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GLOBAL SENSITIVITY ANALYSIS FOR URBAN HEAT ISLAND EFFECT: A CASE STUDY IN A RESIDENTIAL NEIGHBOURHOOD IN ANKARA, TURKEY

A THESIS SUBMITTED TO
THE GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES
OF
MIDDLE EAST TECHNICAL UNIVERSITY

BY

İSMET BERKE ÇAKIR

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FOR
THE DEGREE OF MASTER OF ARCHITECTURE
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GLOBAL SENSITIVITY ANALYSIS FOR URBAN HEAT ISLAND EFFECT: A CASE STUDY IN A RESIDENTIAL NEIGHBOURHOOD IN ANKARA, TURKEY

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ABSTRACT

GLOBAL SENSITIVITY ANALYSIS FOR URBAN HEAT ISLAND EFFECT: A CASE STUDY IN A RESIDENTIAL NEIGHBOURHOOD IN ANKARA, TURKEY

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The rapid pace of urbanization, coupled with inadequate measures of government policies, has led to detrimental consequences for the built environment, the economics of daily urban life, and the life quality of city dwellers. Urban Heat Islands (UHI) exacerbates resource consumption and environmental footprint and threatens human health and comfort. New design and adaptation strategies are needed for urban settlements not only to lower the energy consumption and environmental impact of the built environment. Many factors influence UHI intensity, such as urban morphology, material selection, vegetation, and anthropogenic heat emissions. Therefore, it is essential to identify the most critical and “sensitive” parameters to understand the complex thermal conditions in urban environments under UHI effects. UHI effect can be calculated using simulation tools based on urban canopy models. Sensitivity analysis is a method that can extract valuable information about the model and increase model confidence under different degrees of uncertainty. Sensitivity analysis is also used to explicitly measure the impact of an input variable on the output. This paper presents a global sensitivity analysis of UHI increase in a residential district with a limited green area located in Ankara, Turkey. UHI is measured using Urban Weather Generator (UWG), an existing, validated tool that modifies existing annual time-series weather datasets using an urban canopy model. The parameters that potentially cause the highest UHI effect are identified by investigating the UHI Intensity metric. The seasonal impact on UHI effect is investigated by conducting simulations on average summer and winter weeks. Hourly and weekly parameter importance differences are observed by running sensitivity analyses on respective timeframes. A correlation matrix depicting the correlation between all the possible pairs of parameters is also shown.

Keywords: Urban Heat Island, Sustainability, Sensitivity Analysis, Simulation Analysis

ÖZ

KENTSEL ISI ADASI ETKİSİ İÇİN KÜRESEL DUYARLILIK ANALİZİ: ANKARA, TÜRKİYEDE BİR KONUT MAHALLESİNDE VAKA ÇALIŞMASI

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Yetersiz önlemlerle birleşen hızlı kentleşme, günlük kentsel yaşam ekonomisi şehir sakinlerinin yaşam kalitesi için zararlı sonuçlara yol açmıştır. Dünya çapında şehirlerde yaygın olarak gözlemlenen bir olgu olan Kentsel Isı Adaları (KIA), kaynak tüketimini ve çevresel ayak izini artırarak insan sağlığını ve konforunu tehdit etmektedir. Kentsel yerleşimler için sadece enerji tüketimini ve yapılı çevrenin çevresel etkisini azaltmak ve şehir sakinlerinin konforunu artırmak için yeni tasarım ve uyum stratejilerine ihtiyaç duyulmaktadır. Kentsel morfoloji, malzeme seçimi, bitki örtüsü ve antropojenik ısı emisyonları gibi birçok faktör KIA yoğunluğunu etkiler. Bu nedenle, kentsel ortamlardaki karmaşık termal koşulları KIA etkileri altında anlamak için en kritik ve hassas parametrelerin belirlenmesi esastır. KIA etkisi, kentsel gölgelik modellerine dayalı simülasyon araçları kullanılarak hesaplanabilir. Duyarlılık analizi, model hakkında değerli bilgiler çıkarabilen ve farklı belirsizlik derecelerinde model güvenini artırabilen bir yöntemdir. Duyarlılık analizi, bir girdi değişkeninin çıktı üzerindeki etkisini açıkça ölçmek için de kullanılır. Sonuç olarak, model çıktı belirsizliği ölçülebilir ve çıktı kesinliğine en fazla katkıda bulunan girdiler tanımlanabilir. Bu tez, Ankara, Türkiyede sınırlı yeşil alana sahip bir yerleşim bölgesinde KIA artışının küresel bir duyarlılık analizini sunmaktadır. KIA , bir kentsel gölgelik modeli kullanarak mevcut yıllık zaman serisi hava durumu veri kümelerini değiştiren mevcut, doğrulanmış bir araç olan Urban Weather Generator (UWG) kullanılarak ölçülmüştür.

Anahtar Kelimeler: Kentsel Isı Adası, Sürdürülebilirlik, Duyarlılık Analizi, Simülasyon Analizi

To my parents,

For their support and endless love

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CHAPTER 1

INTRODUCTION

The first chapter of the thesis presents an introduction to the thesis study, including four sections that are (1) background and significance (2) the problem statement, (3) research questions, and (4) the structure of the thesis.

1.1 Background and Significance

Urbanization has an adverse effect on the environment because of its production of pollution, change in physical and chemical properties of the atmosphere, and soil coverage and vegetation on the ground. Knowledge of microclimates in urban areas helps informed decision makers and designers to create better environments for humans by manipulating the urban environments through better planning of the urban fabric with the structures which constitute it and the spaces urban dwellers experience daily [1].

Former studies have found that the design and maintenance of a comfortable microclimate in an urban area increase the number of people present in an urban space [2]. In addition, too hot and too warm climate conditions have been documented to be having a negative emotional impact on the residents of the city [3].

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[1] Evyatar Erell, David Pearlmutter, and Terence Williamson, *Urban Microclimate : Designing the Spaces Between Buildings*, *Urban Microclimate*, 1st edn (Routledge, 2010) <https://doi.org/10.4324/9781849775397>.
[2] Jan Gehl, 'Life Between Buildings', 2011, 358.
[3] Ingegärd Eliasson and others, 'Climate and Behaviour in a Nordic City', *Landscape and Urban Planning*, 82.1–2 (2007), 72–84 <https://doi.org/10.1016/J.LANDURBPLAN.2007.01.020>.

As urban areas grow in size, increased air temperatures compared to rural areas start to define their microclimate. Referring to the collective effects of urbanization on the microclimate, this situation is called the Urban Heat Island (UHI) Effect [4]. UHI phenomenon leads to the creation of human made “warm islands” inside the lower temperature locations defined by the surrounding natural areas.

Urban air temperatures all around the world are increasing due to many reasons. To name a few, the decline in the proportion of green areas to its surrounding urban area, decreased wind speed due to vertical increase in urban geometry, and the urban road construction materials’ response to the solar heat gain. In addition, the use of heating, ventilating, and air conditioning systems to address the urban temperature problem caused by UHI by maintaining thermal comfort, therefore, increasing the indoor air quality will intensify the magnitude of UHI as those systems release heat as a response to the anthropogenic activity [5].

The urban heat island intensity (UHII) is used to quantify the UHI phenomenon. Spatially averaged surface or air temperature inside the urban volume is compared to the surrounding rural areas and the resultant temperature difference (ΔT_{u-r}) is denoted as the intensity of the inspected UHI effect [6],[7].

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[4] T. R. Oke, ‘Boundary Layer Climates - 2nd Edition’, *Boundary Layer Climates*, 2002, 464.
[5] Paul J. Crutzen, ‘New Directions: The Growing Urban Heat and Pollution “Island” Effect - Impact on Chemistry and Climate’, *Atmospheric Environment*, 38.21 (2004), 3539–40 <https://doi.org/10.1016/J.ATMOSENV.2004.03.032>.
[6] Yeon Hee Kim and Jong Jin Baik, ‘Spatial and Temporal Structure of the Urban Heat Island in Seoul’, *Journal of Applied Meteorology and Climatology*, 44.5 (2005), 591–605 <https://doi.org/10.1175/JAM2226.1>.
[7] ,Ahmed Memon Rizwan, Leung Y.C. Dennis, and Chunho Liu, ‘A Review on the Generation, Determination and Mitigation of Urban Heat Island’, *Journal of Environmental Sciences*, 20.1 (2008), 120–28 <https://doi.org/10.1016/S1001-0742(08)60019-4>.

Calculation of atmospheric (air temperature based) UHII is usually made through the utilization of data collected from air stations, meanwhile, surface temperature based UHI is typically determined using data from satellite imagery [8].

Even though the UHI phenomenon was first inspected by Howard in 1833 [9], predicting future climate and weather patterns is still uncertain due to the inherent uncertainties, in Washington, DC, New York, Vancouver, Marseille, London, and Abu Dhabi the UHI effect has been measured and documented [10]. Past studies have found that the UHI effect can raise the urban air temperature by 1-3°C when compared to surrounding rural areas[11]. Furthermore, the UHI effect negatively impacts urban dwellers' daily life by causing health problems and potentially amplifies the effects of heatwaves [12].

1.2 Problem Statement

One of the prominent problems in many urban centers today is the haphazard state of the urban fabric in the city as a result of the rapid development of urban areas. As cities develop, buildings, built and paved areas replace natural landscapes. Darker

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[8] Rizwan Ahmed Memon, Dennis Y.C. Leung, and Chun Ho Liu, 'An Investigation of Urban Heat Island Intensity (UHII) as an Indicator of Urban Heating', *Atmospheric Research*, 94.3 (2009), 491–500 <https://doi.org/10.1016/J.ATMOSRES.2009.07.006>.
[9] Luke Howard, 'The Climate of London: Deduced from Meteorological Observations', *The Climate of London*, 2012 <https://doi.org/10.1017/CBO9781139226899>.
[10] Jiachen Mao and others, 'Global Sensitivity Analysis of an Urban Microclimate System under Uncertainty: Design and Case Study', *Building and Environment*, 124 (2017), 153–70 <https://doi.org/10.1016/J.BUILDENV.2017.08.011>.
[11] T. R. Oke, 'Canyon Geometry and the Nocturnal Urban Heat Island: Comparison of Scale Model and Field Observations', *Journal of Climatology*, 1.3 (1981), 237–54 <https://doi.org/10.1002/JOC.3370010304>; Sue Grimmond, 'Urbanization and Global Environmental Change: Local Effects of Urban Warming', *Geographical Journal*, 173.1 (2007), 83–88 <https://doi.org/10.1111/J.1475-4959.2007.232_3.X>; Zsolt Bottyán and János Unger, 'A Multiple Linear Statistical Model for Estimating the Mean Maximum Urban Heat Island', *Theoretical and Applied Climatology 2003 75:3*, 75.3 (2003), 233–43 <https://doi.org/10.1007/S00704-003-0735-7>; Rizwan, Dennis, and Liu.
[12] Dan Li and Elie Bou-Zeid, 'Synergistic Interactions between Urban Heat Islands and Heat Waves: The Impact in Cities Is Larger than the Sum of Its Parts', *Journal of Applied Meteorology and Climatology*, 52.9 (2013), 2051–64 <https://doi.org/10.1175/JAMC-D-13-02.1>.

colored materials with lower thermal inertia such as roofs, roads, and parking lots absorb vast quantities of heat. Large urban masses constructed from reinforced concrete and steel structures both produce and absorb large amounts of heat, which is later transmitted to the surroundings. As a result, the urban center is several degrees warmer compared to the surrounding areas.

Rapid population growth in Ankara has its roots in its designation as the capital of the newly found Republic of Turkey in 1923 and the migration from rural areas to the city center due to the rapid modernization that followed. Ankara had a population of 75,000 in 1927 which rapidly increased to 5,747,325 in 2021 [13]. This drastic change in population adversely affected the urban fabric, which was initially designed to house 500,000 people [14]. Ankara developed considerably in control and according to the urban plans until the 1950s. However, as people seeking a better living standard in cities started to migrate to the city in masses, a sudden increase in city population gave way to the construction of illegal houses and uncontrolled urban spawn. This problem is addressed to a large extent by redevelopment and reconstruction of those areas by proper urban planning, nevertheless, some areas in modern Ankara still await redevelopment.

The case study area, Bahçelievler district was initially planned to be a low-rise residential area in the vicinity of the administrative area of Ankara. However, the urban population increased with immense speed and urban sprawl converted the Bahçelievler district to be a central location in Ankara. Then, Bahçelievler residences were demolished with the green areas that were contained within it and were turned into a mid-rise residential neighborhood. This conversion resulted in a dramatic

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[13] 'TÜİK Kurumsal' <https://data.tuik.gov.tr/Bulten/Index?p=Adrese-Dayali-Nufus-Kayit-Sistemi-Sonuclari-2021-45500> [accessed 3 July 2022].
[14] Sinan Burat, '"Yeşilyollarda Hareketle İstirahat": Jansen Planlarında Başkentin Kentsel Yeşil Alan Tasarımları ve Bunların Uygulanma ve Değiştirilme Süreci (1932-1960)', *İdealkent*, 2.4 (2011), 100–127.

change in the urban morphology of the city, and as a result, today UHI effect can be properly examined in this district about the impact of urbanization on the microclimate.

Sensitivity analysis inspects how uncertainty in a mathematical model's output can be associated with the different uncertainties in its inputs. Coupling sensitivity analysis with UHI computer simulations can detect the most important parameters in simulations via utilizing the model output as UHII measured in Celsius as the output uncertainty and input parameters' mathematical range definitions as the input uncertainties. From the results of the sensitivity analysis, parameter importance can be assessed and with the utilization of variance-based sensitivity analysis methods, parameter interactions can be observed [15].

As the UHI effect varies in magnitude with respect to the seasonal conditions, an inspection of the UHI effect in different seasons is necessary in order to be able to properly examine and compare shifts in parameter importance with regard to the external climate conditions. Daytime conditions are of immense importance concerning the mechanisms of UHI, and a study of UHI by hourly changes is required for the apprehension of parameter response to the changing daily conditions due to the sun's position and climate state.

In order to acquire all of the aforementioned data and to be able to conduct sensitivity analysis, a proper simulation method must be chosen as the computational cost of the preferred simulation method is immensely important due to the exponential increase in total computation time with the required amount of simulation runs as dictated by the chosen sensitivity analysis method. Also, sensitivity analysis

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[15] Tian Wei, 'A Review of Sensitivity Analysis Methods in Building Energy Analysis', *Renewable and Sustainable Energy Reviews*, 20 (2013), 411–19 <https://doi.org/10.1016/J.RSER.2012.12.014>.

preference is a very significant decision, as all methods differ from each other in the sense of how sensitivity indices are calculated, how parameters are sampled from the examined parameter space, and whether non-direct effects of the parameters on the output are calculated.

As urban areas continue to expand and further intensify the effects of the UHI phenomenon, there is an urgent need to identify root causes and assess the importance of factors main factors driving the intensity of the UHI effect to measure risks associated with climate change and thermal behaviors of the built environment in order to help policymakers and designers to make informed decisions about the future of the built environment.

1.3 Aim and Research Questions

This study aims to quantify and understand the impact of parameters contributing to the UHI effect and decompose the interactions between the causative factors via sensitivity analysis with respect to seasonal, weekly, and daily temporal differences in a case study conducted in the Bahçelievler district in Ankara. This study is conducted to contribute to the field of architecture by informing designers about the urban heat island impact of building and urban scale design decisions. Based on this aim, four objectives have been identified as the thesis aim:

- What are the main factors amplifying the UHI intensity in the Bahçelievler district?
- Which parameter pairs have substantial positive impacts on the UHI effect that further intensifies the increase in urban air temperature?
- What are the impacts of the seasonal differences on the assessment of parameter importance?
- How does parameter importance change with respect to hourly differences?

The answers to the following sub-questions will be provided throughout the research to be able to address these questions:

- What is the UHI effect?
- What causes the UHI effect?
- Which factors drive the UHI effect?
- What are UHI estimation and calculation methods?
- What are the commonly used computer simulation models for estimation of the UHI effect and what are their advantages and disadvantages from the perspective of sensitivity analysis?
- What is sensitivity analysis?
- How do different sensitivity analysis methods quantify parameter importance?

This thesis aims to contribute to the field of architecture by answering the questions outlined above, therefore informing architectural designers on the effects of their design decisions on the urban microclimate. As building and urban designers will continue to expand the area the built environment covers, city dwellers' health and their quality of life are closely correlated with the quality of the air in their urban settlements. Therefore, in order to be able to expand the urban areas in a more informed way, the effects of the factors which contribute adversely to the urban microclimate by causing the UHI effect are examined in this thesis study.

1.4 Chapter Overview

The thesis consists of six main chapters, including the current chapter. The current chapter presents an overview of the involved topics along with this thesis' research questions, motivation, and contribution to the field of architecture. The upcoming chapters' contents can be briefly explained as follows,

Chapter 2: This chapter consists of a literature review on the UHI effect and its sensitivity analysis applications on it. Former studies' findings and definitions of the UHI phenomenon are discussed and previously identified factors affecting the intensity of the UHI effect are explained. Sensitivity analysis and its premises are discussed. Various categories and methods of sensitivity analysis are reviewed with their scope, sampling method, and sensitivity index outputs they provide. Existing tools for the determination and simulation of the UHI effect are listed along with their advantages and disadvantages for the sensitivity analysis process.

Chapter 3: The methodology chapter outlines this thesis' approach for assessing the parameter importance regarding the UHI effect. UHI simulation tool and sensitivity analysis method decisions are explained. Data generating, processing, sampling, and uncertainty calculation methods are explained. How UHI is calculated and the mechanism of processing simulation results are outlined.

Chapter 4: The case study chapter explains the steps taken while conducting this thesis study. Details about the selected site of the study, selection and grouping of the inspected parameter with regards to the chosen sensitivity analysis and UHI simulation methods, data collection from the selected site, and processing of collected data for determination of uncertainty about parameter ranges are discussed.

Chapter 5: This chapter reviews sensitivity analysis results calculated from different timeframes and seasonal conditions. UHI intensity findings are shown and correlation with literature findings is discussed. Parameter interaction is discussed to gather information about the underlying causes of the UHI effect and the UHI intensifying effect of parameter interactions. The main factors which are found to be the most important by the sensitivity analysis are discussed with respect to daily and weekly timeframes and seasonal conditions are discussed with their UHI intensifying mechanisms and urban conditions which result in parameter uncertainty range values.

CHAPTER 2

LITERATURE REVIEW: SENSITIVITY ANALYSIS OF URBAN HEAT ISLAND

2.1 Introduction

This chapter starts with an explanation of the UHI effect with its definition, causes, and calculation methods. Existing literature about the main factors contributing to the UHI effect is presented. Sensitivity analysis, its scope, and working principles are listed along with prevalent sensitivity analysis methods. UHI calculation and simulation methods are listed with their strong and weak points. Lastly, sensitivity analysis of the UHI effect is discussed with the prior studies that conducted a sensitivity analysis on the UHI effect.

2.2 Urban Heat Island Effect

Since it was first described for the city of London by Luke Howard in 1818[16], the urban heat island effect has been the subject of much research. The urban heat island effect is one of the most vital signs of the microclimatic impact that urbanization causes. The magnitude of the urban heat island changes with daily and seasonal cycles and the urban heat island is known to be a complex subject. This part of the chapter reviews the literature on urban heat island with the aim of inspecting the relationship between the various factors that cause urban heat island and the phenomenon itself. Initially starting with the relation between urban area

[16] Howard Luke, *The Climate of London: Deduced from Meteorological Observations, Made at Different Places in the Neighbourhood of the Metropolis* (London, 1818), i.

size and temperature difference between rural and urban areas, several models will be explained in order to have a better understanding of the factors which cause the urban heat island effect.

2.2.1 Introduction

The considerable temperature difference between rural and urban areas can be detected in certain weather conditions. When isotherms are drawn for the urban area that is inspected for its thermal behavior, dense urban areas can be easily detected by following a series of concentric and close lines of higher temperature. The highest temperature values are typically recorded in the densest parts of the urban area. *Figure 1* illustrates the phenomenon called the "urban heat island". *Figure 2* shows the typical UHI effect's cross section where urban heat island intensity increases in magnitude as the urban area gets denser. "The urban heat island (UHI) can be described as a pattern of temperatures upper in urban areas than in the surroundings"[17]

The conventional method of determining urban heat island intensity $\Delta T_{urb-rur}$, denotes the difference in measured temperature between two locations, one representing a "rural" condition where built structures are not present and housing a natural landscape with moist soil and vegetation, other representing an "urban" condition where vegetation is very limited or not present, having many reinforced concrete and steel structures and pavement and roads constructed from hard surfaces. However, in real life urban-rural duality does not exist because they both represent extreme cases of what in real life is a continuum[18]. Urban land use varies significantly from one district to another with the specific utility that the district is expected to deliver. Also, untouched natural landscapes are rarely found in the near

[17] Juan P. Montávez, Antonio Rodriguez, and Juan I. Jimenez, 'A Study of the Urban Heat Island of Granada', *International Journal of Climatology*, 20.8 (2000), 899–911.
[18] Erell, Pearlmutter, and Williamson.

vicinities of the cities, as land near cities is often used for food production. This creates the problem of detecting the rural temperature, as these temperature measurement locations need to be far away from the cities the mesoscale climate effect can disturb the measurement such as a passage of a cold front which makes co-temporal temperature measurement difficult[19].

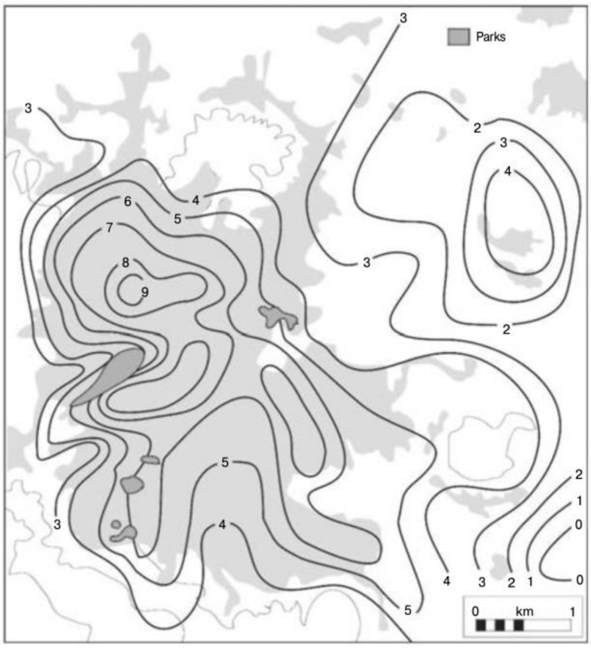

Figure 1 Demonstration of a night time urban heat island by isotherms drawn using mean minimum temperature in Mexico City, 1981[20]

[19] Erell, Pearlmutter, and Williamson.
[20] E. Jauregui, 'Tropical Urban Climates: Review and Assessment', *Urban Climatology and Its Applications with Special Regard to Tropical Areas*, 1986, 26–45.

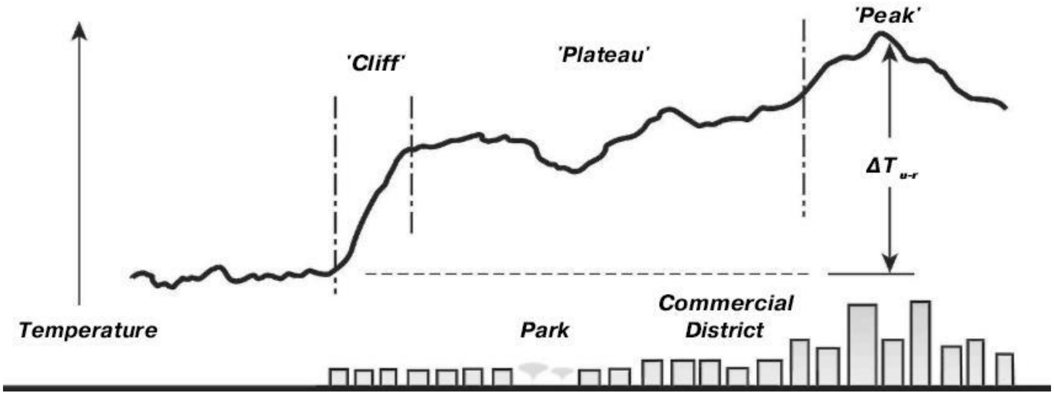

Figure 2 Cross section of a typical UHI effect in a city and its surrounding area[21]

However, despite the difficulty in measurement and location of urban and rural temperatures, UHI intensity can be still calculated with proper location decisions and proper meteorological equipment.

The addition of pollution and anthropogenic heat in the air generates UHI intensity[22]. Dense urban areas such as city centers generally consume more energy compared to the surroundings because of the population density present in those areas[23]. Energy need in city centers is amplified with the utilization of HVAC systems to condition warm air for the provision of indoor comfort, which releases anthropogenic heat into the canyon and further intensifies the UHI effect. Power generation for cities usually involves the burning of fossil fuels such as coal and petroleum based fuels, which in turn results in more air pollution in the urban areas. For these reasons, energy demand could increase and air quality can get worse and cause health problems for the residents in the urban areas with high density.

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[21] Erell, Pearlmutter, and Williamson.
[22] H. Taha, 'Urban Climates and Heat Islands: Albedo, Evapotranspiration, and Anthropogenic Heat', *Energy and Buildings*, 25 (1997), 99–103.
[23] HE Landsberg, 'The Urban Climate', *International Geophysics Series*, 28 (1981), 275.

For these reasons, the urban heat island effect is important to study, especially in looking for a better understanding of the factors that constitute it and to inform designers about the results of their urban and structural designs. Before giving more detailed information about the sensitivity analysis studies concerned with the UHI effect, the types, causes, and effects of UHI are explained to understand the concept clearly.

2.2.2 Scales of the Urban Heat Island

Three urban scales are used to understand the urban heat island effect, as they form the UHI effect in tandem, as shown in *Figure 3* . Analysis through different scales and temporal condition has immense importance for a deep understanding of the UHI effect.

2.2.2.1 Microscale

The microscale encompasses the part of the urban environment where individual structures, artificial surfaces, and roads define a canopy. This canopy layer stretches from the street level to the top of the average building height, and the top layer of this scale is called the urban canopy layer. Microscale can extend up to hundreds of meters horizontally[24].

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[24] Vincenzo Costanzo, Gianpiero Evola, and Luigi Marletta, *Urban Heat Stress and Mitigation Solutions : An Engineering Perspective* <https://www.routledge.com/Urban-Heat-Stress-and-Mitigation-Solutions-An-Engineering-Perspective/Costanzo-Evola-Marletta/p/book/9780367493639> [accessed 8 July 2022].

2.2.2.2 Local Scale

The local scale consists of similar urban areas, houses, office buildings, etc. Horizontally, they can cover several kilometers and vertically they extend up to the roughness sublayer (RSL). The effect of turbulence, originating from the height of the structures present in the urban area takes place in the RSL layer, and it is typically as tall as the height of several buildings. Urban climate has a great amount of variation, and this variation is caused by different microscales existing side by side. As a result, different magnitudes of heat stress are experienced throughout the urban area.

2.2.2.2.1 Mesoscale

Several local scales make up the mesoscale horizontally, and it extends up to the urban boundary layer in height. Urban boundary originates from the top of the urban canopy layer and reaches vertically to the height of the mixing layer. One of the striking characteristics of the urban boundary layer is that its height depends on the daily cycles, as heat originating from hard and impervious surfaces causes air near the surface level to rise, the height of the urban boundary layer can exceed 1kilometer, and in night cycles it is much shorter, it is generally a few hundred meters tall.

Using this classification, urban heat islands can be inspected as a phenomenon existing at the scale of urban canopy layer (canopy layer urban heat island), boundary layer (boundary layer urban heat island), and at the surface level (surface urban heat island)[25].

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[25] Harindra Joseph S. Fernando, *Handbook of Environmental Fluid Dynamics: Systems, Pollution, Modeling, and Measurements*, *Handbook of Environmental Fluid Dynamics: Systems, Pollution, Modeling, and Measurements* (CRC Press, 2012), ii <https://doi.org/10.1201/B13691>.

