Investigating the Relationship Between Outdoor Thermal Comfort and User Behaviour Patterns in Public Open Spaces in a Winter City

An Empirical Study of Oodi Library Plaza in Helsinki

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Title

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Degree: Master in Urban Climate & Sustainability

Abstract

Urban microclimates significantly influence outdoor thermal comfort (OTC) and consequently human behaviour within public spaces. This study delves into the intricate relationship between these factors, with a specific focus on winter city conditions. By examining Oodi Library Entrance Plaza (in Kansalistori Square) in Helsinki, a prominent public space characterised by its dynamic urban context, this research aims to contribute to the development of climate-sensitive design strategies that optimise Winter Cities' public space utilisation year-round.

To investigate the relationship between OTC and user behaviour, a mixed-methods approach was employed. Qualitative field observations were conducted across seasons to understand user experiences and activity patterns. Simultaneously, quantitative simulations using ENVI-met and Grasshopper were used to assess microclimatic conditions and their impact on space utilisation.

Key findings reveal a complex interplay between OTC and user behaviour. Engaging features and interactive elements were found to attract users regardless of microclimate, highlighting the importance of social magnetism in public space design. However, thermal comfort played a crucial role in seasonal variations in user behaviour. Winter observations indicated a preference for sun-exposed areas, suggesting a need for design strategies that maximise sunlight exposure during colder months. Conversely, in summer, users sought refuge from heat, emphasising the importance of urban design elements for cooling effects.

This research addressed this need by proposing design interventions for the Oodi Library Plaza, targeting user comfort in all seasons (winter, summer, and transitional months). Simulations of these interventions in winter and summer conditions demonstrated positive impacts on the plaza's OTC, particularly during winter months.

By understanding the relationship between OTC and user behaviour and implementing climate-sensitive design strategies like those proposed in this study, urban planners and designers can create more comfortable, engaging, and inclusive public spaces that promote year-round use.

Keywords

Urban Microclimate, Winter City, Outdoor Thermal Comfort, User Behaviour Pattern

Originality statement. I hereby declare that this Master’s dissertation is my own original work, does not contain other people’s work without this being stated, cited and referenced, has not been submitted elsewhere in fulfilment of the requirements of this or any other award.	**Signature**

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CHAPTER 1: INTRODUCTION

1.1. Rationale

Urban climatic studies span various scales, including mesoscale, local scale, and microscale. Understanding the microscale is particularly critical as it sheds light on the behaviour of microclimates within urban areas and between buildings (Oke et al., 2017), offering insights into how these microclimates affect the outdoor thermal environment. In recent years, there has been a notable surge in research applying urban morphology and the urban climate relationship in urban studies. Numerous projects have investigated outdoor thermal comfort (OTC) across different climates globally, examining aspects such as people's perceptions of thermal comfort, the influence of urban geometry on microclimatic conditions, and the impact of these conditions on building energy consumption. However, there has been relatively less emphasis on understanding the effects of microclimate on user behaviour patterns and how urban form can shape these dynamics.

The Winter Cities movement addresses the challenge of diminished livability in winter, resulting in underused and less vibrant public spaces (Pressman, 2004). The primary obstacle lies in climate-insensitive design, neglecting public spaces during colder months. Two contrasting approaches exist; enclosed and heated pedestrian spaces prevalent in North America versus the revitalisation of outdoor public spaces, considered vital for successful winter cities. However, it's crucial to acknowledge the challenges of replicating Mediterranean social street life in Nordic climates like Finland (Costamagna et al., 2018, Stout et al., 2018). Encouraging outdoor activities becomes imperative for mental well-being, especially in regions with low temperatures and limited daylight, as evidenced by studies in Finland indicating the escalation of negative health impacts during dark and cold seasons like seasonal depression and even suicide (Ruuhela, 2018). Despite overcast conditions, outdoor sunlight significantly surpasses indoor light levels, emphasising the need for design solutions that draw people outside (Young, 2007) and prioritise their outdoor presence over enclosed spaces like pedways and malls.

Efforts to activate public spaces in winter through events, recreation initiatives, and tourism promotion are common, yet addressing the challenge of promoting optional outdoor physical activity in winter remains crucial. The quality of public spaces significantly influences outdoor activity levels, but research on the relationship between outdoor thermal comfort (OTC) and human behaviour in winter cities, particularly in Nordic regions like Finland, is limited. This lack of emphasis on winter design knowledge in mainstream planning education hampers the creation of spaces functional across all seasons, even in southern regions like Helsinki, which still experience substantial snow cover.

Predicting human behaviour pre-construction remains challenging, with cognitive processes shaping the environment-behaviour relationship. There's a shortage of research objectively observing behavioural patterns and their correlation with OTC in winter cities. This study aims to investigate this relationship, focusing on microclimate, user behaviour, and space design in Helsinki, with the aim of informing the design of more user-friendly outdoor spaces conducive to vibrant urban environments and public health.

Traditionally, design methods struggle to capture the intricacies of human behaviour, prompting growing interest in human behaviour modelling and simulation research. While indoor simulations typically focus on energy consumption, outdoor simulations are crucial for enhancing urban development's economic, environmental, and social aspects. Public spaces thrive on human presence and utilisation for social interaction, cultural engagement, health benefits, and economic activities. Without winter-specific design considerations, public spaces risk underutilisation and fail to deliver positive user experiences, particularly during the dark winter months.

Helsinki, situated in a Nordic climate, prioritises sustainable development and residents' well-being, as evident in its master plan (2050 Helsinki City's Plan), emphasising urban growth and improvement. This focus highlights the significance of urban public spaces in enhancing social interaction and community health (Tomassen, 2022). Given the unique climate, this research recognises the importance of studying these spaces' thermal comfort and people's behaviour to ensure optimal design and usability. The city's focus on sustainable development and resident well-being makes it an ideal context for this research.

Kansalaistori Square, a recently established central square, occupies a prominent location along Mannerheimintie, situated between the Helsinki Music Centre and the Museum of Contemporary Art Kiasma. This multifunctional space caters to a variety of user groups. The presence of an artificial turf playground facilitates various sports activities, and a dedicated bicycle path traverses the area. Kansalaistori Square further serves as a vibrant venue for public events, including New Year's celebrations, the Taste of Helsinki food festival, and the Picnic Cinema during the Helsinki Festival.

Adjacent to Kansalaistori Square lies the Helsinki City Library Oodi, a flagship project (completed in 2019) celebrating Finnish independence and serving as a major indoor public space. This research focuses specifically on Oodi Plaza, the library's entrance plaza. Oodi Plaza has the potential to enhance user experience and public utilisation of the indoor space. To distinguish it from the broader Kansalaistori Square, this entrance plaza will be referred to as "Oodi Plaza" throughout this study.

1.2. Aims and Objectives

This research aims to analyse the relationship between outdoor thermal comfort (OTC) and user behaviour patterns in winter city public open spaces. By examining this relationship, the study seeks to understand how OTC influences human behaviour in public open spaces in the Nordic climate. There are three main objectives for this research:

1. To critically examine the current knowledge on the use of outdoor space in winter cities
2. To examine the correlation between objectively observed user behaviour patterns and outdoor thermal comfort (OTC) during distinct cold and warm seasons
3. To evaluate the effectiveness of climate-sensitive design interventions for winter cities, using the Oodi Library Plaza as a case study through simulations to optimise user behaviour and year-round urban livability

1.3. Methodologies and Approaches

This research employs an experimental and interpretative approach to explore and understand a specific sample inductively. The methods encompass both qualitative and quantitative techniques, ensuring a comprehensive analysis. To address the qualitative aspect of the research, a field study is conducted, focusing on the background and space characteristics and the overall quality of the public space. It involves observing and recording the behavioural patterns of individuals in different seasons. By closely examining their actions and interactions within the space, valuable insights can be gained regarding the overall user experience and satisfaction.

On the other hand, the quantitative dimension of the research is approached through simulation methods. These simulations provide a detailed understanding of the environmental factors and their impact on the overall quality of the space. This quantitative analysis complements the qualitative findings, allowing for a more comprehensive public space assessment.

Integrating qualitative and quantitative methods ensures a holistic and nuanced understanding of the public space under investigation.

It is important to note that this research is experimental, utilising innovative approaches to explore the complexities of the public space. By focusing on the Oodi Library Plaza as a case study, this research aims to evaluate the effectiveness of climate-sensitive design interventions through simulations. The findings derived from this study have the potential to contribute to the field of urban design and planning, offering valuable insights for enhancing the quality and functionality of public spaces in winter cities.

1.4.Research Structure

Chapter 1 provides an overview of the current understanding of the research topic, identifies areas requiring further investigation, and outlines the aims and objectives of the study. Additionally, it briefly discusses the research philosophy and methodology, laying the groundwork for subsequent chapters.

Chapter 2 conducts a comprehensive literature review of urban microclimate, winter cities, and user behaviour patterns. It aims to identify gaps in existing research concerning the relationship between behavioural patterns and Outdoor Thermal Comfort (OTC) in winter city open spaces.

Chapter 3 details the methodology, including its various steps and the rationale behind the processes. It also explains how the objectives will be addressed.

Chapter 4 presents the results obtained from executing the methodology and discusses them compared to similar research studies.

Chapter 5 discusses the connections between the results and the literature review, providing personal interpretations. It includes a summary of the main findings for each critical day and offers specific proposals for the site.

Chapter 6 covers the conclusions drawn from the study, acknowledges the limitations and offers recommendations for future research endeavours.

CHAPTER 2: Literature Review

2.1. Urban Microclimate

Human settlement history is marked by a consistent adaptation to environmental constraints, leading to diverse urban forms and architectures tailored to various climatic conditions. The adaptive response is evident from Inuit igloos designed for Arctic climates to portable tents used by desert nomads and the organic configuration of mountainous cityscapes following natural topography to plateaus integrating with water pathways. In arid regions, courtyards emerge, while areas with ample precipitation inspire roofs with gentle inclines. While researchers like Rapoport (1987) emphasise sociocultural factors and present instances of "anti-climatic" solutions influenced by diverse belief systems (Rapoport, 1987), acknowledging the enduring significance of the ecological environment is crucial. Despite variations in traditional designs due to cultural considerations, the environmental context remains pivotal in shaping sustainable and climatically responsive solutions.

Urban climates arise from the intricate interplay between morphologies and materials within cities, shaping distinctive weather patterns. As dynamic cultural communities, cities serve as unique arenas where the interaction of morphology and atmospheric dynamics significantly influences local weather, contributing to the individual identity of each urban space. The morphological complexities within cities introduce a level of intricacy that manifests in microclimatic variations extending beyond global predictions (Williams, 1991, Oke et al., 2017).

Initially a meteorological concept, microclimate gained traction among architects and urban planners in the latter half of the twentieth century. Microclimatology, rooted in examining air layers above the ground, especially within the boundary layer, seeks to comprehend the autonomous behaviour of these layers, where global climate and local conditions intersect. Notably, Germany played a pivotal role in establishing the foundations of microclimatological research, with Geiger's seminal 1927 publication and Kratzer's 1937 work on the Climate of Cities. Against the backdrop of increasing urbanisation and population growth, there is an increasing emphasis on scrutinising urban microclimates (Santucci, 2021, Yang et al., 2023). Researchers actively explore the nuances of the urban microclimate, encompassing various climatic phenomena within urban physics, and investigate the intricate relationship between human activities and their immediate surroundings, seeking effective strategies to mitigate adverse impacts. The anthroposphere, situated within the boundary layer and extending 2 meters above the ground, emerges as the most influential layer where the natural atmosphere intricately intertwines with human energy. It highlights the symbiotic relationship between the human senses and the built environment (Rodger Fleming and Jankovic, 2011).
In the late 1960s, Banham introduced the term "architecture of the well-tempered environment," emphasising the impact of artificial climate on architectural considerations. This concept underscores the role of urban climatology in understanding the consequences of urban geometry on altering the radiative energy balance and reducing heat loss through wind-driven turbulence (Santucci, 2021).

In the realm of public health research and management, spatially mapping microclimatic variations becomes imperative. This approach facilitates the identification of thermal discomfort hotspots and enables a nuanced assessment of individual impacts. Navigating this context, microclimatic intricacies add layers of complexity, emphasising the significance of understanding the interplay between urban form and microclimates. This understanding is crucial for designing resilient, sustainable urban spaces and holding the promise of valuable insights into environmentally responsive and human-centric urban development.

2.1.1. Urban Form

Various schools of thought contribute to exploring urban morphology, with distinct approaches associated with national identities like the Italian, British, and North American schools, while others, like space syntax, are rooted in specific methodologies (Scheer, 2016). Despite unique theoretical frameworks, data collection methods, and change theories, significant common ground exists among these schools. A consensus regarding the components of urban form remains elusive across schools. However, shared emphasis prevails on street patterns in relation to the built environment. Street patterns and the spatial configurations they generate are deemed crucial dimensions of urban form, collectively termed the 'urban grain' (Chapman, 2018). Urban Morphology, focusing on built forms, offers insights into the layout and dimensions of the built configuration, with building density, geometry, and air temperature at pedestrian levels forming interrelated variables (Carmona, 2003).

Urban geometry's relationship with the local climate is evident, with urban patterns adapting to the specific climatic conditions of each region. For instance, hot climates favour a combined pattern with narrow canyons to maximise shading and reduce direct solar radiation exposure. In contrast, cold areas exhibit increased spatial distances between buildings, allowing for more solar radiation penetration. The impact of urban geometry on the local climate is significant, influencing outdoor spaces' thermal comfort based on geometrical variables (Mahmoud and Ghanem, 2019).

The urban form, encompassing building sizes and spaces in between, plays a crucial role in determining average radiant temperature, surface shading patterns, and wind speed. Advanced parameters of urban morphology, including urban plan area density, frontal area density, aspect ratio, orientations, and surface-to-volume ratio, hold relevance in design processes such as urban scale modelling for city planning. Retrieving and validating typical urban morphological parameters, such as building coverage ratio (BCR), building height (BH), building volume density (BVD), frontal area index (FAI), roughness length (RL), are essential for urban climatic applications (Boeri et al., 2023, Xu et al., 2017).

Crucial variables arise from the intricate interplay between urban morphology and microclimate, with notable significance placed on the urban heat island (UHI) index, sky view factor (SVF) index, and Outdoor Thermal Comfort (OTC) index (Johansson, 2006, Santucci et al., 2017, Miao et al., 2020, Khan, 2022)

2.1.2. Outdoor Thermal Comfort (OTC)

To comprehend the impact of microclimate on human behaviour, an understanding of how humans respond to different microclimatic conditions is imperative. Urban microclimates play a pivotal role in shaping pedestrian comfort and influencing the energy performance of buildings, with a growing emphasis on comfort as a critical attribute for public spaces. In acknowledging the impact of microclimate on urban living quality, outdoor comfort involves a combination of objective (climatic and physiological) and subjective (psychological and behavioural) elements encompassing factors such as safety, familiarity, acoustic, olfactory, and visual conditions, along with convenience and physical comfort (Ki LAM, 2011, Zhang et al., 2022, Urban et al., 2022, Khan, 2022). The primary focus is on pedestrian comfort due to their direct interaction with the microclimate, experiencing variations in atmospheric parameters that influence their perception of the outdoor environment. Research in this domain concentrates on two significant aspects: the mechanical impact of wind and thermal sensation (Ebrahimabadi, 2015).

"Wind comfort" refers to the mechanical impact of wind on individuals, considering discomfort regardless of its impact on thermal sensations. Wind effects range from calm air (0-0.1 m/s) to strong gale (14.6-17.1 m/s) (Arens et al., 1986, Blocken and Carmeliet, 2004), with optimal comfort and safety observed for traversing up to 10 m/s (Willemsen and Wisse, 2007).

"Thermal comfort", a crucial factor influencing the utilisation and acceptance of public spaces, is a complex interplay of subjective and objective elements. These objective and subjective characteristics of human thermal sensation shape various approaches to studying and estimating thermal comfort, encompassing models focusing on physiological aspects and those emphasising subjective elements such as adaptation measures and psychological processes (Nikolopoulou, 2011). Understanding thermal comfort is crucial as it predicts the utilisation of public spaces and outdoor activities (Urban et al., 2022)

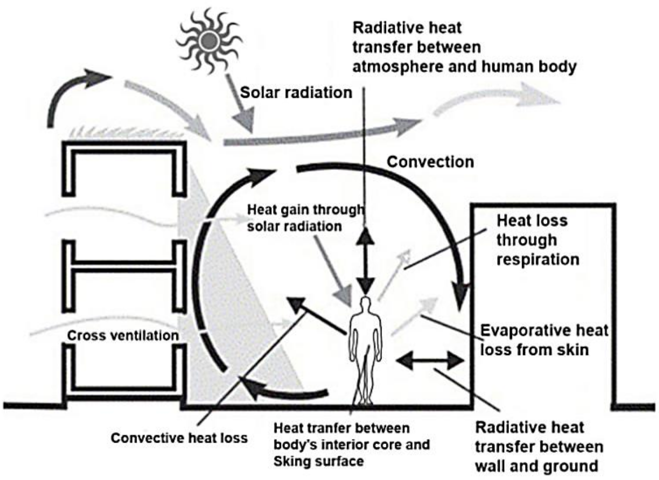


Figure 1. Heat exchange between the human body and the surrounding outdoor environment (Ebrahimabadi, 2015)

Climatic factors encompass meteorological parameters converted into microclimatic variables influencing human thermal sensation and comfort (Coccolo and Scartezzini, 2016). These include air temperature (T_{air} °C), representing the average temperature around the body; land surface temperature (LST), mean radiant temperature (MRT °C), measuring exposure to solar shortwave and longwave radiation; relative humidity (RH %), indicating the ratio of partial water vapour pressure to saturated water vapour pressure; and airspeed (m/s), denoting the rate of air movement around the body, irrespective of direction (Figure 1).

Physiological factors are rooted in the thermoregulatory mechanism known as homeostasis, which enables the human body to uphold a core internal temperature of 37°C, which is crucial for properly functioning internal systems and the brain. This equilibrium is maintained through the human thermoregulatory system, incorporating processes such as vasomotion, sweating, and shivering (Fu et al., 2022, Khan, 2022).

Table 1. OTC assessment and classified models adapted from (Coccolo and Scartezzini, 2016, Khan and Azari, 2021, Zhang et al., 2022, Zhao and Lai, 2021)

Objective Factors	Environmental	T_{air}, RH, W, MRT, LST	Linear equation based idx	WBGT[1], AT[2], DI[3], ESI[4], PSI[5], ET[6], H[7], HI[8], CPI[9], RSI[10], WCI[11]
	Physiological	Age, Gender, ATR[12], PTR[13]	Thermal idx	UTCI[14], PET[15], SET[16], PMV[17], COMFA, ETU[18], ITS[19], MENEX[20], PT[21]
Subjective Factors	Behavioural	Clothing Insulation, Metabolic Rate[22], Culture, Social Dynamics	Empirical idx	ASV[23], TS[24], TSV[25]
	Psychological	Climate Naturalness, Preferred Temperature, Expectations, Experience, Exposure Time, Perceived Control, Environmental Stimuli		

Due to variations in their calculation methods, each index possesses distinct applicability. For instance, MRT is more effective in discerning between locations due to differences in solar radiation intensity. The PMV, an OTC index, is derived from a heat balance model using thermal sensation votes shows weak correlations with subjective perceptions (Nikolopoulou, 2011, Thorsson et al., 2004, Zhao and Lai, 2021). OUT_SET, another common OTC index, has limitations, particularly in defining extreme cold stress conditions (Coccolo and Scartezzini, 2016). Despite lacking detailed categories for neutral and slight stress levels, PET is the most widely utilised OTC index, incorporating a comprehensive range of weather parameters, including air temperature, radiation, and humidity (Höppe, 1999, Khan and Azari, 2021, Yang et al., 2023). Physiological Equivalent Temperature (PET) is an Outdoor Thermal Comfort (OTC) index derived from the Munich Energy-balance Model for Individuals (MEMI), initially introduced by Höppe based on the heat balance equation (Höppe, 1999). It is defined as the air temperature at which, in a typical indoor setting without wind and solar

[1] Wet Bulb Globe Temperature Index
[2] Apparent Temperature
[3] Discomfort Index
[4] Environmental Stress Index
[5] Physiological Strain Index
[6] Effective Temperature
[7] Humidex
[8] Heat Index
[9] Cooling Power Index
[10] Relative Strain Index
[11] Wind Chill Index
[12] Active Thermoregulation
[13] Passive Thermoregulation
[14] Universal Thermal Comfort Index
[15] Physiologically equivalent temperature
[16] New Standard Effective Temperature
[17] Predicted Mean Vote
[18] Universal Effective Temperature
[19] Index of Thermal Stress
[20] Man-environment heat exchange model
[21] Perceived Temperature
[22] Activity level and type
[23] Actual Sensation Vote
[24] Thermal Sensation
[25] Thermal Sensation Vote

radiation, the energy budget of the human body is balanced, maintaining the same core and skin temperature as under complex outdoor conditions being assessed. Human responses to ambient environmental conditions exhibit shared characteristics, as a cross-cultural meta-analysis suggests remarkable similarities in subjective (Table 1) judgments of indoor climatic conditions across diverse nations and climates. Despite variations in societal norms related to heating and cooling, there is a noticeable commonality in perceptions of outdoor microclimatic conditions. Notably, humans can adapt to local conditions over time, implying sustained engagement in various activities across various conditions (Ki LAM, 2011).

Several studies consistently affirm the interdependence between functional use and microclimatic conditions (Thorsson et al., 2004, Gehl, 2010, Nikolopoulou, 2011). These investigations underscore that favourable weather conditions, marked by elevated temperatures and abundant sunlight exposure, positively impact the utilisation of urban spaces by attracting more individuals. Conversely, excessively cold and warm conditions (Table 2) adversely affect emotional states, potentially leading to aggressive behaviour. Emotional and cognitive research suggests a connection between emotional states and cognitive processes. Modifying emotional states by climate implies its influence on various aspects of the environmental experience, including visual aesthetics (Hatakeyama et al., 2018). Moreover, a correlation emerges between thermal comfort and specific psychological facets of the environmental experience (Eliasson et al., 2007).

Table 2. Thermal Stress Comparison in OTC Indices adapted from (Matzarakis, 2014, Oke et al., 2017)

PET	UTCI	PMV	SET	Physiological Stress	Thermal Sensitivity
41°C<	46<	3	>27	Extreme heat stress	Very Hot
	38_46			Very strong heat stress	
35.1_41°C	32_38	2.5	34_37	Strong heat stress	Hot
29.1_35°C	26_32	1.5	30_34	Moderate heat stress	Warm
23.1_29°C		0.5		Slight heat stress	Slightly Warm
18.1_23°C	9_26	0	17_30	No thermal stress	Neutral
13.1_18°C	0_9	-0.5		Slight cold stress	Slightly Cool
8.1_13°C	-13_0	-1.5	<17	Moderate cold stress	Cool
4.1_8°C	-27_-13	-2.5		Strong cold stress	Cold
	-40_-27			Very strong cold stress	Very Cold
<4°C	<-40	-3		Extreme cold stress	

The outdoor thermal comfort range is not universally constant and exhibits substantial variation across different regions. These perceptions influence adaptive behaviours, such as clothing choices and commuting patterns. In planning for temperate and cool climates, the required sunlight exposure is often specified in planning codes, typically as a proportion of open surface area exposed to sunlight during the day. While sunlight calculation is conventionally based on the fall equinox, this may not align with optimal conditions for human comfort. Sunlight is particularly desirable in conjunction with low temperatures and wind, situations not consistently addressed by equinox-based sunlight rules. Unlike sunlight, wind presents challenges due to its unpredictable path and occurrence, compounded by urban modifications to natural air flows. Tall buildings can further complicate matters, deflecting wind force downwards and creating exceptionally high wind speed around building bases (Ki LAM, 2011).

Climatic factors, crucial for shaping the usage patterns in public spaces, extend beyond common thermal comfort assessments. Personal modifications and psychological factors influence people's thermal comfort in outdoor environments, resulting in a broader range of acceptable conditions than traditional standards. Considering the sun's defined path throughout the year, access to direct sunlight becomes a key consideration. In tropical regions, excessive radiation is often undesirable, unlike mild and cool climates where sunlight is essential for warmth, even during daylight hours.

In addition to the microclimate factors influencing the thermal environment, such as urban geometry, vegetation, material, and albedo, other elements play a crucial role in shaping perceptions of microclimates and thermal comfort. Factors like distance from the sea, impacting the cooling effect due to water's high specific heat capacity, and seasonal variations driven by the Earth's revolution contribute significantly. OTC studies often concentrate on hot summers and cold winters due to their propensity for inducing high levels of thermal discomfort. Less-explored factors include altitude, where higher altitudes typically offer cooler conditions due to lower air density, and latitude, a key macroclimate factor influencing sunlight angles and thermal perceptions in outdoor spaces. Individuals in high-latitude zones may experience cold stress, while those in low-latitude zones may face heat stress. The effect of latitude is intertwined with local climate zones, geographical features, and meteorological factors, making it challenging to isolate (Zhang et al., 2022). During the Northern Hemisphere summer, sunlight reaching far northern latitudes encounters greater atmospheric absorption, scattering, and reflection, resulting in pronounced effects as the sun's rays become more oblique (Ahrens and Henson, 2009).

