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# Urban Comfort and Connectivity in Hot-Climate Cities: Evaluating Public Space Usability with the UCCI Framework in Riyadh

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## Abstract

Public spaces in hot-climate cities face compounded challenges where extreme thermal exposure, fragmented pedestrian networks, and limited microclimatic adaptation reduce outdoor usability. This thesis develops the Urban Comfort–Connectivity Index (UCCI), an integrated framework that evaluates public-space performance by combining thermal comfort (Universal Thermal Climate Index, UTCI), spatial connectivity (Flipped Betweenness Centrality, FBC), and user perception (Composite Perception Index, CPI). The framework is applied across five major sites in Riyadh to examine how climate, form, and experience interact to shape public-space use.

The environmental modelling was conducted using a geometry-based simulation workflow to estimate UTCI across four representative months. Spatial connectivity was assessed using a network-based FBC metric adjusted for thermal penalties, while user perceptions were collected through on-site surveys. These datasets were normalised, weighted, and integrated to generate UCCI values reflecting combined comfort–connectivity conditions.

Results indicate that thermal stress is the strongest constraint on usability, with UTCI frequently exceeding 40°C in exposed spaces. Regression analysis shows that connectivity ($\beta = 0.66$) and perception ($\beta = 0.44$) also contribute significantly to perceived usability. Sensitivity testing confirms that the UCCI remains robust under alternative weighting schemes. Among the five sites, the Diplomatic Quarter demonstrates the highest overall performance, while KAFD and Roshn Front show overlapping deficits due to exposure, weak shading, and limited micro-connectivity.

The UCCI offers a structured analytical tool to support climate-responsive urban design; however, its application in planning practice should be considered a recommendation, pending further validation in operational contexts. The study contributes new evidence on thermal behaviour, equity, and urban form in Gulf cities and provides pathways for integrating comfort-aware strategies into ongoing development and policy frameworks.

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**Terminology and Abbreviations**

| **Term / Abbreviation** | Definition |
|---|---|
| **UTCI** | Universal Thermal Climate Index – A metric used to assess outdoor thermal comfort based on air temperature, humidity, wind speed, and solar radiation. It categorises the level of heat or cold stress experienced by pedestrians. |
| **BC** | Betweenness Centrality – A Space Syntax metric that measures how often a street segment lies on the shortest paths between all pairs of nodes in a network. It identifies critical connectors but often prioritises long, direct routes, making it less suitable for pedestrian analysis in hot climates. |
| **FBC** | Flipped Betweenness Centrality – A modified version of traditional BC that prioritises shorter, shaded, and thermally comfortable pedestrian routes, better reflecting movement preferences in hot-climate urban settings. |

| **Term / Abbreviation** | Definition |
|---|---|
| **UCCI** | Urban Comfort–Connectivity Index – A composite index developed in this thesis, integrating thermal comfort (UTCI), spatial connectivity (FBC), and user perception data (CPI) to evaluate the overall usability and comfort of public spaces. |
| **CPI** | Composite Perception Index – An index derived from user survey data assessing perceived thermal comfort, accessibility, safety, and spatial satisfaction across study sites. |
| **POI** | Point of Interest – Specific urban features or destinations such as benches, shaded areas, retail outlets, trees, or seating areas that influence pedestrian behaviour, activity clustering, and thermal experience. |
| **IDW** | Inverse Distance Weighting – A spatial interpolation method used in GIS to generate continuous surfaces from point data. It assumes that points closer in space are more similar than those farther apart, producing smooth gradient maps. |
| **UPC** | Urban Public Comfort – A term used in this thesis to describe the combined physical, thermal, and perceptual quality of outdoor spaces as experienced by the public. It reflects both objective conditions and subjective satisfaction. |
| **GIS** | Geographic Information Systems – Technology used for spatial analysis, mapping, and visualising environmental and urban data. |
| **EPW** | EnergyPlus Weather File – A standard file format containing historical and simulation-ready weather data used in UTCI and other environmental modelling tools. |
| **Space Syntax** | A spatial analysis methodology that quantifies how spatial configurations influence pedestrian movement and accessibility using metrics like BC and FBC. |

| **Term / Abbreviation** | Definition |
|---|---|
| **Land Use** | The classification of urban spaces based on their function (e.g. residential, commercial, green space), which can influence thermal conditions and walkability. |
| **Perceived Usability** | The subjective assessment by users of how comfortable, accessible, and safe a public space feels, influenced by both environmental and spatial factors. |
| **Urban Heat Island (UHI)** | A phenomenon where urban areas experience higher temperatures than surrounding rural areas due to human activities, materials, and land use patterns. |
| **Shading Ratio** | A measure indicating the proportion of shaded areas (from buildings, trees, or structures) relative to total open space used to assess thermal relief potential. |
| **Thermal Adaptation** | The behavioural or physiological adjustments individuals make to cope with thermal stress in outdoor environments (e.g. seeking shade, altering routes). |
| **Behavioural Mapping** | A qualitative method for recording and analysing how people use and move through public spaces often used to understand spatial preferences and comfort. |
| **Pedestrian Congestion** | The density or clustering of pedestrian movement, often analysed in relation to spatial configuration and comfort conditions. |
| **Comfort Threshold** | A defined range of UTCI values (e.g., < 32°C) considered acceptable for outdoor thermal comfort in a specific climatic context. |
| **Kernel Density Estimation (KDE)** | A spatial analysis technique used to visualise clustering patterns of POIs, behaviours, or amenities across a map. |
| **KAFD** | King Abdullah Financial District – A master-planned financial and business hub in Riyadh, used as one of the thesis case study sites. |

| Term / Abbreviation | Definition |
| --- | --- |
| **DQ** | Diplomatic Quarter – A residential and institutional district in Riyadh characterised by high walkability, greenery, and urban design features. |
| **Equity** | Fair and just access to public space, comfort, and amenities for all population groups, regardless of socioeconomic status, gender, age, or physical ability. In this thesis, equity relates to how thermal comfort, walkability, and spatial accessibility are distributed across different urban areas and user groups. |

# Chapter 1

## 1.1 Background and Context

Public spaces fundamentally shape urban social, environmental, and cultural life, serving as essential venues for community interaction, active mobility, and social inclusion (Carmona, 2010; Gehl, 2010). Globally, urban planning agendas increasingly emphasize walkable, inclusive, and liveable public spaces as integral components of sustainable urban development (UN-Habitat, 2020; Dempsey et al., 2012). However, usability of public spaces in hot-climate cities, particularly in arid regions like the Arabian Gulf, is severely constrained by extreme thermal conditions, especially during prolonged summer periods (Nikolopoulou & Lykoudis, 2006; Middel et al., 2021).

Cities like Riyadh, the capital of Saudi Arabia, exemplify rapid urban expansion and infrastructural transformation characteristic of the Arabian Gulf region. With its metropolitan area exceeding seven million residents, Riyadh's sprawling urban form significantly impacts land use, transportation networks, and environmental sustainability (Al-Hathloul, 2017; Al-Ghamdi & Moore, 2018). Despite substantial investment aimed at creating comfortable, resilient public spaces through initiatives such as Riyadh Metro Project, King Abdullah Financial District (KAFD), and Green Riyadh, practical usability remains critically limited due to inadequate climate-responsive design. Often, urban design prioritizes accessibility and aesthetics without adequately addressing microclimatic performance under extreme heat (Emmanuel & Johansson, 2006).

Recognizing this critical oversight, this research develops the Urban Comfort–Connectivity Index (UCCI), an integrative analytical framework specifically designed to assess public space usability by explicitly integrating thermal comfort, spatial connectivity, and user experience. This study aligns closely with Saudi Arabia's Vision 2030 strategic goals, offering practical insights and tools to planners and policymakers committed to creating vibrant, inclusive, and climate-responsive urban environments.

### 1.2 Study Rationale and Research Gap

Urban public spaces play an essential role in fostering social interaction, cultural exchange, and well-being. However, outdoor public life in hot-arid cities such as Riyadh is frequently constrained by extreme temperatures, prolonged sun exposure, and insufficient climate-responsive design. Although thermal comfort has increasingly informed urban climatology studies and spatial analyses, the practical integration of these factors into urban design remains limited, creating a disconnect between public-realm investments and actual usability (Anguelovski & Connolly, 2021; Gehl, 2011).

Existing thermal indices, such as the Universal Thermal Climate Index (UTCI), effectively model heat stress, yet their operational use in urban design practice remains underexplored particularly in Gulf cities, where high solar exposure, limited shading, and rapid urbanisation amplify thermal stress. Likewise, Space Syntax provides valuable insight into spatial connectivity but seldom incorporates environmental variables that modify pedestrian decisions in hot climates. This lack of integration between thermal performance and spatial configuration represents a critical analytical gap, preventing accurate assessment of how microclimate and geometry interact to influence usability.

Moreover, most existing frameworks rely heavily on global datasets and temperate-climate calibrations, overlooking local acclimatisation and behavioural adaptation in hot-arid contexts. Studies in Riyadh, Doha, and Dubai (Al-Bishi et al., 2021; Aljawabra & Nikolopoulou, 2018) reveal that residents routinely tolerate higher UTCI values up to 38–40 °C than the global comfort range, highlighting the need to justify whether UTCI thresholds are applied globally or locally adapted. This regional evidence underscores the necessity for a Gulf-calibrated usability framework grounded in empirical observation rather than universal assumptions.

To address these deficiencies, this thesis develops the Urban Comfort–Connectivity Index (UCCI), a multi-layered analytical framework that combines thermal simulations (UTCI), climate-sensitive spatial analysis (Flipped Betweenness Centrality, FBC), and structured user-perception surveys (Composite Perception Index, CPI). The framework integrates these components through normalisation, weighting, and overlay operations, enabling a composite evaluation of public-space usability under thermal stress. These weights are subsequently tested through sensitivity analyses, ensuring methodological robustness and identifying which UCCI elements are context-specific, and which are transferable to other hot-climate cities.

By integrating thermal, spatial, and perceptual dimensions, the UCCI offers an analytically explicit and empirically grounded method for enhancing inclusivity, resilience, and adaptability in public spaces across the Arabian Peninsula.

### 1.3 Research Aim and Objectives

This research aims to develop and apply the Urban Comfort–Connectivity Index (UCCI), an integrated analytical framework designed to evaluate and enhance the usability of public spaces in hot-climate cities, with a particular focus on Riyadh, Saudi Arabia. The framework links environmental, spatial, and perceptual dimensions to identify how urban form and microclimate interact to influence comfort and usability.

**Research Objectives:**

1. Model seasonal and diurnal thermal comfort conditions across selected public spaces using the Universal Thermal Climate Index (UTCI), establishing a baseline of climatic performance and identifying periods of critical thermal stress.
2. Evaluate spatial connectivity and walkability through Flipped Betweenness Centrality (FBC), adapting classical Space Syntax analysis to incorporate thermal penalties reflecting the deterrent effects of heat on movement.
3. Collect and analyse user perception data on thermal comfort, spatial usability, and adaptive behaviour, creating a Composite Perception Index (CPI) that captures subjective experience and behavioural response.
4. Integrate UTCI, FBC, and CPI through a systematic process of normalisation, weighting, and spatial overlay, producing the composite Urban Comfort–Connectivity Index (UCCI) to visualise and quantify public-space usability.

5. Test alternative weighting schemes and perform sensitivity analysis to assess the relative influence of environmental, spatial, and perceptual factors, clarifying which UCCI components are context-specific to Riyadh, and which are transferable to other hot-climate cities.
6. Identify spatial inequalities and usability gaps by mapping variations in thermal exposure, connectivity, and perception across distinct urban morphologies, providing a diagnostic basis for prioritising interventions.
7. Formulate practical, evidence-based design recommendations for urban planners and designers to improve comfort, inclusivity, and liveability in public spaces within the context of Saudi Vision 2030 and the Quality-of-Life Programme.

### 1.4 Research Questions

**Central Question:** What factors determine public-space usability in hot-climate cities, and how can this usability be comprehensively assessed through the integration of thermal comfort, spatial connectivity, and user perception?

**Sub-Questions:**

• How do seasonal and diurnal variations in thermal stress influence public-space usability as measured by UTCI?

• How does spatial connectivity, adjusted for thermal penalties (FBC), affect pedestrian comfort and movement patterns in hot climates?

• How do users perceive thermal comfort, accessibility, and usability across diverse public spaces (CPI), and what behavioural adaptations emerge?

• How can thermal, spatial, and perceptual datasets be integrated through a normalised and weighted composite index (UCCI) to evaluate overall usability?

• To what extent are the relationships identified in UCCI transferable beyond Riyadh, and how sensitive are they to alternative weighting approaches??

## 1.5 Scope and Limitations

**Scope:** This research evaluates public-space usability in Riyadh through an integrated analytical approach (UCCI), focusing on thermal comfort (UTCI), spatial connectivity (FBC), and user perception (CPI). It examines five distinct public spaces representing varied urban typologies: Downtown Riyadh, King Abdullah Financial District (KAFD), Diplomatic Quarter (DQ), Museum District, and Roshn Front.

**Limitations:**

- User-perception surveys were conducted primarily during cooler months, which may underrepresent peak summer experiences; however, seasonal modelling helped mitigate this bias.
- Equal weighting of UCCI components may not perfectly represent user priorities; therefore, sensitivity analyses were performed to assess robustness.
- Thermal-comfort simulations rely on parametric assumptions and reference meteorological datasets, introducing inherent modelling uncertainty.
- The geographical focus on Riyadh may limit direct generalisation; nonetheless, the analytical framework is transferable, provided local climatic calibration.

These limitations were addressed through methodological triangulation, seasonal validation, and comparative analysis across multiple public-space typologies.

## 1.6 Methodological Overview

Adopting a mixed-methods design, this research combines quantitative simulations (UTCI and FBC) with qualitative observations and perception surveys (CPI) to comprehensively evaluate public-space usability. Thermal comfort was modelled using parametric environmental simulation tools (for heat balance and radiation exchange), spatial connectivity was assessed through network-based analysis adapted for thermal sensitivity (FBC), and structured surveys captured user perceptions and adaptive responses (CPI).

These datasets were normalised, weighted, and spatially integrated within the composite UCCI framework, enabling a multi-dimensional evaluation of how environmental and spatial parameters collectively influence urban usability in hot climates.

### 1.7 Structure of the Thesis

This thesis comprises seven chapters:

- **Chapter 2:** Literature Review – Contextualizes public space usability, thermal comfort, and spatial analysis.
- **Chapter 3:** Theoretical Framework – Provides interdisciplinary conceptual foundations.
- **Chapter 4:** Methodology – Details mixed-methods approach and UCCI development.
- **Chapter 5:** Results – Presents empirical findings across selected sites.
- **Chapter 6:** Discussion – Interprets results within broader theoretical and practical contexts.
- **Chapter 7:** Conclusions and Recommendations – Summarizes key findings, contributions, and provides practical design guidelines.

## Chapter 2: Literature Review

### 2.1 Introduction

This chapter provides a critical review of the key bodies of knowledge that inform the conceptual and methodological foundation of this research. It examines how public-space usability has been studied across three intersecting dimensions environmental performance, spatial configuration, and human perception and identifies how these strands remain insufficiently integrated within the context of hot-climate cities. The purpose of the review is to position the Urban Comfort–Connectivity Index (UCCI) within existing scholarship and to justify its contribution as a comprehensive analytical framework.

The discussion is organised around five thematic areas:
(1) public space and urban usability;
(2) thermal comfort in outdoor environments;
(3) spatial configuration and movement behaviour;
(4) perception and behavioural adaptation; and
(5) the urban context of Riyadh.
Together, these themes highlight the conceptual evolution from traditional design-based evaluations toward evidence-based, climate-responsive approaches that link human comfort and spatial performance.

Although global research on public-space quality is extensive, relatively few studies have addressed the specific challenges of hot-arid Gulf cities, where extreme heat, rapid urbanisation, and socio-cultural factors converge. Cities such as Riyadh, Doha, and Dubai demonstrate how imported urban-design models often prioritise visual form and accessibility over environmental resilience. Consequently, outdoor environments are frequently under-utilised during large portions of the year. Understanding the relationship between thermal comfort, spatial structure, and user behaviour therefore requires an integrative lens that connects physical form, climatic context, and lived experience.

This chapter argues that bridging these disciplinary silos is essential to developing adaptive, human-centred planning tools for hot-climate urbanism. By synthesising insights from environmental science, spatial analysis, and social behaviour, the literature review establishes the theoretical basis for the UCCI framework, which is introduced and operationalised in the following chapters.

### 2.2 Public Space and Urban Usability

#### 2.2.1 Evolving Concepts of Usability

The concept of public-space usability has evolved significantly in urban design theory and practice over the past four decades. Earlier approaches regarded usability as a matter of physical provision and accessibility, where the quantity and distribution of open spaces were used as indicators of quality. However, contemporary scholarship positions usability as a multidimensional construct, reflecting the interplay between spatial configuration, environmental performance, and social experience (Carmona 2010; Gehl 2010; Mehta 2014). Rather than focusing solely on form, usability is now understood as a dynamic state that depends on how people perceive, inhabit, and adapt within space under varying environmental and social conditions.

William H. Whyte's seminal observations (1980) established that successful public spaces are defined less by their design form and more by how they accommodate everyday patterns of behaviour sitting, lingering, conversing, or observing. Later research by Mehta (2014) extended this idea, describing usability as a continuous negotiation between users and the built environment, where microclimate, comfort, and sensory experience are integral to sustaining activity. Similarly, Carmona (2010) framed usability as part of the broader concept of "place value," linking it to the tangible and intangible qualities that encourage people to remain, interact, and return.

In recent years, the notion of usability has become closely tied to climate-responsive urbanism, recognising that comfort and accessibility are inseparable in determining spatial performance. Gehl (2010) Scholars have long argued that physical design alone cannot guarantee vitality unless climatic and sensory dimensions support prolonged occupancy (Gehl, 2011; Carmona, 2019). The usability of public spaces, therefore, extends beyond aesthetics or function; it encompasses the capacity of the environment to sustain human activity under diverse temporal and climatic conditions (Nikolopoulou & Lykoudis, 2006; Aljawabra & Nikolopoulou, 2018). In hot-climate cities, where outdoor thermal stress strongly limits movement and gathering, usability becomes as much an environmental as a spatial and social question (Johansson et al., 2018; Middel et al., 2021).

Accordingly, assessing usability requires integrating objective spatial indicators with subjective human responses. This shift toward evidence-based evaluation underpins emerging interdisciplinary methods that merge spatial analysis, environmental simulation, and behavioural observation (Emmanuel & Johansson, 2006; Almhafdy et al., 2020; Taleb & Sharples, 2019). These approaches recognise that the success of public spaces depends not only on connectivity and design intention but also on their capacity to provide thermally and socially inclusive environments (Mehta, 2014; Hamzah & Mohamed, 2021). This conceptual evolution provides the theoretical foundation for the analytical framework developed in this thesis, where usability is examined through the integrated lenses of comfort, connectivity, and perception.

**Theoretical Perspectives on Space and Usability**

The conceptualisation of usability also resonates with broader theoretical perspectives on the social production of space. Henri Lefebvre's (1991) notion of the *production of space* frames urban environments as socially constructed phenomena, continuously shaped by the interaction between spatial form, lived experience, and symbolic meaning. Similarly, Amin and Thrift (2002) emphasise the sensory and experiential dimensions of the urban realm, describing cities as dynamic assemblages where physical form, human perception, and environmental stimuli interact to shape everyday life. Within this view, usability transcends physical design, emerging as an outcome of spatial practice and sensory negotiation. These theoretical perspectives reinforce the epistemological foundation of this study, situating the Urban Comfort–Connectivity Index (UCCI) within a socio-spatial framework that views comfort and connectivity as co-produced rather than separate phenomena.

### 2.2.2 The Design–Use Gap

While contemporary urban design increasingly values pedestrian experience and place quality, there remains a persistent mismatch between the intended design performance of public spaces and their actual patterns of use. This discrepancy commonly referred to as the *design–use gap* has been widely documented across climates and cultural contexts (Carr et al. 1992; Madanipour 1996; Németh & Schmidt 2007). Well-designed plazas, boulevards, and waterfronts that meet all spatial or visual design standards frequently remain underutilised, indicating that formal qualities alone do not guarantee usability.

In temperate cities, this gap has often been attributed to social, managerial, or cultural issues, but in hot-arid environments, the causes are more directly environmental. Microclimatic discomfort particularly solar exposure, glare, and radiant heat often override spatial accessibility and aesthetic appeal (Nikolopoulou & Lykoudis 2006; Aljawabra & Nikolopoulou 2018). Studies show that users actively avoid even highly integrated or visually prominent routes when they lack shading or air movement. In these conditions, spatial logic is reconfigured by thermal experience: connectivity is not determined by geometry alone but by the *perceived cost* of movement through heat.

This design–use gap is particularly evident in rapidly modernising Gulf cities. Large public plazas and open malls designed according to Western urban-design paradigms often fail to attract regular pedestrian use, especially during daytime hours. Research in Doha (Aljawabra & Nikolopoulou 2018) and Riyadh (Al-Bishi et al. 2021) reveals that user occupancy drops dramatically once UTCI values exceed 38 °C. These findings suggest that aesthetic ambition and investment intensity do not necessarily translate into spatial performance if thermal realities are overlooked.

Bridging the design–use gap therefore requires a methodological shift from form-driven evaluation toward climate-sensitive usability assessment. Understanding how heat stress interacts with spatial configuration and behavioural patterns can reveal why some spaces thrive while others remain empty. This insight underpins the rationale for developing the Urban Comfort–Connectivity Index (UCCI), which integrates environmental simulation and spatial analysis to quantify how comfort and connectivity together influence the lived experience of urban public space.

#### 2.2.3 Usability as a Climate-Sensitive Concept

As the influence of climate on outdoor activity has become increasingly apparent, the concept of usability has evolved from a purely spatial notion into a climate-responsive construct. In this view, the capacity of a public space to support human activity is inseparable from its microclimatic performance. Studies by Emmanuel and Johansson (2006) and Middel et al. (2021) demonstrate that outdoor thermal comfort is a primary determinant of pedestrian presence, frequency, and dwell time. When thermal stress exceeds comfort thresholds, physical design qualities such as aesthetics, visibility, or integration lose their capacity to attract use.

In hot-arid environments, climatic factors exert a decisive influence on spatial usability. Daytime air temperatures in Gulf cities often exceed 45 °C, producing UTCI values in the "very strong heat stress" range for much of the year. Under such conditions, even well-designed plazas and promenades become temporarily uninhabitable. The usability of public space therefore fluctuates diurnally and seasonally in direct relation to the thermal environment. Research in Riyadh and Doha has shown that shaded areas and vegetated corridors sustain activity up to three times longer than unshaded ones (Al-Bishi et al. 2021; Aljawabra & Nikolopoulou 2018), illustrating how local design interventions can significantly mitigate climatic exclusion.

This reconceptualization positions usability as both a design performance indicator and an equity measure. When extreme heat prevents certain groups children, elderly people, outdoor workers, or women constrained by cultural norms from using open spaces, environmental comfort becomes a matter of social justice (Wolch et al. 2014; Soja 2010). Ensuring equitable access to comfortable spaces thus demands that planners and designers evaluate usability not only through geometric accessibility but also through climatic resilience.

Accordingly, a climate-sensitive definition of usability requires interdisciplinary integration: combining environmental simulation, spatial network analysis, and human-perception research. This integrated perspective moves beyond the traditional separation between physical form and environmental conditions, proposing instead that comfort and connectivity are co-determinants of public-space success. The analytical framework developed in this thesis the Urban Comfort–Connectivity Index (UCCI) is grounded in this paradigm shift, operationalising usability as the intersection of thermal comfort, spatial configuration, and perceived experience in hot-climate cities.

### 2.2.4 Regional Insights from the Gulf

Urban research in the Arabian Gulf has grown rapidly over the past two decades, reflecting increasing recognition of the environmental constraints shaping public-space usability. Cities such as Riyadh, Doha, Dubai, and Kuwait City provide critical case studies of how imported planning paradigms encounter local climatic and cultural realities. Despite large-scale investment in urban regeneration, pedestrian activity in these cities remains highly seasonal and spatially concentrated, revealing a persistent gap between design ambition and everyday use.

Aljawabra and Nikolopoulou (2018) demonstrated in Doha that thermal comfort and wind availability are the strongest predictors of outdoor occupancy, often outweighing aesthetic or spatial qualities. Similarly, Taleb and Sharples (2019) found that in Dubai, narrow shaded streets achieved three times the pedestrian density of adjacent open boulevards during summer. In Riyadh, Al-Bishi et al. (2021) quantified this relationship, reporting that footfall decreases by more than 70 per cent once UTCI values exceed 38 °C, a threshold frequently reached from May to September. Collectively, these studies confirm that the usability of public space in Gulf cities is governed by microclimatic performance as much as by spatial connectivity or visual form.

However, Gulf research remains fragmented. Many projects analyse single variables such as shading ratio or surface material without integrating them into broader spatial or behavioural frameworks. Few studies explicitly link thermal indices (UTCI or PET) with Space Syntax metrics, leaving the interaction between environmental comfort and network configuration largely unexplored. Moreover, while some experiments document user perception, they rarely address demographic or socio-cultural variation, which strongly influences outdoor behaviour in gender-segregated and car-dominated contexts.

The emerging body of Gulf literature therefore underscores both opportunity and urgency: these cities possess sufficient empirical data to support quantitative analysis yet lack an integrative model that translates climatic and spatial insights into actionable design guidance. This thesis responds directly to that gap by developing the Urban Comfort–

Connectivity Index (UCCI), applying it to Riyadh as a representative Gulf metropolis. The UCCI framework extends the regional discourse from descriptive observation toward a replicable, evidence-based approach capable of guiding climate-sensitive urban design across the Arabian Peninsula.

#### 2.2.5 Spatial Equity and Inclusive Access

The notion of spatial equity extends the idea of usability beyond physical design to encompass the fair distribution of comfort, accessibility, and environmental quality across the urban fabric. It draws on justice-based perspectives that view public space as a shared right rather than a discretionary amenity (Soja 2010; Wolch et al. 2014). In hot-climate cities, equitable access is closely linked to microclimatic performance: when thermal stress renders outdoor areas intolerable for parts of the population, exclusion becomes not only physical but also social and economic.

Studies in the United States and the Middle East (Harlan et al. 2006; Mitchell & Chakraborty 2015) reveal that heat exposure often correlates with income, vegetation cover, and neighbourhood morphology. Similar disparities are evident in Riyadh, where low-income districts and peripheral developments typically have sparse shading and minimal tree canopies compared with higher-income enclaves. These inequalities compound gendered and cultural constraints on mobility, limiting who can comfortably occupy outdoor environments and when.

Addressing such inequities requires planning approaches that visualise and quantify thermal and spatial disparities across the city. Quantitative mapping of UTCI values, connectivity metrics, and perceptual data can reveal where comfort deficits align with social vulnerability. Integrating these dimensions moves beyond descriptive equity debates toward *diagnostic evidence* that can guide interventions whether by planting strategies, shaded-route design, or prioritised infrastructure investment.

The Urban Comfort–Connectivity Index (UCCI) developed in this thesis contributes directly to this agenda. By combining environmental (UTCI), spatial (FBC), and perceptual (CPI) layers into a unified index, it provides planners with a measurable representation of spatial equity under extreme-heat conditions. This facilitates more informed policy decisions aligned with the humanisation and liveability objectives of Saudi Vision 2030, ensuring that comfort and connectivity are distributed as collective urban rights rather than privileges of specific districts or social groups.

## 2.3 Thermal Comfort in Urban Environments

Thermal comfort represents one of the most significant environmental determinants of outdoor usability and urban liveability. It expresses the degree to which an individual feels thermally satisfied within a specific environment, reflecting the combined influence of meteorological conditions, urban morphology, and human adaptation. The pioneering work of Oke (1987) and Eliasson (2000) established the principles of urban microclimatology, demonstrating how surface materials, canyon geometry, and building density modulate radiation balance, air temperature, and wind flow. These insights laid the foundation for contemporary computational approaches that evaluate comfort using bioclimatic indices.

Among the indices developed for outdoor applications, the Universal Thermal Climate Index (UTCI) has gained broad acceptance due to its strong physiological basis and cross-climatic comparability (Jendritzky et al. 2012). UTCI integrates air temperature, humidity, wind speed, and mean radiant temperature into a single numerical output expressed in degrees Celsius, allowing direct interpretation as “perceived” thermal stress. The index categorises thermal experience on a continuous scale, ranging from “extreme cold stress” to “extreme heat stress,” providing a standardised reference for research, simulation, and design evaluation in diverse climatic contexts.

### 2.3.1 Local Calibration and Acclimatisation

Although the Universal Thermal Climate Index (UTCI) provides a globally standardised measure of outdoor comfort, its original calibration based on European mid-latitude data does not fully capture the realities of hot-arid environments. Populations in these regions exhibit both physiological acclimatisation and behavioural adaptation, enabling them to tolerate substantially higher thermal loads than those predicted by the standard UTCI comfort classes. Consequently, applying the global UTCI thresholds to the Arabian Peninsula can underestimate local comfort capacity and exaggerate perceived heat stress.

Empirical research across the Gulf supports this divergence. Al-Zamil et al. (2020) established that the neutral UTCI value in Riyadh the temperature range associated with thermal neutrality occurs approximately 3–5 °C higher than in central Europe. Johansson et al. (2021) reached similar conclusions in Kuwait City and Muscat, noting that residents continued moderate outdoor activity even under UTCI values classified as “strong heat stress.” Such findings illustrate that perceived comfort thresholds are culturally and climatically contextual, reflecting adaptation through clothing, hydration, timing of activities, and reliance on shade.

This evidence underscores the importance of local calibration when applying UTCI in Gulf cities. Adaptive comfort models that integrate both physiological acclimatisation and behavioural factors provide a more realistic representation of human experience in these climates (Nikolopoulou & Steemers 2003; Lin et al. 2018). Accordingly, this thesis interprets UTCI values within a contextual comfort framework, maintaining the global scale for comparability while recognising that “comfortable” conditions in Riyadh may correspond to UTCI values up to the mid-30 °C range. Such contextualisation ensures that subsequent analyses of usability reflect not only physical exposure but also the adaptive capacities of local populations living under extreme heat. Nevertheless, debates persist regarding the most appropriate calibration method for the Arabian Peninsula. Some researchers advocate for locally recalibrated UTCI scales, while others support adaptive comfort models that incorporate behavioural factors and cultural expectations (Klemm et al., 2023; Al-Zamil et al., 2023).

### 2.3.2 Quantifying Thermal–Usability Relationships

Quantifying how thermal conditions influence public-space usability has become a key research priority in environmental urbanism. While early studies on outdoor comfort focused primarily on physical measurements of temperature and humidity, contemporary approaches integrate empirical behavioural data to reveal how people respond to environmental stress in real-world settings. This quantitative linkage between thermal variables and spatial behaviour is essential for translating climate analysis into actionable design knowledge.

Empirical studies in Gulf cities provide valuable benchmarks for this relationship. Al-Bishi et al. (2021) documented a 70 per cent reduction in pedestrian counts in Riyadh once UTCI values exceeded 38 °C, identifying a behavioural threshold that effectively defines the limits of outdoor usability during summer. In Doha, Aljawabra and Nikolopoulou (2018) observed that outdoor occupancy was concentrated within shaded or semi-enclosed microzones when UTCI rose above 36 °C. Similarly, Taleb and Sharples (2019) found that shaded, vegetated streets in Dubai maintained up to three times the pedestrian density of adjacent exposed boulevards, confirming that design interventions such as tree canopies, arcades, and water features have measurable behavioural effects.

Beyond empirical observation, several modelling studies have sought to quantify the mitigating potential of microclimatic design strategies. Middel et al. (2021) demonstrated that increasing tree canopy cover by 20 per cent can reduce mean radiant temperature by approximately 10 °C, translating to a UTCI reduction of 4–6 °C depending on wind conditions. Such findings underscore the capacity of urban design to extend the duration and frequency of outdoor activity even in extreme-heat contexts. However, these analyses often evaluate comfort and usability in isolation from spatial connectivity, providing limited insight into how microclimate and urban morphology jointly shape pedestrian movement.

To overcome this limitation, an integrated framework is required one that quantifies not only *how hot* an environment feels but also *where* and *why* people choose or avoid certain routes. Establishing these quantitative links forms the empirical foundation for the Urban Comfort–Connectivity Index (UCCI) developed in this thesis. By coupling thermal data derived from UTCI simulations with spatial accessibility metrics from Space Syntax analysis, the UCCI translates environmental performance into measurable spatial usability, offering a replicable method for evaluating the liveability of public spaces in hot-climate cities such as Riyadh. Recent assessments indicate that, under present climatic conditions, usable outdoor hours in Gulf cities fall to less than 30 per cent of annual daytime periods, underscoring the magnitude of thermal exclusion in public-space usability (Al-Bishi et al., 2021; Khan & Johansson 2024). Recent assessments indicate that, under present climatic conditions, usable outdoor hours in Gulf cities fall to less than 30 per cent of annual daytime periods, underscoring the magnitude of thermal exclusion in public-space usability (Al-Bishi et al., 2021; Khan & Johansson 2024).

### 2.3.3 Integrating Thermal Comfort and Spatial Analysis

Although thermal comfort research and spatial analysis have developed in parallel, their integration remains relatively recent and crucial for understanding how climate modifies movement patterns and spatial usability. Conventional thermal studies assess microclimate and material performance, while spatial analyses such as Space Syntax focus on configuration and accessibility. Yet, in hot-climate cities, these two dimensions are inseparable: spatial accessibility determines exposure, and microclimate conditions determine whether that accessibility can be used.

Early attempts to connect the two domains began with temperature-weighted path models and heat-exposure mapping (Johansson et al., 2016; Middel et al., 2019). These studies introduced the idea of assigning a *thermal cost* to street segments based on simulated mean radiant temperature or UTCI values, thereby allowing climatic penalties to influence spatial metrics. Kriegel and Nikolopoulou (2020) advanced this approach by coupling UTCI simulations with Space Syntax's angular integration, revealing that the most connected routes often coincided with thermally stressful corridors indicating a conflict between spatial efficiency and environmental comfort. Wang et al. (2022) further demonstrated that incorporating thermal weighting into betweenness calculations significantly improved predictions of observed pedestrian routes in subtropical settings.

Despite these advances, applications in hot-arid contexts remain limited. Most Gulf studies continue to evaluate heat mitigation strategies such as shading, vegetation, or materials without considering how these changes alter connectivity or route choice. Integrating UTCI-based penalties within network analysis offers a way to quantify this interaction and identify thermally resilient pathways, where environmental comfort and spatial accessibility reinforce rather than oppose each other.

The methodological foundation of this thesis builds upon this emerging body of work by introducing Flipped Betweenness Centrality (FBC), a modified form of betweenness that inversely weights spatial distances by UTCI-derived thermal stress. In the Urban Comfort–Connectivity Index (UCCI), FBC serves as the spatial component through which the environmental penalty from UTCI is spatially propagated, enabling comparative evaluation across multiple public-space typologies. This integration transforms traditional accessibility analysis into a climate-sensitive model of spatial usability, directly linking the geometry of the city with its thermal realities.

### 2.4 Spatial Configuration and Movement

Understanding the relationship between spatial configuration and human movement forms the foundation of Space Syntax theory, which conceptualises the city as a network of interconnected spaces whose configuration shapes patterns of accessibility, visibility, and interaction (Hillier & Hanson, 1984). Within this framework, pedestrian movement is not random but a spatially structured response to the hierarchy of connections between urban spaces. Key metrics such as Integration and Betweenness Centrality quantify how spatial structure influences potential movement flows, providing an objective basis for analysing accessibility and spatial performance.

Spatial configuration thus operates as a proxy for collective human cognition the way people perceive, choose, and traverse urban environments. Hillier (1996) argued that spatial form acts as a “social logic,” shaping not only pedestrian flows but also patterns of land use, safety, and social interaction. In temperate climates, high-integration routes often correspond with commercial activity and pedestrian vitality (Penn et al., 1998). However, in hot-arid environments, this relationship is more complex: routes that are geometrically optimal may also be thermally hostile, discouraging use during large parts of the day.

### 2.4.1 Space Syntax in Hot-Climate Contexts

Space Syntax theory provides a powerful analytical framework for understanding how urban configuration influences movement behaviour. Its core premise is that spatial form shapes accessibility, visibility, and potential co-presence, thereby structuring patterns of human activity (Hillier & Hanson, 1984; Hillier, 1996). In its classical form, Space Syntax has been highly effective in predicting pedestrian flows and land-use distribution in temperate cities. However, its direct application to hot-arid environments has exposed critical limitations, as it assumes that movement is primarily driven by geometric efficiency rather than environmental tolerance.

In Gulf cities, the predictability of Space Syntax metrics such as Integration and Betweenness often diminishes under extreme heat conditions. Routes that are geometrically central or well-connected may experience minimal use during the day because of solar exposure and radiant heat. Al-Sallal et al. (2018) demonstrated in Abu Dhabi that highly integrated boulevards exhibited lower pedestrian occupancy than shaded alleys, despite being structurally dominant within the network. Similarly, Al-Mansouri and Sharples (2020) observed in Doha that movement intensity shifted dramatically with solar orientation, revealing that pedestrians selectively use shaded segments even when they are spatially less efficient.

These findings reveal a crucial behavioural adaptation: in hot-arid cities, thermal comfort outweighs geometric directness as a determinant of route choice. Movement patterns become temporally and climatically dynamic, varying by time of day and season. This adaptation challenges the core assumptions of traditional Space Syntax analysis, which treats distance and connectivity as the primary movement drivers. As Johansson et al. (2016) note, neglecting microclimatic variation in spatial models leads to overestimation of activity in exposed areas and underestimation in shaded macrozones.

To address this discrepancy, researchers have begun to develop climate-adapted variants of Space Syntax. Kriegel and Nikolopoulou (2020) integrated thermal exposure weighting into angular integration measures, demonstrating how heat stress modifies spatial accessibility. Wang et al. (2022) introduced temperature-weighted path models, showing that the inclusion of climatic penalties significantly improves movement prediction accuracy. These hybrid approaches recognise that the usability of a space is co-determined by configuration and climate, and that accessibility in hot regions must be redefined as a thermally contingent phenomenon rather than a purely geometric one.

Building on this evolving discourse, the current research extends Space Syntax into the domain of climate-sensitive urban analytics. By incorporating UTCI-derived penalties into network models through Flipped Betweenness Centrality (FBC), it explicitly links thermal stress with spatial accessibility. This integration makes it possible to identify thermally resilient pathways those that balance geometric connectivity with environmental comfort thereby advancing both the methodological and practical frontiers of urban analysis in hot-climate contexts. More recently, Zhang et al. (2023) extended this hybrid approach by coupling Space Syntax with ENVI-met simulations to optimise shaded connectivity networks, reinforcing the growing convergence between thermal and configurational modelling.

reflecting how people navigate

**2.4.2 Flipped Betweenness Centrality and Behavioural Logic**

Traditional Betweenness Centrality measures the degree to which a spatial segment lies on the shortest paths connecting all other pairs of segments in a network (Hillier & Iida 2005). Segments with high betweenness are expected to attract more pedestrian flows because they form part of the most efficient routes in geometric terms. While this logic holds in temperate climates, it does not adequately represent pedestrian decision-making in hot-arid cities, where individuals often prioritise thermal comfort over geometric directness.

Field observations in Doha, Abu Dhabi, and Riyadh indicate that pedestrians routinely modify their routes to minimise solar exposure, even when this requires detours or additional distance (Al-Mansouri & Sharples 2020; Al-Bishi et al. 2021). Meir et al. (2016) describe this as thermal-avoidance behaviour, a strategy of consciously seeking shade, colonnades, or vegetation to reduce heat stress. Consequently, the most traversed paths under extreme heat are not always those that are geometrically shortest but those that balance acceptable distance with environmental protection.

To capture this adaptive behaviour, the present study employs Flipped Betweenness Centrality (FBC) a modification of the conventional betweenness measure that integrates thermal penalties derived from UTCI simulations. In this formulation, each network segment receives a cost factor proportional to its level of thermal stress. Segments with higher UTCI values (i.e., hotter and less comfortable) are assigned greater traversal cost, reducing their contribution to total network centrality. Conversely, shaded or cooler segments, which require lower thermal effort, gain higher relative importance. The “flipping” refers to the reversal of preference: comfort replaces directness as the dominant optimisation criterion.

Mathematically, FBC can be expressed as:

$$FBC_i = \sum_{a \neq b} \frac{\sigma_{ab}(i)}{\sigma_{ab}} \cdot \frac{1}{p_i}$$

where $\sigma_{ab}$represents the number of all possible shortest paths between nodes $a$and $b$; $\sigma_{ab}(i)$is the subset of those paths passing through segment $i$; and $p_i$denotes the thermal penalty derived from the mean UTCI of that segment. This inversion means that cooler, shaded routes effectively become “shorter” in the thermal-cost network, while exposed segments become “longer” and less attractive.

The behavioural validity of this approach is supported by recent hybrid studies. Kriegel and Nikolopoulou (2020) showed that integrating UTCI into angular analysis aligns predicted and observed pedestrian paths more closely than geometry-only models. Wang et al. (2022) confirmed that assigning temperature-weighted costs to paths improved model accuracy by up to 40 per cent in subtropical contexts. In Gulf environments, where movement patterns are acutely shaped by climatic extremes, such integration offers a realistic representation of pedestrian decision-making.

Within the Urban Comfort–Connectivity Index (UCCI), FBC functions as the spatial component linking network configuration with thermal experience. By embedding environmental penalties directly into spatial computation, the model transcends traditional distinctions between *where people could move* and *where they actually choose to move* under heat stress. This behavioural grounding ensures that the UCCI captures the true usability of public space not merely its geometric accessibility but its climate-adaptive connectivity, reflecting how people navigate, seek comfort, and occupy the city in extreme conditions. Empirical path-tracking in Muscat by Rahman et al. (2022) further validated this behavioural logic, showing that 82 per cent of pedestrians deliberately chose shaded detours over shorter exposed routes, confirming that thermal comfort outweighs geometric directness in real movement decisions. envisioned under Vision 2030

The introduction of Flipped Betweenness Centrality (FBC) thus reframes spatial efficiency through the lens of environmental realism. It acknowledges that in hot-climate cities, spatial usability is contingent upon both morphological logic and human adaptation. This reframing shift spatial analysis from static geometry to thermally mediated accessibility, establishing the conceptual foundation for integrating environmental and behavioural data. Within the UCCI, this modified centrality measure becomes the critical mechanism through which spatial configuration translates environmental stress into measurable impacts on human movement and public-space vitality.

### 2.5 Perception and Behavioural Adaptation

Understanding public-space usability in hot-climate cities requires recognising that thermal experience is fundamentally behavioural and perceptual, not merely physical.

Individuals evaluate outdoor environments through sensory, cognitive, and cultural lenses that shape when, where, and how they choose to occupy space (Nikolopoulou & Steemers 2003; Lin et al. 2021). In arid environments such as Riyadh, these evaluations are intensified by strong solar exposure, seasonal extremes, and limited shade provision conditions that make adaptive behaviour the primary determinant of outdoor activity.

### 2.5.1 Behavioural Adaptation to Thermal Stress

Behavioural adaptation refers to the range of actions, decisions, and spatial choices that individuals adopt to reduce discomfort and maintain usability in thermally challenging outdoor environments. It constitutes one of the three core adaptation pathways identified by de Dear and Brager (1998) physiological, psychological, and behavioural with the latter being most visible in urban public spaces. In hot-arid climates such as Riyadh, behavioural adaptation plays a decisive role in shaping how residents use, avoid, or modify their interaction with outdoor settings across daily and seasonal cycles.

Individuals develop adaptive habits that include temporal adjustments such as shifting outdoor activities to early morning or late evening hours and spatial strategies, such as choosing shaded, vegetated, or colonnaded paths even when these routes are longer or less direct (Johansson et al., 2018; Aljawabra & Nikolopoulou, 2018). These adaptations indicate that thermal comfort is not a fixed physiological condition, but a dynamic behavioural response shaped by personal expectation, cultural norms, and environmental opportunities.

Empirical studies across hot regions support this adaptive logic. In Abu Dhabi, Meir et al. (2016) observed that residents adjust walking patterns based on shading intensity rather than distance efficiency. Similarly, in Doha and Riyadh, users exhibit a strong preference for transitional zones semi-open courtyards, colonnades, and arcades that provide psychological relief and microclimatic moderation (Mahmoud, 2019; Almhafdy et al., 2020). Such spaces facilitate temporary occupation, social gathering, and movement pauses, reflecting the behavioural notion of “thermal avoidance”—the tendency to seek environmental refuge when conditions exceed comfort thresholds (Nikolopoulou & Steemers, 2003).

Behavioural adaptation is also reinforced through cultural and social practices. The extended evening activity pattern, known locally as *sahar*, exemplifies temporal adaptation embedded in Gulf social life, where family and leisure activities occur after sunset to avoid daytime heat. This behavioural rhythm generates distinct spatial implications: plazas and promenades designed for night use, artificial lighting strategies, and microclimatic interventions that extend outdoor usability into twilight hours.

From an analytical standpoint, behavioural adaptation introduces a critical mediating variable between thermal exposure (measured by UTCI) and spatial accessibility (modelled by FBC). It moderates how climatic and spatial conditions are experienced in practice, transforming abstract indices into lived spatial behaviour. Incorporating these adaptive tendencies within the Urban Comfort–Connectivity Index (UCCI) framework ensures that usability assessment reflects both environmental constraints and human agency.

Thus, behavioural adaptation under thermal stress is not merely a coping mechanism but a structural component of urban functionality in hot climates. Recognising it enables planners and designers to anticipate real-world patterns of space use and to design public environments that support flexible, climate-responsive behaviours through shading, orientation, vegetation, and programmatic diversity.

#### 2.5.2 Perceptual Mapping and User Satisfaction

While climatic simulations and spatial analyses provide objective measures of thermal and morphological conditions, the perceived quality of public spaces is ultimately determined by users' subjective experiences. Perception mapping is a methodological approach that spatially represents these subjective evaluations such as comfort, satisfaction, and usability—by linking survey data or participatory feedback to physical space (Nikolopoulou & Lykoudis, 2006; Nasrollahi & Taleghani, 2018). This method bridges the gap between environmental performance and human experience, allowing researchers to visualise where and why people feel comfortable or stressed in outdoor environments.

In hot-climate contexts, however, perceptual data often diverge from bioclimatic indices because thermal acceptability is highly context-dependent. Studies in Doha, Abu Dhabi, and Riyadh reveal that users routinely tolerate higher Universal Thermal Climate Index (UTCI) values than global benchmarks suggest reflecting physiological acclimatisation, cultural resilience, and expectation adjustment (Johansson et al., 2018; Aljawabra & Nikolopoulou, 2018). For instance, while the UTCI classifies 36 °C as "strong heat stress," field surveys in Riyadh demonstrate that many respondents still perceive conditions as acceptable when adequate shading and air movement are present. These discrepancies highlight the need to calibrate perception-based comfort thresholds to local adaptation patterns rather than relying on universal scales.

Nevertheless, perception mapping faces several methodological challenges. Many studies are conducted during cooler seasons or limited observation windows, which constrains their representativeness across annual thermal extremes (Thorsson et al., 2014; Lin et al., 2021). Responses can also be influenced by non-climatic factors, such as aesthetic appeal, noise levels, or social presence, which introduce subjective bias into comfort assessment (Chen & Ng, 2012). In addition, cultural expectations, gendered mobility norms, and social hierarchies can shape how individuals report comfort, satisfaction, or accessibility. For example, women may rate visually exposed areas as less comfortable not due to temperature but due to privacy or security concerns (Mahmoud, 2019).

In this research, these methodological challenges are addressed through the construction of a Composite Perception Index (CPI) a quantitative measure derived from structured surveys conducted across multiple public spaces in Riyadh. The CPI aggregates responses related to thermal comfort, aesthetic satisfaction, perceived accessibility, and social usability. Each response is spatially interpolated using an Inverse Distance Weighting (IDW) approach to generate continuous comfort surfaces. These surfaces are then normalised to a 0–1 scale and integrated with UTCI and FBC maps to form the Urban Comfort–Connectivity Index (UCCI).

The inclusion of CPI in the UCCI framework transforms perception data from isolated survey points into spatially explicit behavioural evidence. By capturing how comfort is perceived under varying microclimatic and morphological conditions, CPI enables comparison between objective simulation results and subjective experience. This alignment allows for validation of thermal–spatial models and provides insight into areas where design interventions could improve perceived usability, even without major structural change.

Therefore, perceptual mapping within this research is not merely descriptive but diagnostic. It identifies mismatches between environmental potential and human experience, offering planners actionable evidence to prioritise design improvements that enhance user satisfaction, inclusivity, and overall quality of life in Riyadh's public spaces.

Recent advances in smart-city analytics further expand the potential of perception mapping by integrating citizen feedback with digital data streams. Mobile-based comfort surveys, GPS traces, and social-media geotags allow real-time mapping of pedestrian comfort and movement patterns (Resch et al., 2021; Hong et al., 2022). These data-driven approaches enable dynamic calibration of indices such as UTCI and CPI, aligning physical simulations with lived, temporal experience. Incorporating such participatory sensing techniques could enhance future iterations of the UCCI framework, providing planners with near-real-time insights into how users perceive and adapt to fluctuating thermal conditions. This evolution from static to adaptive comfort modelling reflects the transition of Gulf cities toward data-informed, human-centred urbanism envisioned under Vision 2030. Nevertheless, perception-mapping methods remain limited by short observation periods and small seasonal samples. Future research should adopt longitudinal or real-time sensing approaches to capture temporal variation and reduce perceptual bias.

Recent Gulf-region studies further emphasise the need for local calibration of both thermal indices and perception-based analyses. For instance, Al-Zamil et al. (2023) demonstrated that residents in Riyadh and Dammam consistently tolerate higher UTCI thresholds than global comfort benchmarks, underscoring the importance of cultural and physiological acclimatisation in thermal assessment. Similarly, Klemm et al. (2023) and Khan & Johansson (2024) highlight the methodological limitations of perception mapping when applied in heterogeneous urban contexts—particularly the difficulty of isolating thermal comfort from confounding visual, social, and acoustic stimuli. These findings support the need for locally adapted UTCI classifications and more nuanced perception models that account for behavioural adaptation and expectation adjustment in hot-arid cities.

### 2.5.3 Cultural Mediation and Social Adaptation

Thermal experience in public spaces is not only a physiological or sensory matter but also a culturally mediated phenomenon shaped by shared social norms, religious practices, and gendered spatial codes (Al-Hathloul & Mughal, 2004; Mehta, 2014). In Gulf societies, patterns of modesty, privacy, and family cohesion influence how and when individuals inhabit outdoor environments. Research in Riyadh and Doha reveals that cultural expectations often determine the degree of exposure people consider acceptable, especially for women and older adults, leading to preferences for semi-enclosed or shaded environments that preserve comfort and social propriety (Mahmoud, 2019; Almhafdy et al., 2020).

Seasonal and ritual practices also generate temporal rhythms that affect space use. For instance, during Ramadan or evening “sahar” gatherings, public activity peaks after sunset when air temperatures fall and social interaction aligns with climatic relief (Aljawabra & Nikolopoulou, 2018). These collective routines reinforce adaptive design logics plazas illuminated for night-time use, shaded walkways leading to mosques, and cooling fountains that double as cultural symbols. Such examples demonstrate that cultural adaptation and thermal adaptation co-evolve, producing hybrid spatial patterns that combine environmental necessity with social meaning.

Recognising cultural mediation is thus essential to understanding behavioural variability across demographic groups. What may appear as climatic avoidance is often a culturally coded behaviour a negotiation between comfort, visibility, and identity. Integrating this perspective into the Urban Comfort–Connectivity Index (UCCI) underscores that usability is not a universal condition but a contextually embedded outcome shaped by intertwined climatic and socio-cultural dynamics.

### 2.5.4 Technological and Design Adaptation

Alongside behavioural and cultural adjustments, technological and design innovations constitute an increasingly important layer of adaptation in hot-climate cities. Contemporary urban projects in Riyadh, Abu Dhabi, and Dubai have begun employing passive and hybrid cooling strategies high-albedo pavements, water features, interactive shading canopies, and photovoltaic pergolas to moderate microclimates and extend outdoor usability (Taleb & Sharples, 2019; Johansson et al., 2020). Smart-city initiatives further enhance this capacity through sensor-based monitoring of temperature, humidity, and footfall, enabling responsive lighting or misting systems that activate during peak heat hours (Resch et al., 2021; Hong et al., 2022).

These technological interventions translate climatic data into design intelligence, bridging environmental analytics with user experience. From a methodological standpoint, they complement behavioural observations by providing quantitative evidence of environmental modification and its perceptual impact. Within the UCCI framework, such innovations can be interpreted as design-level adaptations that alter the underlying environmental variables of UTCI (by reducing radiant load) or modify FBC (by creating shaded, connected routes). Incorporating these parameters allows planners to evaluate not only existing usability but also the adaptive potential of proposed design solutions.

However, technology alone does not ensure comfort if it disregards human perception or socio-cultural context. Over-mechanised cooling infrastructure may offer short-term relief but undermine sustainability or equity if limited to privileged zones (Anguelovski & Connolly, 2021). Thus, technological adaptation must operate within a human-centred paradigm, reinforcing rather than replacing behavioural flexibility and cultural continuity. By embedding technological and design variables into the UCCI, this research advances a multi-scalar understanding of adaptation from individual agency to systemic urban response.

### 2.5.5 Theoretical Link: Urban Resilience and Adaptive Systems

The conceptual integration underpinning the Urban Comfort–Connectivity Index (UCCI) aligns closely with broader theories of urban resilience and adaptive-systems thinking. Resilient urbanism emphasises the city's capacity to absorb, adapt to, and recover from environmental stresses while maintaining essential functionality and social vitality (Meerow et al., 2016). Likewise, adaptive-systems theory conceptualises urban environments as dynamic, self-organising networks in which spatial, climatic, and social components interact continuously through feedback loops (Batty, 2018).

Within this paradigm, the UCCI operates as a diagnostic and feedback mechanism that captures how urban form mediates between environmental stressors and human adaptation. By integrating thermal (UTCI), spatial (FBC), and perceptual (CPI) dimensions through processes of normalisation, weighting, and spatial overlay, the index quantifies the degree to which public spaces sustain usability under heat extremes. The inclusion of sensitivity analyses further reflects adaptive-systems logic by testing how changes in variable weights influence overall resilience outcomes, thereby identifying which components are context-specific and which are transferable across different urban settings.

Through this lens, resilience is operationalised not as a static end state but as an evolving relationship among comfort, connectivity, and perception a measure of how effectively environmental and social systems co-adapt to maintain liveability. This theoretical connection situates the UCCI within the wider discourse on climate adaptation, urban liveability, and human-centred resilience, reinforcing its value as a transferable planning and diagnostic tool for hot-climate cities seeking to align spatial design with adaptive capacity.

### 2.6 Integrated Research Gaps and Objectives Alignment

The preceding review demonstrates that while considerable progress has been made in understanding urban thermal comfort, spatial configuration, and public-space perception, there remain substantial conceptual, methodological, and empirical deficiencies in their integration particularly within hot-arid contexts such as Riyadh. Addressing these gaps requires an analytical framework that unites climatic simulation, spatial morphology, and user experience into a single, reproducible model capable of guiding climate-sensitive urban design.

#### Gap 1 – Fragmented Integration Between Thermal and Spatial Analysis

Most existing research on outdoor comfort treats thermal performance and spatial configuration as separate domains. Microclimatic models such as UTCI or ENVI-met provide high-resolution thermal data but often disregard how connectivity, shading distribution, or movement networks influence comfort outcomes (Ali-Toudert & Mayer, 2007; Johansson et al., 2018). Conversely, space syntax studies prioritise accessibility and morphological efficiency but typically omit climatic penalties. This fragmentation limits our ability to explain how environmental exposure affects spatial usability.

Objective 1 directly responds to this gap by integrating Universal Thermal Climate Index (UTCI) outputs with Flipped Betweenness Centrality (FBC) to quantify spatial accessibility under thermal constraints.

**Gap 2 – Limited Empirical Understanding of Behavioural and Perceptual Adaptation**

Although behavioural adaptation is recognised as central to outdoor comfort, few quantitative models operationalise it within spatial or environmental analysis. Perception mapping studies remain isolated and methodologically inconsistent often small-scale, seasonally biased, and lacking statistical integration with environmental variables (Thorsson et al., 2014; Aljawabra & Nikolopoulou, 2018). The absence of standardised perception indicators hinders cross-case comparison and limits design applicability. Objective 2 addresses this limitation by constructing a Composite Perception Index (CPI) that spatially translates survey-based comfort and usability responses into a quantifiable layer. By correlating CPI with UTCI and FBC, the study examines how subjective satisfaction aligns with objective environmental and spatial measures.

**Gap 3 – Lack of Regional Calibration and Contextual Relevance**

A significant proportion of thermal-comfort and urban usability studies are derived from temperate or Western contexts, with minimal calibration for the socio-cultural, behavioural, and climatic conditions of Gulf cities. Consequently, global thresholds for UTCI or PMV often underestimate local adaptation, and imported design guidelines fail to reflect cultural or temporal usage patterns (Mahmoud, 2019; Almhafdy et al., 2020). Objective 3 fills this gap by developing and validating the Urban Comfort–Connectivity Index (UCCI) through case studies in Riyadh, incorporating regional climate data, behavioural surveys, and spatial typologies representative of Gulf urbanism. The framework thus produces a locally grounded yet transferable tool for hot-climate cities.

**Gap 4 – Weak Link Between Analytical Models and Planning Practice**

Finally, while climate-responsive urban design has gained policy attention under Saudi Vision 2030, the translation of analytical models into planning frameworks remains underdeveloped. Existing studies often stop at technical assessment without exploring how findings can inform regulatory, spatial, or investment decisions.
Objective 4 addresses this shortfall by demonstrating how the UCCI can function as a diagnostic and policy-support tool, enabling planners to visualise comfort–connectivity trade-offs and prioritise interventions that enhance spatial equity, accessibility, and human well-being.

Each gap–objective pair ensures continuity between the literature review and the methodological design presented in Chapter 4, providing a clear analytical bridge from theoretical synthesis to empirical implementation.

**Synthesis and Research Contribution**

By addressing these four interrelated gaps, the study establishes a unified methodological approach that integrates environmental simulation, spatial network analysis, and user perception within a single evaluative framework. The Urban Comfort–Connectivity Index (UCCI) thus represents both a conceptual innovation bridging environmental and social dimensions of urban design and a practical contribution that aligns with Vision 2030 objectives for city humanisation and sustainability.

This integration provides a transferable framework for assessing public-space usability in other hot-climate cities, enabling comparative evaluation, scenario testing, and evidence-based planning decisions grounded in the lived experience of thermal adaptation.

Chapter 2 has consolidated the theoretical, empirical, and methodological foundations for examining public-space usability in hot-climate cities. It demonstrated that comfort, connectivity, and perception are interdependent determinants of spatial performance and highlighted the need for integrated evaluation through the Urban Comfort–Connectivity Index (UCCI). The review also established quantitative evidence of thermal exclusion, outlined regional calibration challenges, and identified four research gaps aligned with this study's objectives.

Collectively, these insights position UCCI as a bridge between environmental simulation, spatial network analysis, and user perception, advancing an evidence-based framework for human-centred, climate-adaptive urban design.

The next chapter translates this synthesis into a formal theoretical structure for the UCCI, defining its conceptual propositions, variable relationships, and weighting logic that guide the methodological implementation presented in Chapter 4.

## Chapter 3: Theoretical Framework

### 3.1 Introduction

In the evolving discourse on urban planning and public space design, it has become increasingly clear that no single discipline can adequately address the multifaceted challenges presented by extreme climate conditions (Emmanuel and Johansson, 2006; Santamouris and Osmond, 2020). This chapter lays the conceptual groundwork for this research by bringing together theoretical insights from multiple domains urban studies, thermal comfort science, spatial network theory, and behavioural psychology. It argues for the necessity of an interdisciplinary approach in evaluating the usability of public spaces in hot-climate environments, where conventional design principles often fall short (Aljawabra and Nikolopoulou, 2018; Middel et al., 2021).

The chapter begins by revisiting foundational urban theories that underscore the social and spatial functions of public space. It then explores the physiological and perceptual dimensions of thermal comfort, followed by a discussion of spatial configuration theory, particularly through the lens of Space Syntax. The chapter also examines environmental perception and behavioural adaptation theories, which offer crucial insights into how people experience and respond to urban environments (Nikolopoulou and Steemers, 2003; Gehl, 2010).

Classic urban theories of space, such as Lefebvre's (1991) *production of space* and Hillier and Hanson's (1984) *social logic of space*, are here operationalised within the extreme climatic conditions of Riyadh. Rather than treating spatial form as a static artefact, this study interprets it as a dynamic mediator between environmental stress and social adaptation. Gehl's (2011) human-scale design principles are likewise extended to include thermal thresholds as determinants of social vitality, recognising that spatial interaction in hot-arid cities is conditioned as much by environmental tolerance as by morphology. By embedding these classic ideas in the quantitative framework of the Urban Comfort–Connectivity Index (UCCI), the research translates abstract urban theory into measurable variables that capture how comfort, connectivity, and perception co-produce usability in extreme climates.