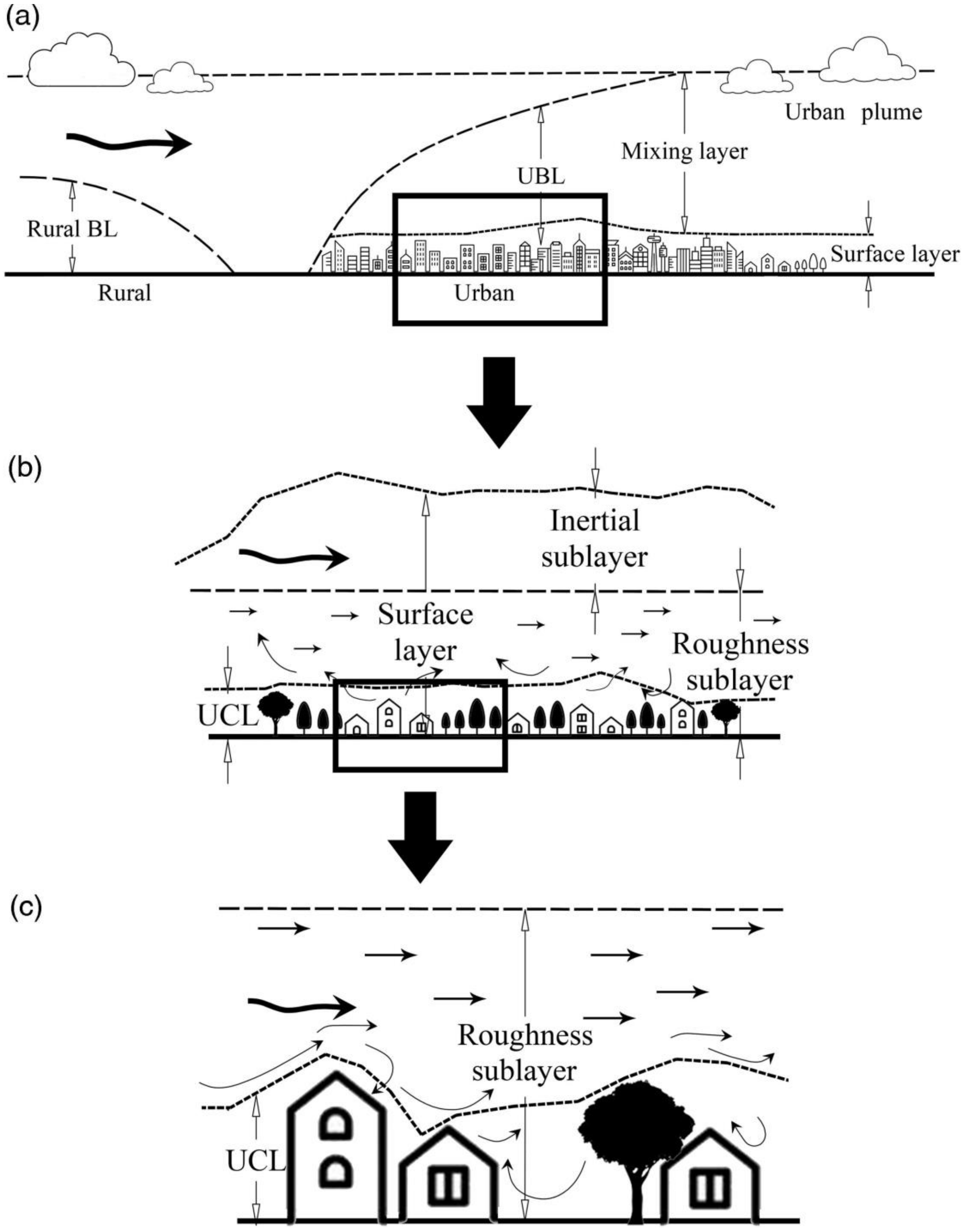

Figure 3 Diagrams for different scales of the UHI effect: (a) mesoscale, (b) local scale, (c) microscale[26]

2.2.3 Types of the Urban Heat Island

Urban heat islands can be detected both above the city, in the atmosphere (atmospheric heat islands), and at the surface (surface heat islands). The former can be inspected in two groups, boundary layer heat islands (BLHI) and canopy layer heat islands (CLHI). These categories differ in their response to daily effects, intensity, and physical form. Although they are all caused by interactions of several physical factors, they are not necessarily observed at the same and or the same place, and their characteristics are different.

2.2.3.1.1 Canopy Layer Heat Island

Canopy layer heat island can be observed in the layer of atmosphere which is closest to the surface in cities, which typically extends upwards along the mean building height in the urban area. The canopy layer covers the area between horizontal hard paved surfaces such as streets and is bounded by an upper area defined by the roof height of the average building height in the urban area[27]. CLHI is usually detected at night in relatively stable atmospheric conditions with scarce amounts of clouds and wind and is non-existent or weaker in daytime conditions [28]. CLHI diagrams can be seen in *Figure 4* and *Figure 5*. Measurements of CLHI are usually taken at 1.5m to 3m height, about the height of a person, or from the first level of the buildings. If the measured temperature is higher than the temperature detected at the rural station, then it is an urban canopy layer heat island[29] .

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[26] Costanzo, Evola, and Marletta.
[27] J.A. Voogt, 'Urban Heat Island: Hotter Cities', *Action Bioscience*, 2004.
[28] Erell, Pearlmutter, and Williamson.
[29] T. R. Oke, 'The Distinction between Canopy and Boundary-layer Urban Heat Islands', *Http://Dx.Doi.Org/10.1080/00046973.1976.9648422*, 14.4 (1976), 268–77 <https://doi.org/10.1080/00046973.1976.9648422>; T. R. Oke, 'The Heat Island of the Urban Boundary Layer: Characteristics, Causes and Effects', *Wind Climate in Cities*, 1995, 81–107 <https://doi.org/10.1007/978-94-017-3686-2_5>.

2.2.3.1.2 Boundary Layer Heat Island

In the urban boundary layer which exists just above the canopy layer, heat island formations can be observed. Heat islands that form at this layer are called boundary layer heat islands. BLHI forms a dome of warmer air that extends downwind of the city. It may be one kilometer or more in thickness by day, shrinking to hundreds of meters or less at night [30]. *Figure 4* and *Figure 5* show the BLHI shape with its surroundings. This boundary layer's thickness can extend up to 1km during the day and can have a height of 100m during the night[31].

2.2.3.1.3 Surface Heat Island

Surface heat island materializes when the temperature of urban surfaces exceeds surrounding natural surfaces in rural areas. In the cities where the urban fabric is surrounded by vegetated areas or moist soil, this sort of heat island is the most common as the surface temperature of rural surface temperature is generally lower compared to the impervious and dry urban surfaces. Nevertheless, in urban conditions where an urban area is surrounded by deserts, sandy soil with little or no humidity and exposed dry rocks can have temperatures higher than the urban surfaces, as shown in *Figure 6*. Urban surface heat islands are most pronounced in the daytime, particularly on sunny days with little wind. However, surface heat island is commonly weak in nighttime conditions, in contrast to the atmospheric UHI where it is generally a nocturnal occurrence and is less detectable in daytime conditions [32]. *Figure 5*(b) illustrates the surface heat island phenomenon. This type

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[30] Erell, Pearlmutter, and Williamson.
[31] Voogt.
[32] L. W.A. van Hove and others, 'Temporal and Spatial Variability of Urban Heat Island and Thermal Comfort within the Rotterdam Agglomeration', *Building and Environment*, 83 (2015), 91–103 <https://doi.org/10.1016/J.BUILDENV.2014.08.029>.

of UHI is measured by satellite and aircraft thermal infrared imagery, which allows solid thermal comparison of urban land surface and the surrounding rural surface.

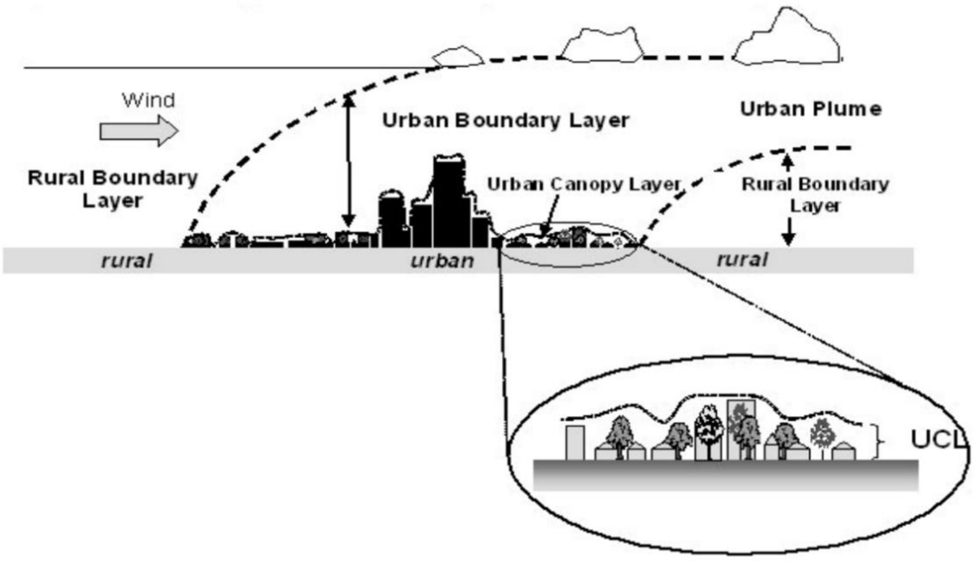

Figure 4 Diagram of boundary and canopy layer heat islands[33]

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[33] Voogt.

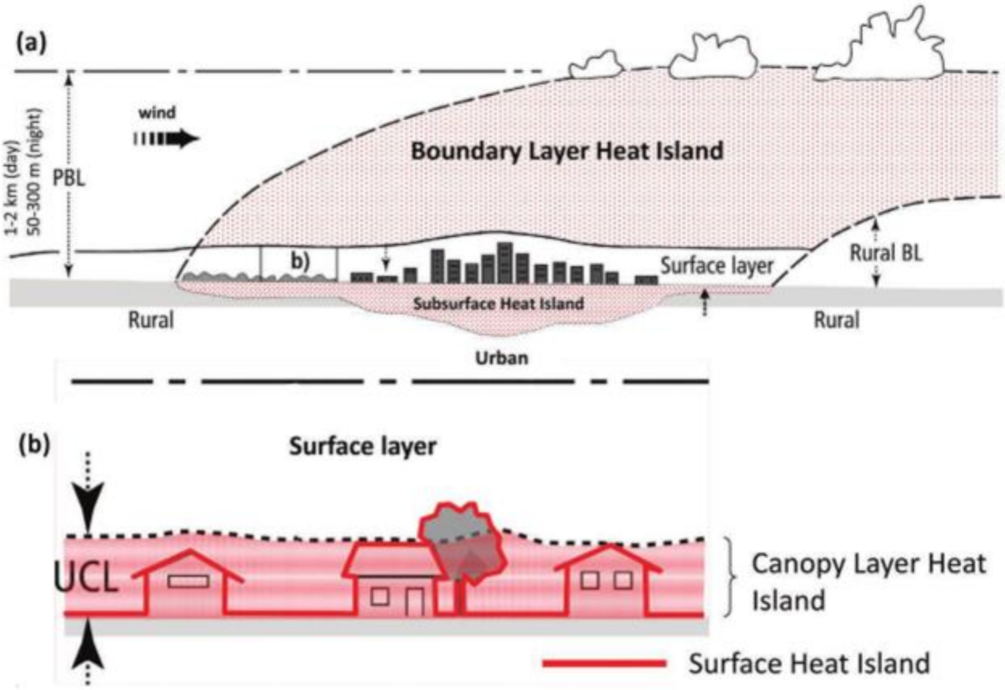

Figure 5 (a): Under certain weather conditions, inside the planetary boundary layer (PBL) which exists 1-2km above the planet's surface, a characteristic plume shape extending in the downwind direction defines the boundary layer heat island (b): Zoomed in diagram of a canopy layer and surface heat island[34]

[34] T. R. Oke, 'Urban Climates and Global Environmental Change', *Applied Climatology: Principles and Practice*, 1997, 273–87.

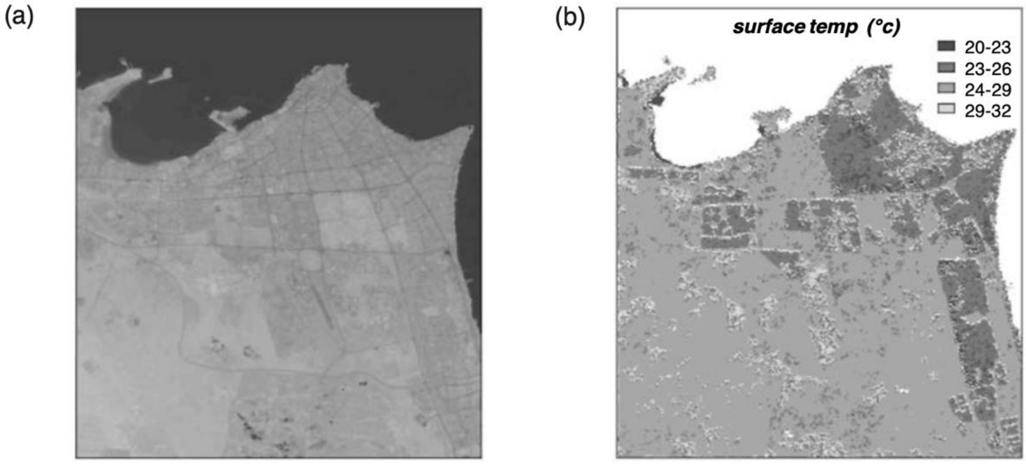

Figure 6 Thermal image depicting the surface thermal island of Kuwait city (a): Composite satellite image showing Kuwait city with its surrounding desert (b): Light gray areas denote higher temperatures, which in this case cover the surrounding desert area covering the city meanwhile dark gray areas corresponding to urban areas show lower temperature areas, as expected from a city surrounded with dry soil and rocks. This image was taken on the morning of 6 March 2001[35] *and redrawn by Erell et. al.*[36]

2.2.4 Formation of Urban Heat Islands

The root cause of the UHI effect can be traced back to the alterations humans have made and continue making to the natural environment in the city. A building can cause tremendous disturbance to surround lands in a variety of ways, therefore in order to understand the UHI phenomenon, physical processes and alterations in the city must be simplified in order to be able to understand the process at all. Particularly, energy balance differences in surrounding rural areas and the urban area must be examined with an aim of understanding the formation of the urban heat island. Energy balance ultimately decides whether the thermal behavior in the

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[35] Erell, Pearlmutter, and Williamson; Andy Y. Kwarteng and Christopher Small, 'Remote Sensing Analysis of Kuwait City's Thermal Environment', *2007 Urban Remote Sensing Joint Event, URS*, 2007 <https://doi.org/10.1109/URS.2007.371794>.
[36] Erell, Pearlmutter, and Williamson.

inspected area cools or warms it and it determines the speed at which these occurrences take place[37].

The urban heat island phenomenon is generally detected at night, particularly in dense cities, however, daytime UHI has been documented in the past as well. Every area has a unique cooling rate, which can be observed from late afternoon to early evening every day, and the cooling rate of the cities are generally lower than the surrounding rural areas. As a byproduct of this process, a temperature difference is formed between the urban area and the natural landscape around it, and this temperature difference usually reaches its peak several hours after sunset[38] as shown in *Figure 7*. This process works the other way around after sunrise, urban areas lag in temperatures when compared to the adjacent natural environment. These occurrences have been documented in various studies all over the globe. Although intensity and timings of the documented UHI effect change across the studies, similar findings have been found in cities with different densities, locations and shapes[39] an illustration of various former studies can be seen in *Figure 8*. As a result of this situation, "nocturnal heat island" is also used when referring to the urban heat island phenomenon.

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[37] Erell, Pearlmutter, and Williamson.
[38] T.R. Oke, *Boundary Layer Climates*, 2nd Editio (London: Methuen Co., 1987).
[39] Lemercier Cyril, MACHARD Anaïs, and JATO ESPINO Daniel, 'Sensitivity Analysis of Urban Heat Island Parameters Based on Urban Weather Generator Model', 2019 <https://repositorio.unican.es/xmlui/handle/10902/16976> [accessed 9 May 2022]; Agnese Salvati, Massimo Palme, and Luis Inostroza, 'Key Parameters for Urban Heat Island Assessment in A Mediterranean Context: A Sensitivity Analysis Using the Urban Weather Generator Model', *IOP Conference Series: Materials Science and Engineering*, 245.8 (2017), 082055 <https://doi.org/10.1088/1757-899X/245/8/082055>; Athar Kamal and others, 'Impact of Urban Morphology on Urban Microclimate and Building Energy Loads', *Energy and Buildings*, 253 (2021), 111499 <https://doi.org/10.1016/J.ENBUILD.2021.111499>; Noelia Liliana Alchapar and others, 'Thermal Performance of the Urban Weather Generator Model as a Tool for Planning Sustainable Urban Development', *Geographica Pannonica*, 23.4 (2019), 374–84 <https://doi.org/10.5937/GP23-24254>; J. Litardo and others, 'Urban Heat Island Intensity and Buildings' Energy Needs in Duran, Ecuador: Simulation Studies and Proposal of Mitigation Strategies', *Sustainable Cities and Society*, 62 (2020), 102387 <https://doi.org/10.1016/J.SCS.2020.102387>; E. Aydin and J. Jakubiec, 'Sensitivity Analysis of Sustainable Urban Design Parameters : Thermal Comfort , Urban Heat Island , Energy , Daylight , and Ventilation in Singapore', 2018; Mao and others; Erell, Pearlmutter, and Williamson.

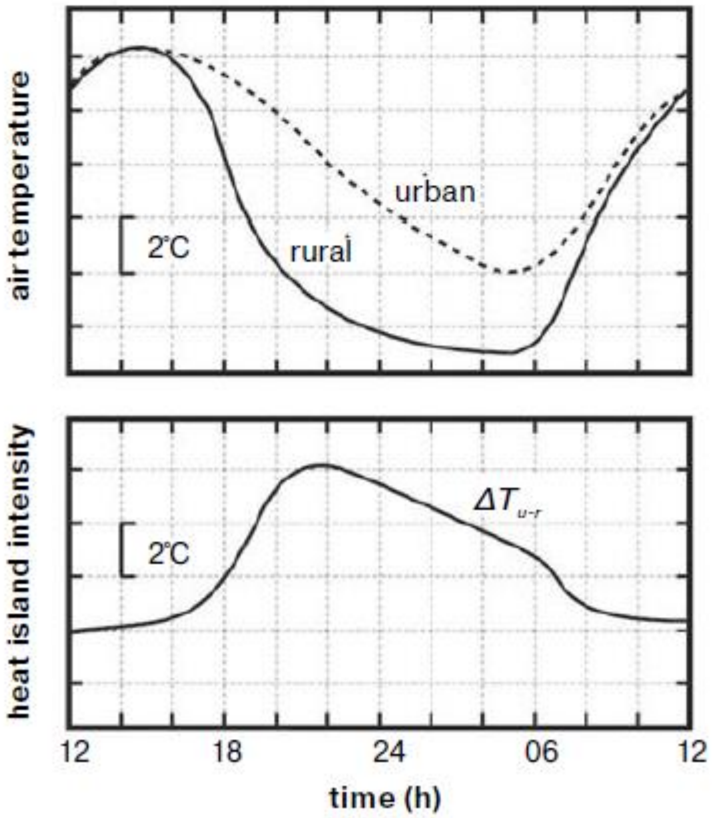

Figure 7 - (top) Typical behaviour of temperatures observed at rural and urban stations throughout the day, (bottom) resultant heat island heat effect intensity[40]

[40] T.R. Oke.

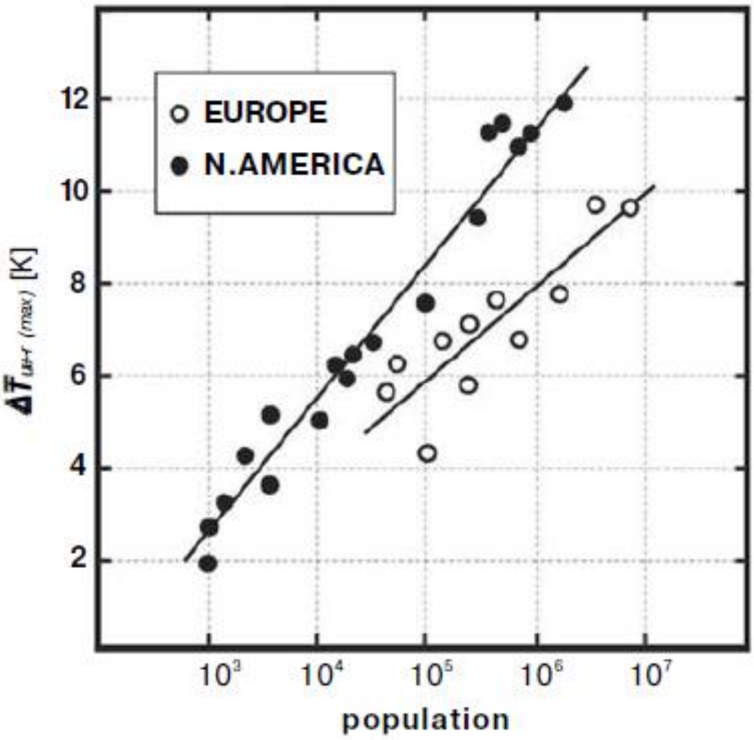

Figure 8 - Population and recorded heat island effect intensity relation in North American and European cities[41].

As shown in *Figure 8*, early studies in the field of urban heat island research have found a correlation between city size which was derived from population and urban heat island intensity. However, many studies have found that population is only an expression of the physical structure of the city which is constructed from reinforced concrete and steel structures with hard paved surfaces along its transport lines. The processes of energy exchange taking place in those cities caused by the physical structure then culminate into the formation of an urban heat island. Although how particular geometries and forms of the city affects the energy balance of each element existing at the surface level is of utmost significance, season, time of the day, geographical location, and weather conditions also affect the intensity of the

[41] T. R. Oke, 'The Distinction between Canopy and Boundary-layer Urban Heat Islands'.

urban heat island effect, which is the same for the heat released by the anthropogenic activities.

2.2.5 Causes of the Urban Heat Island Effect

In this section, previously identified sources that contribute to the intensity of the urban heat island effect are discussed, and a summary is provided at the end of this chapter.

2.2.5.1 Urban Geometry

Cities throughout the world have unique forms and different districts addressed to provide different amenities to the city dwellers, however, they all have a common point which is they differ from the surrounding natural areas. Many of these differences result in surface energy balance disparities between urban and rural areas and thus contribute to the formation of the urban heat islands. Building dimensions, geometry, and spacing in the urban area are the main factors that define urban form, but also the significance of the hard paved artificial surfaces which are impervious at the same time and the quantity of the vegetated space can't be underestimated.

Buildings' dimensions and form throughout the city determine the urban geometry, which is one of the main factors intensifying the urban island effect, especially at night. In nocturnal conditions, wind speed which is very closely linked to the urban geometry can amplify the urban heat island effect if it gets slower compared to the surrounding natural areas[42].

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[42] Young Hee Ryu and Jong Jin Baik, 'Quantitative Analysis of Factors Contributing to Urban Heat Island Intensity', *Journal of Applied Meteorology and Climatology*, 51.5 (2012), 842–54 <https://doi.org/10.1175/JAMC-D-11-098.1>.

2.2.5.1.1 Building Density

The concentration of buildings in a dense manner is one of the most prominent characteristics of the city. Most of the modern human activity takes place in the spaces enclosed by buildings, and the rapid pace of modernization led urban areas to be denser than ever. Tall buildings have risen on the modern streets, resulting in an urban fabric that resembles a canyon[43]. In general, these artificial canyons are taller than they are wide, and continuous building façades define their vertical elements.

Urban heat islands get intensified by a number of processes linked to the presence of dense urban fabric. One of the major processes that occur in the urban area is that solar radiation gets trapped much more in the urban canyon because of the abundance of absorption and reflection in the urban area. As albedo values of the dense urban areas are generally lower when compared to the surrounding natural lands, solar energy gets absorbed in the canyon more efficiently. Thus, energy stored in the urban fabric is amplified as a result of this process.

2.2.5.1.2 Façade to Site Ratio

The façade to site ratio of a canyon is calculated from the ratio of the total building façade area to the total horizontal area which buildings occupy. As the façade to site ratio gets higher in a dense matrix of buildings that define the urban canyon, the canyon becomes too deep and/or too narrow which leads to the solar radiation getting absorbed in the canton more frequently.

[43] Erell, Pearlmutter, and Williamson.

2.2.5.1.3 Building Height

Building height has immense importance for the wind behavior observed in dense urban areas. In nocturnal conditions where the wind gets slowed and trapped by the urban façades, the release of heat originating from anthropogenic heat intensifies the urban heat effect much more quickly[44]. Building height determines the strength and scale of the turbulence which originates at the street level due to the warm air rising. Rising warm air merges with the wind present at the urban site and this flow of air gets disrupted by the buildings present in the urban area[45]. Building height also dictates the average building floor count in a given urban area, therefore it scales up the release of heat produced as a byproduct of the anthropogenic heat with respect to its magnitude. Also, as the aspect ratio of a canyon defined by the ratio of the average height in the canyon to the canyon width gets higher, the emission of the long wave radiation to the sky is slowed down due to the low restricted sky view of buildings. This negative change in the rate of long wave emission results in the occurrence of a slower cooling after the sunset. *Figure 9* illustrates the former findings in the research of height to width ratio's relation with the urban heat island intensity.

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[44] Ryu and Baik.
[45] Costanzo, Evola, and Marletta.

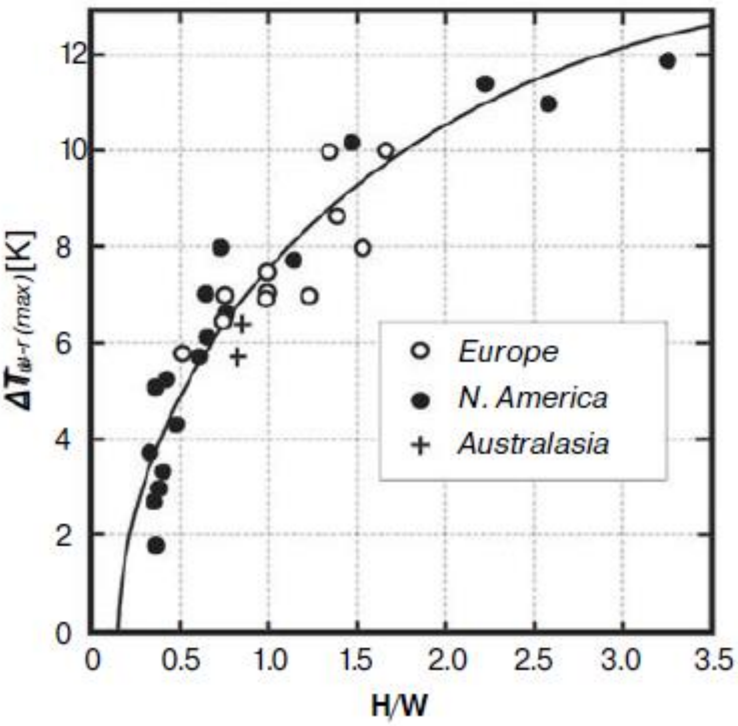

Figure 9 - Maximum observed urban heat island intensity and canyon height to width ratio relation documented from data documented at 31 urban canyons located in the city center[46]

2.2.5.2 Heat Released by the Anthropogenic Activity

Anthropogenic activity changes the atmosphere in various ways, such as releasing exhaust fumes from cars and industrial fumes mixing with the atmosphere. In addition, human activity also affects the urban heat island intensity as a byproduct of the main activity or directly[47].

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[46] T.R. Oke; Erell, Pearlmutter, and Williamson.
[47] Lisa Gartland, *Heat Islands: Understanding and Mitigating Heat in Urban Areas*, *Heat Islands: Understanding and Mitigating Heat in Urban Areas* (Taylor and Francis, 2012), i <https://doi.org/10.4324/9781849771559>.

Indirect effects of human activity on the urban heat island intensity encompass the release of carbon dioxide into the atmosphere as a result of fossil fuel burned by vehicles, industry, and power generation.

Anthropogenic heat fluxes are very hard to calculate, therefore they are measured in general by either energy balance closure or inventory based approaches[48].

Energy balance closure approaches utilize building energy modeling to estimate the energy spent at the building scale, and it scales up the findings to find out the total energy consumption at the city scale. Inventory based approaches utilize large scale energy consumption data at a wide timescale and then downscale it to local or hourly units. In either case, total energy usage measured in an urban context is assumed to be converted to waste heat emissions in the form of sensible heat flux[49], nevertheless, latent heat fluxes and additions to heat storage are possible as well in principle.

Interaction of heat flux with the environmental elements causes air temperature to increase, however, this increase is as dependent on the strength and magnitude of the heat flux as it is dependent on the environmental processes that take place in the urban context. Cold winter conditions in dense city centers most profoundly experience urban heating due to anthropogenic heat release, where heated air in enclosed spaces leaking to the outside can raise outdoor temperatures by a considerable margin[50]. In addition, summertime urban air temperature increases can also be measured in dense city centers, originating from the waste heat produced by the air conditioning and refrigeration systems. However, the magnitude of this temperature increase is generally much smaller when compared to the winter conditions. As stated by the studies conducted before the 1980's,

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48 Changhyoun Park and others, 'Comparative Estimates of Anthropogenic Heat Emission in Relation to Surface Energy Balance of a Subtropical Urban Neighborhood', *Atmospheric Environment*, 126 (2016), 182–91 <https://doi.org/10.1016/J.ATMOSENV.2015.11.038>.
49 Costanzo, Evola, and Marletta.
50 Erell, Pearlmutter, and Williamson.

anthropogenic heat increase trends when observed from the perspective of seasons were assumed to range between 70 to 210 $W \cdot m^{-2}$ in winter and 20 to 40 $W \cdot m^{-2}$ in summer with two peaks observed in diurnal cycles[51]. The first of these peaks occur when residents in a city wake up and go to work, between 6 a.m. and 9 a.m., meanwhile the second one takes place in the late afternoon and early evening between 5 p.m. and 7 p.m. when urban dwellers finish working and start to move away from their working spaces. Thermal gains originating from anthropogenic heat release have been found to be considerably bigger in quantity nowadays due to the increased energy use in the modern world, and this increase in energy usage is linked mainly to the extensive air conditioning usage in summer conditions in a more recent study[52]. For example, a study focused on the case of Tokyo, Japan has found out that anthropogenic heat release in summer conditions can reach up to 400 $W \cdot m^{-2}$ in summer and up to 1590 $W \cdot m^{-2}$ in winter[53]. Anthropogenic heat release in winter conditions was nearly equal to the solar energy received by the area and was nearly equated to 40% of solar heat gain magnitude documented in summer conditions.