2.2. Winter Cities

> *"It doesn't matter the temperature, when the sun is shining and the wind is tame, it is a good day in Nordic countries" (Gehl, 2010).*

High-latitude cities, characterised by long winters and temperature extremes, pose challenges and opportunities for urban design. Urban climatology, traditionally employed in urban planning, has predominantly concentrated on 'hot' climatic zones, investigating the impact of microclimatic factors on perceived thermal comfort and outdoor space utilisation (Larsson and Chapman, 2020). Elements such as air temperature, solar radiation, and wind speed are crucial in research and design strategies for hot climatic zones. Extending this knowledge, recent research contributes to understanding urban climatology for settlements in cold climates (Figure 2), broadening the scope of insights. Harsh winter conditions, including heavy snowfall and sub-zero temperatures, limit outdoor activities and impact urban life. Residents often spend more time indoors, affecting the vibrancy of outdoor spaces.

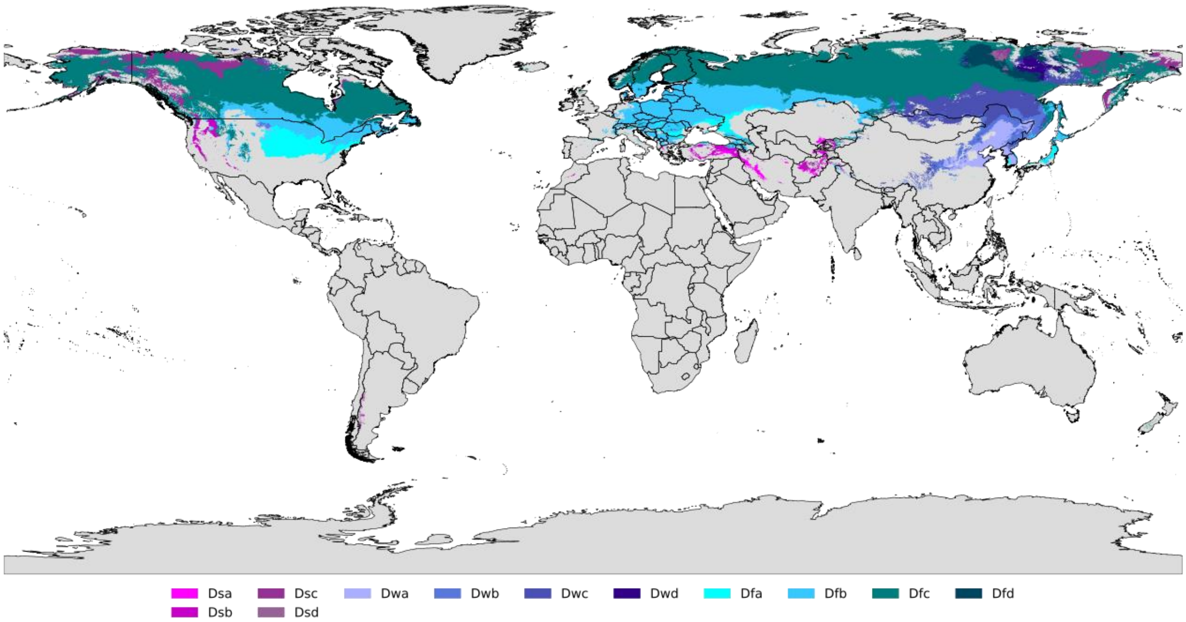


Figure 2. Köppen-Geiger climate classification of high latitude region; adapted from (Kottek, 2006)

Numerous studies consistently highlight the substantial impact of thermal stress on mortality, where thermal comfort represents subjective satisfaction with the thermal environment, and thermal stress arises when ambient temperatures disrupt the delicate physiological balance between the body and its surroundings (Santucci, 2021). Despite this, limited attention has been given to the anticipated effects of extreme temperatures in subarctic climates, exposing older adults to heat-related illnesses during heatwaves and cardiovascular stress and hypothermia during extreme cold (Fonseca-Rodríguez, 2023)

A recent European study by Masselot et al. (2023) sheds light on the annual death toll attributed to both cold and heat across the continent (Figure 3). Notably, the study found a significant increase in mortality rates during cold spells, particularly in northern regions (Masselot et al., 2023). This is especially concerning for Nordic cities at high latitudes, where harsh winters bring extreme cold and limited daylight (Figure 4). Finnish studies provide a deeper understanding of this phenomenon. They explore the intricate relationship between thermal conditions and all-cause mortality, revealing a fascinating link between weather and mental health.

Research in Finland highlights the challenges posed by both cold and hot weather. During winter months, the lack of sunlight may contribute to seasonal affective disorder, potentially leading to higher suicide rates among men, particularly from November to March (Ruuhela, 2018). Conversely, rising temperatures are associated with increased mortality rates. Even the first day of a heatwave in Finland can lead to a spike in deaths, with the effect persisting for several days following the initial heat exposure (Pilli-Sihvola et al., 2019). Interestingly, research suggests an optimal temperature range for minimal mortality in Finland, falling between 13°C and 17°C (ibid).

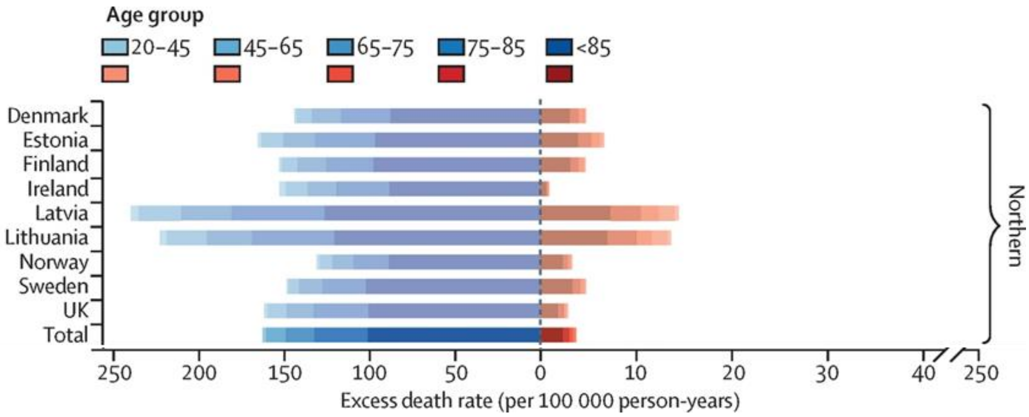


Figure 3. Country-level cold (in blue) and heat (in red) annual raw death rates broken down by age group in northern regions of Europe; adapted from (Masselot et al., 2023)

The lack of sunlight can have detrimental effects on health and well-being, potentially disrupting serotonin synthesis, a neurotransmitter essential for mood regulation. Various strategies are emerging to address this issue. Bright light therapy is a common treatment for seasonal depression. Architects are increasingly incorporating methods to maximise natural light within buildings, and innovative concepts like "light cafes," originating from Scandinavia, provide city dwellers with access to natural light. Light therapy lamps, specifically designed for seasonal affective disorder, emit a higher light intensity than standard indoor lighting, though their widespread use may pose challenges for some individuals. Nonetheless, research indicates that even on overcast days, outdoor light levels significantly surpass those indoors, often exceeding 1000 lux, a level seldom reached indoors (Young, 2007), sometimes more than double the amount found in brightly lit indoor environments like shopping malls.

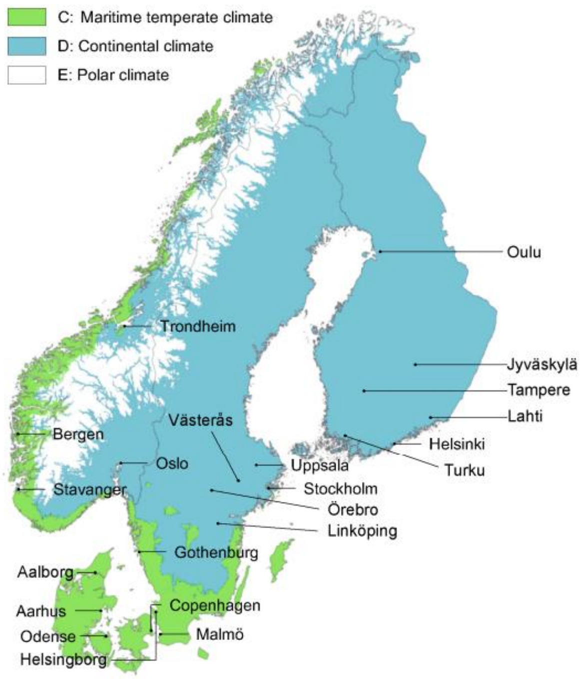


Figure 4. Climate classification map for Nordic countries to the Köpen-Geiger system (Ingebretsen, 2022)

Therefore, outdoor and physical activities are crucial for mental health, particularly during winter months, when low temperatures and limited daylight influence reduced outdoor activity (Pressman, 2004). Studies in Finland and Sapporo, Japan, underscore leisure activities as significant sources of wintertime cold exposure, emphasising the necessity for winter-friendly urban design (Mäkinen et al., 2006, Kusaka et al., 2018). As mentioned, winter cities remain an understudied area in urban design research. Existing literature, although limited, offers valuable insights into the intricate connection between urban design, outdoor thermal comfort, and human behaviour in these urban environments.

2.2.1. Climate-Sensitive Design

> *"To overcome the critical [winter] condition, the main goal of urban design should be to extend the outdoor season by encouraging people to remain outdoors while maximising the beneficial aspects of winter and minimising thermal discomfort" (Pressman, 2004).*

While vernacular architecture and urban design often demonstrate a high degree of microclimatic sensitivity, it is important not to assume they were explicitly designed to achieve thermal comfort in the modern sense. Carmona et al. (2003) stress the integration of microclimate considerations into urban design, viewing comfort as a fundamental element for successful places and the need for "climate-sensitive urban design".

Despite extensive research on winter city design during the mid-to late-twentieth century, there has been a decline in such studies in the first part of the twenty-first century. The prevailing guidance often adheres to traditional winter city design principles, primarily from Canada. In Nordic countries, there is a recognised need for increased consideration of winter conditions in urban planning strategies, resulting in the development of new "blue-green-white" approaches (Costamagna et al., 2018). While these strategies focus on the structure, function, and design of green, blue, and public areas during snowy and icy conditions, they lack contemporary research on how winter climate impacts people's use of public space.

Research on winter city design emphasises crucial factors such as solar access, wind protection, and snow management, consistent across North American and European publications. Notably, a peak in research activity occurred between 1985 and 1989, coinciding with the establishment of the Winter Cities Association (WCA). The WCA's later replacement by the Winter Cities Institute underscores the lasting impact of Pressman's work on climate-responsive design. His contributions extended to addressing sustainability, transportation, pollution, and mental health, indicating a heightened awareness of broader issues and underscoring how winter modifies the visual landscape of cities. Participants observed a "white-out" effect caused by snow, blurring distinctions between streets, walkways, and public spaces. This interplay between urban form and winter conditions holds significant implications for urban design and the overall townscape, emphasising the importance of considering how winter transforms cities' visual experience and spatial organisation (Chapman, 2018).

The visual effects of winter, including snow obstructing public realm elements, alter the townscape and influence how individuals interact with these spaces. To enhance the utilisation of public spaces in winter, design considerations must address both the physical discomfort associated with snow accumulation and the potential for winter-specific outdoor activities. Despite well-documented discomfort factors like snowdrifts, research on snow in urban environments remains limited compared to studies on wind and sun.

Pressman (2004) highlights the positive role of snow in urban design, emphasising its ability to encourage public space use and create opportunities for outdoor activities. He advocates for designing public spaces that perceive snow as an asset rather than a maintenance burden (Pressman, 2004). Chapman's research uncovers rainfall and ice as primary obstacles to public space utilisation in winter, highlighting the significance of integrated planning and soft mobility (Chapman, 2018). Ebrahimabadi (2004) explores the intricate relationship between winter conditions and urban public space design, highlighting documented discomfort factors associated with snow and the unexplored recreational opportunities it offers (Ebrahimabadi, 2015).

Another essential aspect to take into account is the role of ambient lighting. Snow's reflective nature significantly improves visibility in comparison to ice or water. With the prospect of warmer winters and decreased snow cover, the decrease in ambient lighting could substantially hinder the utilisation of public spaces, particularly in high-latitude winter communities where daylight hours are limited (Larsson and Chapman, 2020).

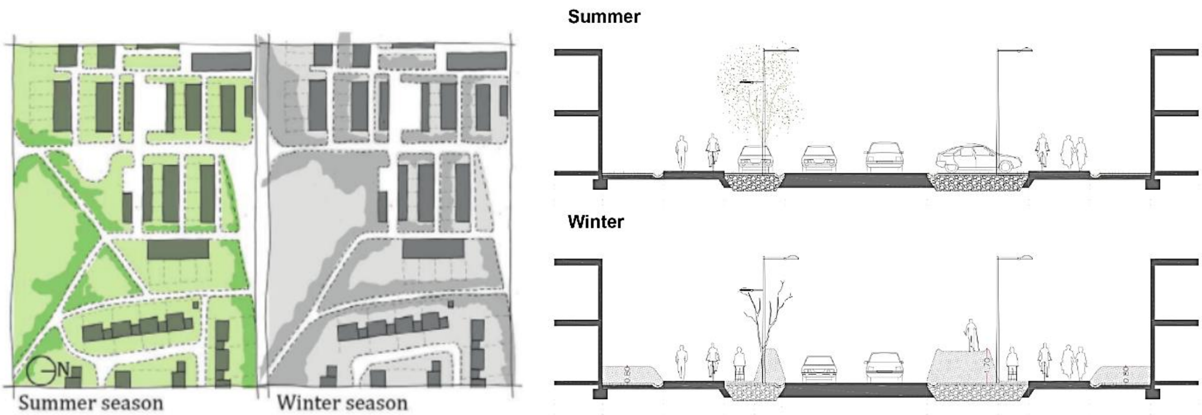


Figure 5. Alternation of urban grain in the winter season; left (Chapman, 2018), ways of using snow in urban environments; right (Ebrahimabadi, 2015)

While buildings and structures play a role in organising public space in the built environment in summer, the scenario changes in winter when the public space becomes 'snow-covered,' undergoing physical alterations due to the winter season. Snow cover shrinks physically accessible areas, while the harsh conditions alter the perception of these spaces, turning designed landscapes into wintery vistas (Figure 5). The very configuration of urban infrastructure, public realm layout, and street design are all affected by the interplay between urban form and winter weather. Winter's visual effects significantly change the "townscape," potentially masking design elements. Designers need a more nuanced approach to create more resilient and user-friendly urban environments. It means considering both summer and winter conditions during design, focusing on understanding a place's winter character and public realm (Chapman et al., 2018, Ki LAM, 2011).

This analysis indicates that the interplay between urban form and the winter season can potentially modify a settlement's urban morphology, consequently influencing public space.

2.2.2. Public Open Spaces

> *"First life, then spaces, then buildings - the other way around never works". (Gehl, 2010)*

> *"For a city, such [small public] places are priceless, whatever the cost. They are built of a set of basics, and they are right in front of our noses. If we will look." (Whyte, 1980)*

Public space has evolved beyond its traditional confines, as articulated by Arendt (1958), who reconceptualised it as a platform for human interaction, drawing inspiration from the ancient Greek agora. Arendt's concept of public space, characterised by freedom, motion, relationships, and plurality, revolves around the idea of appearing to one another in a material world with spatial, durable, and representative qualities (Teerds, 2022). Technological advancements have further expanded the concept and transcending physical boundaries. Consequently, contemporary public spaces now fulfil the dual purpose of accommodating leisure and economic activities, shifting from their historical focus on rituals to more commercially driven environments. While modern metropolises understandably prioritise economic exchange, the enduring value of well-designed public spaces is evident in their role in fostering a sense of place and overall life satisfaction.

Moreover, recent work by Richard Florida on the spread of COVID-19 in cities highlights the ongoing importance of exploring metrics for effective public space design (Florida, 2020). The pandemic undeniably layered the experience of public space, initially marking it as dangerous, then as a necessary platform for voices, and finally as a desired space for social and political engagement. This shift aligns with concurrent findings from a study by Gehl, encompassing four Danish cities (Gehl, 2020). The study revealed a surge in the popularity of local spaces that already offered public activity opportunities. Notably, the use of public space remained relatively constant, while utilitarian movements decreased significantly. This suggests a heightened appreciation for the ability of public spaces to fulfil essential outdoor and sensory needs, even during a pandemic. The core human desire for sensory experiences and comfortable environments remained a driving force, with the most sought-after spaces being those that catered to these needs. Interestingly, the pandemic also fostered the emergence of new activities and adaptations in urban life. Public spaces were utilised in novel ways, with increased usage observed among children, older adults, and in some cases, a higher proportion of females, particularly in pairs. Overall mobility patterns shifted, with a decrease in general movement but a rise in pedestrian activity, especially in neighbourhoods outside of city centres. This trend suggests a potential long-term shift towards walking and cycling as preferred modes of transportation.

Public open spaces are a vital element of the city, integrating landscape architecture and outdoor spaces within the built environment. Unlike private spaces designed for individual needs, high-quality public spaces serve a communal purpose. These spaces, encompassing pedestrian streets, squares, parks, playgrounds, and more, play a significant role in people's daily lives (Han et al., 2022). The term "square" commonly denotes an open area surrounded by buildings, with distinctions between those designed for grandeur or to showcase specific buildings and those serving as "people places" for informal public interaction. While some squares fulfil both purposes, challenges may arise when judging one type based on the criteria of the other (Carmona, 2003). Camillo Sitte, a notable urban design theorist, advocated for keeping the centre of a square open while recommending the addition of a focal point, preferably off-centre or along the edge. Collins highlighted the centrality of the proper statue and monument placement in Sitte's study, drawing parallels between this approach and children situating snowmen on cleared paths. Sitte argued that this strategy served functional purposes and enhanced the square's aesthetic appeal (Sitte, 1979).

Jane Jacobs emphasises public spaces transcend their physical form to become vital social spheres (Jacobs, 1961). Oscar Newman's "Defensible Space" theory demonstrates how a lack of community space in public housing can lead to higher crime rates, which later led to the "Broken Windows" theory by Wilson and Kelling (Newman, 1996). They foster social interaction, encounters, and exchange between diverse groups as a glue for communities. From a political perspective, they are crucial for public participation and expression. Beyond their social function, public spaces contribute to the well-being of communities and are not just spaces but vital components in creating vibrant and healthy urban environments.

Influential urban design literature underscores the significance of ensuring environmental comfort in public spaces (Bentley, 1985, Carmona, 2003, Zucker, 2003, Gehl, 2010). A comfortable microclimate contributes to increased resident participation, higher outdoor activity frequency, improved urban public space utilisation, and supports sustainable urban development. Kevin Lynch discusses the climate of cities concerning "vitality," where the structure of the settlement supports essential functions, biological needs, and human capabilities (Lynch, 1984). A vibrant and sustainable public space should address users' needs for uniqueness, accessibility, safety, comfort, relaxation, and both active and passive participation. Scholars have proposed a comprehensive evaluation method for the quality of urban public activity spaces by integrating spatial vitality with microclimate (Eliasson et al., 2007, Guo and Han, 2023), exploring the interplay between human behaviour and the design of public spaces in cities. It emphasises the importance of understanding how people interact with outdoor environments to create thriving urban areas. This behaviour plays a crucial role in urban planning and design, influencing decisions that benefit the city's well-being. Public spaces can promote physical activity (health), cultural exchange (arts), and economic activity (local businesses). Increased participation in these activities fosters a vibrant city, thriving at social, cultural, economic, and environmental levels. In essence, people act as key players in shaping city planning decisions through their actions in public spaces (bottom-up approach) (Khan, 2022).

Public open spaces represent significant assets that play a vital role in urban life, serving as the focal point for a multitude of behaviour-based studies. These inquiries often utilise one or more case studies to observe individuals' preferences and behaviour patterns, examining influencing factors such as outdoor thermal comfort, environmental conditions, urban configuration, and local settings. A comfortable microclimate in public spaces encourages individuals to spend time outdoors, fostering social interactions and engagement with city life. It positively impacts personal well-being and social connections and contributes to the local economy (Ebrahimabadi, 2015, Mahmoud and Ghanem, 2019, Han et al., 2022). Some research suggests a clear link between thermal comfort, a key component of microclimate, and people's behaviour in outdoor spaces; people's unconscious responses to microclimate influence their usage patterns of urban spaces across varying climatic conditions (Nikolopoulou, 2011, Costamagna et al., 2018).

2.3. Users Behaviour Patterns

> *"Cultures and climate differ all over the world, but people are the same. They'll gather in public if you give them a good place to do it". (Gehl, 2010)*
>
> *"What attracts people most, it would appear, is other people." (Whyte, 1980)*

Over the past 30 years, researchers from various fields (Whyte, 1980, Lynch, 1984, Gibson, 1988, Hillier, 1993, Gehl, 2011) have explored the relationship between the built environment and pedestrian behaviour across various disciplines. However, the complexity of pedestrian movement has led to diverse approaches to understanding it within urban spaces, with research focuses varying across fields. For instance, in health and urban design domains, the emphasis lies in examining urban design's qualities and attributes, particularly street conditions. These studies have highlighted associations between street-level design, pedestrian activity, and environmental factors affecting walking. Conversely, research in transportation and planning has directed attention towards the urban form aspects of walkability, such as proximity, distance, and connectivity, to uncover their influence on pedestrian movement behaviour (Stanitsa et al., 2023).

Within public spaces, which encompass any outdoor area accessible for movement, walking is pivotal. This fundamental act of navigation allows us to not only move from one point to another but also to experience space through our bodies and senses. Walking is more than just physical movement; it has a characteristic pace and rhythm that shapes our interaction with the environment. By examining these spontaneous interactions, we can gain valuable insights into how design elements encourage exploration and social connection within public spaces (Vroman and Lagrange, 2017).

Behavioural settings in outdoor environments offer more choices and adaptability for individual behaviour compared to more rigidly defined spaces. The greater the preference for a particular behavioural setting, the higher the probability of it being used by people. This value can be considered an attractive index (Khan, 2022). Considering both personal space (Hall et al., 1968) and territoriality (Altman, 1975) allows designers to create spaces that encourage specific behaviours. Whyte's study in "Social Life of Small Urban Spaces" bypasses theory and uses real-life observations to reveal the intricacies of everyday social interactions in public spaces. He focuses on details like street greetings, unplanned encounters, and casual exchanges, highlighting the features of urban spaces that make them inviting.

The challenge of predicting human behaviour before design and construction remains, particularly in public open spaces where various factors influence individuals' perceptions, emotions, and needs. Research in this area has focused on understanding user experiences, with walking, sitting, and thermal adaptation being key behaviours studied. Walking, integral to daily life, has been extensively examined in spaces such as riverfronts and squares. Outdoor sitting, often associated with leisure and social activities, presents distinct characteristics compared to indoor sedentary behaviour. Thermal adaptation behaviours, crucially explored in outdoor thermal studies, include adjustments like clothing choices and activity preferences. These behaviours are closely tied to the usage patterns of outdoor built environments, with thermal comfort being a central factor. Successful places prioritise user comfort, safety, accessibility, social interaction opportunities, and diverse activities (Project for Public Spaces, 2008). The significance of accessibility is paramount, with definitions encompassing unrestricted areas and open access for various activities (Bentley, 1985, Madanipour, 2003). Elements like sunlight, seating, comfortable temperatures, and wind protection further enhance usability (Whyte, 1980, Gehl, 2010). Below is a table summary of recent research findings (Table 3).

Table 3. Summary of Recent Research Findings on User Behavior and Thermal Comfort in Outdoor Spaces

Study	Location	Findings
Zacharias et al. (2004)	San Fracisco; USA	Users adapt their behaviour in urban spaces to accommodate varying microclimatic conditions, particularly temperature.
Eliasson (2007)	Gothenburg; Sweden	Higher air temperature, lower wind speed, and less cloud cover significantly influence user perception of weather and increase the number of people.
Katzschner (2006)	Kassel; Germany	People prioritise moderate warmth in open spaces, with behaviour primarily influenced by solar radiation and wind speed.
Huang et al. (2015)	Taiwan	User preference for shaded areas over sunlight suggests a need for outdoor space design that optimises usability and quality in open urban areas.
Santucci (2017)	London; UK	Fluctuations in outdoor comfort conditions directly correlate with the presence of people in the space.
Elnabawi and Hamza (2020)	Cairo; Egypt	Individuals exhibit higher tolerance for warmer temperatures in shaded areas. Sociocultural factors and context-specific behaviours influence user adaptation and thermal comfort preferences.
Qin et al. (2021)	Chongqing; China	Thermal conditions significantly impact visitor distribution patterns, especially in spaces designed for extended stays or high-intensity activities during extreme seasons.
Santucci (2021)	Boston; USA	Microclimate influences pedestrian flows and aligns with people's walking patterns and outdoor thermal comfort.
Khan (2022)	Chicago; USA	A moderate correlation exists between microclimate and human behaviour in fall, weakening in summer. User behaviour appears unaffected by PET values exceeding 35°C.
Guo and Han (2023)	Beijing; China	Microclimate is linked to various behaviours such as walking, recreation, and physical activity. Winter square attendance correlates with temperature, radiant temperature, and PET temperature.