The UCCI is proposed as a comprehensive evaluative tool that captures the interaction between climate, space, and behaviour a triad that is especially relevant in cities like Riyadh, where extreme heat significantly shapes urban life (Al-Hathloul and Mughal, 2004). Traditional models tend to isolate these variables, resulting in partial or inadequate understandings of public space performance. By contrast, this chapter advocates for a holistic model that reflects the lived realities of urban dwellers, accounting for both objective environmental conditions and subjective human responses (de Dear and Brager, 1998; Nikolopoulou and Lykoudis, 2006).

Ultimately, this chapter not only provides the theoretical rationale for the development of the UCCI but also positions this research within a broader scholarly conversation about the future of climate-responsive, human-centred urban design. The goal is to move beyond fragmented analyses toward an integrative understanding of what makes public spaces truly usable, sustainable, and inclusive in the face of environmental extremes (UN-Habitat, 2020; Gehl and Svarre, 2013).

### 3.2 Urban Theories and Public Space Usability

Urban theory has long acknowledged the fundamental role of public spaces in shaping the social, cultural, and spatial dynamics of cities. These spaces are not merely functional voids within the built environment but serve as vital arenas for social interaction, civic engagement, cultural expression, and everyday life. Theories of urban form, social vitality, and public-realm design provide a foundational lens through which we can understand what makes a public space successful, inclusive, and adaptable especially under the stress of extreme climates (Carmona, 2010; UN-Habitat, 2020).

One of the most influential contributors to urban thought, Jane Jacobs, challenged the prevailing modernist planning ideologies of her time by emphasising the importance of mixed uses, fine-grained urban fabric, and vibrant street life. In *The Death and Life of Great American Cities*, Jacobs (1961) argued that active, safe, and lively streets depend on “eyes on the street,” a metaphor for natural surveillance created by a diversity of people engaging in daily routines. Her critique of monofunctional zoning and large-scale infrastructure projects remains central to contemporary debates on urban liveability and resilience. The relevance of Jacobs’s principles in hot-climate cities lies in their emphasis on density, diversity, and street activity—elements that, while often desirable, must be adapted to climate constraints such as extreme heat and solar exposure (Jacobs, 1961; Aljawabra and Nikolopoulou, 2018). Within the UCCI, Jacobs’s call for fine-grained interaction is reinterpreted as spatial connectivity weighted by thermal comfort, captured quantitatively through Flipped Betweenness Centrality (FBC). This translation recognises that social vitality depends not only on geometric proximity but also on the thermal feasibility of movement between active edges and nodes.

Kevin Lynch introduced another key theoretical contribution through his concept of urban legibility. In *The Image of the City*, Lynch (1960) proposed that the ease with which people navigate and understand the urban environment through elements such as paths, edges, nodes, districts, and landmarks greatly influences accessibility and usability. In thermally challenging environments, legibility must be reconceived to include not just spatial clarity but also microclimatic intelligibility. A shaded path or vegetated node may offer legibility and comfort simultaneously, helping users not only find their way but also feel encouraged to stay and interact (Lynch, 1960; Santamouris and Osmond, 2020). This notion is embedded in the UCCI through the thermal-weighted mapping of spatial nodes, where UTCI simulations identify comfort "landmarks" that guide pedestrian decision-making.

Further extending this tradition of human-centred design, Jan Gehl focused on how cities can better accommodate pedestrian life. In *Cities for People*, Gehl (2010) synthesised decades of empirical research to argue that successful public spaces must respond to human scale, sensory engagement, and patterns of use. He emphasised slow movement, visual stimulation, and comfortable resting points as prerequisites for meaningful urban interaction. Gehl's theory is particularly relevant in hot-climate cities where the duration and timing of public-space use are dictated not only by function but also by comfort and shelter (Gehl, 2010). For example, Gehl's emphasis on active street life assumes moderate climates; however, in hot-arid cities, thermal discomfort significantly restricts continuous street-level activities, requiring adaptive design solutions. Within the UCCI, these human-scale comfort variables correspond to the Composite Perception Index (CPI), which quantifies subjective experience and perceived usability under thermal stress.

The theoretical evolution of public-space design has also intersected with broader movements in sustainable urbanism and resilience planning. Scholars such as Beatley (2000) and Ahern (2011) have called for multifunctional, adaptive, and green public spaces that simultaneously support ecological integrity, social equity, and climate mitigation. These theories advocate for integrating public spaces into wider systems of green infrastructure, urban metabolism, and social networks. In hot-arid environments, resilience theories are particularly relevant, as they call for flexible design strategies that can accommodate shifting patterns of use driven by environmental extremes (Beatley, 2000; Ahern, 2011; Salata et al., 2017). However, while these theories offer valuable normative frameworks, their application in hot-climate cities such as Riyadh requires empirical calibration. Traditional public-space ideals such as continuous street life, high walkability, and mixed-use vibrancy presume thermal conditions conducive to year-round outdoor activity. In cities where summer temperatures routinely exceed 45 °C, these assumptions become problematic. Pedestrian presence, lingering behaviours, and spontaneous interactions are severely constrained by thermal discomfort. As a result, urban theories must be re-contextualised to account for seasonal, temporal, and physiological dimensions of use (Middel et al., 2021).

In such settings, Jacobs's call for active, mixed-use streets might translate into temporally adaptive spaces that function differently by time of day or season. Lynch's paths and nodes must also function as thermal pathways, offering wayfinding through comfort as much as through geometry. Gehl's focus on public life must incorporate climatic responsiveness, including shaded microclimates, heat-tolerant materials, and passive-cooling strategies. Theories of resilience, meanwhile, must embrace not only infrastructural flexibility but also human adaptability and thermal inclusivity (Santamouris and Osmond, 2020; Al-Sayed et al., 2014).

This research therefore draws on these urban theories not as fixed models but as evolving frameworks, reinterpreted through the lens of environmental stress and behavioural adaptation. The Urban Comfort–Connectivity Index (UCCI) operationalises these principles by embedding them into a composite metric that accounts for both spatial configuration and thermal comfort. In doing so, it bridges the gap between idealised notions of public space and the lived realities of users navigating extreme climates. In hot-arid contexts, empirical studies show that thermal neutrality occurs 3–6 °C above global UTCI comfort thresholds due to acclimatisation and behavioural adaptation (Al-Zamil et al., 2023; Johansson et al., 2021). Incorporating these locally calibrated values ensures that the UCCI reflects real thermal perception rather than imported temperate-climate standards, grounding classic urban theory within measurable environmental realities.

Ultimately, by critically adapting classic urban theories to suit the context of hot-climate cities, this study contributes to a broader movement in urban research—one that foregrounds environmental justice, thermal equity, and the right to comfort in the public realm (Gehl and Svarre, 2013; UN-Habitat, 2020).

### 3.3 Thermal Comfort Theory

Thermal comfort is a central concept in environmental and urban design, referring to the condition in which individuals feel neither too hot nor too cold and are generally satisfied with their thermal environment (ASHRAE, 2017). It plays a vital role in shaping public-space usability, particularly in climates characterised by extreme heat. Thermal comfort is determined by both objective environmental factors including air temperature, relative humidity, wind speed, and solar radiation and subjective personal variables such as clothing insulation, activity level, and individual expectations (Fanger, 1970; Nikolopoulou and Steemers, 2003).

Among the most widely used models for assessing thermal comfort are the Predicted Mean Vote (PMV), Physiologically Equivalent Temperature (PET), and the Universal Thermal

Climate Index (UTCI). The PMV model, developed by Fanger (1970), uses heat-balance equations to predict average thermal sensation among a population. While influential in HVAC engineering, its reliance on static indoor assumptions limits its applicability in complex outdoor environments (Parsons, 2003). The PET model, introduced by Höppe (1999), offers a more dynamic assessment, translating outdoor conditions into a temperature equivalent that relates to a typical indoor setting. Although PET has been adopted in landscape and urban-planning studies, it lacks physiological nuance compared to the UTCI. The UTCI, developed by Jendritzky et al. (2009), incorporates an advanced thermoregulatory model that simulates dynamic heat exchange between the human body and its environment. It accounts for radiant heat, air velocity, and relative humidity, allowing for nuanced classification of thermal-stress levels. Blazejczyk et al. (2012) further validated the UTCI across a range of climates, reinforcing its suitability for urban public-space assessment.

Crucially, thermal comfort is not a static physiological state. Adaptive thermal-comfort theory posits that comfort varies depending on acclimatisation, expectation, and behavioural adjustment. De Dear and Brager (1998) argue that individuals in naturally ventilated environments demonstrate greater tolerance to temperature fluctuations, adapting through actions such as altering clothing, changing activity level, or seeking shaded locations. This perspective is particularly relevant in outdoor urban contexts where environmental conditions are less controlled and behavioural adaptation is more common (Nikolopoulou and Lykoudis, 2006).

Understanding thermal comfort in urban public spaces therefore requires a multifactorial approach that captures environmental variables, user behaviour, and spatial context. Urban microclimates are shaped by geometry, vegetation, materials, and anthropogenic heat. The Urban Heat Island (UHI) effect intensifies thermal stress, particularly in dense, impervious areas with limited shade or airflow (Oke, 1987; Santamouris and Osmond, 2020). Conversely, shaded zones, vegetated corridors, and reflective materials can significantly enhance thermal perception and usability (Bowler et al., 2010).

Recent empirical evidence from hot-arid cities substantiates this relationship. In Riyadh, Al-Bishi et al. (2021) observed that pedestrian activity declined by over 70 per cent once UTCI exceeded 38 °C, but shaded or vegetated routes retained substantially higher occupancy. Similarly, Taleb and Sharples (2019) found that shaded streets in Dubai supported three times the pedestrian density of adjacent exposed boulevards, while Johansson et al. (2018) and Mahmoud (2019) documented that people in Doha and Abu Dhabi consciously deviated from geometrically direct routes to follow shaded paths or colonnades demonstrating that comfort outweighs distance efficiency in route choice.

These findings empirically confirm that microclimatic moderation directly determines spatial usability and should therefore be integrated within spatial-network analysis rather than treated as an external variable.

In this research, the Universal Thermal Climate Index (UTCI) is adopted as the primary thermal-comfort measure due to its robust physiological basis, dynamic modelling, and international acceptance. However, global UTCI comfort classes are adjusted to reflect local acclimatisation patterns, as studies in Riyadh and Muscat indicate thermal neutrality occurs approximately 3–6 °C above standard thresholds (Johansson et al., 2021; Al-Zamil et al., 2023). This calibration ensures that the assessment of comfort aligns with regional tolerance levels and observed behavioural adaptation.

By mapping UTCI values across multiple seasons and spatial segments, the study identifies both areas of extreme thermal stress and pockets of relative comfort. These thermal insights are then integrated with spatial and behavioural data within the UCCI framework, enabling a comprehensive understanding of how heat influences public-space usability in Riyadh. In particular, shaded-route preference, derived from both observed behaviour and UTCI-weighted accessibility (Flipped Betweenness Centrality), captures how pedestrians navigate thermally optimal pathways a behavioural logic central to the UCCI's spatial component.

By grounding this assessment in thermal-comfort theory, the research addresses not only the environmental determinants of usability but also the behavioural strategies that users employ to mitigate thermal stress. This dual perspective is essential for developing public spaces that are both physically and experientially inclusive, especially in hot-climate urban contexts (Emmanuel and Johansson, 2006; Elnabawi et al., 2016).

### 3.4 Spatial Connectivity and Urban Form Theories

Spatial connectivity and urban form significantly influence pedestrian movement, accessibility, and the usability of public space. The way urban environments are configured determines how easily people can navigate and interact within the city, shaping patterns of mobility, encounter, and place attachment. Theories and tools for analysing spatial structure, particularly Space Syntax and network analysis, offer valuable insights into the relational qualities of urban form (Hillier and Hanson, 1984; Hillier, 1996).

Space Syntax provides a theoretical and methodological framework for quantifying spatial relationships within the built environment. It introduces key measures such as integration (how accessible a space is from all others), connectivity (the number of immediate links), and choice (a proxy for betweenness centrality, estimating how often a space lies on the shortest paths between others). These measures reveal how urban design influences movement potential, encounter frequency, and spatial prominence (Hillier et al., 1993; Penn, 2003).

Of particular relevance to this study is the metric of choice, which relates closely to betweenness centrality in graph theory. It captures how frequently a given segment is traversed when people move between origins and destinations within a defined radius, identifying likely pedestrian corridors or bottlenecks. However, in hot-climate contexts, spatial efficiency is often overridden by thermal comfort preferences. Pedestrians may deviate from shortest routes to follow shaded, vegetated, or thermally buffered paths that minimise exposure to direct sunlight (Aljawabra and Nikolopoulou, 2018; Johansson et al., 2018). Empirical studies in Dubai and Abu Dhabi have shown that shaded routes experience up to four times higher pedestrian use than unshaded equivalents of equal spatial centrality (Taleb and Sharples, 2019; Elnabawi et al., 2016). In Riyadh, Al-Zamil et al. (2023) documented that pedestrian flows concentrate along streets with tree canopies and arcaded facades, even when these routes are less direct, highlighting that thermal avoidance behaviour modifies spatial logic.

This divergence exposes a limitation of traditional spatial analysis tools when used in isolation. While Space Syntax provides a robust representation of formal spatial hierarchy, it does not account for the environmental constraints and adaptive behaviours that modulate movement in extreme climates. A segment with high global integration may remain underutilised if it lacks shade or exhibits high radiant heat, while spatially peripheral routes may attract users if they offer thermal refuge (Middel et al., 2021).

To address this limitation, the study introduces a modified metric, Flipped Betweenness Centrality (FBC), that embeds climate adaptation into spatial-network logic. FBC inverts traditional betweenness scoring by penalising highly exposed segments and rewarding those with comfort-enhancing attributes such as shading, vegetation, wind alignment, or lower UTCI values. In effect, the flipped weighting recalibrates accessibility to reflect real-world behavioural preferences for cooler, shaded, and climatically tolerable routes. This modification preserves the structural foundation of Space Syntax while introducing an environmental-behavioural correction factor, making the model more applicable to cities such as Riyadh where microclimatic constraints profoundly influence urban mobility.

In operational terms, the FBC is calculated by combining normalised betweenness centrality with inverse thermal exposure (1/UTCI), producing a climate-sensitive connectivity surface. This output is further weighted by the Composite Perception Index (CPI) to align structural accessibility with user-perceived comfort. Through normalisation and overlay, the FBC contributes to the Urban Comfort–Connectivity Index (UCCI) as one of three interdependent dimensions thermal, spatial, and perceptual each assigned equal weight in the base model. Sensitivity tests are later applied to examine how varying these weights (for example, thermal dominance versus spatial dominance) affects the resulting UCCI outputs, ensuring robustness and transparency in index formulation.

Parallel to Space Syntax, urban morphology examines the physical structure of cities, including street patterns, block sizes, and land-use configurations. Research suggests that compact, permeable street networks with small blocks support higher walkability and social interaction (Marshall, 2005; Oliveira, 2016). Conversely, fragmented morphologies with cul-de-sacs and superblocks inhibit movement and reduce spatial legibility. Network indicators such as intersection density, average block length, and network centrality correlate strongly with walkability and accessibility to services (Frank et al., 2006; Porta et al., 2009). Yet in hot climates these relationships are mediated by environmental stress: a well-connected grid may remain underutilised if it lacks adequate shade or airflow.

Theories of urban permeability and walkability therefore require extension to account for climate-responsive connectivity. Permeability traditionally describes the ease of moving through an area via interconnected networks, while walkability extends this to include safety, comfort, and destination access. In hot-climate environments these qualities are contingent upon microclimatic design features such as shaded colonnades, tree canopies, and reflective materials that mitigate heat stress (Southworth, 2005; Speck, 2012). Empirical evidence from Doha and Riyadh confirms that shaded and vegetated routes maintain up to 50–70 per cent higher footfall than unshaded streets of equal connectivity, underscoring the behavioural logic underpinning thermal preference (Mahmoud, 2019; Al-Bishi et al., 2021).

Within the context of Riyadh, this study therefore integrates spatial analysis through Space Syntax with behavioural and thermal modelling to produce the UCCI. Embedding FBC within this composite index operationalises a climate-sensitive understanding of connectivity one that reflects not only network geometry but also adaptive human response to environmental stress.

This integrative approach recognises that spatial usability is not a purely geometric attribute but a product of dynamic interaction between urban form, thermal comfort, and behaviour. By quantifying this interaction, the UCCI advances the conceptual and methodological basis for climate-responsive urban design in hot-climate cities, translating theoretical principles of connectivity into empirically grounded, human-centred evaluation.

### 3.4.1: Betweenness Centrality: Traditional Approaches

Betweenness centrality is a core concept in spatial network analysis that quantifies how often a segment or node lies on the shortest path between all other nodes in a network (Freeman, 1977). In urban analysis, it has been widely applied to understand movement potential, identify key connectors, and model accessibility in both pedestrian and vehicular systems (Hillier and Iida, 2005; Turner, 2007).

In the context of Space Syntax, betweenness centrality (often operationalised as *Choice*) is used to estimate the probability that a street segment will be traversed as part of the shortest route between any pair of origins and destinations in the system. This makes it a valuable tool for predicting potential flows, locating spatial attractors, and guiding infrastructure investment.

Traditionally, betweenness centrality is calculated using a topological approach, where the shortest paths are determined by minimising angular or metric distances between nodes. The assumption is that users prefer routes that are more direct, with fewer angular deviations or shorter Euclidean lengths (Turner, 2007). These models are often validated against observed movement patterns and are widely used in urban design, transport planning, and retail analysis (Peponis et al., 2007).

However, while traditional betweenness centrality offers valuable insights into network efficiency and integration, it tends to privilege long, uninterrupted axial lines and global connectivity over local, climatically sensitive routing behaviours. In hot-climate cities, this can result in overestimating the usability of exposed or uncomfortable segments, and underestimating the importance of shaded or behaviourally preferred paths (Karimi, 2012; Mehta, 2014).

Consequently, although betweenness centrality remains a foundational spatial metric, its application in thermally extreme environments requires adaptation to account for environmental comfort and human-scale experience. The following section (3.4.2) introduces Flipped Betweenness Centrality (FBC), a modified approach developed in this study to reflect pedestrian behaviour under thermal constraints.

### 3.4.2: Flipped Betweenness Centrality (FBC): Rationale and Application

While traditional betweenness centrality provides valuable insights into spatial configuration and movement potential, it tends to prioritise long, direct routes that maximise network efficiency. In hot-climate environments, however, pedestrian movement is rarely dictated by topological efficiency alone. People often choose routes that offer thermal relief, even if they are less direct or more complex in spatial terms (Johansson and Emmanuel, 2006; Harlan et al., 2006).

To address this behavioural divergence, this study introduces Flipped Betweenness Centrality (FBC) a modified centrality metric designed to better reflect how pedestrians navigate urban space under thermal stress conditions. The core rationale behind FBC is to penalise exposed, thermally uncomfortable segments and prioritise shaded, climatically buffered routes in the estimation of movement potential.

**Rationale**

Traditional centrality measures implicitly assume a preference for minimal angular or metric deviation. However, in Riyadh and similar cities where outdoor temperatures regularly exceed 40°C, users often prioritise shaded routes, covered walkways, and vegetated edges, even if these are longer or more circuitous. Ignoring this behavioural adaptation can result in overestimating the usability of certain axial lines and underestimating the role of thermally strategic micro-routes.

FBC addresses this by reversing the centrality logic: rather than simply measuring the shortest, most integrated paths, it adjusts those paths based on environmental penalties. Segments with poor thermal conditions (e.g., high UTCI values, low shade) receive higher friction weights, effectively lowering their betweenness contribution in the network.

**Application in this Study**

FBC was implemented using the Decoding Spaces Toolkit in Grasshopper, modified to include thermal resistance scores derived from simulated UTCI values. The calculation process involved:

- Generating a simplified street centreline network for each site.
- Assigning UTCI-based thermal scores to each segment, normalised on a 0–1 scale.
- Applying inverse weighting so that exposed or hot segments incurred higher friction costs in shortest-path calculations.
- Calculating betweenness centrality based on these adjusted paths, resulting in FBC scores that favour shaded, thermally adaptive connections.

The final FBC outputs were spatially visualised and integrated into the Urban Comfort–Connectivity Index (UCCI) to assess segment-level usability across five case study sites. This approach better aligns with pedestrian behaviour in thermally extreme environments, where comfort not just spatial logic shapes movement and space use.

### 3.5 Perception and Behavioural Theories in Urban Environments

Understanding how people perceive and behave in public spaces is fundamental to evaluating spatial usability, particularly in environments characterised by climatic extremes. Perception and behavioural theories provide the psychological and experiential lens through which environmental conditions and spatial structures are interpreted by users. These frameworks highlight that public-space performance cannot be fully understood through spatial or environmental variables alone but must incorporate user interpretation, adaptation, and decision-making processes (Kaplan and Kaplan, 1989; Nasar, 1998).

Environmental perception theory focuses on how individuals interpret their surroundings through sensory inputs, cognitive mapping, and emotional responses. Kevin Lynch (1960), for example, explored how people form mental images of urban spaces based on elements such as paths, nodes, edges, and landmarks. These perceptual cues shape spatial legibility, orientation, and place attachment. In hot-climate environments, perception extends beyond visual clarity to include thermal comfort and sensory relief. A shaded corridor or vegetated node may offer not only visual interest but also physiological ease, reinforcing its perceived usability (Lynch, 1960; Nikolopoulou and Lykoudis, 2006).

The Attention Restoration Theory (ART) proposed by Kaplan and Kaplan (1989) suggests that urban environments can restore cognitive function when they include natural elements, moderate stimuli, and a sense of fascination. In hot urban contexts, restorative experiences may be particularly valuable, providing both psychological recovery and respite from thermal and social stress. Trees, water features, and soft surfaces enhance perceived comfort and support longer outdoor engagement (Ulrich et al., 1991). Affordance theory, introduced by Gibson (1979), adds a behavioural dimension by examining how environments offer or limit opportunities for action. A bench affords sitting; a wide sidewalk affords walking. In hot climates, environmental affordances extend to features such as shaded alcoves, water misters, and arcaded walkways that offer refuge from heat and enable adaptive use. Urban spaces that fail to provide such affordances are often avoided, regardless of their spatial prominence or connectivity (Gibson, 1979; Clark and Uzzell, 2002).

Behavioural adaptation theories explain how users modify their actions in response to discomfort or changing environmental conditions. In hot-climate cities, adaptive behaviours may include selecting shaded or vegetated routes, shifting activities to cooler hours, or avoiding exposed areas entirely. These strategies represent conscious negotiation between physical constraints and comfort expectations (Nikolopoulou and Steemers, 2003; Lai et al., 2019). In the Gulf context, social practices such as evening promenades, family gatherings after sunset, and gendered mobility norms further shape when and how spaces are used. For example, in Riyadh, women may prefer semi-private shaded courtyards or enclosed plazas due to combined concerns of heat exposure and privacy (Low and Smith, 2006; Al-Azzawi and Raeside, 2007). Thus, perception and behaviour are not merely individual responses but expressions of cultural and environmental adaptation.

Methodologically, these theories justify the inclusion of perception surveys, observational mapping, and participatory tools within urban research. Such tools provide empirical access to user experience, revealing patterns of satisfaction, adaptation, and dissonance between design intention and thermal reality. In this study, perception data collected across five public spaces in Riyadh are synthesised into the Composite Perception Index (CPI), one of the three core components of the Urban Comfort–Connectivity Index (UCCI). The CPI translates theoretical constructs into measurable dimensions: (1) perceived thermal comfort and heat tolerance, (2) aesthetic and environmental satisfaction, (3) perceived accessibility and safety, and (4) social usability and inclusivity. Each indicator is normalised to a 0–1 scale and spatially interpolated to generate continuous comfort and perception surfaces.

Integrating CPI with the thermal (UTCI) and spatial (FBC) components ensures that user perception is embedded in the overall evaluation of urban usability. This allows the model to distinguish between physically comfortable but socially underused spaces and thermally stressed areas that remain active due to cultural adaptation or social attraction. In doing so, the UCCI operationalises perception and behavioural theories as quantifiable components of environmental experience, providing a human-centred framework for assessing and designing public spaces in hot-climate cities.

### 3.6 Integrative Framework for UCCI Development

The preceding sections have presented a series of theoretical foundations—urban theory, thermal comfort science, spatial configuration analysis, and behavioural perception—that collectively inform a holistic approach to assessing public space usability. To operationalise this interdisciplinary understanding, this study introduces the Urban Comfort–Connectivity Index (UCCI) as an integrated analytical framework. The UCCI merges these theoretical strands into a composite metric that evaluates urban public spaces based on their climatic, spatial, and experiential performance.

Conventional methods of public-space assessment often isolate spatial configuration from climatic conditions or thermal modelling from human experience. Such disciplinary separation produces limited insights, particularly in hot-climate cities where usability is co-determined by physical exposure, adaptive movement, and perceptual comfort. Empirical studies confirm that pedestrians in these settings do not merely follow geometrically optimal routes but adapt behaviourally to heat stress, navigating shaded or vegetated paths and interpreting spaces through cognitive and social filters (Elnabawi et al., 2016; Middel et al., 2021).

Accordingly, the UCCI is structured around three interrelated dimensions that translate theory into measurable variables:

- Thermal Comfort: Represented by the *Universal Thermal Climate Index (UTCI)*, this dimension quantifies the environmental stress experienced by users across seasons and times of day. It operationalises adaptive comfort theory by identifying local thresholds of heat tolerance and thermal vulnerability (Jendritzky et al., 2009; Blazejczyk et al., 2012).
- Spatial Connectivity: Captured through *Flipped Betweenness Centrality (FBC)*, this dimension integrates principles from Space Syntax and behavioural adaptation, penalising exposed or uncomfortable routes while rewarding shaded and climatically resilient pathways. FBC therefore transforms classical geometric efficiency into climate-sensitive accessibility (Hillier and Hanson, 1984; Aljawabra and Nikolopoulou, 2018).
- User Perception: Measured through the *Composite Perception Index (CPI)*, this dimension embodies perceptual and behavioural theories by quantifying user-reported comfort, accessibility, safety, and social usability. CPI ensures that subjective experience is systematically embedded in spatial evaluation (Kaplan and Kaplan, 1989; Clark and Uzzell, 2002).

The integration of these dimensions involves multi-scalar data collection, spatial modelling, and environmental simulation across five case-study sites in Riyadh. Each spatial segment is evaluated using normalised UTCI, FBC, and CPI scores, which are combined through a weighted composite function. Weighting schemes are tested through sensitivity analyses, allowing the relative importance of climatic, spatial, or perceptual factors to be adjusted according to seasonal or policy priorities—for example, emphasising thermal comfort during summer months or spatial accessibility during cooler periods.

This integrative approach produces a series of UCCI outputs—including maps, heatmaps, and radar charts—that visualise segment-level performance across all three dimensions. These visualisations serve as diagnostic tools for planners and designers, identifying zones of high comfort-connectivity synergy as well as areas of climatic or spatial vulnerability.

By uniting climatic, spatial, and experiential perspectives, the UCCI advances both theory and practice in the evaluation of public space. It moves beyond fragmented analytical models toward a context-sensitive, human-centred, and transferable framework suitable for hot-climate cities such as Riyadh. In doing so, it aligns with broader global agendas for climate resilience, spatial equity, and urban liveability (UN-Habitat, 2020; Santamouris and Osmond, 2020).

**Table 3.1 UCCI Translation Framework**

| Theoretical Domain | Core Concept / Theory | Operational Metric in UCCI | Purpose in Analysis |
|---|---|---|---|
| **Urban Theory** | Jacobs (1961); Lynch (1960); Gehl (2010) – Human-centred, liveable streets | **Spatial Connectivity (FBC)** | Quantifies network permeability, accessibility, and pedestrian potential under climatic constraints |
| **Thermal Comfort Science** | Fanger (1970); de Dear & Brager (1998); Jendritzky et al. (2009) – Physiological and adaptive comfort | **Thermal Comfort (UTCI)** | Models outdoor heat stress and microclimatic variation across sites and seasons |
| **Behavioural & Perceptual Theory** | Gibson (1979); Kaplan & Kaplan (1989); Nikolopoulou & Steemers (2003) – Environmental perception and adaptation | **User Perception (CPI)** | Captures subjective comfort, satisfaction, and behavioural adaptation through survey data |
| **Resilience & Adaptive Systems** | Meerow et al. (2016); Batty (2018) – Dynamic city systems responding to stress | **Integrated UCCI Index** | Combines climatic, spatial, and experiential metrics to assess adaptive capacity and usability |

### 3.7 Summary

This chapter has outlined the theoretical foundations underpinning the development of the Urban Comfort-Connectivity Index (UCCI), an interdisciplinary tool for evaluating public space usability in hot-climate cities. Drawing on a wide range of conceptual perspectives including urban design theory, thermal comfort science, spatial configuration analysis, and environmental perception this framework offers a holistic and context-sensitive approach to assessing how public spaces perform under climatic stress.

Key urban thinkers such as Jacobs (1961), Lynch (1960), and Gehl (2010) have highlighted the importance of spatial diversity, legibility, and human-scale design in fostering vibrant public life. These ideas remain central but must be critically reinterpreted in environments where thermal stress imposes physical and social constraints on outdoor activity (Aljawabra and Nikolopoulou, 2018; Middel et al., 2021).

Thermal comfort theory, particularly as operationalised through the Universal Thermal Climate Index (UTCI), provides a rigorous method for quantifying heat stress and identifying environmental barriers to usability (Jendritzky et al., 2009; Blazejczyk et al., 2012). Spatial analysis methods such as Space Syntax reveal movement potential and connectivity but require adaptation to account for behavioural responses to climate. The Flipped Betweenness Centrality (FBC) metric introduced in this study integrates spatial logic with climate sensitivity (Hillier and Hanson, 1984).

Equally important are theories of perception and behaviour, including the work of Kaplan and Kaplan (1989), Gibson (1979), and others, which demonstrate how user interpretation, expectation, and adaptation influence the actual use of space. By incorporating user surveys and behavioural observations, the UCCI reflects these subjective but critical aspects of spatial experience.

The integrative framework presented in this chapter brings these theoretical strands together in a composite model that can assess public space usability with attention to environmental conditions, spatial structure, and lived experience. The UCCI does not treat usability as a static or universal condition, but as an emergent quality shaped by climate, design, and user behaviour. As such, it is uniquely suited to evaluating and guiding public realm interventions in cities like Riyadh, where extreme temperatures present ongoing challenges to liveability and inclusion.

The next chapter will translate this theoretical framework into a detailed methodological strategy, outlining how the UCCI is operationalised, validated, and applied across the study sites. In doing so, it builds a bridge between conceptual analysis and empirical research, ensuring that the proposed framework is both academically rigorous and practically relevant

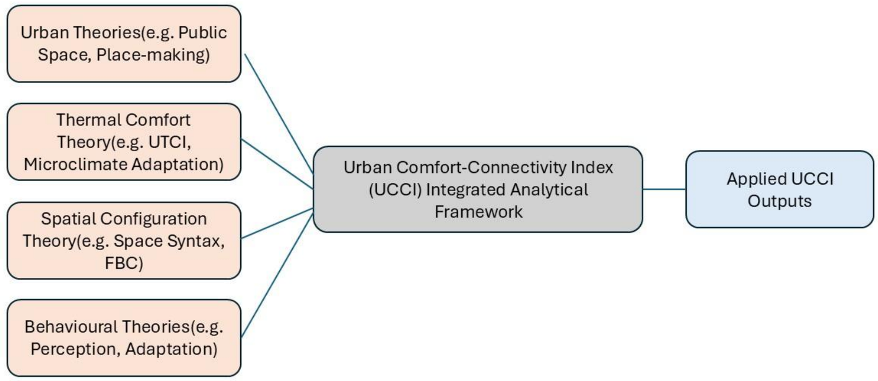


Figure 3.4: Conceptual integration of theoretical frameworks into the UCCI model

# Chapter 4: Methodology

## 4.1 Introduction to the Methodology

This chapter outlines the methodological framework developed to evaluate the usability of public spaces in hot-climate urban environments, with Riyadh, Saudi Arabia, serving as the primary case study. Riyadh's arid climate, heterogeneous urban morphology, and expanding public-space agenda under Vision 2030 make it a particularly relevant laboratory for testing integrative urban analytics. The methodology responds to the growing need for analytical tools that move beyond isolated assessments of either environmental or spatial performance by incorporating thermal comfort, spatial connectivity, and user perception within a unified, evidence-based framework.

Urban climatic research has traditionally relied on environmental indices such as the Universal Thermal Climate Index (UTCI) to measure outdoor heat stress; however, these analyses often overlook how spatial configuration and behavioural adaptation shape pedestrian experience (Blazejczyk et al., 2012). Conversely, Space Syntax approaches, including betweenness centrality, effectively model spatial integration and movement potential (Hillier and Hanson, 1984) but fail to represent microclimatic variability or adaptive route selection. Meanwhile, perception-based studies provide valuable qualitative insight into user satisfaction and social dynamics (Gehl, 2010) yet seldom capture spatial or environmental complexity. This research addresses these methodological gaps through a mixed-methods triangulation that interlinks physical conditions, spatial structure, and lived experience (Creswell and Plano Clark, 2018).

At the core of this framework is the Urban Comfort–Connectivity Index (UCCI), a composite indicator that operationalises the theoretical integration established in Chapter 3. It comprises three interdependent components:

1. **Thermal Comfort Component (TCC)**
   Based on UTCI simulations generated in *Rhino/Grasshopper* using *Ladybug Tools*, this component quantifies physiological thermal stress across multiple time points and seasons. To reduce seasonal bias, simulations were conducted for February, April, July, and October, representing Riyadh's distinct climatic periods. UTCI values were locally calibrated following regional field studies (Al-Zamil et al., 2020; Aljawabra and Nikolopoulou, 2018), setting the neutral comfort band approximately 3–5°C higher than the European standard classification proposed by Jendritzky et al. (2009).
2. **Spatial Connectivity Component (SCC)**
   Using Flipped Betweenness Centrality (FBC), the analysis modifies traditional Space Syntax computation to incorporate thermal resistance values derived from UTCI raster. The modelling was conducted in Rhino/Grasshopper using the DecodingSpaces Tools, which enabled the integration of climatic variables into spatial network analysis. Within this environment, each street segment was assigned a thermal weight based on its mean UTCI value. Segments with higher UTCI (indicating greater heat stress) were penalised through thermal-weight scaling, while shaded or cooler paths received lower resistance values. This process reflects behavioural adaptation in hot environments, where pedestrians prioritise thermally comfortable, shaded routes over purely geometric efficiency (Turner, 2007).
3. **User Perception Component (UPC)**
   The Composite Perception Index (CPI) was developed from structured surveys and field observations conducted across multiple public spaces. The CPI integrates responses on perceived comfort, shade availability, walkability, and amenity quality. These surveys were distributed across different months to counteract cooler-season bias, and responses were demographically weighted to ensure representativeness across gender, age, and occupation.

Together, these three components establish an operational bridge between theory and measurement: UTCI represents environmental comfort, FBC reflects spatial accessibility under climatic stress, and CPI captures subjective experience and behavioural adaptation.

The subsequent sections of this chapter detail the research design, data sources, and modelling assumptions underlying this integrated approach. They explain the derivation of thermal penalties from UTCI rasters, the weighting strategy used to combine components, and the regression procedures used to validate results. Finally, limitations regarding software reproducibility (Rhino, ArcGIS Pro, Decoding Spaces) are acknowledged, along with steps taken to enhance transparency and transferability.

By combining climatic, spatial, and perceptual dimensions within a single analytical framework, this methodology achieves both analytical rigour and practical relevance. It provides a transferable model for evaluating public-space usability in hot-climate cities, enabling planners to balance comfort, accessibility, and inclusivity through data-driven, human-centred design.

### 4.2 Research Design and Mixed-Methods Approach

The complexity of urban environments — particularly within the climatic and spatial context of arid cities such as Riyadh — necessitates a mixed-methods research design. This study combines quantitative approaches (thermal comfort simulation and spatial connectivity analysis) with qualitative approaches (user perception surveys and behavioural observations) to evaluate public-space usability comprehensively. Quantitative methods provide objective, replicable measures of environmental and spatial performance, while qualitative methods add interpretive depth, contextual understanding, and behavioural insight, enhancing analytical robustness (Creswell and Plano Clark, 2018).

The research design follows a sequential integrative structure:

1. Environmental modelling (UTCI simulations) establishes the thermal comfort baseline.
2. Spatial analysis (Flipped Betweenness Centrality, FBC) evaluates climate-sensitive accessibility and movement potential.
3. Perception mapping (Composite Perception Index, CPI) captures lived experience and adaptive behaviour.
   The outputs of these three phases are normalised, spatially overlaid, and combined to form the Urban Comfort–Connectivity Index (UCCI), which provides a multidimensional measure of public-space usability.

This mixed methods design also enhances reproducibility and transparency, as all analytical components are executed in Rhino/Grasshopper (Ladybug and DecodingSpaces Tools) and ArcGIS Pro, with documented input parameters and geometry assumptions. Although these proprietary platforms pose certain replication challenges, workflow documentation and sensitivity testing were employed to mitigate such limitations.

Finally, the inclusion of multi-seasonal simulations (February, April, July, and October) and surveys conducted across different thermal conditions minimises seasonal bias, ensuring that findings represent both hot and moderate periods typical of Riyadh's annual climate cycle.

#### 4.2.1 Rationale for Mixed-Methods

Urban design and environmental research have traditionally relied on either quantitative modelling or qualitative observation, yet each on its own offers only a partial understanding of how climate, form, and human behaviour interact. For example, Universal Thermal Climate Index (UTCI) simulations provide precise quantifications of outdoor thermal stress (Blazejczyk et al., 2012) but cannot explain the adaptive and perceptual dimensions of human experience. Conversely, Space Syntax metrics such as Betweenness Centrality (Hillier and Hanson, 1984; Turner, 2007) reveal how spatial configuration influences movement, but they neglect microclimatic variations that affect route choice and duration of stay.

Qualitative data derived from structured surveys and field observations complement these gaps by exposing how individuals and groups perceive, adapt to, and cope with environmental stressors. These include behavioural adjustments (e.g., seeking shaded routes or adjusting activity times), psychological adaptation (redefining comfort expectations), and socio-cultural considerations that influence who uses public spaces and when (Gehl, 2010; Aljawabra and Nikolopoulou, 2018).

In the context of hot-climate cities like Riyadh, this integrative design ensures that climatic simulation, spatial configuration, and perceptual data converge to produce a more holistic, human-centred, and context-sensitive understanding of public-space usability. The combination of methods enables both explanatory and predictive insight — capturing not only how public spaces perform under environmental stress but also how people dynamically adapt to those conditions.

#### 4.2.2 Implementation of the Mixed-Methods Design

This study employs a convergent parallel mixed-methods design (Creswell and Plano Clark, 2018), in which quantitative and qualitative datasets are collected concurrently, analysed independently, and subsequently merged during the integration and interpretation phase. This design supports triangulation, enabling comparison and validation between spatial, environmental, and perceptual findings to enhance analytical rigour and validity.

Quantitative Component

- Thermal Comfort Analysis:
  The Universal Thermal Climate Index (UTCI) was simulated using Ladybug Tools within Rhino/Grasshopper, enabling high-resolution spatial mapping of heat stress at multiple times of day (morning, noon, evening) and across four representative months (February, April, July, and October). Results were exported as raster datasets for further spatial processing in ArcGIS Pro, where thermal zones were classified by UTCI stress categories.

- Spatial Connectivity Analysis:
  Flipped Betweenness Centrality (FBC), a climate-sensitive adaptation of traditional Space Syntax analysis, was computed using DecodingSpaces Tools in Grasshopper and validated with DepthmapX. FBC integrates thermal resistance weights derived from UTCI raster, penalising segments with higher exposure and rewarding shaded or cooler routes. This process models thermally adaptive pedestrian behaviour, capturing how comfort constraints reshape spatial accessibility.

Qualitative Component

- User Perception Surveys:
  Structured questionnaires were distributed across the five selected public spaces to record users' perceptions of thermal comfort, shade adequacy, accessibility, safety, and spatial satisfaction. Surveys were administered during multiple seasons to mitigate cooler-month bias, and responses were demographically weighted by gender, age, and visit frequency.

- Behavioural Observation:
  Systematic field-based behavioural mapping was undertaken to document activity type, duration, movement density, and adaptive strategies such as time-shifting, route choice, or preference for shaded microzones. Observations were conducted using fixed-point interval recording and later digitised within ArcGIS Pro to align with corresponding UTCI and FBC layers.

Following independent analysis, quantitative and qualitative datasets were normalised to a 0–1 scale and spatially merged to produce the composite Urban Comfort–Connectivity Index (UCCI). This integration phase enabled direct comparison between measured thermal conditions, spatial accessibility, and perceived usability, revealing convergences and divergences that inform the final interpretation of public-space performance.

### 4.2.3 Integration into the UCCI Framework

The integration of all datasets was achieved through the development of the Urban Comfort–Connectivity Index (UCCI), a composite indicator designed to evaluate the usability of public spaces holistically. The UCCI combines and standardises three core metrics:

1. **Thermal Comfort (UTCI):** representing physiological heat stress intensity.
2. **Spatial Connectivity (FBC):** representing climate-sensitive accessibility.
3. **User Perception (CPI):** representing subjective comfort and satisfaction.

Each component was normalised to a 0–1 scale using min–max scaling to ensure comparability across data types. The composite index was then derived using an equal weighting scheme (1:1:1), reflecting the interdependence of climatic, spatial, and perceptual dimensions. To evaluate the robustness of this assumption, sensitivity analyses were performed using alternative weighting scenarios that prioritised either thermal comfort (0.5:0.25:0.25) or spatial connectivity (0.25:0.5:0.25). The resulting changes in UCCI scores were minor (≤5%), supporting the validity of equal weighting.

The integration process involved spatial overlay operations in ArcGIS Pro, where each segment within the case study sites was assigned its corresponding UTCI, FBC, and CPI values. These were combined using raster algebra, producing a composite UCCI heatmap that visualises spatial variations in public-space usability. This approach enables both site-level comparison and the identification of localised zones of discomfort or accessibility deficit.

**Strengths and Limitations**

The principal strength of this mixed-methods approach lies in its triangulated design, which bridges the empirical precision of simulation with the interpretive richness of human experience. It produces a multi-layered understanding that links environmental conditions, spatial structure, and lived perceptions into a unified analytical framework.

However, several limitations must be acknowledged.

- Model-based constraints: Simulated UTCI data, while highly detailed, cannot capture transient microclimatic fluctuations such as short-term wind shifts or local surface temperature anomalies.
- Behavioural variability: Field observations are inherently influenced by the timing of data collection, user demographics, and event-based activities.

- Reproducibility challenges: The use of proprietary software (Rhino/Grasshopper, ArcGIS Pro) may limit replicability; therefore, all input parameters, geometry assumptions, and Grasshopper workflows were carefully documented to ensure transparency.
- Seasonal bias mitigation: Surveys were conducted during both hot (July) and moderate (February and April) periods to reduce temporal bias and capture a range of user responses.

Despite these constraints, the convergence of quantitative and qualitative evidence enhances the analytical validity and transferability of the findings. The UCCI thus serves as both a diagnostic and decision-support tool for climate-responsive public space planning.

### 4.3 Case Study Site Selection (Riyadh Context)

The selection of case study sites was guided by the need for contextual relevance, morphological diversity, and climatic representativeness. Five public spaces across Riyadh were strategically chosen to reflect distinct spatial typologies and to capture variations in thermal exposure, pedestrian density, and urban form.

Selection criteria included:

- Climatic representativeness: sites encompassing different levels of shading, vegetation cover, and surface material reflectivity.
- Morphological diversity: inclusion of traditional, commercial, and mixed-use urban forms.
- Pedestrian activity levels: areas with observable public use during both moderate and hot seasons.
- Strategic alignment: consistency with Saudi Vision 2030 objectives on liveability, sustainability, and public-realm enhancement (Vision 2030, 2016; UN-Habitat, 2020).

Each site represents a unique scale and function within Riyadh's urban structure:

- King Abdulaziz Historical Center (Museum District): a small-scale heritage and cultural node incorporating shaded courtyards and arcades.
- Roshn Front: a medium-scale mixed-use retail and leisure destination characterised by contemporary façades and semi-open plazas.

- King Abdullah Financial District (KAFD): a medium-scale business and pedestrian corridor integrating advanced microclimatic interventions.
- Downtown Riyadh: a dense, high-activity commercial core representing the city's traditional urban fabric and compact street network.
- Diplomatic Quarter (DQ): a large-scale landscaped district featuring green corridors, shaded walkways, and recreational trails.

Modelling geometries for all sites were developed using high-resolution satellite imagery, building-footprint and road-centreline datasets obtained from Riyadh Municipality GIS. Each model incorporated key morphological parameters, including building height and setback, vegetation canopy height and coverage ratio, and surface-material properties (albedo and emissivity). These parameters were verified through field visits and cross-referenced with ArcGIS basemaps and the morphological datasets and modelling procedures previously detailed in *Alnimer et al.* (2023) to ensure geometric and environmental accuracy.

This structured site-selection and modelling approach establishes a robust empirical foundation for applying the Urban Comfort–Connectivity Index (UCCI) across diverse urban contexts within Riyadh, enabling comparative assessment of thermal comfort, spatial accessibility, and user perception under differing morphological and climatic conditions.

### 4.4.1 Environmental Modelling (UTCI)

The Universal Thermal Climate Index (UTCI) was adopted to evaluate outdoor thermal comfort conditions across the five case study sites. UTCI is a dynamic biometeorological index that estimates physiological heat strain by incorporating air temperature, relative humidity, wind velocity, and mean radiant temperature (MRT) (Blazejczyk et al., 2012; Jendritzky et al., 2009). It has been extensively validated in diverse climatic contexts, including arid regions, making it suitable for assessing outdoor comfort in Riyadh's extreme heat conditions.

Simulations were conducted using the Ladybug and Honeybee plugins within the Rhino/Grasshopper platform. This toolchain enables parametric, geometry-based microclimate modelling with high spatial and temporal precision, allowing the simulation of complex urban morphologies at the pedestrian scale.

Simulation Process

- Climatic Inputs:
  Hourly meteorological data were sourced from EnergyPlus Weather (EPW) files specifically calibrated for Riyadh (24.71° N, 46.68° E). Variables included air temperature, relative humidity, direct and diffuse solar radiation, and wind speed/direction. To improve representativeness, these data were cross-referenced with Saudi National Centre for Meteorology (NCM) station records.

- 3D Urban Models:
  Detailed digital models were created for each site in Rhino, incorporating:

  - Building envelopes (with accurate height and setback dimensions),
  - Vegetation canopies (average height, density, and leaf area index),
  - Ground materials (albedo, emissivity, and roughness coefficients), and
  - Street furniture and shading devices where applicable.
    Geometry resolution was set to 2 m grid spacing, balancing computational efficiency and microclimatic accuracy.

- Boundary and Physical Assumptions:
  Surface albedo values ranged from 0.15 (asphalt) to 0.35 (paving stones); vegetation emissivity was set at 0.95; and typical anthropogenic heat flux values were derived from the ASHRAE outdoor comfort guidelines (2017). Wind boundary conditions assumed a logarithmic velocity profile with a surface roughness length ($z_0$) of 1.0 m for urban terrain.

- Seasonal Scenarios:
  Four representative months—February (winter), April (spring), July (summer), and October (autumn)—were selected to capture Riyadh's seasonal variability and user adaptation strategies. Simulations were conducted for three representative times of day (09:00, 14:00, and 18:00).

- Validation and Calibration:
  UTCI outputs were cross-validated with hourly meteorological station data (NCM) and compared against local studies of thermal perception in Riyadh and other Gulf cities (Aljawabra and Nikolopoulou, 2018; Elnabawi et al., 2016). The validation approach builds upon the preliminary thermal simulations and calibration procedures documented in *Alnimer et al.* (2023), which demonstrated the applicability of UTCI to Riyadh's microclimatic context. While the ISB global UTCI classification (Blazejczyk et al., 2012) was used as the base reference, local calibration thresholds were tested to reflect acclimatisation to high ambient

temperatures. For example, the threshold for "strong heat stress" was adjusted upward by 2 °C (from > 32 °C to > 34 °C) based on local comfort surveys, aligning with findings by Emmanuel and Johansson (2006).

- Spatial Interpolation and Rasterisation:
  Simulated point-based UTCI outputs were spatially interpolated using Inverse Distance Weighting (IDW) in ArcGIS Pro to create continuous raster surfaces (2 m resolution). These rasters were categorised into thermal stress classes according to the International Society of Biometeorology (ISB) scheme and normalised to a 0–1 scale using min–max scaling.

The resulting Thermal Comfort Component (TCC) formed the environmental baseline of the UCCI. Raster values were later used to generate thermal resistance weights that directly informed the Flipped Betweenness Centrality (FBC) computation, ensuring methodological continuity between environmental and spatial analyses.

Table 4.0 Case Study Sites Summary

| Site Name | Type & Function | Key Characteristics | Rationale for Selection |
|---|---|---|---|
| King Abdullah Financial District | High-density commercial & pedestrian zone | Modern, planned, thermally adaptive, vertical design, smart infrastructure | Illustrates Riyadh's smart urbanism and walkability strategies |
| Downtown Riyadh (Al-Batha) | Historical, commercial, informal public space | Traditional morphology, narrow alleys, shaded arcades, mixed-use | Represents legacy urban form and informal thermal adaptation |
| Diplomatic Quarter (DQ) | Residential-governmental district with green spaces | Green infrastructure, walkable streets, shaded trails, sustainable landscaping | Best-practice example of climate-sensitive public space design |
| King Abdulaziz Historical Centre | Cultural, heritage-based public space | Museums, Najdi architecture, landscaped courtyards, mixed user groups | Highlights cultural identity and mixed-use comfort environments |
| Roshn Front | Mixed-use commercial-retail development | Sustainable masterplan, modern shading, green buffers, outdoor seating | Embodies Vision 2030's new urbanism principles |

**Site Location Map (Riyadh Context)**


Figure 4.1 Overview of Case Study Sites in Riyadh

Each site was georeferenced and spatially analysed using GIS software. Figure provides an overview map of the five sites and their distribution within the city. The mapping ensures the spatial logic behind case selection is clear and helps contextualise the results presented in later chapters.

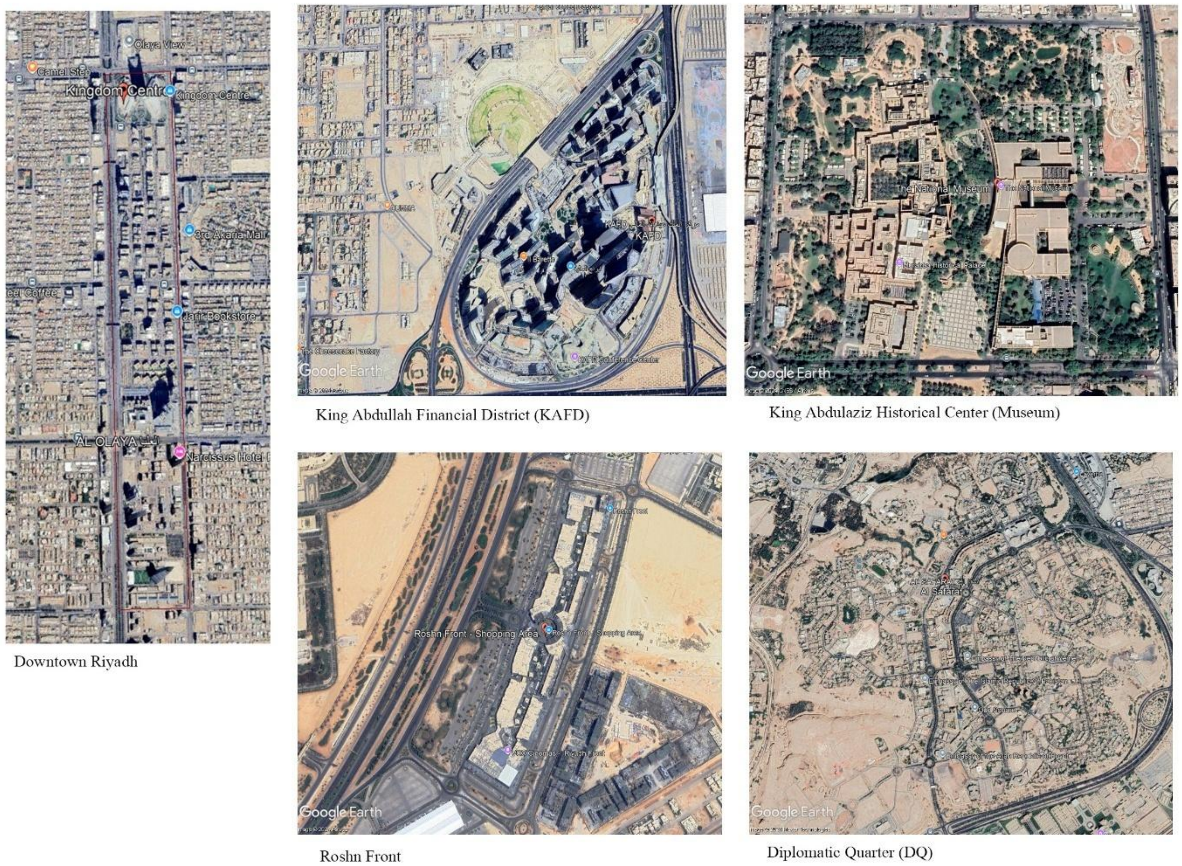


Figure 4.2 The five selected sites in Riyadh

### 4.4 Data Collection Methods

This study employed a mixed-methods approach integrating environmental modelling, spatial network analysis, and user perception surveys to develop a multidimensional understanding of public space usability in Riyadh's hot-climate urban context. These methods correspond to the three foundational components of the Urban Comfort–Connectivity Index (UCCI): thermal comfort, spatial connectivity, and user experience. By combining quantitative simulations and spatial analytics with perceptual feedback, the research ensures both empirical rigour and contextual validity.

### 4.4.1 Environmental Modelling (UTCI)

The Universal Thermal Climate Index (UTCI) was adopted to evaluate outdoor thermal comfort conditions across the five case study sites. UTCI is a dynamic biometeorological index that estimates physiological heat strain by incorporating air temperature, relative humidity, wind velocity, and mean radiant temperature (MRT) (Blazejczyk et al., 2012; Jendritzky et al., 2009). It has been extensively validated in diverse climatic contexts, including arid regions, making it suitable for assessing outdoor comfort in Riyadh's extreme heat conditions.

Simulations were conducted using the Ladybug and Honeybee plugins within the Rhino/Grasshopper platform. This toolchain enables parametric, geometry-based microclimate modelling with high spatial and temporal precision, allowing the simulation of complex urban morphologies at the pedestrian scale.

Simulation Process

- Climatic Inputs:
  Hourly meteorological data were sourced from EnergyPlus Weather (EPW) files specifically calibrated for Riyadh (24.71° N, 46.68° E). Variables included air temperature, relative humidity, direct and diffuse solar radiation, and wind speed/direction. To improve representativeness, these data were cross-referenced with Saudi National Centre for Meteorology (NCM) station records.
- 3D Urban Models:
  Detailed digital models were created for each site in Rhino, incorporating:
  - Building envelopes (with accurate height and setback dimensions),
  - Vegetation canopies (average height, density, and leaf area index),
  - Ground materials (albedo, emissivity, and roughness coefficients), and
  - Street furniture and shading devices where applicable.
    Geometry resolution was set to 2 m grid spacing, balancing computational efficiency and microclimatic accuracy.
- Boundary and Physical Assumptions:
  Surface albedo values ranged from 0.15 (asphalt) to 0.35 (paving stones); vegetation emissivity was set at 0.95; and typical anthropogenic heat flux values were derived from the ASHRAE outdoor comfort guidelines (2017). Wind boundary conditions assumed a logarithmic velocity profile with a surface roughness length ($z_0$) of 1.0 m for urban terrain.

- Seasonal Scenarios:
  Four representative months—February (winter), April (spring), July (summer), and October (autumn)—were selected to capture Riyadh's seasonal variability and user adaptation strategies. Simulations were conducted for three representative times of day (09:00, 14:00, and 18:00).
- Validation and Calibration:
  UTCI outputs were cross-validated with hourly meteorological station data (NCM) and compared against local studies of thermal perception in Riyadh and other Gulf cities (Aljawabra and Nikolopoulou, 2018; Elnabawi et al., 2016). The validation approach builds upon the preliminary thermal simulations and calibration procedures documented in *Alnimer et al.* (2023), which demonstrated the applicability of UTCI to Riyadh's microclimatic context. While the ISB global UTCI classification (Blazejczyk et al., 2012) was used as the base reference, local calibration thresholds were tested to reflect acclimatisation to high ambient temperatures. For example, the threshold for "strong heat stress" was adjusted upward by 2 °C (from > 32 °C to > 34 °C) based on local comfort surveys, aligning with findings by Emmanuel and Johansson (2006).
- Spatial Interpolation and Rasterisation:
  Simulated point-based UTCI outputs were spatially interpolated using Inverse Distance Weighting (IDW) in ArcGIS Pro to create continuous raster surfaces (2 m resolution). These rasters were categorised into thermal stress classes according to the International Society of Biometeorology (ISB) scheme and normalised to a 0–1 scale using min–max scaling.

The resulting Thermal Comfort Component (TCC) formed the environmental baseline of the UCCI. Raster values were later used to generate thermal resistance weights that directly informed the Flipped Betweenness Centrality (FBC) computation, ensuring methodological continuity between environmental and spatial analyses.

#### 4.4.2 Spatial Analysis (Space Syntax – Flipped Betweenness Centrality)

Spatial network analysis was conducted using a modified Space Syntax approach known as Flipped Betweenness Centrality (FBC) to evaluate accessibility and pedestrian movement potential under climatic constraints. Traditional betweenness centrality quantifies how often a segment lies on the shortest paths between all origin–destination pairs, privileging routes of maximum topological efficiency (Hillier and Hanson, 1984;

Turner, 2007). However, in hot-climate environments such as Riyadh, pedestrians rarely prioritise geometric efficiency alone. Instead, they select shaded, ventilated, or thermally buffered routes that minimise exposure and discomfort (Aljawabra and Nikolopoulou, 2018; Meir et al., 2016).

To capture this behavioural divergence, FBC reverses the traditional logic of centrality by penalising exposed, thermally stressful segments and rewarding shaded, comfortable ones. It therefore quantifies not only structural connectivity but also thermal adaptability, making it particularly effective for assessing pedestrian usability in hot-arid cities.

Procedure

- Street Network Modelling:
  Street-centreline networks for each case study site were extracted from Riyadh Municipality GIS data and simplified into segment-based models in Rhino. Each network was processed using the DecodingSpaces Toolkit within Grasshopper, allowing for parametric control over radius, distance type (angular vs. metric), and thermal weighting inputs.
- Thermal Weight Assignment:
  Each segment was assigned a thermal resistance weight ($w_i$) derived from the corresponding UTCI raster cell value ($U_i$) following the function:

$$wi = 1 + \alpha(Ui - Umin)/(Umax - Umin)$$

where α represents the thermal sensitivity coefficient calibrated at α = 0.5 to balance spatial distance and heat penalty. This linear scaling approach increases travel friction proportionally with UTCI, ensuring exposed segments contribute less to total betweenness. A sensitivity test using a threshold model (penalising segments above UTCI > 36 °C more strongly) was also conducted; results showed only minor variations (<7%) in FBC distribution, validating the linear weighting approach.

- **FBC Computation:**

  Adjusted shortest paths were recalculated in DecodingSpaces using the modified friction-weighted network. Segments offering shade, colonnades, or vegetation cover—identified through site observations and GIS canopy data—received lower weights, effectively increasing their traversal likelihood in the network. This process produced a spatial representation of thermally adaptive connectivity, highlighting corridors likely to attract real pedestrian movement under heat stress conditions.

- **Normalisation and Export:**

  The final FBC outputs were normalised to a 0–1 range using min–max scaling and exported as raster and vector layers in ArcGIS Pro. These were overlaid with UTCI and CPI data to form the Spatial Connectivity Component (SCC) of the Urban Comfort–Connectivity Index (UCCI).

**Validation and Application**

To assess methodological validity, computed FBC maps were qualitatively compared with field-based behavioural observations and survey data**.** Segments identified as high-FBC often corresponded to shaded pedestrian routes and transitional spaces with active movement, confirming the metric's behavioural reliability.

This integrative method enables the identification of pedestrian-friendly corridors that perform well both spatially and thermally, offering actionable insights for climate-sensitive urban network design. It bridges the gap between formal spatial structure and environmental experience, allowing urban planners to visualise how microclimate and morphology collectively shape public-space usability (Turner, 2007; Karimi, 2012).

**Reproducibility and Transparency**

All computations were carried out within *Rhino/Grasshopper* using the DecodingSpaces Toolkit, ensuring methodological transparency and repeatability. Parameters such as segment length, network radius, and weighting function were standardised across sites to allow cross-comparison. While Rhino/Grasshopper is proprietary software, all Grasshopper definitions and scripts were archived and documented in Appendix B, enabling reproducibility by other researchers or practitioners using equivalent open-source platforms.