2.2.5.3 Surface Properties

Surface properties such as albedo values, thermal emissivity, and roughness influence the behavior of the urban heat island in various ways, influencing the rate of warm air mixing with the cooler air via turbulence during the day. The variation in the qualities of the surface properties directly influences the characteristics of the energy balance dynamics experienced throughout the urban area.

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[51] Taha.
[52] Park and others.
[53] Toshiaki Ichinose, Kazuhiro Shimodozono, and Keisuke Hanaki, 'Impact of Anthropogenic Heat on Urban Climate in Tokyo', *Atmospheric Environment*, 33.24–25 (1999), 3897–3909 <https://doi.org/10.1016/S1352-2310(99)00132-6>.

2.2.5.3.1 Albedo and Reflectivity

Albedo is the percentage of solar radiation reflected by an object. An object which has the albedo of 1 is purely white and would reflect all the solar radiation it is subjected to. A pure black object would absorb all the solar radiation and have an albedo of 0. Objects which have bright surfaces such as snow, and ice and clouds have albedos that range from 0.5 to 0.95. Darker objects such as newly constructed asphalt, and dark colored soils have albedos between 0.05 and 0.20.

Absorption of the short and long wave radiation from solar energy is mainly determined by the two optical characteristics of the surface, thermal emissivity, and albedo value. *Figure 10* illustrates the common albedo values of the surfaces generally found in urban areas. Thermal emissivity and albedo value correspond to the amount of radiant heat released by the surfaces and the percentage of the solar radiation reflected from the surface respectively[54].

Reflectance is the ratio of the reflected radiation from the surface to total amount of radiation received by the surface. Since reflectance is a ratio of fluxes, it is unitless.

The process of sensible heat releasing from the surfaces is highly dependent on the amount of solar radiation received by the surface, which varies accordingly to the optical qualities of the surface, the geometry of the structures and their surroundings, and the orientation of the buildings and pavements[55].

Despite the differences in the processes that result in the urban heat island effect in the cities, the percentage of the conversion from net solar radiation flux to convective heat flux has been documented to be similar in most documented urban

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[54] Costanzo, Evola, and Marletta.
[55] Julien Bouyer, Christian Inard, and Marjorie Musy, ‘Microclimatic Coupling as a Solution to Improve Building Energy Simulation in an Urban Context’, *Energy and Buildings*, 43.7 (2011), 1549–59 <https://doi.org/10.1016/J.ENBUILD.2011.02.010>.

areas, geographic locations, and climates as it ranges from 35% to 45%[56]. However, conversion from the net all wave solar radiation to the heat stored in urban fabric has been found to display more variation, in the range of 20-55%.

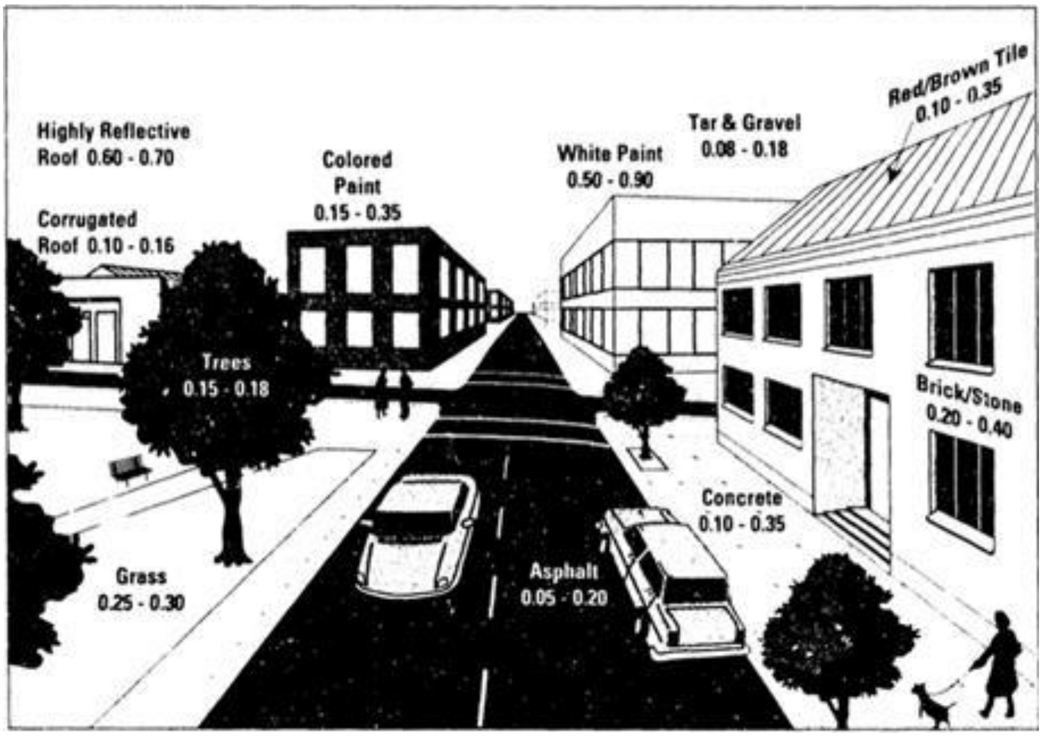

Figure 10 - Albedo values of surface materials commonly found in urban contexts[57].

2.2.5.3.2 Thermal Inertia

Thermal inertia can be defined as the 'property of a material that expresses the degree of slowness with which its temperature reaches that of the environment' Ng

[56] Matthias Roth, 'Review of Urban Climate Research in (Sub)Tropical Regions', *International Journal of Climatology*, 27.14 (2007), 1859–73 <https://doi.org/10.1002/JOC.1591>.
[57] Y J Huang, H Akbari, and H Taha, 'The Wind-Shielding and Shading Effects of Trees on Residential Heating and Cooling Requirements', in *ENERGY & ENVIRONMENT DIVISION, 1990 Winter ASHRAE Meeting*, 1990.

et al. 2011[58]. However, the definition that best describes it is that it is the capacity of a material to delay the transmission of heat by storing it[59]

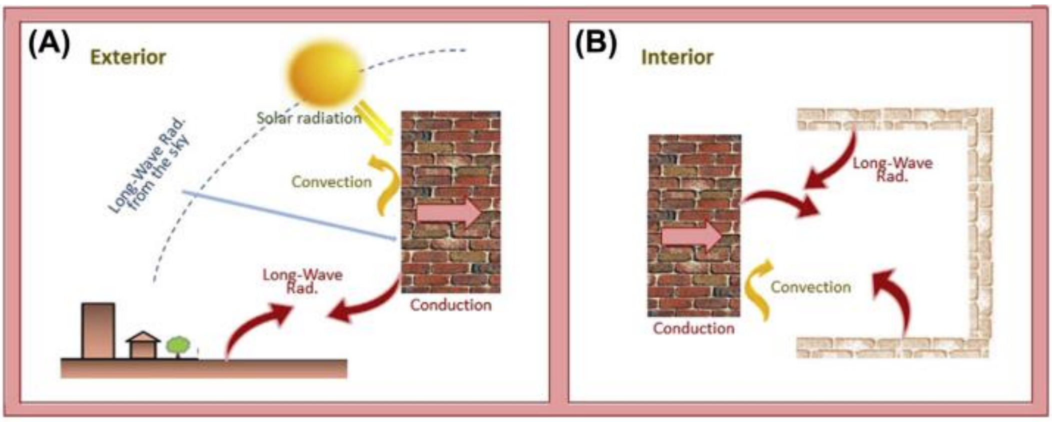

Figure 11 - Mechanisms of heat exchanges (A) on an exterior surface (B) on an interior surface.[60]

Thermal inertia is directly related to the volumetric heat capacity, and to give some references of common materials, concrete's volumetric heat capacity is 1.8-2.0 MJ/(m3 °C), steel is 3.12 MJ/(m3 °C), and air is 0.0012 MJ/(m3 °C).

Thermal intertia affects UHI intensity by releasing the absorbed solar heat during the into the canyon at night.

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[58] Soon Ching Ng and Kaw Sai Low, 'Thermal Conductivity of Newspaper Sandwiched Aerated Lightweight Concrete Panel', *Energy and Buildings*, 42.12 (2010), 2452–56 <https://doi.org/10.1016/J.ENBUILD.2010.08.026>.

[59] S Ferrari, 'Building Envelope and Heat Capacity: Re-Discovering the Thermal Mass for Winter Energy Saving', in *28th AIVC and 2nd Palenc Conference ' Building Low Energy Cooling and Ventilation Technologies in the 21st Century'* (Crete, 2007) <https://www.aivc.org/resource/building-envelope-and-heat-capacity-re-discovering-thermal-mass-winter-energy-saving> [accessed 11 September 2022].

[60] José Ma P Sala Lizarraga and Ana Picallo-Perez, 'Exergy Analysis of Heat Transfer in Buildings', *Exergy Analysis and Thermoeconomics of Buildings*, 2020, 263–343 <https://doi.org/10.1016/B978-0-12-817611-5.00004-7>.

2.2.5.3.3 Impermeability

A considerable proportion of the urban area is covered with rough and impervious surfaces, as urban roads are typically constructed from asphalt and surrounded by masonry, concrete, or asphalt pavements. These impervious surfaces become totally wet during the precipitation phase, and water collected at the urban surfaces starts to rapidly convert sensible heat in the atmosphere and surfaces to latent heat via evaporation and thus causing a rapid drop in the sensible temperature. In addition, the existence of efficient drainage systems with wide impervious surfaces also causes rapid drying of the urban surfaces, as water left on the surface after drainage quickly changes physical form and transforms into water vapor. In the natural environments, water collected at the surface level passes through the pervious soil and gets stored across the height of the soil which water can penetrate, this leaves a lesser amount of the water available to evaporate. This change in the surface permeability results in a less drastic reduction in the air temperatures observed in rural areas. After the precipitation ends, water stored across the depth of the natural soil slowly evaporates over several days, and this evaporation results in a less pronounced sensible heat flux which leads to lesser air temperatures in the natural environment when compared to the urban areas.

The absence of available moisture and water content in the inspected area leads the way for a more efficient conversion of the solar radiation to sensible heat near the surface level due to the lack of evaporation, thus rapid changes in temperatures are experienced more profoundly in urban contexts[61].

[61] Erell, Pearlmutter, and Williamson.

2.2.5.4 Wind

The effects of the wind on the urban heat island effect and its impact on human thermal comfort can be inspected from the perspective of the advection behavior of the air on the local scale and its convective effect on the human body as a thermal mitigation process. Wind behavior in an urban area can alter the urban microclimate by the upward movement of warm air in the daytime and its resultant mixing with the roughness sublayer that mitigates the effects of the urban heat island effect. However, if the wind speeds are slower in an urban area, intake of air from the rural areas is observed at street level with warm air from urban areas moving outwards to the rural areas at higher levels[62]. These processes mitigate the intensity of the urban heat island effect in tandem, and slower speeds of air caused by large scale climate occurrences and blocking off air paths in an urban environment as shown in *Figure 12* and *Figure 13* leads to a slower cooling period, which is usually noticed at night time in winter conditions[63]. Also, the convective effect of the wind on the human body scales with the speed of the wind, which reduces the risk of heat stress, resulting in a more hospitable microclimate in the urban area[64].

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[62] Y. Fan and others, ‘Effect of City Shape on Urban Wind Patterns and Convective Heat Transfer in Calm and Stable Background Conditions’, *Building and Environment*, 162 (2019), 106288 <https://doi.org/10.1016/J.BUILDENV.2019.106288>.
[63] Kim and Baik.
[64] Y. Toparlar and others, ‘CFD Simulation and Validation of Urban Microclimate: A Case Study for Bergpolder Zuid, Rotterdam’, *Building and Environment*, 83 (2015), 79–90 <https://doi.org/10.1016/J.BUILDENV.2014.08.004>; Saba Saneinejad and others, ‘Analysis of Convective Heat and Mass Transfer at the Vertical Walls of a Street Canyon’, *Journal of Wind Engineering and Industrial Aerodynamics*, 99.4 (2011), 424–33 <https://doi.org/10.1016/J.JWEIA.2010.12.014>.

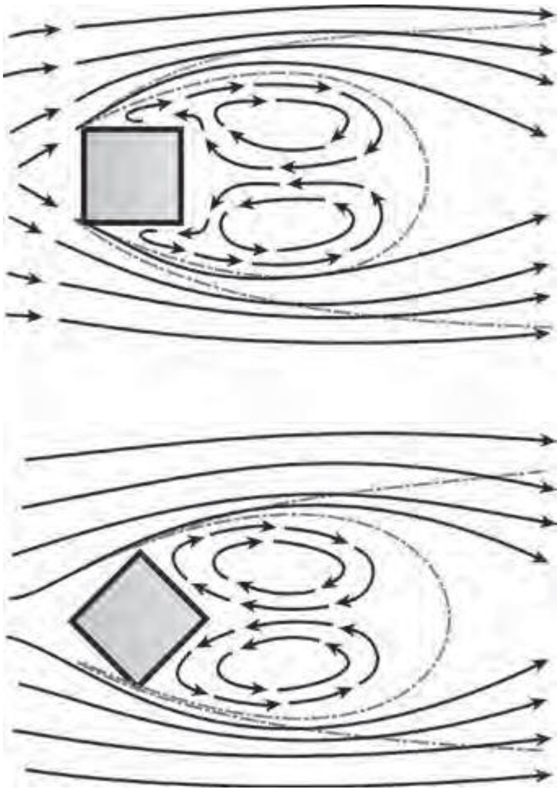

Figure 12 - Air flow pattern in the periphery of a sharp edged building[65].

[65] T.R. Oke.

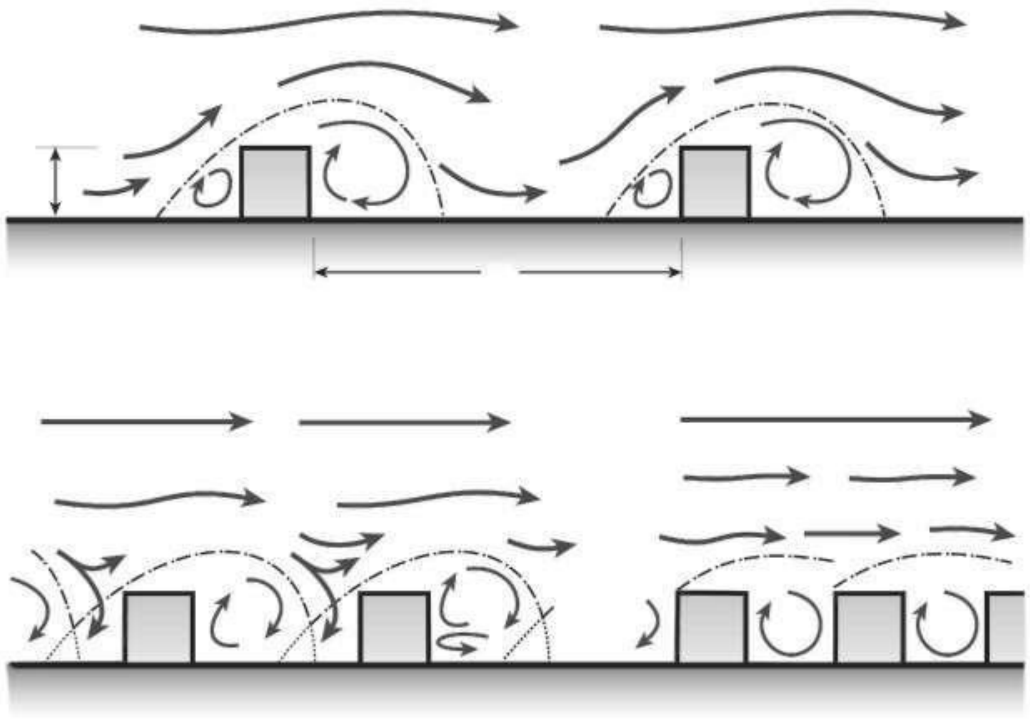

Figure 13 – Air flow patterns associated with various urban geometries, drawn by Oke[66] with regards to the wind tunnel experiments carried out by Hussain and Lee[67] and redrawn by Erell et. al.[68]

2.2.5.5 Trees and Vegetation

The main benefit of trees in urban areas is that they cast shadows on surfaces that are otherwise unshaded[69]. This shading effect reduces the direct impact of solar radiation on pedestrians and also lowers the temperature of the ground. This shading effect lowers the heat gained by the direct long wave radiation as well, the

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[66] T.R. Oke.
[67] M. Hussain and B. E. Lee, 'A Wind Tunnel Study of the Mean Pressure Forces Acting on Large Groups of Low-Rise Buildings', *Journal of Wind Engineering and Industrial Aerodynamics*, 6.3–4 (1980), 207–25 <https://doi.org/10.1016/0167-6105(80)90002-1>.
[68] Erell, Pearlmutter, and Williamson.
[69] Costanzo, Evola, and Marletta.

reason behind this is that trees and vegetation in an urban area absorb the long wave radiation instead of the hard paved surfaces present in the urban area, as shown in *Figure 14*. Trees also absorb the solar radiation reflected from the ground. However, in winter conditions aforementioned shading effect reduces the thermal comfort, therefore it is advantageous to use deciduous tree species that should be preferred over the evergreen ones.

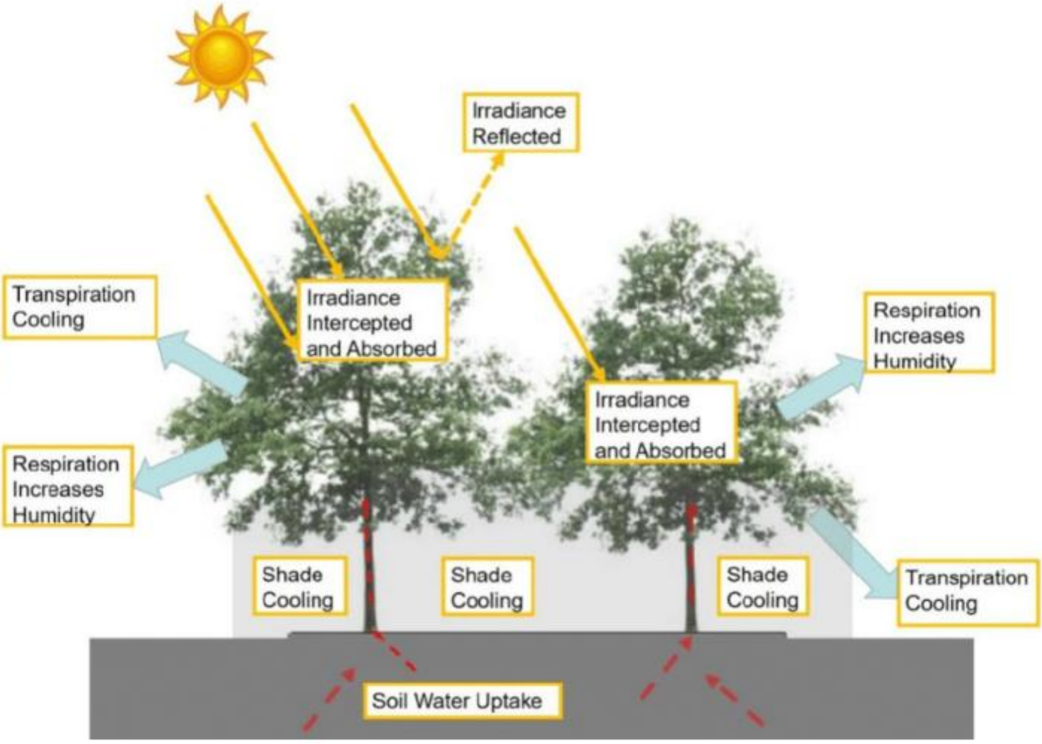

Figure 14 - Cooling effect and solar radiation behavior of the trees[70].

In addition, trees provide humidity in the air and decrease the dry bulb temperature by the means of evapotranspiration[71] and they reduce the speed of air without

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[70] Jian Zhang, Zhonghua Gou, and Leigh Shutter, 'Effects of Internal and External Planning Factors on Park Cooling Intensity: Field Measurement of Urban Parks in Gold Coast, Australia', *AIMS Environmental Science*, 6.6 (2019), 417–34 <https://doi.org/10.3934/ENVIRONSCI.2019.6.417>.
[71] Tobi Eniolu Morakinyo, Ahmed Adedoyin Balogun, and Olumuyiwa Bayode Adegun, 'Comparing the Effect of Trees on Thermal Conditions of Two Typical Urban Buildings', *Urban Climate*, 3 (2013), 76–93 <https://doi.org/10.1016/J.UCLIM.2013.04.002>.

trapping the air in pockets when the wind is blowing, increasing the thermal comfort for the urban dwellers[72].

Trees should be placed in the streets where orientation is towards east-west and height to width ratio is minimal and they should be placed alongside the south facing walls of the structures present in the streets. In addition, they should be placed in groups, as a group of trees is more efficient in reducing the temperature increase originating in direct solar heat gain as they provide better shading[73]. Trees are also more efficient in reducing the urban heat island intensity when they are located in open areas, where building shading does not exist[74].

Urban grass provides a very minuscule amount of thermal improvement when compared to trees[75], however, they still provide low ground surface temperatures and as a result, they reduce the long wave radiant heat flux originating from the direct solar radiation[76].

2.2.5.6 Summary

In summary, the UHI effect originates from complex interactions of many factors, temporal effects, and contextual features of the urban area. Previous studies inspecting the UHI effect have identified various factors magnifying the intensity of the UHI effect such as the three-dimensional geometry of the urban area, the proportion of vegetated urban area relative to the built area footprint, building façade qualities such as reflectivity, and proportion of glazed area to the opaque surface,

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[72] Erell, Pearlmutter, and Williamson.
[73] Jasmine K. Thom and others, 'The Influence of Increasing Tree Cover on Mean Radiant Temperature across a Mixed Development Suburb in Adelaide, Australia', *Urban Forestry & Urban Greening*, 20 (2016), 233–42 <https://doi.org/10.1016/J.UFUG.2016.08.016>.
[74] Thom and others.
[75] Moohammed Wasim Yahia and others, 'Effect of Urban Design on Microclimate and Thermal Comfort Outdoors in Warm-Humid Dar Es Salaam, Tanzania', *International Journal of Biometeorology*, 62.3 (2018), 373–85 <https://doi.org/10.1007/S00484-017-1380-7/FIGURES/12>.
[76] Costanzo, Evola, and Marletta.

building systems for example HVAC systems and electrical equipment which releases waste heat into canyon due to energy conversion, anthropogenic heat released into the canyon by human activity and vehicles, low urban albedo due to color and material choice in the urban area and the diminished number of evaporative areas owing to insufficient or nonexistent water elements and greenery. Previous studies have pointed out morphological factors to be one of the main factors driving the UHI effect, as denser areas are able to store more heat because of the additional thermal mass being present in the urban area from the structures. Darker colored urban material is found to be another reason for UHI intensity, as darker colored materials are capable of absorbing more solar radiation because of low solar reflectivity, therefore increasing the amount of heat trapped in the canyon rather than reflecting it to the atmosphere. Lack of vegetation in an urban area is associated with an increase in average albedo in the urban area and a reduction of moisture, which correlates to the increased thermal inertia of the urban material hence intensifying the UHI effect. Following previous studies, the main factors driving the UHI effect are listed in *Table 1* below:

Table 1 - Main factors driving the UHI effect

Parameter	Description	Explanation	References
Building Density	The ratio of total building footprint area total urban area	Denser urban areas have more thermal mass, therefore they are able to absorb and store more heat.	[77] [78]

[77] Mao and others; Aydin and Jakubiec.
[78] Litardo and others; Salvati, Palme, and Inostroza; Ryu and Baik; Cyril, Anaïs, and Daniel; Kamal and others.

Façade to Site Ratio	The ratio of façade area in a building to its footprint area.	More façade area results in a greater amount of solar radiation captured by the buildings.	[79]
Building Height	The average height of buildings in the urban area	The verticality of built urban stock is directly related to the amount of thermal mass and received radiation as the amount of walls increases.	[80]
Glazing Ratio	The ratio of transparent elements in a building façade to its total façade area	With more façade openings, solar radiation trapped inside increases in the summer, and heat loss increases in the winter, therefore putting more stress on HVAC and building comfort systems.	[81]
Thermostat Setpoint	Average temperature HVAC and heating systems aim to condition indoor temperature	HVAC and heating systems release waste heat into the canyon, and the amount of that heat scales with the difference between desired indoor temperature and canyon temperature.	[82]

[79] Alchapar and others; Litardo and others; Salvati, Palme, and Inostroza; Ryu and Baik; Cyril, Anaïs, and Daniel; Kamal and others.
[80] Mao and others; Aydin and Jakubiec; Alchapar and others; Salvati, Palme, and Inostroza; Ryu and Baik; Cyril, Anaïs, and Daniel; Kamal and others.
[81] Mao and others; Aydin and Jakubiec; Kamal and others.
[82] Mao and others; Rizwan, Dennis, and Liu; Salvati, Palme, and Inostroza; Ryu and Baik.

Albedo	Amount of solar radiation reflected from a surface	Low reflectance on the surface results in more solar heat absorbed by the building stock	83
Tree and vegetation coverage	The ratio of the area covered by greenery to the total urban area	As green areas decrease, urban moisture and albedo also decrease. This results in more solar radiation absorbed by the urban area and an increase in the thermal inertia of surface materials due to a reduction in surface moisture availability.	84
Sensible Anthropogenic Heat	The heat released by human activity and traffic into the canyon	Direct heat released from transportation and urban human activities directly contributes to the canyon temperature	85
Infiltration Rate	Building air infiltration rate in Air Changes per Hour (ACH)	Building air infiltration puts more stress on air conditioning systems in summer and heating systems in winter, resulting in more waste heat released into the canyon.	86

[83] Rizwan, Dennis, and Liu; Alchapar and others.
[84] Rizwan, Dennis, and Liu; Aydin and Jakubiec; Litardo and others; Ryu and Baik; Cyril, Anaïs, and Daniel.
[85] Rizwan, Dennis, and Liu; Salvati, Palme, and Inostroza; Ryu and Baik; Cyril, Anaïs, and Daniel.
[86] Mao and others.

Electrical Load Density	Electricity consumed by equipment and lighting fixtures	Equipment and lighting fixtures create waste heat, which is released into the canyon.	[87]
Material U-Value	Rate of transfer of heat through a structure	High rate of heat transfer results in more stress on air temperature control systems, resulting in more waste heat released into the canyon.	[88]

2.3 UHI Calculation and Simulation Methods

This section covers the prominent methods of urban heat island detection, calculation and simulation.

2.3.1 Introduction

Urban heat island is the result of a complex interaction between many factors, as explained in the previous section. Interactions between factors among different scales like mesoscale interactions in the atmosphere and small scale interactions like heat released from human body. As a result, different scales of inspection is required in order to feasibly quantify and analyze the urban heat island effect, however, this is not feasible as there are too many factors to consider the urban heat island properly as provision of a comprehensive database for the inspected city is a very hard task and existing theories have weaknesses in describing the factors which contribute to the UHI effect at each scale. Therefore, considering the

[87] Mao and others; Rizwan, Dennis, and Liu.
[88] Aydin and Jakubiec.

inherent problems in quantifying the UHI effect, a number of simplifications are made in each of the existing UHI study approaches and that situation is the main reason behind the different findings of the UHI intensity with regards to the study approach taken[89].

The behavior of the urban fabric regarding absorption of long and short wave radiation, release of the anthropogenic heat, blocking of the wind paths and transpiration is very different from the natural environment. The urban energy budget was first proposed by Nunez et. al in 1977[90] as follows:

$$Q^* + Q_F = Q_H + Q_E + \Delta Q_S + \Delta Q_A \qquad \textbf{(1)}$$

In equation (1), Q^* is the net radiation, Q_F is the energy released in the control volume by the anthropogenic activity, Q_H and Q_E correspond to the sensible and latent heat fluxes, ΔQ_S denotes the energy storage flux throughout the totality of energy storage mechanisms inside the control volume, including structures, soil, trees, pavements etc. and ΔQ_A is the net heat advection from the lateral sides of the control volume. Fluxes of sensible heat Q_H in a canyon is illustrated in the *Figure 15*. In addition, energy balance regarding every aspect of this control volume can be calculated as follows:

$$Q^* = Q_H + Q_E + Q_G \qquad \textbf{(2)}$$

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[89] Parham A. Mirzaei and Fariborz Haghighat, 'Approaches to Study Urban Heat Island – Abilities and Limitations', *Building and Environment*, 45.10 (2010), 2192–2201 <https://doi.org/10.1016/J.BUILDENV.2010.04.001>.
[90] Nunez M. and Oke T. R., 'The Energy Balance of an Urban Canyon', *Journal of Applied Meteorology (1962-1982)*, 16.1 (1977), 11–19 <https://www.jstor.org/stable/26177588> [accessed 10 July 2022].

where Q_G corresponds to the conductive heat flux.