Studying the correlation between microclimate, behaviour, and space in the external areas of public buildings in new urban areas is essential for enhancing the quality and vitality of these spaces and contributing to the long-term development of cities. Numerous studies have investigated the correlation between outdoor attendance and outdoor thermal comfort (OTC) to understand how environmental planning affects users.

However, it seems evident that a Mediterranean climate enables a social street life to the extent that is not possible in the Nordic climate (Costamagna et al., 2018); the Winter Cities movement addresses the challenge of reduced livability in winter, leading to underused and less vibrant public spaces. The central issue lies in climate-insensitive design, which neglects public spaces during colder months. Two opposing approaches exist to tackle this problem (Stout et al., 2018): one advocates for enclosed and heated pedestrian spaces like grade-separated pedestrian systems (GSPS) and attached shopping centres, mostly common in North America, while the alternative approach emphasises the value of outdoor public spaces and their revitalisation as central to successful winter cities. By employing climate-sensitive design to mitigate winter's harshness, this approach aims to encourage residents to utilise streets, squares, and parks year-round.

A critical urban design challenge in winter cities is fostering safe year-round outdoor activity while considering how local meteorological conditions influence individuals' choices to visit outdoor public spaces. Moreover, snow and ice can serve as elements within the urban landscape, drawing people in and contributing to the planning of public spaces (Kusaka et al., 2018). Chapman's research on soft mobility in winter cities reveals an interesting observation – the influence of weather conditions on people's use of public spaces appears to be greater than its impact on soft-mobility alternatives like walking or cycling (Chapman, 2018). This observation can be attributed to the essential nature of daily commutes, making the use of public spaces unavoidable regardless of weather conditions. In contrast, leisure activities, which can be deferred, exhibit a lower impact. These findings align with Gehl's categorisation of three activity types (Gehl, 2011):

- *necessary activities*; daily functional tasks
- *optional activities*; using public spaces for rest
- *social activities*; people gathering

The heightened impact of weather on leisure-oriented public space use underscores the resilience of necessary activities even in suboptimal weather conditions. Well-designed outdoor areas have been consistently associated with positive outcomes in urban planning, human well-being, and local economies. Efforts to activate public spaces in winter through events, recreation initiatives, and tourism promotion are common for choosing social activities. Addressing the challenge of promoting outdoor physical activity in winter and increasing the availability of optional activities is crucial, as the quality of public spaces significantly influences outdoor activity levels.

However, in cities facing severe climates, discomfort from extreme temperatures significantly alters the nature and frequency of outdoor activities. Scholars suggest that a broader zone of thermal comfort experienced outdoors, compared to indoors, might contribute to a higher tolerance for thermal extremes. Furthermore, research indicates that human behaviour adapts to mitigate discomfort. This interaction between microclimates and human adaptation highlights the necessity for public space design that integrates both aspects to create vibrant and functional environments adaptable to various weather conditions (Elnabawi and Hamza, 2020).

Existing research on public spaces and climate tends to focus on scientific studies that explain how weather impacts people's comfort outdoors. However, there's a gap in analysing design solutions and strategies to address these challenges.

2.4 Knowledge Gap and Necessity of the Research

Despite increasing recognition of the importance of outdoor public spaces in fostering vibrant urban environments and promoting public health, there remains a significant gap in understanding the relationship between outdoor thermal comfort (OTC) and human behaviour in winter cities, particularly in Nordic regions such as Finland. Existing literature primarily focuses on the negative health impacts of winter and the need for climate-sensitive design solutions but lacks empirical studies on how OTC influences human behaviour in outdoor settings during colder months. Moreover, mainstream planning education often neglects winter design knowledge, hindering the creation of functional spaces across all seasons, even in the southern regions like Helsinki, which still have substantial snow cover __95 days per year based on the observation period 2000– 2019 (Hyvärinen et al., 2022). Consequently, there is a pressing need for research that objectively observes behavioural patterns and their correlation with OTC, particularly in Nordic winter cities, to inform the development of more user-friendly outdoor spaces and enhance urban livability year-round.

CHAPTER 3: Methodology

3.1.Research Rationals and Framework

Building on the existing body of research explored in the literature review, this study delves deeper into the relationship between user behaviour and outdoor thermal comfort (OTC) in public spaces. While previous studies have established the challenges of reduced livability in winter cities and the Winter Cities movement's efforts to counteract them, a gap remains in understanding the specific user behaviour patterns associated with varying levels of OTC. This empirical research, employing an abductive approach, aims to bridge this gap by directly observing user behaviour across distinct seasons and utilising those observations to inform simulations that explore potential explanations for user comfort levels within different microclimates. By combining qualitative and quantitative methods, this study seeks to offer a more nuanced understanding of user experience and promote vibrant public spaces year-round (Figure 6).

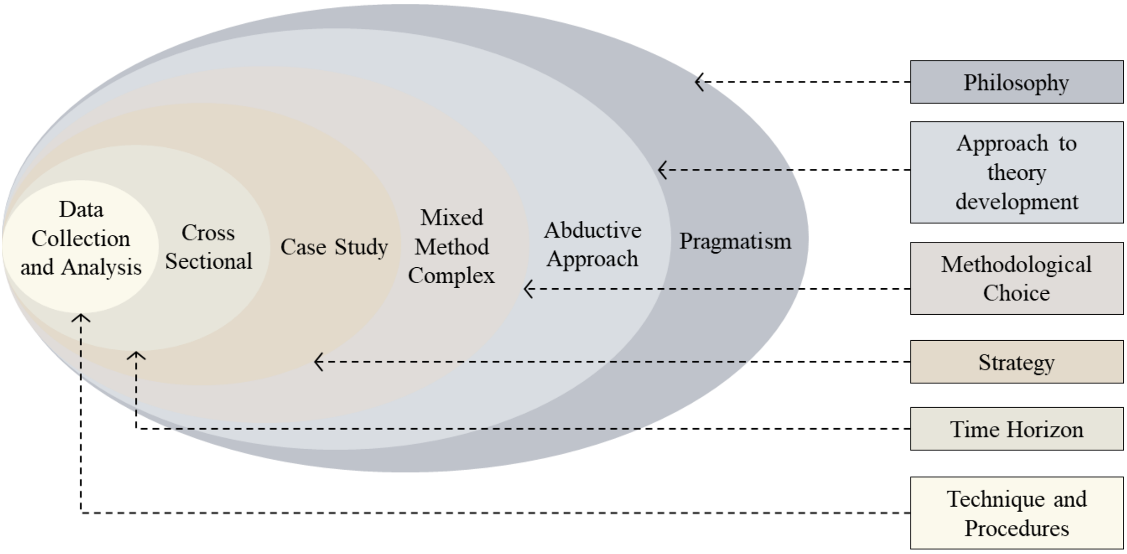


Figure 6. Selected research method for the study Adapted from "Research Onion" (SAUNDERS et al., 2007)

This research pursues its goals through two distinct, concurrent approaches.

Firstly, an abductive case study is conducted within a winter city context. Qualitative inquiry is conducted through field studies, focusing on contextual and spatial characteristics, as well as the overall quality of the public space. Through direct observation and documentation of behavioural patterns across seasons, this approach yields valuable insights into user experiences. The abductive nature of this research allows for a dynamic interplay between theory and empirical data, facilitating the refinement and adaptation of theoretical frameworks in response to emerging insights.

Secondly, the quantitative dimension of the research is addressed through advanced simulation techniques. ENVI-met software is employed to create detailed microclimate simulations, while the PedSim plugin, utilised within Python and Grasshopper visual programming languages, facilitates real-time pedestrian simulations within the Rhino modelling environment. These simulations offer a nuanced understanding of environmental variables and their impact on spatial quality. Complementing the qualitative findings, this quantitative analysis enriches the assessment of public spaces by providing a detailed examination of weather conditions, microclimates, and user behaviour. The comparative-correlational nature of this aspect of the study aims to elucidate the relationship between real-world variables, with the simulation serving as a tool for clarification.

The flowchart below (Figure 7) illustrates the methodological framework of this research:

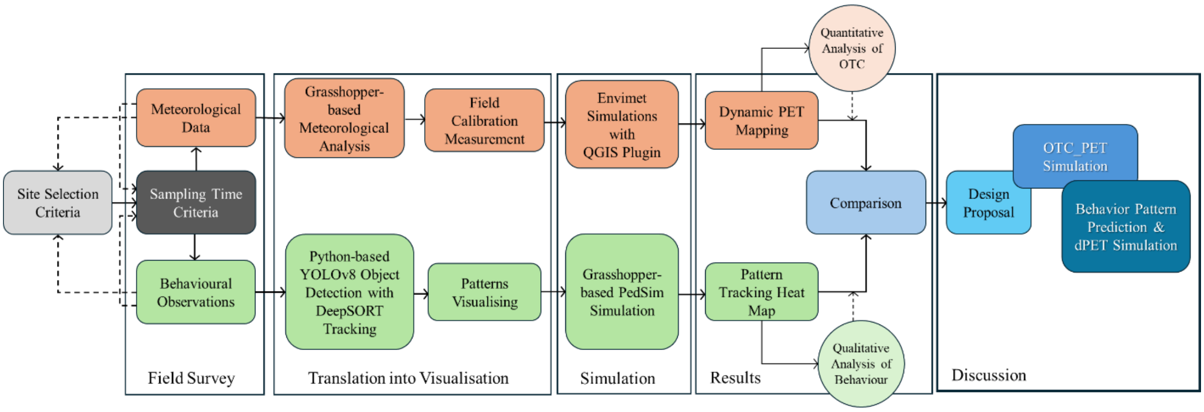


Figure 7. Outline of methodology workflow (Own elaboration)

3.2. Case Study Area: Oodi Library Entrance Plaza in Helsinki

Helsinki, the capital of Finland and one of the northernmost capitals globally, is located at latitude 60°15' N (Figure 8). Classified as Dfb (snow, fully humid, warm summer) on the Köppen-Geiger climate scale, Helsinki boasts a well-established reputation as a winter city with a harsh climate. This characteristic climate aligns perfectly with the study's focus on examining the correlation between thermal comfort and pedestrian movement during cold seasons.

Figure 8. Case study location: Helsinki, Finland

A key selection criterion was the scarcity of existing research on this specific topic within Helsinki. While previous studies have explored the relationship between thermal comfort and people flow in public spaces, these investigations largely focused on attendance numbers or were geographically distant. This research aims to contribute a novel perspective by delving deeper into user behaviour within a Helsinki public space.

3.2.1. Rationale for Observational Approach

The chosen methodology is heavily reliant on an observational approach, requiring data collection during cold and warm seasons during the research timeline. However, limitations associated with time, finances, and technology prevented the use of traditional people-counting methods, such as Wi-Fi signals, GPS tracking, or permanent CCTV installations. These techniques are often employed in larger research projects requiring significant organisational resources.

3.2.2. Criteria for Public Space Selection

Given these limitations, the ideal public space for the case study needed to meet the following criteria:

- *High Pedestrian Activity*: The space should be a popular destination frequented by people daily, allowing for observation of user behaviour across different weather conditions and time periods.

- *Unobtrusive Camera Placement*: The location should offer an accessible yet inconspicuous dominant point for camera placement, minimising disruption to user behaviour within the space.

Several prominent public squares and plazas within Helsinki were evaluated based on these criteria, including Rautatientori Square, Esplanadi Park, Hakaniemi Market Square, Narinkka Square, Tallinnanaukio Square, Töölöntori Square, and Senate Square. The search for an ideal case study area highlights the importance of considering both research objectives and practical limitations during case study selection. The final selection process addressed the limitations and ultimately identified the Oodi Library entrance plaza, part of Kansalaistori Square, as the most suitable location for this research. The following section will provide a detailed description of the chosen space.

Kansalaistori Square (Figure 9), a relatively new public space in central Helsinki, is strategically located between the Music Centre and the Museum of Contemporary Art Kiasma. This square has quickly become a hub for various urban activities. With a mix of paved areas and green spaces, Kansalaistori Square offers both open lawns and urban amenities. In the summer, it is especially popular, drawing skateboarders and other visitors. The area features benches for relaxation, an artificial turf playground for recreation, and a dedicated bicycle path.

Figure 9. Kansalaistori Square (WikimediaCommons, 2019)

Kansalaistori Square also serves as a versatile venue for public events, including New Year's Eve celebrations, the Taste of Helsinki food festival, and the Picnic Cinema during the Helsinki Festival (Figure 10).

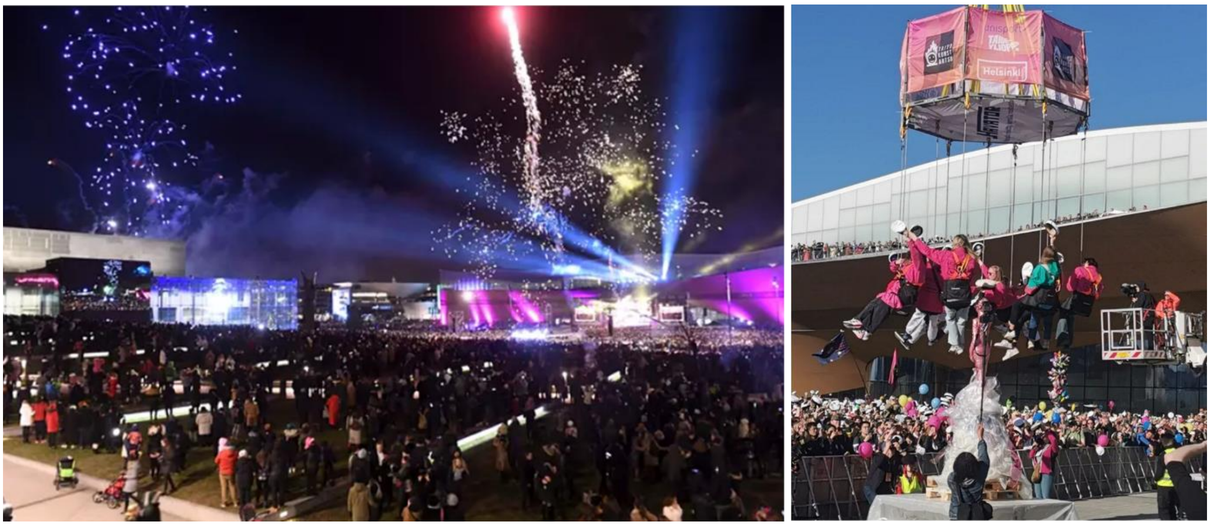


Figure 10. Events in Kansalaistori Square: Left (HelsinginSanomat, 2022); May Day Event (Vahter, 2024)

3.2.3. Oodi Library Plaza

Helsinki's Central Library, Oodi, opened in December 2018 and served as a key project in celebration of Finland's 100th anniversary of independence, quickly garnering recognition and becoming a widely recognised landmark. Designed by ALA Architects, Oodi reimagines the traditional library as a multi-functional hub fostering social interaction and cultural engagement (Oodi Helsinki Central Library, 2024).

The library's innovative architecture features a distinctive wooden façade (Finnish spruce) that extends outwards, creating a sheltered entrance plaza. This design element blurs the lines between the library's vibrant indoor environment and the adjacent public space. The Plaza transforms to accommodate events, extending Oodi's role as a civic node.

Figure 11. Selected study area: Oodi Library entrance plaza

Its central location enhances its potential as a year-round public space, complementing the library's offerings and making it a popular destination for residents (Figure 11). Positioned directly in front of the Finnish Parliament building, Oodi's location underscores its importance within the city and its connection to the monumental Finnish government and culture alliance. This blend of innovative architecture, emphasis on community engagement, and a consistently utilised public space throughout the year makes Oodi an ideal subject for this case study.

3.3. Microclimate simulation

This section details the methodology employed to evaluate the Oodi library entrance plaza's thermal comfort conditions through microclimate simulations. The process involves four key steps:

3.3.1. Meteorological Database Acquisition

Helsinki is equipped with seven weather stations, among which the Kaisaniemi station stands out (Figure 12). This particular station positioned approximately 420 meters from the Oodi library entrance plaza, has been selected as the focal point for this study due to its central positioning and close proximity to the designated case study site. This distance is deemed suitable for a fixed weather station concerning the study area. The meteorological data necessary for the microclimate simulations will be sourced from the Finnish Meteorological Institute (FMI), focusing on key variables recorded at the Kaisaniemi station (Finnish Meteorological Institute, 2024). These variables include cloud cover, precipitation, relative humidity, snow depth (if relevant during the simulation period), air temperature, dew point temperature, wind speed, and wind direction.

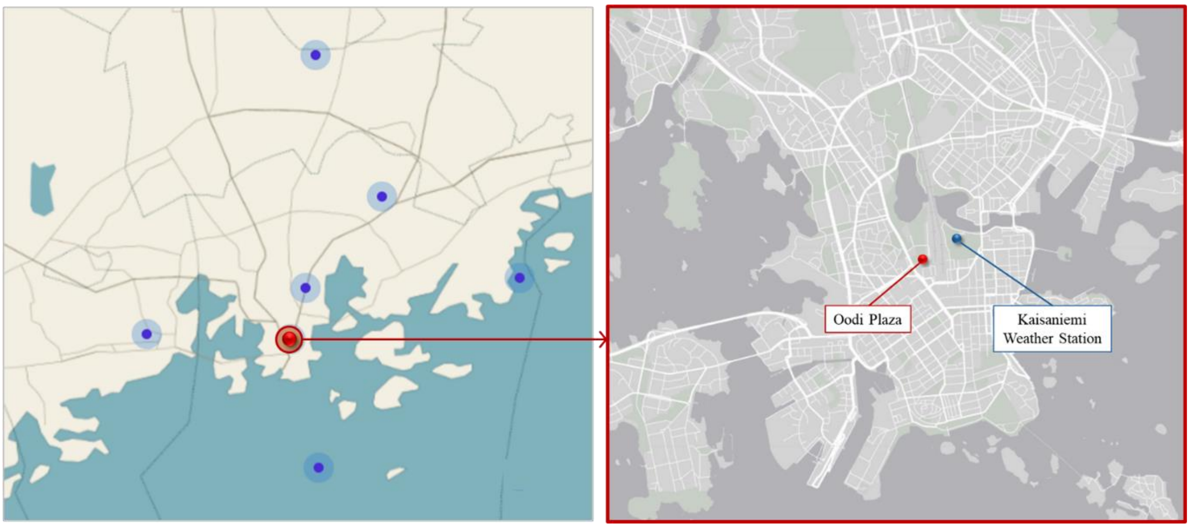


Figure 12. Location of the selected meteorological station relative to Oodi Library

3.3.2. Simulation Software Selection; ENVI-met

Among the array of software options available for microclimate analysis, this study opts for the ENVI-met simulation software due to its distinct advantages in conducting detailed simulations compared to alternatives like Grasshopper (Pacifici and Nieto-Tolosa, 2021).

ENVI-met (www.envi-met.com) is a three-dimensional, non-hydrostatic microclimate model that employs the fundamental principles of fluid dynamics and thermodynamics to compute and simulate the climatic conditions within urban settings. Its capability to closely correlate the architectural and geometric layout of the built environment with resultant microclimate conditions renders ENVI-met a valuable tool for aiding in the design of interventions aimed at enhancing outdoor space comfort. For the purposes of this study, version 5.6.1 Winter23 of ENVI-met will be utilised. Table (4) summarises the model settings used in this study

Table 4. ENVI-met Model and Simulation Settings

ENVI-met Model Settings	
Grid Dimensions	90×81×17
Cell Size (X,Y,Z)	3m×3m×3m
Core XY Domain Size	270m×243m
Method of Vertical Grid Generation	Telescoping (factor: 20%, start after 20 m), dz of lowest grid box is split into 5 subcells
Model Rotation out of Grid Nort	1.7
Nesting Grid	‘real’ grid cells
Highest Point Building	33 m
Vegetation	3D: 010440, 020440, 2D: 0200XY, 0200XX
Soil	CELLAR, 000000, 0200G2, 0200GS, 0200ST, 00200AR, 0000BA, 0200WW
Surrounding Building’s Material	Custom Material_ See Appendix A
Simulation Days	10^{th} Mar 2024 , 11^{th} Mar 2024, 28^{th} May 2024 , 2^{nd} June 2024
Forcing Type	Simple Forcing

3.3.3. Model Calibration and Validation

To ensure the accuracy and reliability of the ENVI-met model in simulating the microclimate of the Oodi library entrance plaza, on-site microclimatic measurements were conducted for model validation. This process involved collecting real-world data at ten strategically chosen locations within the Plaza. These locations (points 1-10) aimed to capture potential variations in microclimate due to factors like shading, wind patterns, and proximity to buildings. An additional five measurements (a-e) were taken outside the Plaza to provide reference points for comparison (Figure 13).

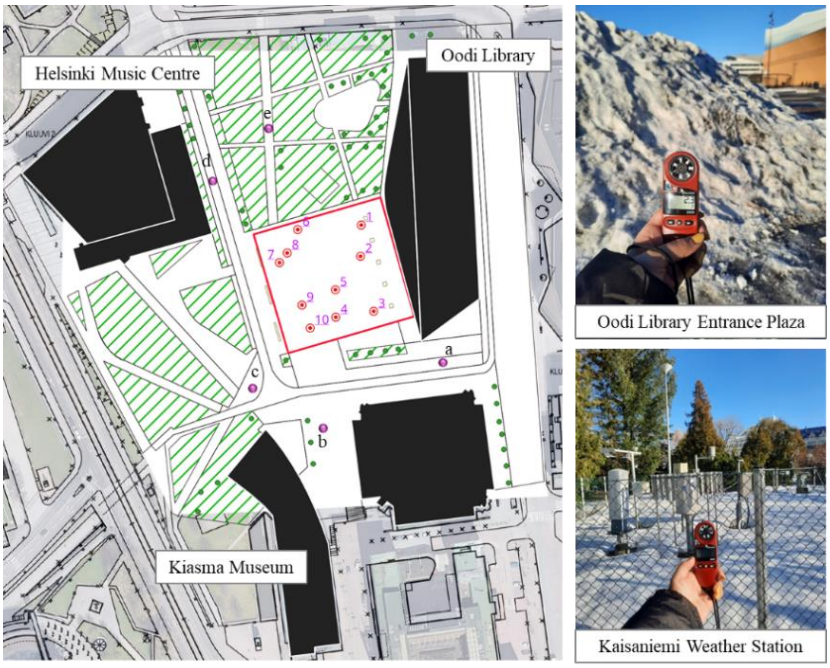


Figure 13. Field measurement points for microclimate model calibration (Base map data from City of Helsinki WMS service)

Air Temperature (±0.5°C), Relative Humidity (±3%), and Wind Speed were measured using a Kestrel 3000 pocket weather meter (Figure 14) held approximately 1.5 meters above ground level to represent the typical experience of Plaza users. All measurements were hand-written into ArcGIS Survey123 for efficient data collection and management. The Root Mean Square (RMS) error will be used to evaluate the degree of agreement between the simulated and measured microclimatic conditions. A lower RMS error signifies a closer match between the model's results and real-world data, indicating a more accurate representation of the Oodi Plaza's microclimate by ENVI-met.

SENSOR	ACCURACY (+/-)	RESOLUTION	SPECIFICATION RANGE
Wind Speed |Air Speed	Larger of 3% of reading, least significant digit or 20 ft/min	0.1 m/s 1 ft/min 0.1 km/h 0.1 mph 0.1 knots 1 B*	0.6 to 40.0 m/s 118 to 7,874 ft/min 2.2 to 144.0 km/h 1.3 to 89.5 mph 1.2 to 77.8 knots 0 to 12 B*
Ambient Temperature	0.9 °F 0.5 °C	0.1 °F 0.1 °C	-20.0 to 158.0 °F -29.0 to 70.0 °C
Relative Humidity	3%RH	0.1 %RH	5 to 95% 25°C non-condensing

Figure 14. Kestrel 3000 Pocket Weather Meter (left) and Kaisaniemi Weather Station (right)

3.3.4. Selection Criteria for Critical Days

In line with the primary aim of the study, which is to investigate the correlation between user patterns and Outdoor Thermal Comfort (OTC) during distinct cold and warm seasons, it is imperative to identify critical warm and cold days within the thesis timeline. The selection of these days adhered to the following criteria:

- *Season and Precipitation*: Critical cold and warm days were chosen in February and late May, respectively. Winter days prioritised the absence of precipitation (e.g., rain or snow) to minimise its influence on thermal comfort.
- *Cloud Cover*: Minimal cloud cover was preferred to ensure low diffused solar radiation and adequate direct shortwave radiation impacting thermal comfort through solar heat gain.
- *Wind Speed*: Extreme conditions, such as prolonged periods of calm or very high speeds (e.g., 6 or 7 m/s), were excluded (Figure 15). ENVI-met, being a computational fluid dynamics model, requires moderate wind speeds for accurate simulation and modelling.
- *Temperature Range*: Due to limitations of the ENVI-met model, days with consistently below-freezing temperatures were excluded. The model's reliable simulation capabilities are limited for scenarios where the entire day remains below 0°C.
- *User Activity Patterns*: To capture diverse user behaviour patterns and potential variations, days included both weekdays and weekends, ensuring the representation of different activity levels and routines within the study timeframe.