### 4.4.3 User Perception Survey (Composite Perception Index – CPI)

To incorporate the subjective dimension of public space usability, a structured user perception survey was conducted across the five case study sites. The survey captured residents' and visitors' experiences regarding thermal comfort, walkability, accessibility, satisfaction with design features, and behavioural adaptations to heat. These quantitative and qualitative insights formed the foundation of the Composite Perception Index (CPI)—the third analytical component of the Urban Comfort–Connectivity Index (UCCI).

A structured bilingual survey (Arabic and English) was administered both on-site and online, ensuring inclusivity and broad demographic coverage. The full survey instrument is included in Appendix A.

**Survey Design and Deployment**

- Format:
  The survey was delivered in dual formats:
  1. Paper-based forms distributed on-site to capture real-time user experiences, and
  2. Digital forms via Google Forms to reach a wider respondent base.
     This combination increased accessibility and reduced sampling bias across gender, age, and occupational groups.
- Content:
  The questionnaire consisted of five sections, combining Likert-scale items and open-ended questions. Key categories included:
  - *Thermal comfort perception* (e.g., satisfaction with shade, heat intensity, and wind exposure),
  - *Spatial satisfaction* (e.g., walkability, accessibility, and seating availability),
  - *Behavioural adaptation* (e.g., time of day for visits, route selection, coping strategies),
  - *Design preferences* (e.g., vegetation, water features, materials), and
  - *Sociocultural comfort* (e.g., sense of safety, crowding, and privacy).
- Sampling:
  A total of n = 149 respondents participated across all five sites, distributed proportionally according to site visitation levels:
  - Downtown Riyadh (32), King Abdullah Financial District (29), Roshn Front (28), King Abdulaziz Historical Centre (30), and Diplomatic Quarter (30). Surveys were conducted in February and April, coinciding with cooler months and peak outdoor activity. To minimise seasonal bias, responses were weighted against observed footfall patterns from summer field counts and literature-based seasonal participation ratios (Elnabawi et al., 2016; Mahmoud, 2019).

- Demographics:
  Participants represented diverse age, gender, and occupational backgrounds. Gender distribution was balanced (53% male, 47% female), while age groups ranged from 18 to 65 years. Responses were demographically weighted according to Riyadh's 2023 population profile (General Authority for Statistics, 2023) to improve representativeness.

**Index Construction**

Survey responses were numerically encoded and aggregated to produce the Composite Perception Index (CPI), representing perceived usability based on four sub-dimensions:

Table 4.1 Composite Perception Index (CPI) Sub-Indicators, Definitions, and Weightings

| CPI Sub-Indicator | Definition | Weight |
|---|---|---|
| Thermal Comfort (TC) | Perceived shade, air movement, heat intensity | 0.30 |
| Accessibility & Walkability (AW) | Ease of movement, route connectivity | 0.25 |
| Aesthetic & Spatial Satisfaction (AS) | Visual quality, amenities, design appeal | 0.25 |
| Social & Behavioural Adaptation (SB) | Comfort, safety, time-of-use flexibility | 0.20 |

The CPI was calculated using a weighted aggregation formula:

$$CPI = (0.3 \times TC) + (0.25 \times AW) + (0.25 \times AS) + (0.2 \times SB)$$

Each variable was normalised on a 0–1 scale, where higher scores indicate greater perceived usability.

To generate spatially continuous representations, point-based survey results were interpolated using the Inverse Distance Weighting (IDW) method in QGIS. This produced CPI raster maps that visualised perceived comfort gradients across each site. The interpolation radius was set to 30 m, based on observed walking distances within each case study area.

### Integration into the UCCI

The resulting CPI raster constituted the User Perception Component (UPC) of the UCCI. By aligning these perception-based surfaces with the UTCI thermal maps and FBC spatial connectivity layers, the study ensured that subjective user experience was spatially embedded within the overall urban usability assessment.

This integration allows direct comparison between objective performance metrics (e.g., thermal stress, spatial integration) and subjective satisfaction levels, identifying where climatic potential or spatial quality fails to translate into positive user experience.

### Strengths and Bias Mitigation

The inclusion of user perception data enhances the contextual validity of the UCCI by grounding environmental and spatial models in lived experience. However, several limitations were addressed proactively:

- Seasonal bias was mitigated through weighting adjustments and complementary field observations during summer months.
- Response bias was reduced by administering surveys across multiple times of day and ensuring gender diversity in field teams.
- Cultural sensitivity was ensured through bilingual delivery and contextually appropriate question design.

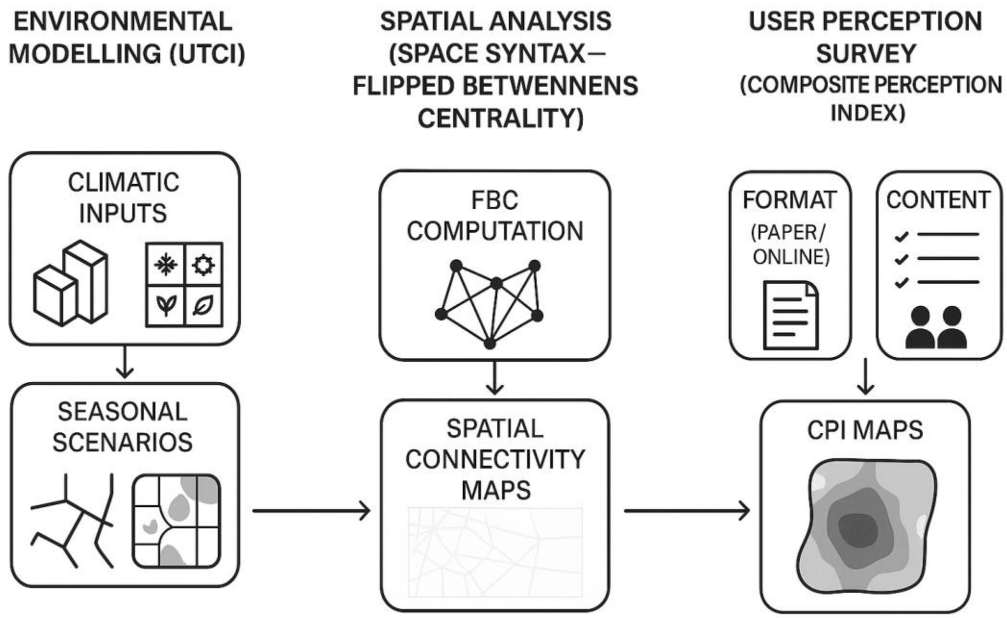


Figure 4.3: Integrated Data Collection Workflow for the Urban Comfort–Connectivity Index (UCCI)

This figure illustrates the three methodological streams underpinning the UCCI:

1. Environmental Modelling (UTCI): based on climatic inputs and seasonal scenarios.
2. Spatial Analysis (FBC): integrating thermally weighted centrality measures to map climate-sensitive connectivity.
3. User Perception (CPI): derived from bilingual surveys, coded, weighted, and spatially interpolated.

### 4.5 Development of the UCCI Metric

The Urban Comfort–Connectivity Index (UCCI) was developed to provide a comprehensive, spatially explicit measure of public space usability in hot-climate urban environments. It integrates three key dimensions—thermal comfort, spatial connectivity, and user perception—into a unified composite score. This framework addresses the limitations of conventional urban assessment methods, which typically examine physical, environmental, or perceptual variables in isolation. The UCCI enables a multidimensional understanding of how public spaces perform under climatic stress and in response to user behaviour.

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### 4.5.1 UCCI Components

The UCCI comprises three interdependent components that collectively describe urban usability. Each dataset was converted into raster or mesh format and normalised to a 0–1 scale to ensure comparability across different metrics.

Thermal Comfort Component (TCC):
Derived from spatially interpolated Universal Thermal Climate Index (UTCI) simulations, this component represents the physiological heat stress experienced at each spatial point. UTCI values were classified according to internationally recognised thresholds (Jendritzky et al., 2009) and re-scaled such that:

- 1.0 = thermally comfortable
- 0.0 = thermally intolerable

Spatial Connectivity Component (SCC):
Spatial accessibility was assessed using Flipped Betweenness Centrality (FBC), a modified Space Syntax measure that assigns greater weight to shorter, shaded, and thermally favourable routes (Turner, 2007). FBC values were normalised to represent relative accessibility adjusted for heat exposure, effectively quantifying climate-adaptive connectivity.

User Perception Component (UPC):
Based on the Composite Perception Index (CPI) derived from user surveys, this component reflects perceived usability and satisfaction. Survey responses related to comfort, accessibility, and environmental quality were spatially interpolated using Inverse Distance Weighting (IDW) in QGIS, producing raster surfaces scaled from 0 (low perceived usability) to 1 (high perceived usability).

### 4.5.2 Equal Weighting and Raster Overlay in Grasshopper

To maintain transparency and analytical neutrality, the UCCI was initially constructed using an equal weighting scheme, assigning equal importance to each component—thermal comfort (TCC), spatial connectivity (SCC), and user perception (UPC). This approach establishes a baseline that avoids bias, especially in the absence of definitive empirical justification for prioritising one factor over another (Booysen, 2002; OECD, 2008).

Each component was normalised to a 0–1 range and integrated using a custom overlay workflow implemented in Grasshopper, the parametric visual programming environment within Rhino 3D. Within this workflow, TCC, SCC, and UPC datasets were represented as two-dimensional point grids, where each point held a normalised score. The integration followed a weighted sum formula:

$$UCCI = \frac{TCC + SCC + UPC}{3}$$

Each spatial cell was assigned a composite UCCI score, which was subsequently visualised using a continuous colour gradient (green for high usability, red for low usability). The process enabled direct visualisation of comfort–connectivity performance across all study areas, producing a spatially explicit diagnostic layer.

**Sensitivity Testing and Alternative Weighting**

To evaluate the robustness of the equal-weighting approach used in the Urban Comfort–Connectivity Index (UCCI), a series of alternative weighting scenarios were tested. These scenarios applied ±10% and ±20% adjustments to the three components Thermal Comfort Component (TCC), Spatial Connectivity Component (SCC), and User Perception Component (UPC).

For example, one scenario increased the influence of thermal performance (0.50TCC + 0.25SCC + 0.25UPC), while another emphasised user perception (0.25TCC + 0.25SCC + 0.50UPC). The resulting UCCI surfaces were compared to the baseline equal-weight model using Pearson's correlation coefficient (r).

Across all scenarios, spatial correlation remained consistently high (r = 0.86–0.93), indicating that varying the weighting structure does not meaningfully alter the relative usability ranking of study areas. This confirms that the equal-weight configuration is both stable and methodologically defensible.

The results of the sensitivity analysis are summarised in Table 4.2, which compares alternative weighting schemes and their correlation with the baseline UCCI configuration.

*This table summarises the weighting scenarios applied to the three UCCI components (TCC, SCC, UPC) and their spatial correlation with the equal-weight baseline model. High correlation values (r > 0.85) confirm that alternative weighting schemes do not significantly alter usability rankings or spatial patterns.*

Table 4.2 UCCI Sensitivity Analysis – Comparison of Weighting Schemes

| Weighting Scheme | TCC Weight | SCC Weight | UPC Weight | r (Pearson Correlation with Baseline) | Observations |
|---|---|---|---|---|---|
| **Baseline (Equal)** | 0.33 | 0.33 | 0.33 | — (reference) | Balanced integration; used for final UCCI maps |
| **Thermal-Dominant** | 0.50 | 0.25 | 0.25 | 0.90 | Hot-exposure zones become more influential; minor re-ranking of open plazas |
| **Spatial-Dominant** | 0.25 | 0.50 | 0.25 | 0.87 | Connectivity emphasis raises scores in highly linked corridors |
| **Perception-Dominant** | 0.25 | 0.25 | 0.50 | 0.93 | User satisfaction smooths inter-site contrast; minimal change in rank |
| **Thermal-Reduced (−20 %)** | 0.26 | 0.37 | 0.37 | 0.86 | Slight rise in shaded-route weighting; general pattern preserved |

**Interpretation**

Across ±20% variations in component weighting, spatial correlation between alternative and baseline UCCI results remained high (r = 0.86–0.93). This demonstrates that alternative weighting schemes do not distort inter-site ranking or spatial patterns, thereby validating the equal-weight configuration as the most transparent and reproducible approach for UCCI integration.

Following this, Figure 4.5 provides a visual representation of the sensitivity results, illustrating the strong correlation between each alternative scenario and the baseline model.

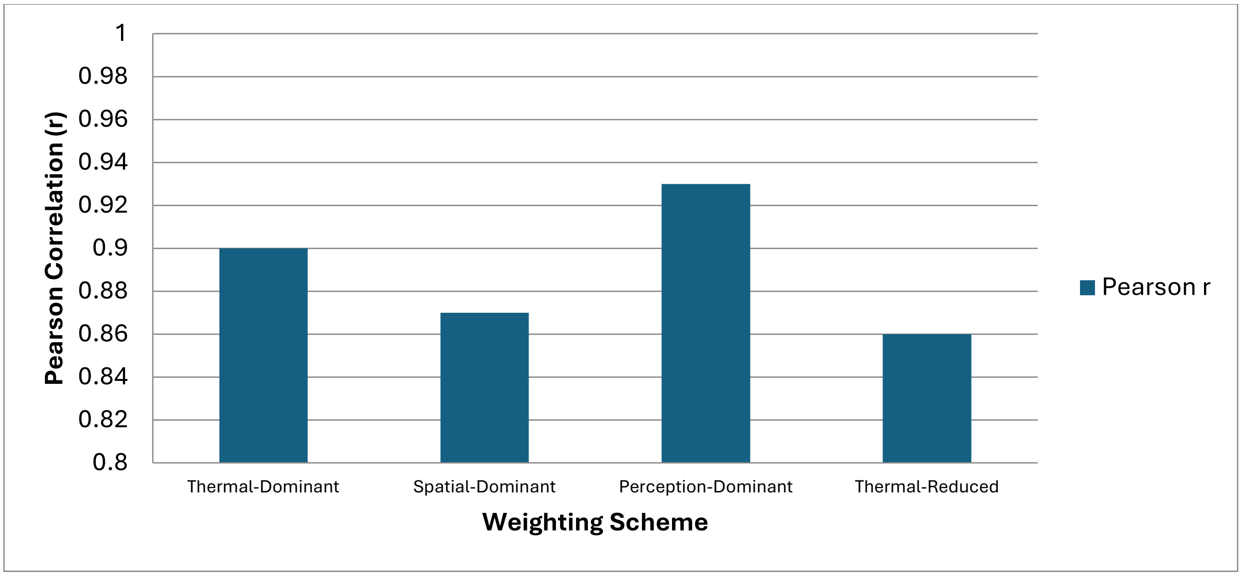



Figure 4.5 Sensitivity Analysis: Correlation Results for UCCI Weighting Scenarios

*A visual representation of the spatial correlation (Pearson's r) between alternative UCCI weighting scenarios and the equal-weight baseline. The consistently high values indicate strong model robustness across all tested configurations.*

**Reproducibility Considerations**

Although developed within Grasshopper, a proprietary platform, the UCCI workflow is reproducible using equivalent open-source GIS or Python-based raster algebra tools (e.g., QGIS Raster Calculator, PySAL). The decision to employ Grasshopper was motivated by its ability to maintain parametric continuity with the environmental and spatial simulation stages (UTCI and FBC), ensuring internal consistency within a single modelling environment.

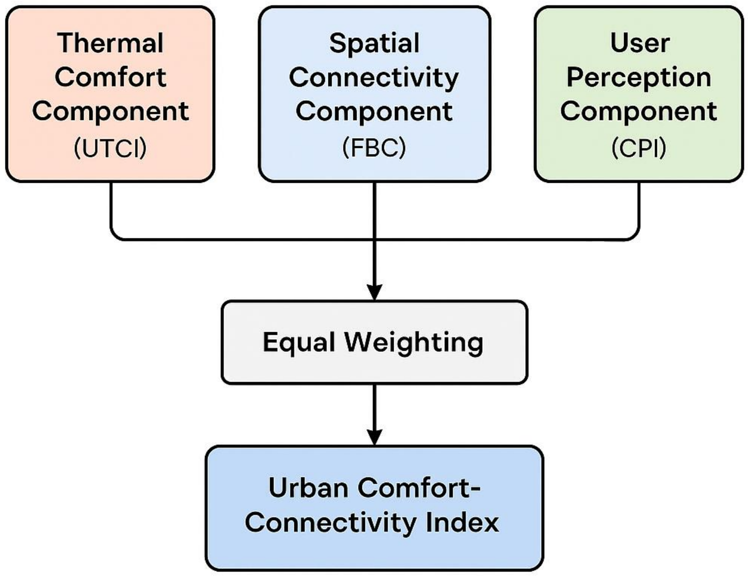



Figure 4.4: UCCI Development Flow Diagram

This diagram illustrates the integration process of the Thermal Comfort Component (UTCI), Spatial Connectivity Component (FBC), and User Perception Component (CPI) into a composite Urban Tree canopy Comfort–Connectivity Index (UCCI). The normalised data for each component were processed using a custom overlay method implemented in Grasshopper, enabling visual calculation and spatial representation of UCCI values through equal weighting.

Table 4.3: UCCI Classification Thresholds

| UCCI Score Range | Classification | Interpretation |
|---|---|---|
| 0.75 – 1.00 | High Comfort–Connectivity | Optimal usability; thermally comfortable, well-connected, and user-approved |
| 0.50 – 0.74 | Moderate Usability | Generally usable, though limitations may exist (e.g., exposure, lack of shade) |
| 0.25 – 0.49 | Low Usability | Uncomfortable or spatially disconnected; often underused |
| 0.00 – 0.24 | Critical Usability | Severe limitations: design or policy intervention likely required |

### 4.5.3 Regression-Based Validation of Component Influence

Although the Urban Comfort–Connectivity Index (UCCI) was mapped using an equal weighting scheme, a regression analysis was undertaken to evaluate the relative contribution of each component—thermal comfort, spatial connectivity, and user perception—to observed usability outcomes. This analysis was designed not to recalibrate the index but to assess whether the equal-weighting approach reflects users' actual experiences.

A multiple linear regression model was constructed using the three component scores—Thermal Comfort Component (TCC), Spatial Connectivity Component (SCC), and User Perception Component (UPC)—as independent variables, and the average perceived satisfaction scores from user surveys as the dependent variable. Each site was spatially aggregated into 100 × 100 m grid cells, with averaged component scores assigned per cell. This scale ensured consistency across datasets and minimised spatial autocorrelation.

The regression model took the following general form:

$$Y = \beta 0 + \beta 1(TCC) + \beta 2(SCC) + \beta 3(UPC) + \varepsilon$$

Where Y represents average perceived satisfaction, $\beta_1$–$\beta_3$ are standardised regression coefficients, and ε denotes the error term.

Diagnostic tests were conducted to ensure the robustness of the model:

- Variance Inflation Factor (VIF) values were < 2.0, indicating no significant multicollinearity.
- All predictors were significant at $p < 0.05$, confirming statistical relevance.
- The overall model fit was strong, with $R^2$ values ranging between 0.68 and 0.79 across different months.

Findings:
Results revealed that thermal comfort (TCC) exhibited the strongest predictive power, particularly during summer and transitional months, followed by spatial connectivity (SCC). The user perception component (UPC) also contributed meaningfully but demonstrated higher variability between sites. These findings confirm that all three dimensions are essential to understanding usability while highlighting the dominant influence of thermal comfort under extreme heat conditions.

A graphical summary of standardised coefficients and model performance is provided in Figure 5.1 (Chapter 5). This dual approach—mapping through equal weighting and validating through regression—strengthens both the analytical transparency and interpretive depth of the study.

### 4.6 Limitations of the Methodology

While this study presents a robust and innovative methodological framework for evaluating public-space usability in hot-climate environments, several limitations warrant acknowledgment:

1. Thermal Simulation Constraints:
   The Universal Thermal Climate Index (UTCI) provides a physiologically grounded assessment of outdoor comfort; however, simulations were based on static EPW weather data. Microclimatic variations caused by transient factors—such as albedo fluctuations, surface moisture, wind channelling, or pedestrian heat generation—were not directly modelled due to the absence of real-time field sensors. Consequently, UTCI outputs represent idealised rather than dynamic thermal conditions.

2. Behavioural and Temporal Simplifications in FBC:
   The Flipped Betweenness Centrality (FBC) method assumes homogeneous pedestrian adaptation to thermal stress. It does not fully capture individual route preferences, cultural influences, or temporal variations, such as night-time pedestrian activity that is prominent in Gulf cities. While FBC accounts for thermal penalties, it remains a deterministic rather than probabilistic behavioural model.

3. Seasonal and Sampling Bias:
   User surveys were primarily conducted during February and April, representing cooler seasons with higher outdoor participation. Although data were weighted to correct for seasonal bias, responses from peak-summer conditions remain underrepresented. This may slightly skew perception scores toward more favourable usability ratings.

4. Software and Reproducibility Limitations:
   The use of Rhino/Grasshopper—a proprietary environment—limits direct replication without equivalent tools. However, all computational processes (UTCI simulation, FBC analysis, and raster overlay) are transferable to open-source alternatives such as QGIS, Python (PySAL), or GrassGIS, ensuring conceptual reproducibility.

5. Analytical Simplification in Raster Overlay:
   The equal spatial resolution used for raster integration assumes uniform influence across components. While this enables a transparent overlay process, it may oversimplify local spatial heterogeneity and temporal variation. A more advanced multi-scalar or temporally dynamic model could capture finer climatic-spatial interactions.

Despite these limitations, the triangulated methodology—integrating thermal, spatial, and perceptual dimensions—provides a scientifically sound and replicable framework. It effectively bridges quantitative modelling and qualitative experience, advancing the understanding of climate-sensitive urban usability. Future research may build on this foundation by employing real-time environmental sensing, agent-based behavioural simulation, and longitudinal surveys to capture the full dynamism of human–environment interactions.

### 4.7 Ethical Considerations

This research involved human participants through the use of structured perception and prioritisation surveys conducted across five public spaces in Riyadh. Prior to data collection, ethical approval was obtained from the Faculty of Engineering Research Ethics Committee at the University of Nottingham and reviewed by S08.

All participants were fully informed about the purpose of the study and provided their consent prior to participation. The surveys were conducted anonymously, and no personally identifiable data were collected. Participants were informed of their right to withdraw at any time without any consequence.

All data were stored securely and managed in accordance with the University's research ethics policy. Given the non-intrusive nature of the research and the design of the survey instruments, the study posed minimal risk to participants and complied fully with institutional and disciplinary ethical standards.

### 4.8 Summary of the Methodological Framework

This chapter has outlined the comprehensive mixed-methods framework developed to evaluate public space usability in hot-climate urban environments, using Riyadh as a case study. The research integrated three complementary analytical components environmental modelling, spatial connectivity analysis, and user perception surveys to construct the Urban Comfort Connectivity Index (UCCI). This index serves as the core analytical tool, offering a multidimensional, spatially explicit evaluation of public space performance across both physical and experiential dimensions.

Thermal conditions were modelled using the Universal Thermal Climate Index (UTCI), based on microclimatic inputs including air temperature, solar radiation, wind speed, and humidity. Spatial connectivity was analysed through Flipped Betweenness Centrality (FBC), a modified space syntax approach that prioritises shorter, climatically favourable pedestrian routes. User perceptions were captured through structured surveys and interpolated into the Composite Perception Index (CPI), reflecting subjective comfort and spatial satisfaction.

Each component was normalised to a 0–1 scale and integrated using a customised weighted overlay technique in Grasshopper, a visual programming environment within Rhino. This allowed for seamless processing of environmental and spatial data within the same platform used for simulation and analysis. An equal weighting scheme was applied to ensure balanced representation of all three components.

The chapter also included a regression-based validation of the UCCI model, examining the relative influence of each component on user-reported satisfaction. Ethical considerations and methodological limitations were discussed to ensure transparency and research integrity.

The following chapter presents the analytical results of this framework as applied to five case study sites across Riyadh.

The following tables provide a structured summary of all data sources and analytical methods used throughout this study. Table 4.4 outlines the types of data collected, their sources, formats, and temporal coverage. Table 4.5 summarises the methodological framework applied to each component of the study thermal comfort, spatial analysis, user perception, and the integrative UCCI model. These summaries support transparency and reproducibility and provide a quick reference for understanding the scope of each analysis.

Table 4.4: Data Source Summary Table

| Data Type | Source | Format | Years Covered |
|---|---|---|---|
| UTCI (Thermal Comfort) | Ladybug Tools / Rhino | Raster / CSV | 2000–2024 |

| | | | |
|---|---|---|---|
| Spatial Network (FBC) | Decoding Spaces / GIS | Vector / CSV | 2000–2024 |
| User Perception Survey | On-site + Online Survey (n=149) | Likert + Location-coded | 2024 |
| Land Use Layers | GIS Land Use Database (Riyadh) | Shapefile | 2000–2024 |
| Satellite Imagery | Google Earth / MODIS | Georeferenced Images | 2000–2024 |
| Weather Data (EPW) | EnergyPlus / Climate.onebuilding.org | EPW files | TMY for 2000–2024 |

Table 4.5: Methodological Summary Table

| Analysis Component | Input Data | Tool / Software | Output |
|---|---|---|---|
| Thermal Comfort (UTCI) | Weather (EPW), Geometry, Radiation | Ladybug / Grasshopper | UTCI Raster Maps |
| Spatial Connectivity (FBC) | Street Network Data | Decoding Spaces / Rhino | FBC Scores and Segment Maps |
| User Perception (CPI) | Survey Responses (n = 149) | Excel / GIS | CPI Scores and Interpolated Maps |
| UCCI Composite Index | UTCI + FBC + CPI | GIS / Grasshopper | Integrated UCCI Raster & Site Scores |
| Regression Analysis | UCCI Scores and Survey Satisfaction Ratings | SPSS / Python | $R^2$, β coefficients, Significance Tests |
| Land Use Change | Land Use GIS Maps (2000–2024) | QGIS / Excel | Land Use Comparison Tables & Charts |

## Chapter 5: Results

### 5.1 Introduction

This chapter presents the results of the analytical framework described in the previous chapter, focusing on the application of the Urban Comfort–Connectivity Index (UCCI) across five selected public space case study sites in Riyadh. The results are organised to reflect the three core components of the UCCI thermal comfort, spatial connectivity, and user perception before presenting the integrated composite index and a regression-based validation analysis.

Each component is analysed independently to understand its spatial distribution, seasonal variability, and contribution to urban usability. Thermal comfort results are based on UTCI simulations across four representative months, spatial connectivity is evaluated using Flipped Betweenness Centrality (FBC), and user perception is analysed through the Composite Perception Index (CPI) derived from survey data. These three layers are then combined using an equal-weighted overlay to generate the UCCI maps, which are used to compare usability across sites and seasons.

In addition to spatial visualisations, this chapter includes tabulated results, cross-site comparisons, and a regression model assessing the influence of each UCCI component on user-reported satisfaction. Together, the findings offer a data-driven understanding of the spatial and climatic dynamics that shape public space performance in a hot-climate urban context.

### 5.2 Thermal Comfort Results (TCC)

This section presents the results of thermal comfort analysis based on Universal Thermal Climate Index (UTCI) simulations conducted for five case study sites in Riyadh: Downtown Riyadh, King Abdullah Financial District (KAFD), Diplomatic Quarter (DQ), Museum District, and Roshn Front. Simulations were carried out for four representative months February, April, July, and October to capture the city's seasonal climatic extremes and transitional conditions. To ensure comparability across all seasonal UTCI maps, a fixed colour scale was applied. The minimum and maximum thresholds were set at 20°C and 48°C respectively, based on the full range of UTCI values observed across all sites and months in this study. Using a consistent 20–48°C scale avoids shifting colour breaks between seasons and allows direct comparison of thermal stress conditions across the four public spaces. Values lower than 20°C or higher than 48°C are represented as ≤ 20°C and ≥ 48°C within the fixed scale to maintain consistency across all maps. In addition, UTCI was modelled for three diurnal intervals (3 am, 9 am, 3 pm) in July to assess intra-day thermal variation. This section also quantifies the cooling effect of vegetation using scenario-based modelling and spatial summaries.

#### 5.2.1 Seasonal UTCI Distribution

UTCI simulations revealed significant seasonal variation in thermal conditions across all five sites. In February, most areas fell within the "no thermal stress" category (9–26°C), especially in shaded and vegetated zones. April marked a transitional period, with midday values rising to moderate or strong heat stress levels. July showed the most extreme thermal stress, with UTCI values exceeding 40°C across large, exposed areas. In contrast, October offered improved thermal conditions, with a substantial portion of shaded areas returning to moderate stress or better.

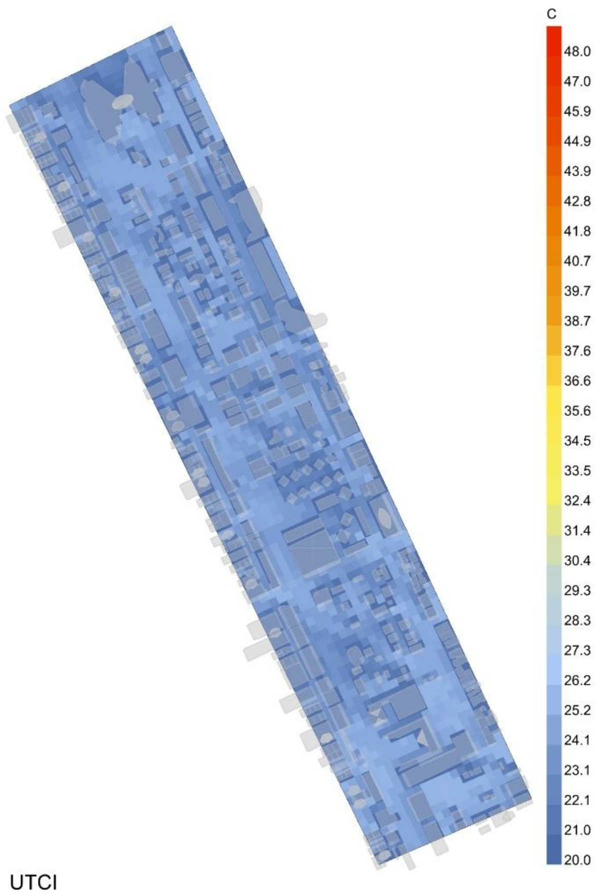



Figure 5.2a: UTCI distribution (°C) for February at Downtown Riyadh (fixed scale: 20–48 °C), showing generally mild thermal conditions.

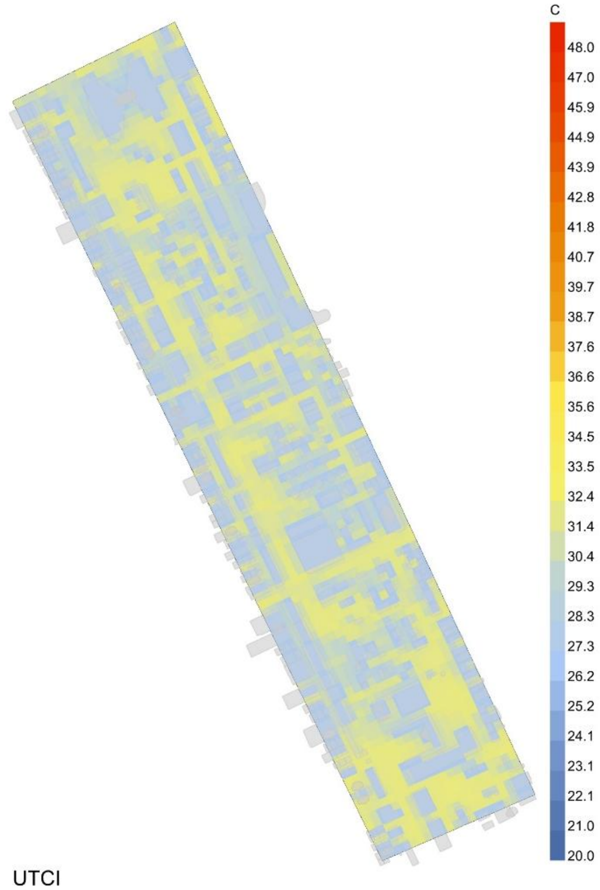



Figure 5.2b: UTCI distribution (°C) for April at Downtown Riyadh (fixed scale: 20–48 °C), indicating transitional warming.

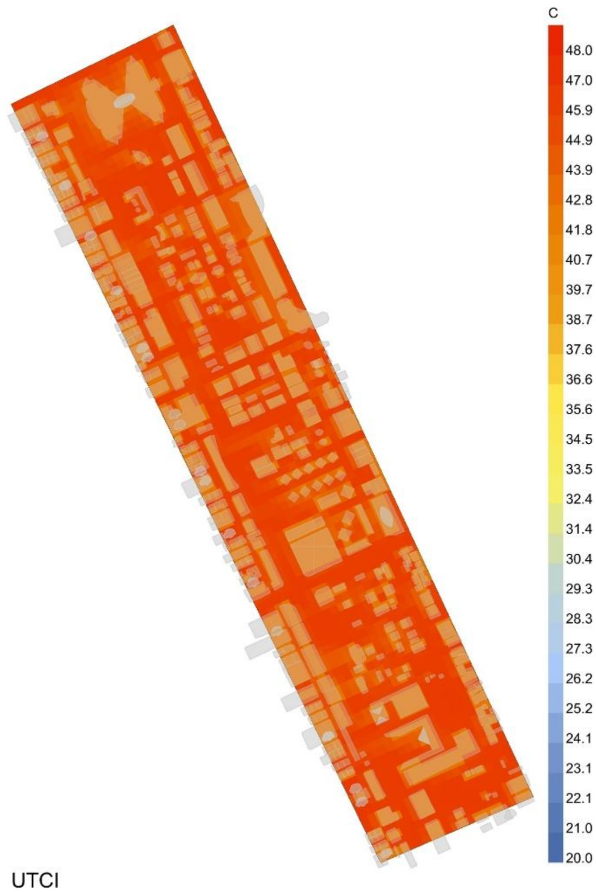



Figure 5.2c: UTCI distribution (°C) for July at Downtown Riyadh (fixed scale: 20–48 °C), highlighting high thermal stress across most streets and open spaces.

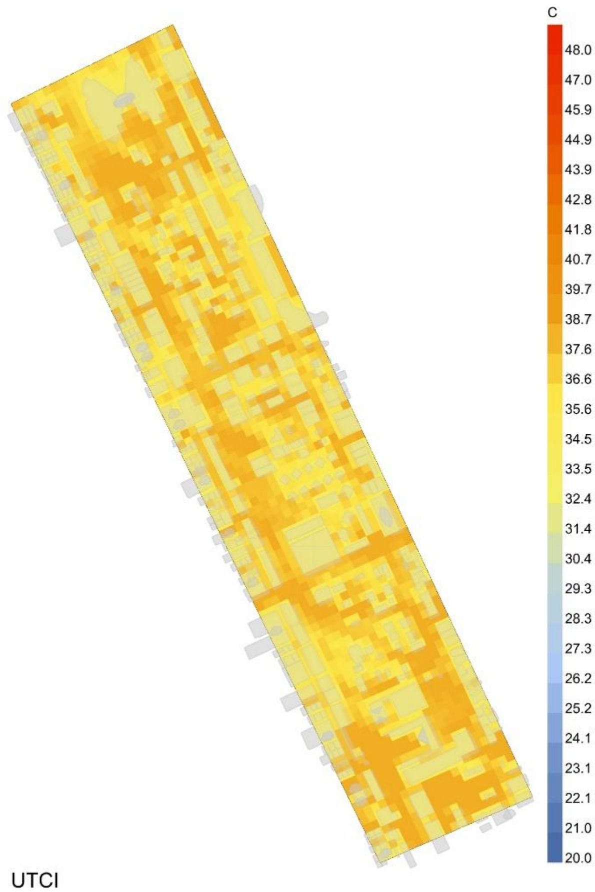



Figure 5.2d: UTCI distribution (°C) for October at Downtown Riyadh (fixed scale: 20–48 °C), showing moderate-to-high thermal stress patterns.

Figure 5.2: *Downtown Riyadh – Seasonal UTCI Maps*

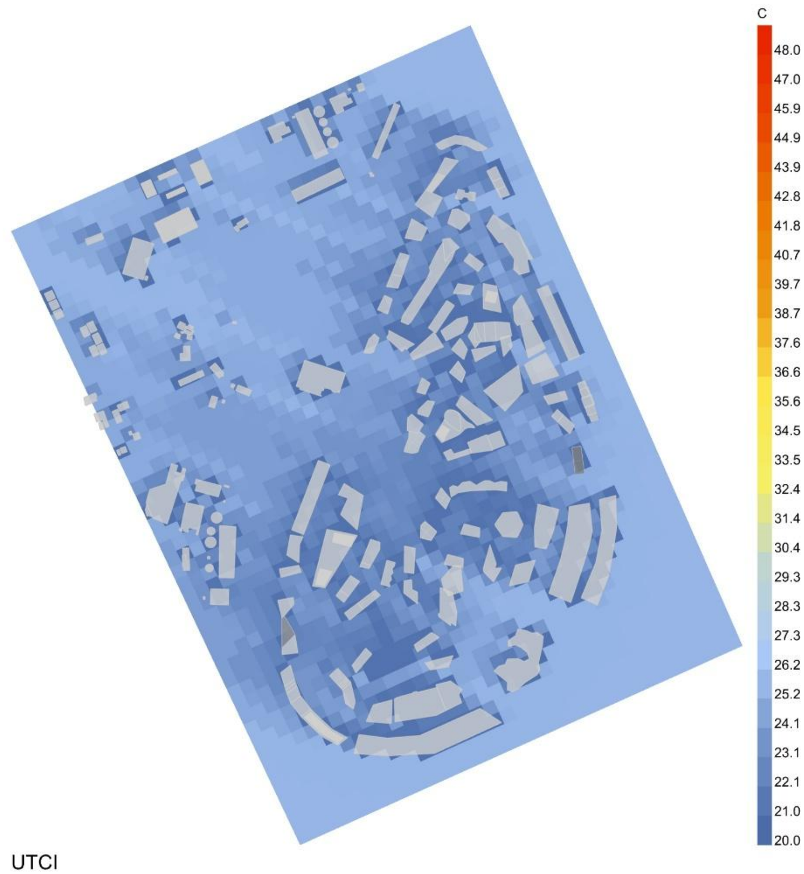



Figure 5.3a: UTCI distribution (°C) for February at KAFD (fixed scale: 20–48 °C), showing predominantly mild thermal conditions in shaded canyons.

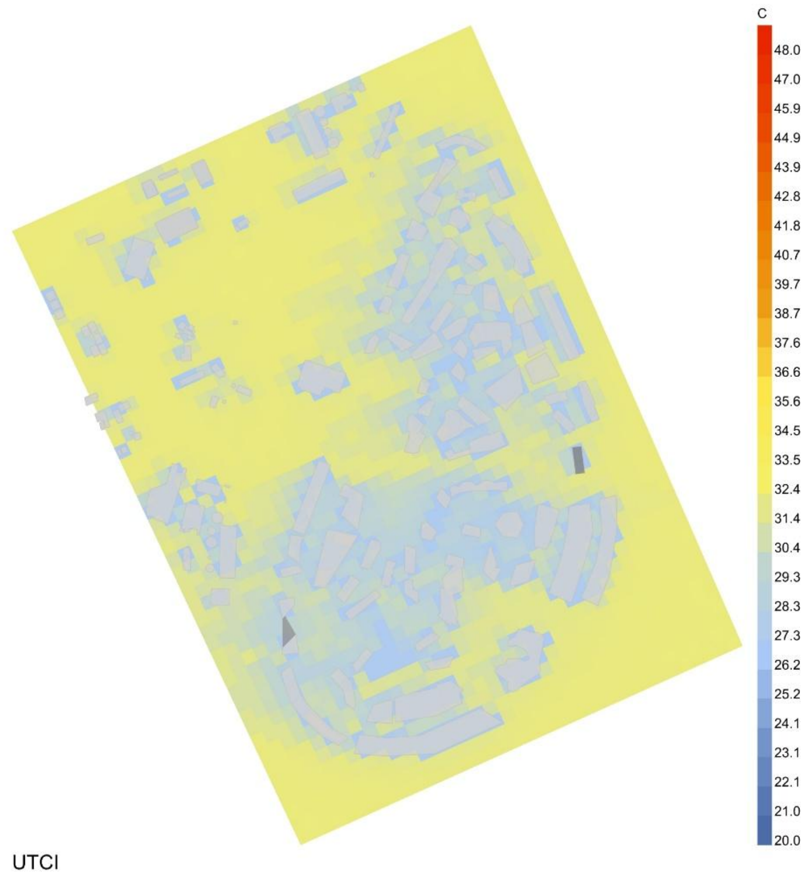



Figure 5.3b: UTCI distribution (°C) for April at KAFD (fixed scale: 20–48 °C), indicating transitional warming with moderate stress in open courtyards.

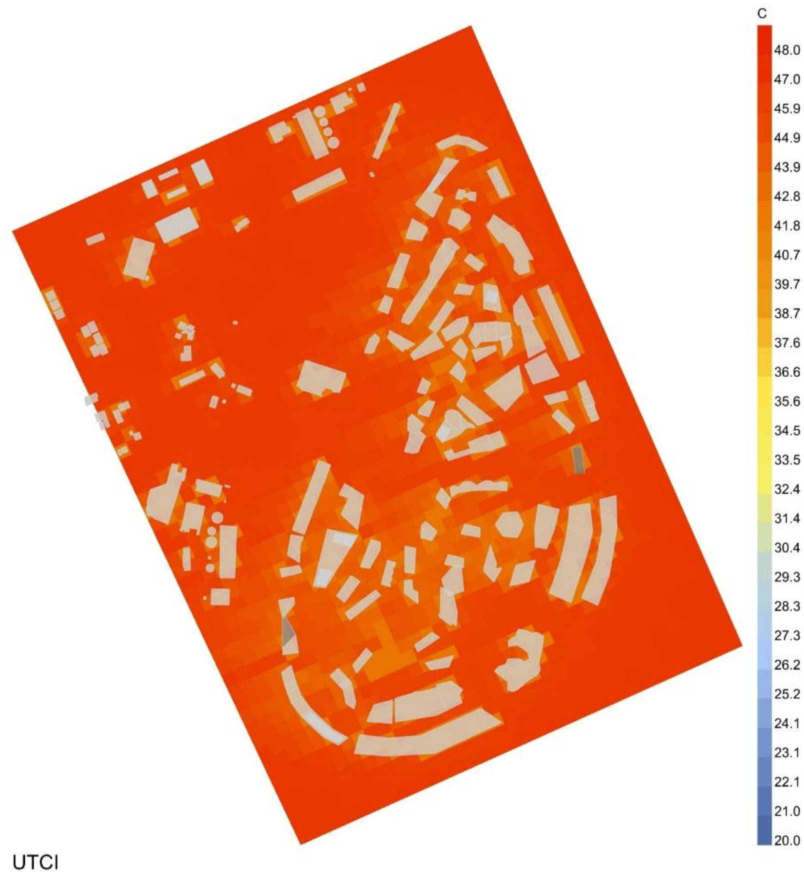



Figure 5.3c: UTCI distribution (°C) for July at KAFD (fixed scale: 20–48 °C), highlighting widespread very strong to extreme heat stress (>40–46 °C) across plazas and unshaded walkways.

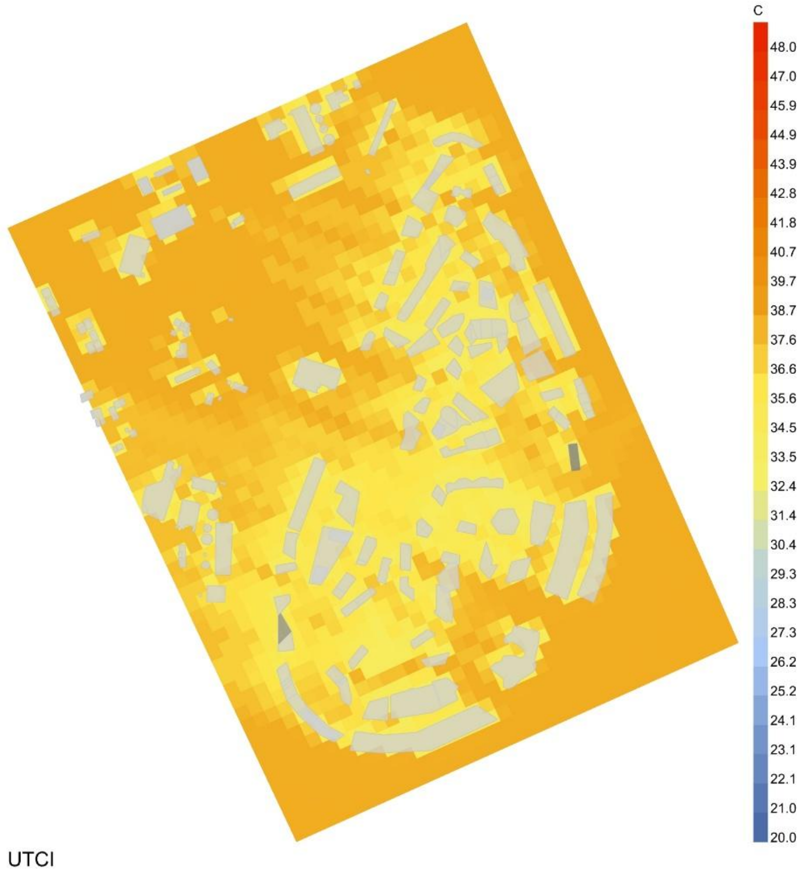



Figure 5.3d: UTCI distribution (°C) for October at KAFD (fixed scale: 20–48 °C), showing moderate–high thermal conditions as temperatures decline.

Figure 5.3: *KAFD – Seasonal UTCI Maps*

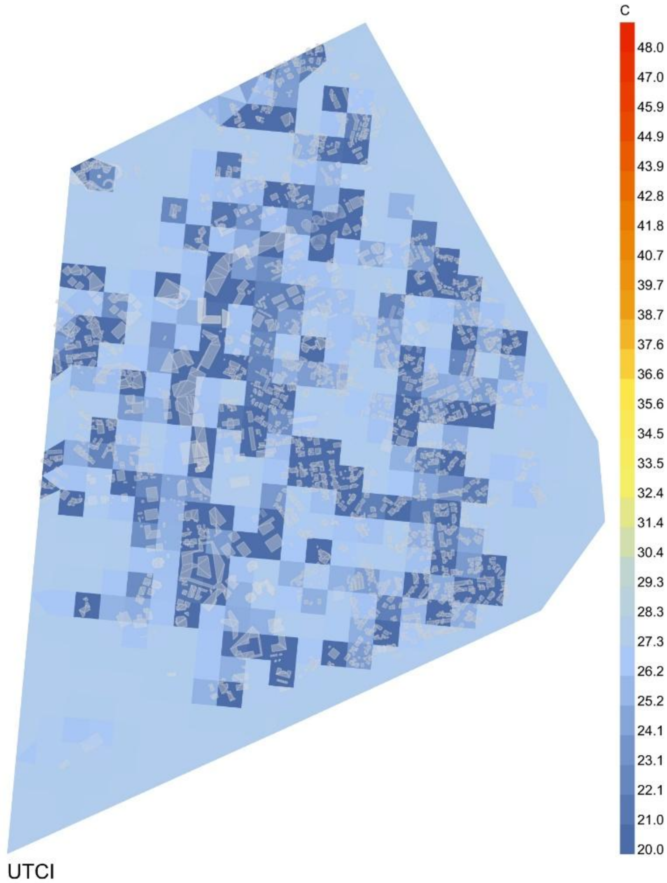



Figure 5.4a: UTCI distribution (°C) for February at the Diplomatic Quarter (fixed scale: 20–48 °C), showing mild to moderate thermal conditions across vegetated and shaded areas.

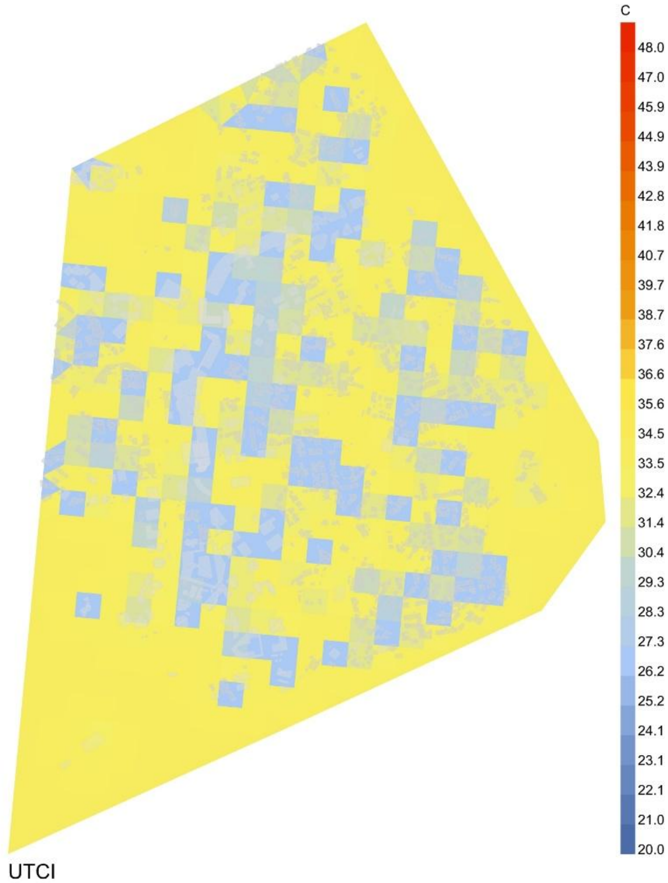



Figure 5.4b: UTCI distribution (°C) for April at the Diplomatic Quarter (fixed scale: 20–48 °C), indicating warming conditions with moderate heat stress emerging in exposed zones.

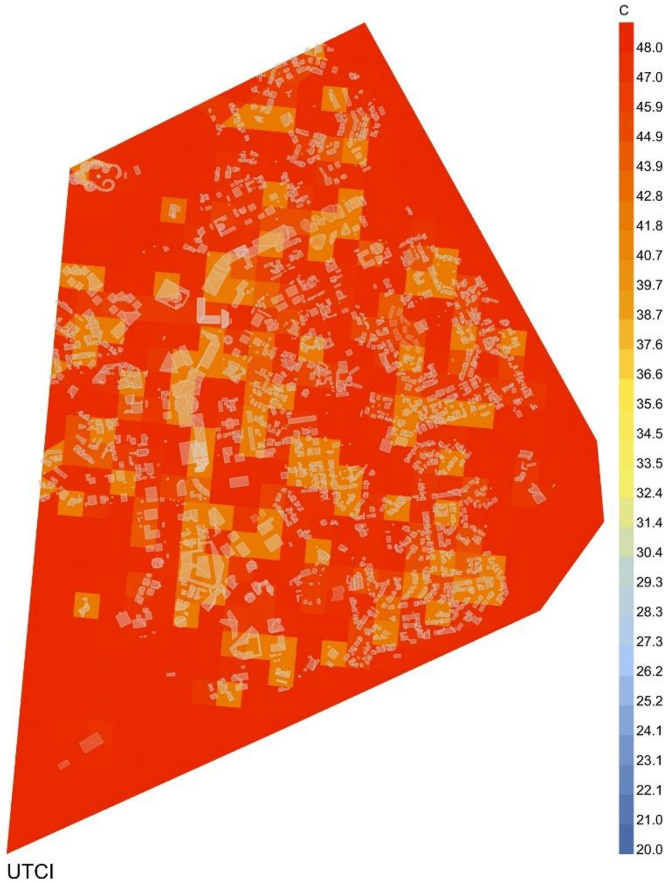



Figure 5.4c: UTCI distribution (°C) for July at the Diplomatic Quarter (fixed scale: 20–48 °C), highlighting very strong to extreme heat stress (>40–46 °C) across the majority of external spaces.

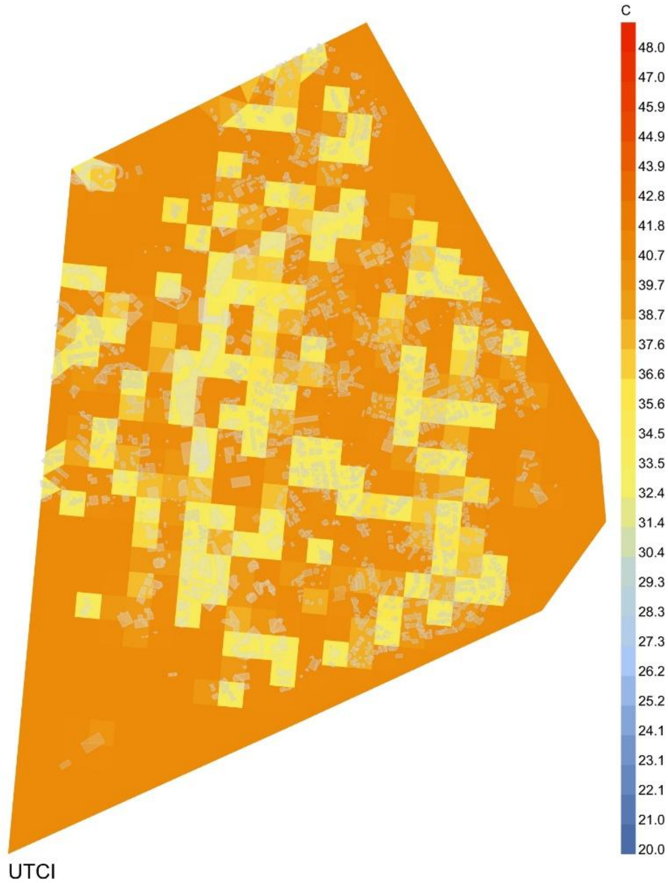



Figure 5.4d: UTCI distribution (°C) for October at the Diplomatic Quarter (fixed scale: 20–48 °C), showing moderate-to-high thermal stress as temperatures decline after summer.

Figure 5.4: Diplomatic Quarter (DQ) – Seasonal UTCI Maps

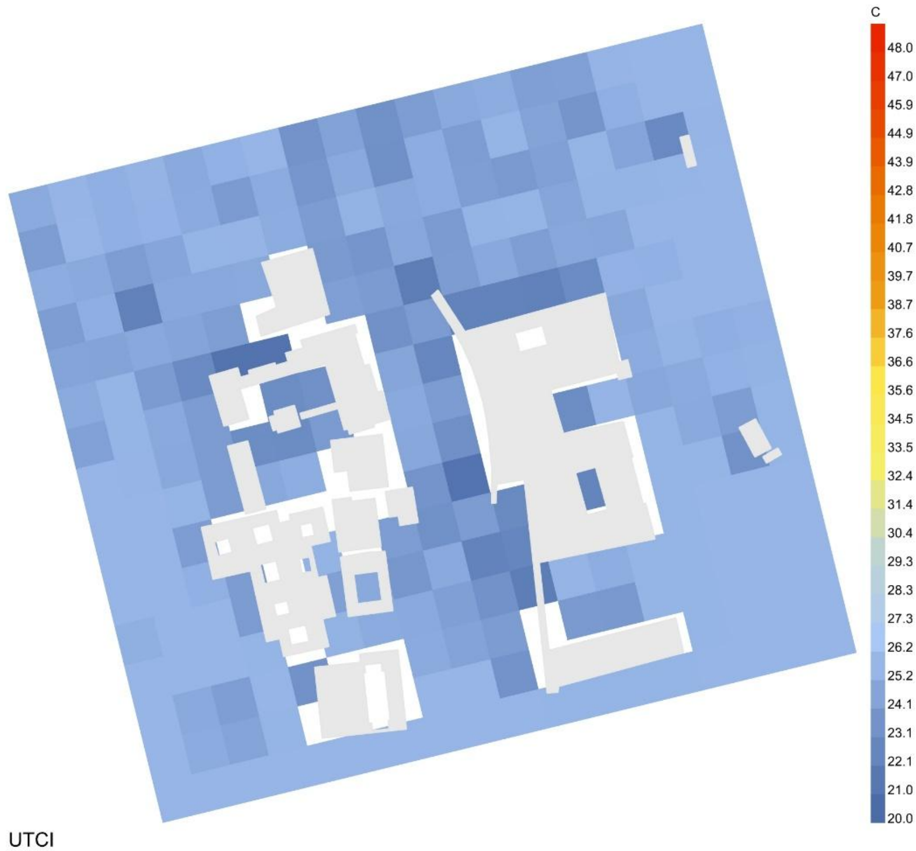



Figure 5.5a: UTCI distribution (°C) for February at the Museum District (fixed scale: 20–48 °C), showing mild thermal conditions across most outdoor spaces.

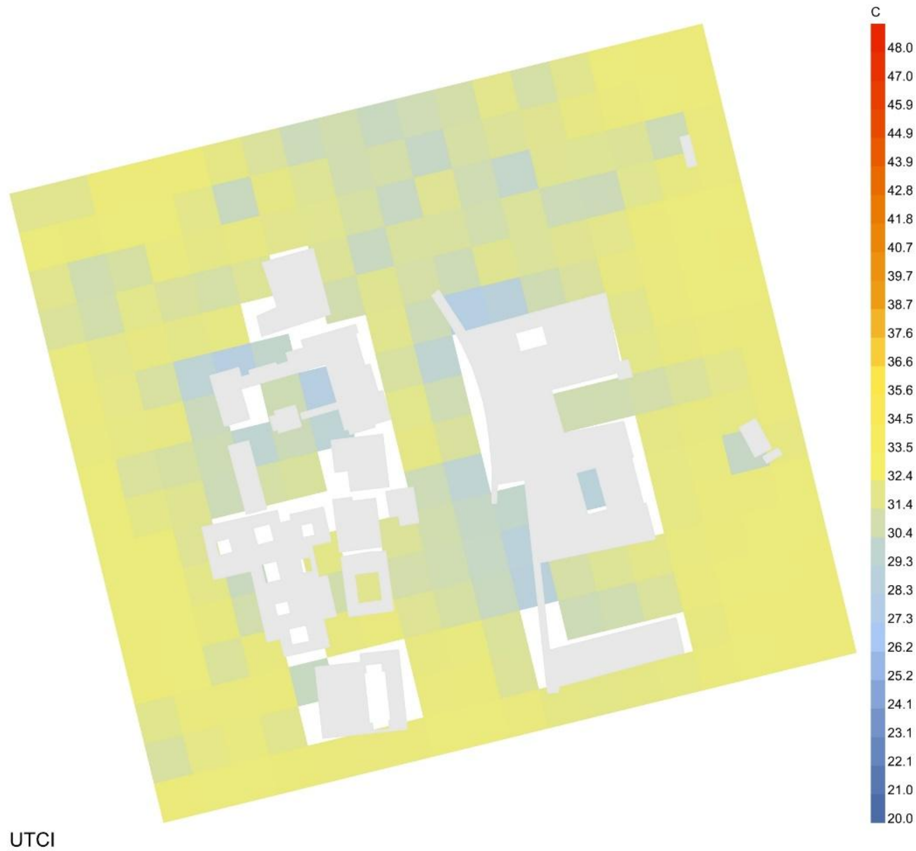



Figure 5.5b: UTCI distribution (°C) for April at the Museum District (fixed scale: 20–48 °C), indicating transitional warming with moderate thermal stress.

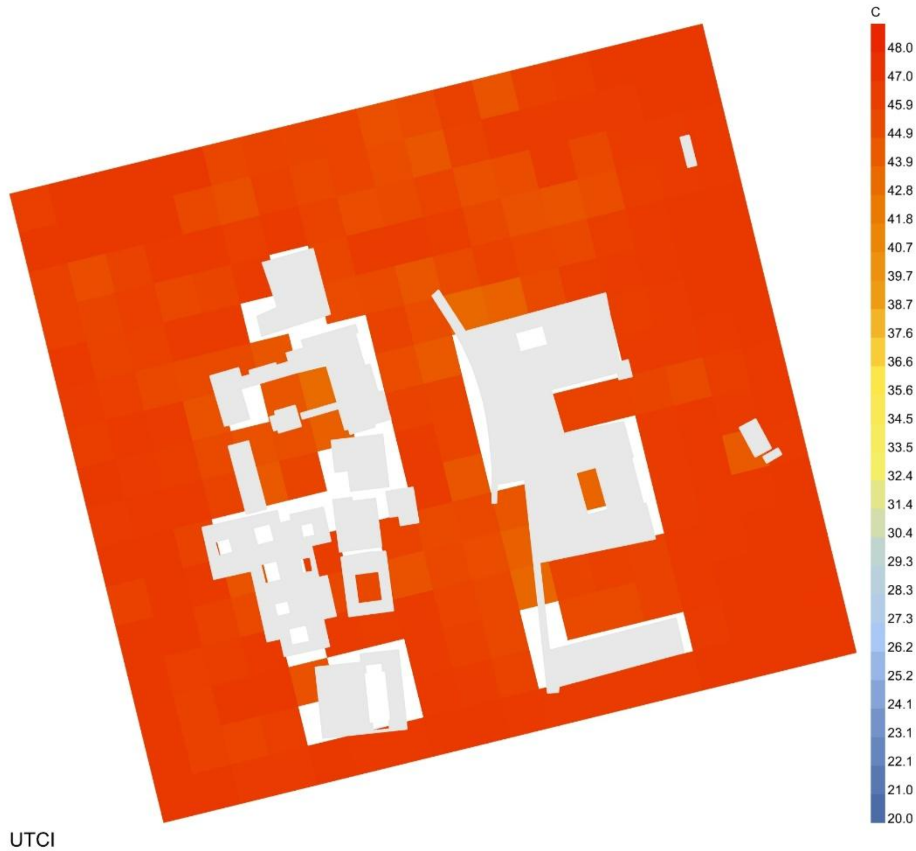



Figure 5.5c: UTCI distribution (°C) for July at the Museum District (fixed scale: 20–48 °C), highlighting dominant very strong to extreme heat stress (>40–46 °C) across plazas and outdoor circulation spaces.