As the functions represented by parameters in equations (1) and (2) are based on city location and characteristics, it can be inferred that when the parameters vary, resulting energy balance inside a urban area also varies. This situation leads to the conclusion that the UHI intensity is different regarding temporal and spatial patterns in different urban areas. To give a few examples, anthropogenic heat release can be the main factor affecting the UHI intensity at night conditions in a high rise urban area whereas energy intake from solar radiation can be the leading factor affecting the UHI intensity at daytime in equatorial climate when the sky is not cloudy[91].

[91] Mirzaei and Haghighat.

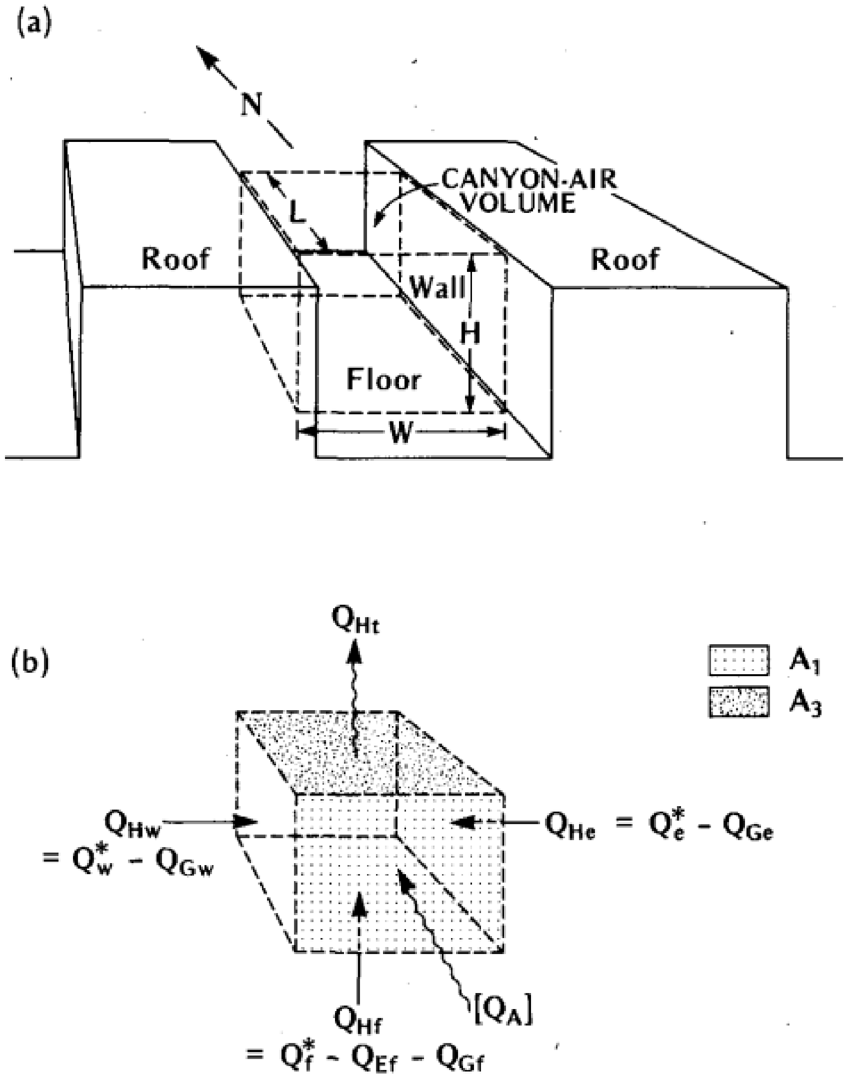

Figure 15 – Diagrammatic description of (a): relationship between urban canyon volume and atmosphere, (b): exchanges of sensible heat flux towards and outside of the canyon volume. t, f, e, w corresponds to the direction of the faces of the canyon volume top, forward, east and west[92].

Techniques to study and measure the UHI phenomenon can be categorized as observational and simulation-based approaches [93]. Observational approaches include field measurement, where the near-surface temperature in urban areas is

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[92] Nunez M. and Oke T. R.
[93] Mirzaei and Haghighat.

compared to rural areas using fixed or mobile stations [94], thermal remote sensing, utilizing sensors from satellites, aircrafts, and airborne platforms to compare rural and urban surface temperatures, and small-scale modeling, where a small scale model is tested in a wind tunnel or outdoor space and the model is assumed to obey similarity theory between real case and small-scale model [95]. Simulation approaches include energy balance models which use the law of conservation energy for the calculation UHI effect for a given volume and use atmospheric effects as heat fluxes [96]. Energy balance models are based on Urban Canopy Model (UCM) where all control volumes and surfaces are assumed to be connected to each other continuously. Within that model, energy balance is solved taking into consideration heat leaving the observed area via wind and heat introduced to the area by solar heat gain and anthropogenic heat sources. Other simulation-based approaches include Computational Fluid Dynamics (CFD) based approaches which calculate UHI by solving fluid dynamics inside a given volume.

2.3.2 Observational Approaches

In the past decades, many observations were made with the geographic scope used in the UHI studies in mind. Arnfield[97] reaches general conclusions from these observations as follows:

- UHI intensity increases with the increasing city size and population
- UHI intensity decreases as wind speed increases
- UHI intensity decreases as cloud cover increases

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[94] A. John Arnfield, 'Two Decades of Urban Climate Research: A Review of Turbulence, Exchanges of Energy and Water, and the Urban Heat Island', *International Journal of Climatology*, 23.1 (2003), 1–26 <https://doi.org/10.1002/JOC.859>.
[95] J. E. Cermak, 'Physical Modelling of Flow and Dispersion over Complex Terrain', *Boundary-Layer Meteorology 1984 30:1*, 30.1 (1984), 261–92 <https://doi.org/10.1007/BF00121957>.
[96] Mirzaei and Haghighat.
[97] Arnfield.

- UHI intensity is more pronounced in the summer or the warm part of the year
- UHI intensity reaches its peak during night conditions

However, findings by Arnfield contradicts with other studies. To name a few, in Reykjavik rural temperatures were found to be higher than urban temperatures[98], in Saskatoon maximum UHI intensity values was documented during sunny days with calm and clear sky conditions[99]. These contradictions in findings have their roots in the weakness of statistical analysis in the representation of several of the physical processes that take place in the urban environments as shown in the equation (1).

2.3.2.1 Field Measurement

Field measurement approach involves the detection of urban – rural near surface temperature difference statistics using mobile stations. Field measurement was first utilized to detect temperature difference in the city of London by Luke Howard in 1818[100]. Results of the field measurement are generally used to analyze spatial distributions and intensity of the urban heat island within a city. In addition to the details of proper method to conduct field measurement as defined by the Arnfield[101], observational studies specifically focused on the cities of Europe was conducted by Santamouris[102].

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[98] K. Steinecke, 'Urban Climatological Studies in the Reykjavík Subarctic Environment, Iceland', *Atmospheric Environment*, 33.24–25 (1999), 4157–62 <https://doi.org/10.1016/S1352-2310(99)00158-2>.
[99] E. A. Ripley, O. W. Archibold, and D. L. Bretell, 'Temporal and Spatial Temperature Patterns in Saskatoon', *Weather*, 51.12 (1996), 398–405 <https://doi.org/10.1002/J.1477-8696.1996.TB06171.X>.
[100] Howard Luke, I.
[101] Arnfield.
[102] Mat Santamouris, 'Heat Island Research in Europe: The State of the Art', *Advances in Building Energy Research*, 1.1 (2007), 123–50 <https://doi.org/10.1080/17512549.2007.9687272>.

In addition to temperature difference, other parameters such as turbulence fluctuations, pollution concentration, humidity and air velocity have been also measured along with the advances in the technology in order to examine the relationship between aforementioned parameters and the UHI intensity.

One of the main drawbacks associated with the field measurement technique is that it is very expensive to acquire all of the gear associated with the measurement, and also it is very hard to simultaneously record temperature and other parameter values throughout the city.

2.3.2.2 Small Scale Modeling

In small scale modeling approach, a prototype replaces the urban area for the most part, following the similarity theory between small scale model and the reality[103]. Test of the small scale models are usually conducted through use of outdoor spaces[104] or wind tunnels[105]. However, ensuring similarity between real case and the small scale is not always possible, for example heat gains from the solar radiation is a very important factor affecting the intensity of the UHI but it can not be accounted for in wind tunnel experiments.

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[103] Cermak, 'Physical Modelling of Flow and Dispersion over Complex Terrain'.
[104] M. Kanda and others, 'A Simple Energy Balance Model for Regular Building Arrays', *Boundary-Layer Meteorology 2005 116:3*, 116.3 (2005), 423–43 <https://doi.org/10.1007/S10546-004-7956-X>; Francisco Sánchez De La Flor and Servando Alvarez Domínguez, 'Modelling Microclimate in Urban Environments and Assessing Its Influence on the Performance of Surrounding Buildings', *Energy and Buildings*, 36.5 (2004), 403–13 <https://doi.org/10.1016/J.ENBUILD.2004.01.050>.
[105] Kiyoshi Uehara and others, 'Wind Tunnel Experiments on How Thermal Stratification Affects Flow in and above Urban Street Canyons', *AtmEn*, 34.10 (2000), 1553–62 <https://doi.org/10.1016/S1352-2310(99)00410-0>.

Small scale modeling can be used to study the effects of a limited number of parameters such as urban area dimensions have on the environment or a small part of the city[106].

The main drawback associated with the small scale modeling approach is that it is expensive to conduct experiments with them. In addition, generation of thermal stratification with a small scale model is a very hard task, and observation of pollution concentration and flow patterns of the air due to temperature chance is very hard to perform[107].

2.3.2.3 Thermal Remote Sensing

With the improvements in the sensor technology, use of satellite, aircraft and airborne thermal remote imaginary made it possible to document the UHI effect from a considerable distance via use of sensors. The thermal image produced by them contains a considerable amount of information, as turbulent transfer from the surface, surface emissivity and albedo, surface radiative and thermodynamic properties, surface moisture, solar heat gains on the surface can be deduced from those images[108]. The use cases of the thermal remote sensing for calculation of the UHI intensity distribution were reviewed by Voogt and Oke[109].

Thermal remote sensing is one of the most expensive approaches, if not the most expensive. Also, images acquired via thermal remote sensing are always unstable

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[106] Michael Poreh, ‘Investigation of Heat Islands Using Small Scale Models’, *Atmospheric Environment*, 30.3 (1996), 467–74 <https://doi.org/10.1016/1352-2310(95)00011-9>; J. E. Cermak, ‘Thermal Effects on Flow and Dispersion over Urban Areas: Capabilities for Prediction by Physical Modeling’, *Atmospheric Environment*, 30.3 (1996), 393–401 <https://doi.org/10.1016/1352-2310(95)00142-5>.
[107] Uehara and others.
[108] F. Becker and Zhao-Liang Li, ‘Surface Temperature and Emissivity at Various Scales: Definition, Measurement and Related Problems’, *Remote Sensing Reviews*, 12.3–4 (2009), 225–53 <https://doi.org/10.1080/02757259509532286>.
[109] J. A. Voogt and T. R. Oke, ‘Thermal Remote Sensing of Urban Climates’, *Remote Sensing of Environment*, 86.3 (2003), 370–84 <https://doi.org/10.1016/S0034-4257(03)00079-8>.

due to the movement of the parts which hold the sensor. In addition, climactic conditions like cloud cover can obstruct the view and make it not possible to acquire a image that depicts the urban area at all[110].

2.3.3 Simulation Based Approaches

Mathematical models have also been developed to study the UHI effect in addition to the observational techniques. However, due to the sheer complexity causative effect behind the formation of the UHI and its convoluted effects on the climate at different scales, mathematical simplifications are required to be able to study the phenomenon at all. Nevertheless, computational simulation techniques have developed rapidly in the last decades, allowing researchers to solve mathematical models in order to assess UHI intensity and its effects on the climate. Among these models, dynamical numerical approaches and energy balance demonstrated the most satisfactory results[111].

2.3.3.1 Computational Fluid Dynamics

Computational Fluid Dynamics (CFD) models solves all of the equations of the fluid inside the control volume such as potential temperature, momentum, conservation of mass and type of the fluid that is simulated such as chemical reactions and water vapor. As a result, CFD models are able to obtain very accurate results, however this accuracy comes with a heavy computational cost, as resolution of the model increases, number of nodes approximating the fluid dynamics increases exponentially, so that very accurate estimations of the UHI, even with the modern equipment requires a significant amount of time and computational power. A theoretical problem which exists within the CFD

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[110] Mirzaei and Haghighat.
[111] Mirzaei and Haghighat.

simulations regarding the UHI effects at the climactic scale is that canopy scale and atmospheric turbulence can not be modeled at the same resolution of time and length due to the mismatch of the temporal and spatial characteristics of the phenomena. As a result, analysis of the UHI effect via CFD simulations are generally split into two scales in order to assess the UHI effect more accurately[112].

2.3.3.1.1 Micro Scale Computational Fluid Dynamics Model

Micro scale CFD model is concerned with solving the conservation equation inside the surface layer. In micro scale model, simulation of the UHI effect is conducted with actual geometry and details of the surface layer, also accounting for the interactions happening inside this layer. However, it is not computationally effective to simulate entirety of a city with the micro scale CFD models, as these are very computationally expensive models. Therefore, simulations utilizing this methods are generally limited horizontally to few hundred meters, in the magnitude of encompassing few blocks of buildings[113]. As the interaction between planetary boundary layer which exists between the earth surface and geostrophic wind and has a height between 200 meters to 2 kilometers can not be accounted for thoroughly in the micro scale CFD model, it can be deduced that this sort of models does not account for atmospheric interactions like Coriolis effect and vertical mixing[114].

2.3.3.1.2 Mesoscale Computational Fluid Dynamics Model

Horizontal extents of the mesoscale computational dynamics models typically ranges from one to several hundred kilometers. In addition, height of these models

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[112] Mirzaei and Haghighat.
[113] Mirzaei and Haghighat.
[114] Mirzaei and Haghighat.

typically range from 200m to 2km due to the varying height of the planetary boundary layer. In the mesoscale CFD approach, large scale interactions happening inside the planetary boundary layer is calculated, also accounting for surface layer treatment and atmospheric stratification. As addition of micro scale interactions to the mesoscale model is very computationally expensive and details about the micro scale phenomenon is very hard to acquire, they are rarely used in tandem. Since the inspected area is measured by the kilometers, it is necessary to treat the mesoscale zone as a homogenous area and treat the surface properties in average values in order to make the simulation feasible in the sense of computational costs. Accuracy of the mesoscale models are often measured by the observations taken at the real case urban area, aiming to quantify wind and surface temperature conditions[115].

2.3.3.1.3 ENVI-met

ENVI-met is a popular software which has many studies preferring it due to its ability to simulate the convoluted interactions between vegetation, the urban surfaces and the atmosphere[116]. For example, Perrini et. al have used ENVI-met to investigate the outdoor thermal comfort and temperature distribution's relation to vegetation, urban geometry and atmospheric conditions[117]. Taleghani et. al investigated the effects of archetypal urban morphologies (courtyard block, linear block, singular block) have on the urban microclimate using ENVI-met[118] and

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[115] T. S. Saitoh, T. Shimada, and H. Hoshi, 'Modeling and Simulation of the Tokyo Urban Heat Island', *Atmospheric Environment*, 30.20 (1996), 3431–42 <https://doi.org/10.1016/1352-2310(95)00489-0>; Hua Tong and others, 'Numerical Simulation of the Urban Boundary Layer over the Complex Terrain of Hong Kong', *Atmospheric Environment*, 39.19 (2005), 3549–63 <https://doi.org/10.1016/J.ATMOSENV.2005.02.045>.
[116] Michael Bruse and Heribert Fleer, 'Simulating Surface–Plant–Air Interactions inside Urban Environments with a Three Dimensional Numerical Model', *Environmental Modelling & Software*, 13.3–4 (1998), 373–84 <https://doi.org/10.1016/S1364-8152(98)00042-5>.
[117] Katia Perini and Adriano Magliocco, 'Effects of Vegetation, Urban Density, Building Height, and Atmospheric Conditions on Local Temperatures and Thermal Comfort', *Urban Forestry & Urban Greening*, 13.3 (2014), 495–506 <https://doi.org/10.1016/J.UFUG.2014.03.003>.
[118] Mohammad Taleghani, David J. Sailor, and others, 'Thermal Assessment of Heat Mitigation Strategies: The Case of Portland State University, Oregon, USA', *Building and Environment*, 73

found out that, the best protection of the microclimate is performed by the courtyard block, as it receives the least amount of sunlight in summer conditions. As a result, they advocate the usage of courtyard blocks in temperate climates in order to mitigate the UHI intensity.

ENVI-met has a rather low resolution and uses a simplified numerical model[119], and although it produces accurate results in regards to small scale CFD modeling, it is computationally very expensive, and simulating entire city districts with the ENVI-met model is a very computationally expensive task.

2.3.3.2 Energy Balance Model

Energy balance budged for a building urban canyon was first proposed by the Oke[120] building on the equation (1) proposed in a former study[121]. The law of conservation of energy for a control volume is the foundation of the energy balance model, and this model also takes heat and velocity fluxes, turbulence fluctuations, and atmospheric phenomena into account. These aforementioned fluxes are generally defined by empirical or analytical equations.

The energy balance equation inside a control volume is used to deduce the urban canopy model which consists of two adjacent buildings. The energy exchanges between the ambient air in the canopy and the urban surfaces is calculated by the

(2014), 138–50 <https://doi.org/10.1016/J.BUILDENV.2013.12.006>; Mohammad Taleghani, Laura Kleerekoper, and others, 'Outdoor Thermal Comfort within Five Different Urban Forms in the Netherlands', *Building and Environment*, 83 (2015), 65–78 <https://doi.org/10.1016/J.BUILDENV.2014.03.014>.

[119] Jonas Allegrini, Viktor Dorer, and Jan Carmeliet, 'Influence of Morphologies on the Microclimate in Urban Neighbourhoods', *Journal of Wind Engineering and Industrial Aerodynamics*, 144 (2015), 108–17 <https://doi.org/10.1016/J.JWEIA.2015.03.024>.

[120] T. R. Oke, 'The Energetic Basis of the Urban Heat Island', *Quarterly Journal of the Royal Meteorological Society*, 108.455 (1982), 1–24 <https://doi.org/10.1002/QJ.49710845502>.

[121] Nunez M. and Oke T. R.

urban canopy model. As a result, surface temperatures of the urban elements and temperature of the air in the canyon is predicted by the urban canopy model.

However, as the airflow is not considered by these equations and must be considered by a separate input to the control volume.

In the urban canopy modeling approach, every surface and control volume inside the inspected area is assumed to be connected to each other like electrical nodes. With that assumption in mind, equation (1) is then applied to the each of the nodes, and a matrix of surface temperatures and humidity is generated. By the solution of these matrices, surface temperatures and relative humidity of each node is calculated. Multi-layer[122] and single layer[123] models can be used in relation to the count of the nodes in the walls of the inspected buildings. This method of simulating the effects of the UHI is generally more computationally cheap by a wide margin and only requires a miniscule amount of computation time when compared to the other UHI simulation methods.

2.3.3.2.1 Urban Weather Generator

Bueno et al. developed Urban Weather Generator (UWG) [124] in order to simulate the urban microclimate conditions, namely the urban heat island effect as a computational model in order to correlate weather files documented at rural stations to predicted situations at the urban neighborhood scale by considering specific urban area characteristics. Urban Weather Generator was originally

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[122] Hiroaki Kondo and others, ‘Development of a Multi-Layer Urban Canopy Model for the Analysis of Energy Consumption in a Big City: Structure of the Urban Canopy Model and Its Basic Performance’, *Boundary-Layer Meteorology*, 116.3 (2005), 395–421 <https://doi.org/10.1007/S10546-005-0905-5>.

[123] Hiroyuki Kusaka and others, ‘A Simple Single-Layer Urban Canopy Model For Atmospheric Models: Comparison With Multi-Layer And Slab Models’, *Boundary-Layer Meteorology*, 101.3 (2001), 329–58 <https://doi.org/10.1023/A:1019207923078>.

[124] Bruno Bueno and others, ‘The Urban Weather Generator’, *Https://Doi.Org/10.1080/19401493.2012.718797*, 6.4 (2013), 269–81 <https://doi.org/10.1080/19401493.2012.718797>.

developed in the MATLAB environment, but later it transitioned into a grasshopper add-on and also into a Python library, which was made use of in this study. Urban Weather Generator includes four coupled models; the rural station model, the vertical diffusion model, the urban boundary layer model, and the urban canopy-building energy model [125]. UWG utilizes meteorological data provided by EPW files recorded at rural meteorological stations and creates a UCM layer defined by input parameters describing the built environment characteristics. UWG then solves the heat balance equation by taking UCM characteristics, boundary conditions of the inspected area, and the anthropogenic heat released into the canyon via coupled models. Resultant temperature and humidity values calculated from the models are then outputted in a modified EPW file where data can be processed to find out UHI intensity. UWG has previously been validated in Toulouse (France), Basel (Switzerland), Singapore, and Boston (USA)[126].

2.3.3.2.1.1 UWG Mechanics

The UWG model is bottom up building stock model based on energy conservation principles. The model takes in parameters describing the urban geometry, morphology and surface parameters. The urban morphology inputs used in the UWG are similar to those used in the building energy simulations. *Figure 16* and *Figure 17* demonstrate the sub-models that make up the UWG model.

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[125] Bruno Bueno and others.
[126] Mao and others.

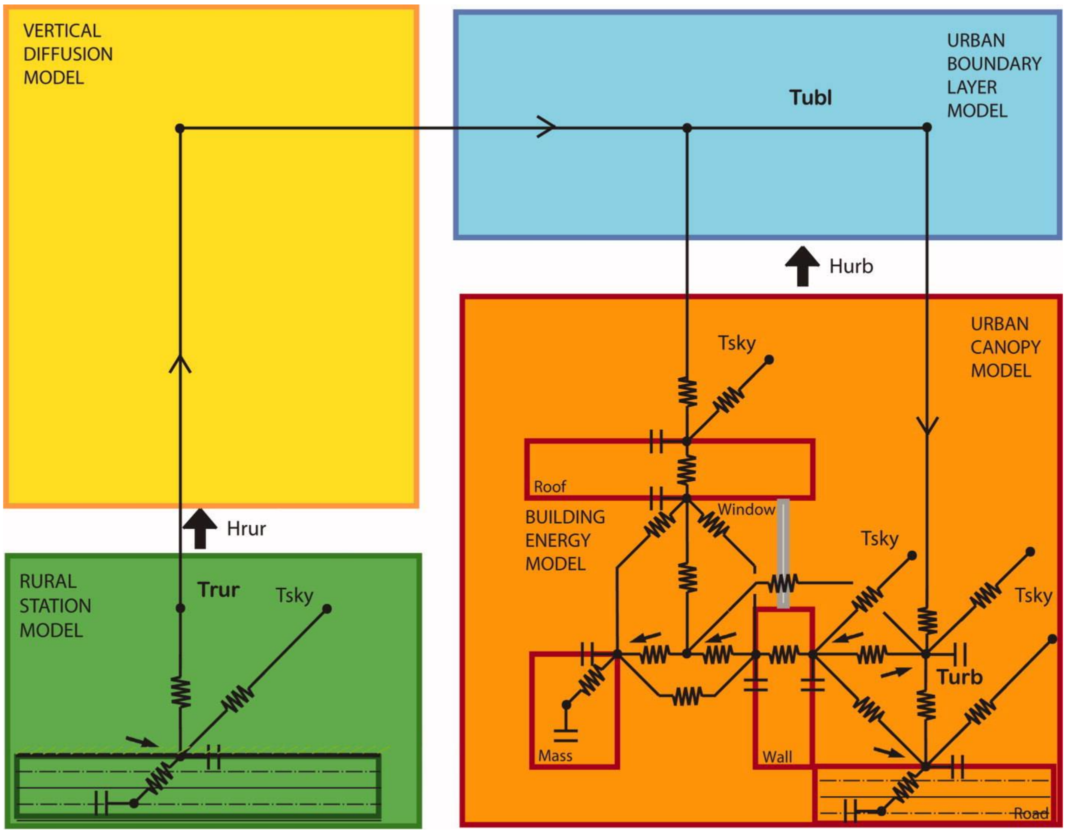

Figure 16 - Diagram of UWG scheme, which is composed of four modules: the Rural Station Model (RSM), the Vertical Diffusion Model (VDM), the Urban Boundary Layer (UBL) model and the Urban Canopy and Building Energy Model (UC-BEM)[127].

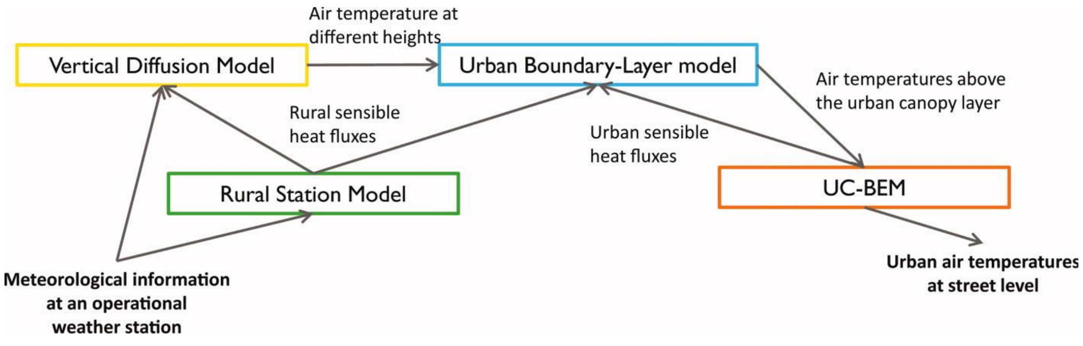

Figure 17 - Information exchanged between different modules of the UWG[128].

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[127] Bruno Bueno and others.
[128] Bruno Bueno and others.

2.3.3.2.1.2 Rural Station Model

The rural station model is a rural canopy model which calculates the heat fluxes occurring at the rural area and provides them to the vertical diffusion and urban boundary layer models via referring to the meteorological data measured at the rural site.

The model is based on the energy balance at the soil surface[129]. Release and storage of the heat from the soil calculated via transient heat diffusion equation applide on the discrete layers of the soil.

2.3.3.2.1.3 Vertical Diffusion Model

Vertical diffusion model processes the sensible heat fluxes as calculated by the rural station model, velocity and temperature of the air measured at the weather station in order to calculate temperature of the air above the weather station. *Figure 18* depicts the schema of the physical domains that make up the UWG.

[129] Bruno Bueno and others.

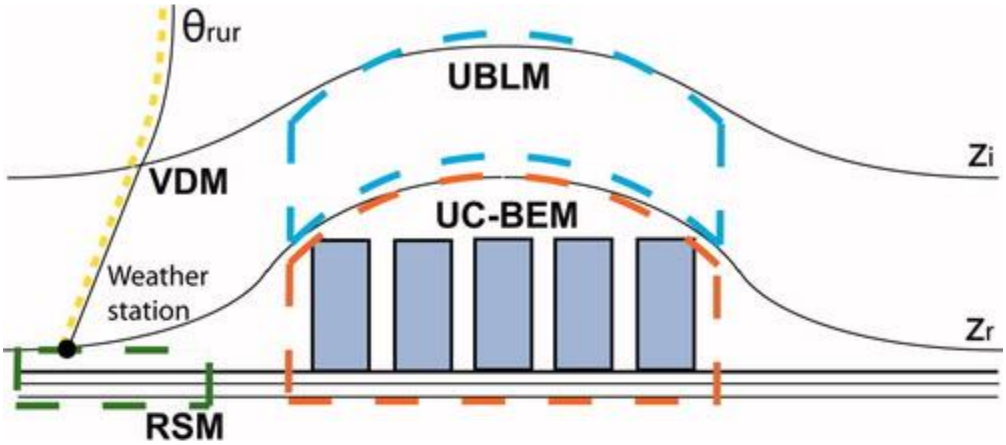

Figure 18 – Diagram of city and physical domains of the UWG modules. This diagram depicts a nighttime condition[130].

2.3.3.2.1.4 Urban Boundary Layer Model

The urban boundary layer model is concerned with calculation of the air temperature in the layer above the urban canopy layer. This calculation utilizes the temperatures at different heights provided by the vertical diffusion model and sensible heat fluxes as read from the rural station model and the urban canopy and building energy model.

The model is based on the energy balance equation of a control volume inside the urban boundary layer which is defined by the blending height (denoted as Z_r in *Figure 18*) and the boundary layer height[131] (denoted as Z_i in *Figure 18*).

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[130] Bruno Bueno and others.
[131] Bruno Bueno and others.

2.3.3.2.1.5 Urban Canopy and Building Energy Model

The urban canopy and building energy model evaluates the humidity and the temperature of the canyon with respect to the radiation and precipitation data, humidity and air velocity measured by the rural weather station, and the air temperature above the urban canopy layer as calculated from the urban boundary layer model.