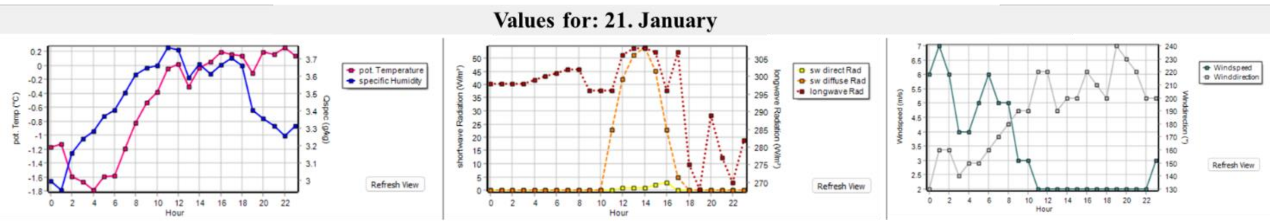


Figure 15. Meteorological Data for January 21st (Excluded Due to: Temperature Range, Cloud Diffusion, Wind Range) - One of the Coldest Days of Winter

February 18th, the fifth coldest day of the entire winter, initially emerged as a candidate for a critical cold day based on the selection criteria, particularly the absence of precipitation and minimal cloud cover. However, the presence of temporary structures in the Plaza, such as banners on stands and snow piles, presented a challenge. These structures had the potential to significantly influence user behaviour patterns in ways that deviated from typical usage on a standard day. Since the primary objective of this research is to examine the correlation between user patterns and OTC under unaltered conditions, February 18th was not chosen as a primary day for this analysis. Despite its exclusion from the primary analysis, it offers valuable insights. Observing user behaviour patterns on this day with temporary structures (banners on stands and snow piles) and comparing them to user behaviour on a day with minimal disruptions can provide insights into how these structures might influence user activity and space utilization within the Plaza.

Therefore, the next most suitable days meeting the selection criteria were identified as March 10th (Sunday) and March 11th (Monday). These days offered minimal cloud cover and no precipitation (Figure 16) while also capturing user behaviour variations between a weekend and a weekday.

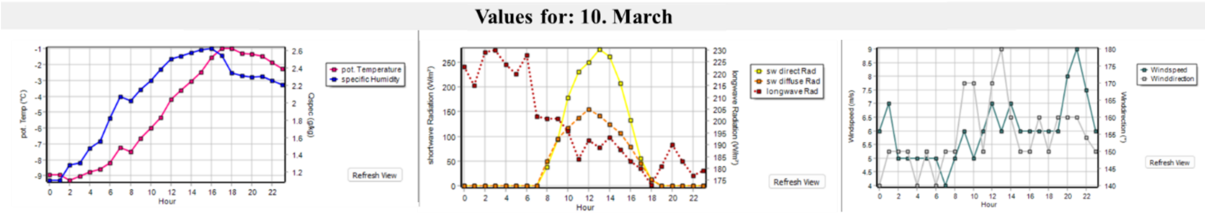


Figure 16. Meteorological Data for March 10th (Included Due to: Temperature Range, Cloud Diffusion, Wind Range) – One of the Coldest Days of March

In accordance with the timeline, user data collection for warm days, originally planned for the end of May (May 26th, Sunday, and May 27th, Monday), needed to be rescheduled due to a conflicting food event. To ensure a comprehensive investigation of user patterns and Outdoor Thermal Comfort (OTC) during warm seasons, observations were shifted to May 28th (Tuesday) and June 2nd (Sunday). This revised schedule incorporates both weekend and weekday variations, allowing for a more thorough analysis.

3.4. User Behaviour Pattern Simulation

This section outlines the methodology for simulating user behaviour patterns within the Plaza.

3.4.1. Data Collection

The observation period targeted peak activity levels between 12:00 and 2:00 PM on selected days. This timeframe coincided with microclimate stability (and calibration measurements) and high user activity (lunchtime patrons, students arriving after classes, professionals on breaks). A fixed camera on the library's 3rd floor captured time-lapse videos with a dominant view of the Plaza, minimising obstructions and ensuring uninterrupted recording. Additionally, on-site observations with interpretive notes were documented (Figure 17).

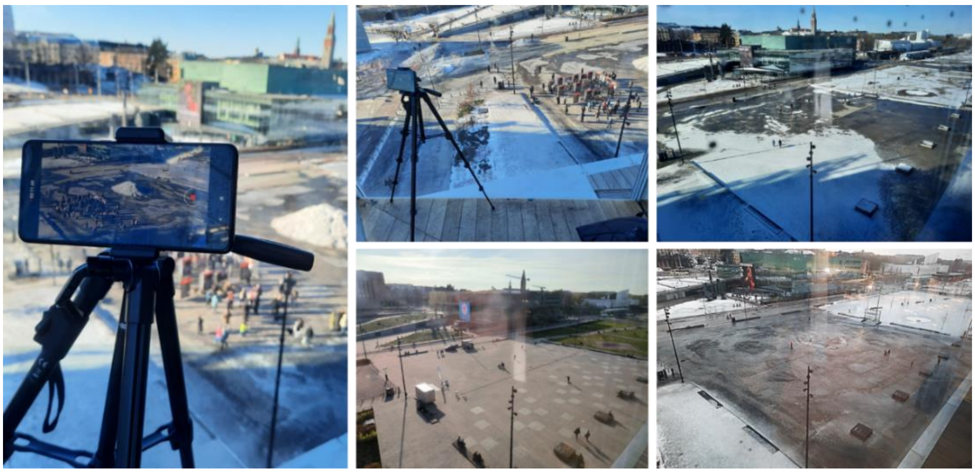


Figure 17. Camera placement for recording behaviour observations

3.4.2. Data Processing and Analysis

Video analysis was facilitated using Python programming. The YOLOv8 object detection algorithm identified individuals within the Plaza, while the Deep Sort tracking algorithm precisely tracked their movement. This combination enabled a more accurate assessment of user behaviour and people flow. Subsequently, dominant movement patterns were visualised manually (Figure 18).

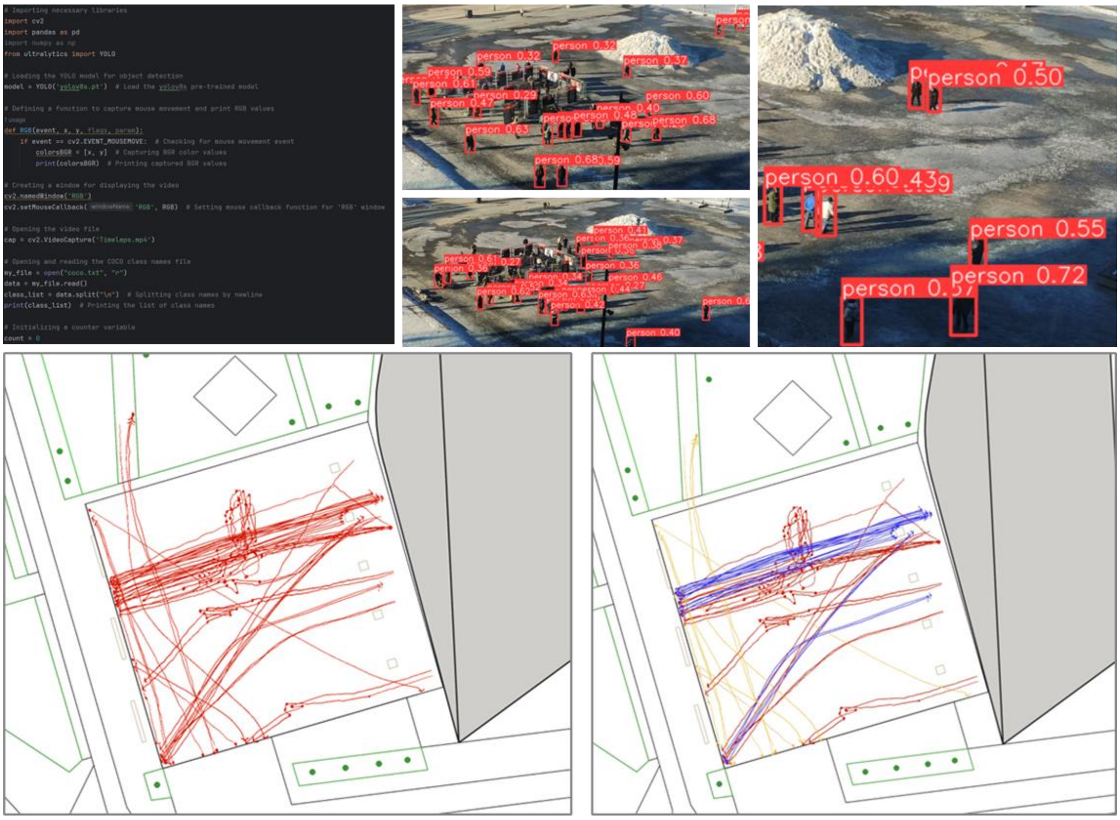


Figure 18. Visualisation of behaviour patterns using a combination of programming techniques and manual drawing

3.4.3. User Behavior Simulation

Data from two sources informed the user behaviour simulation in Rhino7 with the Grasshopper using the PedSim plugin: (1) people counting data from the Plaza entrances provided user influx information, and (2) observed average stay times from data collection offered insights into user dwell times in specific locations (Figure 19).

Following the simulation, heatmaps were generated for the dominant user movement pattern for each observation, visually representing the intensity of pedestrian activity within different Plaza areas.

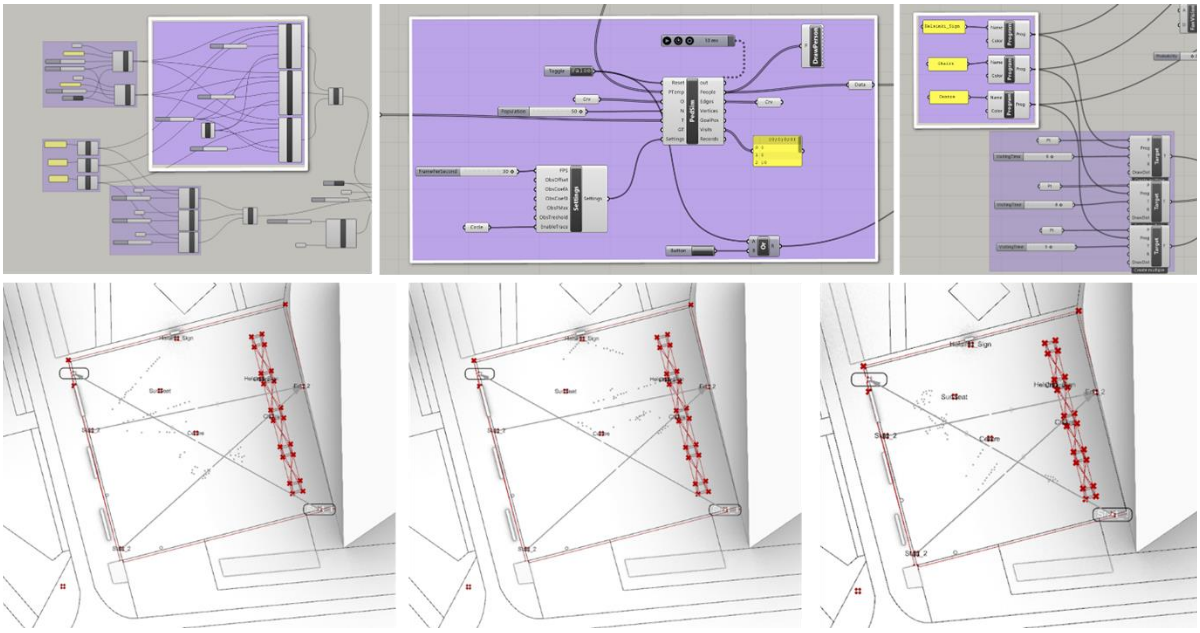


Figure 19. Grasshopper example workflow using the PedSim plugin for simulating user behaviour: movement of people from a starting point to a destination and the probability of stops at defined objects

3.5. Comparison and Correlation

Section 5 leverages the generated heatmaps and the previously established microclimate data (PET maps) to explore the relationship between the Plaza's microclimate and user behaviour patterns. This section will employ a two-pronged approach:

3.5.1. Qualitative and Interpretive Comparison:

A qualitative and interpretive comparison will be conducted by visually comparing the user behaviour heat maps with the PET maps. This comparison aimed to identify potential correlations between specific microclimatic conditions (represented by PET values) and observed user behaviour patterns (shown by the heatmaps).

3.5.2. Quantitative Evaluation with ENVI-met:

ENVI-met will be utilised to quantitatively assess how users perceive thermal changes as they move through the space. This software will simulate the dynamic thermal comfort (DTC) associated with the simulated agents' dominant behaviour patterns within the Plaza (Figure 20). The results of this simulation will provide quantitative insights into how user thermal perception may vary depending on their movement and location within the Plaza.

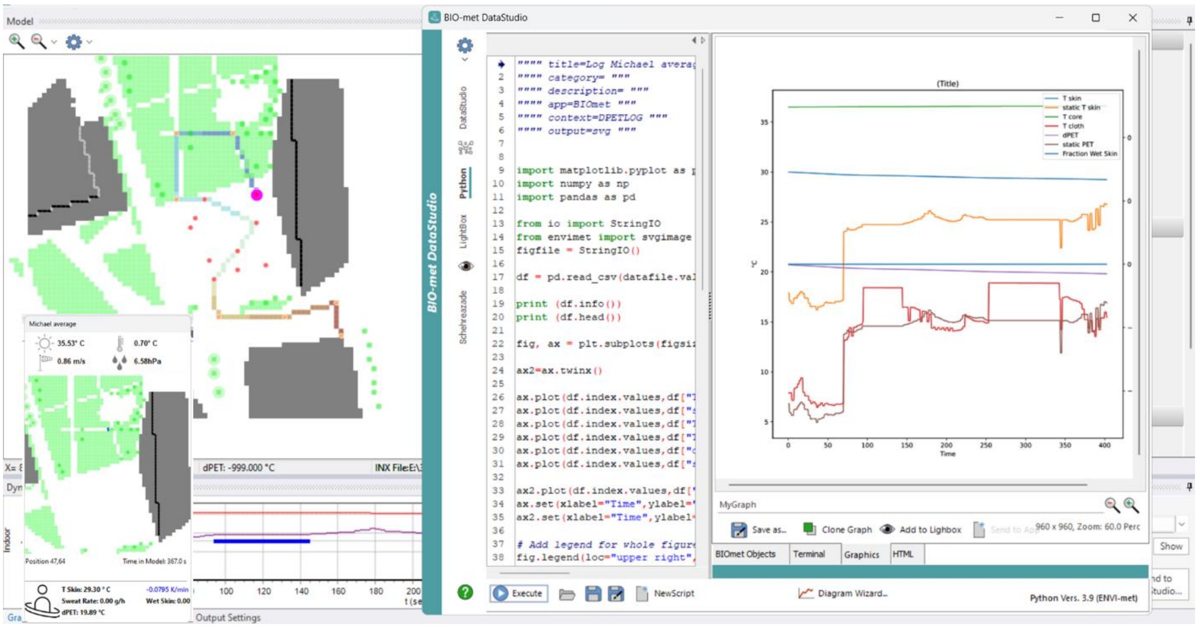


Figure 20. ENVI-met simulation example workflow with Biomet post-processing for calculating dynamic physiological equivalent temperature

3.6.Proposal and Validation

Drawing upon qualitative analysis of user behaviour, observations, insights from the literature review, and results from previous sections, this section presents a proposal for temporary interventions aimed at enhancing year-round outdoor space quality for users, with a primary focus on improving thermal comfort within the Plaza.

This proposal transcends numerical solutions by integrating user behaviour and preferences to design for the human experience. A core objective is to enhance the usability of the outdoor space during winter months, thereby fostering user well-being through improved mental and physical health.

3.6.1. Proposal for Temporary Interventions

Building upon the findings from the preceding sections, specific temporary interventions (such as shading structures, winter shelters, seating arrangements, water features, etc.) will be suggested to address the Plaza's identified thermal comfort challenges. These proposed interventions will be tailored to suit the Plaza's unique characteristics and the identified user behaviour patterns.

3.6.2. Validation

To validate the effectiveness of the proposed interventions, a second round of simulations will be conducted using ENVI-met software. This phase aims to ensure that the proposed design yields a positive impact on the study area. The effectiveness of the interventions will be evaluated based on two primary criteria:

- *Physiological Equivalent Temperature (PET):* Changes in PET values within the Plaza will be compared between the baseline scenario and the scenario incorporating the proposed interventions.
- *Predicted People Flow:* Based on the observed data, user behaviour patterns, including the duration of user stays within the Plaza, will be predicted and simulated. An increase in predicted user stay time would suggest a more inviting and usable space.

The results of the validation simulations will be used to refine the proposed interventions, if necessary. Ultimately, the goal is to develop a climate-sensitive design that tangibly enhances thermal comfort and encourages user occupancy of the outdoor space year-round.

CHAPTER 4: Results and Analysis

4.1. Meteorological Analysis

This section presents a two-part analysis of Helsinki's climate relevant to the site studies.

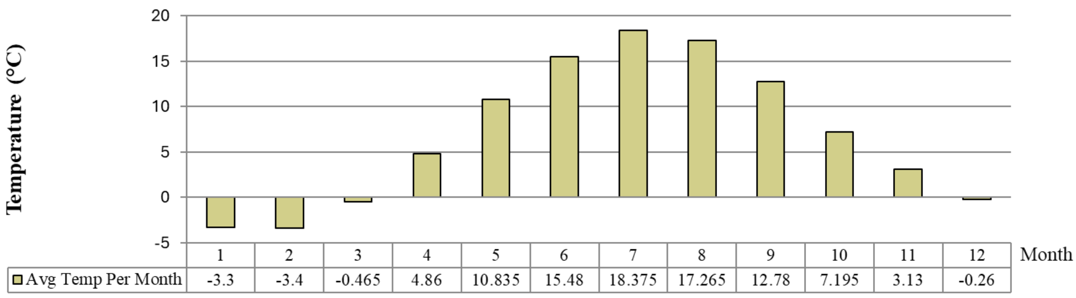
The first part focuses on general weather data for Helsinki, including temperature trends over past years, outdoor thermal comfort indices (UTCI and PET), precipitation, solar radiation, wind rose, and sun path. These factors provide a comprehensive understanding of the city's overall climate.

The second part delves into the microclimatic analysis and simulations of the specific site (Oodi Plaza). This includes assessments of direct sunlight hours during hot and cold seasons, environmental simulations using ENVI-met software to represent air temperature, mean radiant temperature (MRT), and PET, and calibration with measured data for validation.

4.1.1. Helsinki meteorological analysis

The bar chart (Graph 1) depicts the average monthly temperatures in Helsinki over a 20-year period (2004-2023), as mentioned in the methodology outlined in Section 3.3.1; this data were obtained from Kaisaniemi weather station. February stands out as the coldest month, with an average temperature of -3.4°C, while July is the warmest at 18.3°C. This substantial seasonal variation highlights the pronounced temperature fluctuations characteristic of Helsinki's climate. The data demonstrates a consistent rise in temperatures from winter to summer and a subsequent decrease from summer to winter, reflecting the anticipated seasonal climatic patterns. Notably, the consistency of these monthly averages over two decades provides a robust representation of the region's long-term seasonal temperature dynamics.

Helsinki Monthly Mean Temperature (°C) Over 20 Years (2004-2023)

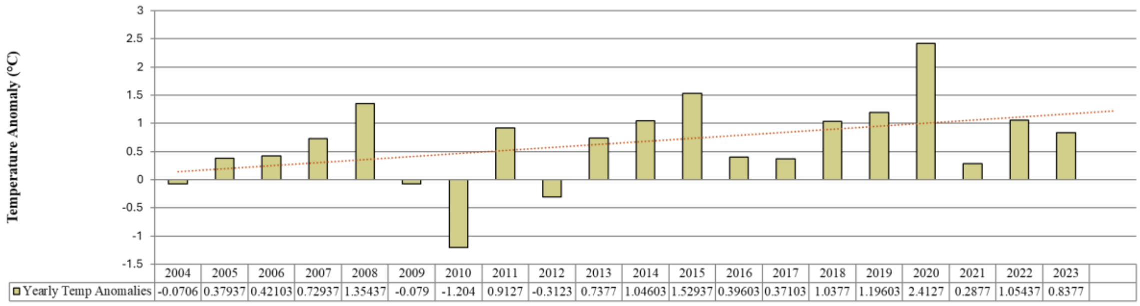


Graph 1. Helsinki monthly temperature; 2004 _2023 (Own elaboration, 2024 information retrieved from FMI[26], n.d.)

An analysis of annual temperature anomalies from 2004 to 2023 reveals a warming trend in this particular city. While fluctuations occurred, with a maximum anomaly of 2.4°C in 2020 and a minimum of -1.20°C in 2010, the overall pattern suggests a gradual increase in temperatures (Graph 2).

Helsinki Annual Mean Temperature Anomaly (°C) Over 20 Years (2004-2023)

[26] Finnish Meteorological Institute

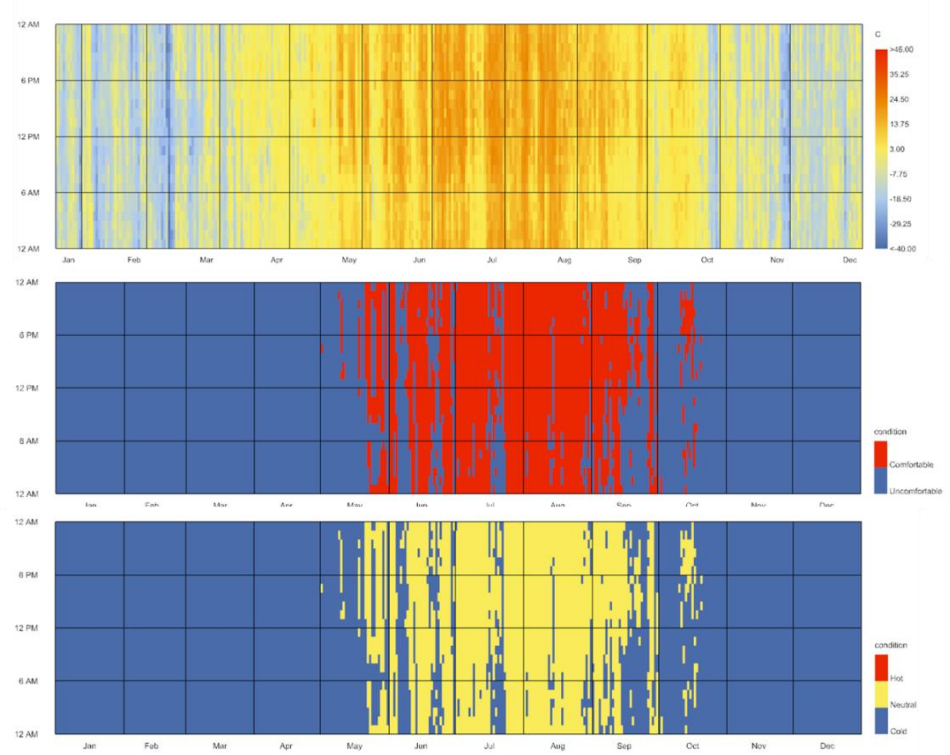


Graph 2. Helsinki annual temperature anomaly; 2004-2023 (ibid)

According to the City of Helsinki report, "Weather and Climate Risks in Helsinki", winters are projected to become warmer, wetter, and icier by 2050 (Pilli-Sihvola et al., 2019). This shift in climate translates to increased rain and decreased snowfall, leading to slippery conditions that threaten pedestrian and cycling safety. While intense snowstorms remain a possibility, overall snowfall is expected to decline. Fluctuating temperatures around freezing will create more frequent icy patches due to freeze-thaw cycles. Additionally, a decrease in winter sunshine could exacerbate seasonal depression. Increased winter rainfall also raises concerns about stormwater management, nutrient runoff into waterways, and the potential for more frequent freezing rain events.

