alleys, the vegetation cover became restricted to courtyards; therefore, the cooling and shading effects are limited for the inhabitants of each house. However, one should bear in mind that the historical principle of building dense urban structures was to avoid the penetration of sunlight into buildings. Similar dense urban structures that avoid exposure to direct sunlight can also be seen in Morocco, Italy, Portugal, Iraq, India and Spain. To increase the albedo and keep the surface cool, methods using light, bright colors such as mixing straw with mud when molding bricks were historically used.

In contrast with the outdoor temperature results, indoor temperatures in the historical district are on average cooler than those in the new district. The findings of spatial hot and cold spot analysis of the indoor air temperature records show this pattern, as presented in Figure 4. The indoor temperature of the historical district frequently crosses the z-factor of +1.65 (and a p-value of less than 0.05), indicating that the confidence level is larger than 90 percent and that the indoor temperature records show a clustered spatial pattern. In contrast, the indoor measurements for the new district frequently cross the z-factor of -1.65. This indicates that it is highly probable (>90%) that the spatial pattern of the indoor temperature of the new district results from random processes.

The findings of this study, along with previous findings, suggest that urban configuration plays a critical role in determining outdoor temperatures as well as defining the inner temperatures of buildings. Unlike the warmer outdoor temperature of the historical district, its indoor temperature shows a cooler temperature trend than other districts, likely due to the dense urban structure. Although dense historical urban structures may trap heat, leading to warmer outdoor temperatures, they also limit the penetration of sunlight into buildings. The 3D study of Yazd, published by Alavipanah et al. (2017), shows that the new district shares more wall surface with its surroundings than the historical district, where the walls are shared among buildings. Objects with smaller areas exposed to sunlight are exposed to less heat. Therefore, although the closely constructed buildings may trap and store the heat, they are also less exposed to solar radiation than buildings in the new district. This could be one of the main reasons for the cooler historical indoor temperature levels. Moreover, the different building materials and the 3D spatial orientations of the buildings in both districts also play a role in shaping the indoor and outdoor temperatures. The adobe walls are not only thick (from 1 to 1.5 meters) but also have great thermal conductivity (1.0 W/mK) compared to concrete (0.3 W/mK). This suggests that the thick adobe walls have greater ability to store heat, rather than transmit it. Therefore, smaller wall areas being exposed to sunlight, thicker walls, the higher thermal conductivity of adobe, higher ceilings and the cool micro-climates created by the planted central courtyards are the main reasons explaining the cooler temperatures in the historical district.

The findings of this research call into question whether the role of indoor temperature on human health has been considered on a city scale. This research focused more on using remote sensing capabilities than on in situ measurements. Therefore, combining remote sensing and instrumental measurements could help to fill this gap and open new venues for future research. Analyzing and understanding outdoor and indoor temperature patterns and behaviors provides valuable information to districts vulnerable to indoor and outdoor heat stress. Measuring the indoor and outdoor heat stress can also be tested for different cities; however, there are several limitations to this study. First, it is not possible to include all the factors that are known to influence indoor and outdoor temperatures. Second, we were not able to measure the indoor temperature of all the districts of the city due to several restrictions. Third, due to time restrains we could not record the air temperature for the entire year and observe seasonal temperature variations; therefore, the results of this study are applicable only to cities comparable to Yazd during its warm period.

## 5. Conclusions

Most previous studies have investigated indoor and/or outdoor temperatures independently of one another. This study combined the results of indoor and outdoor temperature patterns into a single analysis. The results of this study suggest that in addition to outdoor temperature, indoor temperature can also strongly impact the health of city inhabitants, especially because humans spend most of their time indoors. City dwellers are mobile and dynamic, and spend much of their time either indoors (at home or work) or outdoors (commuting). City inhabitants are always exposed to heat regardless of how much time they spend indoors or outdoors; therefore, if the temperature is higher than the human thermal comfort level it could result in heat stress. Thus, measuring outdoor and indoor temperatures could reveal those districts vulnerable to heat stress. In addition, the results show that building characteristics such as orientation, density, material and shape each play different roles in shaping the indoor and outdoor temperature levels. The building material, regardless of the extent of each urban district, could characterize the indoor temperature, while the density of urban districts could characterize the outdoor temperature.