This model is based on the town energy balance scheme by Masson[132] with its building energy model[133]. The urban air inside the urban canopy is assumed to be well mixed by the model. Final temperature of the canyon is calculated via heat balance method, meanwhile the heat capacity of the urban canyon is also taken into consideration. The sensible heat transfer between atmosphere and canyon air, the heat fluxes due to waste heat from heating, ventilation and air-conditioning (HVAC), anthropogenic heat sources, electrical equipment, the radiant heat exchange between the sky and the canyon air and the heat fluxes from windows, walls and the road are calculated via the urban canyon energy balance[134].

2.4 Sensitivity Analysis

This section covers the practice of sensitivity analysis, its goals, and the popular methods which are used to conduct sensitivity analyses. Introduction

Sensitivity analysis is used to extract information from linear and non-linear models, and to assess model accuracy and parameters which have the most impact on the

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[132] Valéry Masson, 'A Physically-Based Scheme For The Urban Energy Budget In Atmospheric Models', *Boundary-Layer Meteorology*, 94.3 (2000), 357–97 <https://doi.org/10.1023/A:1002463829265>.
[133] B. Bueno and others, 'Development and Evaluation of a Building Energy Model Integrated in the TEB Scheme', *Geoscientific Model Development*, 5.2 (2012), 433–48 <https://doi.org/10.5194/GMD-5-433-2012>.
[134] Bruno Bueno and others.

model's output. Sensitivity analysis is a useful tool to determine critical inputs which must be given the most importance and determine model weak spots. Sensitivity analysis determines the importance of a given parameter with its inherent uncertainties on the variation of the output, with regards to how much variation a given parameter accounts for the total output variation. The most common use case for the application of sensitivity analysis is the identification of the parameters which have the most impact on the output, combined with a uncertainty analysis of those parameters[135]. Another reason for conducting sensitivity analysis is to estimate the value of parameters which are uncertain and have a miniscule amount of impact on the output, so that they can be neglected in further studies or not included at all, therefore simplifying the model[136]. In addition, sensitivity analysis can be used to diagnose model errors, identify weak points in the examined model and to improve the understanding of the model via inspecting the relationship between model inputs and the output[137].

2.4.1 Input Variations

The initial step taken when conducting sensitivity analysis is to determine the range of inputs. Probability density functions also needs to be defined before starting the

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135 Zheng Yang and Burcin Becerik-Gerber, 'A Model Calibration Framework for Simultaneous Multi-Level Building Energy Simulation', *Applied Energy*, 149 (2015), 415–31 <https://doi.org/10.1016/J.APENERGY.2015.03.048>; Y. Heo, R. Choudhary, and G. A. Augenbroe, 'Calibration of Building Energy Models for Retrofit Analysis under Uncertainty', *Energy and Buildings*, 47 (2012), 550–60 <https://doi.org/10.1016/J.ENBUILD.2011.12.029>; Fernando Domínguez-Muñoz, José M. Cejudo-López, and Antonio Carrillo-Andrés, 'Uncertainty in Peak Cooling Load Calculations', *Energy and Buildings*, 42.7 (2010), 1010–18 <https://doi.org/10.1016/J.ENBUILD.2010.01.013>.

136 Clara Spitz and others, 'Practical Application of Uncertainty Analysis and Sensitivity Analysis on an Experimental House', *Energy and Buildings*, 55 (2012), 459–70 <https://doi.org/10.1016/J.ENBUILD.2012.08.013>; Sunil Ahuja, Slaven Peleš, and Satish Narayanan, 'Uncertainty Quantification in Energy Efficient Building Performance Simulations', 2014 <https://www.researchgate.net/publication/263843206> [accessed 9 July 2022].

137 Thierry A. Mara and Stefano Tarantola, 'Application of Global Sensitivity Analysis of Model Output to Building Thermal Simulations', *Building Simulation 2008 1:4*, 1.4 (2008), 290–302 <https://doi.org/10.1007/S12273-008-8129-5>.

sensitivity analysis if sampling based sensitivity analysis methods are preferred, such as variance based or Monte Carlo sensitivity analysis[138]. The distributions (or ranges) are highly dependent on the purpose of research for the sensitivity analysis[139]. Most commonly used probability density functions are uniform, lognormal and normal distributions, as shown in the *Figure 19*.

If sensitivity analysis used for design purposes, for example assessing the importance of parameters when a new urban area is in the planning phase and the analysis is focused on the design options. Therefore, sensitivity analysis should account for the possible ranges of the input variables. In this particular case, design parameters should be considered as continuous uniform or deiscrete distributions as all of these parameters have equal chance of selection, as this experiment is considering the design phase and all choices have the same probability for selection[140]. For example, the floor height values of the urban area is dependent on the preference of the designer and local laws dictating a lower and higher bound for the height of the floors, therefore all of the floor height values available for decision is equally probable for the final decision. Sensitivity analysis is then can be utilized to compare the impact of floor height on the urban environment and a proper floor height can be chosen, both satisfiying the urban environment and design criteria.

Secondly, if sensitivity analysis used for estimating the importance of parameters in an existing urban stock regarding their impact on the urban environment and point out the key parameters affecting it, sensitivity analysis should focus on the plausible ranges for urban inputs in a specific city part. For example, U-value of

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[138] J. C. Helton and others, ‘Survey of Sampling-Based Methods for Uncertainty and Sensitivity Analysis’, *Reliability Engineering & System Safety*, 91.10–11 (2006), 1175–1209 <https://doi.org/10.1016/J.RESS.2005.11.017>.
[139] Wei.
[140] Houcem Eddine Mechri, Alfonso Capozzoli, and Vincenzo Corrado, ‘USE of the ANOVA Approach for Sensitive Building Energy Design’, *Applied Energy*, 87.10 (2010), 3073–83 <https://doi.org/10.1016/J.APENERGY.2010.04.001>.

the buildings in the given urban context can be regarded as normal distributions in this case[141]. This is because U-values is generally similar in an given urban context and variations of the U-values are typically rooted in the age, construction quality, insulation quality and maintenance of the buildings[142]. In the urban areas where U-values are in a specific range but skewed towards the end or beginning of the distribution, triangular or lognormal distributions could be also preferred. These distributions could be truncated to avoid negative values in some cases[143].

Another example is optimizing the environmental behaviour of an existing urban area by manipulating insulation thickness and other methods which increase thermal insulation of the built stock. This case is the most complicated, as U-value in the built stock exhibit variations in their values in the building envelope and natural variations also change the efficiency of the thermal insulation. Identification of the key parameters are dependent on two sets of uncertainty regarding input variables in this case, as design decisions and existing variability at the site should be considered, so two dimensional Monte Carlo method can be utilized to extract information about this model[144]. This sort of analysis consist of two loops to analyze two effects independently, therefore this sort of analysis is computationally expensive and its results are hard to interpret[145]. A workaround from this problem is to only consider design variations, as natural variations are much more limited when compared to the natural variations therefore their significance on the variance of the output values are considerably higher.

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141 Wei Tian and Pieter De Wilde, 'Uncertainty and Sensitivity Analysis of Building Performance Using Probabilistic Climate Projections: A UK Case Study', *Automation in Construction*, 20.8 (2011), 1096–1109 <https://doi.org/10.1016/J.AUTCON.2011.04.011>.
142 Fernando Domínguez-Muñoz and others, 'Uncertainty in the Thermal Conductivity of Insulation Materials', *Energy and Buildings*, 42.11 (2010), 2159–68 <https://doi.org/10.1016/J.ENBUILD.2010.07.006>.
143 Pieter de Wilde and Wei Tian, 'Identification of Key Factors for Uncertainty in the Prediction of the Thermal Performance of an Office Building under Climate Change', *Building Simulation*, 3.2 (2009), 157–74 <https://doi.org/10.1007/S12273-009-9116-1>.
144 de Wilde and Tian.
145 Wei.

Input variations are also highly dependent on the sensitivity analysis type which is preferred for the given analysis. For example, if local sensitivity analysis methods are preferred, input variation decision is pretty straightforward as this type of sensitivity analysis methods don't require sampling in order to assess parameter importance by generating combinations of input parameters. For the majority of the global sensitivity analysis methods, sampling strategies are required in order to produce samples when conducting sensitivity analysis. For meta-model and regression models, Latin hypercube sampling is very popular because of its high performance stratification properties[146]. As for variance and screening based methods, generally they require special sampling methods to conduct sensitivity analysis[147].

[146] Helton and others.
[147] Andrea Saltelli, Marco Ratto, Terry Andres, and others, 'Global Sensitivity Analysis: The Primer', *Global Sensitivity Analysis: The Primer*, 2008, 1–292 <https://doi.org/10.1002/9780470725184>.

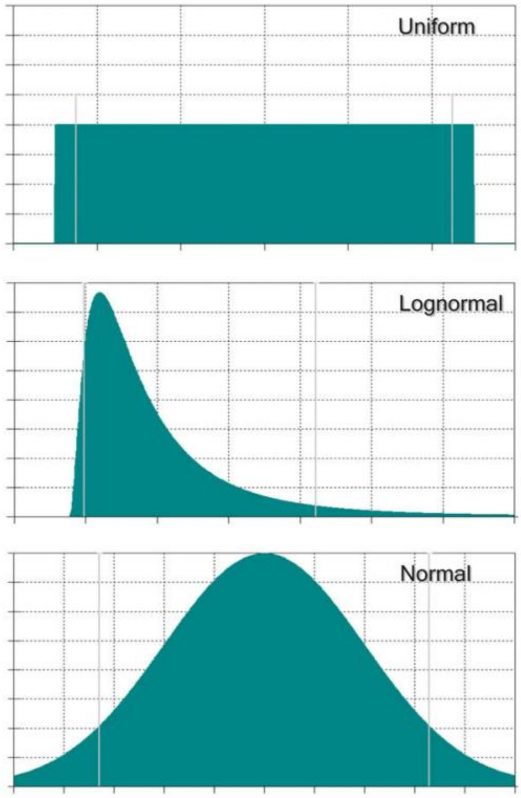

Figure 19 – Plots of the probability density distributions usually applied in sensitivity analysis[148]. Horizontal axis denotes the value, and vertical axis denotes the number of occurrences of the given value.

2.4.2 Categories of the Sensitivity Analysis Methods

This section will review the existing methods for the conduction of sensitivity analysis on the urban heat island intensity in a given context. For a more in-depth an technical definitions of these models, refer to the researches by Helton et. al., Storlie et. al. and Saltelli et.al.[149].

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[148] Per Heiselberg and others, 'Application of Sensitivity Analysis in Design of Sustainable Buildings', *Renewable Energy*, 34.9 (2009), 2030–36 <https://doi.org/10.1016/J.RENENE.2009.02.016>.
[149] Helton and others; Curtis B Storlie and others, 'Implementation and Evaluation of Nonparametric Regression Procedures for Sensitivity Analysis of Computationally Demanding Models', *Reliability Engineering & System Safety*, 2008

2.4.2.1 Overview

The sensitivity analysis methods can be categorized into global and local approaches[150]. The global methods are considered more suited to handle non-additive, non-linear, and non-monotonic models[151] at the expense of a higher computational cost, meanwhile, local methods require less computation, but they are not suited for complex models. Global sensitivity analysis methods can be inspected as screening-based methods, regression based methods, meta model based methods and variance-based methods.

Local sensitivity analysis, which is also called differential sensitivity analysis, is considered to be a part of the one factor at a time methods. In this type of sensitivity analysis, sensitivity measures are calculated by fixing all other factors and only changing the factor which is inspected. This method, however, has significant drawbacks [152], as it only inspects a reduced input factor space which is based around a selected case. Secondly, higher order interactions cannot be evaluated in this method and subsequently, the interaction between parameters cannot be inspected. Lastly, there is no means of self-verification in this method, as compared to the global analysis methods, where variations of the outputs can be accounted for by the input factors [153].

Regression based sensitivity analysis methods involve fitting a linear regression model to the calculated model output. Sensitivity measures are calculated by using

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<http://www.ntis.gov/help/ordermethods.asp?loc=7-4-0#online> [accessed 9 July 2022]; Saltelli, Ratto, Andres, and others, 'Global Sensitivity Analysis: The Primer'; A. Saltelli, 'Sensitivity Analysis in Practice : A Guide to Assessing Scientific Models', 2004, 219.

[150] Marco Ratto Andrea Saltelli, Stefano Tarantola, Francesca Campololongo, 'Sensitivity Analysis in Practice. A Guide to Assessing Scientific Models, John Wiley and Sons, Ltd., England, 39.95 Brit. Pounds, Hard Bound, 220 Pp., ISBN 0-470-87093-1.', *Ecological Modelling*, 181.1 (2005), 92 <https://doi.org/10.1016/J.ECOLMODEL.2004.08.016>.

[151] Torben Østergård, Rasmus L. Jensen, and Steffen E. Maagaard, 'Building Simulations Supporting Decision Making in Early Design – A Review', *Renewable and Sustainable Energy Reviews,* 61 (2016), 187–201 <https://doi.org/10.1016/J.RSER.2016.03.045>.

[152] Wei.

[153] Wei.

standardized regression coefficients. Inspected model is required to be linear for the majority of the methods in this group, as interpreting standardized coefficients gets harder with nonlinear models. These methods groups are fast to calculate and easy to interpret but, on the downside, they are not suitable for nonlinear models [154].

Variance based methods are used to decompose the uncertainty of outputs for the corresponding inputs [155]. Variance based methods are regarded as model free approaches, which makes them suitable for complex nonlinear and additive models [156]. These methods can measure every output change from the model taking every input into consideration and also inspecting the interaction between parameters. These methods mainly inspect two main measures of sensitivity, called the first order effect and the total order effect. First order effects quantify output change due to corresponding input. Total effects account for the complete variation in the output by considering both first order effects and interactions between input parameters.

2.4.2.2 Local Sensitivity Analysis Methods

Local sensitivity analysis relies on one factor at a time methodology, where the effect of a given input parameter is evaluated at a specific point in the input space by observing the output variance of the model while all other parameters are fixed at their reference values. Probability density functions an their ranges and shapes are not taken into account, as all input values are assumed to have same chance of occurrence and probabilistic behavior and nature of the input parameters are not considered. As a result, local sensitivity analysis methods do not consider any non-linear or non-additive model behavior and any effects from the correlated inputs[157].

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[154] Helton and others.
[155] Andrea Saltelli, Stefano Tarantola, Francesca Campololongo.
[156] Wei.
[157] Martin Heine Kristensen and Steffen Petersen, 'Choosing the Appropriate Sensitivity Analysis Method for Building Energy Model-Based Investigations', *Energy and Buildings*, 130 (2016), 166–76 <https://doi.org/10.1016/J.ENBUILD.2016.08.038>.

Besides direct applications of sensitivity analysis, local sensitivity analysis methods are also used to locate unsignificant parameters in a model and reduce the amount of parameters inspected in global sensitivity analysis models as these models are computationally expensive and their computational costs scale up with the amount of parameters which are inspected[158].

2.4.2.3 Global Sensitivity Analysis Methods

Global sensitivity analysis is an umbrella term for sensitivity analysis methods which estimate the importance of the inspected parameters by not only changing the inspected parameter, but all of the chosen parameters in the inspection group. Global sensitivity analysis methods considers the probabilistic nature and shape of the inspected parameters by utilizing probability density functions aimed to better reflect the parameters' behavior in the real world. Defining probability density functions are important and often a hard task, nevertheless, range of variation can usually be constrained between a given range and an appropriate probability density function can be chosen according to the shape of the distribution[159]. A considerable amount of Monte Carlo estimates are required to evaluate model output from multiple input samples randomly picked from the totality of the input space, as dictated by the probabilistic framework of the global sensitivity analysis. Sampling method is crucial for the accuracy of the Monte Carlo analysis, as the sampling method must provide for a throughout coverage of the input space[160].

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[158] Heiselberg and others; Spitz and others.
[159] Heiselberg and others.
[160] Mara and Tarantola.

2.4.2.3.1 Sampling Methods

Various sampling methods are commonly used in sensitivity analysis practice, such as stratified sampling such as Latin hypercube sampling[161], simple random sampling such as Monte Carlo sampling, quasi random low discrepancy sampling such as Sobol's sequences[162] and random sampling generated by a pseudorandom number generator[163]. Monte Carlo random sampling gets surpassed by Latin hypercube sampling and quasi random sampling using Sobol's sequences in resultant sensitivity analysis accuracy[164].

2.4.2.3.1.1 Random Sampling

As illustrated in the *Figure 20*, a distribution such as normal distribution is taken and random samples are generated via usage of software packages. For small sample sizes, sampled values can get clustered or have wide gaps between them, as shown in line a in *Figure 21*. Line b on *Figure 21* was sampled using the same random generation, however it shows better coverage of the input space. This random nature of gaps and clusters pose a significant amount of problem in

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[161] C. J. Sallaberry, J. C. Helton, and S. C. Hora, 'Extension of Latin Hypercube Samples with Correlated Variables', *Reliability Engineering & System Safety*, 93.7 (2008), 1047–59 <https://doi.org/10.1016/J.RESS.2007.04.005>.

[162] Andrea Saltelli, Paola Annoni, Ivano Azzini, and others, 'Variance Based Sensitivity Analysis of Model Output. Design and Estimator for the Total Sensitivity Index', *Computer Physics Communications*, 181.2 (2010), 259–70 <https://doi.org/10.1016/J.CPC.2009.09.018>; I.M. Sobol´ and S.S. Kucherenko, 'On Global Sensitivity Analysis of Quasi-Monte Carlo Algorithms', *Monte Carlo Methods and Applications*, 11.1 (2005), 83–92 <https://doi.org/10.1515/1569396054027274>.

[163] Sebastian Burhenne, Dirk Jacob, and Gregor P Henze, 'Sampling Based on Sobol' Sequences for Monte Carlo Techniques Applied to Building Simulations', in *12th Conference of International Building Performance Simulation Association* (Sydney: Building Simulation, 2011).

[164] Saltelli, Annoni, Azzini, and others, 'Variance Based Sensitivity Analysis of Model Output. Design and Estimator for the Total Sensitivity Index'; Sallaberry, Helton, and Hora.

sensitivity analysis practice, as regions with clusters gets overemphasized and gaps are not accounted for in calculations[165].

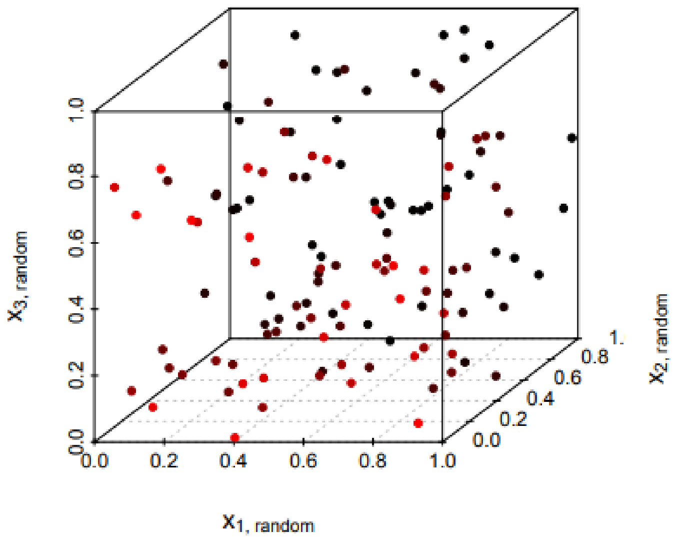

Figure 20 – Three dimensional diagram of the pseudo-randomly sampled points from the the parameter space defined by x1, x2 and x3. The color of the points range from red to black with respect to the value of x2 for a better understanding of the three dimensional plot.[166]

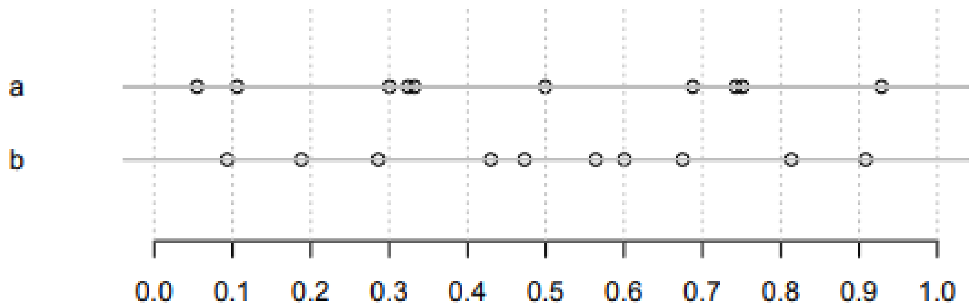

Figure 21 - Two examples derived with sampling from a random sampler[167].

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165 Saltelli, Ratto, Andres, and others, 'Global Sensitivity Analysis: The Primer'.
166 Burhenne, Jacob, and Henze.
167 Burhenne, Jacob, and Henze.

2.4.2.3.1.2 Stratified Sampling

As demonstrated in *Figure 22*, Problem of encountering clusters and gaps in random sampling can be resolved by using a stratified sampling method. Stratified sampling method subdivides the inspected domain into intervals and samples the same amount of points from these intervals. Sampling of points inside the subintervals are made using pseudo random number generation. *Figure 23* shows the plot of the points sampled from a two dimesional space using 10 strata for each parameter. Each of the resultant 100 points are placed within a cell, and their positions are pseudo randomly generated from the limits of their intervals.

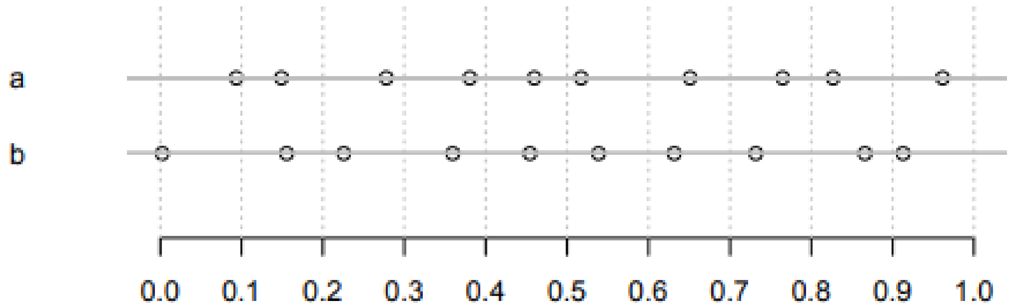

Figure 22 - Example of an plot generated with one dimensional stratified sampling[168].

[168] Burhenne, Jacob, and Henze.

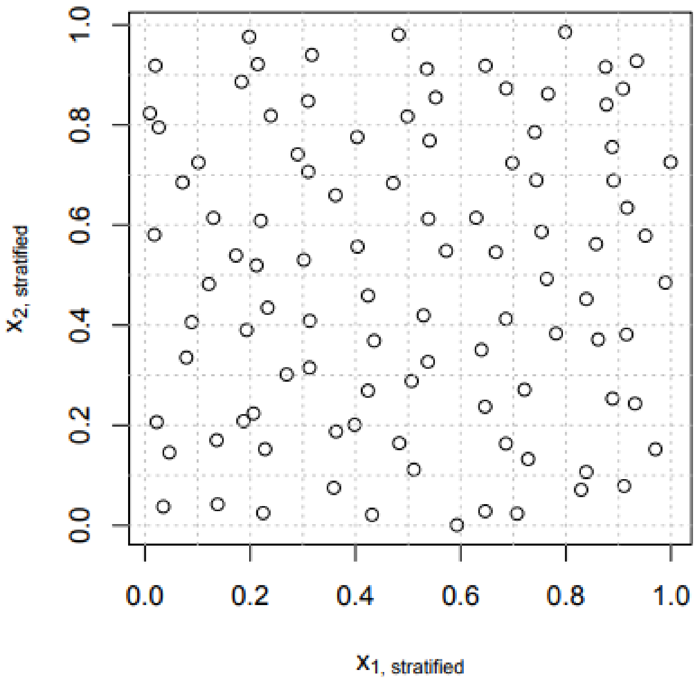

Figure 23 - Scatter plot diagram of a two dimensional stratified sampling. Individual positions of the points inside each of the cells are chosen randomly[169].

2.4.2.3.1.3 Latin Hypercube Sampling

Latin hypercube sampling is a subtype of the stratified sampling. It was first described by Michael Mckay in 1979[170]. The difference between stratified sampling and Latin hypercube sampling is that each parameter is stratified over a minimum of 2 intervals. Each interval should contain the same amount of inputs and they all should correspond to their unique combination of intervals[171]. In *Figure 24*, a Latin hypercube sampling with 10 intervals and a sample size of 10

[169] Burhenne, Jacob, and Henze.
[170] M. D. McKay, R. J. Beckman, and W. J. Conover, 'A Comparison of Three Methods for Selecting Values of Input Variables in the Analysis of Output from a Computer Code', *Technometrics*, 21.2 (1979), 239 <https://doi.org/10.2307/1268522>.
[171] Saltelli, Ratto, Andres, and others, 'Global Sensitivity Analysis: The Primer'.

for two parameters is shown. Reason for clustering for the Latin hypercube sampling in *Figure 25* is the low amount of sample size.

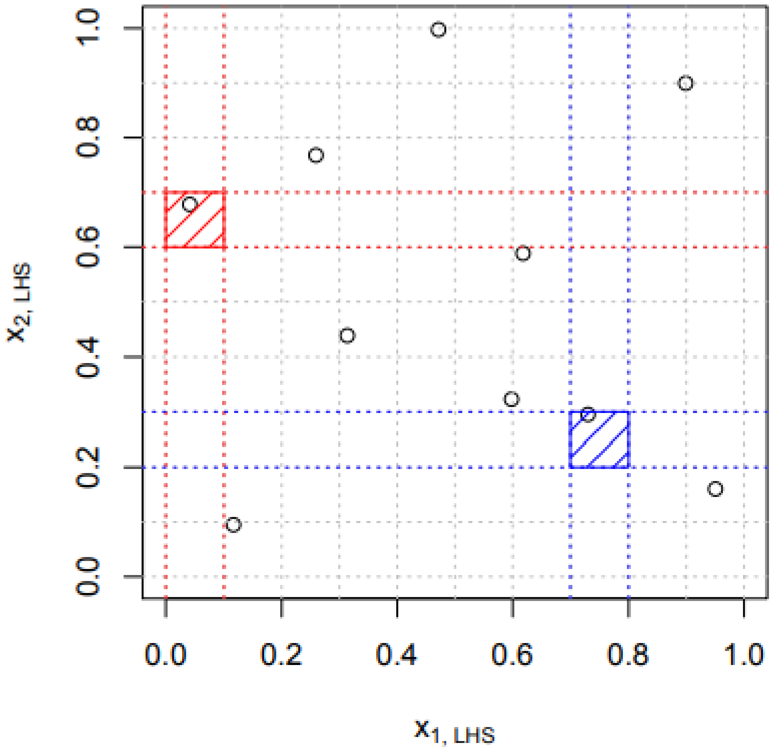

Figure 24 - Scatter plot of samples derived from Latin hypercube sampling in two dimensions. Colored lines denote the two intervals the points belong, which are x1 and x2. Colored lines are drawn for only two points in this sampling result, however all of the points contain the same quality[172].

2.4.2.3.1.4 Sampling based on Sobol sequences

Quasi random sequences which aim generation of multiple parameter samples as uniformly as possible on a multi dimensional parameter space encompass the Sobol sequences[173]. Biggest difference between sampling from quasi random low

[172] Burhenne, Jacob, and Henze.
[173] Saltelli, Annoni, Azzini, and others, 'Variance Based Sensitivity Analysis of Model Output. Design and Estimator for the Total Sensitivity Index'.

discrepancy sequences and pseudo random number generation is that in the former, chosen sample values are picked with an consideration to the formerly picked numbers in order to avoid clustering and gaps in the sample space.

Figure 25 shows that the most homogeneous distribution of the points with absence of gaps and clusters are achieved by a sampling based on Sobol sequences. Points generated from sampling based on quasi random low discrepancy are distributed more evenly when compared to the other methods[174].

2.4.2.3.1.5 Final Remarks on the Sampling Methods

Sampling methods are of crucial importance to the accuracy of the chosen global sensitivity analysis method, and several sampling methods were inspected in this section. Although stratified sampling and Latin hypercube sampling provides excellent results utilizing the samples derived from the intervals and solve the problem of gaps and clusters which is faced when using the pseudo random number sampling method, quasi random low discrepancy sampling based on Sobol sequences is more effective when exploring the input parameter space.

[174] Burhenne, Jacob, and Henze.