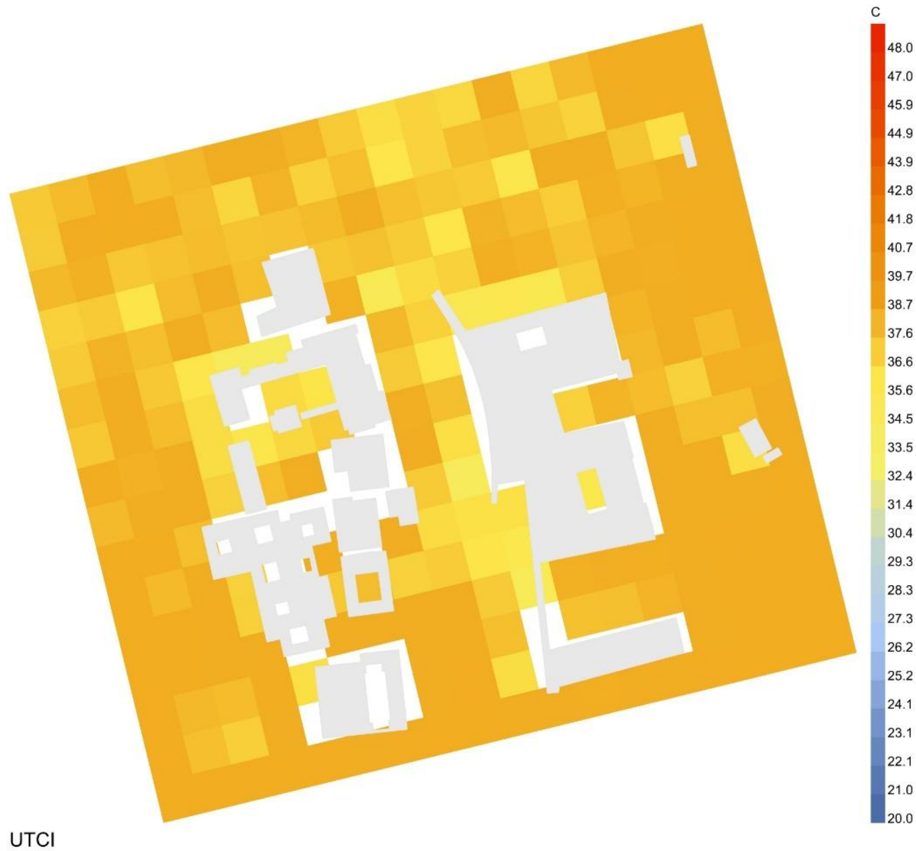



Figure 5.5d: UTCI distribution (°C) for October at the Museum District (fixed scale: 20–48 °C), showing moderate-to-high thermal stress.

Figure 5.5: Museum District – Seasonal UTCI Maps

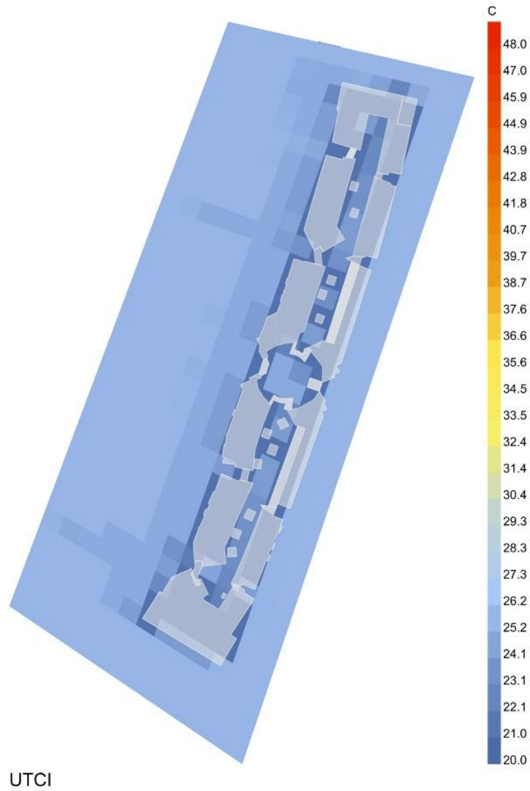



Figure 5.6a: UTCI distribution (°C) for February at Roshn Front (fixed scale: 20–48 °C), showing predominantly mild thermal conditions across the site.

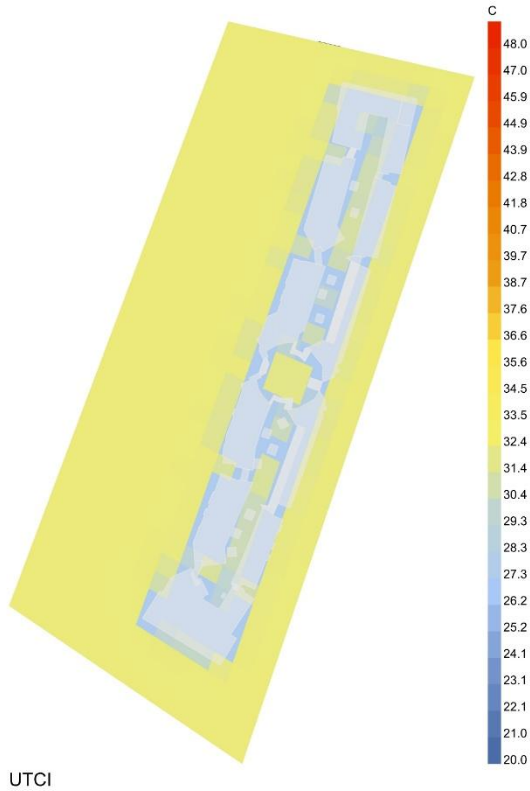



Figure 5.6b: UTCI distribution (°C) for April at Roshn Front (fixed scale: 20–48 °C), indicating transitional warming towards early summer.

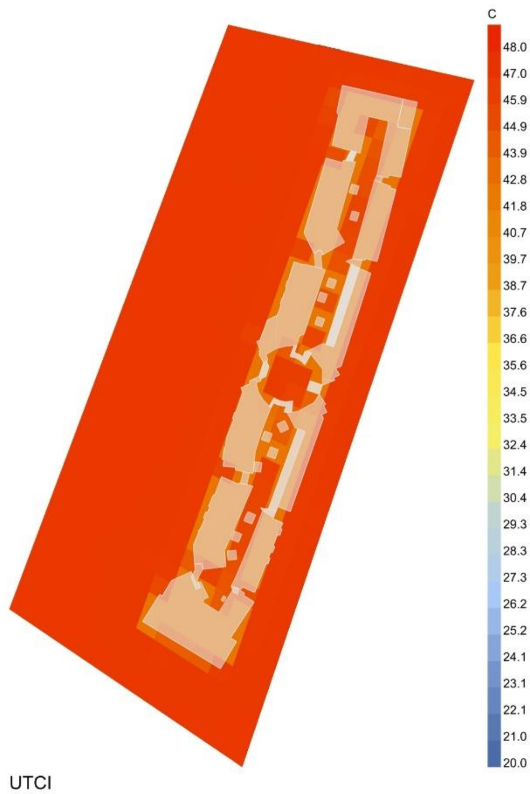



Figure 5.6c: UTCI distribution (°C) for July at Roshn Front (fixed scale: 20–48 °C), highlighting dominant very strong and extreme heat stress conditions (UTCI >40–46 °C) across exposed external spaces.

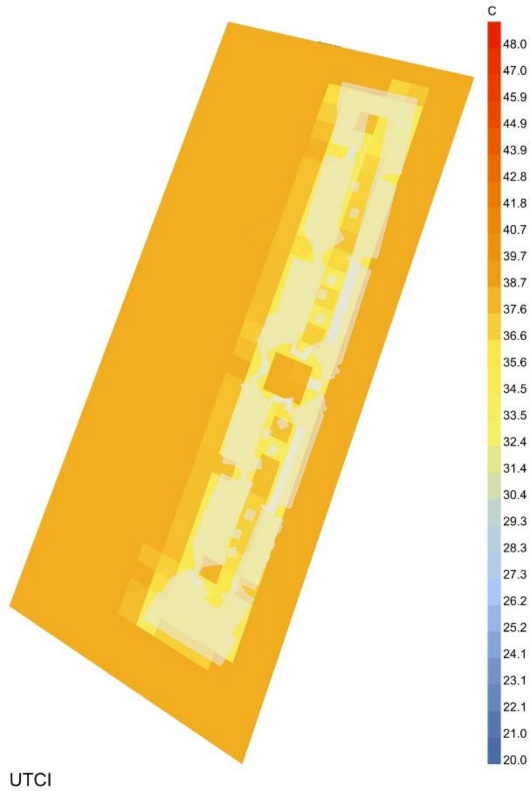



Figure 5.6d: UTCI distribution (°C) for October at Roshn Front (fixed scale: 20–48 °C), showing moderate thermal conditions as the climate cools.

Figure 5.6: Roshn Front – Seasonal UTCI Maps

**5.2.2 Spatial Variation Across Sites**

Spatial differences were observed due to variations in urban form, shading, and vegetation:

- Diplomatic Quarter exhibited the most favourable thermal profile, maintaining lower UTCI values across seasons due to vegetation and green corridors.
- KAFD and Roshn Front experienced extreme thermal stress in open plazas, particularly in July.
- Downtown Riyadh showed heterogeneous results, with traditional narrow streets offering better thermal performance in cooler months.

- Museum District benefited from semi-shaded courtyards, offering partial protection in April and October.

### 5.2.3 Vegetation Impact on UTCI: Scenario-Based Analysis (July)

To evaluate the role of vegetation in mitigating thermal stress in public spaces, a scenario-based UTCI analysis was conducted for the month of July, which represents peak summer conditions in Riyadh. This analysis was designed to isolate and quantify the impact of tree canopy cover on outdoor thermal comfort.

Three microclimatic configurations were modelled:

1. Buildings only – representing the thermal baseline of urban form without vegetation;
2. Vegetation only – isolating the contribution of trees without surrounding buildings;
3. Combined buildings + trees – replicating actual conditions where built form and vegetation interact.

Simulations revealed that vegetation played a significant role in lowering UTCI values, particularly in open plazas, pedestrian corridors, and gathering spaces exposed to direct solar radiation. Compared to the "buildings only" scenario, the inclusion of vegetation resulted in a measurable reduction in heat stress levels across all evaluated locations.

To quantify this effect, UTCI values were compared at seven observation points across a selected site during peak thermal stress hours (July, 3:00 pm). Results showed that tree cover reduced UTCI by between 1.16°C and 3.12°C, with an average reduction of approximately 2.11°C. These findings are summarised in Table 5.2.

Table 5.2: UTCI Reduction from Tree Cover – Sample Comparison (July, 3 pm)

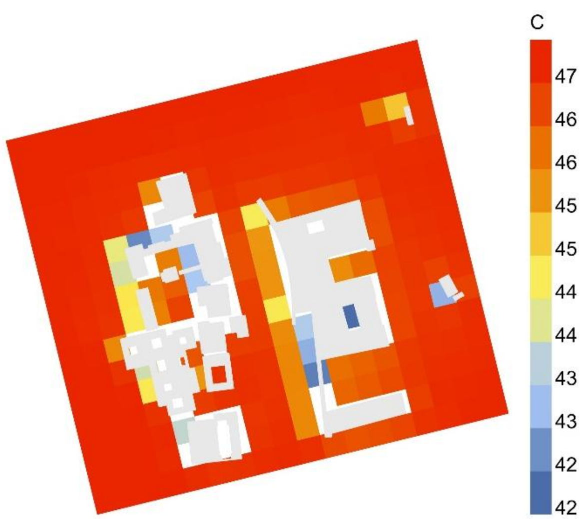
| Point | Buildings Only (°C) | Buildings + Trees (°C) | UTCI Drop (°C) |
|---|---|---|---|
| 1 | 47.41 | 45.34 | 2.07 |
| 2 | 47.41 | 44.96 | 2.45 |
| 3 | 47.41 | 44.29 | 3.12 |
| 4 | 47.41 | 45.56 | 1.85 |
| 5 | 47.41 | 44.79 | 2.62 |
| 6 | 47.41 | 45.94 | 1.47 |
| 7 | 47.41 | 46.25 | 1.16 |
| Average | | | 2.11 |

While reductions in UTCI across vegetated areas were primarily associated with shading and evapotranspiration, these values also encapsulate concurrent microclimatic interactions such as wind acceleration, surface albedo differences, and shading from adjacent structures. Consequently, the cooling observed should be interpreted as a *net microclimatic effect* rather than the isolated impact of vegetation. In compact, shaded environments such as the Museum District and the Diplomatic Quarter, these combined effects amplified the vegetation benefits through canyon shading and wind redirection, whereas in open plazas such as KAFD and Roshn Front, the impact was comparatively weaker due to higher solar exposure and limited aerodynamic shading

Note: Based on UTCI simulations comparing "Buildings Only" vs. "Buildings + Trees" configurations at 3:00 pm during July. Results confirm consistent cooling benefits across all locations.

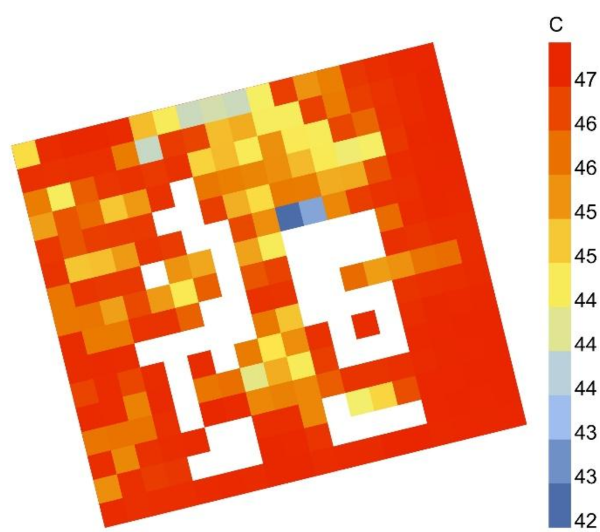
These reductions in UTCI represent a meaningful shift in thermal comfort classification, often changing a zone from "very strong heat stress" to "strong" or "moderate" stress. This thermal gain could enable extended usability of outdoor areas during otherwise thermally prohibitive conditions.

The visual comparison of the three simulation scenarios is presented in Figure 5.3e, where spatial differences in thermal performance are clearly observed. The combined scenario (buildings + trees) offers the most balanced comfort outcomes, supporting the case for integrated climate-sensitive design.



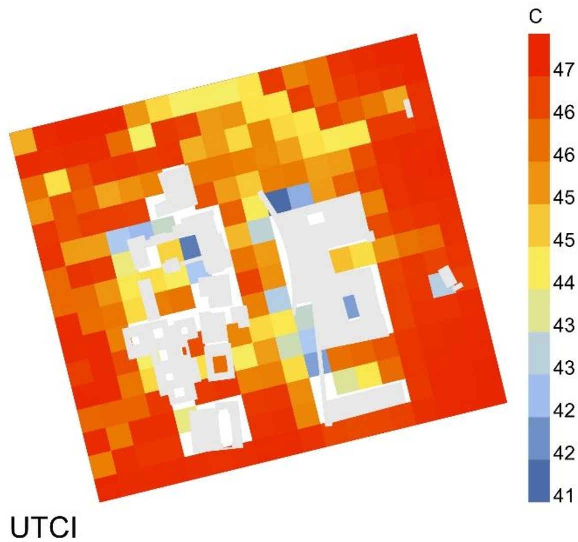

UTCI

Buildings only




UTCI

Vegetation only




Combined buildings + trees

Figure 5.7: UTCI Simulation Comparison – Buildings Only, Vegetation Only, and Combined Layers (July)

Side-by-side thermal comfort maps for the three scenarios show how tree canopy significantly reduces peak UTCI values in open spaces. Combined building–vegetation layers achieve the highest microclimatic performance.

This analysis reinforces the functional value of vegetation in urban heat mitigation and underscores its importance as a spatial design element. In the context of hot-climate cities such as Riyadh, even a 2°C reduction in UTCI during summer peak hours can significantly affect pedestrian usability and thermal resilience. These findings support the incorporation of tree canopies, green corridors, and integrated shading strategies into future urban design guidelines.

### 5.2.4 Diurnal Thermal Variation – Downtown Riyadh (July)

Simulations for three time points 3:00 am, 9:00 am, 3:00 pm revealed a rapid increase in thermal stress throughout the day.

- 3:00 am: UTCI ~28.7°C – mild stress
- 9:00 am: UTCI ~34.6°C – strong heat stress
- 3:00 pm: UTCI ~47.8°C – extreme heat stress

Shaded zones recorded up to 3.2°C lower UTCI, highlighting the critical role of permanent and adaptive shade.

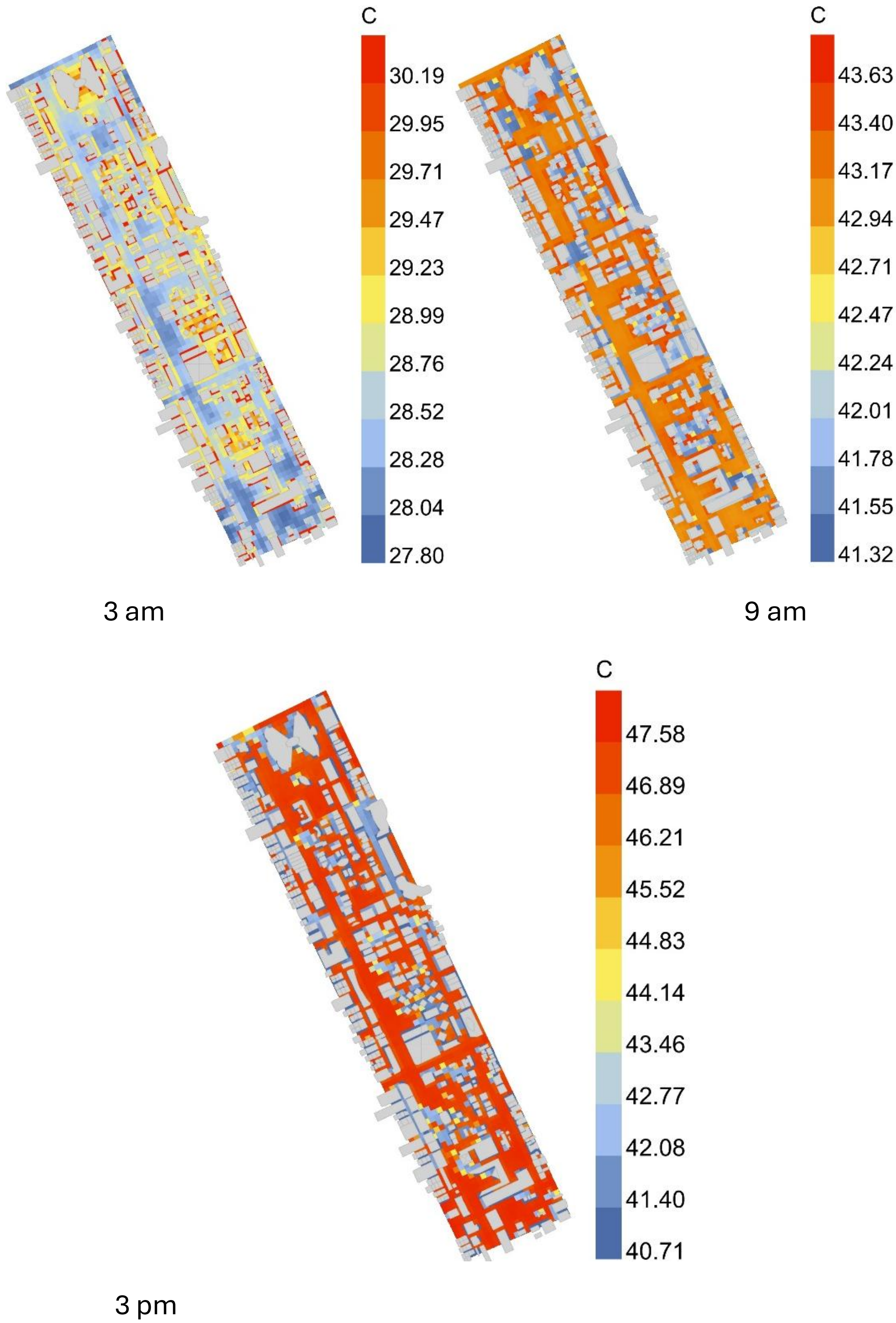



Figure 5.8 – Downtown UTCI – Diurnal Heatmaps (3 am, 9 am, 3 pm)

5.2.5 Intra-day Variation in Thermal Comfort – Roshn Front (July)

Roshn Front followed a similar diurnal profile but reached the highest recorded UTCI levels, exceeding 50°C in open zones by 3:00 pm.

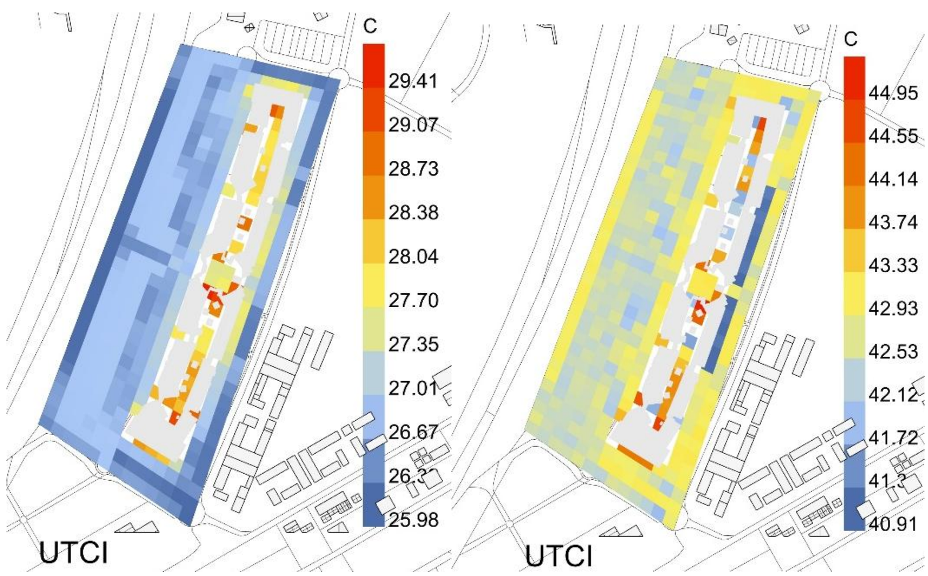
3:00 am: Mild to moderate stress (26–29°C)

9:00 am: UTCI ~35–36°C – strong heat stress

3:00 pm: Extreme heat stress across all areas

These findings indicate severely constrained daytime usability and support the need for night-time programming and thermal design upgrades.

At 3 am




At 9 am

By 3 pm

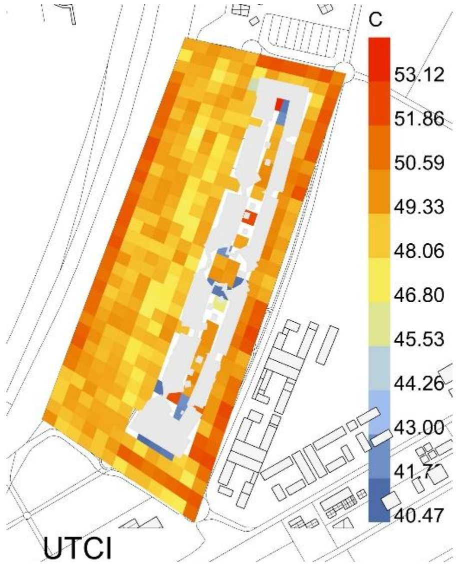



Figure 5.9: Diurnal UTCI – Roshn Front (3 am, 9 am, 3 pm)

UTCI maps reveal intense thermal stress escalation by afternoon, surpassing 50°C in exposed retail and pedestrian areas.

**5.2.6 Summary of UTCI by Time and Site**

A comparative table summarises UTCI values across time for all five sites.

Table 5.3: Comparative UTCI Values Across Time Points – July (°C)

| **Site** | **3:00 am** | **9:00 am** | **3:00 pm** |
|---|---|---|---|
| Downtown Riyadh | 28.7 | 34.6 | 47.8 |
| King Abdullah Financial District (KAFD) | 27.9 | 35.2 | 48.9 |
| Diplomatic Quarter (DQ) | 27.1 | 32.8 | 45.1 |
| Museum District | 28.0 | 33.7 | 47.2 |
| Roshn Front | 29.1 | 35.8 | 50.3 |

Thermal comfort categories follow standard UTCI classification (Jendritzky et al., 2009):

- No Thermal Stress: 9–26°C

- Slight Heat Stress: 26–32°C
- Moderate Heat Stress: 32–38°C
- Strong Heat Stress: 38–46°C
- Very Strong to Extreme Heat Stress: > 46°C

The diurnal UTCI comparison reveals a rapid deterioration in thermal conditions from early morning to mid-afternoon, particularly during the summer months. While 3:00 am and 9:00 am offer short windows of potential usability, 3:00 pm conditions consistently exceed 45°C, rendering most outdoor spaces thermally hostile. Among the five study sites, the Diplomatic Quarter consistently performs better, maintaining lower UTCI levels across all time points due to its green infrastructure and shading, while Roshn Front exhibits the highest thermal load, with UTCI values exceeding 50°C in the afternoon.

These findings reinforce the necessity of time-sensitive design strategies, such as shading, night-time programming, and climate-responsive materials. However, usability also depends on how easily and comfortably people can move through these spaces. The following section examines the spatial configuration and connectivity of each site using Flipped Betweenness Centrality (FBC), which highlights how urban layout and pedestrian access influence usability in tandem with thermal comfort.

### 5.2.7 UTCI Classification by Category and Season

Table 5.4 – Percentage of Area per UTCI Category by Site and Season

| Site | Season | No Stress (9–26°C) | Slight (26–32°C) | Moderate (32–38°C) | Strong (38–46°C) | Extreme (>46°C) |
|---|---|---|---|---|---|---|
| Downtown | Feb | 82% | 15% | 3% | 0% | 0% |
| | Apr | 30% | 40% | 20% | 10% | 0% |
| | July | 0% | 2% | 18% | 40% | 40% |
| | Oct | 25% | 50% | 20% | 5% | 0% |
| KAFD | Feb | 75% | 22% | 3% | 0% | 0% |
| | Apr | 20% | 35% | 30% | 15% | 0% |
| | July | 0% | 1% | 12% | 43% | 44% |
| | Oct | 18% | 47% | 25% | 10% | 0% |
| DQ | Feb | 88% | 10% | 2% | 0% | 0% |

| | | | | | | |
|---|---|---|---|---|---|---|
| | Apr | 35% | 45% | 15% | 5% | 0% |
| | July | 2% | 6% | 22% | 45% | 25% |
| | Oct | 28% | 50% | 18% | 4% | 0% |
| Museum District | Feb | 80% | 17% | 3% | 0% | 0% |
| | Apr | 25% | 40% | 25% | 10% | 0% |
| | July | 0% | 3% | 18% | 47% | 32% |
| | Oct | 22% | 48% | 25% | 5% | 0% |
| Roshn Front | Feb | 70% | 25% | 5% | 0% | 0% |
| | Apr | 15% | 40% | 30% | 15% | 0% |
| | July | 0% | 0% | 10% | 42% | 48% |
| | Oct | 20% | 45% | 25% | 10% | 0% |

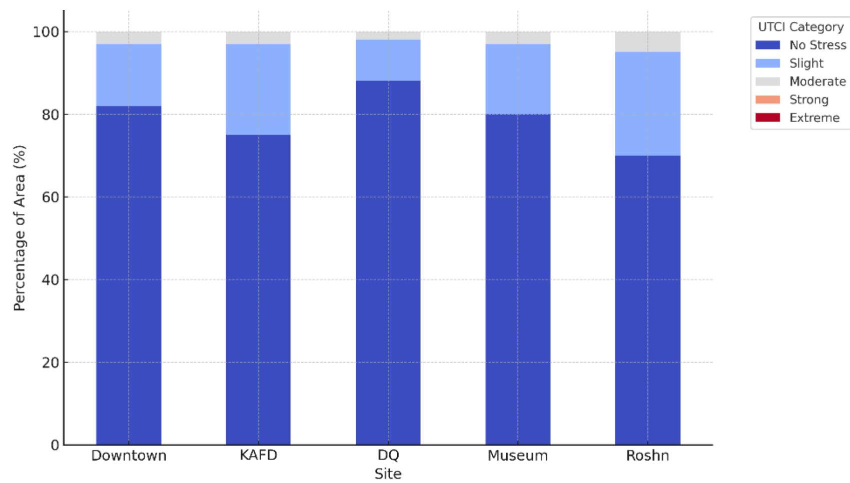



Figure 5.5a: UTCI Classification – February

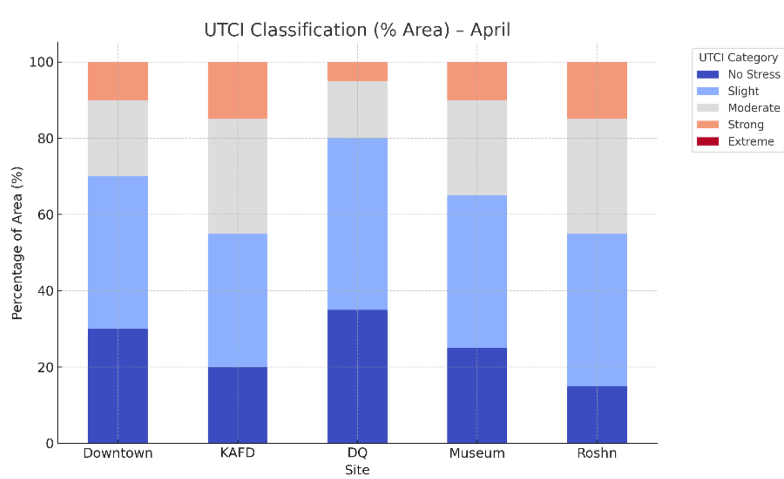


Figure 5.5b: UTCI Classification – April

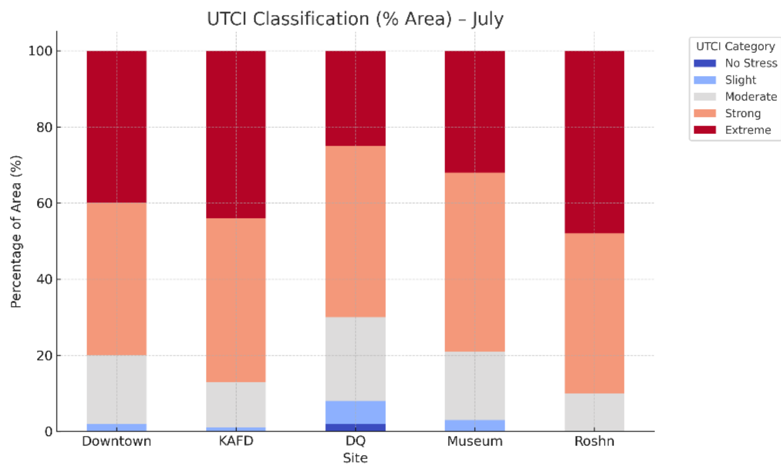



Figure 5.5c: UTCI Classification – July

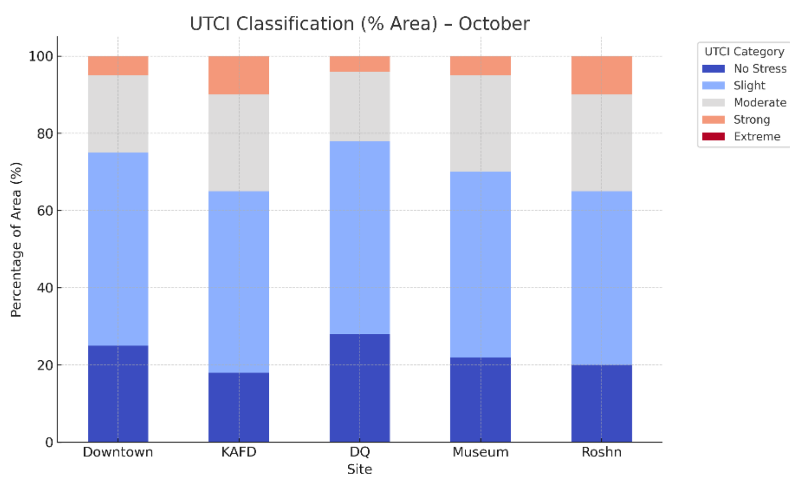



Figure 5.5d: UTCI Classification – October

The seasonal classification analysis confirms that July poses the most extreme thermal challenge, with over 80% of area in some sites falling under “strong” or “extreme” heat stress. In contrast, February and October offer the highest potential for outdoor usability, with most of the public space falling within the “no stress” or “slight heat stress” zones. Sites such as the Diplomatic Quarter consistently demonstrated better thermal performance due to integrated vegetation and shading, while Roshn Front and KAFD showed elevated stress levels due to large unshaded zones and extensive paving.

These patterns highlight the significant role of urban design features such as shading, vegetation, and surface materials in shaping thermal comfort outcomes. However, thermal performance alone does not fully determine spatial usability. The configuration and connectivity of urban networks also play a critical role in how public spaces are accessed and navigated, particularly in hot-climate contexts where route choices are influenced by both efficiency and exposure.

The following section explores these spatial factors in detail, using Flipped Betweenness Centrality (FBC) to assess walkability and connectivity patterns across the same five sites.

## 5.3 Spatial Connectivity Results

### 5.3.1 Introduction

In addition to thermal comfort, the spatial structure of the urban environment plays a critical role in determining the usability of public spaces particularly in hot-climate cities where pedestrians often seek routes that are both spatially efficient and thermally adaptive. This section presents the spatial connectivity analysis results based on Flipped Betweenness Centrality (FBC), a modified Space Syntax measure that accounts for pedestrian-scale decision-making and climate sensitivity.

Unlike traditional betweenness centrality, which typically favours globally integrated, long axial paths, FBC prioritises shorter, angularly efficient routes that align more closely with actual pedestrian behaviour under environmental stress, such as avoiding heat or seeking shade. This thermally informed approach is especially relevant in Riyadh, where extreme temperatures shape spatial practices and route preferences.

The analysis was conducted across the same five case study sites evaluated in the thermal comfort simulations: Downtown Riyadh, KAFD, Diplomatic Quarter (DQ), Museum District, and Roshn Front. Using FBC, each site's pedestrian network was assessed for integration, permeability, and spatial hierarchy, providing insights into how walkability is influenced by urban form.

This section is structured as follows:

- Section 5.3.2 provides site-by-site FBC maps and interpretation.
- Section 5.3.3 compares connectivity performance across sites.

- Section 5.3.4 discusses the climatic implications of connectivity patterns.
- Sections 5.3.5 and 5.3.6 present sensitivity analyses for path radius and intersection density, respectively.
- Section 5.3.7 concludes with key insights and implications for spatial design.

The integration of FBC with climatic and perceptual layers in later sections supports a more holistic understanding of usable public space in hot, arid environments.

### 5.3.2 FBC Spatial Distribution by Site

This section presents the Flipped Betweenness Centrality (FBC) results for each of the five case study sites: Downtown Riyadh, King Abdullah Financial District (KAFD), Diplomatic Quarter (DQ), Museum District, and Roshn Front. FBC maps reveal how movement potential is distributed within each network, with particular emphasis on short, angularly efficient, and thermally adaptive pedestrian paths. High FBC values (represented by red/orange tones) indicate locally integrated and behaviourally preferred segments, while low values (blue tones) highlight thermally exposed, disconnected, or marginal spaces.

*Downtown Riyadh*

Downtown Riyadh exhibits a fine-grained, irregular street network characteristic of traditional Najdi morphology. As shown in Figure 5.8, normalised FBC values (0–1) are distributed across short internal paths, with highest centrality concentrated in shaded alleys, narrow connectors, and side routes. These segments provide both spatial efficiency (short, angularly direct links) and thermal advantage, and they align with observed pedestrian route choices. In contrast, major axial roads show lower FBC because of their greater angular length and exposure

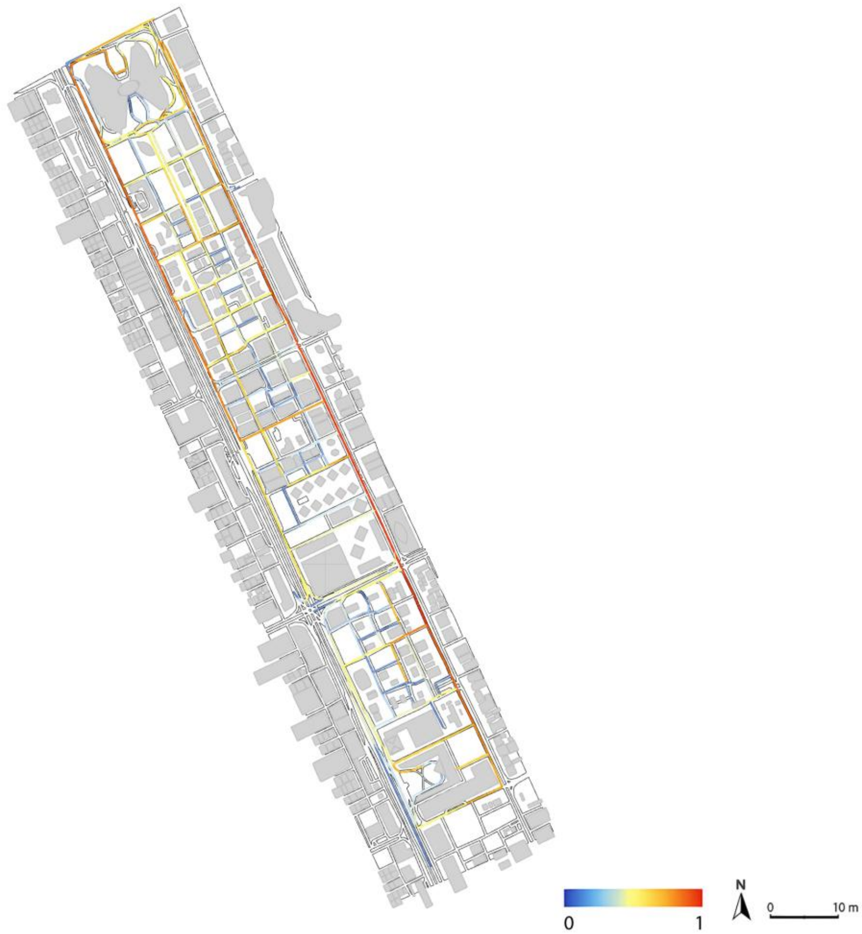



Figure 5.8: Flipped Betweenness Centrality (FBC) – Downtown Riyadh

*Normalised FBC scale 0–1 (0 = lowest connectivity, 1 = highest). High values cluster along shaded internal passages and short connectors; primary axial roads are relatively de-prioritised due to angular length and thermal exposure.*

Overall, Downtown's micro-links act as the main carriers of movement potential, reinforcing the role of fine-grained permeability in hot-climate historic fabrics.

*King Abdullah Financial District (KAFD)*

KAFD's planned urban form is characterised by wide boulevards, formal axes, and a sequence of large open plazas. As shown in Figure 5.9, the normalised FBC values (0–1) reveal that connectivity is strongest along internal corridors, particularly those embedded within shaded or semi-covered passages. These segments offer shorter angular routes and protection from direct solar exposure, reinforcing their role as preferred movement pathways. In contrast, the large, exposed plazas and long perimeter blocks display low FBC, indicating a structural and climatic misalignment that limits continuous pedestrian flow and reduces thermally comfortable walkability across the district.


Figure 5.9: Flipped Betweenness Centrality (FBC) – KAFD

*Normalised FBC scale 0–1 (0 = lowest connectivity, 1 = highest). Centrality is concentrated in shaded internal corridors, while exposed plazas and long perimeter segments display low connectivity.*

KAFD's connectivity pattern demonstrates how architectural enclosure, rather than boulevard hierarchy, drives pedestrian potential in hot climates.

*Diplomatic Quarter (DQ)*

The Diplomatic Quarter demonstrates one of the strongest FBC performances among the study areas. As shown in Figure 5.10, the normalised FBC values (0–1) indicate consistently high centrality across a well-connected system of green corridors, looping pathways, and shaded pedestrian routes. These network characteristics create a balanced spatial hierarchy that distributes movement potential efficiently throughout the district. Centrality is particularly evident along the shaded perimeter routes and internally integrated pedestrian corridors, while connectivity decreases in open or unshaded areas, where exposure and longer angular paths reduce pedestrian attractiveness and continuous walkability.


Figure 5.10: Flipped Betweenness Centrality (FBC) -Diplomatic Quarter (DQ)

*Normalised FBC scale 0–1 (0 = lowest connectivity, 1 = highest). High connectivity is concentrated along shaded corridors and looping pedestrian rout*

*es, with lower values in exposed or unshaded segments.*

The DQ’s spatial form shows how landscaped corridors and shaded circulation loops structurally enhance pedestrian resilience in hot climates.

*Museum District*

The Museum District combines perimeter circulation routes, internal courtyards, and a series of civic plazas. As illustrated in Figure 5.11, the normalised FBC values (0–1) are generally moderate, with the strongest centrality concentrated along the perimeter connectors and the courtyard-loop system. These segments offer angularly efficient routes and shaded movement options. In contrast, the central open spaces exhibit weaker integration, reflecting both spatial fragmentation and greater thermal exposure. This discontinuity reduces pedestrian adaptability and limits the formation of continuous, climate-responsive movement patterns within the site.


Figure 5.11: Flipped Betweenness Centrality (FBC) – Museum District

*Normalised FBC scale 0–1 (0 = lowest connectivity, 1 = highest). Moderate connectivity is observed along courtyard–perimeter loops, while internal fragmentation and exposed open areas result in lower FBC values.*

The Museum District highlights how fragmented open-space structures weaken connectivity despite strong perimeter circulation.

*Roshn Front*

Roshn Front demonstrates the lowest overall FBC performance among the study areas. As shown in Figure 5.12, the street network is dominated by wide, exposed boulevards and large, regularly spaced blocks, resulting in limited angular efficiency and weak internal permeability. Movement is channelled through a small number of linear, thermally exposed routes, with minimal mid-block connectors or shade-responsive pathways. This configuration restricts pedestrian adaptability and reduces the formation of continuous, climate-sensitive movement options.

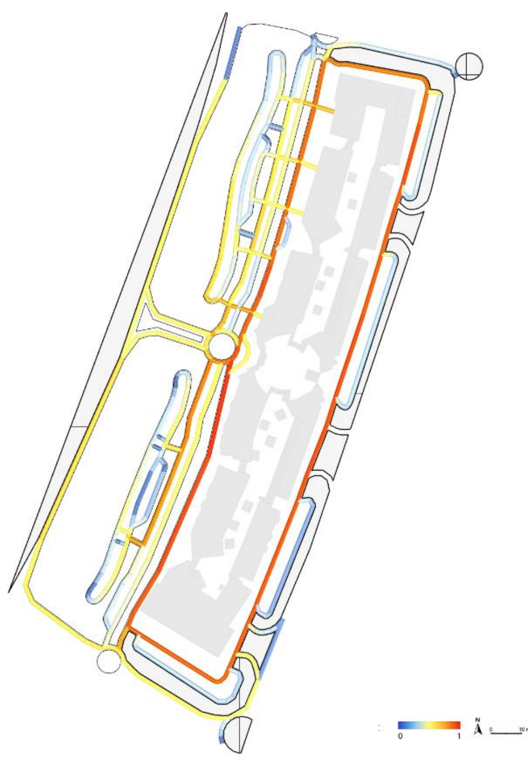


Figure 5.12: Flipped Betweenness Centrality – Roshn Front

*Normalised FBC scale 0–1 (0 = lowest connectivity, 1 = highest). Connectivity is concentrated along exposed linear routes, while low permeability and the absence of micro-connectors reduce walkability and movement continuity.*

The spatial distribution of FBC values across the five study sites reveals a clear relationship between network morphology and climate-sensitive walkability. Areas with compact, fine-grained structures such as Downtown Riyadh and the Diplomatic Quarter demonstrate higher FBC scores due to their abundance of short, shaded, and angularly efficient routes. In contrast, planned environments with large blocks and extensive open spaces most notably KAFD and Roshn Front perform poorly, particularly where mid-block connections and internal shading are limited. These results reinforce FBC's value as a diagnostic metric for identifying movement potential under hot-climate conditions and for understanding how spatial structure shapes pedestrians' ability to navigate thermally challenging environments. The next section builds on these findings by providing a comparative evaluation across all sites using standardised criteria.

### 5.3.3 Cross-Site Comparison of Connectivity Performance

Following the site-specific analysis presented in Section 5.3.2, this section offers a comparative evaluation of spatial connectivity performance across the five case study areas Downtown Riyadh, KAFD, Diplomatic Quarter (DQ), Museum District, and Roshn Front using Flipped Betweenness Centrality (FBC) as the primary metric. The comparison draws on spatial outputs, qualitative observations, and scoring benchmarks to summarise each site's performance across four key dimensions:

1. FBC-based connectivity
2. Pedestrian permeability
3. Thermal adaptation potential
4. Overall spatial usability

The purpose of this cross-site comparison is to identify which urban forms support climate-sensitive walkability and which inhibit it. This synthesis contributes directly to the development of targeted design and planning recommendations in Chapter 6.

Table 5.5: Comparative Summary of Spatial Connectivity and Usability

| Site | FBC Score | Permeability | Thermal Adaptation | Overall Usability |
|---|---|---|---|---|
| Downtown Riyadh | 4.0 | 4.5 | 4.0 | 4.5 |
| KAFD | 2.5 | 2.0 | 2.5 | 2.5 |
| Diplomatic Quarter | 4.5 | 4.5 | 5.0 | 5.0 |
| Museum District | 3.0 | 3.5 | 3.0 | 3.5 |
| Roshn Front | 2.0 | 2.0 | 2.0 | 2.0 |

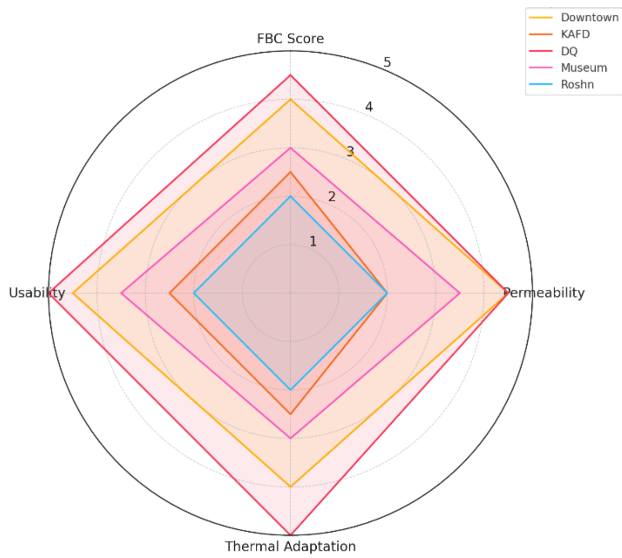



Figure 5.13: Radar Chart – Spatial Connectivity Comparison

The radar chart provides a visual comparison across the four criteria. As seen in Figure 5.13, the Diplomatic Quarter achieves the highest scores overall, excelling in thermal adaptation and spatial coherence. Downtown Riyadh also performs well, particularly in pedestrian permeability due to its fine-grained and organically shaded network. By contrast, Roshn Front and KAFD score lowest, reflecting wide, exposed boulevards and low spatial redundancy, which reduce adaptive pedestrian movement.

Downtown Riyadh performs well in local connectivity, benefiting from narrow paths, small blocks, and informal shading. Its high FBC values reflect climate-adaptive circulation, though long-term resilience is constrained by limited infrastructure investment.

KAFD, though formally well-connected in a traditional sense, exhibits poor performance under FBC due to thermal exposure and block segmentation. Its wide streets lack shade and discourage adaptive movement patterns. The Diplomatic Quarter presents the most climatically coherent and spatially integrated network, with continuous shaded routes, vegetated buffers, and multiple path options that align with thermal adaptation behaviour.

The Museum District shows moderate performance, excelling in perimeter connectivity but weakened by internal fragmentation and thermal exposure in open plazas. Roshn Front, a newer commercial site, ranks lowest across all criteria due to its monofunctional spatial layout, minimal shading, and limited mid-block connections.

This comparative analysis underscores the need for urban design approaches that go beyond geometric efficiency. High FBC performance is not simply a function of integration but depends on the alignment of spatial logic with thermal conditions, human behaviour, and microclimatic adaptation. The best-performing sites DQ and Downtown demonstrate how urban form can support comfortable, flexible, and shaded movement even in extreme climates.

In contrast, areas like KAFD and Roshn Front highlight the risks of relying on formal axial design without considering environmental usability. These insights reinforce the case for using FBC as a diagnostic tool for identifying spatial deficiencies and opportunities for improvement in public realm planning.

### 5.3.4 Climatic Relevance of FBC Results

The previous sections established how Flipped Betweenness Centrality (FBC) identifies pedestrian-scale spatial connectivity under thermal constraints. This section explores the climatic relevance of FBC by examining how high-centrality segments correspond with shaded, thermally adaptive pathways, and how FBC outputs align with thermal comfort conditions measured using UTCI.

Unlike traditional betweenness centrality, which tends to prioritise globally integrated axial lines, FBC reveals movement logic grounded in thermal adaptation. This becomes especially meaningful in hot-climate contexts, such as Riyadh, where microclimatic features such as shade, vegetation, and urban form directly influence pedestrian behaviour.

#### FBC and Shaded Micro-Networks

Across all five case study sites, a strong spatial correlation was observed between high FBC scores and shaded, human-scaled routes. In Downtown Riyadh, for example, internal alleyways with minimal solar exposure scored significantly higher in FBC than wide, open intersections. Similarly, in the Diplomatic Quarter, green corridors and vegetated loops coincided with high centrality values, reinforcing their spatial and environmental significance.

In contrast, in KAFD and Roshn Front, FBC scores were lower in wide, exposed plazas and long boulevards, even if those spaces had strong axial logic in the traditional model. This suggests that FBC is not only spatially informative, but also sensitive to climatic constraints that influence daily usability and route choice.

### Interpreting Movement Potential Under Thermal Stress

Pedestrian behaviour under heat stress tends to favour shorter, more navigable routes that offer thermal protection. FBC maps consistently revealed that these routes often informal, shaded, or secondary were undervalued in conventional analysis but critical for real-world usability. By reflecting these choices, FBC offers a more realistic measure of pedestrian-accessible infrastructure in thermally extreme conditions.

In many cases, segments with high UTCI values (indicating high heat stress) also had low FBC scores, confirming their marginal role in thermally viable movement. Conversely, routes with lower UTCI (shaded or vegetated zones) often had higher FBC, reflecting their dual spatial and environmental importance.

### Implications for Climate-Responsive Planning

The alignment between FBC and microclimatic performance reinforces the value of FBC as a climate-adaptive spatial analysis tool. Its relevance extends beyond geometric efficiency to capture behavioural and environmental realities in cities with extreme heat.

From a planning perspective, this has several implications:

- High-FBC corridors should be prioritised for investment in shading infrastructure, green cover, and active transport amenities.
- Low-FBC areas that coincide with high UTCI may require redesign or retrofitting, such as mid-block connectors, narrower sections, or added canopy coverage.
- FBC can support thermal equity, helping planners identify spatially marginalised areas where connectivity and comfort are lowest.

**Integrating with UCCI**

As part of the broader Urban Comfort–Connectivity Index (UCCI), FBC complements UTCI and CPI by offering a spatial logic layer grounded in both movement theory and environmental adaptation. Its results provide critical context for interpreting the overall usability scores in Section 5.5 and support more nuanced design recommendations in Chapter 6.

The overlay presented in Figure 5.15 provides a combined view of thermal stress (UTCI) and spatial connectivity (FBC) across the pedestrian network. The visualisation reveals a clear inverse relationship in several segments: areas with elevated UTCI values often correspond to lower FBC scores, suggesting that pedestrians not only avoid thermally exposed routes but that these routes are also spatially marginal. Conversely, segments with higher FBC scores tend to align with lower UTCI values, typically found in shaded or vegetated corridors. This alignment reinforces the relevance of FBC as a climate-sensitive metric that reflects actual movement potential under heat stress. It also highlights key spatial segments where thermal and spatial deficiencies coincide, thereby identifying priority zones for targeted interventions such as shade provision, micro-connectors, or surface cooling strategies.

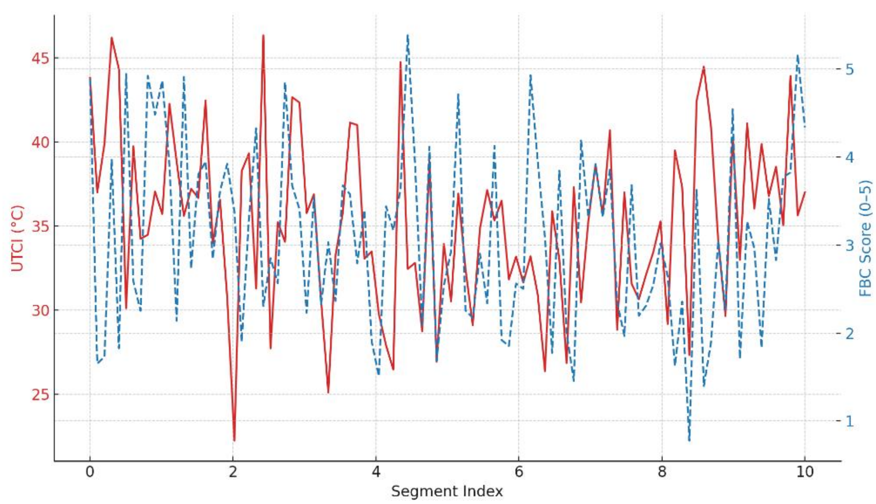



Figure 5.14: Overlay of UTCI and FBC Scores Across Network Segments

This dual-axis chart illustrates the relationship between thermal stress (UTCI, red line) and spatial connectivity (FBC, blue dashed line). Peaks in UTCI often align with troughs in FBC, highlighting segments that are both thermally stressful and spatially marginal areas that may require targeted design interventions to enhance walkability and comfort.

### 5.3.6 Parametric Sensitivity of Spatial Accessibility

While the Flipped Betweenness Centrality (FBC) method offers valuable insights into pedestrian accessibility under thermal stress, its outputs are sensitive to the parameters and network assumptions used in the analysis. This section explores how two key modelling factors shortest path radius and intersection density influence the distribution of accessibility values. These sensitivity tests provide a deeper understanding of how spatial accessibility is not fixed but can be shaped by both analytical framing and real-world design interventions.

#### 5.3.6.1 Sensitivity to Path Radius

The shortest path radius defines the spatial range within which angular relationships are evaluated in Space Syntax models. To test the impact of this parameter on FBC results, three radii were modelled: infinite, 1000 metres, and 500 metres. These reflect movement scales ranging from city-wide (global integration) to local neighbourhood circulation.

At the infinite radius, centrality values are highly concentrated along long axial lines, representing globally significant paths with minimal angular deviation (Figure 5.10). While these paths are topologically dominant, they may not align with the spatial decisions of pedestrians avoiding heat stress. In this case, global centrality overlooks thermal usability.

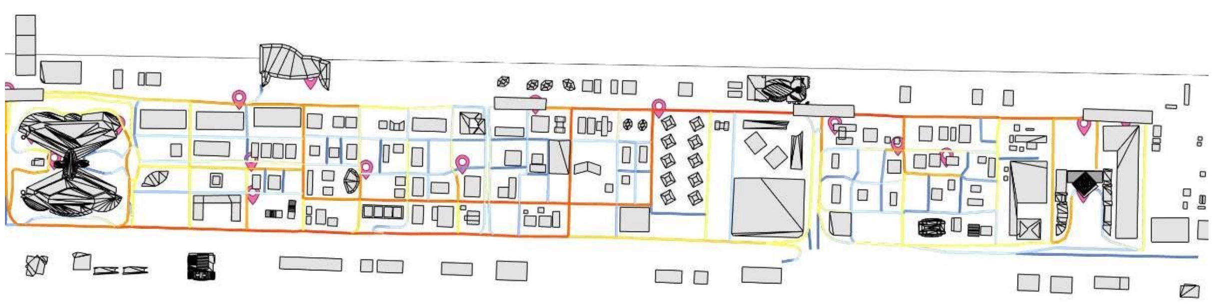


Figure 5.10 Flipped Betweenness Centrality – Infinite Radius.

The highest centrality values are concentrated along long axial segments that serve as global connectors. This output reflects the most angularly efficient paths across the network but may overemphasise geometrically dominant streets that are thermally exposed or underused.


When the radius is reduced to 1000 metres, high FBC values begin to distribute more evenly across the network (Figure 5.11). Mid-range connections gain prominence, revealing more thermally relevant routes between local destinations. This scale corresponds to moderate walking trips such as work commutes or civic visits.

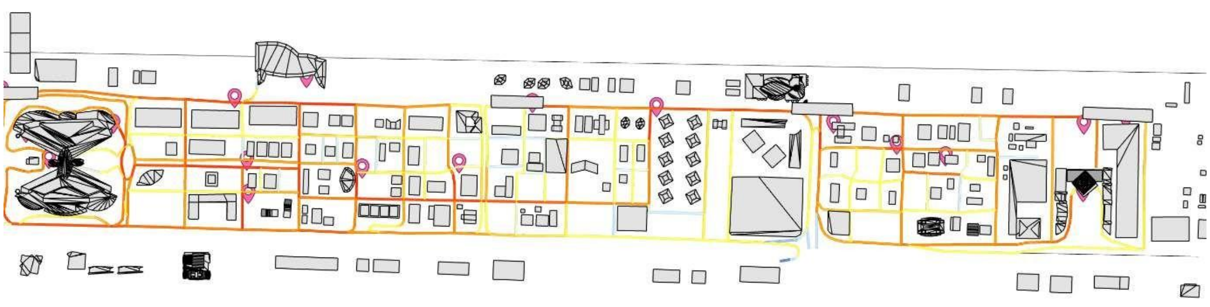


Figure 5.11 Flipped Betweenness Centrality – 1000m Radius.

*Centrality values begin to spread across a wider portion of the network, capturing mid-range connectivity between local destinations. This scale aligns with typical urban mobility patterns such as commuting or district-scale navigation.*

At the 500-metre radius, FBC values concentrate around short segments and local intersections, reflecting a high-resolution understanding of pedestrian-scale movement (Figure 5.12). These results align most closely with user behaviour under thermal constraints, where micro-adjustments in path choice are common. The reduction in path radius thus reveals more thermally adaptive spatial logic.

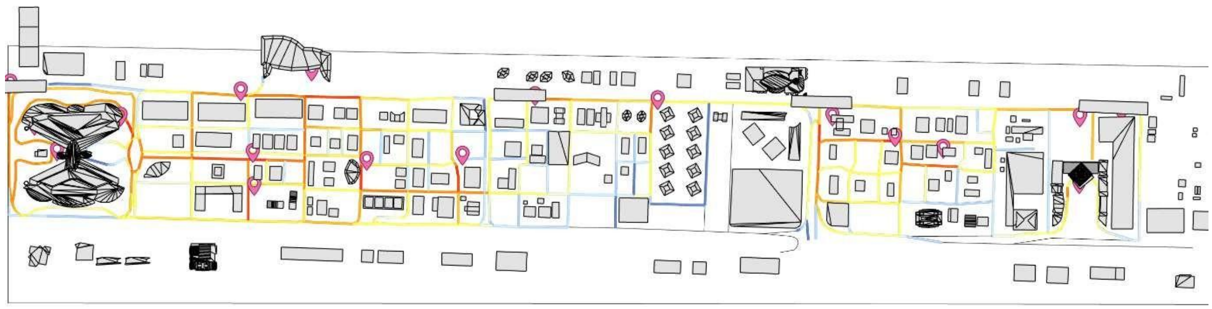


Figure 5.12 Flipped Betweenness Centrality – 500m Radius.

*Centrality concentrates around short segments and intersections within pedestrian-scale areas. The analysis reveals more granular movement patterns, representing micro-level route choices that are more sensitive to shading, exposure, and perceived comfort.*

Planners should use shorter radii when assessing walkability in hot climates, as it better reflects real user adaptation and neighbourhood-scale usability.

**5.3.6.2 Sensitivity to Intersection Density**

Intersections and connection points between spatial zones also significantly affect FBC outcomes. In the initial model of Downtown Riyadh, two adjoining areas (Area A and Area B) were linked by only two edge intersections, forming a bottleneck that inflated centrality scores along those paths (Figure 5.13).

To test the effect of enhanced local connectivity, three additional scenarios were modelled:

- A single added intersection at the centre (Figure 5.14)
- Two new connections across the interface (Figure 5.15)
- A full-width integration with multiple intersections (Figure 5.16)

With each added connection, FBC values became more evenly distributed across the network. In the full integration scenario, movement centrality shifted toward newly introduced paths, decentralising the spatial hierarchy and increasing accessibility of previously marginalised segments. These results demonstrate that strategic additions of intersections can dramatically reshape spatial accessibility and improve navigation options.