This investigation recommends that urban planners consider the thermal conductivity of mud bricks when developing new materials used in constructing buildings. In addition, historical building architecture with its high ceilings and central yards could help reduce the penetration of direct sunlight into houses, and therefore help to reduce heat stress in cities. Future studies are needed to investigate the electricity consumption of air conditioners for both districts. This will improve our understanding of the differences between these two districts, taking into consideration how different building materials, 3D building shapes, densities, etc. affect the resulting $Co_2$ emissions.

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# Chapter IV

## Summary and Synthesis: Take home message of the third-dimension in three minutes

In the first three sections of this chapter, the main results of the research papers are discussed in relation to the research questions of the dissertation (chapter I, section 5). This chapter is the final product of a multi-disciplinary approach, bringing physical geography, urban modelling and city planning closer together. What is presented here is the endpoint of a process that has brought a balanced breadth and depth in researching both theoretical and practical foundations of urban thermal condition. Unveiling the importance of 3D indicators in urban studies (ecosystem services and thermal conditions) was answered concerning my research questions. This final chapter discusses the applicability and the challenges of the urban thermal conditions. It points to additional requirements for methodological improvements and transferability in future research.

*I. The status of the current research addressing the third-dimension of ecosystem services in urban area: How can urban three dimensional studies close the existing knowledge gap about sustainability in cities?*

To have a comprehensive overview of the status of the current research on the third-dimension the temporal overview and the spatial distribution of articles should be investigated simultaneously. Whereas the temporal overview shows the progress of a topic over the years, the spatial distribution emphasizes on the role of countries in leading the topics.

The initial search returned 3480 published articles have met the criteria that were defined to explore the two scientific and academic search engines (Scopus and ISI Web of knowledge). The non-relevant articles were excluded and 298 articles remain. The results show that the publications on 3D started in 1991. With some ups and downs, the number of publications has increased over the years. This shows that although the progress towards 3D research is relatively slow and in infant stages, but it has received plenty of attention across different fields of studies.

The spatial distribution of the selected publications among the countries and continents was assessed based on both the study area of the publications (*study area-spatial-distribution*) and the affiliations of the authors (*affiliation-spatial-distribution*). We found distinguishing between "study area-spatial-distribution" and "affiliation-spatial-distribution" is a very convenient method to distinguish the regional advancement in addressing a research topic. In addition, this type of spatial distribution better represents the research investment from countries.

With the change in the climate, recent publications have shown greater interest in the integration and adaptation of cities with climate change. Thus, the role of sustainability and urban ecosystem services in adaptation and mitigation is being recognized than before. A key element of implementing sustainability in urban area is to understand the increasingly complex urban challenges in all of its details. In this regard, in recent years, remote sensing technologies have become popular and have provided useful data with various spatial, temporal, and spectral scales. In particular, the advancement of multi-sensor data and processing power of computers has enabled the three-dimensional measurements. Three-dimensional data facilitates extracting more accurate and reliable patterns, as well as mining deeper information. Therefore, the 3D configuration of urban area plays an important role in sustainable urban planning. For instance, the 3D configuration of urban form and UES was used to study the microclimate in the Phoenix local climate zone as well as making sound decisions for sustainable urban planning of Abu Dhabi, United Arab Emirates.

This review paper gives an overview on the currently state of ecosystem service in urban area. It also provides us with an insight of the existing gaps in three dimensional studies in urban ecosystems.