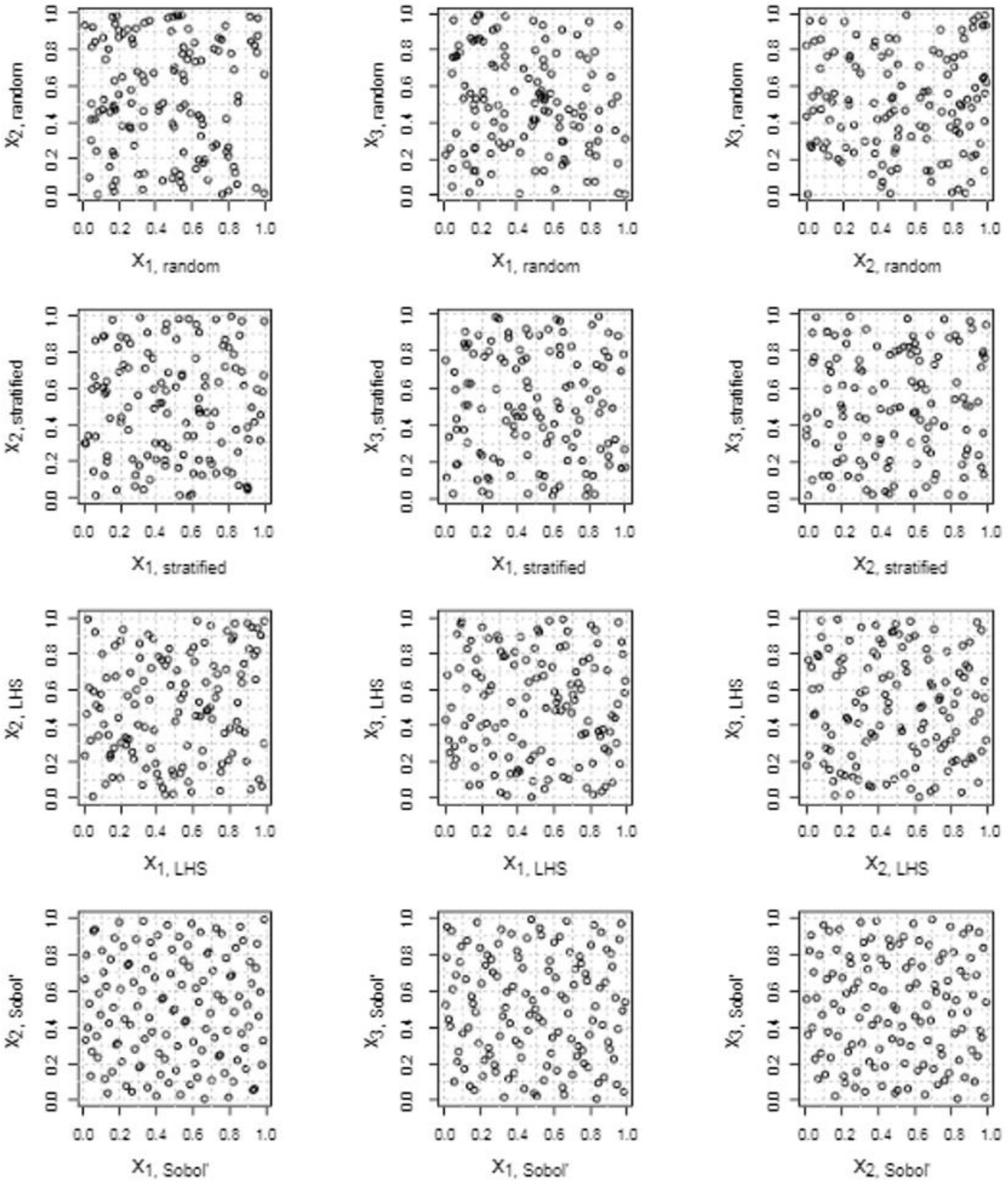

Figure 25 – Plots of three sampled parameters in pairs utilizing different sampling techniques placed side by side.

2.4.2.3.2 Screening Based Sensitivity Analysis Methods

Screening based methods seek to identify the least important parameters by aiming to fix them at any given value without reducing the output variance significantly. Using this method, screening based methods are able to rank the parameters by the importance they cause on the output variation, starting from the most important to the least important parameter using a relatively small number of simulations[175]. Screening based models are good choice for conducting sensitivity analysis on computationally heavy models or models with a vast number of input variables[176]. However, they produce the most accurate results when number of the examined parameters is low, nevertheless having a low number of inspected parameters is the most common case in most of the sensitivity analysis practice, therefore they have a wide application range[177]. For a detailed explanation of screening based methods, see Saltelli et al.[178]. Morris method is one of the most preferred sensitivity analysis methods belonging to the screening based methods family.

2.4.2.3.3 Regression Based Sensitivity Analysis Methods

Regression method is one of the most popular methods in urban heat island intensity sensitivity analysis. Regression based methods are easy to understand and their computational loads are generally low. After a Monte Carlo simulation is performed, the output and input values can be used to generate indicators based on regression such as Partial Correlation Coefficients (PCC), Standardized Regression Coefficients (SRC), and their rank transformations Standardized Rank Regression Coefficient (SRRC), Partial Rank Correlation Coefficient (PRCC).

SRC estimates sensitivity indices by utilizing a regression analysis, the model response gets approximated by a linear multidimensional model, which employs a regression coefficient f_i for each of the input parameters X_i[179]. In order to compare

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175 Andrea Saltelli, Stefano Tarantola, Francesca Campolololongo.
176 Heiselberg and others.
177 Andrea Saltelli, Stefano Tarantola, Francesca Campolololongo.
178 Saltelli A., Tarantola S., and Campolongo F., ‘Sensitivity Analysis as an Ingredient of Modeling’, *Statistical Science*, 15.4 (2000), 377–95 <https://www.jstor.org/stable/2676831> [accessed 10 July 2022].
179 Mara and Tarantola.

estimated regression coefficients, they are standardized with regards to the variance of the model output and the variance of the inspected input parameter[180].

The absolute value of the output standardized regression coefficient for each parameter denotes the importance of a given parameter as higher SRC values corresponding to higher importance on the model outcome. The output of SRC regarding each individual parameter can be negative or positive, and this sign represents whether influence of this parameter results in reduced or increased model outcome[181]. However, SRC is only valid when inputs are not correlated[182].

2.4.2.3.4 Variance Based Sensitivity Analysis Methods

Variance based methods decomposes the uncertainty of the output variation with regards to the corresponding inputs[183]. First order and total order sensitivity indices are the main indicators used for this type of sensitivity analysis methods. First order sensitivity indices denote the direct effects of the input parameters considering the output variance and the total order sensitivity indices correspond to the total contribution of a given parameter on the output variation, also accounting for the higher order interaction effects the parameters have on the output in addition to the first order effects[184]. Therefore, higher order effect which denote the interaction between parameters can be deduced from the difference between total order and first order sensitivity indices. Total order inspection is more suited for a throughout inspection of the parameters, and is more efficient in locating the least important parameters and first order sensitivity indices are used to find out about

[180] Mara and Tarantola.
[181] Domínguez-Muñoz, Cejudo-López, and Carrillo-Andrés.
[182] Helton and others.
[183] Andrea Saltelli, Stefano Tarantola, Francesca Campolololongo.
[184] Wei.

the direct effects the parameters have on the output variation, similar to the aforementioned methods.

One of the prominent advantages of using a variance based approach is that it can be used to assess parameter importance on non-linear and non-monotonic models and they are considered model free approaches. It can account for the direct variation on the output caused by respective parameters and it can quantify the interaction importance between parameters. The negative aspect of using these methods is the high computational cost, as input parameter space should be of considerable size to accurately assess parameter importance. Two of the most popular variance based methods are Fourier Amplitude Sensitivity Test (FAST) and Sobol's method[185].

2.4.2.3.4.1 Sobol's Method

Sobol's global sensitivity analysis is a sensitivity analysis method based on variance decomposition [186]. The following functional form can be used to represent non-linear and non-monotonic models:

$$Y = f(X) = f(X_1, \ldots, X_p) \qquad (1)$$

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[185] Andrea Saltelli, Marco Ratto, Stefano Tarantola, and others, 'Sensitivity Analysis for Chemical Models', *Chemical Reviews*, 105.7 (2005), 2811–27 <https://doi.org/10.1021/CR040659D/ASSET/CR040659D.FP.PNG_V03>; Andrea Saltelli, Marco Ratto, Stefano Tarantola, and others, 'Update 1 of: Sensitivity Analysis for Chemical Models', *Chemical Reviews*, 112.5 (2012) <https://doi.org/10.1021/CR200301U/ASSET/IMAGES/CR200301U.SOCIAL.JPEG_V03>.

[186] I.M. Sobol, 'Sensitivity Estimates for Nonlinear Mathematical Models', *Mathematical Modeling and Computational Experime T*, 1993, 407–17.

Where Y is the output metric which sensitivity analysis is conducted upon, and $X_1,\ldots,$ X_p is the parameters that are inspected. Sobol method is based on the decomposition of the total variance of square integrable function $f(X)$ into variances from each of the parameters and their interactions:

$$V(Y) = \sum_i Vi + \sum_i \sum_{j>i} Vij + \cdots + V12 \ldots k \quad (2)$$
[187]

Where Vi is the quantity of variance that can be attributed to the parameter X_i, and Vij is the joint effect of the parameters X_i and X_j on the total variance of the output. Sobol's sensitivity indices of different orders, such as single parameter sensitivity or parameter interaction can be calculated by the following:

First order sensitivity index $S_i = \frac{V_i}{V}$

Second order sensitivity index $S_{ij} = \frac{V_{ij} - V_i - V_j}{V}$

Total order sensitivity index $S_{Ti} = 1 - \frac{V_{\sim i}}{V}$

Where $V_{\sim i}$ is the sensitivity of all parameters except X_i parameter. The first order sensitivity index computes the main effect from inspected parameter, the second order sensitivity index computes the sensitivity of the combination of two parameters and the total order sensitivity index calculates the overall sensitivity index of the inspected parameter [188].

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[187] Kathrin Menberg, Yeonsook Heo, and Ruchi Choudhary, 'Sensitivity Analysis Methods for Building Energy Models: Comparing Computational Costs and Extractable Information', *Energy and Buildings*, 133 (2016), 433–45 <https://doi.org/10.1016/J.ENBUILD.2016.10.005>.
[188] Chi Zhang, Jinggang Chu, and Guangtao Fu, 'Sobol′'s Sensitivity Analysis for a Distributed Hydrological Model of Yichun River Basin, China', *Journal of Hydrology*, 480 (2013), 58–68 <https://doi.org/10.1016/J.JHYDROL.2012.12.005>.

The variances from equation (2) can be computed using approximate Monte Carlo numerical integrations. These approximations can be especially useful when a model is non-linear and non-monotonic. Previous studies have defined how to estimate V, V_i, V_{ij} and $V_{\sim i}$ variances using Monte Carlo approximations [189].

2.4.2.3.5 Meta Model Based Sensitivity Analysis Methods

Meta model based sensitivity analysis methods consist of a two stage approach[190]. Firstly, a meta model is initialized using non parametric regression methods, of which do not utilize a predetermined form (such as nonlinear or linear regression). As a result of this, this meta model can be used for complex models. After this process, sensitivity indices are calculated via variance based sensitivity methods. The aim of the meta model is to create a statistical machine learning model which approximates the objective function of the examined model[191]. Main point of utilizing the meta models in order to calculate sensitivity indices is that meta model which is created in the first step requires much lesser amount of computational power compared to the initial model they are based on, therefore using a meta model makes the simulation process much more computationally effective[192].

Most popular methods for conducting sensitivity analysis using meta models include Adaptive Component Selection and Smoothing Operator (ACOSSO)[193],

[189] I. M. Sobol, 'Global Sensitivity Indices for Nonlinear Mathematical Models and Their Monte Carlo Estimates', *Mathematics and Computers in Simulation*, 55.1–3 (2001), 271–80 <https://doi.org/10.1016/S0378-4754(00)00270-6>; I.M. Sobol.

[190] Saltelli, Ratto, Tarantola, and others, 'Sensitivity Analysis for Chemical Models'; Saltelli, Ratto, Tarantola, and others, 'Update 1 of: Sensitivity Analysis for Chemical Models'.

[191] Sigal Levy and David M. Steinberg, 'Computer Experiments: A Review', *AStA Advances in Statistical Analysis*, 94.4 (2010), 311–24 <https://doi.org/10.1007/S10182-010-0147-9>.

[192] Levy and Steinberg.

[193] Storlie and others.

Multivariate Adaptive Regression Splines (MARS)[194], Gaussian Process (GP)[195], Support Vector Machine (SVM)[196] and Treed Gaussian Process (TGP)[197].

2.5 Former Studies in Sensitivity Analysis of UHI Effect

There are numerous studies dedicated to investigating the importance of parameters involved in UHI intensity using sensitivity analysis and simulation based UHI calculation tools such as UWG. Mao et. al. researched the importance of parameters contributing to the UHI phenomenon by making use of the SRC global sensitivity method in a case study conducted in Abu Dhabi utilizing the UWG model and assessing the accuracy of the model using weather station data based on hourly and weekly data in summer and winter conditions [198]. Aydin et. al. investigated environmental performance outputs of several parameters defining a hypothetical urban model using the Morris sensitivity analysis method, in which the UHI phenomenon is also investigated via UWG model [199]. Alchapar et.al. investigated the UHI intensity of different albedo, vegetation, façade to site ratio scenarios in two cities located in South America calculated with the UWG model using local sensitivity analysis on hourly data and assessed the accuracy of the UWG model [200]. Litardo et. al. utilized UWG to conduct sensitivity analysis on 10 parameters contributing to the UHI effect by using 28 different morphological zones located in

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[194] Storlie and others.
[195] Jeremy E. Oakley and Anthony O'Hagan, 'Probabilistic Sensitivity Analysis of Complex Models: A Bayesian Approach', *Journal of the Royal Statistical Society: Series B (Statistical Methodology)*, 66.3 (2004), 751–69 <https://doi.org/10.1111/J.1467-9868.2004.05304.X>.
[196] Trevor Hastie, Robert Tibshirani, and Jerome Friedman, *The Elements of Statistical Learning: Data Mining, Inference, and Prediction, Second Edition*, Springer Series in Statistics, 2nd edn (New York, NY: Springer New York, 2009) <https://doi.org/10.1007/978-0-387-84858-7>.
[197] Robert B Gramacy and Matt Taddy Amazon, 'Categorical Inputs, Sensitivity Analysis, Optimization and Importance Tempering with Tgp Version 2, an R Package for Treed Gaussian Process Models', 2022 <http://www.cran.r-project.org/doc/packages/tgp.pdf> [accessed 10 July 2022].
[198] Mao and others.
[199] Aydin and Jakubiec.
[200] Alchapar and others.

Duran, Ecuador [201]. Salvati et. al. focused on 5 different morphological urban areas located in the Mediterranean context, conducting sensitivity analysis on 8 parameters on an older version of UWG (v1.0.0) and calculated UHI intensity on hourly and weekly values [202]. Kamal et. al. investigated the impacts of urban characteristics on the local microclimate in Lusail, Qatar by using the Python version of UWG and conducting sensitivity analysis on 10 UWG characteristics on resultant model electrical energy consumption using yearly and hourly results [203]. The aforementioned studies are incomplete as they don't consider interactions between inspected parameters, which can be achieved via Sobol's global sensitivity analysis method's second-order sensitivity indices. The majority of the prior research has also conducted their study in older versions of the UWG model in a Matlab environment which has a limited number of input parameters when compared to the Python version. Despite the updates in the Python version, the most recent version of UWG does not have a parameter input field for U-values, which is implemented in this study via a custom code injected into the main UWG code. The absence of the U-value parameter in the UWG code forced other researchers who inspected the impact of the U-value to use local sensitivity analysis methods by considering only a minuscule sample size, which is inconsistent in results and doesn't consider higher-order interactions between parameters [204]. Also, the number of parameters inspected in the aforementioned studies is limited and only a limited number of them use global sensitivity analysis methods while none of them utilize Sobol's method therefore not inspecting the interactions between the probed parameters. Moreover, former studies did not consider inspecting changes in parameter importance difference due to the seasonal differences and hourly and weekly timeframe differences.

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[201] Litardo and others.
[202] Salvati, Palme, and Inostroza.
[203] Kamal and others.
[204] Wei.

2.6 Sensitivity Analysis of the UHI effect

In this study, the urban heat island effect is inspected via the Sobol method, a variance-based global sensitivity analysis method [205]. The main advantage of the Sobol method is that it examines interactions between input parameters, which are called higher-order effects, in addition to the sensitivity index attributed to each input parameter which is used to identify each parameter's importance on the output[206].

Sensitivity analysis, presented by Saltelli et al. [207] is used to measure the effects of the inputs of a given mathematical model on its outputs. Sensitivity analysis is used to analyze models, including simulation-based optimization [208], automatic model calibration [209], etc. As many input parameters in the UHI simulation models are faced with a certain degree of uncertainty, due to a lack of knowledge of exact parameter values and varying conditions of the built stock (epistemic and aleatory uncertainty), sensitivity analysis is of utmost importance, as sensitivity analysis provides a pivotal process aimed to obtain credible results and information about the model, and provides confidence in model results [210]. Application of sensitivity analysis is commonly made in order to identify the parameters which have the most importance in model outputs, in accordance with the uncertainty analysis of these parameters. Another use case of the sensitivity analysis is to determine input variables that have the least amount of impact on the model output, in order to simplify the model and to create an ability to make informed decisions to ignore

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[205] I. M. Sobol.
[206] Anh Tuan Nguyen, Sigrid Reiter, and Philippe Rigo, 'A Review on Simulation-Based Optimization Methods Applied to Building Performance Analysis', *Applied Energy*, 113 (2014), 1043–58 <https://doi.org/10.1016/J.APENERGY.2013.08.061>.
[207] Andrea Saltelli, Stefano Tarantola, Francesca Campololongo.
[208] Nguyen, Reiter, and Rigo.
[209] Heo, Choudhary, and Augenbroe.
[210] Francesca Campolongo, Jessica Cariboni, and Andrea Saltelli, 'An Effective Screening Design for Sensitivity Analysis of Large Models', *Environmental Modelling & Software*, 22.10 (2007), 1509–18 <https://doi.org/10.1016/J.ENVSOFT.2006.10.004>.

those parameters. Also, sensitivity analysis can be used to identify model errors and weak model components to improve understanding of input and output relationships in model [211].

Even though the main factors contributing to the UHI effect have been identified, their hierarchy of importance is still uncertain to a greater extent. Therefore, extensive insight into the nature of parameters that contribute to the UHI effect is needed in order to fully grasp the interactions and differences imposed on the UHI effect by methodological and seasonal differences by applying a suited sensitivity analysis method and reviewing the sensitivity analysis method's working principles.

[211] Menberg, Heo, and Choudhary.

CHAPTER 3

METHODOLOGY

3.1 Introduction

The use of variance based global sensitivity analysis methods, especially Sobol's method creates an opportunity for inspecting the UHI phenomenon not only at the base parameter impact level but also in higher dimensions and accounting for interactions between parameters. Thus, Sobol's method is especially effective for systematic analysis of both the computer model which is used to quantify the UHI effect and the UHI phenomenon, as subjects of the examination are highly convoluted and can't be explained by simply investigating the direct effects of parameters on the output. Correspondingly, seasonal differences play a pivotal role in the UHI effect, as factors responsible for the UHI effect vary with seasonal differences, and the UHI effect can't be explained by inspecting a singular timeframe. Processing data for sensitivity analysis holds immense importance as the resultant sensitivity indices are calculated by the input fed into the algorithm, therefore exploring weekly and hourly timeframes in UHI intensity sheds new light on the variation of UHI intensity attributed to the probed parameters.

This study aims to conduct Sobol sensitivity analysis on the Urban Weather Generator (UWG) model running simulations of an existing urban area located in Ankara, Turkey. Parameters that are inspected are grouped in two categories, urban and building characteristics in order to both shorten the simulation time required for each run and for the ability to observe the parameters which are similar to each other in their respective categories. The impact of seasonal conditions is also inspected, with simulations running on typical summer and winter weeks. Different orders of Sobol sensitivity analysis indices are used to extract more information from the analysis results, inspecting parameter interaction as well. The present study aims to determine the relative importance of input parameters used to create the UWG model, the impact of seasonal conditions on the parameter importance, and parameter relationships using the metrics of UHI intensity which are calculated from the simulation results.

3.2 Framework

The proposed framework for urban heat island sensitivity analysis comprises two stages (*Figure 26*):

(a) Site analysis and parameter range definitions;

(b) Sensitivity analysis;

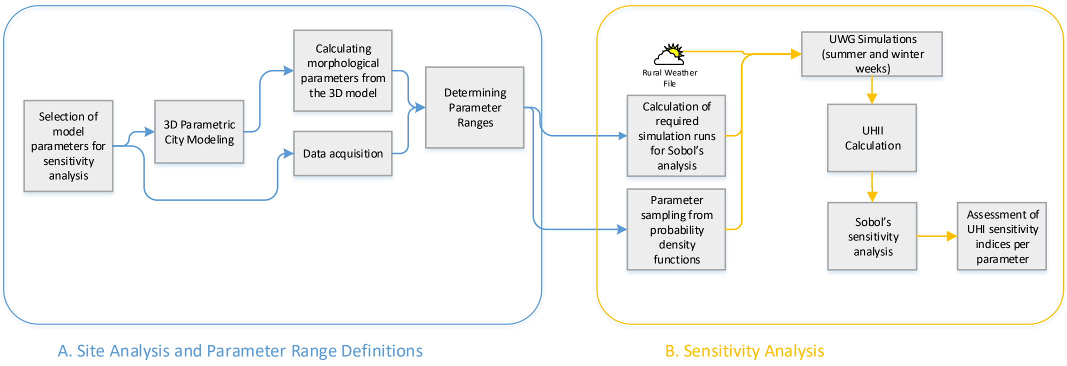

Figure 26 Framework for urban heat island sensitivity analysis

3.3 Information Gathering Process

3.3.1 Site Selection

For this study, Bahçelievler study are is selected because it represents a urban center well in the sense of it being located in a major capital, and also because the building stock is resembles each other and differences between each unit is not so pronounced. This situation is a well fit for the UWG simulation, as it works by abstracting the urban settlement to a single data point which is more consistent with urban settlements with limited variation such as the Bahçelievler case.

3.3.2 Site analysis

Figure 27 Rendering of the 3D modeled study site

A selected site is modeled using Rhinoceros3D software and its plugin, Grasshopper. Modeled site is based on a CAD drawing that has been produced before the study. *Figure 27* shows a 3D rendering of the study site produced in order to better convey the geometric qualities of the inspected site. Site modeling is crucial in the sense of extracting information about the main parameters driving the UHI effect, particularly the ones which are linked to the site geometry such as building density and façade to site ratio. Modeled site is used thereafter to extract morphological information at the site using the Grasshopper plugin to calculate volumes and surface areas from the 3D model. After baseline parameter values are extracted using the plugin, plausible bounds for urban context are defined within the model, which is used for sensitivity analysis to assess parameter importance. Also, open-source databases, UWG reference documents, and energy performance certificates (EPC) are used to gather non-geometric data to define the UCM.

3.3.3 Parameter Range Definitions

This study inspects the importance of numerous parameters, all of which have inherent uncertainties due to the random nature of the elements which contribute to the value denoted by them. This uncertainty exists because of the problems in observing and documenting the data, or in other words, due to the lack of knowledge about reality which describes the parameters [212]. Based on the type of uncertainty faced with each parameter, a Probability Density Function was used to create distributions with each parameter in order to accommodate the uncertainties using data collected at the site. For the parameters which are related to the data from the site, distributions are created using Python libraries numPy and pandas. For other parameters which are hard to collect data, such as thermostat setpoints in air conditioning, a literature review is conducted, and the probability density functions used in other studies are referenced. Selected parameters are inspected in two groups, Building Characteristics, and Urban Characteristics. Grouping was

[212] Zhihong Pang and others, ‘The Role of Sensitivity Analysis in the Building Performance Analysis: A Critical Review’, *Energy and Buildings*, 209 (2020), 109659 <https://doi.org/10.1016/J.ENBUILD.2019.109659>.

made in order to lower the required time for each iteration of the project, as Sobol analysis requires a considerable amount of simulation runs and to better assess parameter correlation.

3.4 Sensitivity Analysis

3.4.1 Sobol's Method

For this study, Sobol's method is chosen as the sensitivity analysis method because of its ability to inspect parameter interactions and total amount of variance caused by the parameter in addition to the first order effects. Other methods of sensitivity analysis is incompatible with this study due to their inability to inspect parameter relationship. Although Sobol's method is computationally expensive, variance based methods are superior in the sense that they can inspect nonlinear models and they provide a throughout inspection of the all variances caused by each of the parameters. As study is conducted on different seasonal conditions and timeframes, Sobol's method gives a deeper insight on how those aforementioned differences affect the behavior of the inspected parameters.

3.4.2 Novelty of the Methodology

This study is unique because although UHI sensitivity analyses has been conducted in the past, Sobol based sensitivity analysis on UHI simulations has not been conducted therefore parameter interactions has not been documented yet. This study offers to inspect not only the parameter interactions, but also the interactions between parameters themselves in order to provide a deeper understanding to the nature of causes which build up the UHI effect.

3.4.3 Sampling from the Parameter Space

Sample matrices are generated using quasi random low discrepancy sampling based on Sobol sequences in order to provide a throughout coverage of parameter space. For the analysis of first-order, second-order, and total effects sample size required in Sobol analysis equates to 2*(k + 1) *N model evaluations, with a sample size of N=500 and a number of parameters equal to k for n inspected simulation runs are required for the calculation of First Order, Total Order sensitivity indices. The additional estimation of the second-order indices for parameter interaction requires additional k * (k-1) / 2 * N model evaluations [213].

The Sobol method computes total output variance and evaluates both the input effects from the inspected parameter and all of the interactions between parameters. However, Sobol's method is the most computationally expensive method in global sensitivity analysis methods. Still, the Sobol method's ability to decompose the direct, indirect, and combined effects of the parameters of the output value is the reason why it is selected for this study.

3.5 Simulations

UWG model is selected for this study as the UHI calculation and simulation method due to its inherent low computational cost, making it viable for global sensitivity analysis methods which require a greater number of simulations. Because sensitivity analysis methods require multiple instances of computer simulations, computationally expensive urban heat island simulation models are not suited for sensitivity analysis, as the required time for a comprehensive study

[213] Menberg, Heo, and Choudhary; Saltelli, Annoni, Azzini, and others, 'Variance Based Sensitivity Analysis of Model Output. Design and Estimator for the Total Sensitivity Index'.

exponentially increases with the selection of the sensitivity analysis method and the computational cost of the simulation model.

Parameters that were defined in the previous steps were translated into the Python UWG code where sensitivity analysis is conducted. Another advantage of the Python version is its ability to process more variables than the grasshopper version, and simulations are much more efficient computational cost-wise. Furthermore, it is possible to run custom code to add more parameters for sensitivity analysis.

As sensitivity analysis with variance-based methods, especially the Sobol's sequence requires many simulation runs, the Python version of Urban Weather Generator is chosen for the task, as it provides accurate results with minimal computational cost.

3.5.1 Processing Simulation Results

The influence of different parameters on the outcome of the UHI effect was tested by running Sobol sensitivity analysis on simulations carried out with the Python version of the UWG model screening the parameter values sampled from the probability density functions assigned to each one. UWG is used with a rural weather file in EPW format, which was recorded in Ankara, Turkey. Required simulation count is determined via referring to Saltelli et. al.'s research [214].

Figure 28 illustrates the occupancy schedule utilized for simulations that were sourced from reference building schedules included with the UWG program. Electricity and lighting schedules were also acquired from the UWG building schedule references.

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[214] Saltelli, Annoni, Azzini, and others, 'Variance Based Sensitivity Analysis of Model Output. Design and Estimator for the Total Sensitivity Index'.

Simulations were conducted over two weeks, an average summer and winter week. Software DView was used for the analysis of the meteorological data stored inside the EPW file. Selected two weeks both are sunny weeks in which the case study area receives direct solar radiation consistently. *Figure 29* and *Figure 30* show both weeks' temperature and direct normal radiation data.

Simulation outputs are then used to calculate the UHI Intensity, where hourly temperature values from the output EPW file are compared to the rural temperature values, and the difference between the two values is used to calculate the UHI Intensity [215].

$$UHII = \frac{\sum(T_{urb} - T_{rur})}{n} \quad if\ and\ only.\ \ T_{urb} > T_{rur} \qquad (3)$$

In equation (3), n denotes each hour in the inspected timeframe. For weekly calculation of the UHII, all given hours in a selected week are used for a general understanding of parameter importance relative to the season the simulation is performed. However, for hourly analysis, every parameter is evaluated for each hour in a day, calculated from corresponding days in the examined week. This approach gives way to a more in-depth look at daily changes in the UHI effect, permitting exploration of comparative parameter importance respective to the day-night cycle and its subsequent effect on UHI.

[215] A. Boccalatte and others, 'Microclimate and Urban Morphology Effects on Building Energy Demand in Different European Cities', *Energy and Buildings*, 224 (2020), 110129 <https://doi.org/10.1016/J.ENBUILD.2020.110129>.