Figure 5.13 Flipped Betweenness Centrality in the original street network with limited intersections between adjoining sub-areas. Movement is constrained through two edge connections, resulting in a spatial bottleneck and inflated centrality scores along those segments.

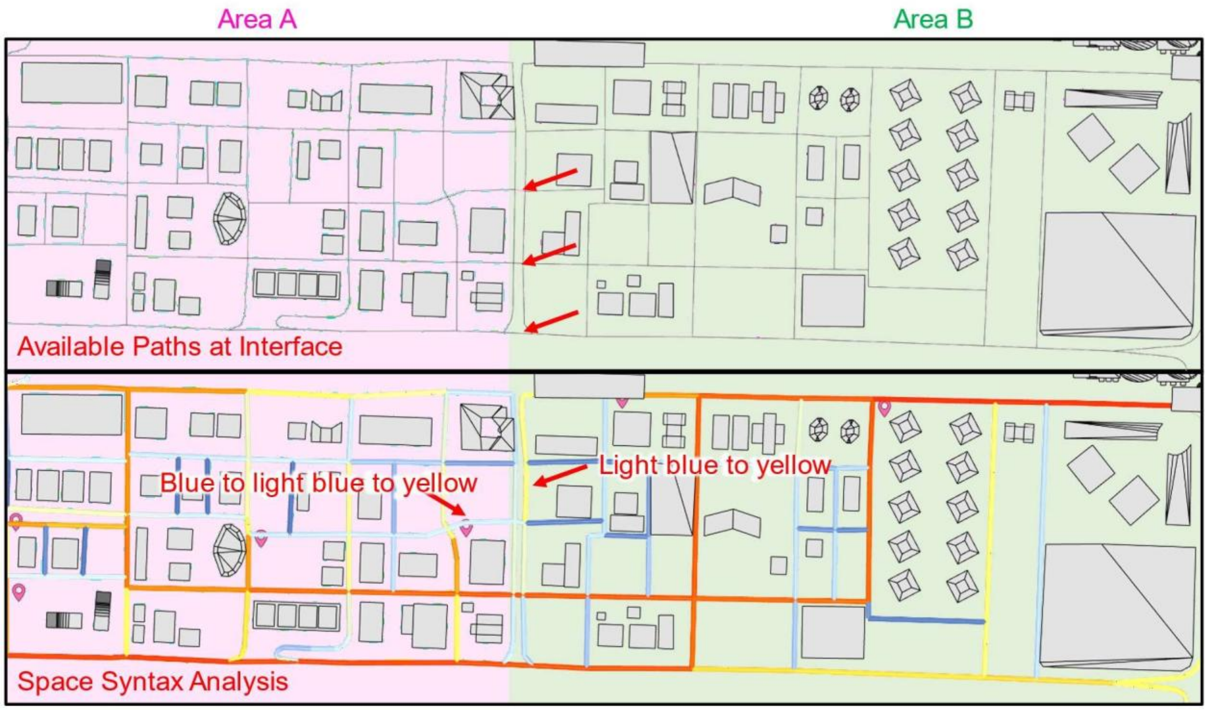



Figure 5.14 FBC after introducing a single new intersection near the centre of the interface between the two sub-areas. Movement begins to redistribute, slightly relieving pressure on the original bottleneck paths.

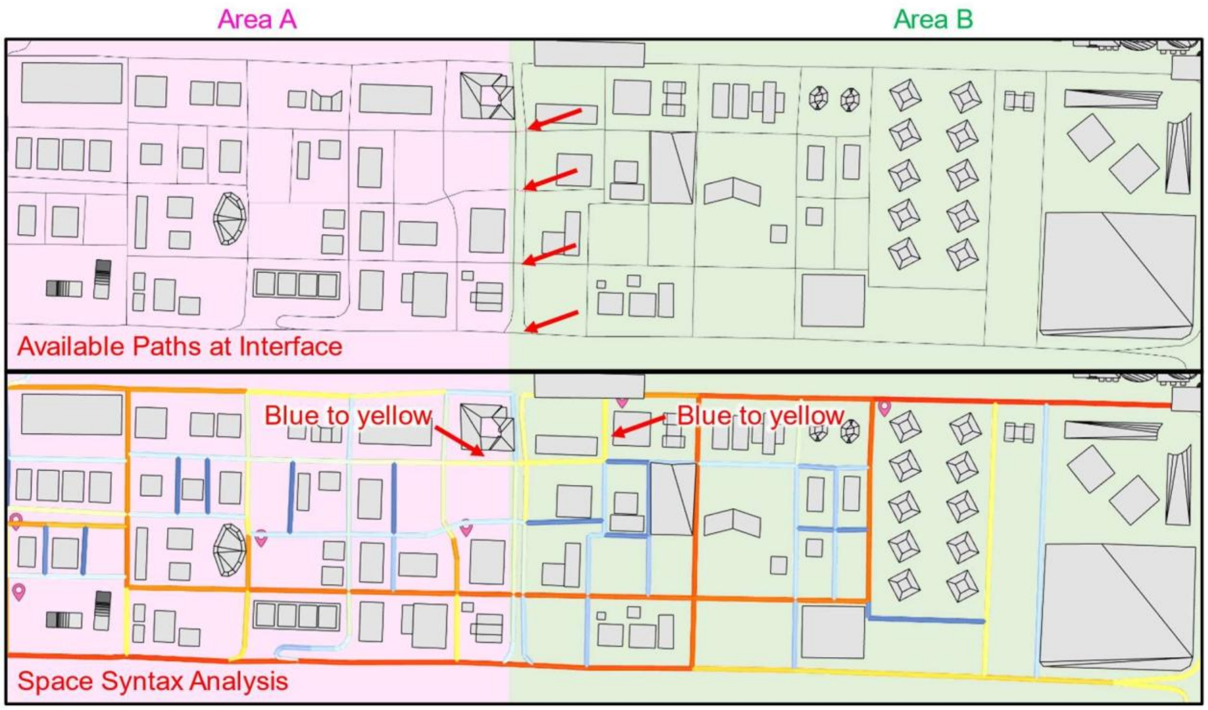



Figure 5.15 FBC with two additional intersections added across the mid-region. Centrality becomes more balanced across the network, increasing accessibility in previously marginalised segments.

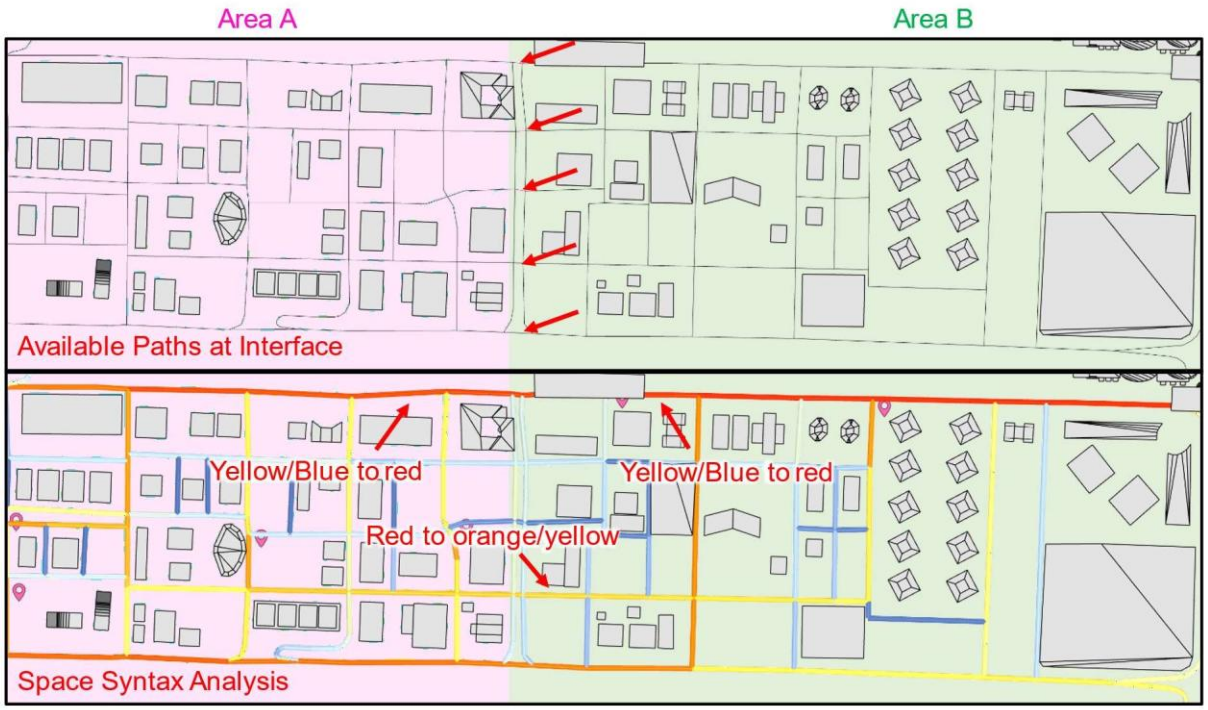



Figure 5.16 FBC in the full-width integration scenario, where multiple new intersections span the interface. The new links create a central corridor and decentralise spatial hierarchy, reflecting significantly improved movement potential and network permeability. Small-scale spatial interventions, such as adding new connectors or mid-block crossings, can significantly improve thermal walkability and reduce pedestrian congestion.

In summary, this sensitivity analysis confirms that spatial performance is not static. Accessibility is influenced both by how it is measured (e.g., path radius) and by the structural conditions of the street network (e.g., connectivity). In hot-climate cities like Riyadh, spatial strategies must be contextualised not only through geometry but through environmental and behavioural logic. This reinforces the importance of using tools like FBC in conjunction with thermal and perceptual analysis for climate-adaptive planning.

#### 5.3.7 Summary of Spatial Connectivity Findings

The Flipped Betweenness Centrality (FBC) analysis across the five case study sites reveals important insights into how urban spatial form influences walkability and usability under climatic constraints. Unlike conventional centrality models, FBC highlights short, thermally adaptive, and angularly efficient routes the kinds of paths that pedestrians realistically use in hot environments to minimise heat exposure and maximise comfort.

High-performing areas such as the Diplomatic Quarter and Downtown Riyadh demonstrate that fine-grained networks, mid-block connectors, and shaded pedestrian corridors significantly enhance spatial connectivity and thermal usability. In contrast, areas like KAFD and Roshn Front, despite their formal legibility and geometric structure, performed poorly in FBC analysis due to low permeability, long axial blocks, and lack of thermally responsive design.

The sensitivity analyses further confirmed that smaller analysis radii (e.g. 500m) better capture micro-scale pedestrian behaviour, while increasing intersection density can decentralise movement and improve local accessibility both of which are essential for climate-adaptive design.

**Key Design Implications:**

The results of the spatial connectivity analysis offer several design-related implications for public space planning in hot-climate contexts. First, the findings emphasise the value of designing for the pedestrian scale, as networks with high Flipped Betweenness Centrality (FBC) scores such as those found in the Diplomatic Quarter and Downtown Riyadh consistently featured short, shaded, and angularly efficient routes that support adaptive pedestrian behaviour. Second, the analysis underscores the importance of network permeability, with permeable environments offering a greater diversity of route choices and enabling users to adjust paths in response to thermal discomfort. This was especially evident in sites with mid-block connectors and distributed intersections, which contributed to decentralised movement and reduced reliance on thermally exposed boulevards.

Moreover, the sensitivity analysis demonstrated that smaller spatial scales (e.g., 500–1000m radii) better capture the behavioural realities of walkability in thermally constrained settings. These results highlight the limitations of over-scaled, vehicular-oriented environments such as KAFD and Roshn Front which, despite formal legibility, underperformed in FBC due to their reliance on long, exposed paths with limited adaptive alternatives. Collectively, these insights suggest that spatial performance and thermal resilience are co-dependent and should be addressed concurrently in the design and planning of future urban developments.

The insights gained from spatial connectivity modelling contribute directly to the development of the Urban Comfort–Connectivity Index (UCCI), and more broadly, to the advancement of climate-sensitive spatial design. These findings underscore the importance of integrating environmental awareness into spatial planning to create equitable, walkable, and resilient urban environments.

## 5.4: User Perception Results

### 5.4.1 Survey Summary

To evaluate the subjective experience of public space usability, a structured user perception survey was conducted across the five selected case study sites in Riyadh: Downtown Riyadh, King Abdullah Financial District (KAFD), Diplomatic Quarter (DQ), Museum District, and Roshn Front. The survey was designed to capture users' thermal comfort perceptions, spatial satisfaction, and adaptive behaviours, forming the basis of the Composite Perception Index (CPI) one of the three core components of the Urban Comfort–Connectivity Index (UCCI).

### Structure of Section 5.4

This section presents the user perception results in five parts:

- 5.4.1 Survey Summary – Describes the survey objectives, structure, sample size, and processing methods.
- 5.4.2 Key Perceptual Trends by Site – Analyses thermal comfort, usability, and satisfaction patterns per site.
- 5.4.3 Spatial Interpolation of Perception Data – Presents Composite Perception Index (CPI) maps.
- 5.4.4 Cross-Site Comparison of Perceptual Usability – Compares perception scores across sites.
- 5.4.5 Summary of User Perception Findings – Concludes with key insights and alignment with UCCI.

**Survey Objectives**

The survey aimed to:

- Understand how users perceive and adapt to thermal conditions in different urban settings.
- Assess perceived walkability, comfort, safety, and accessibility.
- Identify areas of high and low user satisfaction, and their relation to UTCI and FBC results.

**Survey Design and Structure**

The questionnaire was designed in both Arabic and English and distributed in two formats:

- On-site paper-based surveys, conducted during February and April (representing high-activity but climatically tolerable seasons).
- Online distribution via Google Forms, used to reach a broader demographic and supplement in-person sampling.

The instrument included:

- Likert-scale questions (1–5) assessing thermal comfort, walkability, environmental satisfaction, and adaptive behaviour.
- Multiple-choice questions on site use frequency, time-of-day preferences, and perceived challenges.
- Open-ended questions to capture qualitative responses related to thermal discomfort, spatial preferences, and design suggestions.

**Sample Size and Distribution**

A total of n = 149 respondents participated in the survey across all five case study sites. The sample reflected a diverse demographic profile in terms of age, gender, and primary purpose of visit (e.g., leisure, commuting, commercial, or cultural engagement).

- Age Range: 18–54 years
    - 18–24

    - 25–34
    - 35–44
    - 45–54
- Gender Distribution:
    - Male: 61.7%
    - Female: 35.6%

**Data Processing and Reliability**

Quantitative responses were numerically coded and analysed in SPSS. Likert scores were averaged to produce perception scores per indicator, per site, supporting cross-site comparison. Qualitative responses from open-ended questions were thematically analysed to capture dominant issues, including:

- Discomfort from sun exposure or lack of shade
- Preferences for shaded or vegetated routes
- Use of alternative paths or time-shifting to avoid heat
- Suggestions for improved walkability, seating, and comfort

These datasets underpin the Composite Perception Index (CPI) presented in the following sections and are integrated with thermal and spatial outputs to form the final UCCI.

### 5.4.2 Spatial Interpolation of Perception Data

To visualise spatial patterns in perceived usability and comfort, user survey responses were geolocated and interpolated across the five case study sites using GIS-based spatial analysis. This approach allowed for the creation of continuous surfaces that reflect how respondents experience different zones within each public space in terms of thermal comfort, navigation, accessibility, and overall usability. The resulting heatmaps offer a subjective dimension to complement the objective findings from UTCI and Flipped Betweenness Centrality (FBC) analysis.

### Mapping Methodology

Survey responses were manually georeferenced based on Points of Interest (POIs) identified from Google Maps, approximating the respondent's location at the time of data collection. Each geolocated point was assigned individual perception scores derived from Likert-scale responses. To visualise the spatial distribution of these subjective experiences, Inverse Distance Weighting (IDW) interpolation was performed in QGIS, generating raster heatmaps. This method assumes spatial autocorrelation—meaning nearby values are more similar—thus creating smooth gradients that highlight local variations in user experience.

Four thematic interpolations were produced:

- Perceived Thermal Comfort
- Ease of Navigation
- Accessibility and Inclusion
- Overall Usability

Each map employs a green-to-red colour gradient, with green indicating high satisfaction and red indicating low satisfaction or thermal discomfort. These interpolated heatmaps are displayed in Figures 5.12 to 5.16, organised by study site and perception category.

### Interpretation of Spatial Patterns

The interpolated results highlight several important spatial trends across the sites:

- Downtown Riyadh displays high discomfort in vehicular-dominated corridors and open plazas, with better perception scores near shaded arcades and pedestrian edges. Thermal relief and seating availability appeared to increase user satisfaction.
- KAFD is marked by broad zones of low thermal and spatial satisfaction, particularly in wide, unshaded areas. However, isolated pockets of moderate perception appear near vegetated zones and partially enclosed internal boulevards.
- Roshn Front shows mixed perception. Satisfaction is higher around storefront edges and shaded promenades, but drops sharply in large, open courtyards with minimal tree cover or seating.
- Diplomatic Quarter (DQ) and the Historical Centre (Museum District) show more evenly distributed perception scores, with higher user comfort associated with green corridors, cultural landmarks, and shaded pedestrian networks. These

patterns support earlier findings from both UTCI and FBC, suggesting a synergistic relationship between environmental quality, cultural richness, and spatial design.

**Map Integration Strategy**

To contextualise the perception maps and explore correlations with objective spatial metrics, each interpolated surface was overlaid with the following:

- UTCI raster layers, to assess whether perceived comfort aligned with thermal conditions.
- FBC segment maps, to identify whether highly connected areas also scored well in terms of perceived usability and navigation.
- Amenity locations, pedestrian infrastructure, and Points of Interest (POIs)—including benches, shade structures, water features, cultural anchors, and popular destinations—were included to better understand the behavioural logic of space use and areas of user concentration.

This integrative mapping approach provided a robust framework for cross-analysis of thermal, spatial, and experiential dimensions, which will be further elaborated in Section 5.4.3 and synthesised into the overall Urban Comfort–Connectivity Index (UCCI).

To maintain consistency and avoid visual clutter, all integrated UTCI–FBC–CPI overlay maps employ the same standardised colour scales introduced earlier in this chapter. A single, unified legend was applied for each variable as follows:

- UTCI: fixed scale from 20°C to 48°C, where blue indicates cooler conditions and red indicates extreme heat.
- FBC: normalised 0–1 scale, ranging from light yellow (low connectivity) to deep purple (high connectivity).
- CPI: normalised 0–1 scale, where blue represents low perceived comfort and red represents high perceived comfort.

Since these standardised scales were established in Sections 5.2 and 5.3, legends are not duplicated within individual overlay figures. The colours in all composite maps correspond directly to these fixed scales to ensure comparability and interpretive clarity across sites.

**KAFD**

KAFD was analysed through an integrated spatial lens combining subjective perception data, thermal comfort modelling (UTCI), spatial connectivity (FBC), and the spatial distribution of amenities and pedestrian-supporting infrastructure. The purpose of this integration was to identify where the spatial structure and thermal conditions align or diverge from user-reported comfort and usability within this highly formal, master-planned district.

The results reveal that KAFD's formal clarity and strong axial geometry do not automatically translate into walkable, climate-responsive public space. Instead, perceived usability is shaped primarily by micro-shade availability, internal connectors, and amenity clustering, rather than by the large ceremonial boulevards and open plazas. Thermally exposed segments with low FBC values correspond closely to negative perception points, whereas shaded or internally connected routes show consistently higher satisfaction. These findings emphasise the need for retrofit strategies such as increased tree canopy, shading structures, and mid-block links to enhance thermal walkability in KAFD.

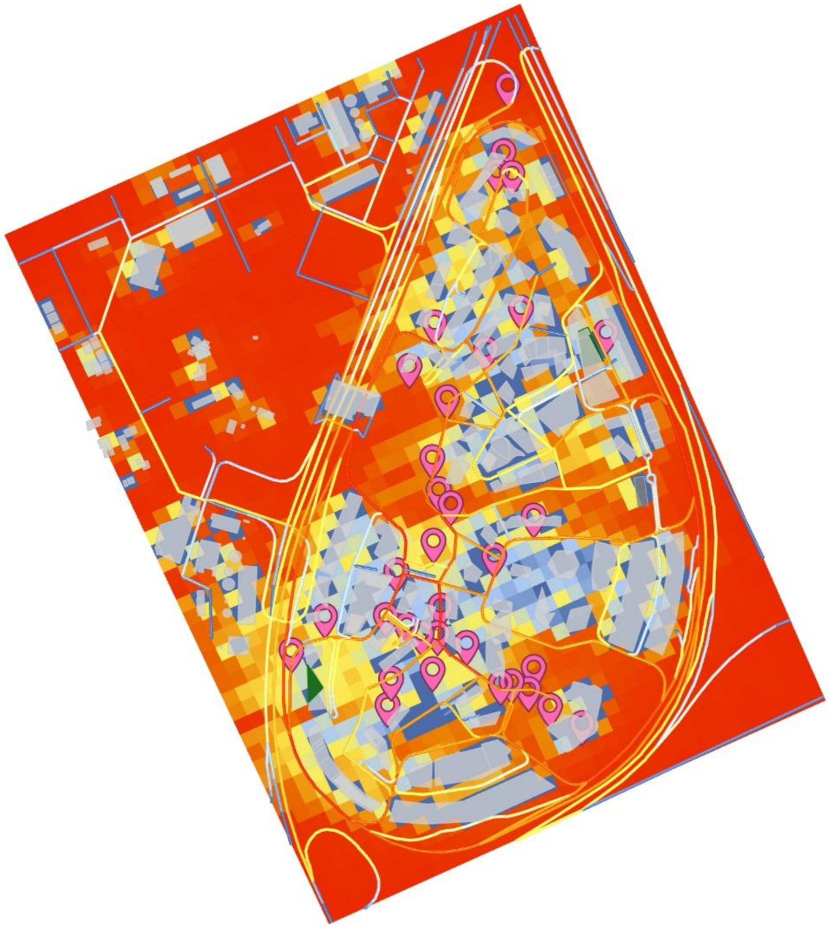


Figure 5.16a Figure 5.16a: Integrated Overlay of Thermal Comfort (UTCI), Spatial Connectivity (FBC), and Perception-Based POIs – KAFD

*This composite map integrates thermal comfort (UTCI raster), spatial connectivity (FBC segment values), and perception-based point data for the KAFD site. All colours correspond to the standardised scales introduced earlier in Chapter 5: UTCI fixed at 20–52°C, FBC normalised 0–1, and CPI/perception points normalised 0–1. Legends are not duplicated within this overlay to maintain clarity. Warmer UTCI areas indicate higher thermal stress, while yellow FBC segments represent strongly connected routes. The map shows that thermally exposed and weakly connected segments align with low user comfort, whereas shaded, spatially integrated internal routes correspond with higher user satisfaction.*

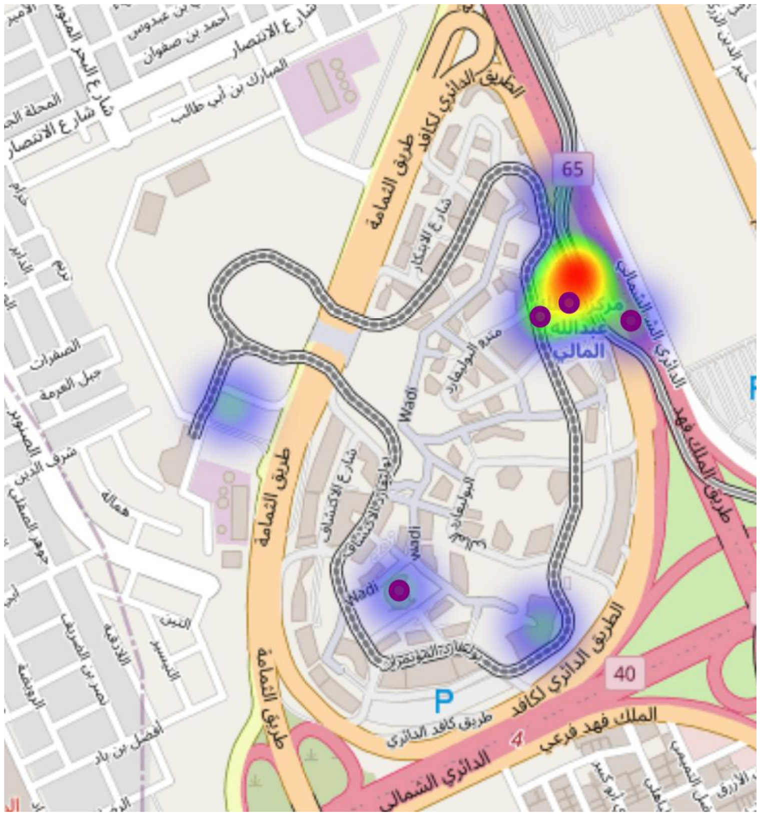



Figure 5.17a: Amenity and Pedestrian Infrastructure Heatmap – KAFD

*The Composite Perception Index (CPI) values are normalised between 0 and 1, where blue indicates lower comfort or satisfaction and red indicates higher perceived comfort. The heatmap shows the spatial concentration of urban amenities and pedestrian-supportive infrastructure across KAFD. High-density amenity zones cluster near shaded entrances and active edges, aligning with higher perception scores. Low-density amenity areas coincide with large open plazas and exposed peripheral routes. All colour intensities follow the standardised perception heatmap scale introduced earlier.*

KAFD exemplifies the disconnect between formal urban geometry and thermal usability. While it scores well in conventional urban design metrics such as axial clarity and legibility, these attributes do not translate into walkable, climate-responsive public space. The integrated spatial overlays demonstrate that perceived usability is tightly coupled with micro-shade conditions, internal connectors, and amenity access, rather than formal boulevards or plazas. These findings reinforce the need for retrofit strategies, including additional tree planting, mid-block links, and shading structures to improve thermal walkability.

**Downtown Riyadh**

Downtown Riyadh was examined using a multi-layered spatial analysis approach integrating user perception data, thermal comfort modelling (UTCI), spatial connectivity (FBC), and amenity distribution. This integration highlights where subjective comfort experiences align with or diverge from spatial performance and thermal stress, offering deeper insight into how traditional urban morphology operates under extreme climatic conditions.

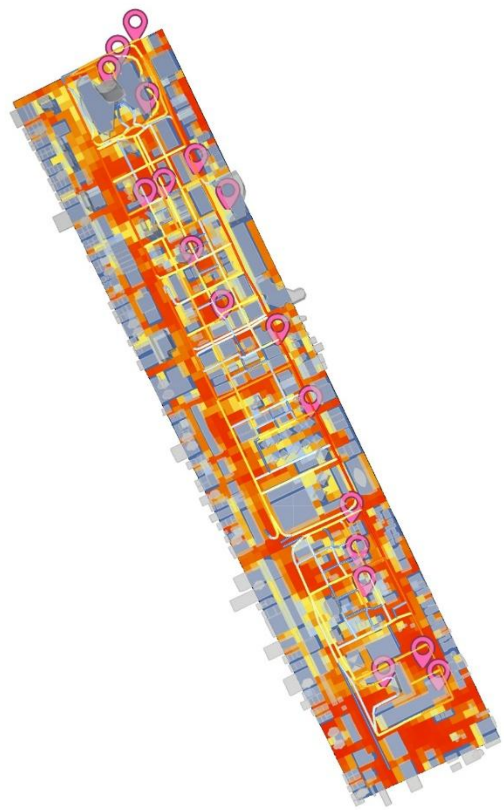


Figure 5.16b: Integrated Overlay of Thermal Comfort (UTCI), Spatial Connectivity (FBC), and Perception-Based POIs – Downtown Riyadh

*This composite map illustrates the spatial relationship between thermal stress (UTCI raster), spatial connectivity (FBC segments), and perception-based points for the Downtown site. The Composite Perception Index (CPI) values are normalised between 0 and 1, where blue indicates lower comfort or satisfaction and red indicates higher perceived comfort. All colours follow the standardised scales introduced earlier: UTCI fixed at 20–48°C, FBC normalised 0–1, and CPI normalised 0–1. Areas of higher satisfaction* *typically occur along shaded arcades, narrow alleys, and inner-block passages, which show both lower UTCI values and higher FBC scores. In contrast, wide intersections and vehicular corridors show weaker connectivity and higher thermal exposure, corresponding to lower perception scores. The figure highlights the spatial–behavioural interplay that defines comfort dynamics within this dense, multifunctional urban context.*

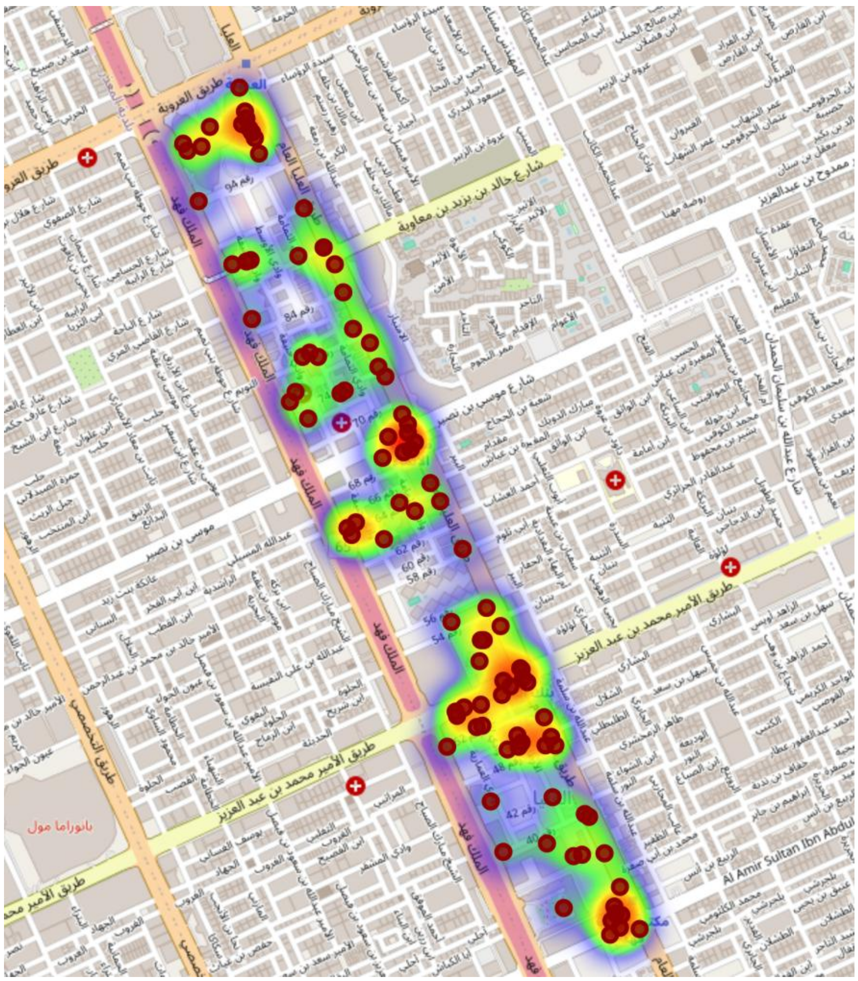



Figure 5.17b: Amenity and Pedestrian Infrastructure Heatmap – Downtown Riyadh

*Heatmap showing the spatial concentration of pedestrian-supportive features and amenities across Downtown Riyadh. High-density amenity zones cluster within shaded pedestrian corridors and near major entrances, corresponding to areas of higher perceived comfort and usability. Conversely, open intersections with limited amenities coincide with lower perception scores and peripheral spatial conditions. All colour intensities follow the standardised perception heatmap scale introduced earlier.*

Overall, the Downtown analysis reveals that perceived comfort in traditional urban fabric is closely tied to microclimatic variation, connectivity, and the provision of shade and amenities. The findings emphasise that small-scale morphological attributes such as narrow shaded passages and internal arcades contribute more effectively to perceived usability than wider, more formal streets exposed to direct solar radiation.

**The Diplomatic Quarter (DQ)**

The Diplomatic Quarter (DQ) was analysed using an integrated spatial framework combining user perception data, thermal comfort modelling (UTCI), and spatial connectivity (FBC) overlaid within a GIS-based environment. In addition, amenity and pedestrian infrastructure data were spatially mapped to contextualise areas of perceived comfort and usability. The objective was to explore how environmental quality, connectivity, and urban amenities collectively influence subjective experiences of comfort, accessibility, and satisfaction within a high-performing, planned pedestrian setting.

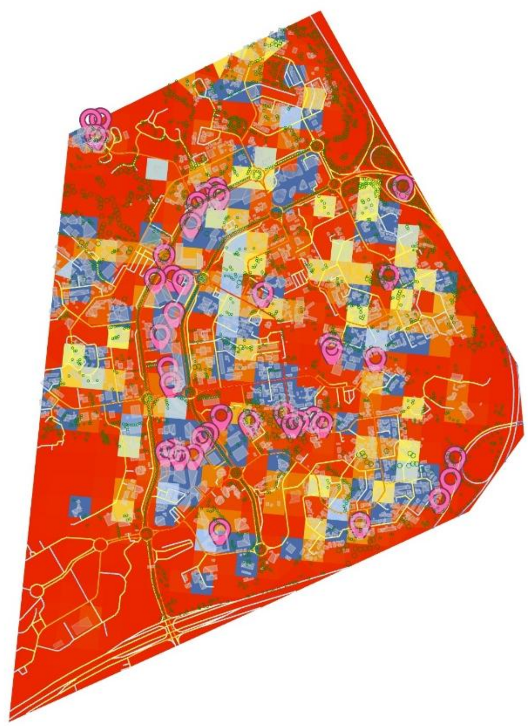


Figure 5.16c. Integrated UTCI–FBC–CPI Overlay – Diplomatic Quarter (DQ).

*This composite map integrates thermal comfort (UTCI raster), spatial connectivity (FBC segment values), and perception-based point data for the Diplomatic Quarter. The Composite Perception Index (CPI) values are normalised between 0 and 1, where blue represents lower comfort or satisfaction and red represents higher perceived comfort. All* *colours correspond to the standardised scales introduced earlier in Chapter 5: UTCI fixed at 20–48°C, FBC normalised 0–1, and CPI normalised 0–1. Areas exhibiting moderate UTCI values (indicating tolerable thermal stress) and high FBC scores correspond with perception points reflecting greater comfort, walkability, and usability. Green corridors and shaded pedestrian loops perform well across all three layers, reinforcing their role as thermally adaptive and spatially integrated environments within the district.*

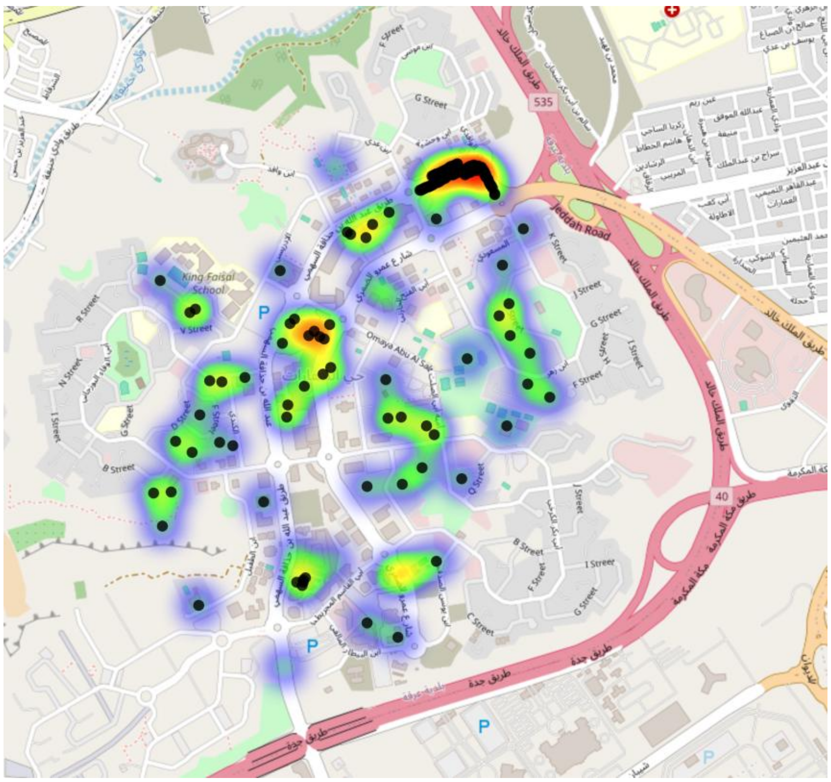



Figure 5.17c. Amenity and Pedestrian Infrastructure Heatmap – Diplomatic Quarter (DQ).

*Heatmap showing the spatial concentration of shaded seating areas, pathways, landscaped edges, and civic anchors across the Diplomatic Quarter. High-density amenity clusters coincide with areas of positive perception and high FBC values, highlighting the relationship between infrastructural provision and perceived usability. Few thermally exposed or underperforming zones are identified, reflecting the district’s effective spatial strategy for distributing walkable and shaded pedestrian routes. All colour intensities follow the standardised perception heatmap scale introduced earlier.*

The Diplomatic Quarter's integrated performance demonstrates how continuous shaded routes and evenly distributed amenities enable spatial coherence and thermal adaptability, distinguishing it as Riyadh's most effective model of pedestrian-oriented, climate-sensitive design.

**King Abdulaziz Historical Center (Museum District)**

The Museum District, which integrates civic, cultural, and public spaces, was analysed using an integrated mapping framework combining user perception data with UTCI thermal comfort modelling, Flipped Betweenness Centrality (FBC), and an amenity heatmap. This approach provides insight into how the district's hybrid urban form blending modern interventions with heritage-inspired typologies performs under spatial and thermal constraints.

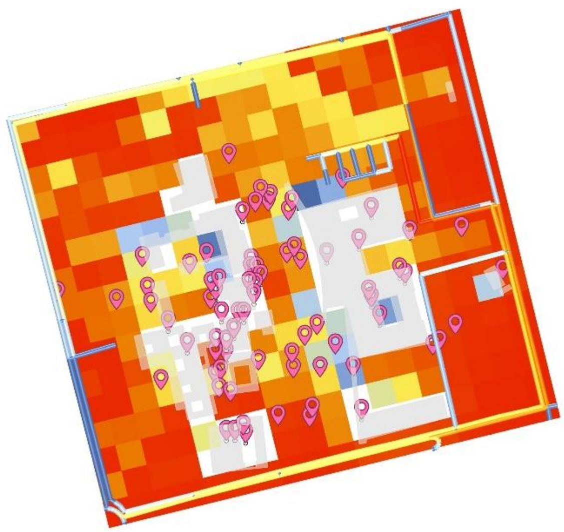


Figure 5.16d. Integrated UTCI–FBC–CPI Overlay – King Abdulaziz Historical Center (Museum District).

*This map presents the thermal (UTCI raster), spatial (FBC segment lines), and perceptual (CPI point) dimensions of the Museum District. CPI values are normalised between 0 and 1, where blue indicates lower perceived comfort or satisfaction and red indicates higher perceived comfort. All variables follow the standardised scales introduced earlier (UTCI fixed at 20–48°C, FBC normalised 0–1, and CPI normalised 0–1). Elevated UTCI values are concentrated in large open plazas and minimally shaded routes, which coincide with lower user satisfaction and weaker spatial connectivity. In contrast, courtyard-based layouts, arcaded walkways, and the shaded perimeter zones of cultural institutions demonstrate* *stronger FBC values and higher perception ratings, reflecting their adaptability to both climatic and behavioural conditions.*

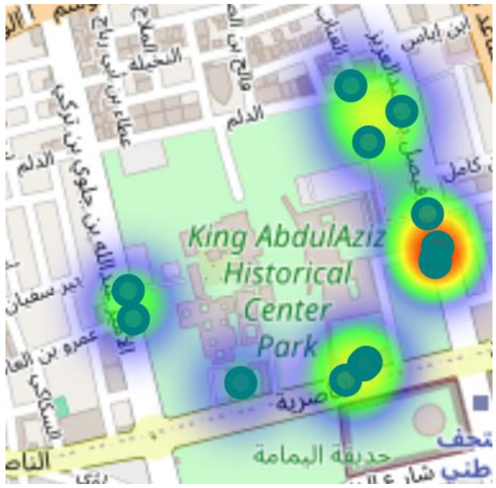



Figure 5.17d. Amenity and Pedestrian Infrastructure Heatmap – King Abdulaziz Historical Center (Museum District).

*The heatmap reveals a moderate and uneven distribution of pedestrian-supportive amenities. Shaded seating areas and activity anchors are concentrated near the museum entrance and along internal loops, while their absence in central open zones corresponds with reduced user comfort. All colour intensities follow the standardised perception heatmap scale introduced earlier. These results highlight the need for additional shade structures and micro-infrastructure in exposed areas to enhance thermal comfort and walkability.*

The Museum District illustrates how hybrid spatial configurations can support moderate thermal and perceptual performance when design continuity, shade, and cultural programming are well integrated. Yet, spatial fragmentation and exposed civic surfaces continue to limit thermal usability, pointing to the need for targeted interventions particularly within plaza areas to enhance shading, cooling, and mid-block pedestrian linkages.

**Roshn Front**

Roshn Front, a newly developed commercial and retail zone, was evaluated using an integrated overlay of UTCI thermal data, Flipped Betweenness Centrality (FBC), user perception, and a pedestrian amenity heatmap. As a contemporary site characterised by a wide linear grid and expansive open courts, it provides a contrasting model to the historic and mixed-use urban areas analysed in this study.

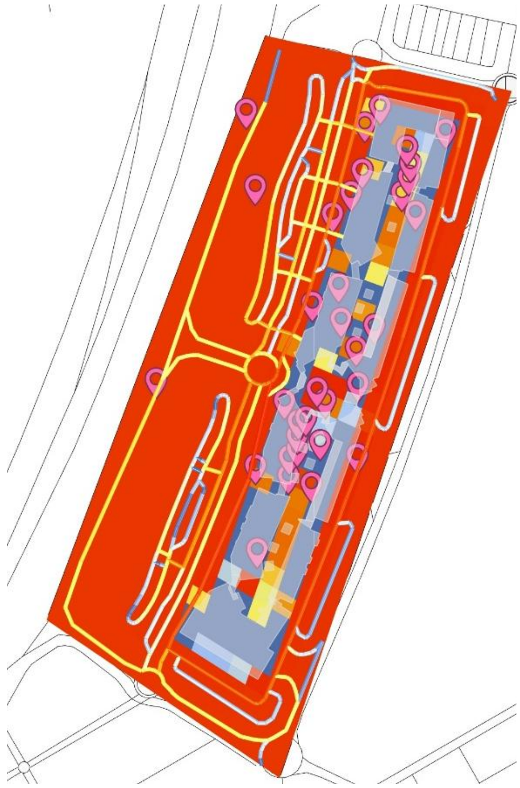


Figure 5.16e. Integrated UTCI–FBC–CPI Overlay – Roshn Front.

*This composite map reveals spatial discrepancies between thermal, spatial, and perceptual performance across Roshn Front. The Composite Perception Index (CPI) values are normalised between 0 and 1, where blue indicates lower comfort or satisfaction and red indicates higher perceived comfort. All colours follow the standardised scales introduced earlier in Chapter 5 (UTCI fixed at 20–48°C, FBC normalised 0–1, and CPI normalised 0–1). High UTCI values dominate open boulevards and central plazas, aligning with low user perception scores and weak FBC connectivity. In contrast, internally shaded corridors and narrow pedestrian links show moderate thermal conditions and improved perception outcomes. The map highlights how large-scale, automobile-oriented design geometries reduce pedestrian adaptability and thermal resilience.*

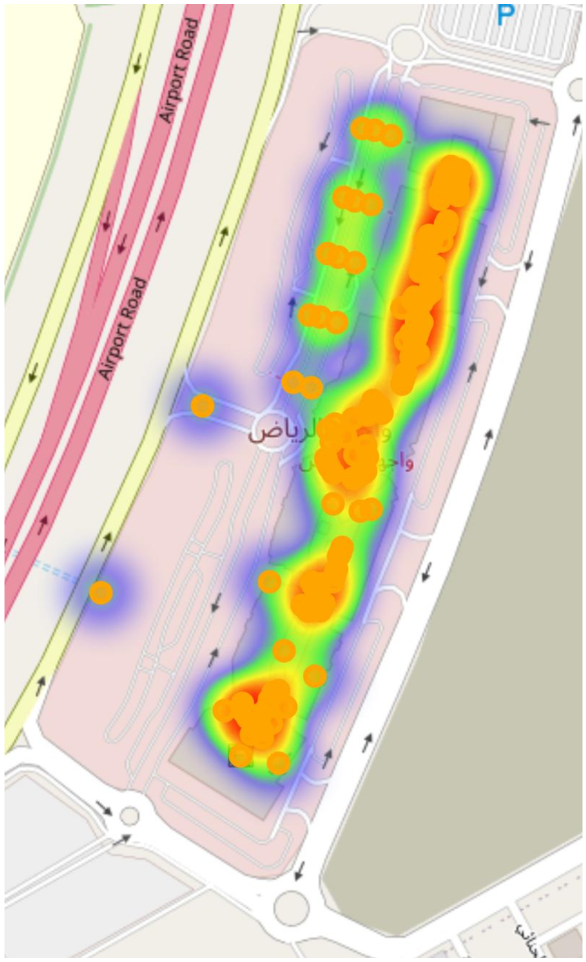



Figure 5.17e. Amenity and Pedestrian Infrastructure Heatmap – Roshn Front.

*The heatmap displays the spatial concentration of pedestrian-supportive amenities across Roshn Front. Amenities are largely clustered near shaded arcades and building entrances, while central open zones remain under-equipped. All colour intensities follow the standardised perception heatmap scale introduced earlier. This spatial imbalance corresponds to low usability ratings and limited connectivity, underscoring the need for greater infrastructural continuity and shading interventions to enhance comfort and movement.*

Roshn Front exemplifies the limitations of applying automobile-scale design principles to pedestrian-oriented environments. Despite its modern architecture, the site lacks the permeability, spatial diversity, and climatic responsiveness required for comfortable urban experience. These findings support retrofit strategies involving mid-block pedestrian links, increased canopy cover, and distributed amenities to activate underutilised public areas and promote walkable microclimates.

### 5.4.4 Temporal Behaviour Patterns Across Sites

**Time-of-Day Usage and Congestion Patterns**

To further understand how users adapt to climatic conditions and daily routines, pedestrian congestion data was analysed by time of day across the five case study sites. As shown in Figure 5.26, congestion levels remain relatively low in the morning and midday periods, likely reflecting avoidance of thermal stress during peak heat hours. The highest activity levels occur in the evening (6–9 PM), with KAFD and Roshn Front exhibiting particularly high congestion, exceeding 80%.

This temporal pattern reflects both behavioural adaptation and site-specific programming. In commercial areas like KAFD and Roshn Front, evening activity is concentrated in shaded courtyards, retail corridors, and semi-climate-controlled zones. In contrast, Downtown and DQ show more balanced congestion patterns, suggesting greater all-day usability, potentially due to tree cover, enclosure, and mixed-use continuity.

These findings reinforce the importance of designing public spaces that perform comfortably and accessibly across different times of day, especially during non-peak cooling hours.

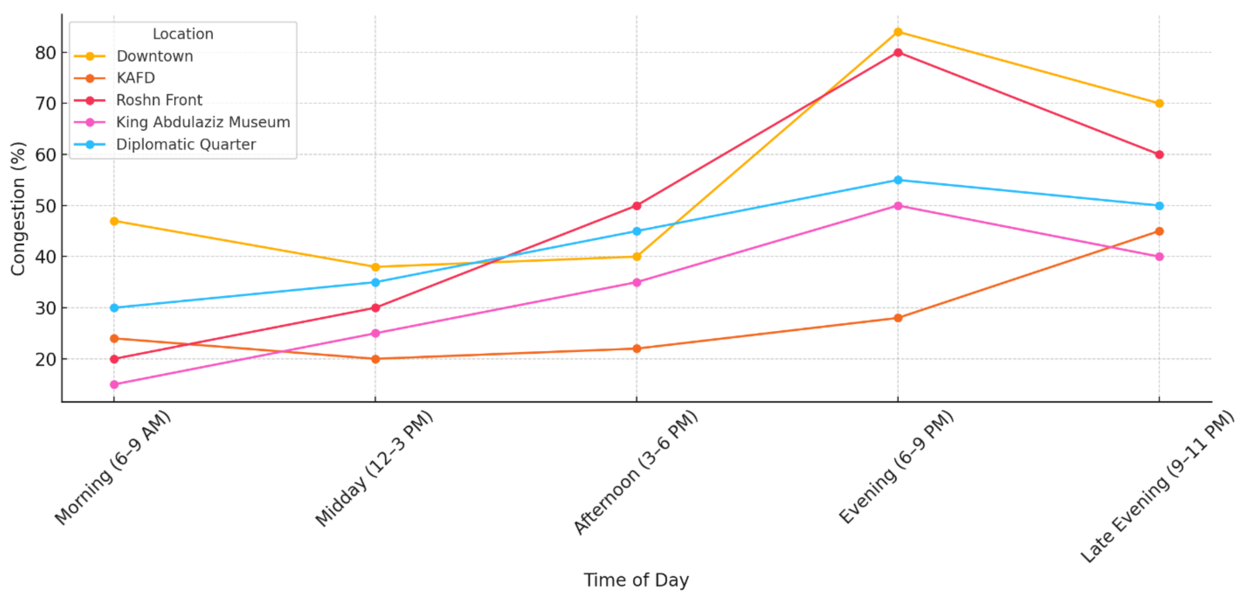



Figure 5.27: Pedestrian Congestion Levels by Time of Day Across Five Case Study Sites

The chart illustrates temporal variations in pedestrian activity. Congestion peaks in the evening (6–9 PM) across all sites, especially in KAFD and Roshn Front. Lower activity during midday reflects avoidance of thermal discomfort. These patterns confirm the influence of time-of-day shading, activity zoning, and microclimatic design on usability.

### 5.4.5 Summary of User Perception Findings

The perception data collected and visualised across the five case study sites Downtown Riyadh, King Abdullah Financial District (KAFD), Diplomatic Quarter (DQ), Museum District, and Roshn Front reveals clear spatial patterns in how users experience thermal comfort, navigation, accessibility, and overall usability.

Across all sites, areas with higher perception scores aligned strongly with segments that combined shaded conditions, spatial enclosure, and localised connectivity. Conversely, areas with low comfort perception were consistently associated with open, thermally exposed spaces, wide vehicular corridors, and segments with poor pedestrian-scale integration.

- Downtown Riyadh performed well in terms of perceived usability, particularly in shaded arcades and narrow streets. However, thermal discomfort remained an issue near large intersections and open plazas.
- KAFD exhibited the lowest average perception scores, with many users reporting discomfort and difficulty navigating expansive, unshaded zones.
- The Diplomatic Quarter received the most consistently positive feedback, driven by its shaded loops, green infrastructure, and walkable scale.
- The Museum District produced mixed responses, with moderate comfort and navigation satisfaction near courtyards and civic edges, but weaker perception in fragmented interior spaces.
- Roshn Front demonstrated generally low perception values in wide, exposed courts, with better scores in edge areas and shaded promenades.

The integrated maps showed that subjective experiences closely align with UTCI and FBC outputs, reinforcing the value of perception data as a third pillar in the Urban Comfort–Connectivity Index (UCCI). The presence of microclimatic modifiers such as trees, shade structures, benches, and pedestrian-scale connectors played a central role in shaping comfort perception across all locations.

These findings demonstrate that user perception is not an abstract measure, but a grounded, spatially variable response to real conditions. The synthesis of subjective and objective layers supports the argument that urban usability must be assessed through thermal, spatial, and experiential dimensions simultaneously.

The following chapter discusses these findings in relation to broader theories of urban design, climate adaptation, and spatial justice, and offers targeted recommendations for creating thermally resilient and user-centred public spaces in hot-climate cities.

Table 5.7: Summary of User Perception Scores Across Sites, visually comparing thermal comfort, navigation ease, accessibility and inclusion, and overall usability as reported by survey participants.

Let me know if you'd like this table exported as an image, formatted for Word, or presented alongside radar charts or cross-site perception comparisons

Table 5.7: Summary of User Perception Scores Across Sites

| Site | Thermal Comfort (Perception) | Navigation Ease | Accessibility & Inclusion | Overall Usability |
|---|---|---|---|---|
| Downtown Riyadh | 4 | 4.5 | 4 | 4.5 |
| KAFD | 2 | 2.5 | 2.5 | 2.5 |
| Diplomatic Quarter | 4.5 | 4.5 | 5 | 5 |
| Museum District | 3 | 3.5 | 3.5 | 3.5 |
| Roshn Front | 2.5 | 2.5 | 2.5 | 2.5 |

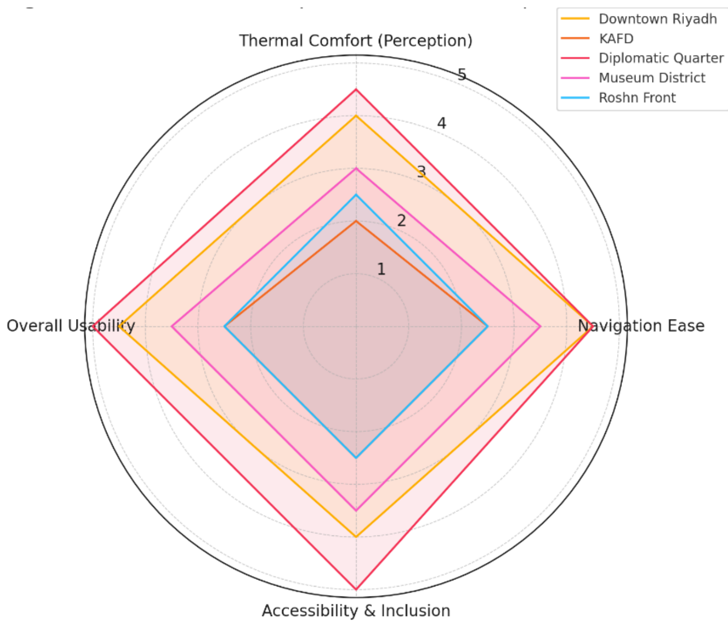



Figure 5.18: Cross-Site Comparison of User Perception Dimensions,

Radar chart illustrating comparative user perception scores across the five case study sites in Riyadh Downtown Riyadh, King Abdullah Financial District (KAFD), Diplomatic Quarter (DQ), Museum District, and Roshn Front. Each site is evaluated based on four dimensions: perceived thermal comfort, navigation ease, accessibility and inclusion, and overall usability. The chart reveals that the Diplomatic Quarter and Downtown Riyadh scored highest across most categories, reflecting greater walkability, spatial coherence, and user satisfaction. By contrast, KAFD and Roshn Front consistently underperform, highlighting the limitations of wide, exposed layouts and lower amenity provision in supporting user comfort and navigability.

The preceding sections have presented detailed analyses of thermal comfort (UTCI), spatial connectivity (FBC), and user perception (CPI) across five public space sites in Riyadh. Each component revealed site-specific strengths and vulnerabilities, highlighting how thermal stress, spatial structure, and subjective experience shape the usability of urban environments. While these individual layers offer valuable insights, they do not operate in isolation. To provide a more holistic and actionable assessment of public space performance, the following section introduces the Urban Comfort–Connectivity Index (UCCI) a composite measure that integrates thermal, spatial, and experiential dimensions into a unified usability framework.

### 5.5 UCCI Results: Integrated Usability Analysis

Having independently analysed thermal comfort (UTCI), spatial connectivity (FBC), and user perception (CPI), this section presents the results of the Urban Comfort–Connectivity Index (UCCI). The UCCI is a composite index that quantifies the integrated usability of public space by combining environmental, spatial, and behavioural data into a single raster-based output. This approach supports spatial decision-making by identifying zones where public space performs well across multiple dimensions, and conversely, areas where interventions are needed.

#### 5.5.1 UCCI Calculation and Output Structure

Each of the three UCCI components UTCI, FBC, and CPI was first normalised to a 0–1 scale, where higher values indicate more favourable conditions (i.e., better thermal comfort, stronger connectivity, and higher user satisfaction). The components were then equally weighted and integrated using raster overlay methods in Grasshopper and GIS. The resulting UCCI score reflects overall usability and is classified into four bands:

- High Usability (0.75–1.00)
- Moderate Usability (0.50–0.74)
- Low Usability (0.25–0.49)
- Critical Usability (0.00–0.24)

Spatial outputs for each site are shown in Figures 5.19 to 5.23, with colour gradients representing overall usability levels.

#### 5.5.2 Spatial Distribution of UCCI by Site

The spatial outputs of the Urban Comfort–Connectivity Index (UCCI) provide a detailed understanding of how each site performs when thermal comfort, spatial connectivity, and user perception are considered together. UCCI raster maps were produced for all five case study locations and classified into four usability bands: High, Moderate, Low, and Critical. These maps are presented in Figures 5.19 to 5.23, accompanied by the following site-level interpretations:

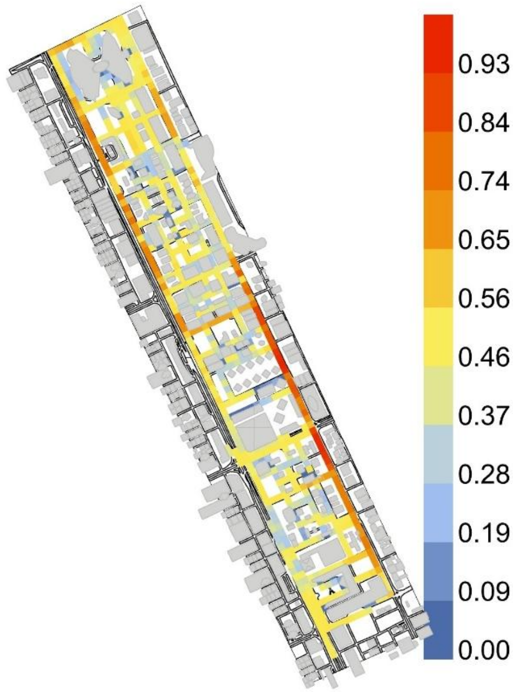



Figure 5.19- UCCI: Downtown Riyadh

Downtown Riyadh exhibits a heterogeneous but overall favourable spatial profile. High and moderate UCCI values are concentrated in inner blocks, shaded arcades, and informal pedestrian paths, where spatial permeability and shading intersect with user-reported comfort. Critical usability zones appear at vehicular intersections and large open corridors, which experience high UTCI values and low spatial coherence. This supports earlier findings that traditional urban forms, when supported by adequate infrastructure, offer thermally adaptive and walkable environments.

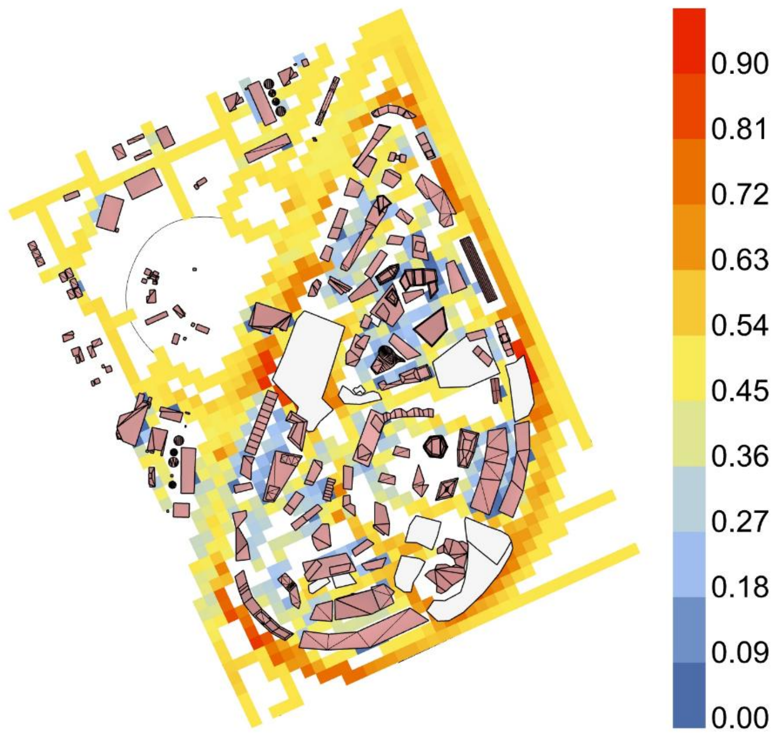



Figure 5.20- UCCI: King Abdullah Financial District (KAFD) UCCI

KAFD reveals a fragmented pattern of usability. UCCI scores are highest in internal shaded corridors and near vegetated buffers, yet large open plazas and major boulevards register critical to low usability. These areas combine high thermal exposure, limited shade, and weak pedestrian integration, resulting in poor overall performance. The map illustrates the spatial disconnect between formal planning and experiential comfort, particularly in environments dominated by scale, formality, and exposure.