The highlights are: i) a shift in the sub-theme of ecosystem services from concept towards local and technical approach. ii) Outcomes of these projects consisted of 2D with respect to the data they used. iii) Studies assessing aspects of the third-dimension of urban ecosystem services – such as volume were absent. iv) 3D study of urban ecosystem services will advance the concept of sustainability in cities. v) Measuring in 3D will bridge gap of the relationship between urban structure and ecosystem services.

*II. Assessing the association of urban multi-dimensional (two- and three-dimensional) indicators on urban surface temperature: Based on the presence of two very different urban geometries in the city of Yazd, how does the surface temperature varies?*

There is no doubt that cities have a complex environment. Nevertheless, cities are just more than buildings, roads, green and blue structures. However, the scale at which urban structure and its components – no matter if it is a two-dimensional o three-dimensional – is often limited with a single dimension. Using individual dimensions usually leads to homogenous scaled outputs (Wong and Lau, 2013) that makes it difficult to capture the complexity of the urban environment. However, urban environments are multi-dimensional settings for which a multi-dimensional approach is undoubtedly needed. Therefore, to assess the association of multi-dimensional indicators on urban surface temperature, several horizontal (2D) and vertical (3D) dimensions were measured.

To examine the impact of multidimensional indicators on urban surface temperature I have chosen a study area that holds two very different urban geometries (historic and new district) in the city: The historic areas having been built in harmony with the harsh climatic conditions. Closely built buildings, one-story buildings made of adobe bricks (mudbricks) and narrow alleys are some of the characteristics of this district. Whereas, the new district are finished with cement and concrete, multi-story buildings with "right" angle arrangements and wide streets. Different urban geometries help to understand how dissimilar urban structures may contribute in shaping the surface temperature in urban area.

To study the multi-dimensional effect a range of multispectral and multiresolution remote sensing images (Landsat-8, WorldView-3) and spatial vector data (GIS building footprint) were used. These data were used to extract multiple 2D - such as surface temperature, building rooftop area, street, vegetation - and 3D indicators - such as building height, building volume, building surface area, shadow footprint and shadow volume – and were then incorporated in a regular spatial grid. To analyze the association of multi-dimensional indicators in the complex urban environment, a machine learning statistical model called boosted regression tree (BRT) was used. This model is advanced for analysis of the morphological relationships (Clarke and Johnston, 1999) that combines the strengths of two algorithms, regression tree and boosting, in a single performance (Friedman, 2002). State-of-the-art methodological approaches of BRT showed to be highly advantageous for analyzing urban environment that is a heterogeneous urban environment. The BRT method is a supervised learning method which requires a labeled dataset containing numerical values. The model can be trained by providing the model and the labeled as an input into the model. Thereafter, the trained model could be used to predict values for the new input examples. BRT could handle different types of predictor variables and accommodating missing data. This method increases the precision of urban environmental information and reduces the uncertainty. In addition, the BRT enabled this research to understand the relative spatial effect of multi-dimensional indicators on a dependent variable (surface temperature). Such a model could not only distinguish between the impact of 2D and 3D indicators and information, but could also rank the strength of each indicator individually. In particular, the advantage of studying several dimensions of a city at the same time is that the influential indicators could be defined individually.

The results show that the spatial temperature pattern of the historic district is other than the new district. In addition, the relative influence of BRT analysis shows that all of the 2D and 3D indicators play a role in defining the surface temperature. However, some indicators have a greater effect than others. Of course, it is expected that the rank of this indicator changes at different cities.

The highlights are: i) association of 2D and 3D urban morphology with surface temperature, ii) a machine learning statistical model of boosted regression analysis was used to reflect the relative influence of 2D and 3D information on surface temperature, iii) two- and three-dimensional indicators have an influence on urban thermal conditions, iv) three-dimensional indicators play an important role in shape the intensity of UHI.