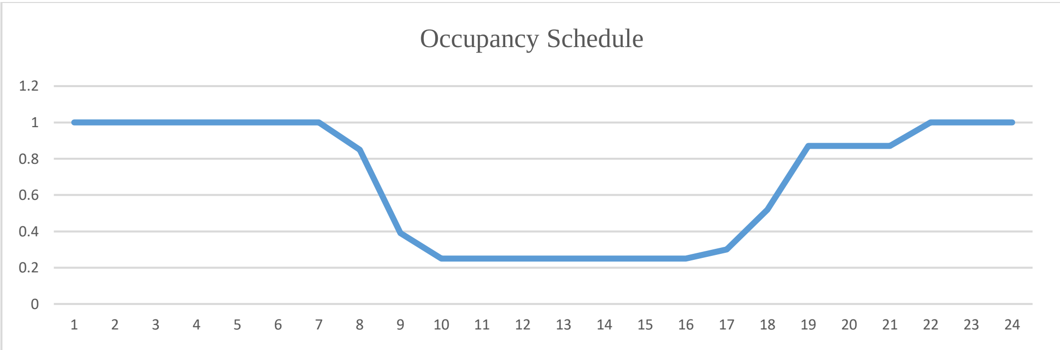

Figure 28 Average occupancy schedule

3.6 Result Evaluation

The tested parameters are then ranked according to their respective total order and second-order Sobol indices. Second-order indices, which explain how parameters are interacting with each other to affect output value, are also inspected. Summer and winter climate conditions have different kinds of impact on the sensitivity results, therefore the final results are evaluated from the perspective of seasonal changes. Parameter rankings are then compared to the other studies to point out discrepancies between the UWG model and UHI effect literature.

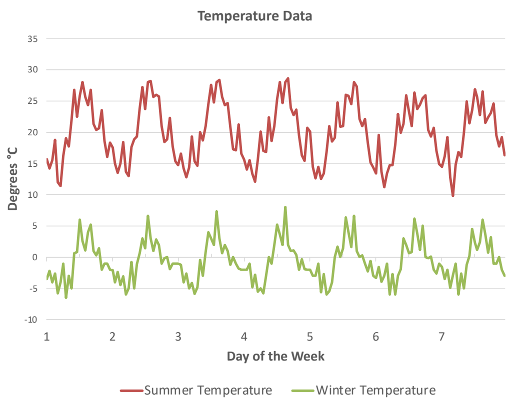

Figure 29 Temperature data

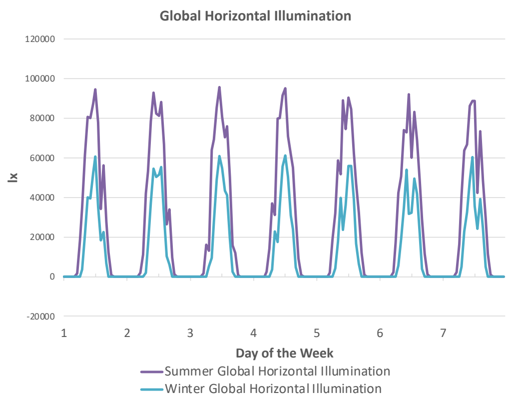

Figure 30 Global horizontal illumination data

3.7 Limitations of the UWG model and Sobol's Method

Sobol method's biggest drawback is that it requires a vast number of samples in order to produce accurate results, and the count for each iteration increases exponentially with the selected sampling method's N count.

This drawback is tried to be remedied by the fast computation times of the UWG method, however , UWG reduces the representation of the urban settlement into a singular point which produces inaccurate results when the case study areas are not homogeneous. Also, UWG is not able to calculate latent heat transfer efficiently and energy calculations regarding albedo calculations of UWG models are not accurate.[216]

UWG model's shortcoming are overcome by the selection of the Bahçelievler case study area, which is mostly homogenous and has very limited amount of vegetation, in order to not assess the intensity of the UHI present in the urban area inaccurately.

[216] Salvati, Palme, and Inostroza; Litardo and others; Alchapar and others; Mao and others.

CHAPTER 4

CASE STUDY

4.1 Selected Urban Context

The selected site for the study is located in the Bahçelievler district in Ankara, Turkey. The case study location is a low to mid-rise residential area with a small number of commercial and educational buildings and very limited green area. Ankara has been developing rapidly since the first quarter of the 20th century and has a population near 5.5 million people. Ankara has a cold semi-arid climate which is assessed by Köppen climate classification is BSk. Due to its elevation and inland location, Ankara has cold and snowy winters and hot and dry summers. Rainfall occurs mostly during the spring and autumn. Precipitation can be observed throughout the year. Monthly mean temperatures range from 0.9 °C in January to 24.3°C in July, with an annual mean of 12.6 °C [217].

The total area of the case study area is about 1,300,000 m^2. Vegetation is limited in the case study area, with most of the urban morphology consisting of roads, residential units, and public service buildings. Building stock was mostly built during the 1980s when Ankara expanded rapidly and the Bahçelievler district was rebuilt to accommodate a denser population near the city center. Buildings in the area show similar characteristics regarding their building systems, façade openings, and construction material.

[217] 'Meteoroloji Genel Müdürlüğü' <https://mgm.gov.tr/veridegerlendirme/il-ve-ilceler-istatistik.aspx> [accessed 12 May 2022].

4.2 Sensitivity Analysis

The sensitivity analysis process starts by defining probability density functions for aleatoric and epistemic uncertainties. For the parameters which were correlated to the data accessible from the site, distributions are regarded as aleatory uncertainties and probability density functions are calculated using Python libraries numPy and Pandas. For other parameters, probability distribution functions used in literature are utilized. Then, the baseline urban EPW file is linked to the UWG simulation, and the simulation process is started afterward respective to the sampled parameters from the associated probability density functions. For each simulation cycle, hourly temperature values are collected and written into an Excel file. These temperature values are then used for calculating UHI intensity indices, which are then used as the output variable of the sensitivity analysis. Simulations are conducted on average summer and winter weeks as read by the source EPW file. Two simulation sets are created with one analyzing the average temperature of each hour in a given week, and another by creating hourly average temperatures for the seven days of the week. 77,000 and 38,500 simulation runs were conducted for building characteristics and urban characteristics parameter groups respectively. Simulations consider UHI intensity values calculated from weekly and hourly average temperatures in each week of average summer and winter weeks as the output function of the sensitivity analysis. The weekly analysis is better for understanding the general importance of a parameter’s effect on a wider timescale, meanwhile, hourly analysis of sensitivity indexes is superior in the sense that it makes clear how parameters change importance related to the time of the day.

4.3 Inspected Parameters and Grouping

Inspected parameters that contribute to the UHI effect can be categorized as building characteristics and urban characteristics as shown in Table 2 and Table 3. This categorization allows for better inspection of the input parameters as parameters that are associated with each other have strong correlations between each other and grouping them paves the way for Sobol's second-order correlation matrix to be more consistent about interactions. As vegetation is limited in the case study area, parameters that are related to the vegetation are not included in the inspection group. Also, due to the Sobol method's high computational cost, splitting parameters allows manageable simulation times for each iteration. Parameters that are surveyed and recorded are then fitted inside a corresponding probability density function through Python libraries numPy, Pandas, and Seaborn. Other parameters' probability density functions which are hard or impossible to get information about are referenced in the other studies.

Table 2. Building Characteristics

Parameter Name	Unit	Probability Density Function	1st Percentile of Distribution	99th Percentile of Distribution	Reference
Glazing Ratio	%	lnN[−1.462; 0.400]	0.129	0.414	OD
Wall U-Value	W/m^2K	lnN[-0.542;0.414]	0.221	1.524	OD
Window U-Value	W/m^2K	lnN[0.965; 0.187]	1,69	4,059	OD
Window SHGC	%	lnN[-0.519; 0.143]	0,42	0,83	[218]
Infiltration Rate	ACH	N[0.775; 0.21]	0,286	1,263	[219]
Chiller COP	Q/W	N[4.45; 0.85]	2,247	6,427	[220]
Thermostat Setpoint	°C	U[20-24]	20	24	[221]
Equipment Load Density	W/m^2	N[4.6; 0.48]	3.48	5,71	[222]
Lighting Load Density	W/m^2	N[4.4; 0.42]	3,19	5,6	[223]
Occupancy Density	$People/m^2$	N[0.02665;0.00443]	0,020	0,0333	OD
Wall Albedo	%	N[0.4235:0.045]	0.318	0.528	[224]
Roof Albedo	%	N[0.4235:0.045]	0.318	0.528	[225]
Wall Emissivity	%	N[0.85;0.025]	0.791	0.908	[226]
Roof Emissivity	%	N[0.85;0.025]	0.791	0.908	[227]
Floor Height	m	lnN[1.059; 0.041]	2,62	3,17	OD
Roof U-Value	W/m^2K	lnN[-0.771;0.464]	0,157	1,362	OD

(*) U: uniform distribution; N: normal distribution; lnN: lognormal distribution; OD: Observed data

[218] Kristensen and Petersen.
[219] Kristensen and Petersen.
[220] Chiller Efficiency, 'Factsheet Chiller Efficiency', 2010, 2–4.
[221] Kristensen and Petersen.
[222] 'Energy Plus Zone Loads - Honeybee - Component for Grasshopper | Grasshopper Docs' <https://grasshopperdocs.com/components/honeybee/setEnergyPlusZoneLoads.html> [accessed 24 May 2022].
[223] 'Energy Plus Zone Loads - Honeybee - Component for Grasshopper | Grasshopper Docs'.
[224] Macdonald Iain Alexander, 'Quantifying the Effects of Uncertainty in Building Simulation' (University of Strathclyde, 2002).
[225] Macdonald Iain Alexander.
[226] Macdonald Iain Alexander.
[227] Macdonald Iain Alexander.

Table 3. Urban Characteristics

Parameter Name	Unit	Probability Density Function	1st Percentile of Distribution	99th Percentile of Distribution	Reference
Building Height	m	lnN[2.716; 0.349]	6,7	34,1	3DM
Façade to Site Ratio	m^2/m^2	N[1.302; 0.332]	0,521	2.074	3DM
Building Density	%	N[0.385508; 0.0375508]	0.308	0.462	3DM
Urban Road Volumetric Heat Capacity	J/m^3K	N[1,960,371; 300000]	1264700	2658280	[228]
Urban Road Albedo	%	N[0.23345; 0.048025]	0.121	0.345	[229]
Sensible Anthropogenic Heat	W/m^2	N[20; 5]	8.36	31.63	[230]
Urban Road Thermal Conductivity	W/m^2	N[1.955; 0.4]	1.02	2.885	[231]

(*) U: uniform distribution; N: normal distribution; lnN: lognormal distribution; OD: Observed data; 3DM 3-Dimensional Model

[228] Abbas Mohajerani, Jason Bakaric, and Tristan Jeffrey-Bailey, 'The Urban Heat Island Effect, Its Causes, and Mitigation, with Reference to the Thermal Properties of Asphalt Concrete', *Journal of Environmental Management*, 197 (2017), 522–38 <https://doi.org/10.1016/J.JENVMAN.2017.03.095>.
[229] Sushobhan Sen and Jeffery Roesler, 'Aging Albedo Model for Asphalt Pavement Surfaces', *Journal of Cleaner Production*, 117 (2016), 169–75 <https://doi.org/10.1016/J.JCLEPRO.2016.01.019>.
[230] Mao and others.
[231] Mohajerani, Bakaric, and Jeffrey-Bailey.

CHAPTER 5

RESULTS AND DISCUSSION

5.1 Initial analysis of daily UHI intensity for summer and winter

Processing all simulation results via averaging for every hour and the using the equation **(3)** shows that UHI intensity for the inspected neighborhood is in the range of 0.01 to 4°C in the winter and 0 to 2.4°C in the summer. *Figure 31* shows that UHI intensity is lower in the noon to evening timeframe, and intensifies in the night until dawn timeframe. This is a result of emission of absorbed heat during day hours back into the canyon at night hours, and at this timeframe UHI intensity is the most sensible. This is due to the increased storage of solar heat gain compared to the rural areas, where thermal storage capacity is limited due to the absence of materials able to effectively store heat and the presence of vegetation and the resultant low thermal inertia. As a result, UHI intensity at night is more pronounced. This findings are consistent with the previous modeling [232][233] and observational [234] studies. Wind trapping in the canyon due to the urban morphological characteristics of the urban area also contribute significantly to the UHI effect being more sensible at night [235], building height is one of the parameters which directly contribute to this situation. In addition, when UHI intensity is

[232] Li and Bou-Zeid.
[233] K. W. Oleson and others, 'An Examination of Urban Heat Island Characteristics in a Global Climate Model', *International Journal of Climatology*, 31.12 (2011), 1848–65 <https://doi.org/10.1002/JOC.2201>.
[234] T. R. Oke, 'The Energetic Basis of the Urban Heat Island'.
[235] Ryu and Baik.

inspected via weekly averages, summer season values show lesser amount of variation when compared to the winter season, as shown in *Figure 32*.

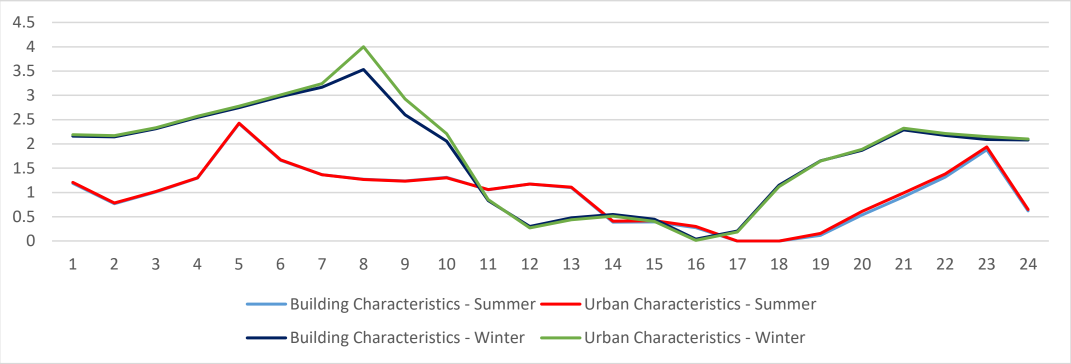

Figure 31 Mean UHI intensity for all parameter groups by hour

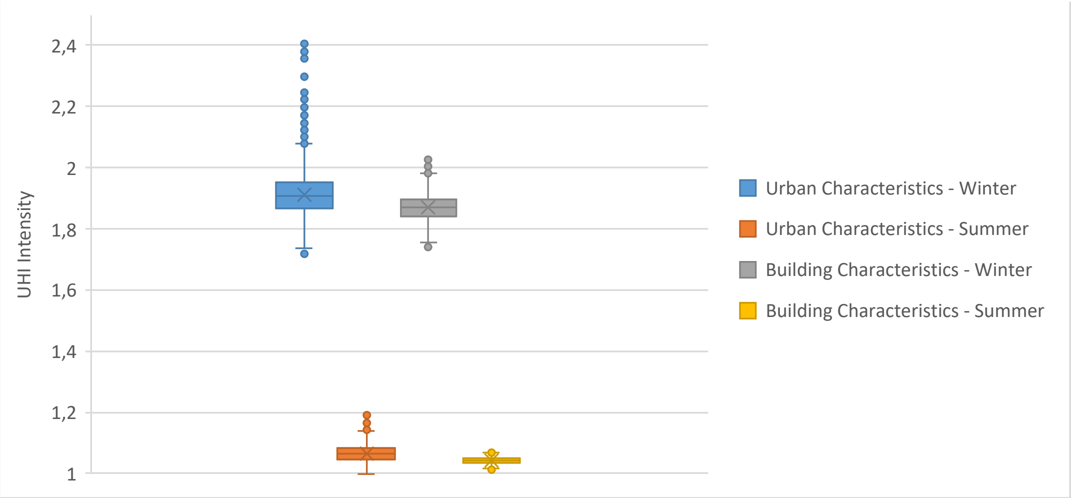

Figure 32 Weekly average UHI intensity for all parameter groups.

5.2 Total Order Weekly Sensitivity Indices

Figure 33 shows building height, urban road thermal conductivity and building density as the leading parameters in importance, followed by the façade to site ratio and urban road volumetric heat capacity. Analysis results point out that in summer season, although morphological factors have the leading position in importance, urban road properties closely follow them, as the heat gained from solar radiation is released back into the canyon and speed and quantity of this process determined by the thermal conductivity and volumetric heat capacity, respectively.

Inspection of UWG code reveals that canyon temperature is directly correlated with the temperature control systems, as waste heat from those systems are transferred to the canyon and the load on those systems are determined by morphological factors for the most part. Urban morphological fabric is responsible for the air volume which is needed to be conditioned and the rate at which conditioned area temperature is equalized with the canyon temperature. Building height in particular has a crucial part in calculation of those loads, as it is included in numerous calculations for determination of those values. Also, increased building height results in more air trapped in the canyon, therefore has a more influential position regards UHI intensity. In addition, morphological factors are very important in determination of how much of the solar gain is kept at the canyon level and not reflected back to the atmosphere as the surface area and built area volume is directly correlated with the urban morphological characteristics.

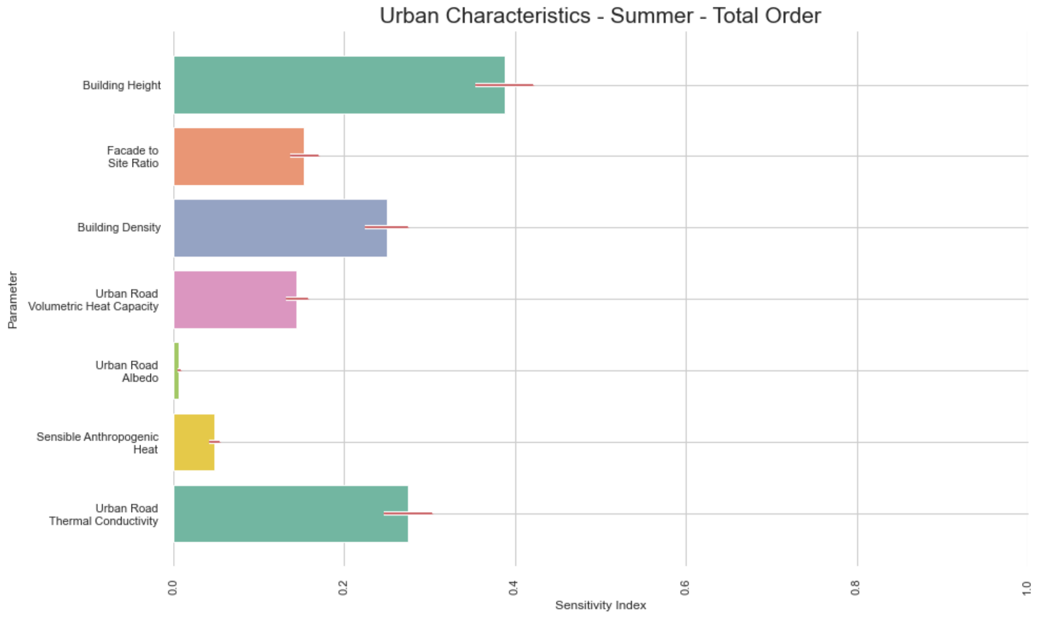

Figure 33 Summer season total order urban characteristics sensitivity analysis result

Inspecting urban characteristics in winter season, *Figure 34* reveals that as solar gain amount is reduced drastically due to the climate conditions, and parameters related to solar heat gain lose importance and temperature control related parameters exhibit increased importance. Urban road related parameters lose substantial amount of importance meanwhile morphological sensitivity indices shift towards building height as it is the main parameter in charge of determination of temperature system load and behavior of the wind in the canyon. Façade to site ratio also gains importance when compared to the summer season but building density loses importance due to the aforementioned situation. Another reason of building height and façade to site ratio’s increased importance is that as effective area which is exposed to wind increases, temperature transfer from warmer enclosed spaces heat up the canyon, rather than cooling it when compared to the summer season behavior. This leakage of warm air into the canyon both increases the load on the temperature control systems therefore increases the waste heat production and also directly increases canyon temperature because of the positive temperature difference.

Seasonal impact on urban characteristics regarding UHI intensity demonstrate that parameter importance varies with amount of solar gain and the resultant urban fabric reaction and the temperature system's target of cooling or heating the enclosed spaces.

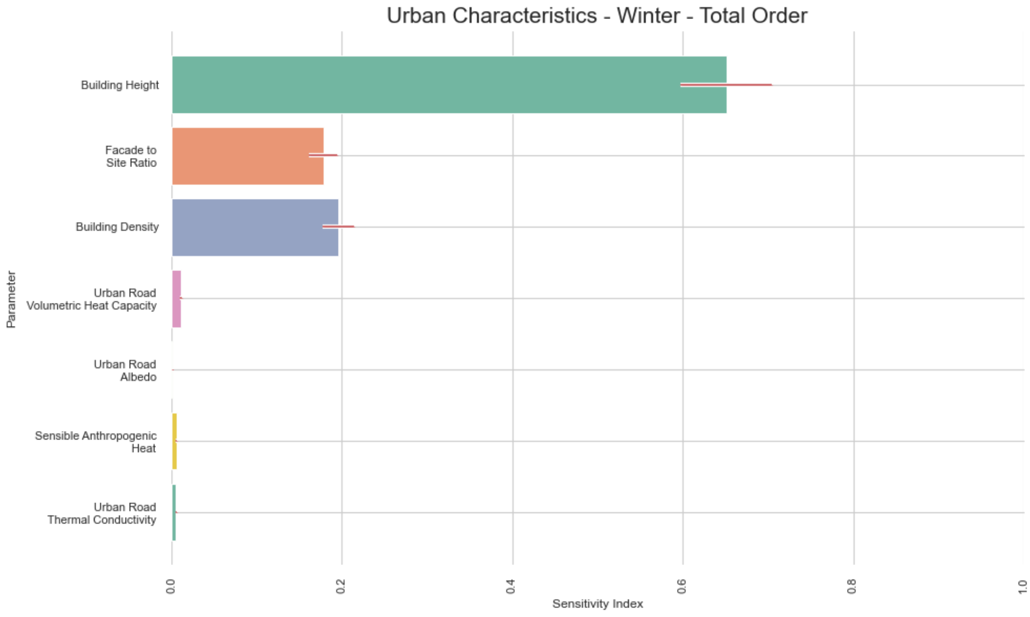

Figure 34 Winter season total order urban characteristics sensitivity analysis result

Building characteristics sensitivity analysis in summer season assesses thermostat setpoint to be the most important parameter. This ranking in *Figure 35Figure 35* occurs in correlation with the building systems and their resultant waste heat released into canyon. Exhaust waste heat from building systems is correlated with many of the parameters in the building characteristics, such as thermostat setpoint, chiller COP, equipment load density, lighting load density, occupancy density, floor height and u-values. However, thermostat setpoint, chiller COP, glazing ratio and wall u-value are the most sensitive parameters for the calculation of the UHI effect, as thermostat setpoint being the most important factor in decision of HVAC load, with chiller COP dictating its effectiveness. Glazing ratio is used in many calculations regarding disposal and production of waste heat and it is one of the main factors in calculation of solar radiation trapped inside the air conditioned volumes, increasing HVAC load in summer scenarios. Wall u-value controls the thermal response of the enclosing walls and decides how much and how fast the solar radiation absorbed in the day conditions are released back into the canyon. In addition, wall-u value is again important in the calculation of the thermal control system load, as heat transfer is from canyon to inside volume in this scenario.

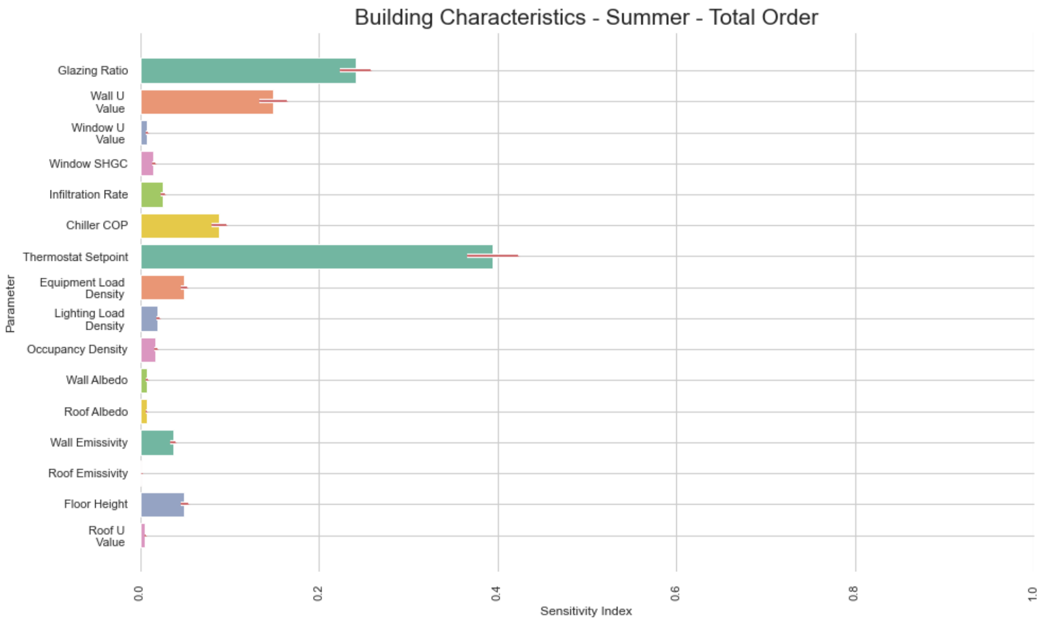

Figure 35 Summer season total order building characteristics sensitivity analysis result

Winter season analysis of building characteristics show a smaller set of parameters having noticeable impact on the UHI effect when compared to the summer season.

This is a result of thermal control systems attempt to increase heat in enclosed spaces in winter season, in contrast to the summer season. This situation makes leaked air and heat from enclosed spaces to the canyon be the most important contributor to the UHI effect. In *Figure 36* infiltration rate is the most sensitive parameter, as how fast the enclosed air is transferred back into the canyon is determined by it. Thermostat setpoint controls the temperature of the enclosed space and the air contained inside of it, therefore it also found to be very sensitive as amount of heat transferred into the canyon scale with the target temperature. Wall and window u-values are used in computation of heat conduction, and they are heavily involved in computation of heat moving from enclosed space to the canyon through construction thus they also show significant importance in UHI intensity calculation. Aforementioned effect is a also a considerable reason for glazing ratio’s importance, as surface areas of glazed and solid areas and their combined thermal conduction in the final construction is determined by the glazed area.

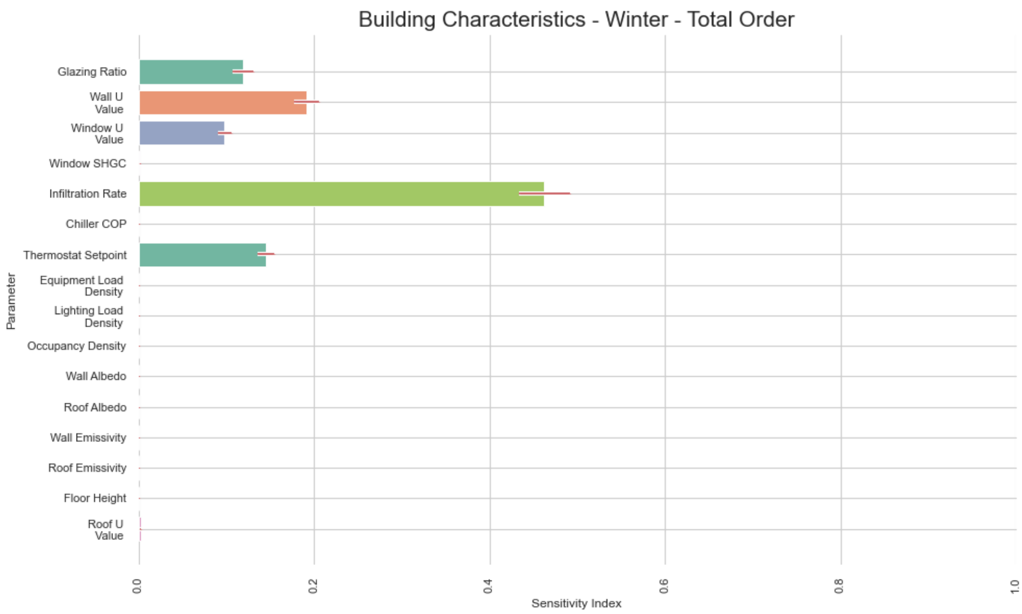

Figure 36 Winter season total order building characteristics sensitivity analysis result

5.3 Second Order Weekly Sensitivity Indices

Second order analysis results in summer season as shown in *Figure 37* finds out that biggest amount of interaction occurs between building height and building density parameters. This finding is directly related to response of the urban area to the solar gain, as building height and building density are the parameters which determine the urban thermal mass and surface area thus the amount of solar radiation which is converted into the sensible heat in the canyon. Also, inspecting source UWG code reveals that these two parameters are used in conjunction while calculating canyon properties such as surface area that is exposed to the wind and solar radiation, total façade area and canyon aspect ratio regarding width and height.

Urban road thermal conductivity and volumetric heat capacity are the parameters which are used to define the same urban element, and thefore they are closely intertwined in calculations they are involved in regarding heat transfer into the canyon. Accordingly, they have the second biggest correlation coefficient regarding second order interaction.