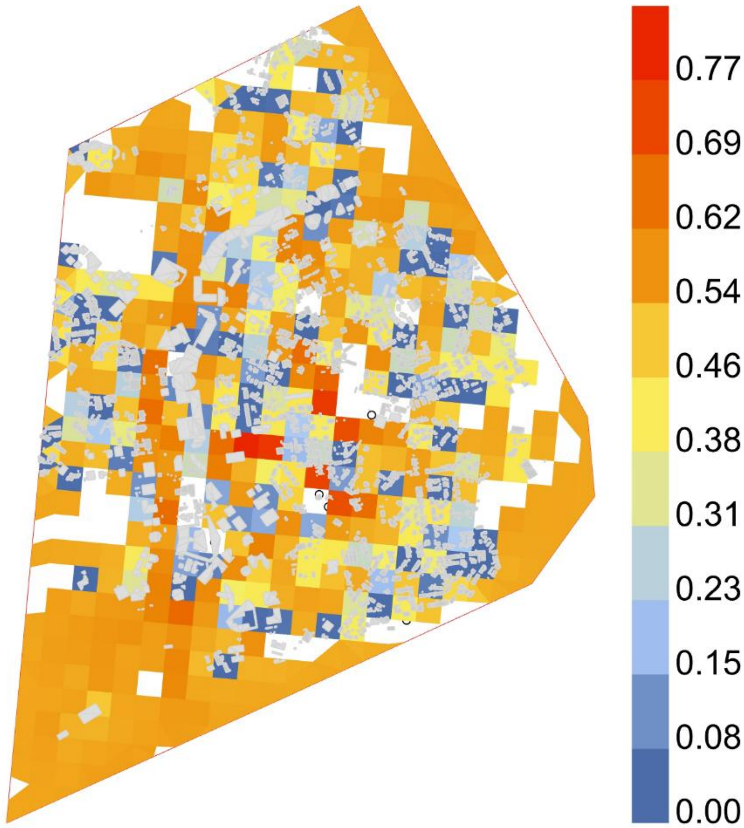



*Figure 5.21- UCCI:* Diplomatic Quarter (DQ)

The Diplomatic Quarter displays the highest overall UCCI scores among all sites. High usability zones are broadly distributed across green pedestrian corridors, looped walkways, and shaded civic spaces. Moderate zones appear at the district edges, while critical zones are nearly absent. This reflects a spatial system that is climatically buffered, behaviourally aligned, and spatially coherent a model of successful integration of environment, form, and experience.

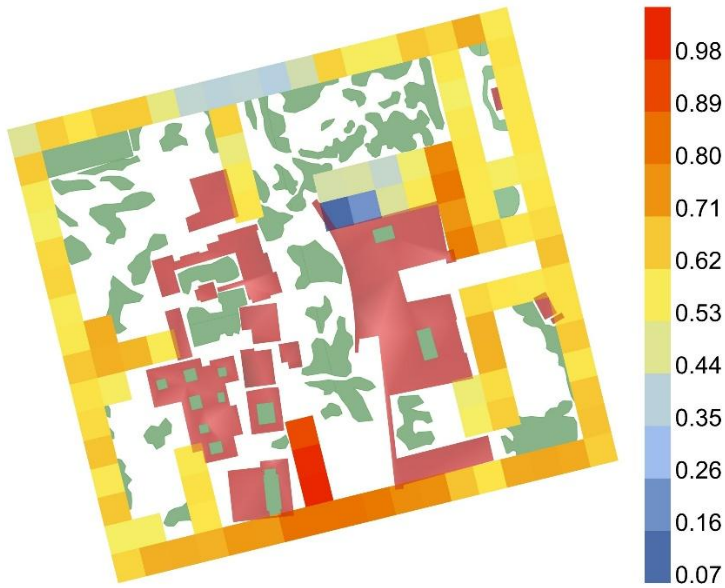



Figure 5.22- UCCI: Museum District

The Museum District shows a mixed pattern of usability. High scores appear along courtyard edges and semi-shaded pedestrian loops, while moderate zones are present near institutional perimeters. Low and critical UCCI values emerge in large plaza-like zones with high solar exposure and limited seating or wayfinding support. These results suggest that while the site performs moderately well overall, spatial fragmentation and thermal intensity remain barriers to consistent usability.

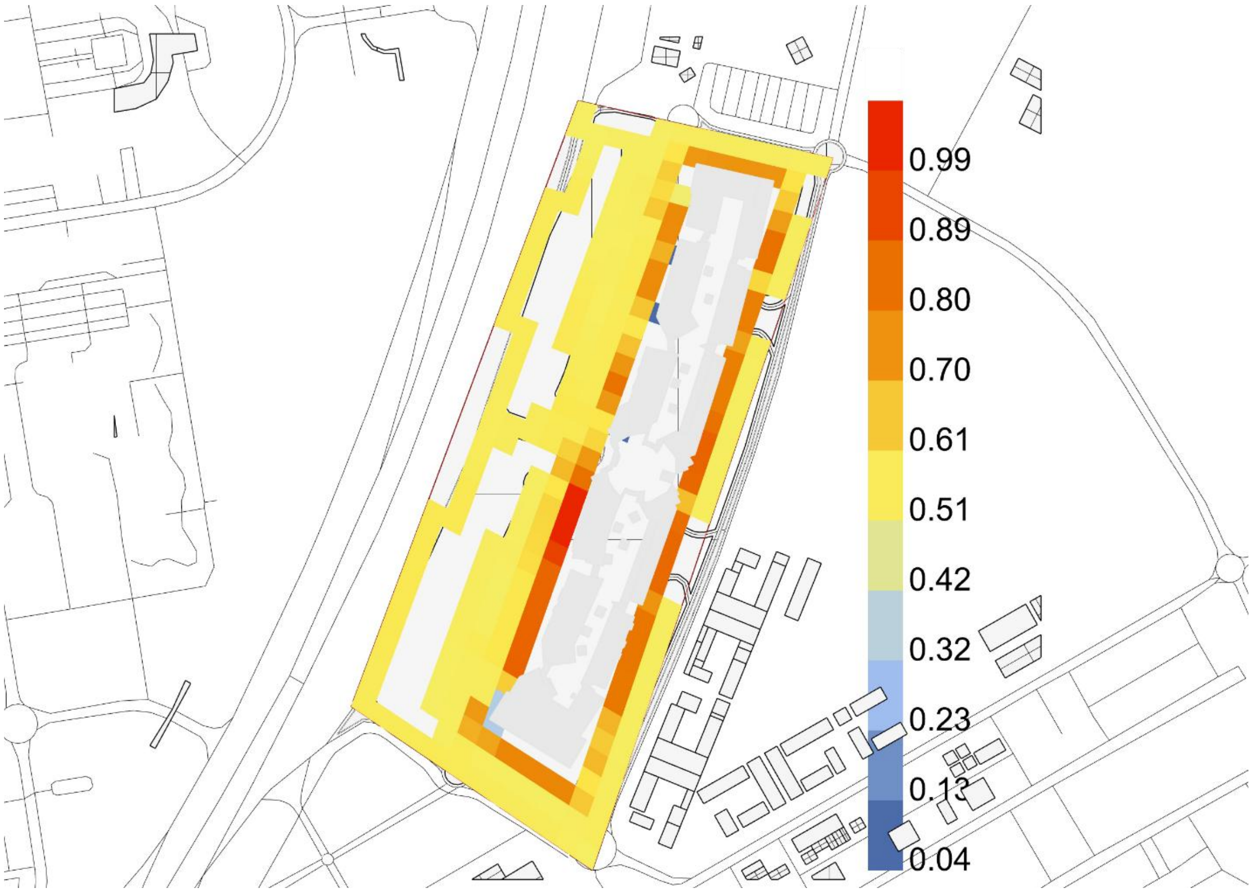



Figure 5.23- UCCI: Roshn Front UCCI

Roshn Front exhibits the lowest overall UCCI performance. While some moderate scores are observed near shaded promenades and storefront edges, the site is dominated by low and critical usability zones. Large, open courtyards and long linear boulevards lack shade, seating, and fine-grained pedestrian networks, making them thermally and functionally challenging. The spatial configuration does not support adaptive behaviours under heat stress, underscoring the disconnect between formal design and experiential quality.

### 5.5.3 Quantitative Comparison of UCCI Scores

A percentage-based classification of each site's UCCI scores is summarised in Table 5.8, showing the share of area in each usability band. This is complemented by Table 5.9, which presents average UCCI scores and highlights the highest-performing zones per site.

Table 5.8: UCCI Classification by Site (% Area)

| Site | High (%) | Moderate (%) | Low (%) | Critical (%) |
|---|---|---|---|---|
| Diplomatic Quarter | 38 | 45 | 15 | 2 |
| Downtown Riyadh | 22 | 48 | 23 | 7 |
| Museum District | 18 | 42 | 32 | 8 |
| Roshn Front | 10 | 30 | 37 | 23 |
| KAFD | 8 | 27 | 40 | 25 |

This Table 5.8 presents the percentage distribution of each site's area classified under four UCCI usability bands: High, Moderate, Low, and Critical. The Diplomatic Quarter stands out with the highest proportion of high- and moderate-usability zones, reflecting integrated spatial and climatic performance. In contrast, Roshn Front and KAFD show substantial areas with critical or low usability, indicating spatial and thermal challenges that hinder walkability and comfort.

Table 5.9: Mean UCCI Scores and Key Performing Zones

| Site | Mean UCCI Score | Std Dev | Highest-scoring Zone(s) |
|---|---|---|---|
| Diplomatic Quarter | 0.78 | 0.09 | Central green spine |
| Downtown Riyadh | 0.69 | 0.12 | Inner blocks |
| Museum District | 0.63 | 0.14 | Courtyard edges |
| Roshn Front | 0.52 | 0.16 | Storefront promenades |
| KAFD | 0.48 | 0.17 | Internal corridors |

This Table 5.9 reports the average UCCI score and standard deviation for each site, along with a qualitative identification of the highest-scoring spatial zones. The Diplomatic Quarter and Downtown Riyadh demonstrate the strongest usability performance, especially in shaded, pedestrian-oriented corridors. By contrast, Roshn Front and KAFD exhibit lower mean scores and higher variability, indicating fragmented spatial usability and thermal discomfort in large, exposed areas.

These results confirm that the Diplomatic Quarter is the most integrated, walkable, and thermally resilient environment. Downtown Riyadh also performs well despite its older urban form, while Roshn Front and KAFD underperform due to spatial fragmentation and thermal exposure.

### 5.5.4 Interpretation and Implications

The spatial distribution of UCCI scores across the five case study sites reveals that high-performing urban areas consistently share three critical characteristics:

1. Shaded or vegetated environments that mitigate heat exposure and enhance microclimatic comfort.
2. Pedestrian-scale spatial connectivity that enables flexible routing, reduces walking distances, and supports behavioural adaptation.
3. Amenity-rich settings including shaded seating, wayfinding elements, and active frontages that enhance usability, safety, and user satisfaction.

These features not only promote physical comfort but also foster a sense of place and encourage sustained use, particularly in thermally challenging environments. Sites such as the Diplomatic Quarter and Downtown Riyadh exemplify these conditions, demonstrating how spatial permeability, green infrastructure, and embedded public amenities can collectively enhance climate resilience and user experience.

Conversely, low-performing zones identified through the UCCI most notably in KAFD and Roshn Front are characterised by large, open spaces, limited shading, and geometric rigidity that restricts pedestrian movement and adaptation. These spaces, while formally accessible, are often perceived as unusable under heat stress due to their lack of human-scale design features.

The implications of these findings are significant for urban design and policy. They highlight the importance of multi-scalar design interventions that go beyond aesthetic or formal logic to prioritise thermal adaptability, spatial legibility, and amenity provision. The UCCI framework provides a replicable method for diagnosing public space performance and guiding targeted, context-sensitive improvements that address both climatic and experiential dimensions of urban life.

These findings will be further explored in Chapter 6, where the UCCI is used as a basis for evaluating spatial equity, identifying marginalisation zones, and developing evidence-based urban design recommendations for hot-climate cities like Riyadh.

### 5.5.5 Spatial Insights for Intervention

The UCCI maps and classification outputs highlight specific spatial zones within each site where targeted interventions can enhance usability and thermal comfort. These zones typically correspond to areas with low UCCI scores reflecting the compounding effects of thermal exposure, poor connectivity, and weak amenity provision.

- In Downtown Riyadh, interventions should focus on widening pedestrian corridors, shading key intersections, and enhancing street furniture in highly trafficked but exposed segments.
- In KAFD, priority should be given to retrofitting open plazas with shade structures, improving mid-block permeability, and introducing micro-scale greenery along axial streets.
- The Diplomatic Quarter, while performing well overall, may benefit from continued maintenance of shaded corridors and the expansion of usable public edges in transition zones.
- The Museum District would gain from softening civic hardscapes, enhancing shaded seating, and improving wayfinding continuity between inner and outer spatial loops.
- In Roshn Front, the most urgent need is to break up large, exposed courts with shaded walkways, new pedestrian cut-throughs, and resting nodes that address both climatic and experiential gaps.

These spatial insights reinforce the importance of designing for climate adaptability at the pedestrian scale, ensuring that usability is not undermined by formal legibility or aesthetic logic. The findings directly inform the recommendations presented in Chapters 6 and 7, particularly regarding climate-responsive urban retrofitting and the role of connectivity and comfort in spatial equity.

## 5.6 Regression Validation

To evaluate the predictive strength of the Urban Comfort–Connectivity Index (UCCI), a multiple linear regression analysis was conducted using user-reported satisfaction as the dependent variable. UCCI integrates three core components thermal comfort (UTCI), spatial connectivity (FBC), and user perception (CPI) into a single usability score. Each component was normalised on a 0–1 scale. To ensure theoretical consistency, UTCI values were inverted, such that lower thermal stress corresponded with higher usability.

### 5.6.1 Model Results

The regression model achieved an adjusted $R^2$ of 0.61, indicating that the three UCCI components explain approximately 61% of the variance in user satisfaction. This suggests a robust relationship between usability factors and how public spaces are experienced by users in thermally extreme conditions.

The final regression equation is expressed as:

$$Satisfaction = -0.42 - 0.03(UTCI) + 0.66(FBC) + 0.44(CPI)$$

All three predictors were statistically significant ($p < 0.001$), and the direction of their coefficients aligned with theoretical expectations:

- UTCI (–0.03): Thermal discomfort (higher UTCI) was negatively associated with satisfaction, confirming that outdoor heat stress diminishes perceived usability.
- FBC (+0.66): Increased spatial connectivity contributed positively, reinforcing the role of walkability and network integration.
- CPI (+0.44): User perception emerged as a strong predictor, capturing subjective experience related to safety, comfort, and accessibility.

Table 5.10 summarises the standardised regression coefficients derived from the model, demonstrating the relative influence of each UCCI component on reported satisfaction.

Table 5.10 Standardised Regression Coefficients for UCCI Components

| **Predictor Variable** | **Standardised β Coefficient** | **Significance (p-value)** | **Interpretation** |
|---|---|---|---|
| **UTCI (inverted)** | –0.03 | p < 0.001 | Higher thermal stress reduces satisfaction |
| **Flipped Betweenness Centrality (FBC)** | +0.66 | p < 0.001 | Connectivity strongly enhances usability |

| Predictor Variable | Standardised β Coefficient | Significance (p-value) | Interpretation |
|---|---|---|---|
| **User Perception Component (CPI)** | +0.44 | p < 0.001 | Positive experiential qualities improve satisfaction |

### 5.6.2 Visual Representation

Figure 5.29 presents the regression plot using the recalculated UCCI scores. The positive slope of the regression line confirms that higher UCCI values are associated with higher satisfaction, in line with the conceptual design of the index. The model captures 64% of the observed variability in user responses, offering strong evidence of the UCCI's predictive reliability.

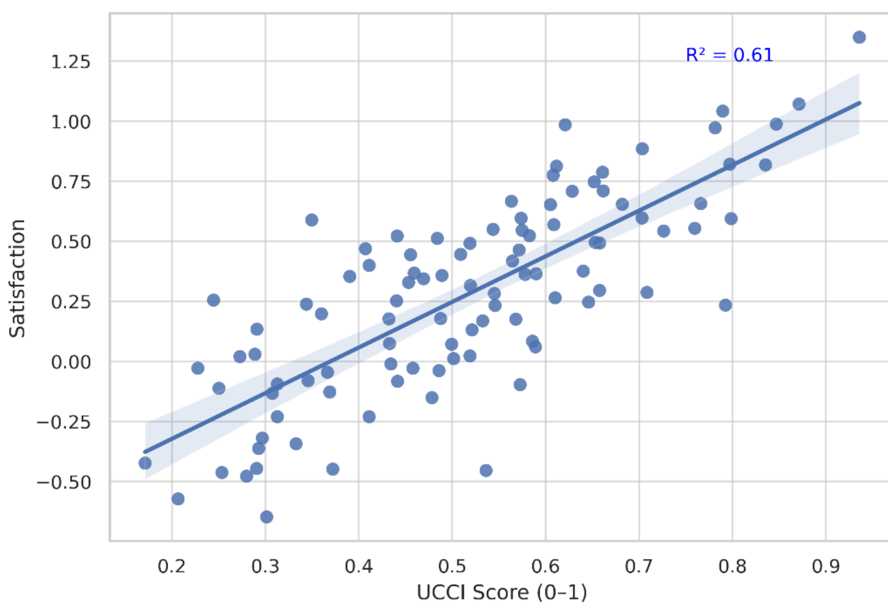



Figure 5.29: *Linear Regression – UCCI vs User Satisfaction*

This regression plot illustrates the relationship between UCCI scores and satisfaction levels across five public space sites in Riyadh. The positive slope indicates that higher UCCI values reflecting improved thermal comfort, spatial connectivity, and user perception are associated with greater satisfaction. The model explains approximately 61% of the variance in user satisfaction ($R^2$ = 0.61), supporting the reliability of UCCI as a predictor of public space usability.

## 5.7 UCCI Trends and Integrated Site Performance (2000–2024)

This section presents a longitudinal assessment of public space usability across five case study sites using the Urban Comfort–Connectivity Index (UCCI). It explores how changes in land use, thermal comfort, and spatial connectivity over a 24-year period have influenced integrated site performance. By evaluating UCCI at four time points 2000, 2010, 2016, and 2024 the study reveals how urban form, vegetation, and infrastructure investments have contributed to or hindered public space usability.

### 5.7.1 Land Use Changes and Spatial Impact

Land use patterns were extracted for each site and compared across time. The most significant shifts occurred in built-up density, loss or gain of vegetation, and transformation of barren land.

Key highlights include:

- Downtown Riyadh densified from 51% to 91% built-up area, while vegetation remained below 6%, reinforcing thermal vulnerability despite improved connectivity.
- Diplomatic Quarter achieved the most balanced development, increasing both built-up area and vegetation (4% to 11%), preserving walkability and comfort.
- KAFD transitioned from a vacant site to a high-density district, reaching 62% built-up by 2024, but green infrastructure remains sparse (8%).
- Museum District lost significant tree cover (34% to 18%) as built-up surfaces increased, weakening its thermal performance.
- Roshn Front, developed post-2016, reached 34% built-up but has minimal green cover (3%), reflecting modern but thermally rigid planning.

*See Appendix A for full land use change tables.*

### 5.7.2 Thermal and Spatial Implications

Thermal comfort modelling (UTCI) and spatial network analysis (FBC) revealed differentiated impacts across sites:

- Downtown and Museum showed elevated UTCI values throughout due to minimal shade and dense paving.
- KAFD and Roshn had poor microclimatic performance in plazas and wide open corridors, despite some connectivity gains.
- DQ consistently maintained lower UTCI values due to tree-lined streets, narrow paths, and shaded zones.

Spatially, DQ retained the highest FBC scores across all years, supported by its looped network and embedded green corridors. KAFD and Roshn, while modern in layout, exhibited rigid block structures and low permeability.

### 5.7.3 UCCI Score Trends and Site Performance

The Urban Comfort–Connectivity Index was calculated for each site across four benchmark years. As shown in Figure 5.25, trends in UCCI scores reflect the cumulative effects of spatial, thermal, and perceptual changes.

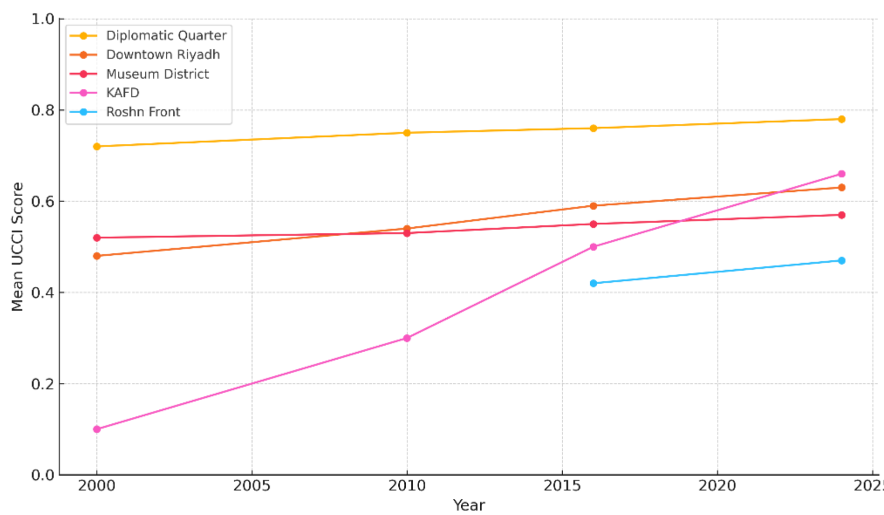



Figure 5.25: UCCI Score Trends by Site (2000–2024)

Key trends:

- Diplomatic Quarter maintained the highest UCCI score consistently, highlighting integrated planning that values vegetation, spatial coherence, and pedestrian experience.

- Downtown Riyadh improved steadily, with connectivity gains offsetting some thermal constraints.
- KAFD rose sharply post-2010, reflecting infrastructure delivery but still limited by thermal discomfort.
- Museum District declined due to vegetation loss, despite stable spatial form.
- Roshn Front entered post-2016 with modest scores and slow improvement due to limited microclimatic adaptation.

### 5.7.4 Summary of Integrated Insights

- Urban densification without greening compromises thermal comfort (Downtown, Museum).
- Spatial upgrades alone do not guarantee usability if thermal conditions are not addressed (KAFD, Roshn).
- Climate-adaptive, well-connected designs (e.g., DQ) consistently perform best over time.

This longitudinal analysis validates the UCCI as a useful tool for tracking public space performance and supports the integration of thermal and spatial logic into long-term urban planning strategies in arid environments like Riyadh.

## 5.8 Summary of Results

This chapter presented a comprehensive analysis of public space usability across five case study sites in Riyadh through the integrated lens of thermal comfort, spatial configuration, and user perception. Using the Urban Comfort–Connectivity Index (UCCI), each site was evaluated in terms of real-time and long-term performance.

The key findings are summarised below:

- Thermal Comfort (UTCI):
  All sites experience high heat stress during midday and summer months, with UTCI often exceeding 45°C. The Diplomatic Quarter was the only site to maintain tolerable thermal conditions, aided by vegetation and shade infrastructure.

Downtown Riyadh and KAFD had consistently high UTCI levels due to limited shade and excessive paving.

- Spatial Connectivity (FBC):
  The Diplomatic Quarter and Downtown Riyadh scored highest in pedestrian-scale connectivity, supported by fine-grained networks and multiple route options. KAFD and Roshn Front, though modern and legible, showed limited permeability and walkability, especially at the local scale.
- User Perception (CPI):
  Survey results showed that shaded, navigable, and amenity-rich areas scored highest in perceived usability. The Diplomatic Quarter achieved the highest CPI, while Roshn and KAFD scored lowest. Perceived comfort was most sensitive to shade availability and pathway continuity.
- UCCI Composite Index:
  The UCCI successfully integrated thermal, spatial, and perceptual data into a unified usability score. The Diplomatic Quarter consistently outperformed other sites. Downtown improved through connectivity, but lacked thermal adaptation. KAFD showed rapid gains in connectivity but underperformed thermally. Roshn Front, as a newer development, showed limited usability due to a lack of pedestrian-scaled and climate-sensitive design.
- Longitudinal Trends (2000–2024):
  Across the 24-year period, the Diplomatic Quarter maintained the most balanced and resilient performance. Downtown saw steady improvement in connectivity, while the Museum District declined slightly due to vegetation loss. KAFD improved significantly post-2010, though thermal discomfort remains a limiting factor. Roshn Front, despite its newness, revealed design limitations linked to usability and climate adaptation.

Overall, the chapter demonstrates that public space usability in hot-climate cities is shaped by the intersection of thermal comfort, spatial accessibility, and user perception. The findings validate the UCCI as a robust framework for evaluating and comparing public spaces in terms of comfort, connectivity, and inclusivity. These insights provide a foundation for the discussion and design implications explored in the next chapter.

Together, these findings demonstrate that public space usability in hot-climate cities is a function of environmental quality, spatial structure, and user experience. No single variable is sufficient to explain usability in isolation; rather, it is the convergence of thermal, spatial, and perceptual dimensions that determines how well a space performs.

These results set the foundation for the interpretive discussion that follows in Chapter 6, where the implications of the UCCI framework will be examined in relation to urban form, design policy, spatial equity, and climate-sensitive planning in Riyadh and similar contexts.

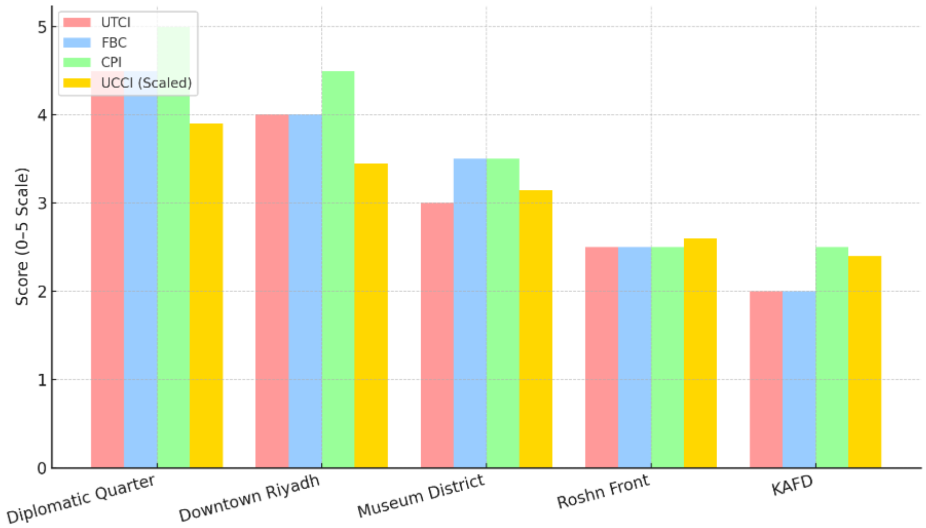



Figure 5.26: Summary of UCCI Components and Composite Scores by Site

This chart displays the component-level scores (UTCI, FBC, CPI) and the scaled composite UCCI index for each site on a unified 0–5 scale. The Diplomatic Quarter leads across all dimensions, indicating a well-integrated urban environment, while KAFD and Roshn Front show the weakest scores, especially in thermal and experiential usability.

Table 5.11: Comparative UCCI Performance Summary Across Sites

| Site | UTCI | FBC | CPI | UCCI (Avg) | Key Strengths | Key Weaknesses |
|---|---|---|---|---|---|---|
| **Downtown Riyadh** | 0.68 | 0.71 | 0.76 | 0.72 | Fine-grained connectivity, shaded streets, walkable alleys | Thermal stress in open plazas, vehicle congestion |
| **Diplomatic Quarter** | 0.75 | 0.78 | 0.81 | 0.78 | Tree cover, shade, high perception, cultural landscape | Peripheral access, formal layout constraints |

| | | | | | | |
|---|---|---|---|---|---|---|
| **King Abdullah FD** | 0.52 | 0.45 | 0.43 | 0.47 | Landmark presence, planned layout | Harsh exposure, fragmented connectivity, underused spaces |
| **Roshn Front** | 0.50 | 0.48 | 0.49 | 0.49 | Commercial activity zones, partial shading near entrances | Low perception, rigid layout, wide unshaded plazas |
| **Museum District** | 0.63 | 0.58 | 0.62 | 0.61 | Heritage setting, shaded arcades, pedestrian network | Loss of greenery, inconsistent comfort zones |

# Chapter 6: Discussion

## 6.1 Introduction

This chapter interprets and contextualises the key findings presented in Chapter 5, drawing on theoretical frameworks, previous research, and site-specific observations. The aim is to explore how the integrated results of thermal comfort (UTCI), spatial connectivity (FBC), and user perception (CPI), as combined through the Urban Comfort–Connectivity Index (UCCI), provide new insights into the design and performance of public spaces in hot-climate urban contexts.

By comparing the five case study sites Downtown Riyadh, King Abdullah Financial District (KAFD), Diplomatic Quarter, Museum District, and Roshn Front this chapter identifies spatial trends, behavioural adaptations, and design conditions that contribute to (or undermine) usable and inclusive environments. The discussion considers how thermal stress, spatial structure, and experiential quality interact, and how these factors shape both the physical performance and perceived value of urban public space.

## 6.2 Interpretation of Key Results

The results presented in Chapter 5 reveal a complex but consistent relationship between thermal conditions, spatial configuration, and perceived usability in Riyadh's public spaces. This section interprets the key findings across the four analytical components UTCI, FBC, CPI, and UCCI to highlight how these dimensions interact and influence the real-world functionality of public space in hot-climate contexts.

### 6.2.1 Thermal Comfort (UTCI)

The UTCI results confirm that thermal discomfort is a defining constraint on public space usability in Riyadh, particularly during summer months. Across all five sites, exposed plazas and open corridors consistently registered strong to extreme heat stress (UTCI > 38°C), limiting usability to early morning hours. However, vegetated areas and shaded pedestrian paths significantly mitigated thermal stress, reducing UTCI values by up to 2–3°C on average. These findings align with prior studies emphasising the microclimatic importance of trees, arcades, and surface materials in hot, arid environments (e.g., Emmanuel, 2005; Johansson & Emmanuel, 2006).

### 6.2.2 Spatial Connectivity (FBC)

The FBC analysis revealed that spatial integration alone is insufficient to support pedestrian usability under thermal stress. While traditional Space Syntax models prioritise long, axial connectors, the Flipped Betweenness Centrality (FBC) model adapted for this study highlighted the value of short, shaded, and angularly efficient segments. Sites with fine-grained, human-scaled networks (e.g., Downtown and DQ) exhibited higher FBC values in walkable areas. By contrast, spatially exposed and monolithic layouts (e.g., KAFD and Roshn Front) showed low connectivity scores in critical pedestrian areas. This supports literature arguing for a shift from geometric legibility to climate-sensitive spatial logic (Karimi, 2012).

### 6.2.3 User Perception (CPI)

Survey results reinforced the importance of amenity quality, shade, and route clarity in shaping perceived usability. Users consistently rated shaded, vegetated, and active frontages higher in terms of comfort, accessibility, and satisfaction. The Diplomatic Quarter and Downtown Riyadh received the highest CPI scores, suggesting that users are highly responsive to environmental and spatial cues. These findings validate arguments that perception is not only a subjective impression but a critical determinant of behavioural use and spatial preference (Gehl, 2011; Mehta, 2014).

### 6.2.4 Integrated Usability (UCCI)

The UCCI maps and classification tables demonstrate that usability emerges through the convergence of spatial, environmental, and experiential qualities. High UCCI values were concentrated in shaded, permeable, and amenity-rich environments most notably in the

Diplomatic Quarter. In contrast, low UCCI zones were typically thermally exposed, spatially fragmented, and behaviourally underperforming, as observed in KAFD and Roshn Front. This reinforces the premise that no single indicator be it climatic, configurational, or perceptual is sufficient to evaluate public space performance in isolation.

The regression analysis further supports this conclusion, showing that all three components of UCCI significantly predict perceived usability, with CPI (perception) having the strongest explanatory power, followed by UTCI and FBC. This confirms the value of using an integrated framework for evaluating public space design under climate pressure.

### 6.3 Cross-Site Comparative Themes

A comparative analysis of the five case study sites Diplomatic Quarter, Downtown Riyadh, Museum District, Roshn Front, and KAFD reveals several recurring themes that influence public space usability in hot-climate urban environments. These themes reflect how different combinations of thermal, spatial, and perceptual factors shape urban comfort and user experience, and they provide a framework for discussing the design strengths and weaknesses of each site type.

#### 6.3.1 Fine-Grained Networks Outperform Formal Grids

Both the Diplomatic Quarter and Downtown Riyadh exhibited strong performance across all UCCI components. These sites share a fine-grained, pedestrian-scaled spatial structure that supports micro-routing, adaptive movement, and shaded connectivity. In contrast, Roshn Front and KAFD, though formally organised and visually legible, suffer from large block sizes, axial rigidity, and long exposed segments that lack spatial flexibility. This contrast reinforces the importance of connectivity at the human scale, particularly in climates where thermal adaptation is critical.

#### 6.3.2 Vegetation and Shade Drive Thermal and Perceptual Performance

Across all sites, areas with higher UCCI scores consistently aligned with vegetated zones, shaded corridors, or tree-lined edges. These conditions not only lowered UTCI values but also received higher perception scores. In the Diplomatic Quarter, continuous green infrastructure contributes to both thermal mitigation and spatial coherence. By contrast, the Museum District and KAFD exhibited usability gaps in exposed civic areas and open plazas, where the absence of shade correlates with both thermal discomfort and low user satisfaction.

### 6.3.3 Perception Strongly Reflects Thermal and Spatial Logic

While perception is inherently subjective, the CPI maps and regression analysis suggest that users respond to very specific spatial and environmental cues. Shaded seating, clear wayfinding, and enclosure consistently enhanced perceived usability, while wide, exposed spaces even when geometrically open were frequently avoided. This highlights the importance of designing environments that invite adaptive behaviours, such as pausing, rerouting, or clustering in cooler zones.

### 6.3.4 High Design Does Not Ensure High Usability

Perhaps most critically, the results challenge the assumption that formal, high-investment developments automatically translate into better urban performance. Both KAFD and Roshn Front feature significant capital investment, aesthetic ambition, and master planning. Yet both underperform in thermal comfort, connectivity, and perception. Conversely, Downtown Riyadh, despite its informal morphology, scores highly in spatial resilience due to its walkability, diversity of form, and organic shading. This illustrates that usability is not guaranteed by design intent alone it must be earned through spatial and environmental responsiveness.

### 6.3.5 Fragmentation Weakens Adaptive Potential

Sites with disconnected segments, fragmented courtyards, or underused intersections tended to score lower in all dimensions. The Museum District, while centrally located and culturally significant, suffers from internal spatial discontinuities that disrupt movement and increase exposure. Addressing these gaps through mid-block connectors, shaded shortcuts, and amenity-rich micro-spaces would significantly enhance usability.

This cross-site thematic comparison reinforces the central insight of this thesis: usable public space in hot-climate cities is created through the convergence of shade, connectivity, and perception not through formal design alone. The next section reflects on the contribution of the UCCI as a framework to diagnose and address these multidimensional challenges in climate-adaptive urbanism.

### 6.4 UCCI as an Integrated Framework

The Urban Comfort–Connectivity Index (UCCI) was developed in this study to provide a holistic and spatially explicit measure of public space usability, grounded in the intersection of three core dimensions: thermal comfort (UTCI), spatial connectivity (FBC), and user perception (CPI). This section reflects on the conceptual and methodological contributions of the UCCI framework and its implications for research and practice.

#### 6.4.1 Beyond Single-Domain Evaluation

Traditional public space assessments often rely on isolated metrics such as thermal indices, accessibility scores, or user satisfaction surveys. While each of these provides valuable insights, they fail to capture the interdependent nature of how comfort, space, and behaviour interact in real-world environments. The UCCI addresses this gap by offering a multi-dimensional assessment tool that reflects the complexity of public space use, particularly in hot-climate urban contexts like Riyadh.

The strong explanatory power demonstrated in the regression analysis (adjusted $R^2 = 0.61$) confirms that the combination of thermal, spatial, and perceptual data more accurately predicts perceived usability than any single factor alone. This validates the integrative design of the UCCI as both a research tool and a planning instrument.

#### 6.4.2 Behaviourally Grounded Spatial Logic

One of the key strengths of the UCCI framework lies in its behavioural orientation. By incorporating the Composite Perception Index (CPI) alongside simulation outputs, the model ensures that user preferences, discomforts, and adaptations are not treated as secondary considerations, but as central indicators of usability. This shift reflects an emerging consensus in urban design and thermal comfort literature that comfort is not only physiological but also spatial, cultural, and perceptual (e.g., Nikolopoulou & Steemers, 2003; Gehl, 2011).

#### 6.4.3 Spatial Resolution and Visual Diagnosis

Because UCCI is generated as a raster-based spatial output, it enables high-resolution mapping of usability gradients within and across sites. This makes it a powerful diagnostic tool for identifying marginalised zones, prioritising design interventions, and communicating performance gaps to stakeholders. The classification bands (high, moderate, low, critical usability) provide a clear framework for evidence-based decision-making in planning and policy.

### 6.4.4 Flexibility and Future Calibration

Although this study applied an equal weighting approach to the three UCCI components, the structure of the framework allows for adaptive calibration. For example, user-based prioritisation of components (via weighting surveys or stakeholder engagement) or site-specific adjustments (e.g. seasonal emphasis) could be incorporated into future iterations. This flexibility makes UCCI a scalable and transferable tool applicable across different urban contexts and climate zones.

### 6.4.5 Contribution to Climate-Sensitive Urbanism

The UCCI framework contributes a novel methodology to the discourse on climate-sensitive urbanism by unifying environmental simulation, spatial network theory, and human-centred data. It offers not just a composite score, but a conceptual model for thinking about public space performance as a multi-scalar and interdisciplinary issue, aligned with contemporary urban resilience and equity agendas.

In summary, the UCCI framework offers a replicable, evidence-based, and spatially detailed method for assessing urban usability in thermally constrained environments. Its integrative design advances both academic understanding and professional practice, enabling cities to move beyond reactive adaptation strategies toward proactive, user-informed spatial planning.

## 6.5 Spatial Equity and Marginalisation

The integration of thermal comfort (UTCI), spatial connectivity (FBC), and user perception (CPI) through the Urban Comfort–Connectivity Index (UCCI) reveals spatial patterns of inclusion and exclusion that extend beyond aesthetics or formal accessibility. In hot-climate cities like Riyadh, spatial equity is fundamentally shaped by the presence or absence of shade, walkability, and microclimatic adaptability.

### 6.5.1 Spatial Equity in a Hot-Climate Urban Context

In traditional planning, equity is often discussed in terms of service access, land value, or transport availability. However, in extreme climates, thermal conditions themselves act as barriers to access (Mitchell & Chakraborty, 2015; Wolch et al., 2014). Spaces that are technically open but thermally uninhabitable are functionally exclusionary, especially for children, older adults, and residents who rely on walking.

In this study, areas characterised by low Flipped Betweenness Centrality (FBC) and high UTCI consistently align with zones of spatial and thermal marginalisation. These include:

- Peripheral open plazas in KAFD
- Wide, unshaded boulevards in Roshn Front
- Central intersections in Downtown Riyadh

Such locations are not only difficult to navigate but are also among the most thermally hostile environments in the city's public realm.

To contextualise these findings, Table 6.0 summarises the socio-demographic characteristics of the five study sites, highlighting variations in population profile, income levels, and mobility dependencies.

Table 6.0 Socio-Demographic Context of the Case-Study Areas

| Site | Population Characteristics | Income Tier / Housing Profile | Mobility & Transport Dependency | Relevant Socio-Spatial Notes |
|---|---|---|---|---|
| **Downtown Riyadh** | High density; diverse age groups; mix of Saudi and expatriate residents | Mixed-income; older building stock with varied rental levels | Lower car dependency; high pedestrian volumes; strong reliance on walkable networks | Historic grid structure supports shaded shortcuts and informal pedestrian routes |
| **King Abdullah Financial** | Low residential density; majority | High-income; premium housing and | Very high car dependency; metro access | Designed for corporate mobility; expansive open |

| Site | Population Characteristics | Income Tier / Housing Profile | Mobility & Transport Dependency | Relevant Socio-Spatial Notes |
|---|---|---|---|---|
| **District (KAFD)** | adult working population | corporate apartments | improving but still underutilised | plazas increase thermal exposure |
| **Museum District (King Abdulaziz Historical Centre)** | Medium density; family-oriented population; many institutional visitors | Mid-income; stable residential fabric | Moderate car dependency; museum visitors rely on structured parking | Large cultural gardens provide shading; socio-cultural mix increases diverse thermal needs |
| **Diplomatic Quarter (DQ)** | Low density; expatriate-heavy demographic; highly educated professional population | High-income; villa compounds and embassy housing | Mixed dependency; strong cycling and walking culture compared to rest of Riyadh | Rich vegetation and microclimatic shading support high thermal comfort |
| **Roshn Front** | Medium density; young families and middle-income groups | Mid-income suburban development; newer housing stock | High car dependency; limited public transport | Wide boulevards and newer urban form reduce shaded walkability |

### 6.5.2 UCCI as a Tool for Equity Diagnosis

By combining thermal, spatial, and perceptual data, the UCCI effectively identifies areas where multiple disadvantages overlap. In these marginalised zones, users must simultaneously contend with:

- Heat stress (UTCI > 45°C)
- Disconnected or exposed circulation routes (low FBC)
- Low perceived usability (CPI < 3.0)

This triple-burden aligns with frameworks of climate vulnerability and spatial injustice seen in cities like Phoenix (Harlan et al., 2006) and Los Angeles (Wolch et al., 2014), where green infrastructure and walkability often bypass low-income or car-dependent communities.

### 6.5.3 Visualising Inequity: Spatial Equity Matrix

A spatial equity matrix was developed to assess each site across thermal access, spatial connectivity, and amenity availability. The Diplomatic Quarter scored consistently high in all dimensions, while KAFD and Roshn Front were found to underperform in each category. This confirms that high-design environments do not guarantee spatial equity unless climate and behavioural use are actively considered. To visualise spatial justice across multiple dimensions, a spatial equity matrix was developed comparing each site's performance in thermal comfort, connectivity, amenities, and perceived usability. The results, summarised in Figure 6.2, reveal that the Diplomatic Quarter consistently outperforms other areas, while KAFD and Roshn Front exhibit overlapping deficits. The full tabulated data is provided in Appendix A, Table A.2.

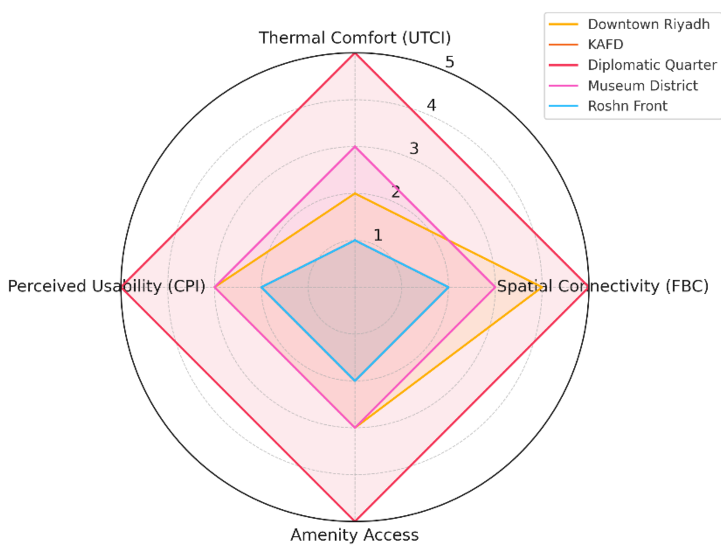



Figure 6.2: Spatial Equity Matrix Across Case Study Sites

This radar chart visualises relative performance across four equity-relevant dimensions: Thermal Comfort (UTCI), Spatial Connectivity (FBC), Amenity Access, and Perceived Usability (CPI). The Diplomatic Quarter performs highest across all categories, reflecting balanced urban design. KAFD and Roshn Front exhibit low thermal and spatial equity due to exposure, poor walkability, and limited public amenities. The matrix highlights overlapping forms of exclusion in low-scoring sites.

#### 6.5.4 Thermal Exclusion as Spatial Injustice

The concept of thermal exclusion provides a critical lens through which to evaluate spatial equity in the context of climate change. As outdoor temperatures rise, previously usable public spaces risk becoming inaccessible, further exacerbating spatial and social inequality (Soja, 2010; Anguelovski & Connolly, 2021). Without equitable investment in shading, tree cover, and human-scale design, thermal exclusion may increasingly shape who gets to use public space and when.

#### 6.5.5 Implications for Equity-Centred Design

The findings suggest that spatial equity must go beyond layout and access to include:

- Distributed shading and greenery
- Micro-connectivity that enables route flexibility
- Comfortable, perceivable, and inviting pedestrian environments

Embedding these dimensions into planning policy and design competitions can help Riyadh move toward spatial justice through climate-responsive urbanism.

**Data Limitations.**

Although the UCCI framework captures spatial inequities through differences in thermal exposure, connectivity, and perceived usability, the socio-economic analysis presented here is based on publicly available district-level descriptors rather than fine-grained GIS demographic datasets. Detailed GASTAT microdata (income bands, gender ratios, household size, age groups, car-ownership levels) were not accessible at the spatial resolution of the study sites. As a result, the socio-demographic context is interpreted qualitatively rather than quantitatively mapped. Future research could integrate neighbourhood-scale census layers or socio-economic deprivation indices to produce fully quantitative equity overlays aligned with UCCI outputs.

### 6.6 Design and Planning Implications

The findings of this study offer important design and policy insights for enhancing the usability, inclusivity, and climate resilience of public spaces in hot-climate cities. The UCCI framework demonstrates that thermally comfortable, spatially connected, and perceptually satisfying spaces are not the product of form alone, but emerge from a strategic convergence of environmental, spatial, and behavioural design elements. This section outlines actionable planning and design implications informed by the results and grounded in existing scholarship.

#### 6.6.1 Redefining Usability in Hot-Climate Urbanism

Traditional measures of public space usability often focus on accessibility, legibility, or density, neglecting the crucial role of thermal comfort and behavioural affordance. In hot-climate cities, a space that is technically accessible but thermally intolerable is effectively unusable (Johansson & Emmanuel, 2006; Nasrollahi, 2009). Design guidelines should move beyond static accessibility metrics and adopt multi-scalar, climate-sensitive definitions of usability, incorporating both physiological and perceptual thresholds (Klemm et al., 2015).

#### 6.6.2 Designing for Thermal Adaptation

This study reinforces the critical need for public spaces to support pedestrian-scale thermal adaptation, particularly through:

- Distributed shading infrastructure, including trees, arcades, and overhangs (Bowler et al., 2010)
- Surface material selection that reduces radiative heat gain (Ali-Toudert & Mayer, 2007)
- Spatial orientation and urban geometry that facilitate airflow and shade continuity (Eliasson, 2000)
- Microclimatic zoning, whereby key pedestrian areas are co-located with shaded seating, rest points, and activity anchors (Johansson et al., 2018)

Findings from the Diplomatic Quarter and Downtown Riyadh show that spaces which prioritise these principles consistently receive higher usability scores.

### 6.6.3 Enhancing Pedestrian Micro-Connectivity

The FBC analysis illustrates that high thermal performance must be matched by high spatial permeability. This calls for urban layouts that prioritise:

- Short, walkable path segments with angular efficiency (Hillier & Iida, 2005)
- Mid-block connectors, especially in large-scale developments (Peponis et al., 2007)
- Shaded, navigable linkages between key programmatic areas (Gehl, 2011)
- Avoidance of monolithic grids that lack micro-scale adaptation opportunities (Karimi, 2012)

Downtown Riyadh exemplifies how informal permeability can produce both spatial and experiential benefits under thermal constraints.

### 6.6.4 Embedding User Perception into Design Evaluation

User perception emerged as the strongest predictor of public space usability in the regression model. This supports the argument that post-occupancy feedback, participatory mapping, and perceptual surveys should be embedded into the design and review process (Mehta, 2014; Carmona et al., 2010). In KAFD and Roshn Front, the disconnection between formal investment and user satisfaction underscores the need to treat perception not as a subjective afterthought, but as a core performance metric.

### 6.6.5 Advancing Spatial Equity through Design

As established in Section 6.5, spatial equity must be approached through climatic as well as social and spatial lenses. This requires designers and policymakers to ensure:

- Equitable access to shaded and usable areas across entire sites not just at focal points (Wolch et al., 2014)
- Distribution of thermal comfort infrastructure based on need and behaviour, not visibility (Shokry et al., 2020)
- Targeted interventions in critical zones identified via UCCI and perception data
- Inclusion of climate equity indicators in urban design guidelines and master plans (Anguelovski & Connolly, 2021)

### 6.6.6 From Composite Metrics to Practice

The UCCI model provides a scalable, replicable framework that can support:

- Climate-adaptive urban audits
- Resilient design competition briefs
- Retrofit strategies for existing public spaces
- Evidence-based policy in master planning and design approvals

This approach aligns with calls for data-driven yet context-sensitive urban governance, where usability is treated as a multi-dimensional, climate-informed, and socially grounded design priority (Fainstein, 2010; Soja, 2010).

## 6.7 Methodological Reflections and Limitations

While the research achieved its core objectives and introduced an integrative framework for evaluating public space usability in hot-climate cities, certain methodological limitations must be acknowledged. These reflections do not undermine the validity of the findings but rather clarify the scope of the results and offer opportunities for future refinement.

### 6.7.1 Seasonal Bias in Perception Data

The user perception surveys were primarily conducted during the cooler months of February and April, when outdoor activity levels are higher and thermal stress is lower. As a result, the Composite Perception Index (CPI) may not fully capture behavioural adaptations or discomfort responses during peak summer months. While the survey did include a question about preferred seasons for public space use, future research could benefit from longitudinal surveys that track user responses across all four seasons (Klemm et al., 2015; Johansson et al., 2018).

### 6.7.2 Normalisation and Weighting Assumptions

All components of the Urban Comfort–Connectivity Index (UCCI) were normalised using a min–max approach and combined using equal weights (1/3 for UTCI, FBC, and CPI). While this allowed for a balanced and interpretable index, it assumes that each factor contributes equally to usability. The regression analysis revealed that CPI had a stronger influence than other components, suggesting that future models could benefit from user-prioritised weighting schemes or sensitivity testing of weight configurations (Mitchell & Chakraborty, 2015).

### 6.7.3 Use of Simulation Data

The thermal comfort component was derived from UTCI simulations using EPW climate files and Ladybug Tools. While validated against regional benchmarks, these models are inherently static and may not account for real-time variations in wind, cloud cover, or humidity. Moreover, assumptions about clothing insulation and activity level were held constant across all users, which may not reflect the diverse physiological and cultural adaptations of Riyadh's residents (Emmanuel, 2005; Ali-Toudert & Mayer, 2007).

### 6.7.4 Subjectivity in Behavioural Interpretation

Although the survey design and interpolation methodology followed standard protocols, spatial interpolation of perception data (IDW) carries some risk of oversimplification. Perception is highly subjective and context-dependent. The spatial surfaces generated from survey points represent a generalised behavioural landscape rather than fixed truths. These maps should therefore be interpreted as indicative rather than definitive tools for policy or design action (Mehta, 2014; Carmona et al., 2010).

### 6.7.5 Site Selection and Generalisability

The five case study sites were chosen to reflect a diversity of spatial typologies, from traditional downtown fabric to master-planned commercial zones. However, all sites are located in central or high-profile areas of Riyadh, which may limit generalisability to informal, peripheral, or under-resourced districts. Future studies should extend the UCCI framework to low-income areas, women-majority spaces, and temporary-use zones (e.g., seasonal pop-ups or transit hubs) to test the robustness of the model in more variable social conditions (Anguelovski & Connolly, 2021; Soja, 2010).

These limitations do not compromise the validity of the findings but underscore the importance of contextual interpretation and methodological transparency. The UCCI model remains a valuable diagnostic tool for evaluating urban usability across climatic, spatial, and behavioural dimensions. However, its future applications would benefit from dynamic calibration, seasonal extension, and demographic sensitivity, ensuring its adaptability to diverse urban contexts and user needs.

### 6.8 Comparative Reflections: Riyadh and Other Hot-Climate Cities

The findings of this study gain further depth when compared with public space development strategies in other hot-climate cities. These comparisons highlight varying degrees of success in integrating spatial logic, climate adaptation, and usability into urban planning.

In Dubai, public space design often revolves around climate-controlled environments, such as underground passages and air-conditioned malls, designed to bypass thermal discomfort altogether (Ratti et al., 2017). While effective in the short term, this strategy reinforces enclosure and dependence on private transport, mirroring challenges seen in KAFD where elevated formality and scale have not translated into thermally usable public spaces.

In contrast, Doha's Msheireb Downtown project reflects a more contextually grounded approach, integrating shaded streets, narrow corridors, and passive cooling strategies into its urban fabric. This mirrors the qualities found in Riyadh's Diplomatic Quarter, which outperformed other sites in UCCI performance. Msheireb has been recognised as a model for climate-sensitive development in the Gulf (Salama & Wiedmann, 2013), combining Qatari heritage with environmental innovation.

Phoenix, a desert city in the United States, has advanced the concept of tree equity prioritising shade infrastructure in socio-economically and thermally vulnerable communities (American Forests, 2021). This emphasis on climate justice parallels the role of the UCCI in identifying spatial marginalisation in Riyadh, especially in newly planned areas like Roshn Front. Phoenix's experience demonstrates how ecological investment can also serve as a tool for equity.

In Singapore, a humid but equally heat-challenged city, public space planning follows a rigorous regime of microclimate zoning, green plot ratio targets, and vertical greenery integration (Tan et al., 2013). Its performance-based planning model offers valuable lessons for Riyadh, particularly in how to operationalise spatial-environmental integration through metrics like UCCI.

These international examples reveal a common insight: climate adaptation must be embedded at the street and site scale, not just addressed through infrastructure or master planning. Riyadh's best-performing site Diplomatic Quarter shares characteristics with Msheireb and Singaporean public spaces, while its least-performing areas KAFD and Roshn reflect global patterns of climate-indifferent urban expansion.

Table 6.1: Comparative Reflections on Urban Comfort and Connectivity in Riyadh and Other Hot-Climate Cities

| **Criteria** | | **Riyadh (Saudi Arabia)** | **Doha (Qatar)** | **Dubai (UAE)** | **Phoenix (USA)** |
|---|---|---|---|---|---|
| **Urban Climate** | | Extremely hot summers, moderate winters; limited humidity | Hot, highly humid summers; mild winters | Hot, humid summers; mild winters | Hot, arid summers; mild winters |
| **Thermal Comfort Strategies** | | Increasing shade structures and vegetation cover | Extensive shading, water features | Emphasis on built shade and cooling | Shade structures and vegetation emphasis |
| **Spatial Connectivity** | | Emerging integration of pedestrian routes; some fragmentation | High spatial integration in newer districts (e.g., Msheireb) | Well-integrated pedestrian networks in developed districts | Well-defined but dispersed pedestrian connectivity |
| **Public Space Usage Patterns** | | Evening-oriented usage; low daytime activity in summer | High evening and night activity | Evening-centric; increasing daytime indoor activities | Early morning and evening peak use |
| **Shade and Vegetation Coverage** | | Moderate but expanding green infrastructure | Moderate, increasing rapidly (Msheireb) | Moderate but heavily reliant on artificial shading | High emphasis on tree planting and canopy cover |
| **User Perception of Comfort** | | Lower daytime comfort; higher satisfaction in shaded areas | High satisfaction due to integrated designs | High satisfaction, particularly in climate-controlled areas | Satisfaction closely tied to shaded pathways |
| **Adaptive Urban** | | Gradual adoption of shade-focused | Extensive climate-responsive | Innovative indoor-outdoor | Progressive urban shading |

| | | | | | |
|---|---|---|---|---|---|
| **Design Innovations** | | public spaces, transit-oriented connectivity | urban renewal projects | integration in urban design | and cooling measures |
| **Integration of Thermal Comfort and Connectivit y (UCCI-like Measures)** | | Recent methodologica l adoption: spatial and thermal factors now jointly considered | Strong integration seen in Msheireb downtown | Advanced but isolated integration examples (Dubai Marina, Downtown) | Incremental integration (Downtown Phoenix, Roosevelt Row) |
| **Key Challenges** | | Thermal extremes, spatial fragmentation, limited pedestrian continuity | Heat and humidity; managing rapid urban expansion | Over-reliance on artificial cooling; pedestrian accessibility | Sprawl and car dependency, low pedestrian continuity |
| **Planning Policy Emphasis** | | Rapid transition towards climate-responsive design and walkability | Comprehensiv e urban regeneration focused on pedestrian comfort | Climate adaptation in select districts; broader implementatio n underway | Ongoing strategies addressing heat mitigation and pedestrianizatio n |

Comparative insights drawn from sources discussed in the main text.

### 6.8 Summary of Discussion

This chapter has interpreted the findings of the Urban Comfort–Connectivity Index (UCCI) through a multi-dimensional lens, highlighting the interplay between thermal comfort, spatial configuration, and user perception in shaping public space usability in hot-climate urban contexts.

The discussion began by unpacking thematic differences across the five case study sites. High-performing environments such as the Diplomatic Quarter and Downtown Riyadh demonstrated the value of fine-grained street networks, continuous shade, and amenity-rich pedestrian corridors. In contrast, KAFD and Roshn Front illustrated how large-scale planning and design investment alone are insufficient when thermal adaptability and pedestrian permeability are lacking.

Comparative analysis underscored how climatic and spatial performance are deeply interrelated, and how perception mediates the experience of usability. The UCCI framework was shown to be both behaviourally grounded and spatially diagnostic, offering a practical tool for identifying spatial marginalisation and thermal exclusion within public environments.

Building on this, the chapter examined the issue of spatial equity, revealing that access to comfortable and usable public space is often concentrated in high-income, master-planned zones, while newer developments or thermally exposed areas are underperforming. The concept of thermal exclusion emerged as a key lens for understanding spatial injustice in the context of climate vulnerability.

The chapter concluded with a set of planning and design implications, calling for a redefinition of usability that prioritises climate resilience, behavioural adaptation, and equitable access. Integrating perception into spatial evaluation and embedding environmental comfort into everyday urban form are critical to designing more inclusive and liveable public spaces.

Together, these insights position the UCCI not only as a technical tool but as a strategic framework for advancing climate-sensitive and socially equitable urbanism. The next chapter builds on these findings to present final conclusions and practical recommendations for urban policy, design practice, and future research.

# Chapter 7: Conclusions and Recommendations

## 7.1 Summary of Research Objectives and Methodology

This research set out to explore how thermal comfort, spatial configuration, and user perception interact to shape public space usability in the context of a hot-climate city. Using Riyadh, Saudi Arabia, as a case study, the study sought to develop and apply a multi-dimensional analytical framework that could identify spatial patterns of comfort, connectivity, and exclusion across different urban typologies.

The core objectives were:

1. To model the thermal comfort of selected public spaces using the Universal Thermal Climate Index (UTCI) and assess seasonal and diurnal variations in heat stress.
2. To evaluate spatial connectivity using Flipped Betweenness Centrality (FBC), a climate-adapted spatial syntax approach focused on pedestrian-scaled routing.

3. To capture and map subjective user experiences through structured perception surveys, generating a Composite Perception Index (CPI).
4. To integrate these three dimensions into a unified, spatially explicit Urban Comfort–Connectivity Index (UCCI) capable of diagnosing strengths and deficiencies in public space usability.
5. To interpret the results of the UCCI through the lenses of spatial equity, marginalisation, and climate-sensitive urban design.

The methodology employed a mixed-methods approach integrating environmental simulation (via Ladybug Tools and UTCI), spatial network analysis (via Grasshopper and Decoding Spaces), and qualitative perception data collected on-site and through online surveys. Each dataset was spatially analysed and visualised using GIS-based raster overlays, enabling high-resolution mapping and cross-site comparison.

Five sites were selected to represent a range of public space morphologies in Riyadh:

- Downtown Riyadh (traditional, fine-grained)
- King Abdullah Financial District (KAFD) (modern, high-density)
- Diplomatic Quarter (DQ) (planned, vegetated)
- Museum District (cultural, civic)
- Roshn Front (contemporary, commercial)

Together, these sites enabled a comparative exploration of how different spatial forms influence usability under thermal stress.

The remainder of this chapter presents the final conclusions of the research, outlines key planning and design recommendations, acknowledges study limitations, and proposes avenues for future work.

### 7.2 Key Findings and Contributions

This study has contributed a new way of understanding and evaluating public space usability in hot-climate cities through the development and application of the Urban Comfort–Connectivity Index (UCCI). By integrating thermal comfort (UTCI), spatial connectivity (FBC), and user perception (CPI), the research moves beyond siloed assessments to offer a holistic, evidence-based framework that reflects how people experience public space under climatic stress.

The key findings of this research are summarised below:

1. Thermal comfort significantly limits usability in open spaces.

Across all case study sites, UTCI simulations confirmed that outdoor usability is constrained by extreme heat for much of the year. Exposed plazas and large paved zones consistently registered strong to extreme heat stress, with usability windows restricted to early morning or evening hours. Vegetation and shade structures were found to reduce UTCI values by up to 2–3°C, reinforcing the value of microclimatic design interventions.

2. Spatial connectivity must operate at the pedestrian scale.

The Flipped Betweenness Centrality (FBC) model revealed that connectivity alone is not enough it must be short, shaded, and behaviourally relevant. High-performing areas were not necessarily the most direct or axial routes, but rather those that offered thermal refuge and adaptive path choices, such as shaded alleyways, narrow connectors, and internal loops.