Building on the analysis of thermal comfort indices (UTCI and PET) presented earlier (Section 2.1.2), this section delves deeper into the factors influencing thermal comfort in Helsinki using weather data from the Kaisaniemi station. Ladybug, a parametric environmental design software within Grasshopper, was employed to calculate the Universal Thermal Climate Index (UTCI), a widely used biometeorological index for assessing thermal comfort (Section 2.1.2, Table 2). UTCI considers air temperature, mean radiant temperature (MRT), relative humidity, and wind speed at 10 meters above ground level to determine the equivalent air temperature in a reference environment that evokes the same thermal sensation as the actual conditions.

The analysis (presented in Graph 3) reveals that Helsinki experiences predominantly uncomfortable thermal conditions throughout most of the year, categorised as "cold" on the UTCI scale. Only during the period from mid-May to mid-October (roughly half the year) do conditions fall within the UTCI's "comfortable" range.

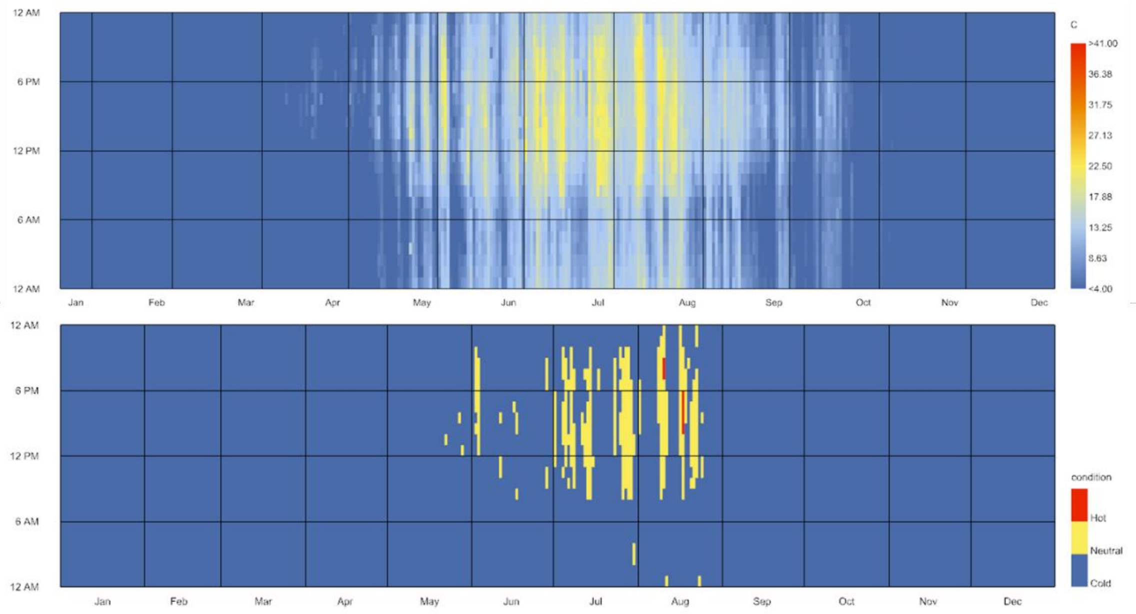


Graph 3. Helsinki UTC index (Own elaboration, 2024 information retrieved from FMI, n.d.)

The Universal Thermal Climate Index (UTCI) considers the impact of weather conditions (air temperature, radiation, humidity) on the human body without directly measuring physiological response. This makes UTCI suitable for representing thermal experience in urban microclimates, where local factors significantly influence comfort levels. However, the outdoor thermal comfort (OTC) range varies geographically, highlighting the limitations of a single, universal index.

As mentioned in the literature review (Section 2.1.2), the Physiological Equivalent Temperature (PET) is the most widely used OTC index. It incorporates a comprehensive range of weather parameters like air temperature, radiation, and humidity, alongside factors influencing heat exchange, such as metabolic activity and clothing. A specific city analysis using Ladybug in Grasshopper with four weather data inputs (air temperature, relative humidity, wind speed, and mean radiant temperature) revealed limited periods within the comfort range. Notably, only the three summer months offered neutral conditions (18-23°C), while the remaining nine months were predominantly cold, with a few hot days in August (Graph 4). However, as mentioned in the literature review, urban form plays a pivotal role in the real PET in different urban spaces. Furthermore, people's perception of comfort varies geographically. Individuals in Nordic regions, accustomed to cooler temperatures, might have a lower tolerance for hot weather compared to those in equatorial regions, and vice versa.

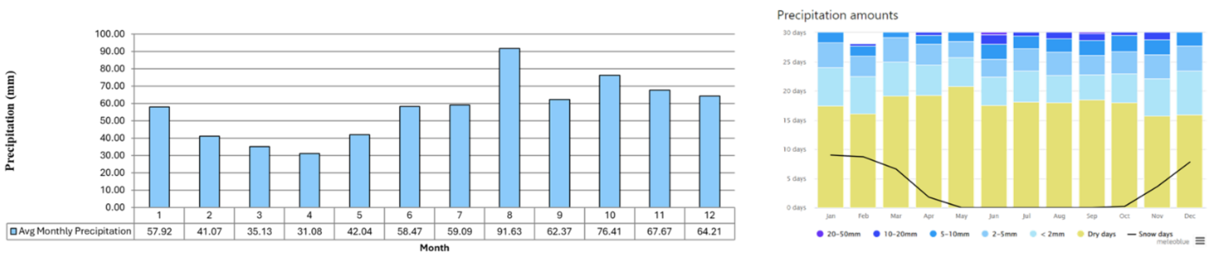
However, this research focuses on observing and interpreting people's behaviour in public spaces, not individual perception surveys. This approach aims to capture the broader influence of climate on how people utilise these spaces.



Graph 4. Helsinki PET index (Own elaboration, 2024 information retrieved from FMI, n.d.)

Graph (5) displays the total monthly precipitation recorded in Helsinki Kaisaniemi over the past two decades (2004-2024). A noticeable trend is observed in the variability of precipitation. For instance, in January 2004, the total precipitation was 45.6 mm, while in January 2023, it was 52.4 mm, indicating an increase. However, some months exhibit significant fluctuations; for example, July 2017 experienced a peak of 120.7 mm, whereas July 2018 had only 60.3 mm. These variations underscore the irregularity and unpredictability of precipitation patterns over the years. Overall, precipitation is recorded in all months, with August having the highest and April the lowest amounts. Additionally, snow events are present from November to May, with peaks in January and February, as illustrated in Graph (5).

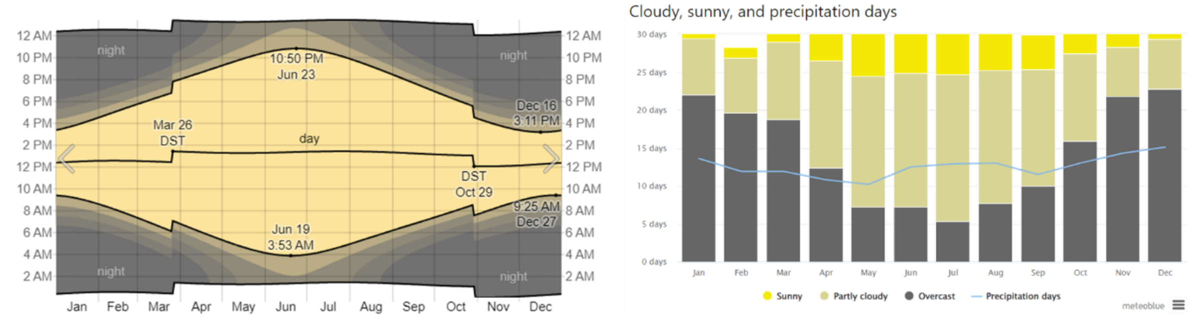
Helsinki Monthly Precipitation (mm) Over 20 Years (2004-2023)



Graph 5. Left: Average monthly precipitation (mm) over 20 years (2004-2023) (ibid) Right: Precipitation frequency and amounts (meteoblue.com, 2024)

Data on sunshine duration (Graph 6; Left) highlights a pronounced difference in daylight hours between winter and summer. Winter months experience a considerably shorter period of daylight with approximately 6 hours of sunlight compared to the extended daylight period of summer, reaching around 19 hours. This disparity can be attributed to the Earth's axial tilt, which influences the sun's angle relative to the horizon. Furthermore, cloud cover patterns (Graph 6; Right) exhibit a seasonal trend. Sunny days are more frequent during the summer months (May, June, July), whereas November, December, and January experience increased cloudiness. This variation in cloud cover significantly impacts the amount of solar radiation received at the surface.

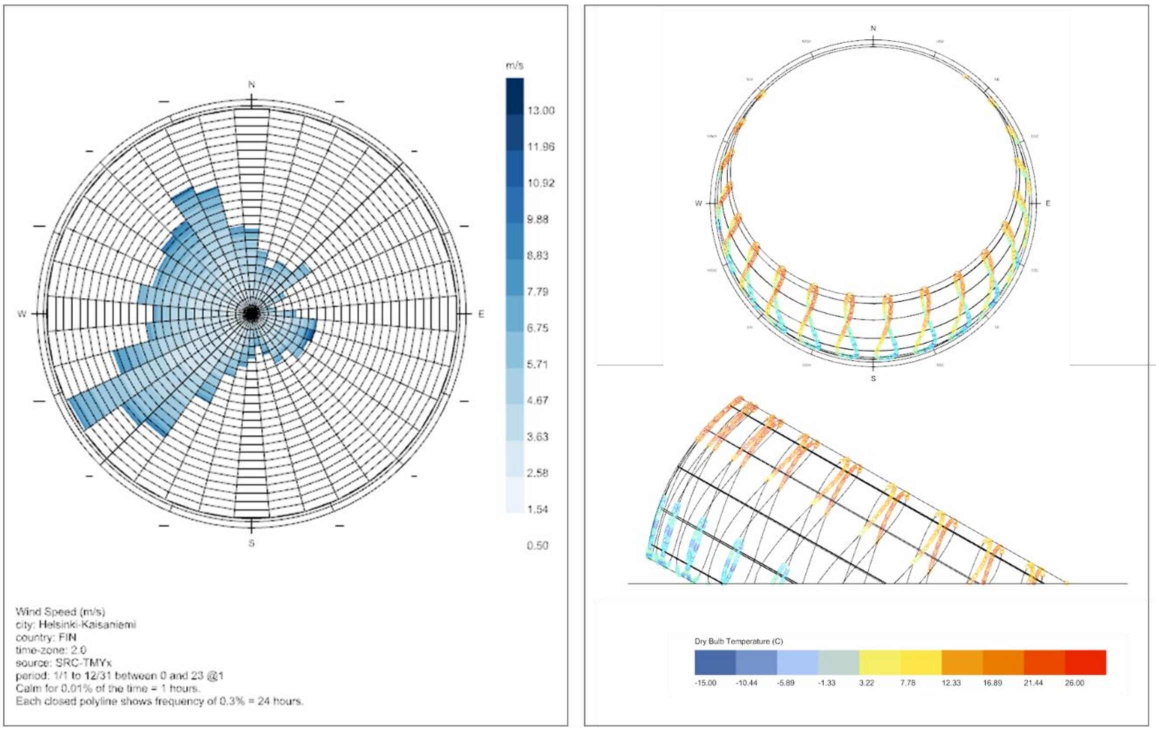
Annual Variability of Solar Radiation in Helsinki



Graph 6. Daylight hours (left), and Cloud patterns (right); (meteoblue.com, 2024)

Sun path diagrams (Graph 7; *right*) visually represent solar movement and corresponding angles throughout the year for Helsinki. These diagrams show the sun's elevation angle, which reaches a maximum of approximately 53 degrees during the summer solstice (June 21st) and drops to around 7 degrees during the winter solstice (December 21st). Additionally, the diagrams illustrate the variations in the sun's path, shifting from northeast to northwest in summer and southeast to southwest in winter. This information on solar angles and paths is crucial for buildings' efficient natural lighting and strategically placing urban furniture to maximise solar exposure. Additionally, it is vital to understand seasonal variations in Helsinki's solar energy potential.

Furthermore, wind speed data indicate that the highest wind speeds, reaching up to 13 m/s, predominantly originate from the south and southwest (Graph 7; *left*). The frequency of these winds is shown by shaded areas, with stronger winds being more frequent from these directions. Conversely, winds from the east and northeast are less frequent and generally have lower speeds. Understanding these prevailing wind patterns aids in designing buildings for optimal natural ventilation, determining wind turbine placement, and assessing potential wind impacts on infrastructure.



Graph 7. Helsinki wind rose (left), and Sun path (right); (Own elaboration, 2024 information retrieved from FMI, n.d.)

4.1.2. Oodi Plaza microclimate analysis

As highlighted previously, access to sunlight is a crucial year-round consideration. While excessive radiation can be undesirable in tropical regions, sunlight remains essential for warmth in cooler climates. Figure (21) illustrates the Plaza's southerly sun exposure, with the minimum angle occurring in winter. Additionally, the prevailing wind originates from the site's southwest corner. These factors will be instrumental in interpreting people's behaviour and informing temporary furniture placement.

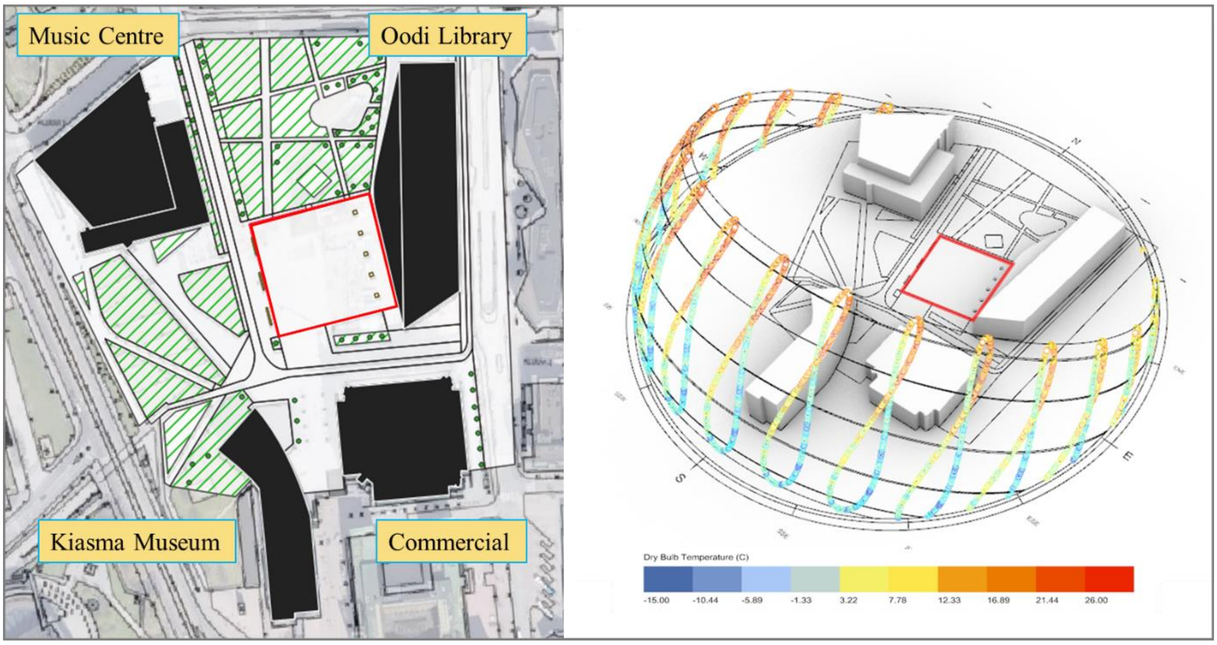
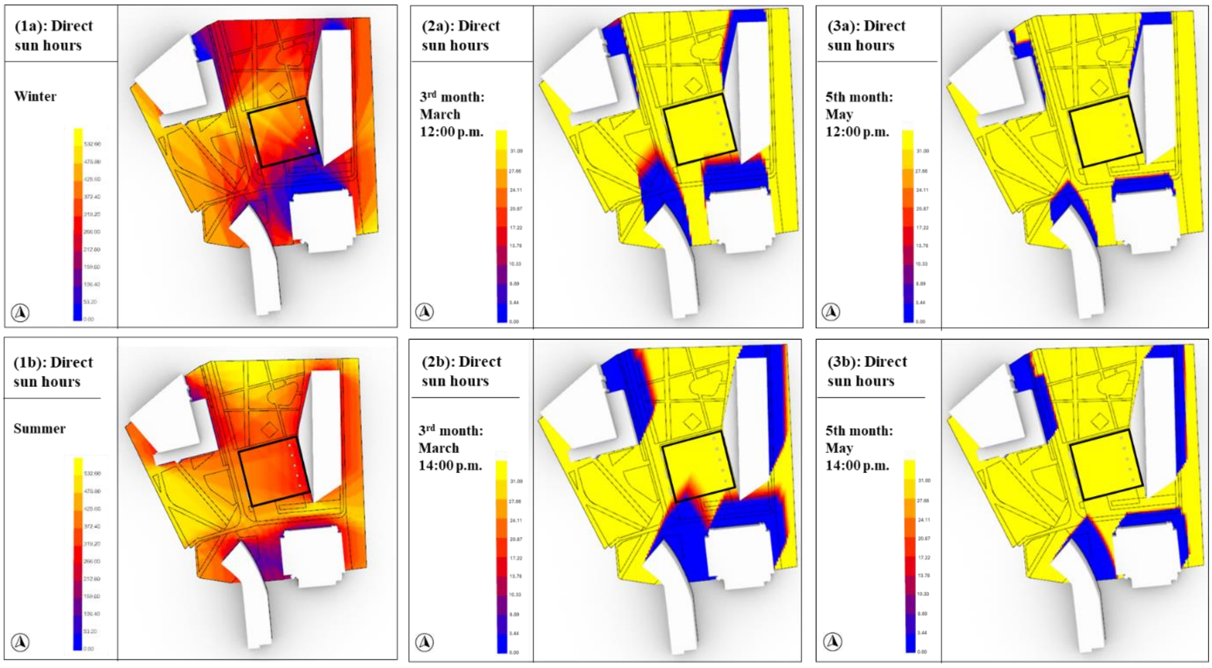


Figure 21. Plaza location and adjacencies (left) and sun path analysis for the site (right); (Own elaboration)

Table (5-1a) illustrates the sun and shadow patterns in the Plaza during winter months, showing the southeastern portion experiencing significant shading while the most direct sunlight falls on the north and northwest corners. This pattern was confirmed through simulations conducted at solar noon (12:00) and early afternoon (14:00) for the specific field study months of March (Table 5-2a,2b) and May(Table 5-3a,3b). The simulations further reveal that the south side of the Plaza receives minimal sunlight in winter, particularly at 2:00 PM. In contrast, during the summer months (Table 5-1b), the entire Plaza receives direct sunlight.

Table 5. Direct Sun Exposure in the Plaza (Winter, Summer, March & May) (Own elaboration)



- **ENVI-met Model Calibration**

This section focuses on calibrating the ENVI-met model to ensure accurate simulation results. Four representative dates: two dates in March, one date in May, and one date in June (Table 6). Further analysis comparing data from different measurement points is presented in section 3.3.3 (Figure 10).

Graph (8) and Graph (9) compare observed and modelled temperatures during late winter and early summer, respectively. The Root Mean Square Error (RMSE) values (0.8 for March and 0.5 for May and June) indicate that the model achieves acceptable results. The higher RMSE in March compared to May and June can be attributed to the software's limitations. ENVI-met currently does not support simulating snow cover. To compensate for this, adjustments were made to the roughness, soil moisture, and soil temperature parameters to approximate the frozen ground conditions present in March.

Graph 8. Observed vs. Model temperature in late winter

Graph 9. Observed vs. Model temperature in early summer

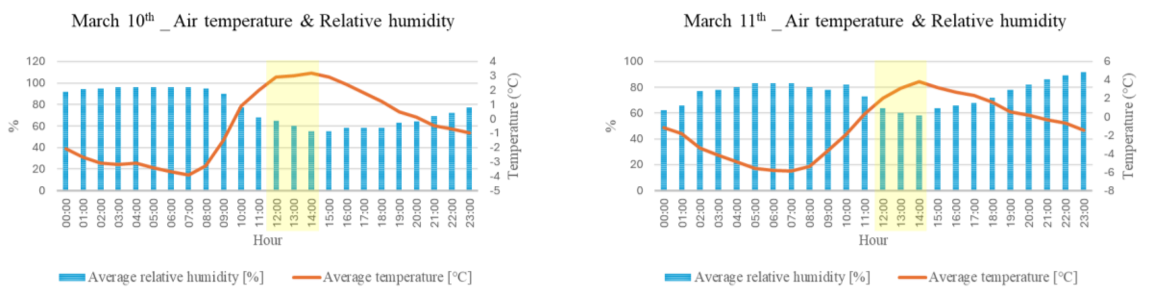
The higher RMSE in March compared to May and June can be attributed to several factors. Even after mechanical snow removal, a thin layer of snow persisted, particularly in the southern part of the Plaza (Figure 22). This residual snow, combined with the influence of direct sun exposure (as shown in Table 5) and shading patterns throughout the day cast by buildings on the southern area, likely contributed to slower melting compared to other parts of the Plaza. These factors, not fully captured by the model, could explain the higher RMSE in March.

Figure 22. Oodi Plaza snow cover on March 10th & 11th

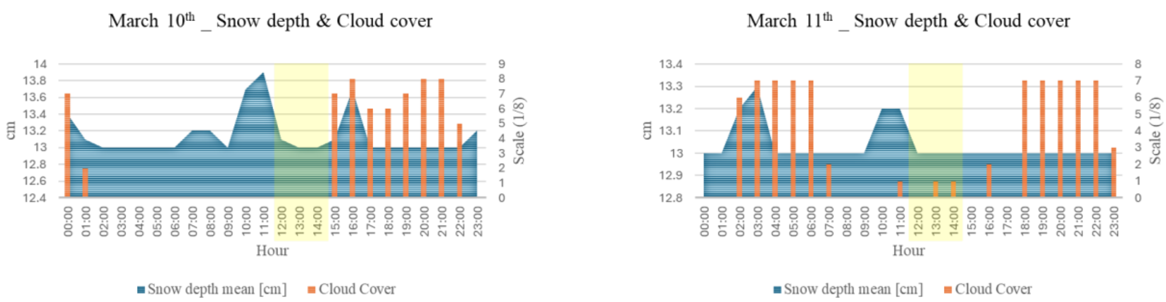
In June, the highest RMSE occurs at 12:00. This could potentially be caused by the direct sunlight impacting both the square and the weather meter, potentially influencing sensor readings and introducing discrepancies with the simulated data. The calibration process successfully adjusted the ENVI-met model to achieve acceptable agreement between measured and simulated temperatures (RMSE: 0.5-0.8).

- **Microclimate and Thermal Comfort Simulations on <u>March 10th & 11th</u>**

As detailed in the methodology section (Section 3.3.4), the microclimate conditions on March 10th and 11th exhibited characteristics typical of a winter season with low air temperatures and moderate humidity.



Graph 10. Air temperature and relative humidity on March 10th (left), and March 11th (right) (Own elaboration,2024)



Graph 11. Snow depth and cloud cover on March 10th (left), and March 11th (right) (Own elaboration,2024)

March 10^{th} experienced an average air temperature of -1.1°C, with a maximum of 3.8°C at 14:00 and a minimum of -5.9°C at 7:00 (Graph 10). Despite the presence of snow and cloud cover reported for the date, the field survey period itself encountered clear skies. However, as mentioned previously, the Plaza surface still retained a partial layer of thin snow (Graph 11). The average relative humidity during this time was 75.16%, with a maximum of 92% and a minimum of 58%. Table (6) presents the results of the March 10^{th} simulation.

March 11^{th} followed a similar pattern, with an average air temperature of -0.47°C, reaching a maximum of 3.2°C at 14:00 and a minimum of -3.9°C at 7:00. Although snow and minor cloudiness were reported for the overall date, the field survey period encountered clear skies. Similar to March 10^{th}, the Plaza surface remained partially covered with thin snow. The average relative humidity on this day was 76.87%, ranging from a minimum of 55% to a maximum of 96%. Table (7) presents the results of the March 11^{th} simulation.