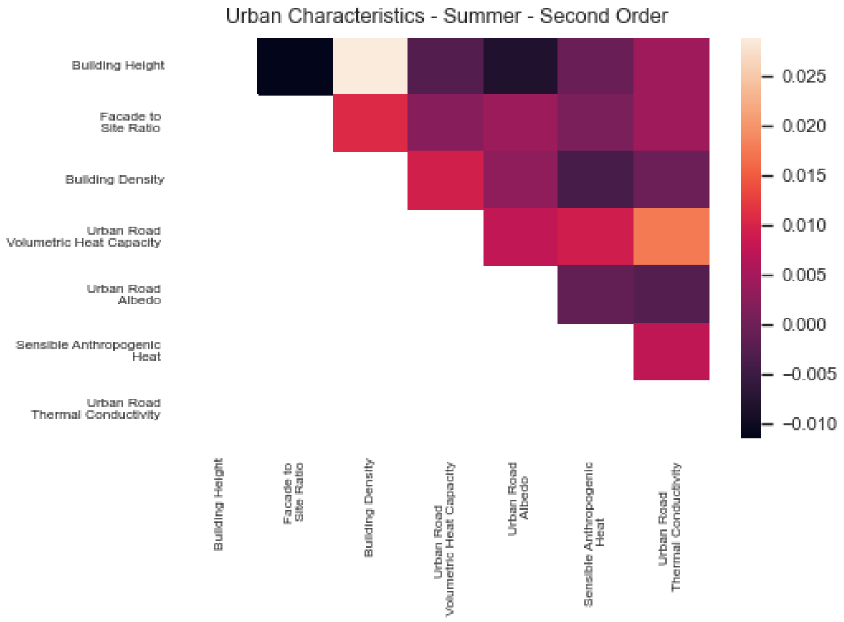

Figure 37 Summer season second order urban characteristics sensitivity analysis result

Urban characteristic parameter group's winter season second order analysis results illustrate seasonal conditions are of crucial importance when determining parameter correlations. Results in *Figure 38* detects the highest correlation between building density and urban road thermal conductivity. This finding can be explained by dependence of urban road surface area to the building density, where UWG calculates the former in respect to the latter. A closer look into the results also shows that the urban road volumetric heat capacity parameter shows higher correlation with urban road thermal conductivity, urban road albedo and the sensible anthropogenic heat from vehicular and human traffic. This finding is to be expected as except for sensible anthropogenic heat, all parameters are used in defining the same object, same as the summer season findings, however, in winter condition urban road albedo is found to be having positive second order interactions as well. For sensible anthropogenic heat, calculations involving this parameter are focused on urban surface level, therefore it has more correlation with the urban element which is closest to the surface area because of the heat transfer between the heat source denoted by the parameter and the urban road. An interesting finding is that building height shows the least amount of correlation with other parameters, inspecting this finding with the perspective of it being the most important parameter in winter conditions reveal that building height’s effect on UHI intensity is mostly self-contained, and when solar gain is not a significant factor for heating, building height dominates importance rankings via its direct effect on thermal control system load, its impact on the air infiltration rate in enclosed spaces and the wind behaviour in the canyon.

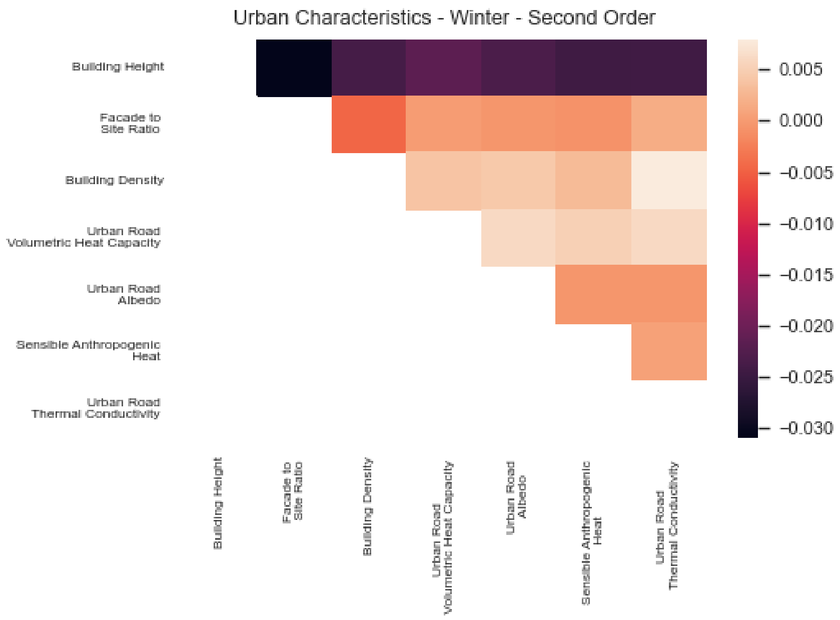

Figure 38 Winter season second order urban characteristics sensitivity analysis result

Summer scenario’s buidling characteristics second order sensitivity analysis results detects considerable second order interaction between wall u-value and thermostat setpoint parameters. Thermal transfer from the canyon into the enclosed space is dependent on the inner temperature as the rate of heat flow between two objects is proportional to their difference in temperature [236]. In *Figure 39* wall u-value exhibits higher second order interaction values compared to the other pairs, which can be explained by it being the main deciding factor of conduction calculations. Importance of conduction and its resultant increased load on HVAC system which leads to increased amount of waste heat released into the canyon can be illustrated by wall-u value and thermostat setpoint having bigger second interaction values than chiller COP and thermostat setpoint pair, which are directly correlated because in energy efficiency calculations.

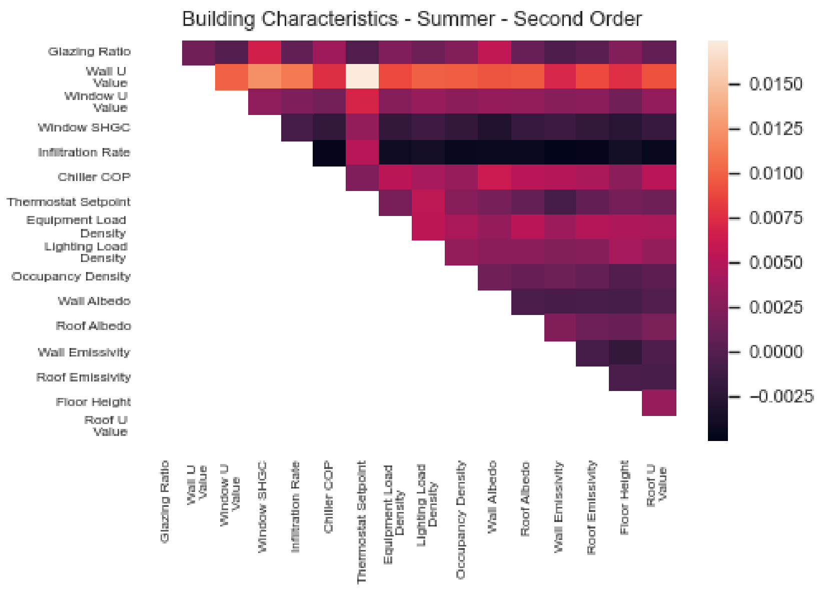

Figure 39 Summer season second order building characteristics sensitivity analysis result

Figure 40 illustrates second order analysis of building characteristics parameters in winter season points out to infiltration rate and thermostat setpoint pair to be the most correlated pair in regards to second order interaction. This is due to the

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[236] R Byron Bird, Warren E Stewart, and Edwin N Lightfoot, 'Transport Phenomena , 2nd Edition', ed. by Wayne Anderson, Katherine Hepburn, and Petrina Kulek, *Transport Phenomena*, 2002, 704–16.

magnitude of canyon heating due to air leaking from the enclosed spaces is highly dependent on the temperature of the air that is transferred to the outside. Wall u-value again shows higher correlation with the other parameters, however this time infiltration rate also exhibits similar behaviour. This correlation pattern denotes that wall u-value and infiltration rate are included in the calculations of most of the parameters which contibute to the UHI effect. Glazing ratio only shows noticeable correlation with the window and wall u-value parameters, and this findings point out to the glazing ratio's effect on determining wall's opaque and transparent material ratio's effect on the conduction properties of the walls.

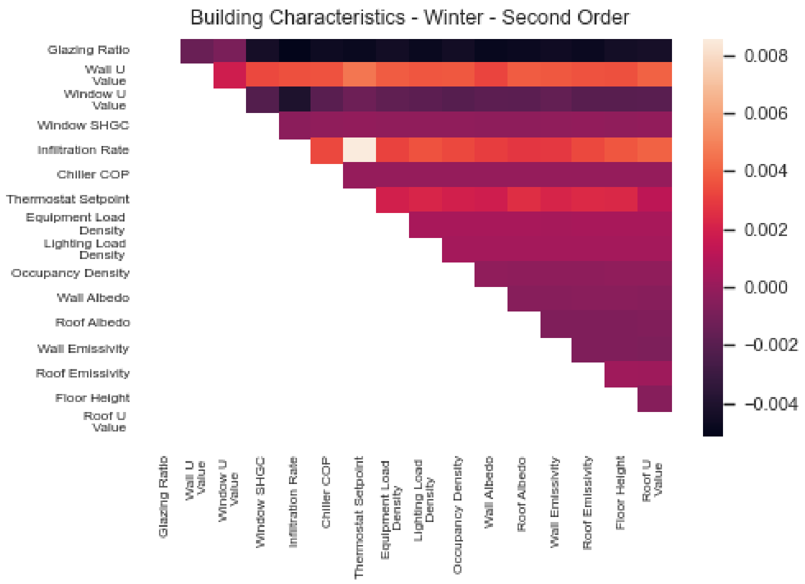

Figure 40 Winter season second order building characteristics sensitivity analysis result

5.4 Total Order Hourly Sensitivity Indices

Urban characteristics group’s summer season hourly sensitivity results show that building density and façade to site ratio’s importance scales with the solar gain being present at the simulation hours, and they show increased sensitivity during day hours. As shown in the *Figure 41(a)*, these two parameters have their importance increased in daylight hours, with building height showing increased sensitivity in evening hours due to its constant impact on thermal conditioning system load. This situation illustrates although all urban fabric characteristics are of immense importance regarding UHI intensity, they alternate in importance with
(a)
regards to occupancy schedules and the presence of solar gain. Stacked column chart in *Figure 41(b)* shows that relative importance of the urban road thermal conductivity parameter becomes one of the most sensitive parameters in night hours until morning, and even becomes the most important parameter in 5:00 AM, this finding is a result of thermal conductivity’s role in releasing absorbed heat during day hours back into the canyon at night hours.

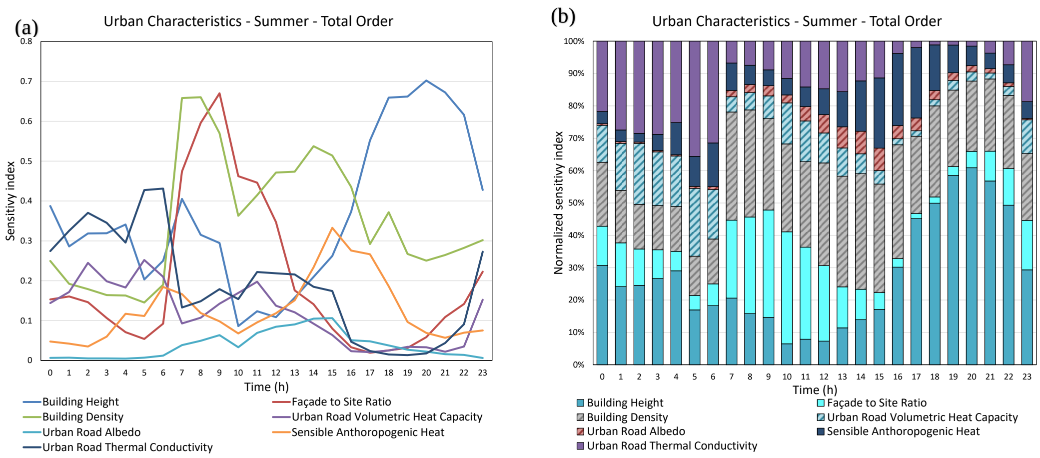

Figure 41 Urban characteristics summer season (a): hourly sensitivity analysis results (b) normalized hourly sensitivity analysis results

Hourly analysis of urban characteristics in winter week depicts building height parameter’s alternating importance with regards to the presence of solar radiation.

Results in *Figure 42(a)* detects increased sensitivity for urban volumetric heat capacity, building density and façade to site ratio parameters thus shows daily change in parameter importance with regards to the additional energy from solar gain during day hours. Although building height is found to be the most sensitive parameter during night hours, *Figure 42(b)* depicts the shift of relative weight of the inspected parameters with regards to the daily solar presence, which can be observed very well on the building height parameter. Increased importance of building height in nighttime is linked to air getting trapped in the canyon, therefore amplifying the weight of anthropogenic heat sources on the UHI effect in the inspected the canyon[237] . Nevertheless, building height is the most sensitive parameter despite its diminished sensitivity during day hours, due to its effect on trapping air in the canyon, scaling of the thermal control system loads and the magnitude of air infiltrated surface area. Another interesting finding of the hourly analysis is the correlation between occupancy schedule and volumetric heat capacity and sensible anthropogenic heat parameters. As these aforementioned parameters are linked closely to the human and vehicular activity near surface level, they show a spike in sensitivity indices in work hours where occupancy schedule depicted in Figure 28 makes residential areas to be less occupied due to the work hours and the resultant increased energy near surface level as a result of urban human and vehicular activity.

[237] Ryu and Baik.

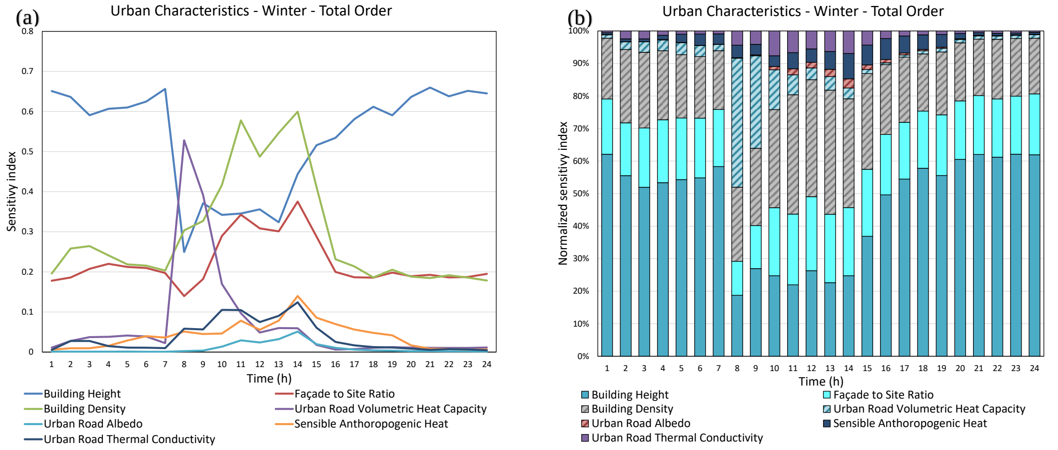

Figure 42 Urban characteristics winter season (a): hourly sensitivity analysis results (b) normalized hourly sensitivity analysis results

Sensitivity analysis results of building characteristics in summer season identifies glazing ratio as the most sensitive parameter in daylight hours in *Figure 43(a)* and *Figure 43(b)*. Although glazing ratio declines in importance during night hours, it is distinguished from the other parameters in weekly sensitivity score as the second most important parameter as illustrated in the weekly analysis in the *Figure 33*. Inspecting the parameter which leads the weekly analysis, the thermostat setpoint reveals that it fluctuates in sensitivity depending on day of the hour, as other parameters which are related to the solar gain start to contribute to the UHI effect in day hours such as glazing ratio, and when parameters which are related to the rate of enclosed space losing its thermal equilibrium due to thermal conductivity and air flow start to be a more dominant factor in deciding intensity of UHI effect at night. This effect is depicted in *Figure 43(a)*, where glazing ratio is the most sensitive parameters in day hours, meanwhile wall u-value and infiltration rate becomes the parameter pair which matches thermostat setpoint parameter’s sensitivity in night hours.

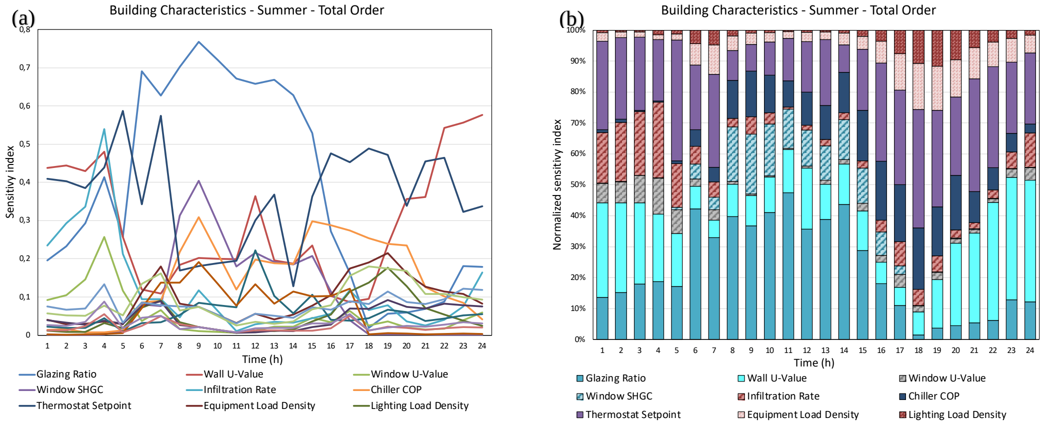

Figure 43 Building characteristics summer season (a): hourly sensitivity analysis results (b) normalized hourly sensitivity analysis results

Infiltration rate is found to be the most sensitive parameter in weekly analysis of the building characteristics group, and hourly results in *Figure 44(a)* and *Figure 44(b)* finds out that infiltration rate parameter behaves similarly to the summer season, where it loses relative importance in hours where daylight is present due the positive change in canyon energy intake and is more sensitive in nocturnal hours. Window SHGC is a parameter which is closely related to amount the solar heat gain, and it is more sensitive in day hours as it calculates the percentage of the solar radiation successfully penetrating enclosed spaces. Thermostat setpoint's relative importance stays considerably equal throughout the day, different from the summer scenario as in winter conditions, escaped air from enclosed spaces starts to release heat into the canyon in addition to the waste heat generated from thermal control systems, thus thermostat setpoint behaves differently from the summer season analysis due to the change in mechanism in which thermal control system contributes to the UHI effect.

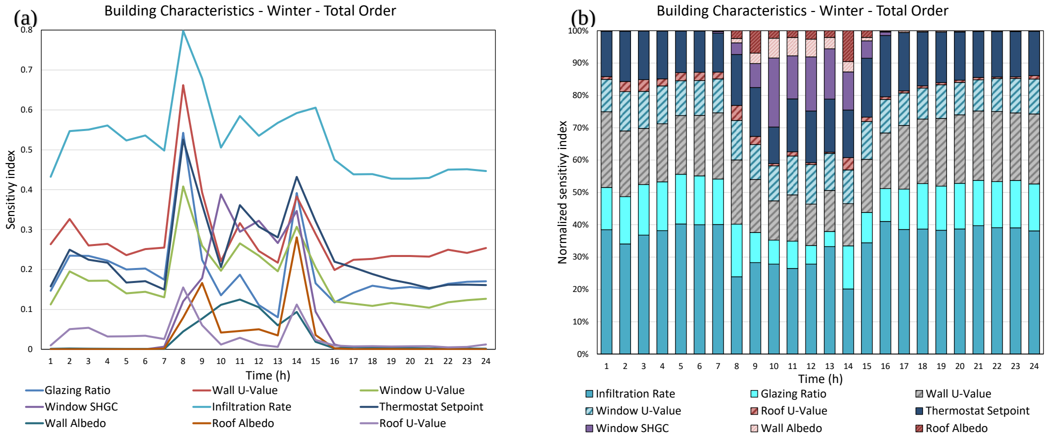

Figure 44 Building characteristics winter season (a): hourly sensitivity analysis results (b) normalized hourly sensitivity analysis results

5.5 Conclusions

Sensitivity analysis results illustrates that inspected parameter importance differs due to the method, sensitivity index and timeframe differences in each of the case study scenarios. Inspection of second order and total order sensitivity indices show that parameters which have minimal or negative importance in total order analysis can have increased importance due to their interaction with other associated parameters. Total order inspection of sensitivity analysis yields greater insight into assessment of parameter importance, nevertheless second order inspection has immense importance due to having ability to observe nature of importance between parameters. Despite the differences, certain parameters show additional weight in every sensitivity index analysis structure. Morphological parameters have a significant impact on every setup and season, most importantly the building height and building density parameters with façade to site ratio following these two parameters. These parameters have the same ranking in every season and setup, however, in winter scenarios building height has greater importance when compared to summer scenarios. This condition can be explained by in winter conditions, heat loss becomes an issue and as buildings get taller, more heat is transferred to the canyon from the enclosed spaces, therefore increasing canyon temperature. In summer conditions, this process works differently, with indoor temperatures kept below outdoor temperature, canyon gets cooled by indoor air temperature that is transferred to the outside. In addition, building height blocks urban wind paths, and causes air to be trapped in the canyon, further amplifying UHI effect in nighttime [238]. Façade to site ratio and building height has substantial impact on calculation of temperature control system loads, thus presence of the solar radiation and its resultant influence in temperature system control is found to be altering importance rankings of those aforementioned parameters in certain hours. In winter conditions, as solar gain through urban built area is present at morning to evening hours, and parameters which are related to solar gain are found to be increasing in importance, such as volumetric heat capacity of the urban roads which becomes one of the main solar heat absorption and storage factors and they begin to compete for building height parameter for being the most important factor at those hours, which plays a pivotal role in determining temperature system control load calculation in both diurnal and nocturnal conditions. Summer conditions tell a similar story, in nighttime conditions as building density and façade to site ratio importance scales down with the absence of solar heat gains in the canyon. However, in summer conditions where the solar gain is relatively abundant when compared to the winter, urban road thermal conductivity, thermal conductance of urban roads and building density becomes much more important than they are in winter conditions. This is due to the nocturnal release of the heat

[238] Ryu and Baik.

stored in urban surface area which becomes a much more vital issue in summer conditions.

In both summer and winter conditions increased surface area by morphological factors, such as building density, façade to site ratio and building height increase the urban surface area and the load on HVAC and heating systems, releasing heat to the canyon due to energy consumption which is required to operate these systems   Parameters associated with heat release by anthropogenic heat sources which is caused by the thermal control systems show a dominant position in every chart such as glazing ratio, which exponentially increases the load on thermal control systems, thermostat setpoint which determines the target temperature that is aimed by the thermal control systems and the infiltration rate, a parameter in charge of regulating how fast indoor air volume is changed with the unconditioned canyon air. In winter scenarios, infiltration rate has the utmost importance, which can be explained by the load imposed on thermal control systems and the canyon temperature increasing with the air lost from the enclosed spaces. Also, thermostat setpoint has a big importance as the parameter deciding the final load on heating systems. Wall u-value is the second most important parameter in winter scenarios, which can be explained by well insulated urban fabric needs lesser heating for maintaining the same indoor temperature, therefore better u-values slow inside out thermal movement therefore reduces the UHI intensity. Same is true for window u-values, which is another important factor in the winter. Inspection of window SHGC parameter in winter conditions show that although it has substantial importance in diurnal hours in winter conditions, weekly timeframe examination of the same parameter assesses it to be one the of the least important parameters, which shows that longer timeframe inspection of some parameters is not optimal, especially ones which are closely bound to daytime conditions. In summer scenarios, thermostat setpoint is found to be the most important parameter, followed by the glazing ratio and wall u-value. Glazing ratio accumulates importance in daylight hours, as it regulates the solar gain and inspection of source code of the UWG model reveals that glazing ratio is utilized in calculation of how much waste heat is transferred into the canyon, therefore it has immense importance in night hours in addition to its importance towards the solar gain calculations. Summer analysis reveals that parameters which are connected to the waste heat released into the canyon originated by the conversion of energy into building systems have much more importance when compared to the winter condition, as UWG directs waste heat inside built environment towards heating of the space therefore reducing the load in temperature control systems in winter as opposed to the summer conditions where waste heat is directly released into the canyon. Wall u-value is yet again important in summer analysis, as better insulation ensures lesser heat loss and energy consumption in the built area. Chiller COP is another important parameter, as efficiency of the thermal control system is directly related to the amount of dissipated heat into the canyon. Surface optical qualities such as albedo and emissivity show increased importance in summer conditions, as solar gain and its subsequent release into the canyon is a viable source of urban heating in summer conditions, nevertheless, surface optical parameters do not show a dominant position as expected from the literature, which can be explained by the findings of Alchapar et. al where a comparison of UHI effect calculations of UWG and ENVI-MET tools was conducted to conclude that UWG was not sensitive enough to urban UHI mitigation strategies, particularly the surface optical qualities and the vegetation [239]. Other studies using UWG model for sensitivity analysis also found similar results, such as research from Mao et. al [240] using UWG for sensitivity analysis also did not detect any parameter related to albedo to be a sensitive parameter in the results section, another study from Salvati et. al did not detect any significant impact on UHI intensity caused by the albedo of surfaces [241] and explained the findings by in the perspective of limited variability in urban albedo values, they found out that urban albedo should be 1.0 to be able to

[239] Alchapar and others.
[240] Mao and others.
[241] Salvati, Palme, and Inostroza.

reduce UHI effect significantly, however they concluded that these values are not realistically achievable, as urban albedo values are normally below 0.5 [242]. Litardo et. al calculating UHI intensity for Duran, Ecuador found out that albedo properties had 0.1°C average reduction in studied 28 zones, meanwhile reduction of built up surface amounted to an average 1°C reduction in UHI intensity where they detected UHI intensity in range 0.52°C to 1.59°C [243]. In addition, they also noted the low variability of albedo values in urban scenarios as the most probable reason for the findings of low sensitivity towards albedo.

Sensitivity analysis results show that urban morphology and anthropogenic heat sources such as temperature control systems are the main factors contributing to the UHI effect as the driving factors behind all dominant sensitivity indices. Examination of second order sensitivity indices reveal that certain parameters have more correlation, therefore although some parameters have limited direct impact on the sensible UHI effect, they are still included in other calculations which indirectly cause UHI effect to intensify . In the summer week, building density and building height show substantial amount of higher order interaction, as both of them are morphological factors and many calculations they are involved in encompass each other. Combination of parameters that show the second biggest higher order interaction is urban road thermal conductivity and volumetric heat capacity combination which are parameters related to the same urban element contributing to the UHI effect. Inspecting building systems in summer for second order sensitivity indices, results represent wall-u value and thermostat setpoint have the leading score in higher order interaction, as expected from two dominant factors which are closely intertwined as how much energy will be spent in order to maintain an air temperature below compared to canyon temperature depends on the target temperature and how fast the enclosed space is returning to the heat

[242] Salvati, Palme, and Inostroza.
[243] Litardo and others.

equilibrium. As expected, infiltration rate and thermostat setpoint have a considerable amount of second order interaction, which can be explained with the former interaction. Looking into the winter season, building density and urban road thermal conductivity are the leading pair of higher order interaction, thus it can be inferred that they follow the correlation that is visible in hourly sensitivity indices, as they both gain importance with the presence of solar radiation and the subsequent transfer of solar heat into the canyon. Interaction of building parameters in winter week is dominated by the infiltration rate, which is also the most sensitive parameter in both weekly and hourly analysis. Particularly, interaction of infiltration rate, window u-value and thermostat setpoint have the most substantial higher order interaction, which can be explained by the important role these parameters play in keeping indoor temperature near desired levels.

Sobol's method and its output of sensitivity indices in different orders illustrate that although information can be extracted from a single timeframe and analysis method, it does not grant access to the complex interactions and nonlinear effects of a phenomenon such as the UHI effect. Analyzing the UHI effect in respect to seasonal conditions and sensitivity index calculation methods sheds new light into the understanding of the UHI effect, as some parameters which can be found to be insignificant can be important in certain hours or in interaction with other parameters. Morphological parameters have the most impact on the UHI effect, particularly the building height parameter due to its daytime and nighttime impact on the UHI effect by its governing role on urban geometry and its role on the energy load calculations. Anthropogenic heat sources, by which waste heat from the thermal systems closely follow the urban morphology in regards to its impact on the UHI effect. Building energy consumption amplifies the UHI effect due to the released exhaust heat and buildings which consume less energy because of better insulation and better energy efficiency release lesser amount of heat to the canyon. Solar gain and the emission of heat back into the canyon in night hours is most pronounced on the summer season, where thermal inertia and increased amount of thermal mass becomes one of the most important factors increasing the

UHI intensity. In addition, solar gain also increases anthropogenic heat release by increasing the load on HVAC systems in the summer conditions.

As this study was conducted using UWG which reduces the input into a singular representation of the urban area, this study is mostly concerned with the analysis of the UHI causes, rather than providing design instructions. However, as results show, generous usage of façade glazing and dense urban areas negatively impact both the thermal comfort and the livability of the urban environment. In order to provide and create livable conditions, material choice and spacing of the urban elements must be carefully designed. Usage of HVAC elements must be reduced by implementing green design standards, and colors of the urban elements should be as reflective as possible to avoid intensification of UHI effect.

Building height must be carefully designed, as it affects both summer and winter UHI intensities and disrupts wind paths with marginally reduce thermal comfort. Canyon depth must be kept as shallow as possible, in order to avoid solar radiation trapping. Building infiltration is another key aspect, where if executed poorly, it both increases the heating load and heats up the urban canyon.

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APPENDICES

A. Simulation Results

Results can be seen at https://drive.google.com/drive/folders/15g6u0kP2ycYS-GxWDf6IZzEF0ajUQkYh?usp=sharing