3. User perception is the strongest predictor of usability.

The Composite Perception Index (CPI) emerged as the most influential component in the regression analysis, indicating that how users feel about a space is more predictive of its usability than spatial or thermal metrics alone. Users consistently valued shaded seating, clear paths, enclosure, and vegetation. Areas perceived as walkable, comfortable, and sociable received the highest scores, regardless of formal layout.

4. UCCI provides an integrated and spatially precise evaluation method.

The UCCI framework successfully captured the intersection of thermal, spatial, and experiential dimensions. High UCCI scores were spatially aligned with shaded, amenity-rich, and permeable areas. Critical zones often overlooked in design were consistently identified in thermally exposed and geometrically fragmented segments. The index proved both behaviourally grounded and operationally scalable.

5. Spatial equity is uneven and thermally unjust.

The research uncovered significant spatial inequalities in comfort, accessibility, and amenity distribution. Wealthier, planned areas such as the Diplomatic Quarter scored consistently high, while newer commercial zones like KAFD and Roshn Front exhibited thermal exclusion, low connectivity, and marginalisation. This underscores the importance of embedding climate justice and spatial equity in public space design and governance.

6. High design quality does not guarantee usability.

Despite considerable investment in formal design and infrastructure, sites such as KAFD underperformed due to lack of human-scaled connectivity, shade, and perceptual comfort. Meanwhile, traditionally evolved environments like Downtown Riyadh performed well, highlighting the value of informality, organic shade, and adaptive behaviour.

### 7.2.1 Key Contributions to Knowledge

This study offers several original contributions to the field of urban design, environmental planning, and spatial equity:

1. A Novel Diagnostic Tool (UCCI):
   Introduces the Urban Comfort–Connectivity Index (UCCI), a new composite metric that integrates spatial, climatic, and perceptual indicators to assess public space usability in hot-climate cities.
2. Behaviourally Informed Spatial Analysis:
   Develops and applies Flipped Betweenness Centrality (FBC) as a modification of traditional network metrics to reflect pedestrian behaviour under thermal stress.
3. Equity-Centred Climate Diagnostics:
   Demonstrates how spatial equity and thermal exclusion can be analysed simultaneously, providing a new method for identifying marginalised spaces in urban environments.
4. Multi-Year Temporal Evaluation:
   Offers a rare longitudinal comparison of spatial and climatic conditions from 2000 to 2024, showing how public space usability has evolved in response to urban development.
5. Grounded in Local Contexts, Scalable Globally:
   Applies the framework to Riyadh as a case study, but designs it to be transferable to other cities facing similar climate and urbanisation pressures.

### 7.3 Planning and Design Recommendations

Based on the integrated results of the Urban Comfort–Connectivity Index (UCCI), this section offers a set of recommendations for urban planners, designers, and policymakers seeking to improve the usability and equity of public spaces in hot-climate cities. The recommendations are drawn from the key findings across thermal, spatial, and perceptual dimensions and are tailored to the urban development context of Riyadh and similar arid cities.

1. Prioritise distributed shade infrastructure
   Shading is the single most effective intervention for improving outdoor comfort in hot climates. Trees, arcades, overhangs, and pergolas should be distributed across the entirety of public spaces not only along main paths or entrances. Design standards should include minimum shade coverage ratios for open plazas, playgrounds, and rest areas, particularly in high-exposure zones.

2. Design for micro-scale pedestrian connectivity
   Urban layouts should support short, thermally adaptive walking routes by incorporating mid-block connections, narrow passageways, and pedestrian-only alleys. The Flipped Betweenness Centrality results revealed that the usability of a path is not based on axial length or directness alone, but on how well it supports shade, rest, and route flexibility.

3. Embed user perception in design processes
   Since user perception was the strongest predictor of usability, participatory tools such as pre-design surveys, perceptual mapping, and post-occupancy evaluations should be integrated into design workflows. Comfort is shaped by both environmental and emotional responses, and these cannot be captured by geometry or climate data alone.

4. Implement equity-based planning assessments
   Spatial equity should be treated as a design requirement, not a by-product. Public space projects should include a spatial equity audit during the design phase, using tools such as the UCCI or perception heatmaps to identify gaps in usability, shade, and access. Special attention should be given to thermally marginalised users, including those who rely on walking, public transport, or passive recreation.

5. Retrofit underperforming spaces with climate-sensitive upgrades
   Many urban plazas and promenades particularly in formal developments like KAFD and Roshn Front can be improved through simple but targeted retrofits. These

include adding shaded seating, creating micro-pathways through large blocks, enhancing tree coverage, and activating dead zones with climate-adaptive uses. Design policies should allow for iterative upgrades and reconfiguration of underused zones.

6. Establish comfort and usability as regulatory performance criteria
   Rather than measuring public space success through visual design or land allocation, planning authorities should adopt composite indices such as the UCCI as part of regulatory review. Guidelines should require that a minimum proportion of public space achieves high usability across thermal, spatial, and behavioural dimensions. This could inform master plan approvals, developer incentives, and climate resilience targets.

7. Integrate adaptive design into zoning and development codes
   Planning regulations should mandate adaptive design features in public spaces, such as summer-oriented seating, water misting, shaded pedestrian corridors, and thermal buffer zones. These elements can be required within zoning overlays for commercial, civic, and recreational areas.

Table 7.2: Time-Phased Urban Design Recommendations Based on UCCI Findings

| Time Frame | Actions | Strategic Focus |
|---|---|---|
| **Short-Term (0–2 yrs)** | • Install modular shading (e.g. canopies).<br>• Add benches, misting systems, and vegetation containers.<br>• Conduct perception-based audits.<br>• Use UCCI maps to prioritise low-performing zones. | Quick-win thermal relief; perception validation; targeted retrofitting |
| **Mid-Term (2–5 yrs)** | • Require thermal comfort metrics in design guidelines.<br>• Improve shaded pedestrian connectivity.<br>• Introduce minimum shade ratios in codes.<br>• Link transit planning with comfort data. | Policy alignment; mobility integration; public realm enhancement |
| **Long-Term (5+ yrs)** | • Implement district-wide shade masterplans. | Systemic integration; equity-driven planning; climate resilience |

| | | |
|---|---|---|
| | • Institutionalise UCCI as a planning diagnostic tool.<br>• Promote human-scaled blocks via zoning reform.<br>• Integrate user perception into smart systems. | |

By following these recommendations, Riyadh and similar cities can move toward a new paradigm of public space design one that recognises the fundamental role of thermal and spatial adaptation in enabling inclusive, equitable, and climate-resilient urban life.

### 7.4 Limitations of the Study and Future Research

While this study achieved its core objectives and contributed a novel framework for evaluating public space usability in hot-climate cities, several limitations should be acknowledged. These do not diminish the validity of the results but highlight areas where further work is needed to expand, adapt, and test the methodology across broader contexts.

1. Seasonal limitations of perception data
   User perception surveys were conducted primarily during the cooler months (February and April), which are more comfortable for outdoor activity in Riyadh. While the survey included a question about seasonal usage, the responses may not fully capture behavioural patterns and thermal stress avoidance during peak summer conditions. Future research should extend data collection across multiple seasons to better account for year-round usability.

2. Equal weighting assumption in UCCI
   The Urban Comfort–Connectivity Index was constructed using an equal weighting of its three components: UTCI, FBC, and CPI. While this approach ensured balance, it may not reflect real-world user priorities, especially in environments where thermal comfort or spatial access dominate user decisions. A future refinement of the model could involve weighted calibration based on user-defined preferences or machine learning sensitivity analysis.

3. Simulation and modelling assumptions
   The thermal comfort data were generated using environmental simulations based on hourly EPW files and standard UTCI assumptions. While these tools are widely validated, they rely on generalisations regarding wind speed, solar radiation,

clothing levels, and user activity. Real-time or sensor-based thermal measurements could improve the empirical accuracy of future models.

4. Site selection scope
   The five selected sites represent a range of typologies in Riyadh, but all are relatively central, planned, or high-profile districts. The findings may not be fully generalisable to more informal settlements, peri-urban neighbourhoods, or under-resourced public spaces. Future applications of the UCCI framework should include diverse spatial and socio-economic contexts to improve its inclusivity.

5. Subjectivity in perception data
   While structured surveys and spatial interpolation methods were used to derive the Composite Perception Index, user feedback remains inherently subjective. Cultural norms, gender, time of day, and personal expectations all influence how comfort and usability are perceived. Further qualitative studies, including interviews or behavioural mapping, could deepen the understanding of perception and its spatial expression.

6. Absence of demographic-specific analysis
   Although the survey included a broad demographic sample, the analysis did not differentiate UCCI outcomes by age, gender, mobility status, or cultural background. Future work could incorporate intersectional analysis to better understand how spatial and thermal exclusion impacts different user groups, especially women, older adults, and low-income residents.

Despite these limitations, the study offers a replicable, scalable, and context-sensitive method for diagnosing urban public space usability under climatic stress. The proposed refinements offer a roadmap for advancing the method toward even greater empirical, behavioural, and spatial accuracy.

### 7.5 Final Reflections and Closing Statement

This research began with a simple but urgent question: what makes public space usable in a city where outdoor conditions often challenge human tolerance? Through a multi-scalar analysis of thermal comfort, spatial structure, and user perception, the study has shown that usability is not just a product of design intent or physical accessibility, but the result of a careful and adaptive balance between climate, form, and behaviour.

The development of the Urban Comfort–Connectivity Index (UCCI) marks a meaningful contribution to the growing field of climate-sensitive urbanism. By integrating objective simulation, spatial network analysis, and subjective user experience, the UCCI offers a new way of diagnosing, comparing, and improving public spaces in hot-climate environments. Its strength lies not only in its analytical depth but in its practical applicability: the framework is scalable, spatially explicit, and grounded in real user behaviour.

Across five diverse case study sites in Riyadh, the research revealed both successful spatial patterns and critical usability gaps. The Diplomatic Quarter and Downtown Riyadh demonstrated how fine-grained, shaded, and human-scaled environments foster thermal and social resilience. In contrast, large-scale, exposed, and fragmented developments despite their formal planning and investment often fail to support daily public life under extreme heat conditions.

Ultimately, the thesis argues for a shift in how we evaluate and design public space in arid cities. Usability must no longer be defined by physical openness or aesthetic coherence alone, but by how well a space supports comfort, movement, and activity across a range of users and conditions. It is time for planners, designers, and policymakers to move beyond isolated metrics and adopt integrated, evidence-based approaches that treat shade, connectivity, and perception as central tools of inclusion and sustainability.

As climate extremes become increasingly common, the urgency of these insights will only grow. The UCCI offers not a static solution, but a starting point an invitation to reimagine public space as a system of overlapping environmental, social, and spatial experiences. With the right tools, we can design cities that are not only livable, but equitable, comfortable, and adaptive even under the harshest of skies.

754.

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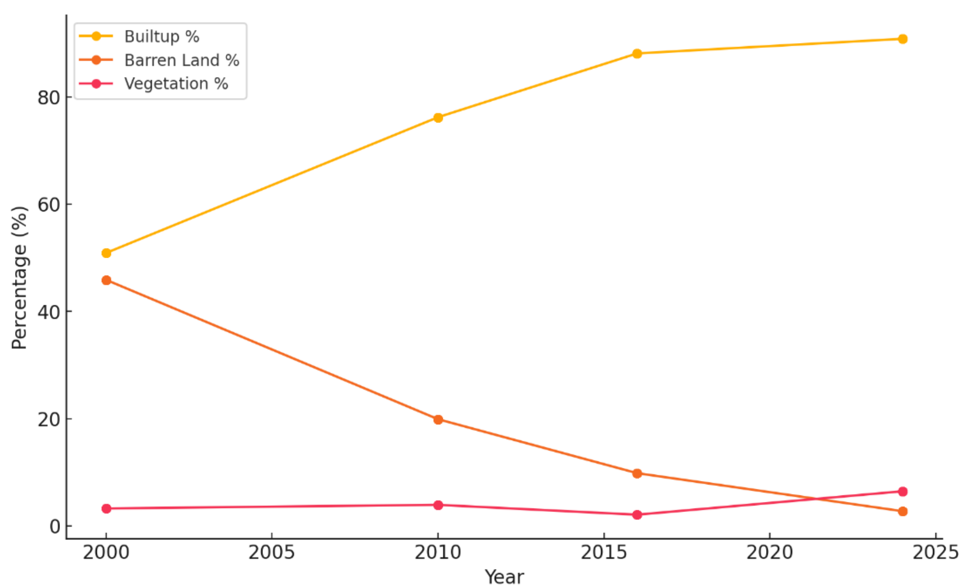
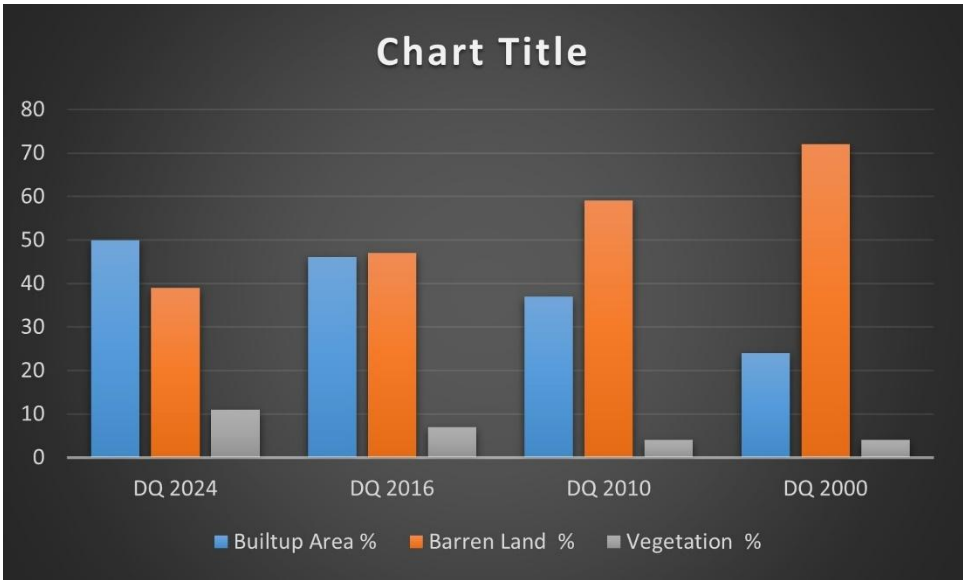
**Appendix A:**

Supporting Data and Documentation

### A.1 Historical Land Use Data (2000–2024)

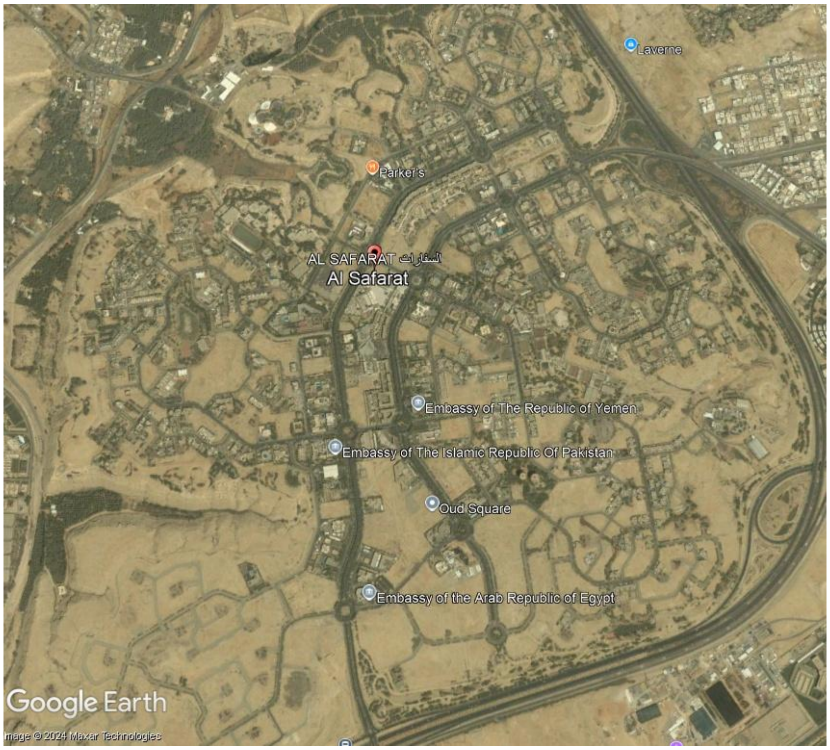


- **DQ**




| Place | Builtup Area | Barren Land | Vegetation | Toal Area m2 |
|---|---|---|---|---|
| DQ 2024 | 1490953 | 1177320 | 317713 | 2985986 |
| DQ 2016 | 1371841 | 1404958 | 209187 | 2985986 |
| DQ 2010 | 1093762 | 1760703 | 131521 | 2985986 |
| DQ 2000 | 724315 | 2152204 | 109467 | 2985986 |

| Place | Builtup Area % | Barren Land % | Vegetation % |
|---|---|---|---|
| DQ 2024 | 50 | 39 | 11 |
| DQ 2016 | 46 | 47 | 7 |
| DQ 2010 | 37 | 59 | 4 |
| DQ 2000 | 24 | 72 | 4 |



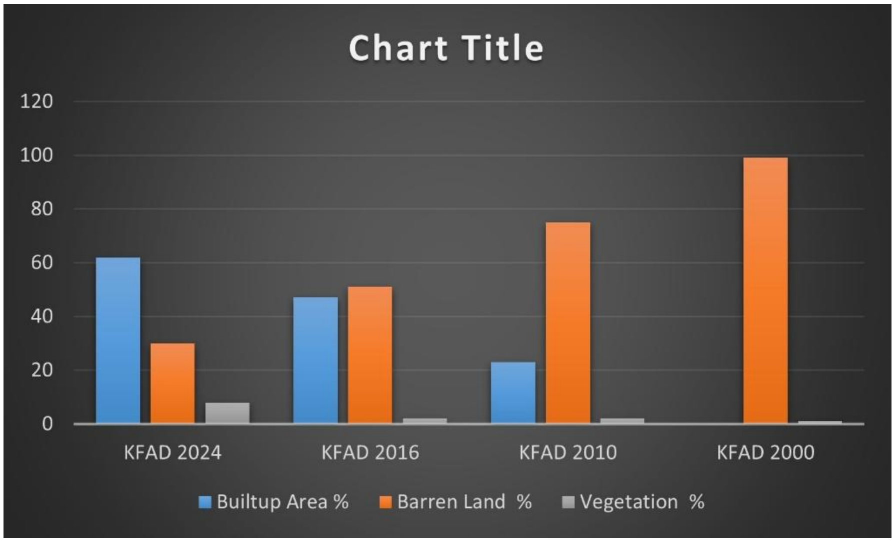

DQ 2000


DQ 2010


DQ 2016

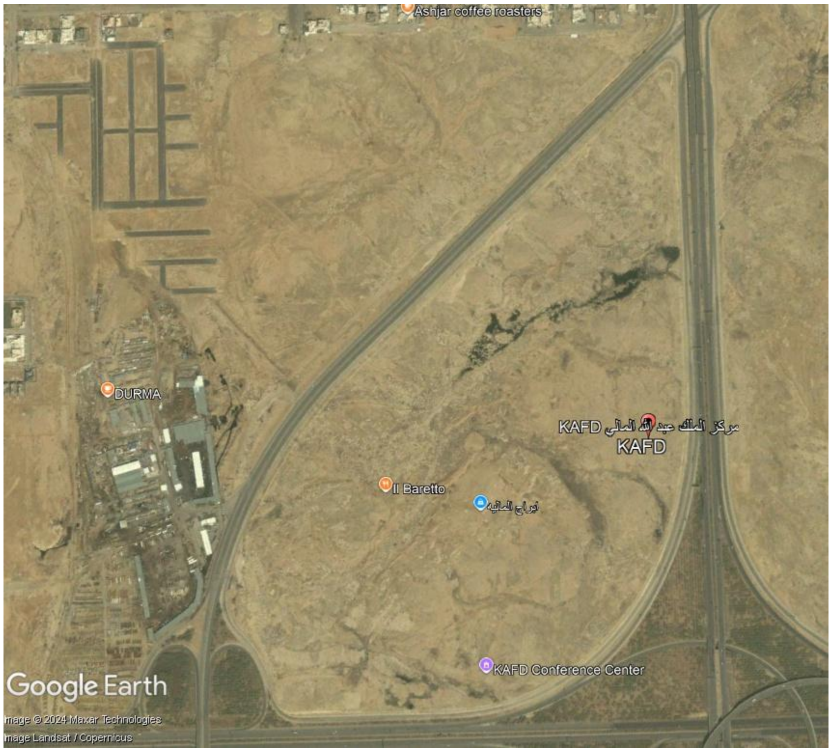

DQ2024

- **KAFD :**




| Place | Builtup Area | Barren Land | Vegetation | Toal Area m2 |
|---|---|---|---|---|
| KFAD 2024 | 886220 | 450452 | 112898 | 1449570 |
| KFAD 2016 | 685319 | 745931 | 18320 | 1449570 |
| KFAD 2010 | 321910 | 1113139 | 14521 | 1449570 |
| KFAD 2000 | 0 | 1440000 | 9570 | 1449570 |

| Place | Builtup Area % | Barren Land % | Vegetation % |
|---|---|---|---|
| KFAD 2024 | 62 | 30 | 8 |
| KFAD 2016 | 47 | 51 | 2 |
| KFAD 2010 | 23 | 75 | 2 |
| KFAD 2000 | 0 | 99 | 1 |



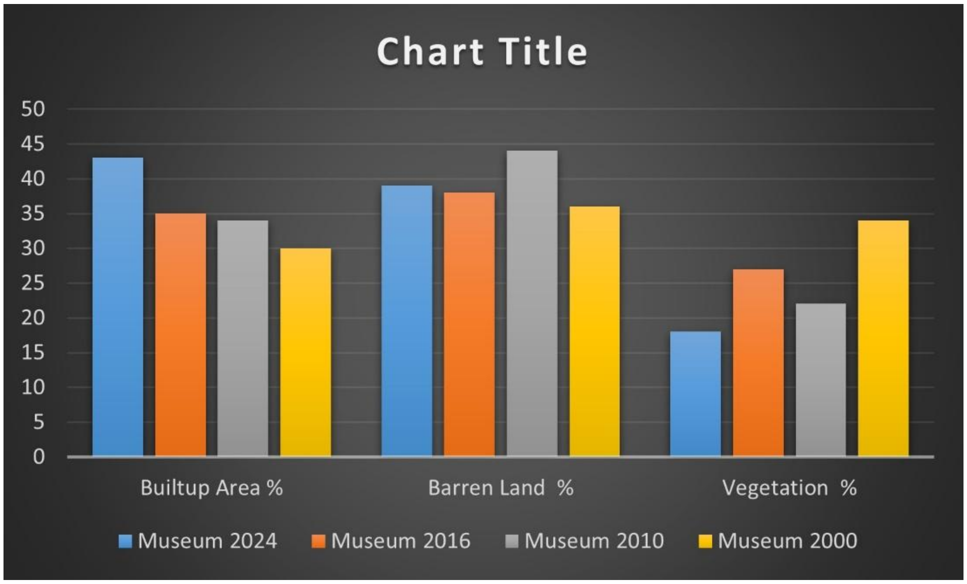

KAFD 2000


KAFD 2010


KAFD 2016


KAFD 2024

- **Museum**

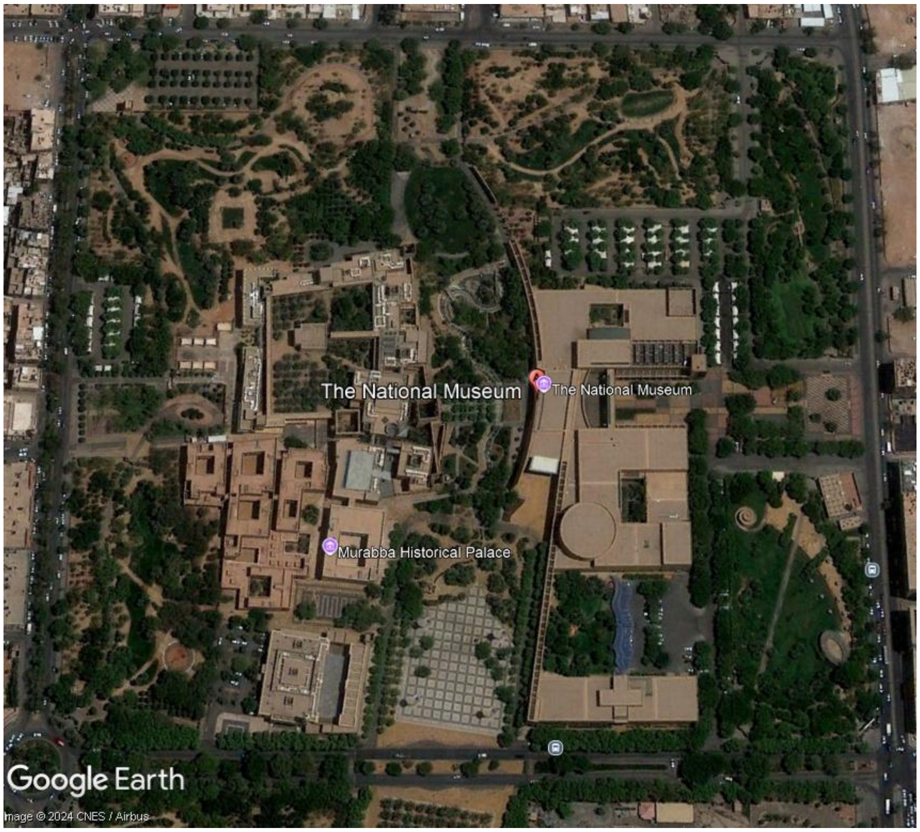



| Place | Builtup Area | Barren Land | Vegetation | Toal Area m2 |
|---|---|---|---|---|
| Museum 2024 | 118738 | 105323 | 46964 | 271025 |
| Museum 2016 | 96738 | 101828 | 72459 | 271025 |
| Museum 2010 | 92547 | 118766 | 59712 | 271025 |
| Museum 2000 | 83658 | 95477 | 91890 | 271025 |

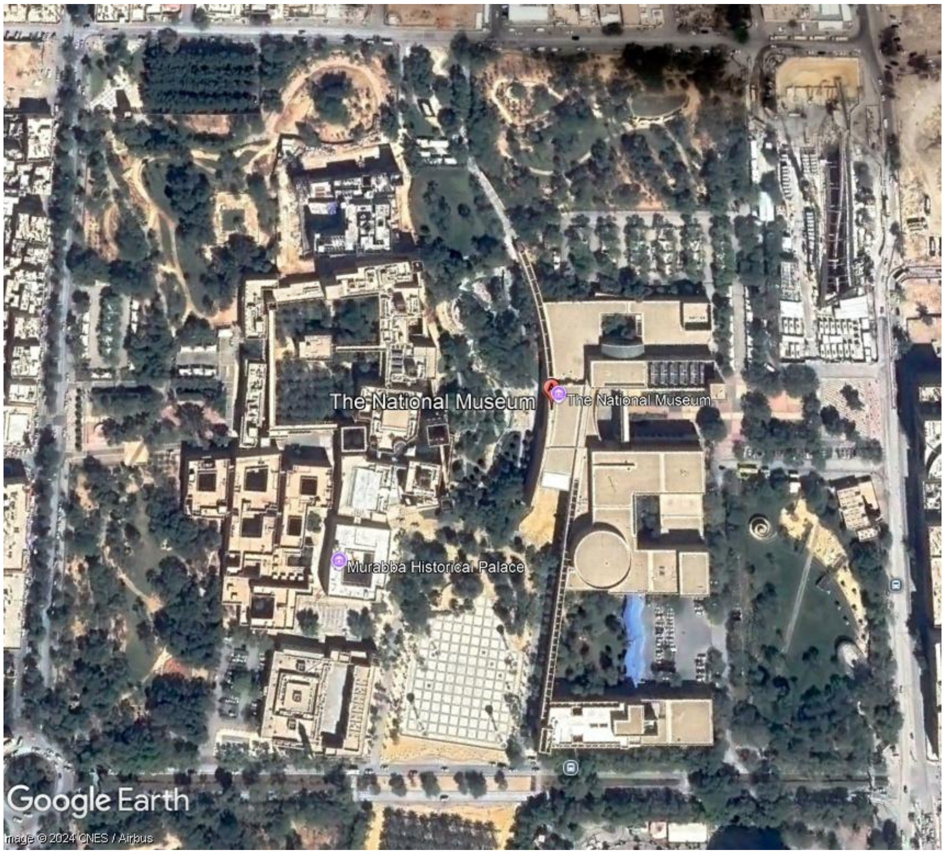
| Place | Builtup Area % | Barren Land % | Vegetation % |
|---|---|---|---|
| Museum 2024 | 43 | 39 | 18 |
| Museum 2016 | 35 | 38 | 27 |
| Museum 2010 | 34 | 44 | 22 |
| Museum 2000 | 30 | 36 | 34 |


The National Museum
The National Museum
Murabba Historical Palace
Google Earth
Image © 2024 CNES / Airbus

2000


The National Museum
The National Museum
Murabba Historical Palace
Google Earth
Image © 2024 CNES / Airbus

2010


The National Museum
The National Museum
Murabba Historical Palace
Google Earth
Image © 2024 CNES / Airbus

2016


The National Museum
The National Museum
Murabba Historical Palace
Google Earth
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2024

- **Roshn**

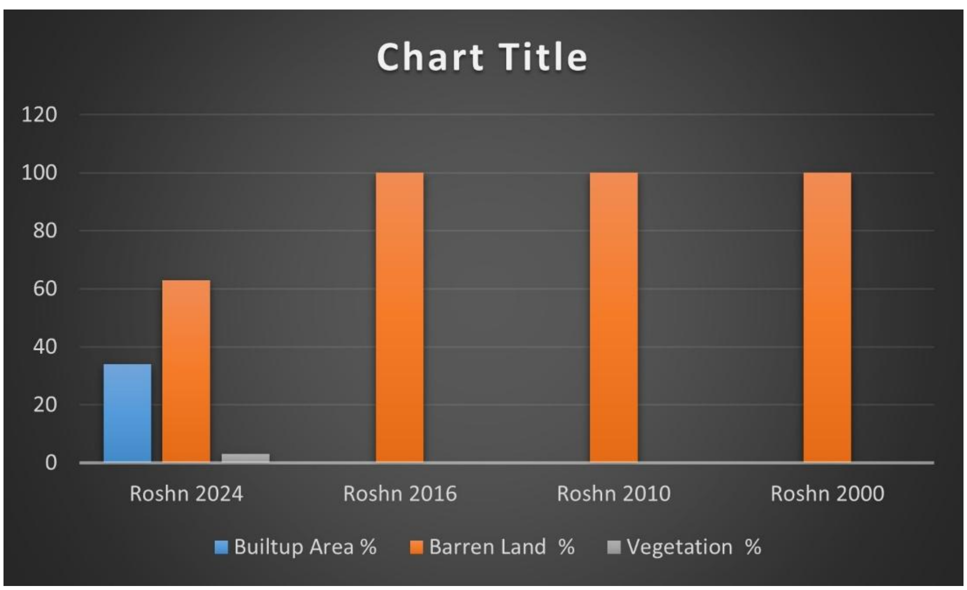
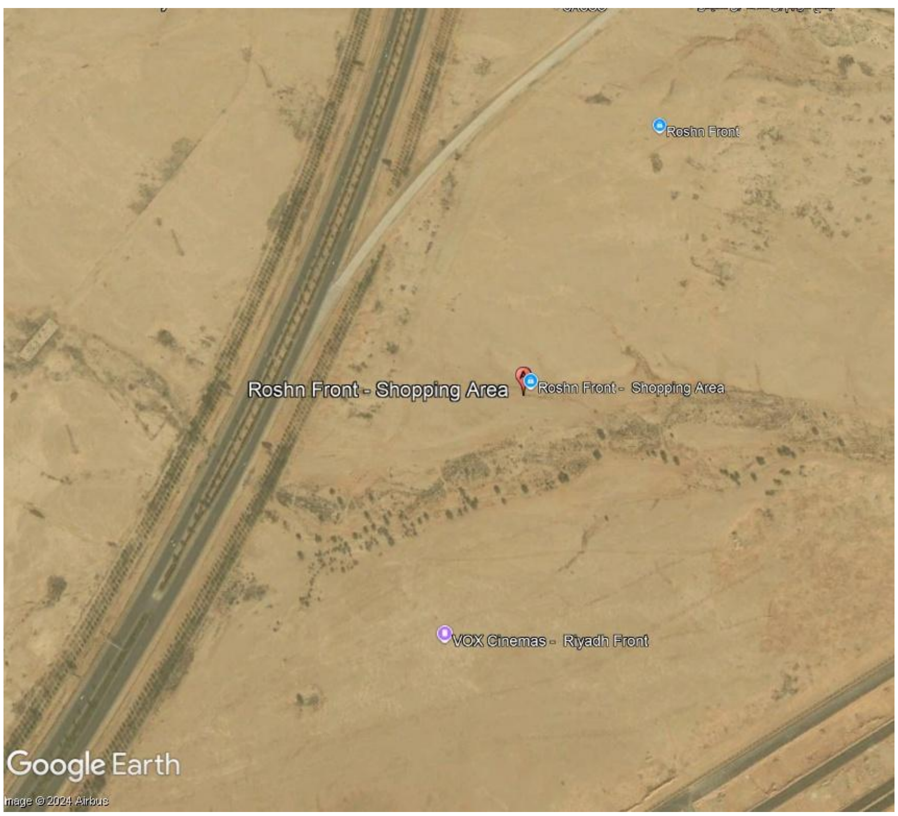


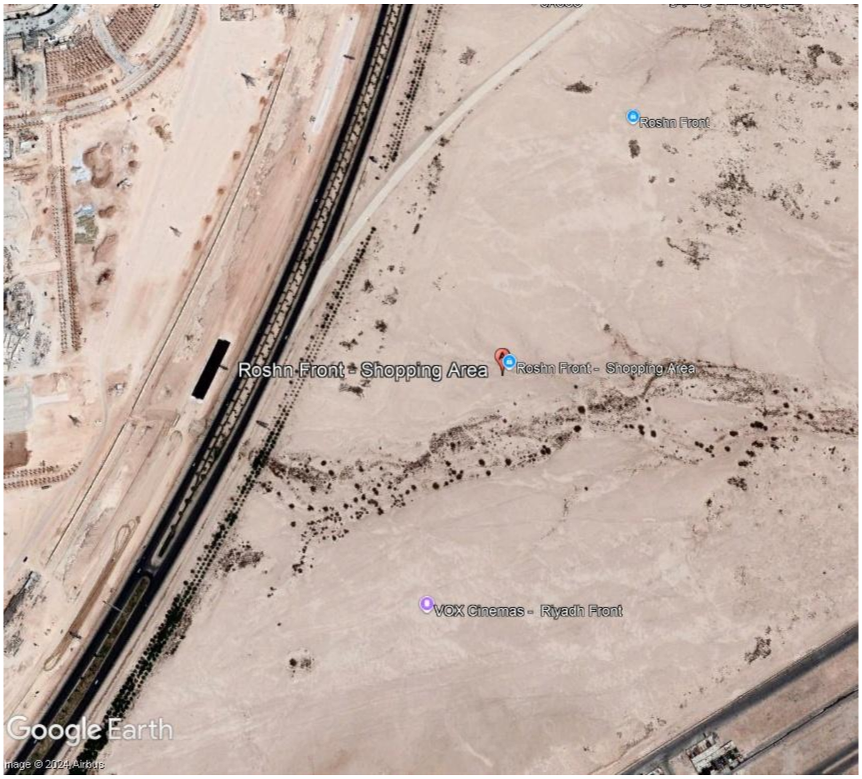
Chart Title
120
100
80
60
40
20
0
Roshn 2024
Roshn 2016
Roshn 2010
Roshn 2000
Builtup Area %
Barren Land %
Vegetation %

| Place | Builtup Area | Barren Land | Vegetation | Toal Area m2 |
|---|---|---|---|---|
| Roshn 2024 | 90557 | 169346 | 1475 | 261378 |
| Roshn 2016 | 0 | 261378 | 0 | 261378 |
| Roshn 2010 | 0 | 261378 | 0 | 261378 |
| Roshn 2000 | 0 | 261378 | 0 | 261378 |

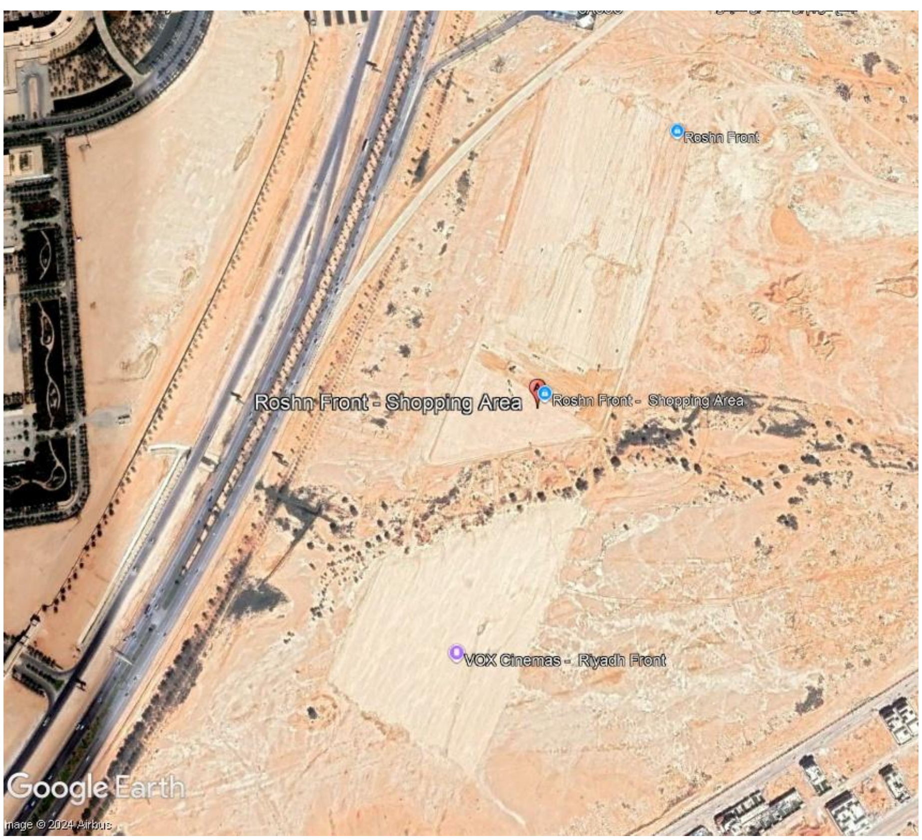
| Place | Builtup Area % | Barren Land % | Vegetation % |
|---|---|---|---|
| Roshn 2024 | 34 | 63 | 3 |
| Roshn 2016 | 0 | 100 | 0 |
| Roshn 2010 | 0 | 100 | 0 |
| Roshn 2000 | 0 | 100 | 0 |



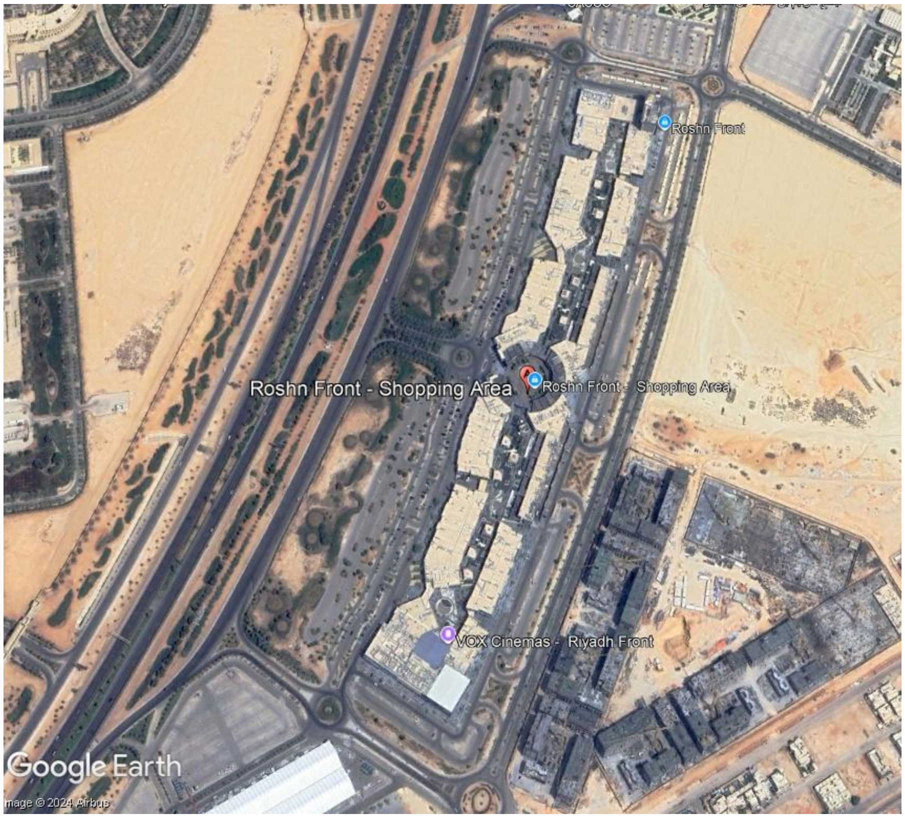

2000


Roshn Front
Roshn Front - Shopping Area
Roshn Front - Shopping Area
VOX Cinemas - Riyadh Front
Google Earth
Image © 2024 Airbus

2010


Roshn Front
Roshn Front - Shopping Area
Roshn Front - Shopping Area
VOX Cinemas - Riyadh Front
Google Earth
Image © 2024 Airbus

2016

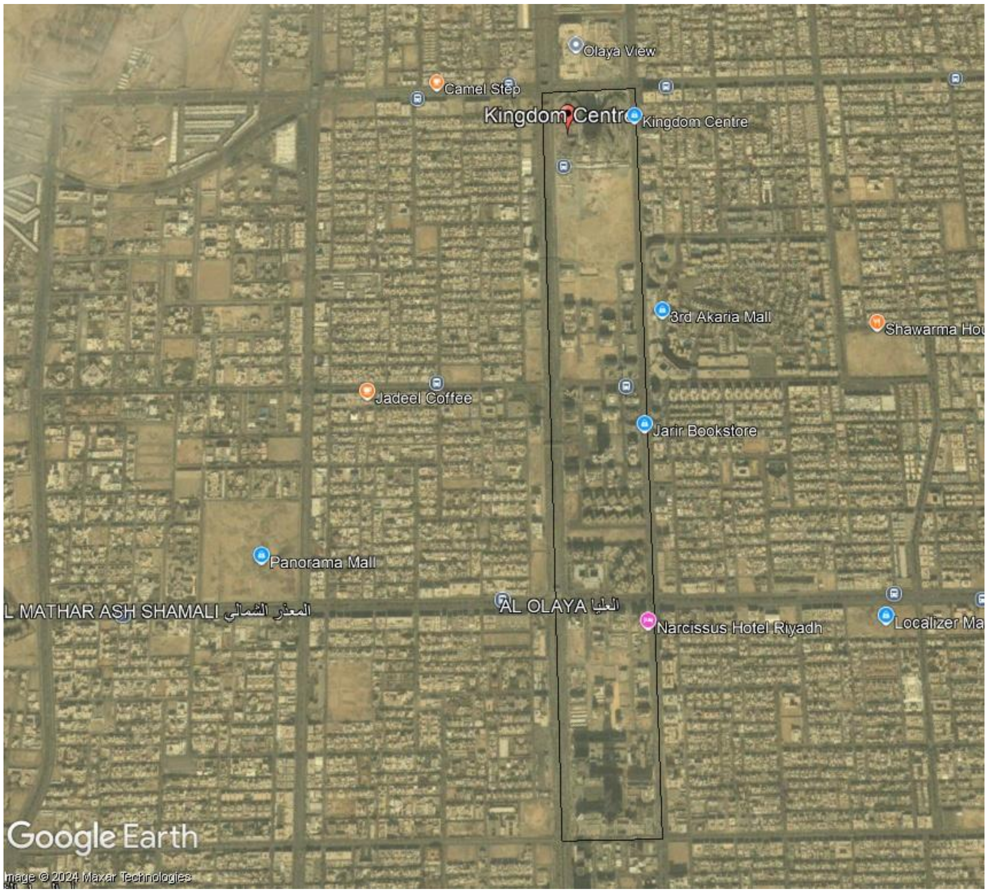



2024

- **Downtown**

| Place | Builtup Area | Barren Land | Vegetation | Toal Area m2 |
|---|---|---|---|---|
| Downtown 2024 | 815881 | 24567 | 57981 | 898429 |
| Downtown 2016 | 791410 | 88294 | 18725 | 898429 |
| Downtown 2010 | 684524 | 178692 | 35213 | 898429 |
| Downtown 2000 | 457190 | 412085 | 29154 | 898429 |

| Place | Builtup Area % | Barren Land % | Vegetation % |
|---|---|---|---|
| Downtown 2024 | 91 | 3 | 6 |
| Downtown 2016 | 88 | 10 | 2 |
| Downtown 2010 | 76 | 20 | 4 |
| Downtown 2000 | 51 | 46 | 3 |


Olaya View
Camel Step
Kingdom Centr
Kingdom Centre
3rd Akaria Mall
Shawarma Hou
Jadeel Coffee
Jarir Bookstore
Panorama Mall
L MATHAR ASH SHAMALI المعذر الشمالي
AL OLAYA العليا
Narcissus Hotel Riyadh
Localizer Ma
Google Earth
Image © 2024 Maxar Technologies

2000


Olaya View
Camel Step
Kingdom Centre
Kingdom Centre
3rd Akaria Mall
Jadeel Coffee
Jarir Bookstore
Panorama Mall
L MATHAR ASH SHAMALI المعذر الشمالي
AL OLAYA العليا
Narcissus Hotel Riyadh
Google Earth
Image © 2024 Maxar Technologies

2010


Olaya View
Camel Step
Kingdom Centre
Kingdom Centre
3rd Akaria Mall
Shawarma Hou
Jadeel Coffee
Jarir Bookstore
Panorama Mall
L MATHAR ASH SHAMALI المعذر الشمالي
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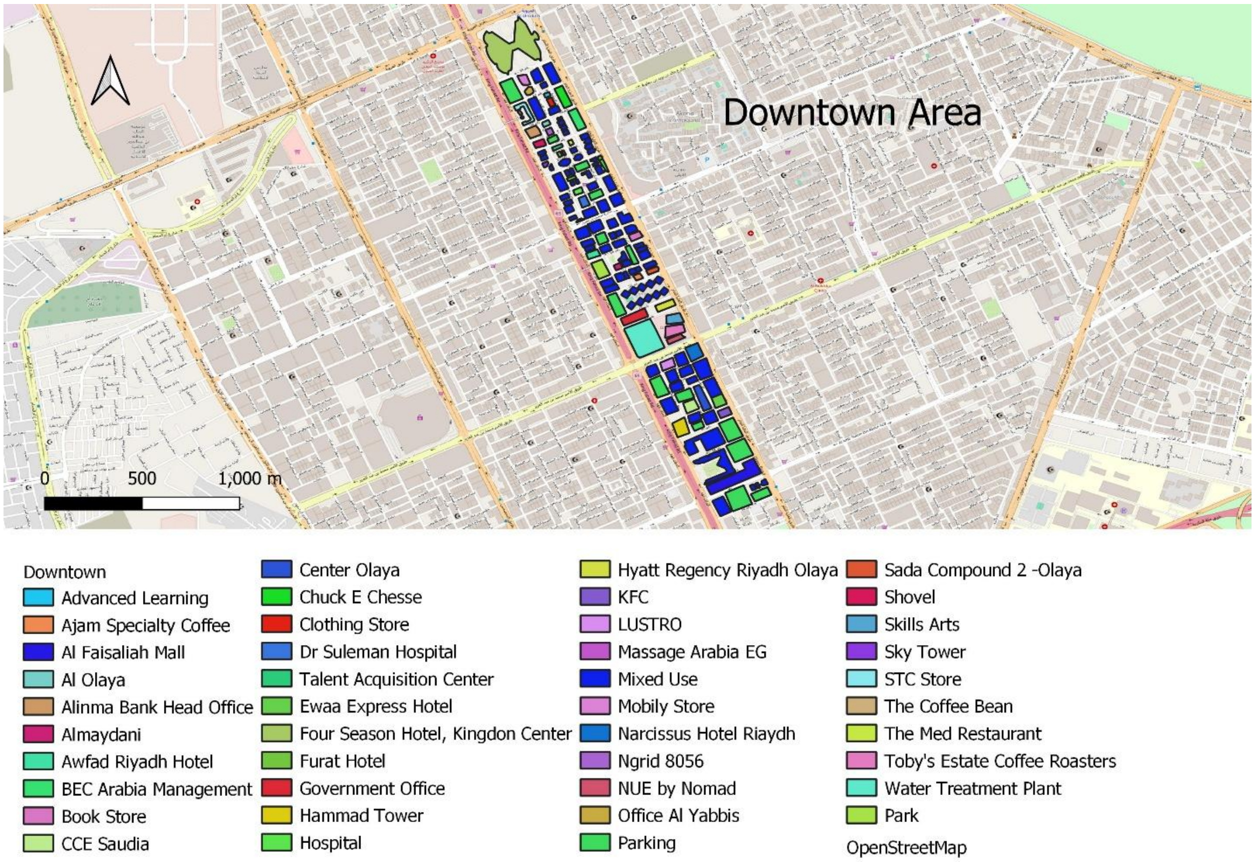
Narcissus Hotel Riyadh
Localizer Ma
Google Earth
Image © 2024 Maxar Technologies

2016


2024

### A.1.1 Land Use Data (2024)


Downtown Area
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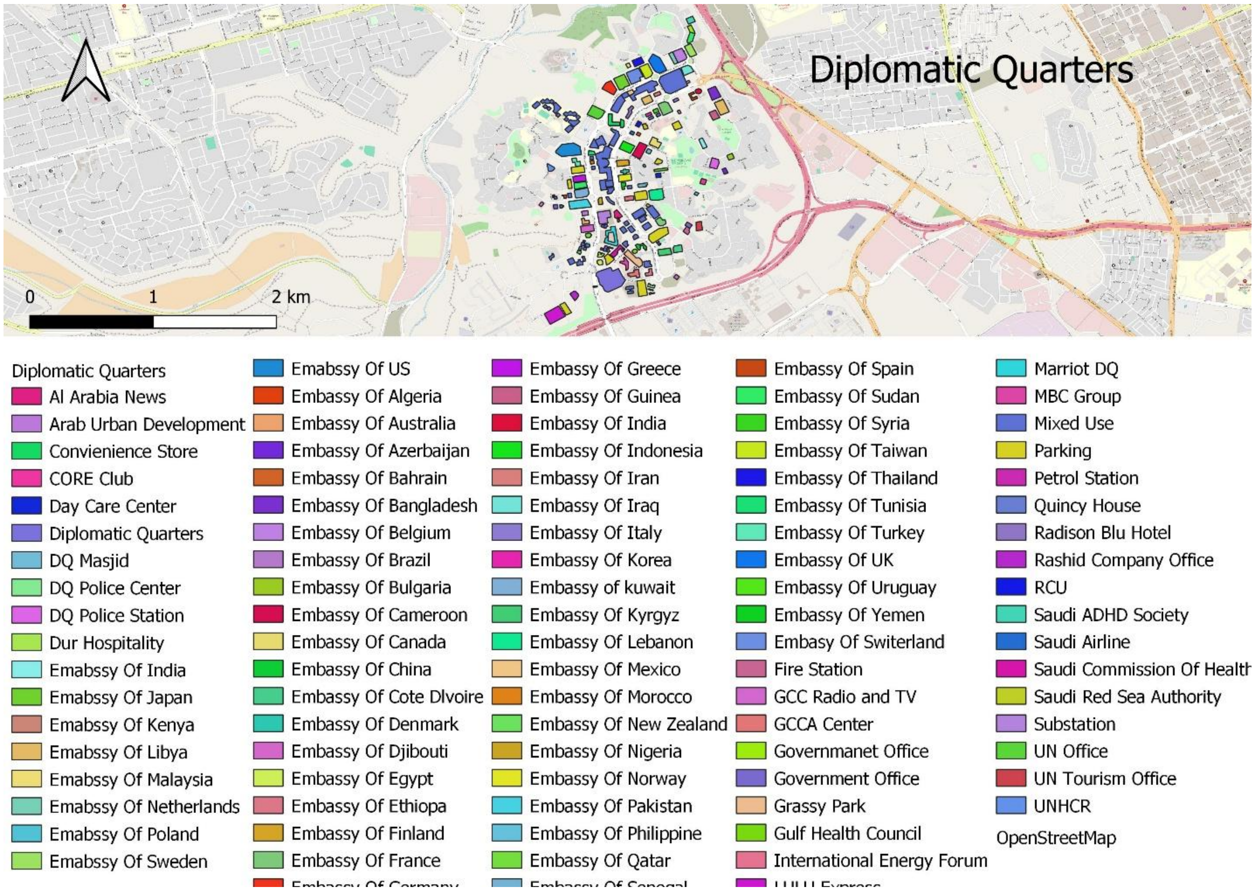
500
1,000 m
Downtown
Advanced Learning
Ajam Specialty Coffee
Al Faisaliah Mall
Al Olaya
Alinma Bank Head Office
Almaydani
Awfad Riyadh Hotel
BEC Arabia Management
Book Store
CCE Saudia
Center Olaya
Chuck E Chesse
Clothing Store
Dr Suleman Hospital
Talent Acquisition Center
Ewaa Express Hotel
Four Season Hotel, Kingdon Center
Furat Hotel
Government Office
Hammad Tower
Hospital
Hyatt Regency Riyadh Olaya
KFC
LUSTRO
Massage Arabia EG
Mixed Use
Mobily Store
Narcissus Hotel Riaydh
Ngrid 8056
NUE by Nomad
Office Al Yabbis
Parking
Sada Compound 2 -Olaya
Shovel
Skills Arts
Sky Tower
STC Store
The Coffee Bean
The Med Restaurant
Toby's Estate Coffee Roasters
Water Treatment Plant
Park
OpenStreetMap


Diplomatic Quarters
0
1
2 km
Diplomatic Quarters
Al Arabia News
Arab Urban Development
Convienience Store
CORE Club
Day Care Center
Diplomatic Quarters
DQ Masjid
DQ Police Center
DQ Police Station
Dur Hospitality
Emabssy Of India
Emabssy Of Japan
Emabssy Of Kenya
Emabssy Of Libya
Emabssy Of Malaysia
Emabssy Of Netherlands
Emabssy Of Poland
Emabssy Of Sweden
Emabssy Of US
Embassy Of Algeria
Embassy Of Australia
Embassy Of Azerbaijan
Embassy Of Bahrain
Embassy Of Bangladesh
Embassy Of Belgium
Embassy Of Brazil
Embassy Of Bulgaria
Embassy Of Cameroon
Embassy Of Canada
Embassy Of China
Embassy Of Cote DIvoire
Embassy Of Denmark
Embassy Of Djibouti
Embassy Of Egypt
Embassy Of Ethiopa
Embassy Of Finland
Embassy Of France
Embassy Of Greece
Embassy Of Guinea
Embassy Of India
Embassy Of Indonesia
Embassy Of Iran
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Embassy Of Lebanon
Embassy Of Mexico
Embassy Of Morocco
Embassy Of New Zealand
Embassy Of Nigeria
Embassy Of Norway
Embassy Of Pakistan
Embassy Of Philippine
Embassy Of Qatar
Embassy Of Spain
Embassy Of Sudan
Embassy Of Syria
Embassy Of Taiwan
Embassy Of Thailand
Embassy Of Tunisia
Embassy Of Turkey
Embassy Of UK
Embassy Of Uruguay
Embassy Of Yemen
Embasy Of Switerland
Fire Station
GCC Radio and TV
GCCA Center
Governmanet Office
Government Office
Grassy Park
Gulf Health Council
International Energy Forum
Marriot DQ
MBC Group
Mixed Use
Parking
Petrol Station
Quincy House
Radison Blu Hotel
Rashid Company Office
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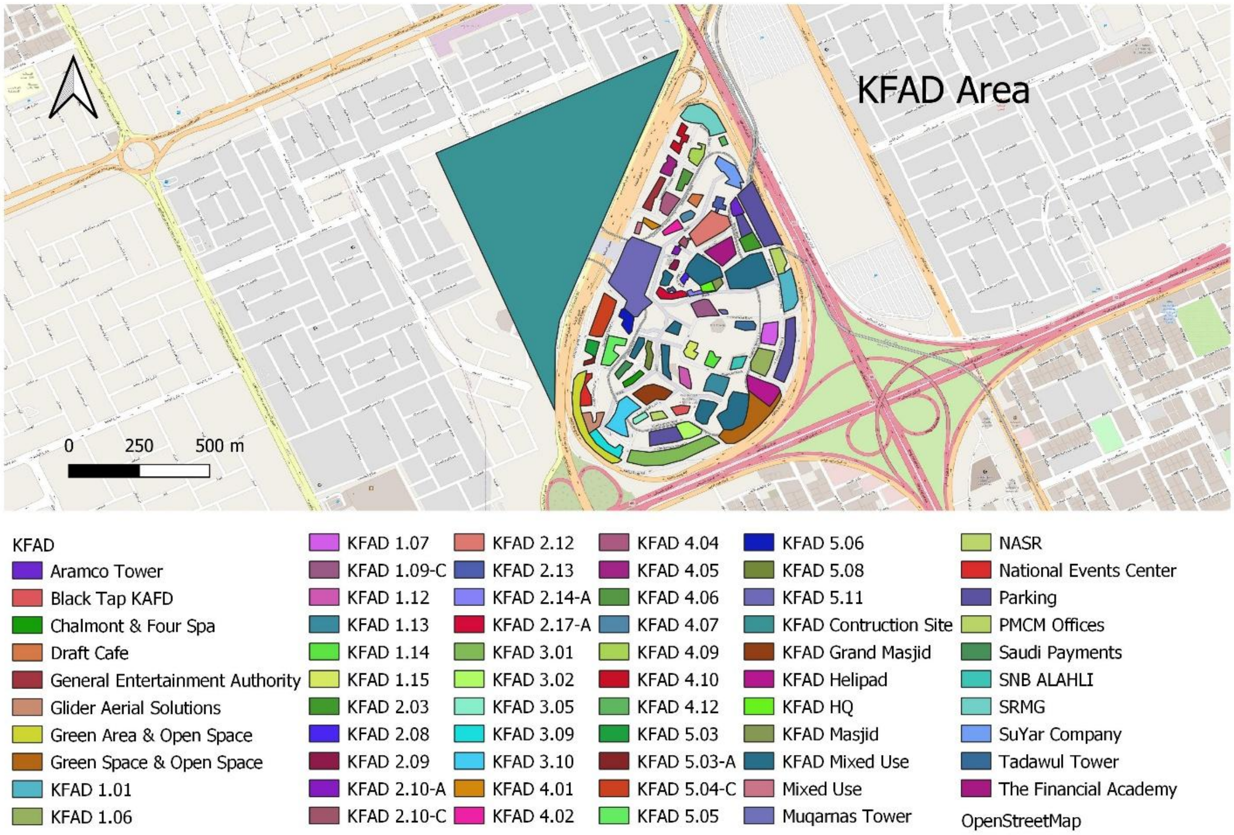
Saudi Commission Of Health
Saudi Red Sea Authority
Substation
UN Office
UN Tourism Office
UNHCR
OpenStreetMap