Table 6. Simulated T_{air} (a), MRT (b), PET (c), and Thermal Sensitivity (d) on March 10^{th} at 12:00 (1) and 14:00 (2) (Own elaboration, 2024)

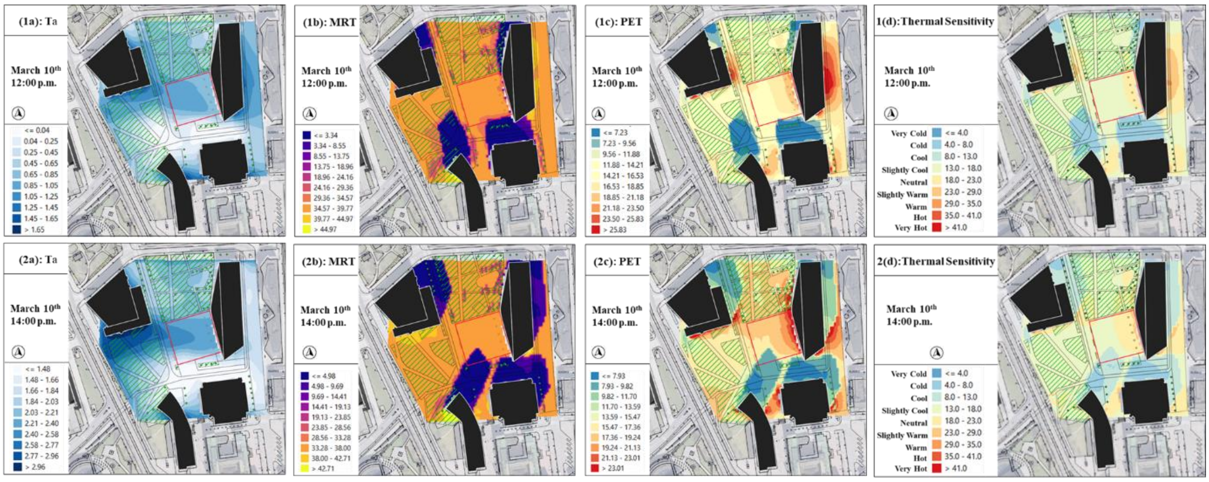
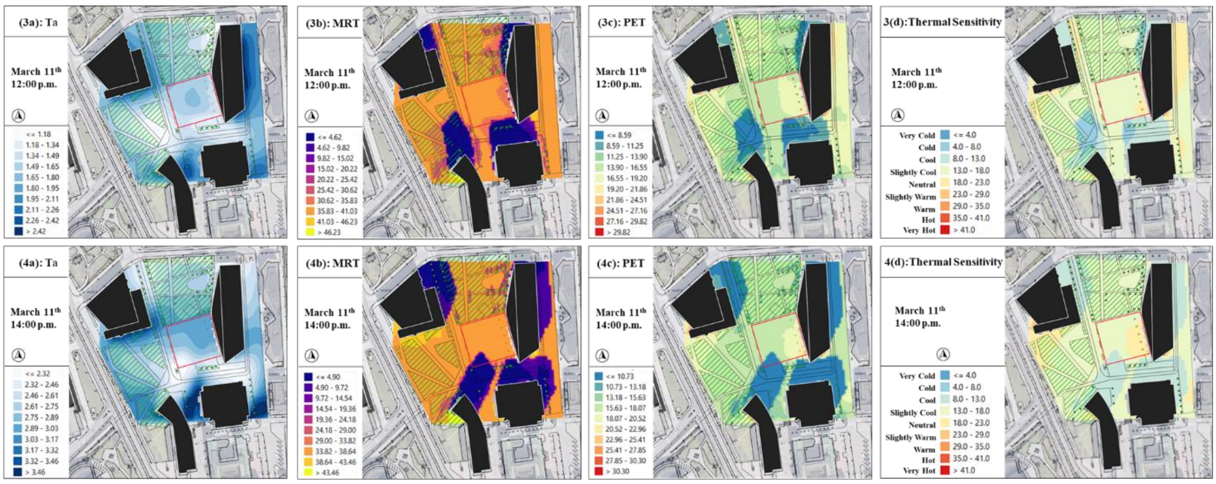


Table 7. Simulated T_{air} (a), MRT (b), PET (c), and Thermal Sensitivity (d) on March 11^{th} at 12:00 (3) and 14:00 (4) (Own elaboration, 2024)



The **Potential Air Temperature (T_{air})** analysis reveals a consistent pattern on March 10^{th} and 11^{th}. Both days exhibit a rise in $TAir$ from 12:00 to 14:00, with the maximum temperature increase observed on March 10th (1.31°C difference) compared to March 11th (1.04°C difference). This trend suggests a potential influence of solar radiation, with the afternoon period likely experiencing the most significant impact. Across both days and time periods, the lowest T_{air} values are consistently observed in the southern part of the Plaza. This spatial variation could be attributed to factors such as shading patterns or differential heating of surface materials in different areas.

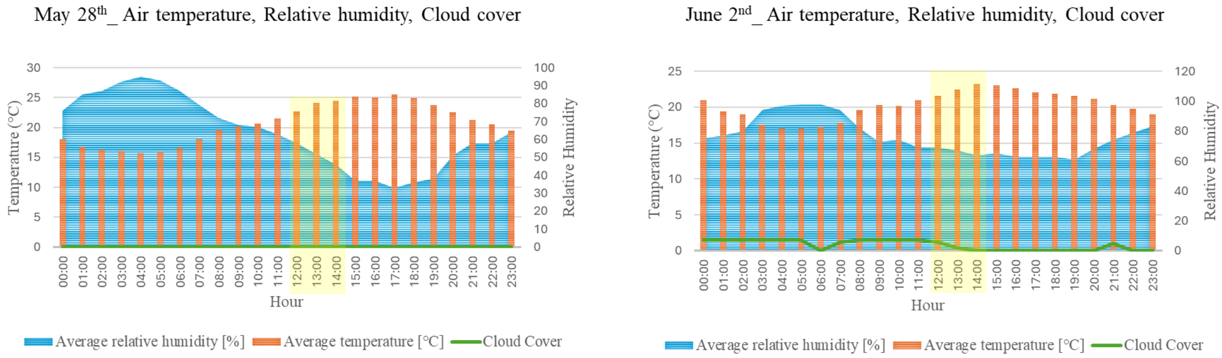
The most significant difference in **Mean Radiant Temperature (MRT)** on both March 10th and 11th occurs between 12:00 and 14:00. This observation aligns with the movement of the sun and shadows throughout the day. The spatial distribution of MRT also follows a pattern, with the lowest values consistently observed in the southern part of the Plaza at 14:00. This can be explained by the rapidly changing solar angle during winter, which results in the southern area receiving less direct sunlight in the afternoon compared to other parts of the Plaza.

Despite the low air temperatures (T_{air}) observed across the Plaza, the **Physiological Equivalent Temperature (PET)** analysis reveals a spatial variation in thermal comfort perception. The results suggest that the Plaza can be divided into two distinct zones: "slightly cool" and "neutral" or "comfortable." The "neutral" or "comfortable" zone is particularly noticeable near the library building. At 14:00, a distinct pattern emerges. The "neutral" zone expands eastward across the Plaza, while a new "cool" zone appears in the southern area. This negative effect appears to be linked to the movement of the sun and MRT throughout the day.

Furthermore, the PET analysis highlights the influence of vegetation. The trees in the northern lawns adjacent to the Plaza show a distinct "cold" zone, especially at 12:00. This zone diminishes by 14:00, likely due to changes in sun exposure and radiative loss.

- **Microclimate and Thermal Comfort Simulations on May 28th and June 2nd**

May 28th and June 2nd marked a distinct shift towards warmer conditions, reflecting the transition into early summer. Average air temperatures hovered around 20°C on both days (May 28th: 20.61°C, June 2nd: 20.25°C). Minimum temperatures remained mild, ranging from 15.7°C at 4:00 on May 28th to 17°C at 4:00 on June 2nd. While both days experienced similar minimum temperatures, May 28th reached a higher maximum temperature of 25.5°C at 17:00, compared to June 2nd's maximum of 23.2°C at 14:00 (Graph 12).



Graph 12. Air temperature, relative humidity and cloud cover on May 28th (left), and June 2nd(right) (Own elaboration,2024)

Relative humidity levels also displayed some variation. May 28th saw a wider range, with values fluctuating between 33% and 95%, indicating a more dynamic moisture content in the air. In contrast, June 2nd exhibited a more moderate range of relative humidity, averaging 76.25% with a minimum of 61% and a maximum of 98%. The results of the May 28th and June 2nd simulations are presented in Tables (8) and (9), respectively.

Table 8. Simulated T_{air} (a), MRT (b), PET (c), and Thermal Sensitivity (d) on May 28th at 12:00 (1) and 14:00 (2) (Own elaboration, 2024)

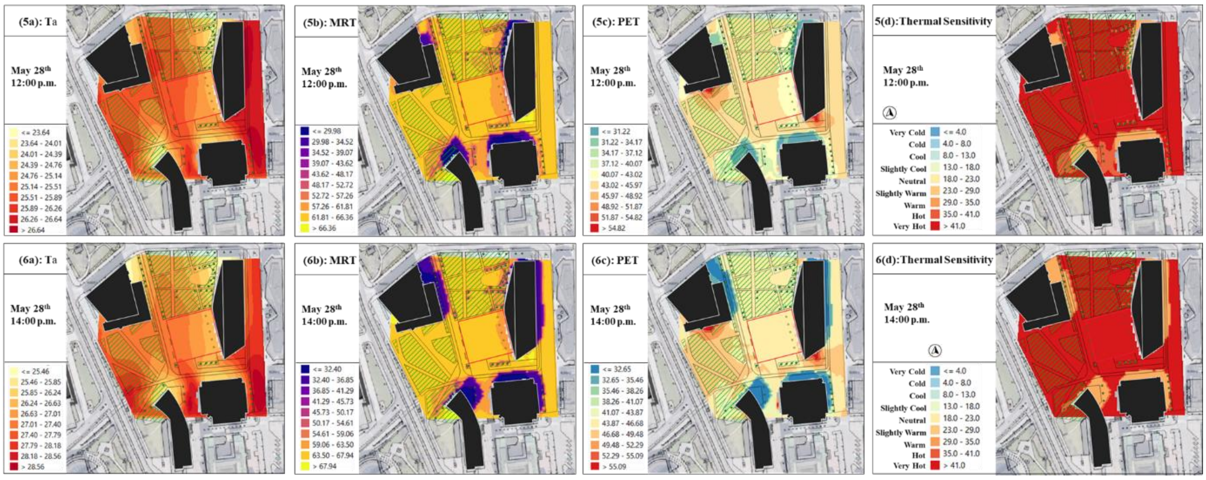
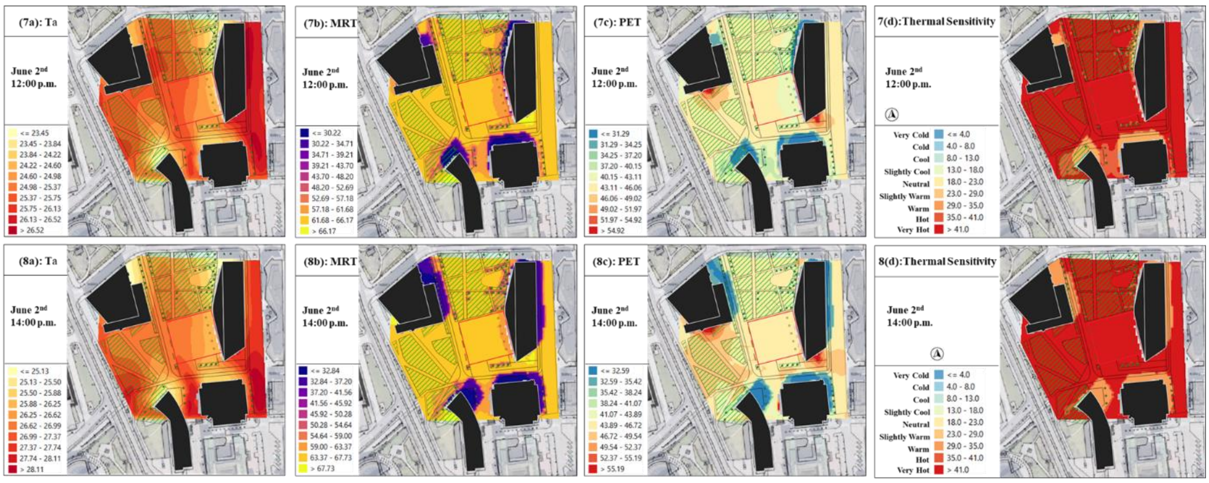


Table 9. Simulated T_{air} (a), MRT (b), PET (c), and Thermal Sensitivity (d) on June 2nd at 12:00 (3) and 14:00 (4) (Own elaboration, 2024)



The **Potential Air Temperature (T_{air})** analysis reveals a consistent spatial pattern across both May 28th and June 2nd. The west and south sides of the Plaza consistently exhibit the highest temperatures, with values decreasing gradually towards the east side and the library building. This observed temperature gradient suggests potential influences from factors such as solar radiation patterns or differential heating of surface materials (wooden façade). A notable observation emerges at 12:00 on both dates. The Plaza's west side experiences a slight decrease in temperature (around 0.4°C) compared to 14:00.

Similar to the observations in March, the analysis of **Mean Radiant Temperature (MRT)** on May 28th and June 2nd reveals the most significant difference occurring between 12:00 and 14:00. This pattern aligns with the changing sun angle and associated building shadows throughout the day. The spatial distribution of MRT within the Plaza also exhibits a distinct pattern. At 12:00, the lowest MRT values are observed in the eastern sector. This zone shrinks in size by 14:00, while the remaining areas of the Plaza maintain consistently higher MRT values.

The **Physiological Equivalent Temperature (PET)** analysis reveals a significant contrast in thermal comfort within the Plaza between late winter and early summer. While the winter analysis indicated a presence of partially "neutral" zones, the PET results for May 28th and June 2nd show the entire Plaza categorised as "warm" to "very hot." This finding highlights the influence of local factors beyond general meteorological data. In contrast to Graph (4), which depicts the overall PET for Helsinki and suggests that 'hot' temperatures only occur on a few days in August, the PET analysis of the Plaza reveals a significantly different microclimate. In early summer (May 28th and June 2nd), the entire Plaza and most of the surrounding area experience "very hot" conditions, indicating a significant risk of heat stress. This finding highlights the importance of considering local factors beyond general meteorological data when assessing thermal comfort in urban spaces.

Significantly, "warm" zones are concentrated near buildings and shaded areas, offering some relief from the intense heat. Notably, only the trees on the northern lawns provide a slight respite, creating localised zones of "slightly warm" conditions.

Furthermore, the PET analysis reveals a consistent pattern across both May 28th and June 2nd. The entire Plaza experiences "very hot" conditions (ranging from 41°C to 46°C) at both 12:00 and 14:00. This observation highlights the need for potential mitigation strategies to address thermal discomfort within the Plaza during the early summer months.

Informed by the findings of the PET analysis, the next Section delves into the dominant patterns of human behaviour observed within the Plaza. This analysis will be further explored to identify potential correlations between these behaviour patterns and the microclimatic conditions revealed by the PET data.

4.2. User flow pattern analysis in Oodi Plaza

This section explores user patterns within the Plaza, focusing on dominant flow patterns observed during midday (12:00 PM - 14:00 PM). Video recordings from six non-consecutive days were analysed using YOLOv8, a Python object detection algorithm, to identify pedestrian movement. These days were spread across two sessions: winter (February 18th, March 10th, March 11th) and early summer (May 26th, May 28th, June 2nd). Each session included observations on a weekday, weekend day, and event day. Dominant flow paths were then manually depicted. Subsequently, heatmaps representing these dominant flow patterns were generated using the PedSIM plugin for Grasshopper. The analysis emphasises recurring patterns, excluding sporadic or infrequent movements.

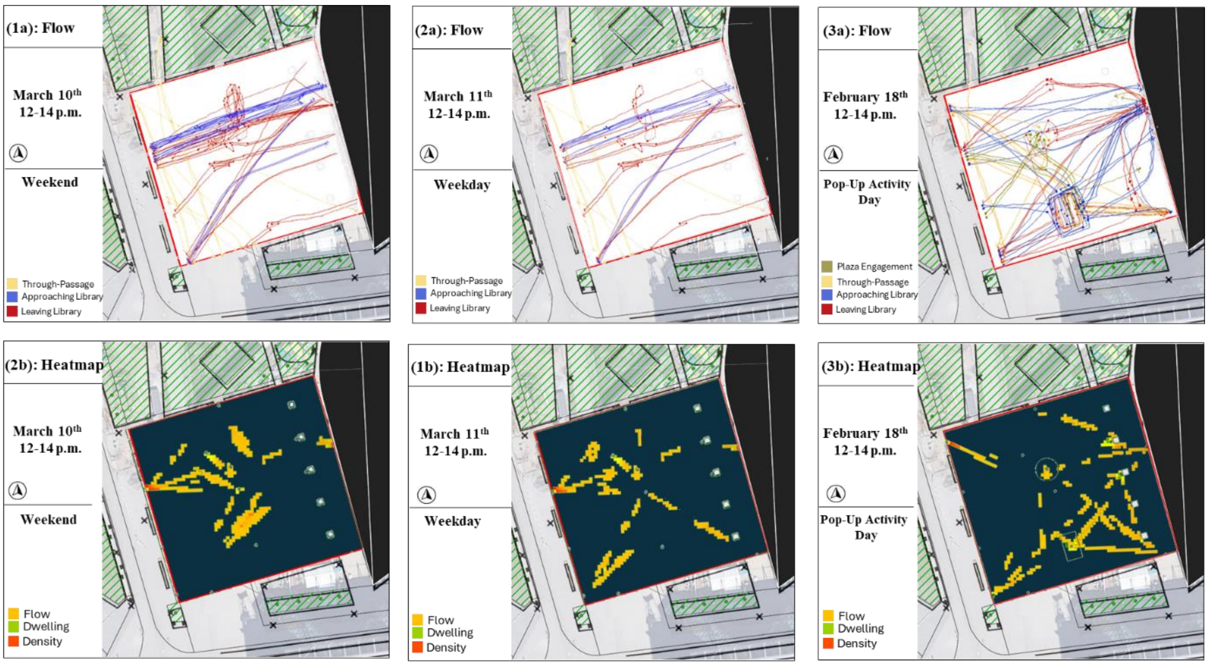
4.2.1. Dominant user flow patterns on February 18th, March 10th and March 11th

The analysis of pedestrian flow (Table 10) in the Plaza revealed three main categories observed on both March 10th (Sunday) and March 11th (Monday):

- *Approaching Oodi library*: This flow concentrated on accessing the library.
- *Leaving Oodi library*: This flow involved exiting the library and dispersing within the Plaza.
- *Through-passage*: This category consisted of pedestrians using the Plaza as a shortcut, primarily travelling diagonally from northwest to southeast.

While the flow patterns remained similar on both days, a key difference emerged in the density of pedestrian movement. On Sunday lunchtime (midday), approaching and leaving the library exhibited significantly higher density than on Monday. The library entrance situation significantly influenced these two dominant flows. Despite the library's west-side architecture featuring additional doors (facing the east side of the Plaza), only one entrance remained open to the public. This resulted in a concentration of library traffic in the northern part of the Plaza.

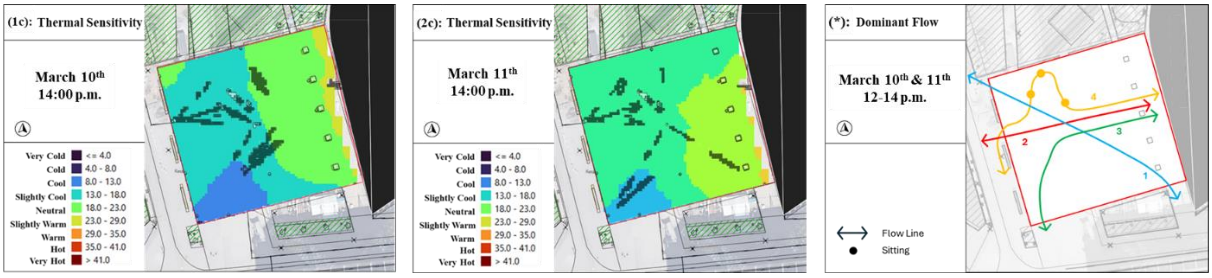
Table 10.Dominant Pedestrian Flow Patterns (a) and Simulated Movement Heat Maps (b) at Midday (12:00-14:00) for March 10th(1), March 11th(2) and February 18th(3) (Own elaboration, 2024)



Interestingly, behavioural differences were observed between those entering and leaving the library. People leaving the library tended to linger in the Plaza for short periods, engaging in activities like taking photos with the HELSINKI sign, photographing the library itself, socialising briefly with friends, or simply enjoying the sunshine in the north and northwest zones. These zones receive the most direct sunlight during winter, suggesting that people might be drawn to these areas for warmth before continuing their journey. In contrast, the southern portion of the Plaza, partially covered by a thin layer of snow and shaded by buildings, displayed less pedestrian traffic due to the slippery conditions.

The analysis identified two primary Plaza entrances and exits. The first is located directly in front of the library entrance, while the second is situated on the southern side, connecting to streets leading to the city's collector and access roads for the south terminal (train and bus station).

Table 11.Dominant Pedestrian Flow Patterns of the March 10th & 11th and Simulated PET (*) at Midday (12:00-14:00) (Own elaboration, 2024)



An analysis of the microclimate within the Plaza during midday on March 10th and 11th, as detailed in Table (11) and informed by the PET maps presented in Section 4.1.2, revealed a gradient in thermal comfort zones. These zones ranged from cold in the southwest corner to slightly cold in the central Plaza area, transitioning to comfort and neutrality in the eastern section with a small zone of slightly warm conditions adjacent to the library.

Notably, comparing these thermal comfort zones with the observed dominant user flow patterns (*) does not suggest a direct correlation. The dominant flows include:

- Straight path to the library entrance (flow 2).
- Diagonal path to/from the southern exit (flow 1 & 3).
- Limited engagement patterns in the northern portion of the Plaza (flow 4)

While the northern area falls within the slightly cold zone, user behaviour in this area suggests that factors beyond thermal comfort may be more influential. The observations suggest that engaging activities and access to sunlight might be more significant drivers of user behaviour than the slight variations in thermal comfort across the Plaza.

However, the flow patterns differed significantly on February 18th, which was a pop-up activity day (Figure 23). An additional flow category emerged:

- *Plaza-engagement*: This flow consisted of pedestrians not approaching or leaving the library or using the Plaza as a shortcut. Instead, they actively engaged with the Plaza due to the pop-up activity.

Figure 23. Oodi Plaza February 18th Pop_Up Activity Day

On February 18th, a snow pile dominated the northern part of the Plaza, while banner stands and stalls were set up near the Helsinki memorial of Alexei Navalny, a key figure in Russian opposition politics. The Plaza-engagement flow included people who:

- Read the banners near the memorial.
- Brought flowers or candles to the memorial (located in the south).
- Engaged with the snow pile in the north (mostly parents and children, with some adults): Activities included climbing, playing, and sliding on the snow.

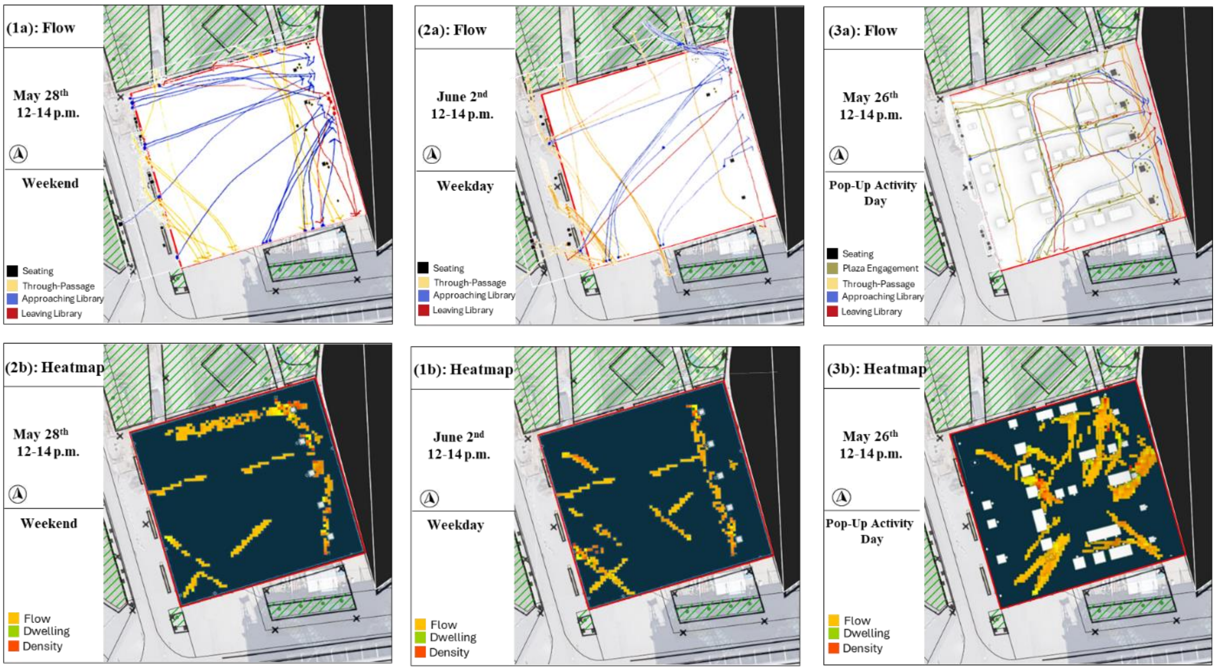
Even the through-passage behaviour changed on this day. Many pedestrians who would normally just pass through the Plaza stopped to engage with the memorial before leaving. Notably, some people took photos in the northern part of the Plaza, similar to the March observations.