III. *Variation of indoor and outdoor urban temperature pattern: How does different urban settlement, in particular the newly built-up area and the historic buildings behave in different thermal conditions.*

Studies in the field of human activity show that urban dwellers spend about 87% of their time at enclosed buildings (Schweizer et al., 2006). Of course this time could vary in different cultures, climatic and geographic conditions, etc. However, there is no doubt both indoor and outdoor temperature are essential factors in determining human thermal comfort. Both indoor and outdoor temperature should be considered in climate adaptation strategies. To examine the temperature behavior at different physical morphological urban structure, the outdoor and indoor temperature was measured at the same time. Remote sensing thermal data was used to retrieve the surface temperature (outdoor temperature) and temperature data loggers were used to measure the indoor air temperature. Associating the indoor and outdoor temperature in this study provides a better understanding of the temperature pattern at the study area.

Results show a higher outdoor temperature (surface temperature) at the historical district in comparison to the new district. Dense urban structure, building material (adobe brick) and few vegetation cover are the main reasons for the higher outdoor temperature (surface temperature) at the historical district. Dense urban structure and the high heat capacity of the adobe brick traps the incoming solar energy, which heats up the district. Lack of vegetation cover and fragile cooling effect of urban vegetation is an additional reason to the higher temperature at the historical district. However, the indoor temperatures measured by the mobile temperature loggers tell a different story. The temperature recorded by the temperature loggers installed in the historical district shows a cooler indoor temperature (air temperature) than the indoor temperature (air temperature) recorded in the new district during both day and night. The indoor temperature spatial pattern of the historical district is very likely to be statistically significant. Whereas the temperature observations in the new district are the result of random process. Other than previous studies, the results of this dissertation shows that considering the hot climate in constructing the buildings – such as the material and architecture – has shown to be effective in reducing the temperature in the city of Yazd.

The highlight are: i) using remote sensing data and air temperature data logger measurements, ii) assessing the indoor and outdoor temperature patterns of different urban settlements, iii) a distinct temperature pattern across the historic and newly built residential units.

## Conclusion: Taking urban ecosystem services one step forward

Even though Yazd is an exceptional city in terms of its urban structure and climate, valuable results and information have been understood within its boundary. As was shown in this dissertation, urban three-dimensional structure plays an important and crucial role in shaping the thermal condition of the city. The fact that the historic district shows a different temperature behavior, indicates that the ancient architecture has perfectly adapted the buildings with the harsh surrounding climate. Today, science is providing reliable data for stressing the importance of the urban thermal condition on urban dwellers. This is especially important in time that the climate is changing.

The scale of this project is of course small and therefore the results are also limited to the study area. However, the advantage of this dissertation is that its methodology could be implemented for other cities as well. Therefore, it would be interesting to study the impact of three-dimensional structure of different cities on the local thermal condition.

An important question for future research will be how much greening are required in districts valuable to heat stress. Even in cities with rich vegetation, knowing of where and how much greening is required could help to combat the local heat stress. Does the greening volume play a role in cooling the air? Does the same amount of broad-leaf and needle-leaf green provide equal cooling effect? These are questions that future research will answer.

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# Selbständigkeitserklärung

# Declaration of authorship

**Erklärung:** Hiermit erkläre ich, die Dissertation selbstständig und nur unter Verwendung der angegebenen Hilfen und Hilfsmittel angefertigt zu haben. Ich habe mich nicht anderweitig um einen Doktorgrad in dem Promotionsfach beworben und besitze keinen entsprechenden Doktorgrad. Die Promotionsordnung der Mathematisch-Naturwissenschaftlichen Fakultät, veröffentlicht im Amtlichen Mitteilungsblatt der Humboldt Universität zu Berlin Nr. 42 am 11. Juli 2018, habe ich zur Kenntnis genommen.

**Declaration:** I declare that I have completed the thesis independently using only the aids and tools specified. I have not applied for a doctor's degree in the doctoral subject elsewhere and do not hold a corresponding doctor's degree. I have taken due note of the Faculty of Mathematics and Natural Sciences PhD Regulations, published in the Official Gazette of Humboldt-Universität zu Berlin no. 42 on July 11 2018.

Berlin,
15.10.2018

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