KFAD Area
0 250 500 m
KFAD
Aramco Tower
Black Tap KAFD
Chalmont & Four Spa
Draft Cafe
General Entertainment Authority
Glider Aerial Solutions
Green Area & Open Space
Green Space & Open Space
KFAD 1.01
KFAD 1.06
KFAD 1.07
KFAD 1.09-C
KFAD 1.12
KFAD 1.13
KFAD 1.14
KFAD 1.15
KFAD 2.03
KFAD 2.08
KFAD 2.09
KFAD 2.10-A
KFAD 2.10-C
KFAD 2.12
KFAD 2.13
KFAD 2.14-A
KFAD 2.17-A
KFAD 3.01
KFAD 3.02
KFAD 3.05
KFAD 3.09
KFAD 3.10
KFAD 4.01
KFAD 4.02
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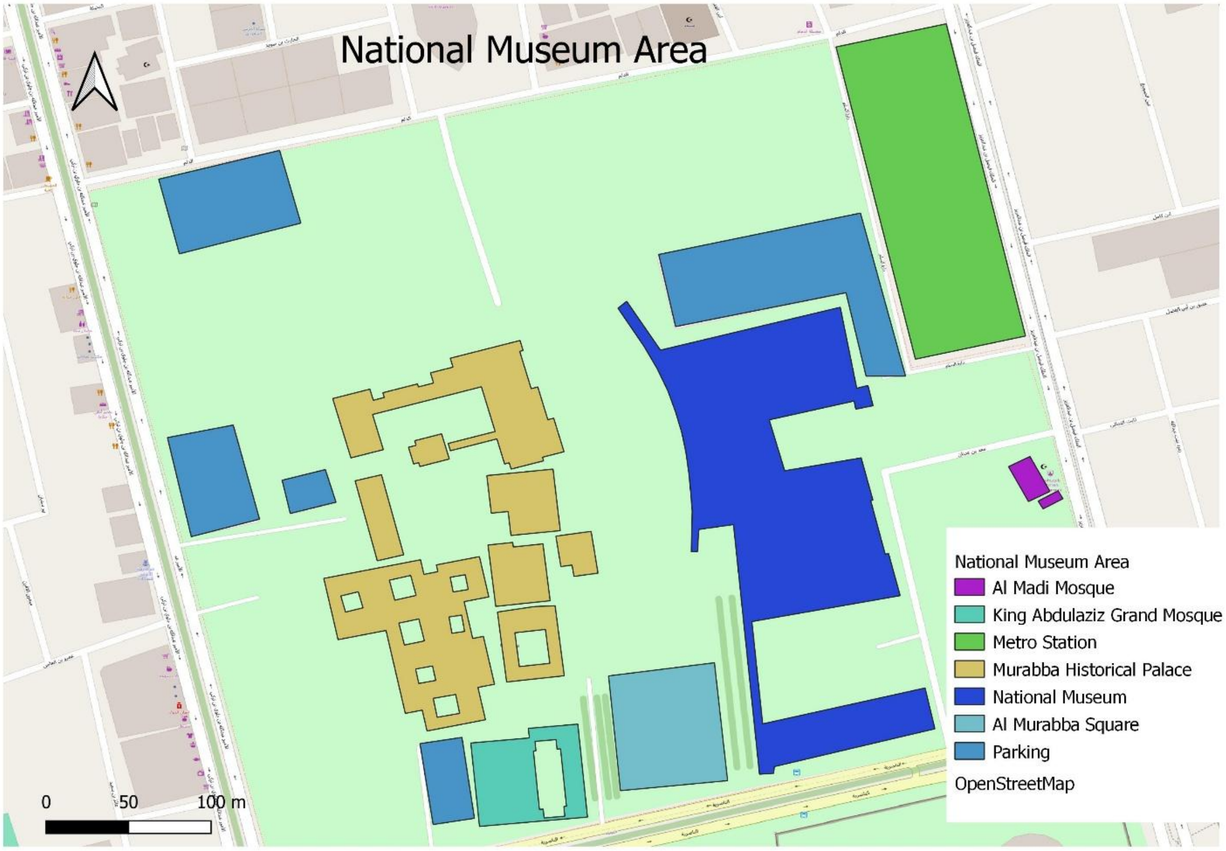
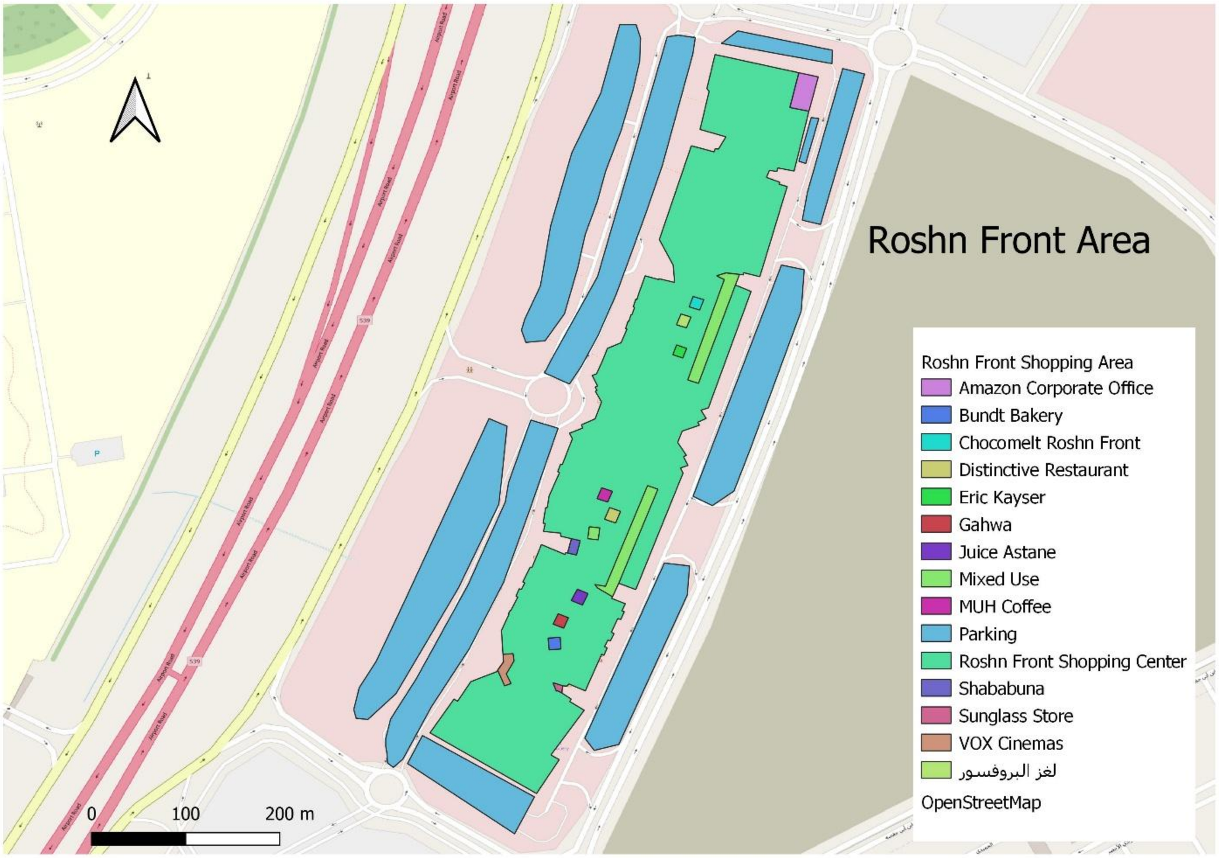
KFAD 4.05
KFAD 4.06
KFAD 4.07
KFAD 4.09
KFAD 4.10
KFAD 4.12
KFAD 5.03
KFAD 5.03-A
KFAD 5.04-C
KFAD 5.05
KFAD 5.06
KFAD 5.08
KFAD 5.11
KFAD Contruction Site
KFAD Grand Masjid
KFAD Helipad
KFAD HQ
KFAD Masjid
KFAD Mixed Use
Mixed Use
Muqarnas Tower
NASR
National Events Center
Parking
PMCM Offices
Saudi Payments
SNB ALAHLI
SRMG
SuYar Company
Tadawul Tower
The Financial Academy
OpenStreetMap

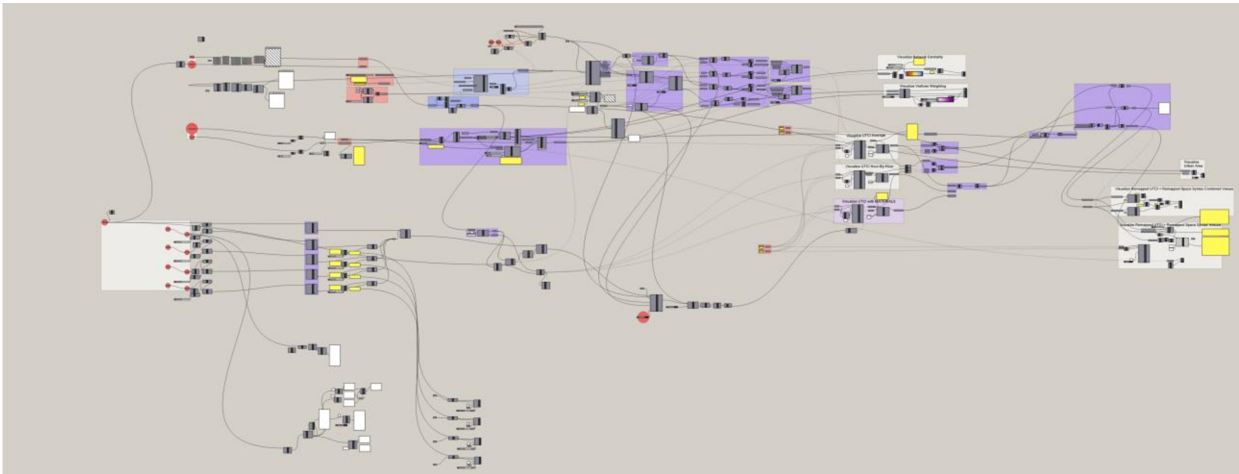

National Museum Area
0
50
100 m
National Museum Area
Al Madi Mosque
King Abdulaziz Grand Mosque
Metro Station
Murabba Historical Palace
National Museum
Al Murabba Square
Parking
OpenStreetMap



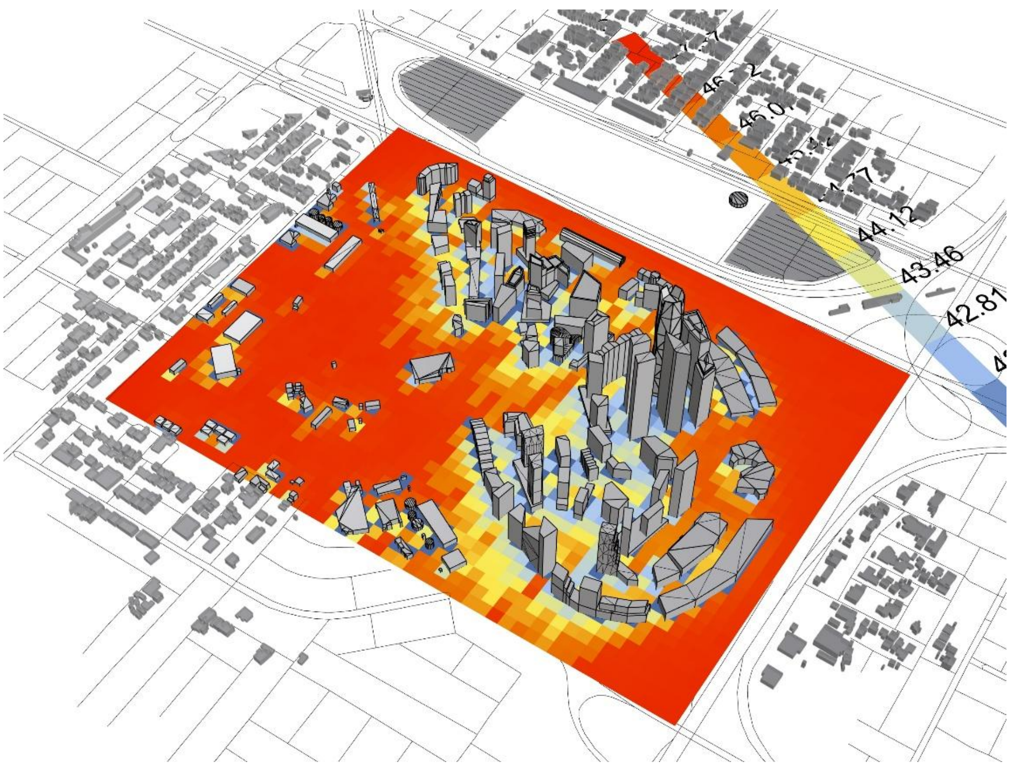

### A.2 Raw UTCI Data

**Table: Raw UTCI Data Example (July 2024)**

| Date | Time | Temp (°C) | RH (%) | Wind (m/s) | Solar Radiation (W/m²) | UTCI (°C) |
|---|---|---|---|---|---|---|
| 2024-07-01 | 09:00 | 35.2 | 28 | 2.4 | 480 | 39.6 |
| 2024-07-01 | 12:00 | 42.5 | 20 | 1.8 | 730 | 46.2 |
| 2024-07-01 | 15:00 | 45.3 | 17 | 2.0 | 820 | 48.7 |
| 2024-07-02 | 09:00 | 36.1 | 30 | 2.6 | 500 | 40.2 |
| 2024-07-02 | 12:00 | 43.8 | 19 | 1.7 | 750 | 47.0 |

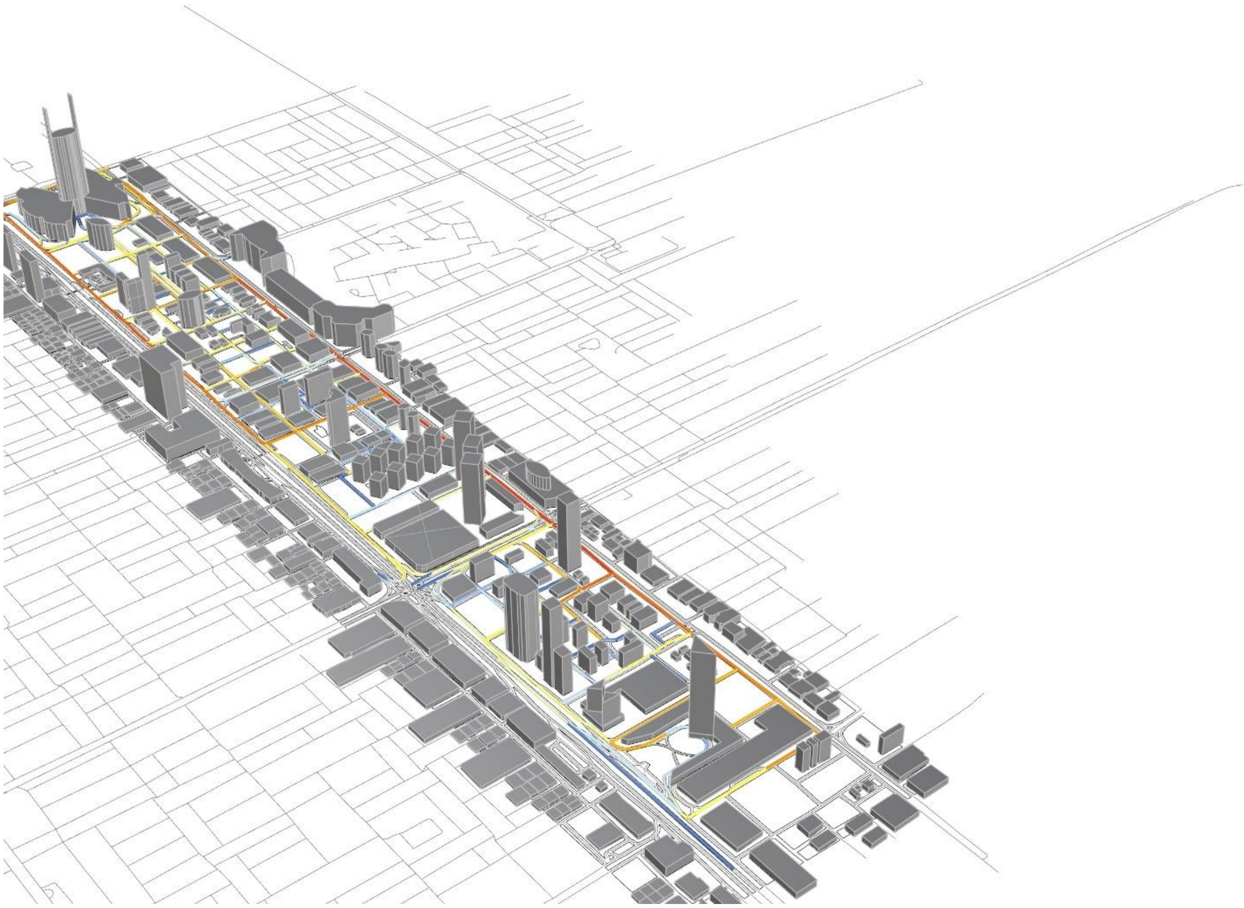


grasshopper script

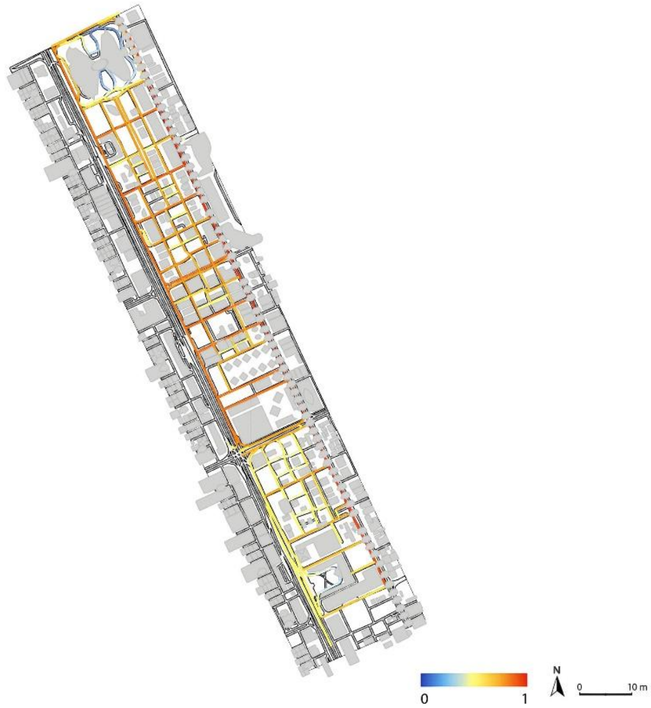



3D UTCI map in KAFD

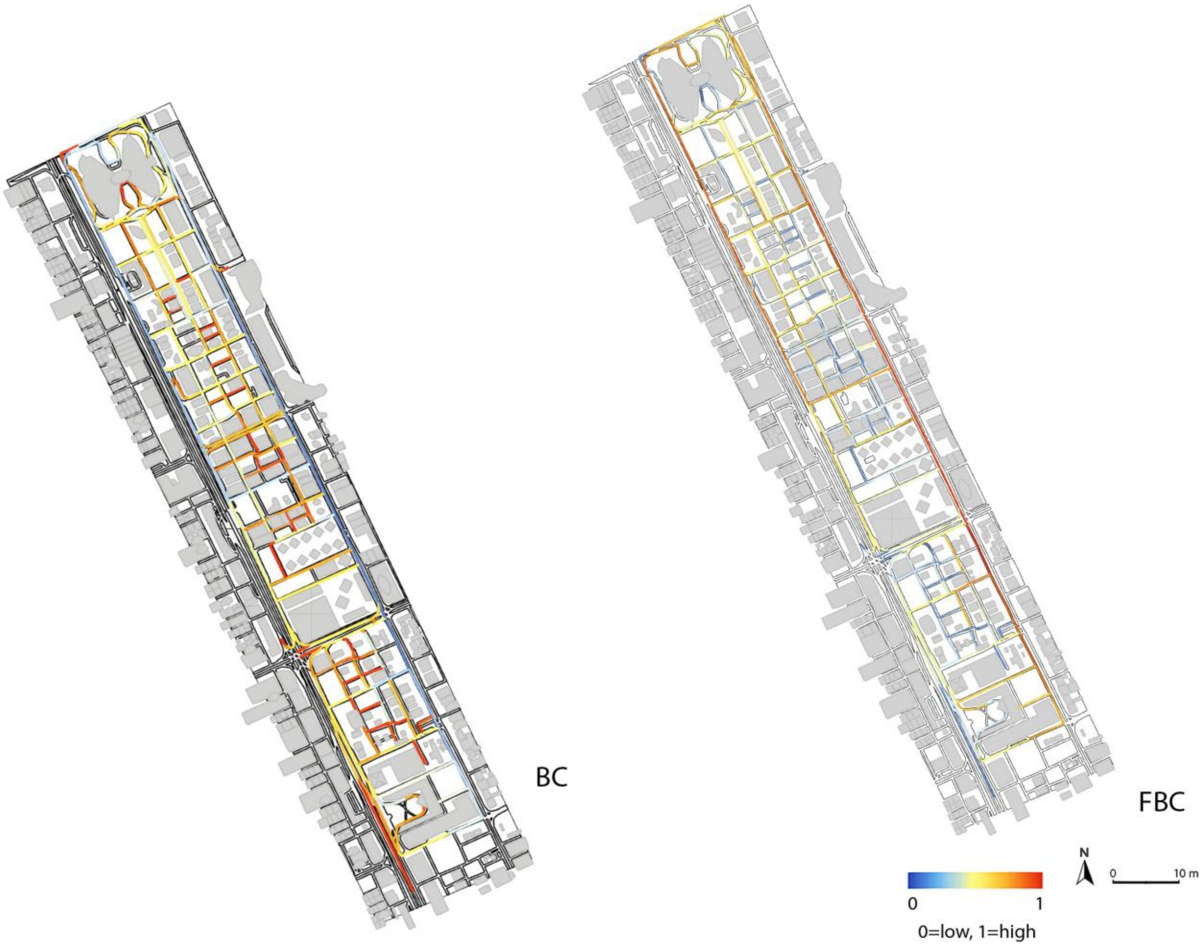
### A.3 Space Syntax (FBC and BC) Results



3D FBC downtown




Downtown Local Angular Integration Map




(BC) Betweenness centrality vs (FBC) Flipped betweenness centrality

**Table: Space Syntax Results (FBC )**

| Location | Segment ID | FBC Score |
|---|---|---|
| Downtown Riyadh | D-101 | 0.45 |
| Downtown Riyadh | D-102 | 0.67 |
| Downtown Riyadh | D-103 | 0.38 |
| KAFD | K-201 | 0.22 |
| KAFD | K-202 | 0.3 |
| KAFD | K-203 | 0.27 |
| DQ | Q-301 | 0.6 |
| DQ | Q-302 | 0.74 |
| DQ | Q-303 | 0.69 |

Location: The specific site or urban area analysed.

Segment ID: Unique identifier for each street segment.

FBC Score: Flipped Betweenness Centrality score indicating pedestrian-centric connectivity.

**A.4 User Perception Survey Instruments**

This appendix provides the full version of the structured questionnaire used to assess thermal comfort, spatial usability, and adaptive behavior across five public space case study sites in Riyadh.

**Section 1: Demographic Information**

1. Age Group
   - 18–24
   - 25–34
   - 35–44
   - 45–54
   - 55+

2. Gender
   - Male
   - Female
   - Prefer not to say

3. Main Purpose of Visit
   - Leisure / Recreation
   - Commuting / Walking
   - Shopping / Dining
   - Cultural / Religious visit
   - Work-related
   - Other (please specify): __________

4. Frequency of Visits
   - Daily
   - Weekly
   - Monthly
   - Rarely

**Section 2: Thermal Comfort Perception**

5. At the time of survey, how thermally comfortable do you feel?
   - Very uncomfortable
   - Uncomfortable
   - Neutral
   - Comfortable
   - Very comfortable

6. What is currently affecting your thermal comfort the most? (Select all that apply)
   - Direct sun exposure
   - Lack of shade
   - Wind / breeze
   - Surface materials (e.g. asphalt, concrete)
   - Lack of seating
   - Clothing
   - Other: __________

7. Which seasons do you find yourself using public spaces most frequently?
   - Winter
   - Spring
   - Summer
   - Autumn

**Section 3: Spatial Usability**

8. How easy is it to navigate this space?
   - Very difficult
   - Difficult
   - Neutral
   - Easy
   - Very easy

9. How would you rate the comfort of walking paths and sidewalks?
   - Very poor
   - Poor
   - Adequate
   - Good
   - Excellent

10. Are there sufficient shaded areas in this space?
   - Not at all

- A few
- Some
- Many
- Fully shaded

11. How connected do you feel this space is to nearby areas?
  - Not connected
  - Poorly connected
  - Somewhat connected
  - Well connected
  - Very well connected

**Section 4: Adaptive Behaviour**

12. Do you change your route or behaviour based on thermal conditions?
  - Yes
  - No

13. If yes, how do you usually adapt? (Select all that apply)
  - Walk on shaded paths
  - Avoid open areas
  - Use covered or enclosed walkways
  - Visit only at specific times (e.g. morning/evening)
  - Shorten the duration of stay
  - Carry water / sun protection
  - Other: __________

14. Would you visit this space more often if it were more thermally comfortable?
  - Yes
  - No
  - Not sure

**Ethics Committee Reviewer Decision**

This form must be completed by each reviewer. Each application will be reviewed by two members of the ethics committee. Reviews may be completed electronically and sent to the Faculty ethics administrator from a University of Nottingham email address, or may be completed in paper form and delivered to the Faculty of Engineering Research Office.

Applicant full name: Mona Alnimer

**Reviewed by: S08**

Signature (paper based only) ..........................................................................................................

06/11/24

- [x] Approval awarded - no changes required
- [ ] Approval awarded - subject to required changes (see comments below)
- [ ] Approval pending - further information & resubmission required (see comments)
- [ ] Approval declined – reasons given below

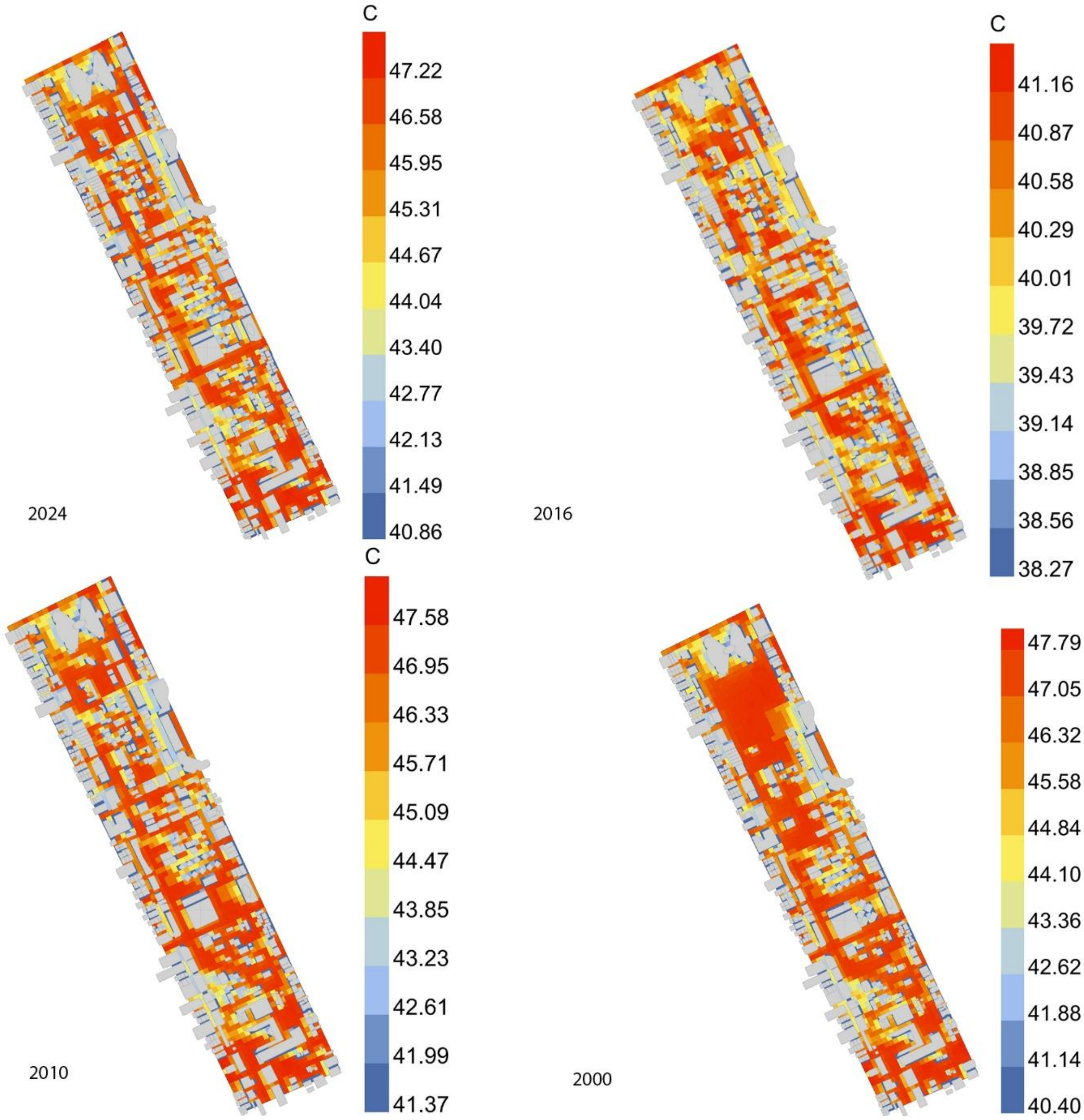
Comments:

n/a

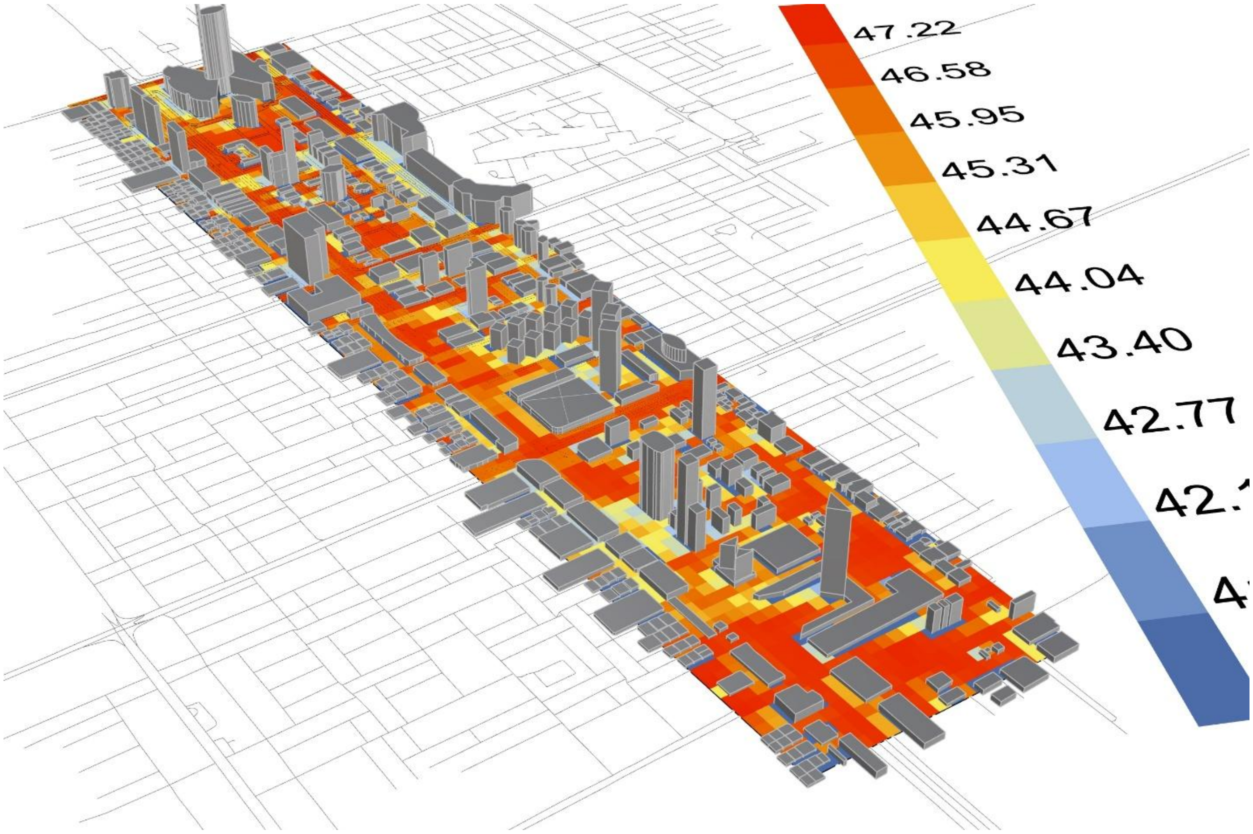
## A.5 CPI (Composite Perception Index) Raw Scores

| Site | Thermal Comfort Score | Accessibility Score | Safety Score | Aesthetics Score | Composite CPI Score |
|---|---|---|---|---|---|
| Downtown Riyadh | 2.8 | 3.5 | 3.2 | 3.4 | 3.23 |
| KAFD | 2.4 | 2.9 | 2.6 | 2.8 | 2.68 |
| Diplomatic Quarter | 4.1 | 4.3 | 4.5 | 4.6 | 4.38 |
| Museum District | 3 | 3.2 | 3 | 3.1 | 3.08 |
| Roshn Front | 2.5 | 2.7 | 2.8 | 2.9 | 2.73 |

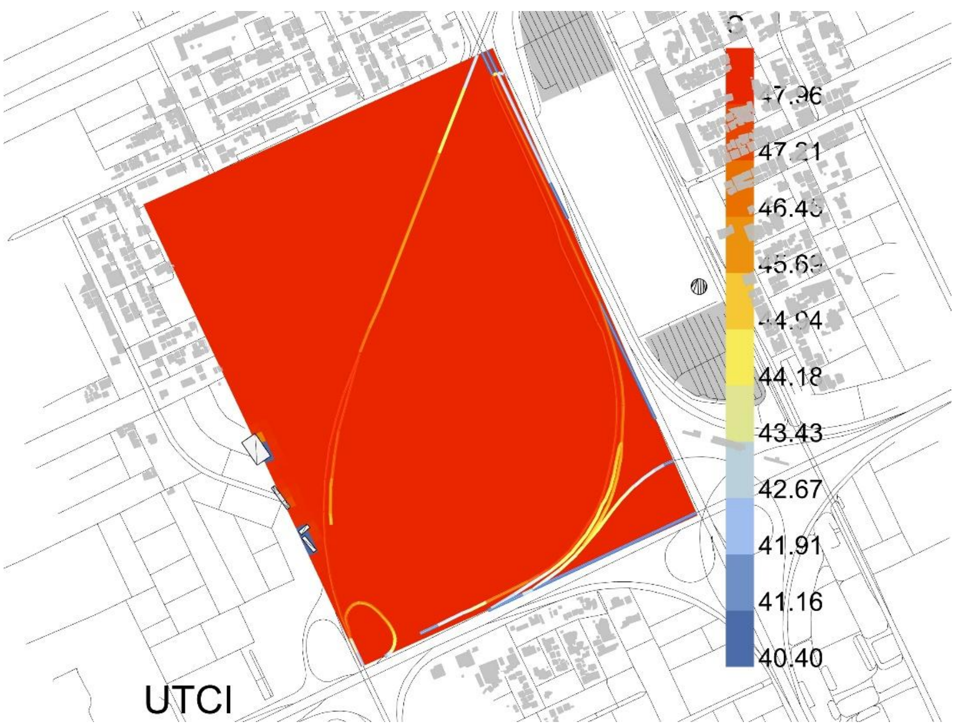
## A.6 GIS Data and Maps



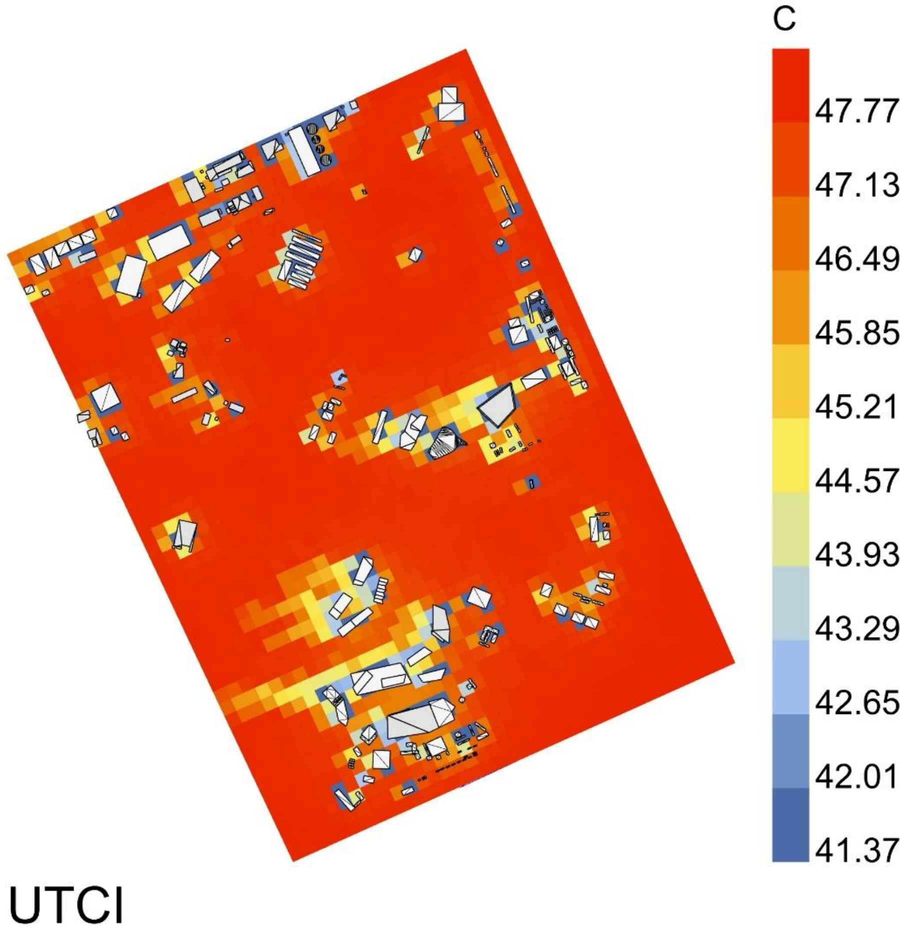

UTCI heatmap in Downtown (2000 – 2024)



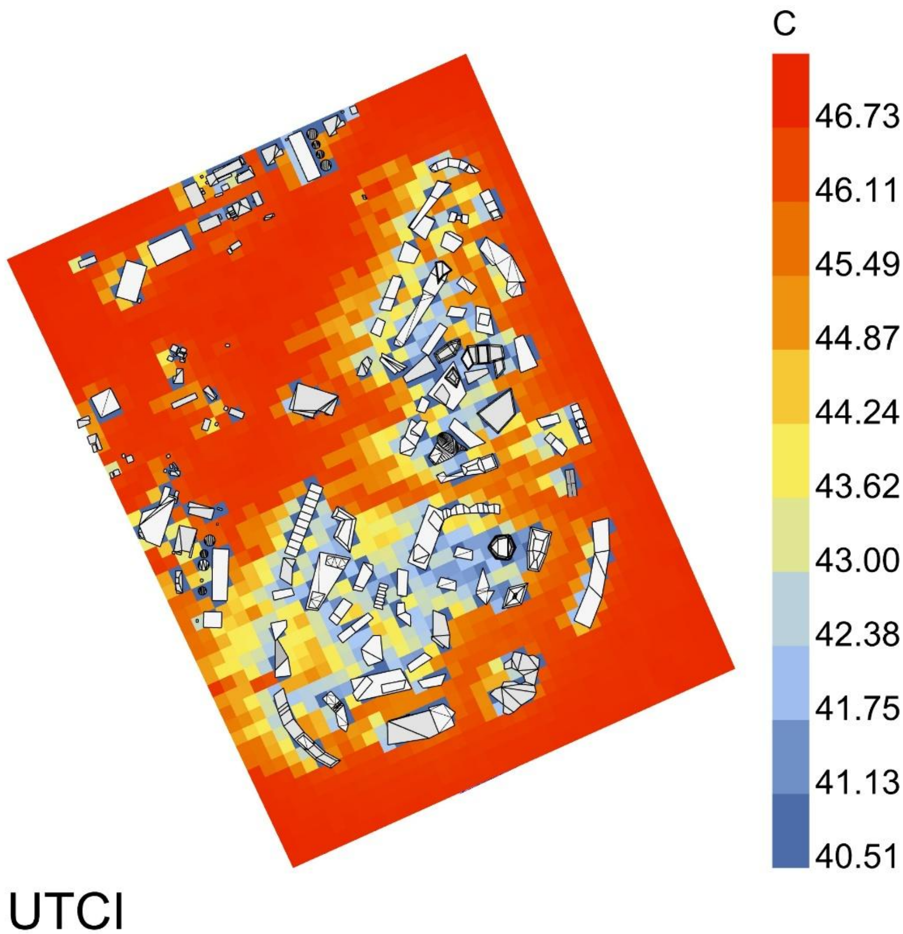

UTCI Downtown 2024



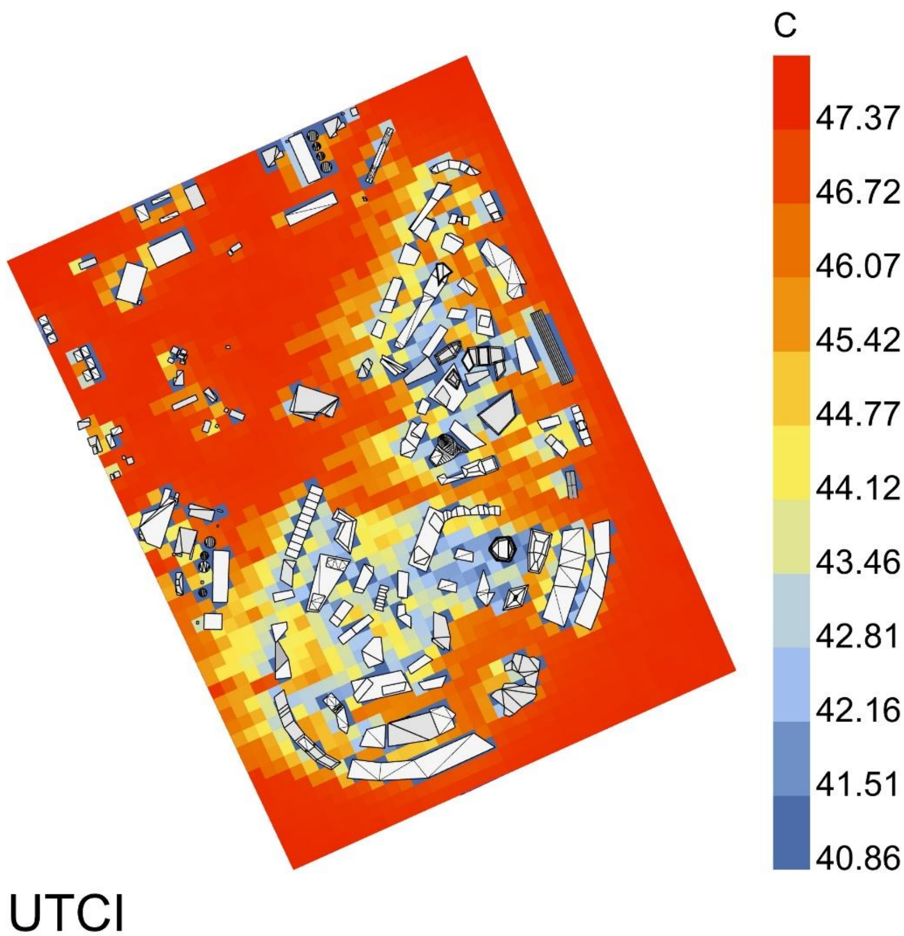

KAFD 2000




KAFD 2010

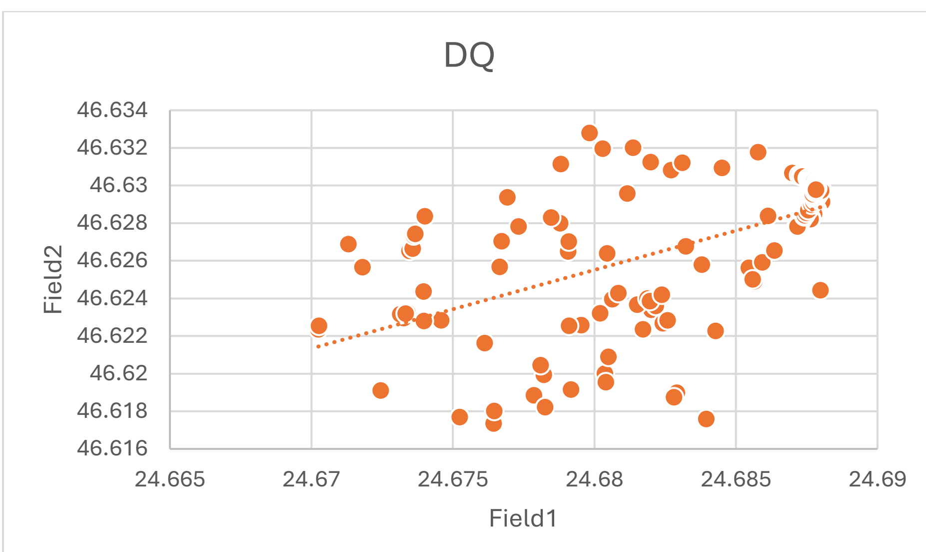


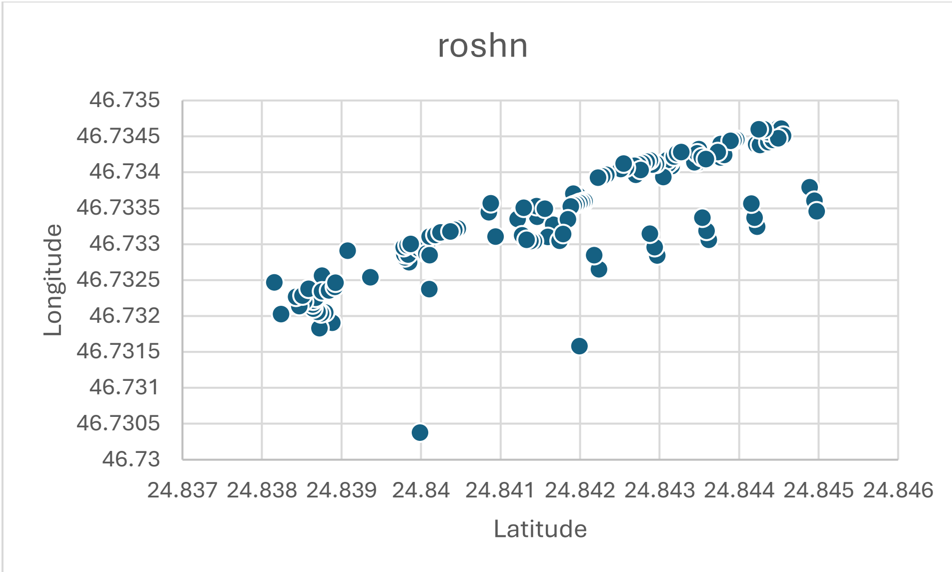

KAFD 2016



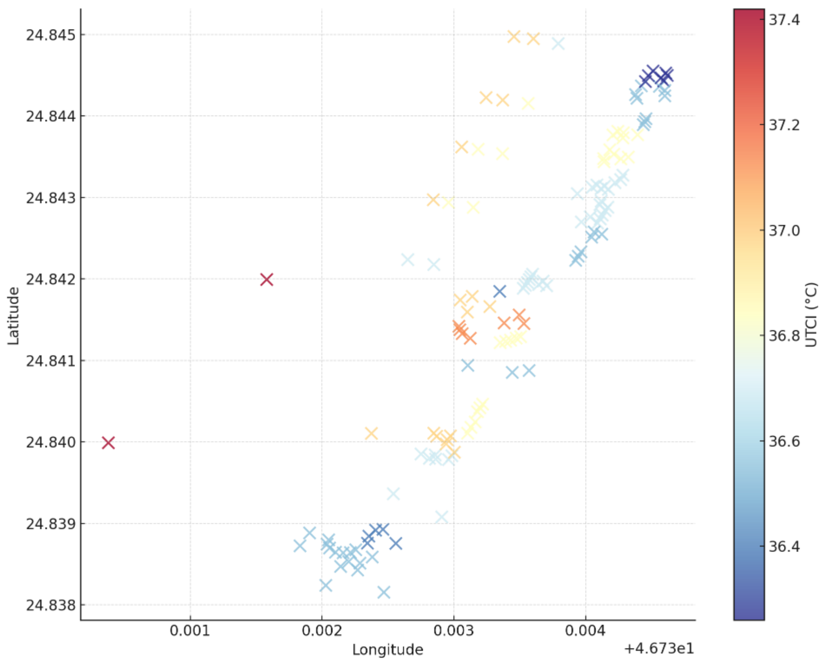

KAFD 2024

**People Points of interests (POIs)**

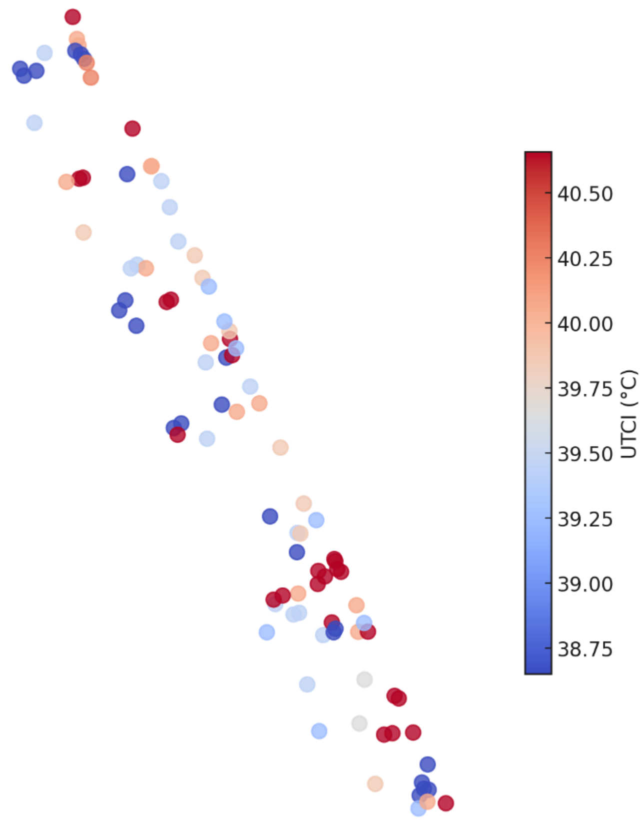




roshn
46.735
46.7345
46.734
46.7335
46.733
46.7325
46.732
46.7315
46.731
46.7305
46.73
Longitude
24.837 24.838 24.839 24.84 24.841 24.842 24.843 24.844 24.845 24.846
Latitude

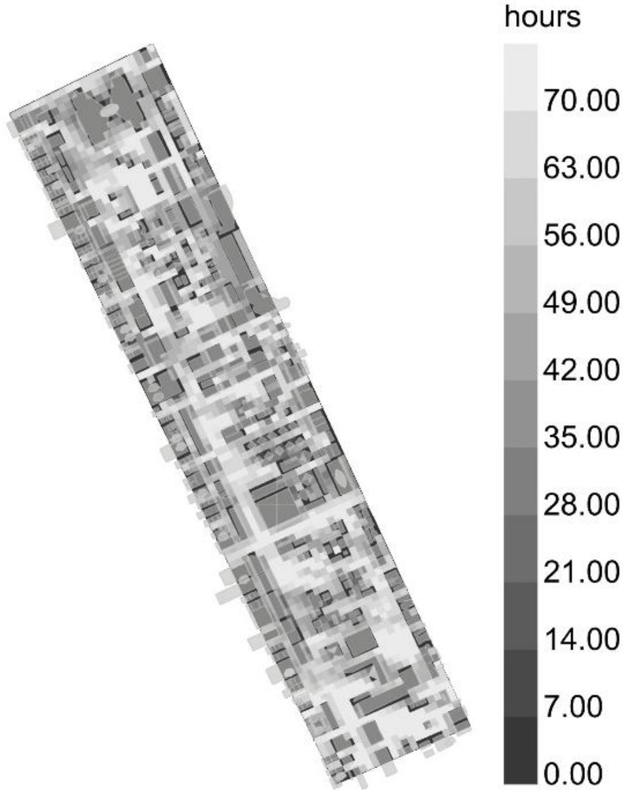



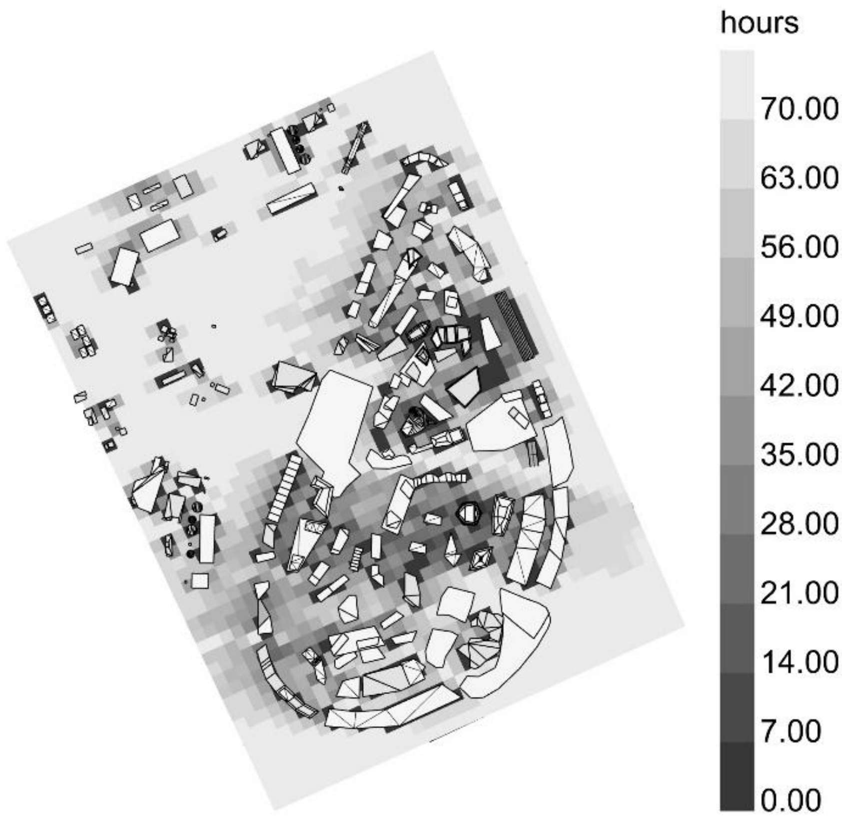
24.845
24.844
24.843
24.842
24.841
24.840
24.839
24.838
Latitude
0.001
0.002
0.003
0.004
Longitude
+4.673e1
37.4
37.2
37.0
36.8
36.6
36.4
UTCI (°C)

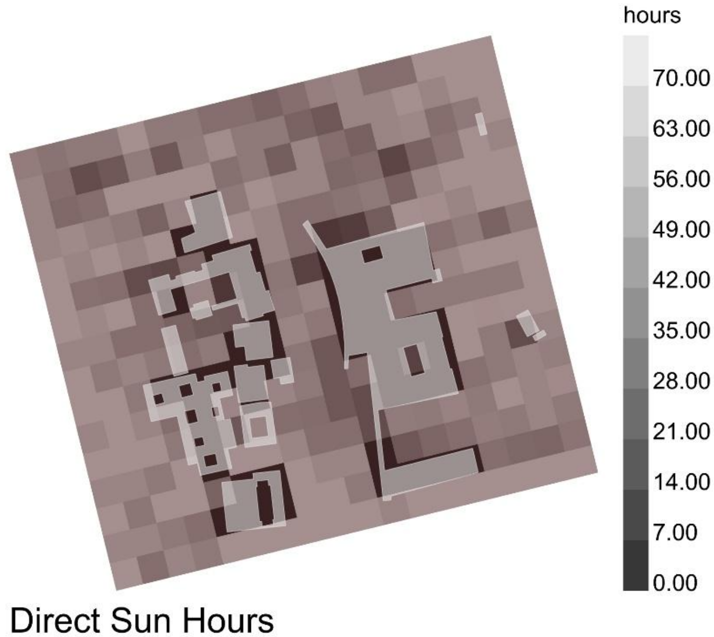



## A.7 Additional

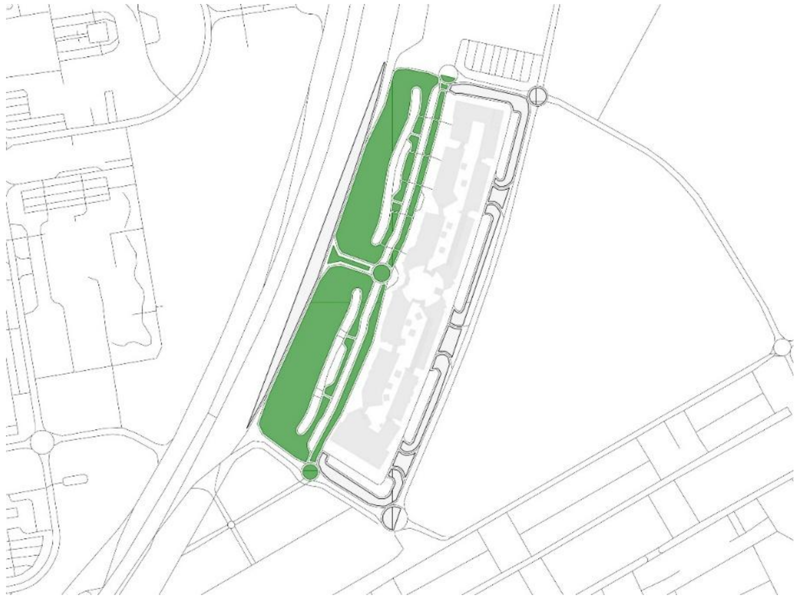
- **Shade Availability Map**

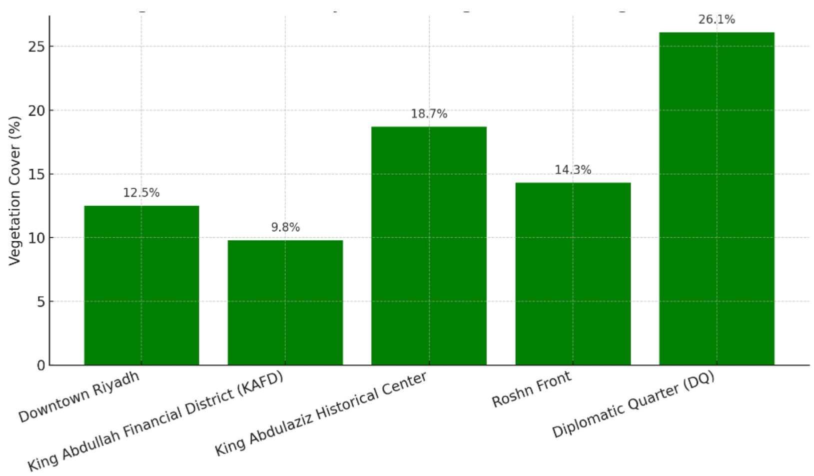
- 
hours
70.00
63.00
56.00
49.00
42.00
35.00
28.00
21.00
14.00
7.00
0.00

- 
hours
70.00
63.00
56.00
49.00
42.00
35.00
28.00
21.00
14.00
7.00
0.00




- **vegetation cover.**

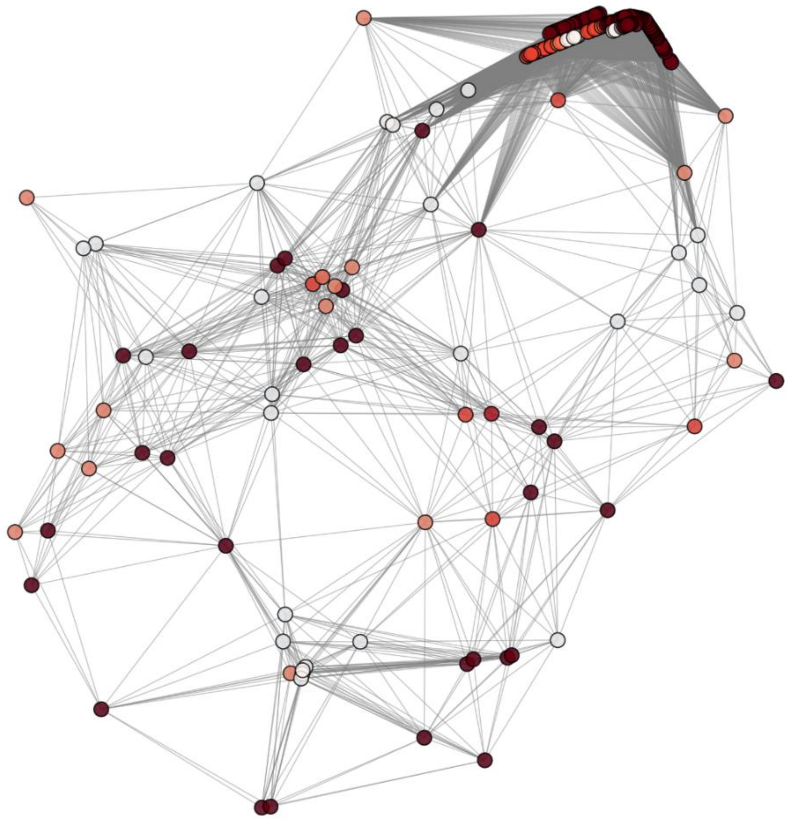




Vegetation Cover (%)
0
5
10
15
20
25
12.5%
9.8%
18.7%
14.3%
26.1%
Downtown Riyadh
King Abdullah Financial District (KAFD)
King Abdulaziz Historical Center
Roshn Front
Diplomatic Quarter (DQ)

- **Movement flow map**

Downtown



DQ

**Table A.2: Spatial Equity Matrix Scores by Site**

| Site | Thermal Comfort (UTCI) | Spatial Connectivity (FBC) | Amenity Access | Perceived Usability (CPI) |
|---|---|---|---|---|
| Downtown Riyadh | 2 | 4 | 3 | 3 |
| KAFD | 1 | 2 | 2 | 2 |
| Diplomatic Quarter | 5 | 5 | 5 | 5 |
| Museum District | 3 | 3 | 3 | 3 |
| Roshn Front | 1 | 2 | 2 | 2 |

This table presents site-specific scores (on a 1–5 scale) across four core dimensions influencing spatial equity: UTCI-based thermal comfort, FBC-derived connectivity, amenity access, and CPI-based user perception. It complements the visual radar plot shown in Figure 6.2.