This observation underscores how a minor intervention, like a pop-up activity, can substantially reshape people's movement patterns within the Plaza, independent of microclimatic factors.

4.2.2. Dominant user flow patterns on May 26th, May 28th, June 2nd

The analysis of pedestrian flow patterns observed on both May 28th (Tuesday) and June 2nd (Sunday) in the Plaza, as detailed in Table (12), revealed a continuity with the three main categories observed in March: *approaching Oodi Library*, *leaving Oodi Library*, and *through-passage*. However, early summer presents additional factors influencing user behaviour.

Table 12.Dominant Pedestrian Flow Patterns (a) and Simulated Movement Heat Maps (b) at Midday (12:00-14:00) for May 28th(1), June 2nd (2) and May 26th(3) (Own elaboration, 2024)



Early summer presents a significant difference in user flow patterns compared to winter. This is primarily due to the melting snow on the northern lawns and playground, creating an additional approach route to the library from the north side. This flow pattern is consistent across weekends and weekdays, with only a higher density observed on weekends.

There are two possible explanations for this new flow pattern:

- Shortcut to South Exit: Users might utilise this approach to access the south exit of the Plaza more directly.
- Building Terrace Shade: Alternatively, users may prefer this route to take advantage of the shade provided by the library's east-side terrace.

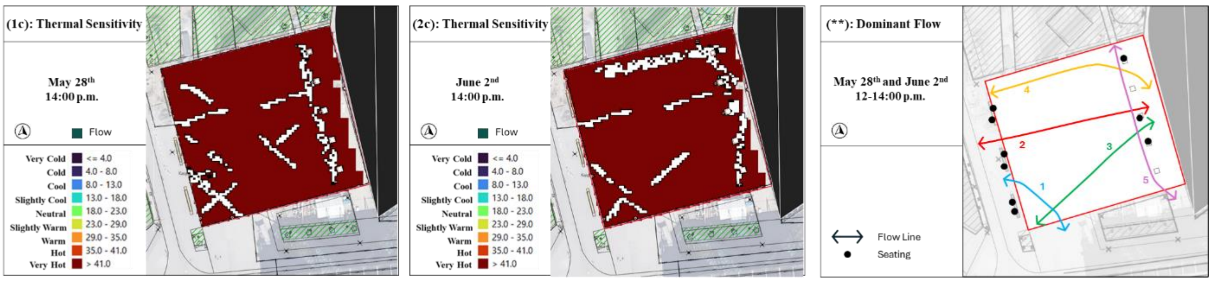
Another key observation in early summer is the emergence of a dominant flow pattern associated with approaching or leaving the library next to the northern lawns and playground area on weekends. The melted snow has created a direct walking path from the north side to the library. This clearly indicates a significant increase in activity within that space during weekends.

Furthermore, the southwest corner of the Plaza reveals another shortcut behaviour. Pedestrians and cyclists utilising the south and west side walking/cycling path appear to use this corner as a direct route to the southern exit of the Plaza exit. This suggests that the west side pathway becomes a more active flow line during summer, potentially drawing users away from the previous diagonal path.

The previously observed direct flow to the library entrance and the diagonal flow pattern persist in early summer but with a lower density. This decline could be attributed to increased sun exposure and heat stress within the main Plaza space. Consequently, users might choose shorter shortcuts along the edges or corners of the Plaza to avoid the central area.

The Plaza offered limited seating options throughout the year, primarily located in front of the library and on the west side. However, factors like cold temperatures and snow cover in winter likely discouraged people from utilising the seating elements as frequently as they did in early summer's warmer and more inviting conditions.

Table 13.Dominant Pedestrian Flow Patterns of the May 28^{th} &June 2^{nd} and Simulated PET (**) at Midday (12:00-14:00) (Own elaboration, 2024)



As detailed in Table (13), an analysis of PET values reveals the entire Plaza within the "very hot" zone during midday hours (12:00-14:00). This thermal discomfort, coupled with sun exposure, is likely a contributing factor to user behaviour patterns observed during this period.

User flows (**) during early summer demonstrate a tendency to avoid the central Plaza area. This is evidenced by:

- Pedestrians favouring the northern edges, likely seeking shade from the lawns (flow 4).
- Increased movement along the eastern side, potentially benefiting from shade cast by the library terrace (flow 5).
- A preference for shorter, more direct shortcuts across the Plaza (flow 1).

In contrast, flows 2 and 3, representing direct movement towards the library entrance and the main Plaza entrance, remain consistent with patterns observed in previous months.

On May 26^{th}, the Plaza hosted a food event with food stalls (Figure 24). Unlike the winter pop-up activity (focused on the Helsinki memorial), this event primarily drew people interested in purchasing and consuming food or snacks. This explains the observed increase in seating activity near the library and stalls, as people used the seating elements for these purposes.

Figure 24. Oodi Plaza May 26th Pop_Up Activity Day

Furthermore, similar to the winter event day, May 26th witnessed a heightened level of Plaza engagement. This refers to user behaviour that goes beyond simply approaching, leaving the library, or using the Plaza as a shortcut. In this case, "Plaza-engagement" likely involved activities like browsing food stalls, socialising with friends while enjoying food, or simply sitting and eating.

This observation aligns with the findings from the winter event day, highlighting how interventions like pop-up activities or food events can significantly influence user behaviour and encourage engagement within the Plaza space.

However, a crucial observation emerges from photographic evidence of event days. While Plaza engagement demonstrably increased, most seating activity involved commercially operated tables and chairs associated with the food stalls. This suggests a potential limitation in the availability of free public seating within the Plaza, particularly during events.

Despite the presence of the library as a public resource, the Plaza may not currently offer sufficient free seating areas for casual use during the summer months. This observation, alongside the existing library facilities, highlights a potential design consideration for the future. The Plaza design proposal should explore ways to strike a balance for providing enough free seating areas.

4.3. Dynamic Thermal Comfort (DTC) for Dominant Pedestrian Flows

Building upon the understanding of pedestrian behaviour and dominant movement patterns in the Plaza during late winter and early summer (as discussed in previous sections), this section delves into the Dynamic Thermal Comfort (DTC) experienced by pedestrians navigating the Plaza. Traditional thermal comfort models, such as the Universal Thermal Comfort Index (UTCI) and Physiological Equivalent Temperature (PET), are valuable tools for providing a baseline assessment of thermal comfort for stationary individuals. However, these models primarily focus on static conditions, neglecting the dynamic nature of walking. As pedestrians move through urban environments, they encounter variations in air velocity, temperature gradients, and radiative heat exchange. These factors, along with the physical exertion associated with walking, significantly impact thermal comfort compared to static positions.

To address this limitation, the ENVI-met Dynamic Thermal Comfort Model, specifically designed for pedestrians, is employed. A more comprehensive analysis is offered by this model through the incorporation of factors like changing skin temperature and body energy balance. Simulations of virtual walks within the Plaza are facilitated by the model, enabling the identification of areas requiring microclimate improvements or design adjustments. These insights can then be used to inform strategies for optimising the Plaza's design and microclimate, ultimately promoting thermal comfort for pedestrians throughout early summer and late winter.

To validate the effectiveness of proposed design adjustments on the Plaza's microclimate, this section presents the results of a Dynamic Thermal Comfort (DTC) analysis conducted for dominant pedestrian flows. The analysis focuses on two distinct days, both at 14:00, chosen due to the observed higher variations in Physiological Equivalent Temperature (PET) compared to midday (12:00):

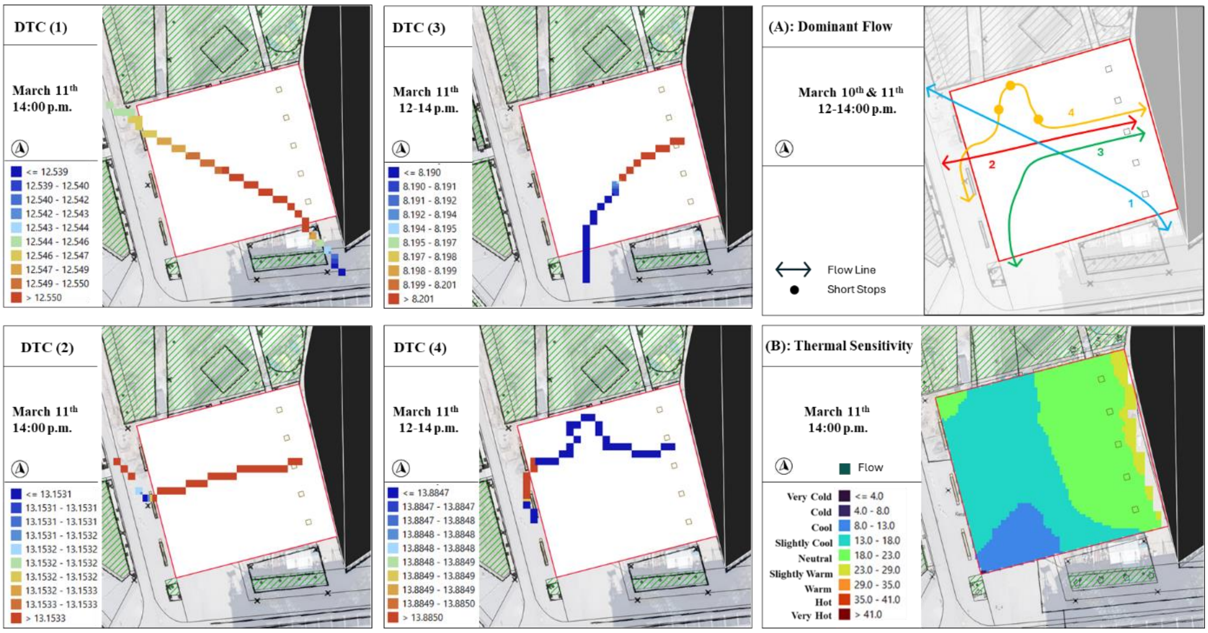
- *Late Winter*: March 11th was chosen as a representative day for late winter simulations.
- *Early Summer*: June 2nd was chosen as a representative day for early summer simulations.

4.3.1. DTC analysis for dominant pedestrian flows in late winter

This section presents the results of the Dynamic Thermal Comfort (DTC) analysis conducted for dominant pedestrian flows within the Plaza during late winter (March 11th). The analysis is based on the observed movement patterns depicted in Table (14) (flows 1 to 4).

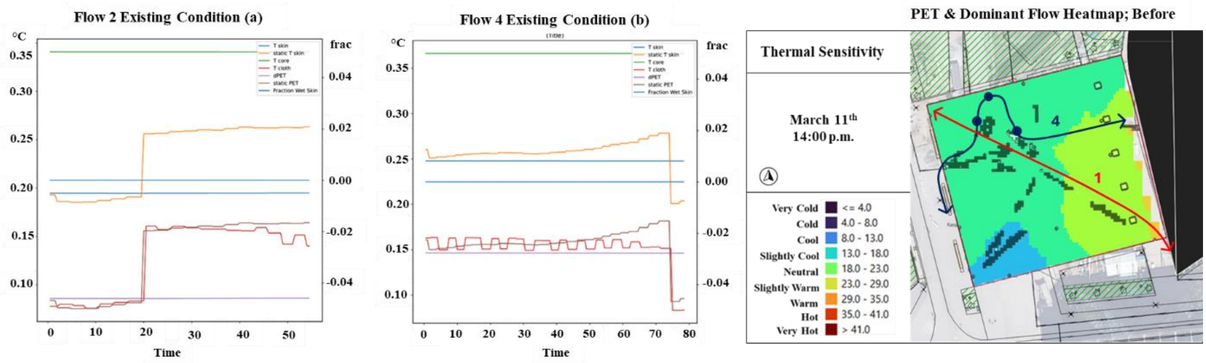
The simulations employed a virtual pedestrian characterised as a 35-year-old male wearing average clothing, with initial microclimate conditions set to represent the average for the area during late winter. The initial condition for thermal comfort involved iterating the energy balance until a static skin temperature was reached, representing a stationary state before the virtual walk commenced.

Table 14.DTC analysis for dominant pedestrian flows in late winter (March 11th ;14:00)



A consistent pattern emerged across all four dominant flow paths: DTC values increased slightly as pedestrians approached the library (maximum change 0.1°C). This aligns with the previously presented results showing higher PET values in the zone near the library (increased static PET). Interestingly, the analysis also revealed an increase in static T-skin of approximately 7°C (Graph 13(a)). While both static PET and T-skin suggest the potential for increased thermal comfort, the observed change in DTC remained minimal across all flows.

Flow path 4 (Table 14) began within the library, simulating an indoor starting point. Stop points in sunlight zones along the walking paths were also considered, reflecting real-world pedestrian behaviour observed in Table 14 (A). While exposure to sunlight elevated DTC, the observed changes were minimal across all flows, with a maximum increase of only 0.001°C. This suggests that despite transitioning from "comfortable" PET zones (around 18-19°C) to areas with potentially cooler PET values due to sun exposure, the overall change in dynamic thermal comfort (DTC) remained with minimal increase during the short walk simulation.



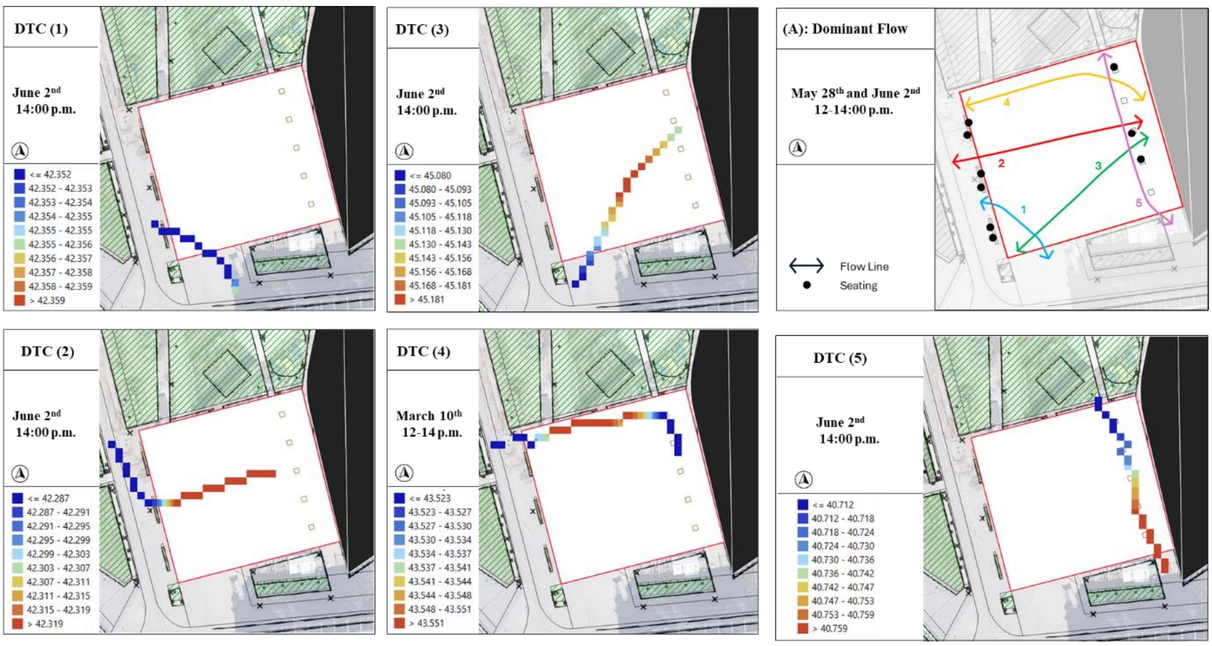
Graph 13. Comparison of Static T-skin, Static PET, and Dynamic PET (dPET) for Walking Paths: Flow 2 (to Library) and Flow 4 (from Library with Sunlight Stop)

Interestingly, despite PET zones indicating a potential for a cooler environment, the dynamic thermal comfort analysis revealed a decrease in DTC to the slightly cold range (13-14°C) during the short Plaza walk (Graph 13(b)). This discrepancy might be attributed to the limited duration of the simulated walk compared to how long people typically remain outdoors in cold weather. Static PET analysis may not fully capture the dynamic nature of thermal comfort experienced during walking.

4.3.2. DTC analysis for dominant flows in early summer

This section presents the results of the Dynamic Thermal Comfort (DTC) analysis conducted for dominant pedestrian flows within the Plaza during early summer (June 2nd). The analysis is based on the observed movement patterns depicted in Table (15) (flows 1 to 5).

Table 15.DTC analysis for dominant pedestrian flows in early summer (June 2nd ;14:00)

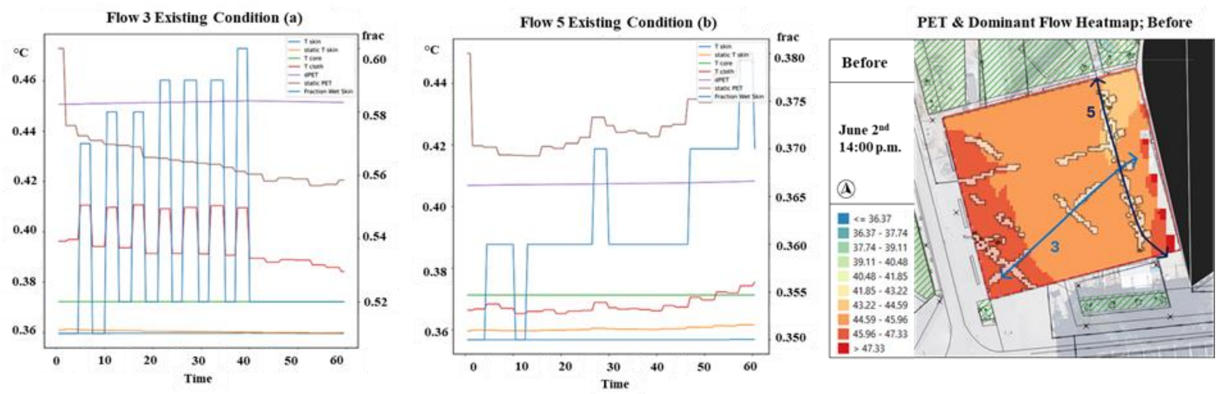


Building upon the methodology established for the late winter analysis (Section 4.3.1), the early summer simulations employed an identical virtual pedestrian model. This model represents a 35-year-old male wearing average clothing, and initial microclimate conditions were set to reflect the average for the area during early summer. As with the late winter analysis, the initial thermal comfort condition involved iterating the energy balance until a static skin temperature was reached, signifying a stationary state before the virtual walk commenced.

The previous chapter confirmed widespread heat stress and discomfort across the Plaza in summer. This section analyses dominant flow paths during summer and reveals a consistent pattern: DTC values increase as pedestrians traverse the Plaza. While this confirms the overall discomfort, the observed variations in DTC across different paths suggest potential spatial variability in thermal discomfort.

Flow 3 (Through Plaza): Compared to the starting point on the lawn, pedestrians traversing the Plaza in early summer exhibited a further increase in DTC (maximum: 0.1°C). This rise in discomfort stems from continued exposure to the Plaza's microclimate, characterised by higher temperatures and potentially stronger solar radiation compared to the late winter conditions. Although there is a decrease in PET and static T-skin, the DTC slightly increases (Graph 14 (a)).

Flow 5 (From Lawn): Pedestrians initiating their walk on the lawn area experienced a slight increase in DTC values as they entered the Plaza (maximum change: 0.04°C). This rise is likely attributed to the combined effects of higher ambient temperatures and potentially increased solar radiation exposure compared to the lawn environment (Graph 14 (b)).



Graph 14. Comparison of Static T-skin, Static PET, and Dynamic PET (dPET) for Walking Paths: Flow 3 (to Library) and Flow 5 (from Lawn)

CHAPTER 5: Discussion

5.1.Late Winter and Early Summer Microclimate and Pedestrian Flow

5.1.1. Microclimate and Static Thermal Comfort

The microclimate analysis revealed distinct seasonal variations in Physiological Equivalent Temperature (PET) within the Plaza. While the Plaza experiences cold discomfort during winter, comfort zones can still be found, as evidenced by data collected on specific dates like March 10th and 11th. This finding suggests that even within a cold season, microclimate variations can create pockets of relative warmth, often influenced by factors like solar access or wind protection from surrounding buildings. However, a significant contrast emerged in early summer, with the Plaza feeling substantially hotter compared to late winter. Notably, the Plaza exhibited "very hot" PET conditions throughout most of the day on May 28th and June 2nd, exceeding the overall PET trend for Helsinki, which indicated minimal heat stress in August (Section 4.1.1).

These findings highlight the critical need for strategies to enhance comfort within the Plaza during the early summer months. This also underscores the significant role that urban form plays in shaping the microclimate. In winter, the snow cover itself, along with the material properties and heat transfer characteristics of buildings, can influence thermal comfort. For example, areas with more sunlight or wind protection from buildings create pockets of relative warmth. However, these same factors can have negative consequences in summer. The lack of shade, vegetation, and water features contributes to the "very hot" PET values recorded during early summer. This showcases the changing nature of microclimate in winter cities and emphasises the need for flexible urban design strategies that incorporate temporary interventions suited for different seasons.

5.1.2. Pedestrian Flow Patterns: Beyond Microclimate

The analysis of pedestrian flow patterns revealed that microclimate is not the sole determinant of pedestrian behaviour within the Plaza. Other intentions, such as taking photographs, navigating towards specific locations (e.g., library), or utilising shortcuts, appeared to be prioritised over slight variations in PET, especially during periods of extreme discomfort. This finding aligns with Gehl's assertion (Section 2.2) that "*It doesn't matter the temperature when the sun is shining, and the wind is tame, it is a good day in Nordic countries*", as evidenced by shortstop durations for photography or staying for a while in sunlight zones observed during winter. Conversely, areas characterised by cold discomfort, shade, and slippery snow cover were generally avoided by pedestrians.

In contrast to winter, summer presented a scenario where the entire Plaza experienced heat stress and discomfort. Consequently, short or long stops were rarely observed, and a prominent tendency emerged towards utilising the most direct shortcuts. Notably, the melted snow from winter formed a preferred walking path from the north side to the library, likely serving a dual purpose: acting as a shortcut and offering shade from the library's west-facing terrace. This phenomenon further highlights the influence of temporary conditions. As winter snow melted, the Plaza's previously underutilised west-side path became a popular route for pedestrians and cyclists. This trend is further amplified by the recent opening of the new Kaisatunneli route on May 4^{th}, 2024, which provides a direct cycling and walking connection between Kaisaniemi Park and the Kansalaistori Square's southern edge (Figure 25). This increased connectivity is likely to further encourage the use of the Plaza's southwest corner as a shortcut.

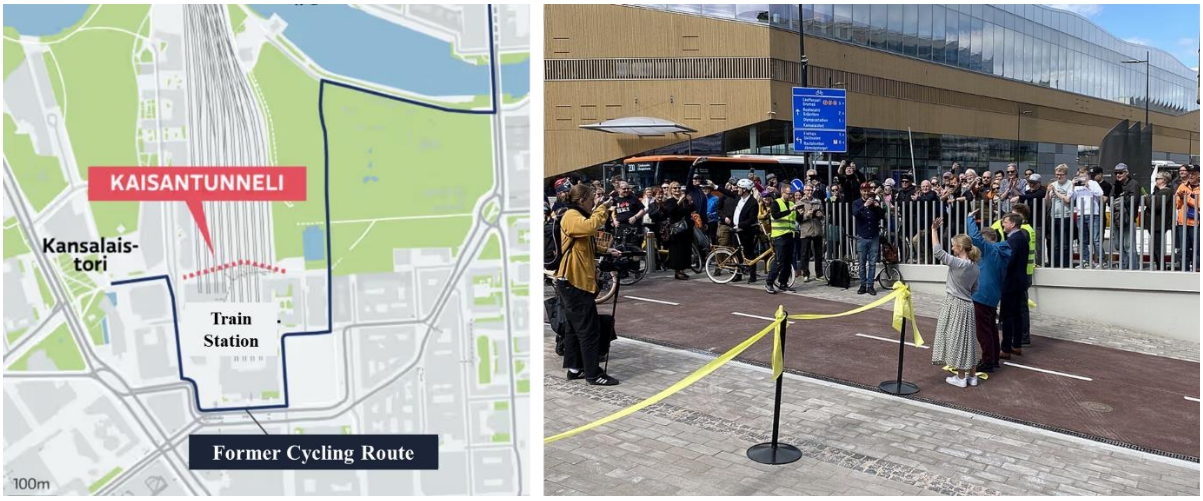


Figure 25. Kansalaistunneli walking and cycling route opened on May 4^{th},2024 (MyHelsinki, 2024)

This finding highlights the seasonal variation in pedestrian flow patterns and prioritisation of thermal comfort during extreme heat. This suggests the potential for temporary design elements that respond to seasonal variations and encourage pedestrian movement throughout the Plaza.

Interestingly, the analysis of event days in both winter (February 18^{th}) and summer (May 26^{th}) demonstrated that thermal conditions become secondary factors when engaging activities occur within the Plaza. Regardless of the season, people prioritised participation in events over thermal comfort. This suggests that incorporating engaging features (furniture, elements, and events) can potentially increase the likelihood of spending time outdoors, which is crucial for physical and mental well-being, particularly during the challenging winter months in Winter Cities.

Microclimate influences pedestrian flow patterns, but other factors hold greater sway. These include pedestrian intentions, destinations, engagement with the Plaza, and the specific activities taking place. Slight variations in Plaza thermal comfort appear less significant in these circumstances.

5.1.3. Dynamic Thermal Comfort and Pedestrian Flow

Static PET analysis provides valuable insights into thermal comfort; however, it may not fully capture the dynamic nature of thermal experience, particularly during walking. While static PET values within the Plaza displayed seasonal variations, the Dynamic Thermal Comfort (DTC) analysis revealed a more nuanced picture.

- *Seasonal Variations and Baseline DTC*: The DTC analysis revealed distinct seasonal patterns. Early summer exhibited significantly higher starting DTC values than late winter due to warmer seasonal temperatures. This suggests pedestrians were already experiencing thermal strain before entering the Plaza, potentially increasing their susceptibility to discomfort within the space.

- *DTC Patterns Along Flow Paths*: Both winter and summer analyses revealed a consistent pattern; DTC values increased as pedestrians traversed the Plaza. However, the observed rise in DTC was considerably more pronounced during early summer compared to late winter. This indicates a more substantial rise in discomfort throughout the walking experience in the warmer season.
- *Limitations of Static Thermal Comfort Models*: A critical discrepancy emerged between static PET and dynamic thermal comfort data. While late winter PET values indicated comfort zones within the Plaza, the DTC data revealed a colder experience for pedestrians traversing the area, with sensations ranging from "cold" to "slightly cold". Similarly, during summer, users entering the Plaza from adjacent lawns initially recorded a cooler sensation (around 40°C) compared to the measured PET values of 41-44°C in those zones.

These observations highlight the limitations of static thermal comfort indices like PET in capturing pedestrians' dynamic experiences. Walking introduces variable factors that static measurements miss, such as fluctuating air speeds, temperature gradients, and changing exposure to radiant heat sources. These factors significantly influence thermal comfort, and current indices struggle to account for them effectively. Additionally, the physical exertion inherent to walking further impacts a person's thermal comfort compared to someone standing still. This emphasises the need to consider dynamic thermal comfort alongside static PET measurements when evaluating pedestrian comfort in urban spaces. This approach can provide a more nuanced understanding of how seasonal variations and dynamic factors shape pedestrian experience, ultimately informing the design of thermally comfortable and inviting public spaces throughout the year.

The following section delves into potential design strategies for mitigating discomfort and enhancing pedestrian thermal comfort during different seasons. It proposes a series of targeted interventions, such as the implementation of shade structures or water features, and outlines a plan for conducting a second round of simulations to evaluate their effectiveness in creating a more thermally comfortable environment within the Plaza.

5.2. Proposals and Validation

As highlighted in the literature review (Section 2.2.1), while enclosed and heated spaces are crucial in winter cities, creating vibrant outdoor public spaces that encourage year-round use is equally important. This section proposes design strategies for Oodi Plaza, informed by the research objectives to evaluate climate-sensitive design strategies, analyse seasonal effects on user behaviour, and propose interventions to encourage outdoor use throughout the year.

5.2.1. Seasonal Challenges and Opportunities in the Plaza

Each season presents unique challenges and opportunities for a Winter City:

- *Winter*: Cold weather, heavy snowfall, and slippery surfaces create challenges. However, leveraging snow's high albedo offers an opportunity for visual appeal.
- *Summer*: Urban geometry and materials can cause heat stress and discomfort, negatively impacting user health and enjoyment. However, long daylight hours offer potential for outdoor activities if appropriate cooling mechanisms are provided.
- *Transitional Months*: November (dark and rainy) and March (overcast and snowmelt) offer fewer opportunities for outdoor activities due to reduced daylight and potential discomfort.

Several key points emerge from observations at Oodi Plaza:

- **Plaza Design**: The current design prioritises event flexibility but lacks dedicated seating areas for everyday use (Figure 26). This discourages people from lingering during non-event times.

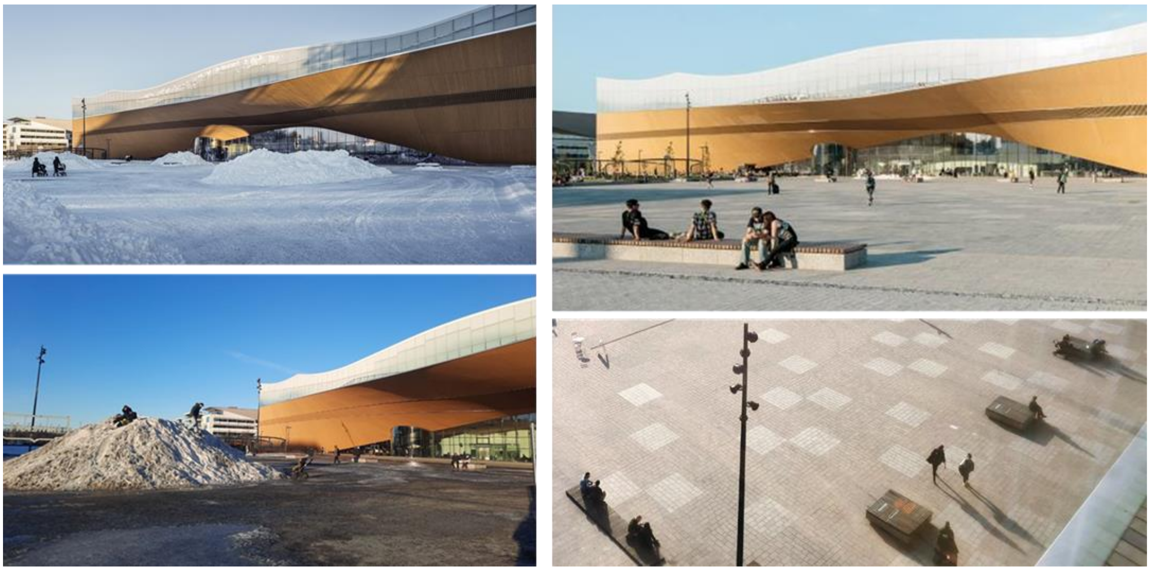


Figure 26. Impact of Plaza Design on Seasonal Use: Few users engage with the plaza on regular winter days, but sunlight encourages the use of elements like snow piles (left, February). Limited seating necessitates short stays in summer, with users drawn back to sunlight due to the lack of shade (right, June).

- **Microclimate**: In winter, comfort zones exist, with sunlight being the most critical factor for attracting users (Figure 27). The plaza experiences discomfort in summer, leading to quick pass-throughs rather than extended use.

Figure 27. Seasonal User Behavior in Oodi Plaza: Sunlight attracts users in winter (left, February)—fewer users in the plaza during overcast transitional months (right, late March).

- **Pop-up Activities**: Temporary installations significantly increase user engagement and time spent in the plaza, regardless of the season (Figure 28).

Figure 28. Temporary Installations and User Engagement: Temporary installations (stands and banners in February, left; food stalls in May, right) attract and engage users, influencing their behaviour patterns regardless of the season.

Key observations from Oodi Plaza include the preference for winter sunlight, summer discomfort due to heat, and increased engagement during pop-up activities regardless of season.

5.2.2. Design Proposals for Year-Round User Comfort

The following sections will explore each design strategy in detail, examining their potential contribution to a year-round engaging Oodi Plaza. These proposed design strategies aim to transform the Plaza into a vibrant and user-friendly space throughout the year. The Plaza can be optimised for year-round outdoor engagement in urban settings by addressing seasonal challenges like harsh winters and hot summers. Innovative solutions include incorporating modular seating, green spaces, interactive water features, and adaptable visual displays. Design concepts were visualised using a combination of hand-drawn sketches and digital illustration tools, with some elements benefiting from the design contributions of visualisation software AI tools. The proposal design strategies are in 3 categories of winter, summer and transitional months. Three categories of strategies will be explored: those designed for winter, summer, and transitional months.

5.2.2.1.Winter Strategies for the Plaza:

- Harnessing Snow's Potential: Spruce or oak wood structures, reflecting the library's facade and Finland forest context, can be implemented to create:
  -Wind shelters (especially from the west side of the Plaza)
  - Interactive elements for children, such as sliding structures
- Addressing the "White Out" Effect: Employing strategically placed mirrors will add a sense of mystery and artistic appeal, encouraging exploration, photography, and user attraction.

These winter interventions will provide the following:

- *Shelter and Warmth*: Wind protection and seating with potential heat sources will enhance comfort in cold weather.
- *Interactive Play Elements*: Children's play structures will encourage family visits and extended stays.
- *Visual Interest*: Mirrors will add a unique visual experience and encourage visitors to linger and capture photos.

A broader range of winter intervention strategies can be explored to further enhance the plaza's usability and user experience during the winter season. Table (16) outlines these strategies, and Table (17) presents the proposed design solutions for winter in Oodi Plaza.

Table 16. Additional Winter Intervention Strategies for the Plaza (Own elaboration)

Strategy Category	Design Strategies	Description
Weather Protection	Covered and Heated Shelters	Install covered shelters with integrated heating to provide warm, comfortable spaces protected from snow and wind.
	Windbreaks	Use trees, shrubs, and specially designed structures to block wind and create more sheltered areas.
Lighting	Bright and Warm Lighting	Install bright, warm lighting to improve visibility and create a cozy atmosphere during dark winter days.
	Pathway Lighting	Use ground-level lighting along pathways to ensure safety and enhance the aesthetic appeal of the snow-covered landscape.
Comfort and Warmth	Heated Seating	Include benches and seating areas with built-in heating elements to keep users warm.
	Fire Pits and Outdoor Heaters	Set up fire pits or outdoor heaters in gathering areas to provide warmth and a focal point for social interaction.
Active and Engaging Spaces	Snow Play Areas	Designate areas for snow play, such as snowman building zones or snowball fight areas, to engage children and families.
	Winter Sports Facilities	Create spaces for ice skating, sledding, or cross-country skiing to encourage physical activity.
Seasonal Adaptations	Temporary Installations	Install temporary winter-themed art installations or sculptures to attract visitors.
	Seasonal Landscaping	Use winter-hardy plants and decorations to enhance the visual appeal of the plaza.
Water Management	Efficient Snow Removal	Design efficient snow removal and management systems to keep pathways clear and accessible.
	Snow Storage Areas	Designate areas for snow storage that can also serve as playful mounds or sculptural elements in the plaza.
Technology Integration	Interactive Displays	Set up interactive digital displays with information about weather, events, and activities to engage visitors.
	Wi-Fi and Connectivity	Provide robust Wi-Fi coverage to enable people to stay connected and use digital services while outdoors.
Community and Social Spaces	Enclosed Social Hubs	Create enclosed or semi-enclosed social hubs with heating and comfortable seating for group gatherings.
	Food and Beverage Stalls	Set up food and beverage stalls or pop-up cafes offering warm drinks and snacks to attract people to the plaza.

Table 17. Proposed Design Solutions for Winter in Oodi Plaza (Own elaboration)

Description	Justification	Expected Outcomes
❖ ***Dedicated Snow Event Space:*** Designate a specific area for snow-related activities, including snow sculptures, installations, and event platforms.	Fosters community, provides a focal point for winter activities, and attracts visitors.	- Increased foot traffic, unique winter atmosphere, community involvement, and potential partnerships.
		

Table 17 (continued). Proposed Design Solutions for Winter in Oodi Plaza (Own elaboration)

Description	Justification	Expected Outcomes
❖ ***Vertical Mirrors for Reflection and Engagement:*** Deploying vertical mirrors strategically between the library and parliament will - Reflect the snowy ambience - Enhance user interaction - Promote photo opportunities ❖ ***Symbolic Reflections of Finland's Forest:*** Utilise strategically placed mirrors to create a symbolic representation of a Finnish forest: - Reflective and angled surfaces: Create an illusion of multiplied images, evoking a dense forest - Abstract tree reflections: Subtle reference to the shapes and forms of trees.	Creates a visually appealing winter scene, encourages interaction with the plaza, and entices visitors to capture photos. Creates a symbolic connection to the Finnish landscape and adds visual interest.	- Increased user engagement with the plaza - Enhanced visual interest and aesthetics - More photography opportunities for visitors - Enhanced visual interest and aesthetics - Symbolic connection to Finland's natural environment



Description	Justification	Expected Outcomes
❖ ***Interactive Mirror Installations:*** Introduce a variety of mirror installations to add playful elements: - Small kiosks: Visitors can step inside for distorted reflections - Mirrored boxes: Offer unique photo opportunities with multiplied reflections.	Provides playful elements for user interaction and encourages exploration.	- Increased user engagement, especially for children and families. - More playful and interactive atmosphere. - Additional photo opportunities.


Table 17 (continued). Proposed Design Solutions for Winter in Oodi Plaza (Own elaboration)

Description	Justification	Expected Outcomes
❖ ***Wooden Play Structures with Glass Features*** Introduce wooden play structures featuring a transparent ceiling and partially glazed sides: - Skylight: Provides natural light and winter sky views. - Glass sides: Offers views while maintaining enclosure. - Play elements: Encourages children's winter activities. - Wind shelter: Protects from wind, especially from the west. - Material harmony: Spruce or oak wood complements the library facade.	Creates a multifunctional winter space for play and shelter. Provides natural light and a connection to the outdoors. Protects users from wind, especially on the west side. Harmonises visually with the library façade material.	- Increased user engagement, especially for children and families. - Enhanced comfort and enjoyment of the winter plaza. - Symbolic connection to the natural environment through wood



Description	Justification	Expected Outcomes
❖ ***Digital Screen:*** Display short movies, animations, or city/library information for passive entertainment.	Provides a focal point for passive entertainment and information sharing.	- Increased user engagement with the plaza, especially during short breaks. - Provides opportunities for passive entertainment and information sharing.



Table 17 (continued). Proposed Design Solutions for Winter in Oodi Plaza (Own elaboration)

Description	Justification	Expected Outcomes
❖ ***Curved Winter Furniture and fireplaces:*** Curved shapes echo the library facade. - Suitable for children's play and sliding in winter. - Sheltered spaces within the structures offer protection from the elements. - Include small, integrated fireplaces for additional warmth and ambiance.	Offers comfortable seating options with play areas, protection from the elements, and additional warmth.	- Offers comfortable and sheltered seating for winter use. - Encourages children's play. - Creates a warm and inviting atmosphere.

5.2.2.2.Summer Strategies for the Plaza:

- Shade and Cooling: Implement a range of free, shaded seating areas throughout the plaza to provide respite from the sun's heat. Consider incorporating canopies, pergolas, and shade sails to create extensive shaded zones. Additionally, explore integrating water features such as misting nozzles or fountains to provide evaporative cooling and enhance comfort during hot summer days.
- Greenery and Aesthetics: Introduce strategically placed flower beds, shrubs, fully grown trees, and other drought-resistant plants throughout the plaza to create a visually appealing and refreshing environment. Vegetation provides shade and contributes to a more relaxed atmosphere.

These summer interventions aim to achieve the following:

- *Comfort and Cooling*: Shaded seating areas and water features will create a more comfortable microclimate, encouraging extended stays within the plaza during summer.
- *Aesthetics and Relaxation*: The introduction of vegetation will enhance the plaza's aesthetics and contribute to a more calming and inviting atmosphere.

A broader range of summer intervention strategies can be explored to further enhance the plaza's usability and user experience during the summer season (Table 18), and Table (19) presents the proposed design solutions for summer in Oodi Plaza.

Table 18. Additional Summer Intervention Strategies for the Plaza (Own elaboration)

Strategy Category	Design Strategies	Description
Shade and Shelter	Canopies and Shade Structures	Install large canopies, pergolas, and shade sails to provide extensive shaded areas and reduce direct sun exposure.
Cooling Elements	Water Features	Incorporate fountains, misting systems, and splash pads to provide cooling through evaporative processes.
	Reflective Surfaces	Use reflective or light-colored materials for urban furnitures to reduce heat absorption.
Vegetation and Landscaping	Trees and Plantings	Plant deciduous trees and shrubs to create natural shade and cool the air through transpiration.
Seating and Comfort	Cool Seating Areas	Install seating made from materials that stay cool or include integrated cooling elements, such as air circulation systems.
	Movable Umbrellas	Provide movable umbrellas that can be adjusted to offer shade as the sun's position changes.
Technology Integration	Smart Cooling Systems	Implement smart cooling systems that activate misting or fans based on real-time temperature and humidity data.
	Interactive Digital Displays	Use digital displays to provide information on heat stress, hydration stations, and cooling areas within the plaza.
Activities and Engagement	Seasonal Events	Organize summer events that encourage evening activities when temperatures are cooler, such as night markets or concerts.
	Water Play Areas	Set up areas specifically designed for water play to attract families and provide cooling activities.
Community and Social Spaces	Pop-up Cafes and Kiosks	Install pop-up cafes and kiosks with free shaded seating areas to encourage social interaction and provide refreshments.
	Enclosed Cool Zones	Create enclosed cool zones with air conditioning or evaporative cooling systems for people to escape the heat.

Table 19. Proposed Design Solutions for Summer in Oodi Plaza (Own elaboration)

Description	Justification	Expected Outcomes
❖ ***Modular Wooden Cubes with Plant and Water Features:*** Introduce modular wooden cubes for a multifunctional summer space: - Thermal Comfort: Wood's low thermal conductivity helps regulate heat, providing a cooler surface for seating. - Modular Design: Easy assembly and disassembly allow for flexible configuration of the space. - Integrated Features: - *Plants and water features*: Enhance aesthetics and create a refreshing microclimate. - *Water nozzles*: Offer playful water activities for children. - *Vegetation and flower boxes*: Incorporate greenery and add visual interest. - *Seating and Shade*: Provide comfortable seating areas with shade from the sun.	Creates a comfortable and visually appealing summer space. Offers opportunities for children's play and interaction with nature. Provides shade and a refreshing microclimate during hot weather.	- Increased user engagement with the plaza during the summer months. - Enhanced aesthetics and connection to nature. - Improved thermal comfort for users.

5.2.2.3.Transitional Month Strategies for the Plaza:

- <u>Light and Well-being</u>: Introduce sheltered seating areas throughout the plaza to provide warmth and protection from unpredictable weather elements. Additionally, explore incorporating vitamin D therapy kiosks to address potential vitamin D deficiencies during these periods with shorter daylight hours.
- <u>Engaging the Senses</u>: Transitional months also present an opportunity to introduce playful and interactive elements. Implement dynamic lighting installations that respond to user movement or ambient conditions. These features can add a unique visual experience and encourage exploration during evenings with less sunlight.

These transitional interventions aim to achieve the following:

- *Comfort and User Well-being*: Sheltered seating areas and potential vitamin D therapy kiosks can address the challenges of reduced daylight and contribute to overall user well-being.
- *Engagement and Activation*: Interactive lighting installations will add a playful and engaging element to the plaza experience, particularly during evenings.

A broader range of intervention strategies can be explored to further enhance the plaza's usability and user experience during the transitional months (Table 20). Table (21) presents the proposed design solutions for the transitional months in Oodi Plaza.

Table 20. Additional Transitional Months Intervention Strategies for the Plaza (Own elaboration)

Strategy Category	Design Strategies	Description
Weather Protection	Canopies and Shelters	Install large canopies, pergolas, or transparent shelters to provide protection from rain and wind.
	Arcades and Covered Walkways	Design arcades or covered walkways around the perimeter to offer continuous protection from the elements.
Lighting	Enhanced Lighting	Utilize high-quality, warm lighting to create a welcoming atmosphere.
	Interactive Lighting	Incorporate interactive lighting installations that respond to movement or weather conditions.
Comfort and Warmth	Heated Elements	Include heated benches, tables, and surfaces to provide warmth and comfort.
Active and Engaging Spaces	Public Art and Installations	Install public art pieces and interactive installations to draw people into the space.
	Event Programming	Plan and promote events that encourage community participation, such as markets and performances.
Seasonal Adaptations	Flexible Furniture	Use movable and adaptable furniture that can be rearranged or stored as needed.
Water Management	Permeable Pavements	Use permeable paving materials to manage rainwater effectively and improve drainage.
Technology Integration	Smart Systems	Implement smart systems for lighting, heating, and information dissemination that activate based on real-time data.
	Wi-Fi and Connectivity	Ensure robust Wi-Fi coverage and digital connectivity to attract users year-round.
Community and Social Spaces	Enclosed Social Hubs	Create enclosed or semi-enclosed social hubs within the plaza for comfortable gathering and interaction.
	Food and Beverage Stalls	Include food and beverage stalls or pop-up cafes with outdoor seating areas equipped with heating and shelter.

Table 21. Proposed Design Solutions for Transitional Months in Oodi Plaza (Own elaboration)

Description	Justification	Expected Outcomes
❖ ***Illuminated Seating and Art Installations*** Introduce urban furniture and art installations that integrate lighting: - Warm yellow and white light focused on seating areas. - Lighting design balances the ambience on dark and overcast days.	Creates a welcoming and comfortable atmosphere during winter, especially on dark days.	- Increased user comfort and sense of safety during low-light periods. - Enhanced visual interest and nighttime aesthetics. - Extended usability of the plaza in the evenings.

5.2.3. Implementation and Location Considerations

Design elements should be strategically placed to maximise user comfort and interaction, considering seasonal variations and plaza functionality.

- *Winter*: Locating installations in the northwest zone, where sunlight offers comfort, to maximise user benefit (see Table 11).

- *Summer*: Distributing installations throughout the plaza, avoiding the central area to minimise disruption of shortcut routes (see Table 13).

- *Transitional Months*: Placement can be flexible, considering seasonal needs and potential interaction with other elements.

5.2.4. Proposal Validation

In the following section, a comprehensive evaluation process involving microclimate simulations and pedestrian flow predictions will be undertaken to ensure the effectiveness of the proposed seasonal design strategies for Oodi Plaza.

Simple modular pieces shaped like wooden cubes will be used to simulate the design objects (Figure 29). These cubes offer a practical solution due to their easy relocatability across seasons. In summer, they can serve as planters for flowers and shrubs, seating areas, and games. In winter, they can house fireplaces and shelters.

Figure 29. Modular wooden cubes for seasonal design simulation (Own elaboration)

The placement of these cubes will be strategic (Figure 30). In winter, they will be positioned in the northwest of the plaza to capitalise on the winter sun. In summer, they will be scattered throughout the plaza to provide a cooling effect in areas experiencing heat stress.

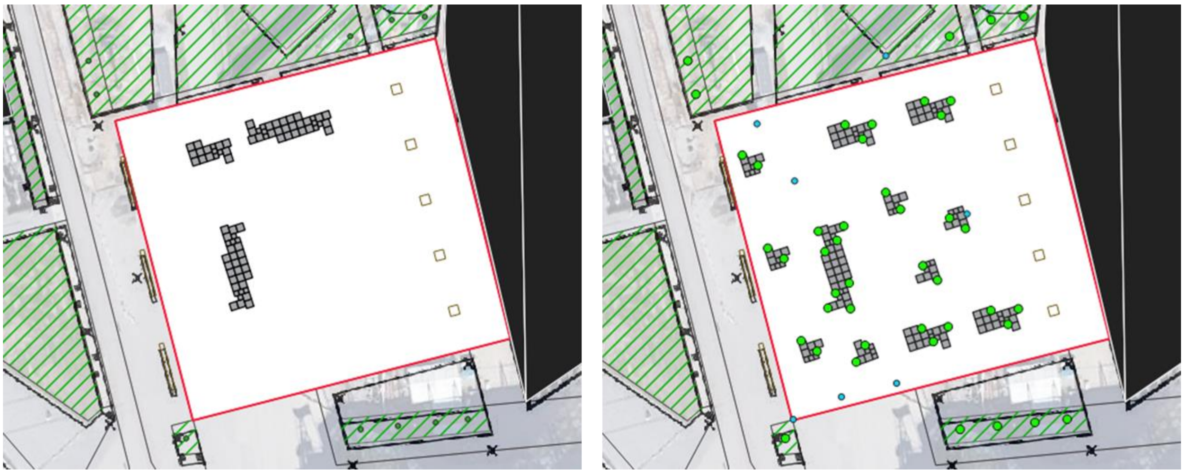


Figure 30. Winter (Left) and Summer (Right) Configurations of Modular Design Elements in Oodi Plaza

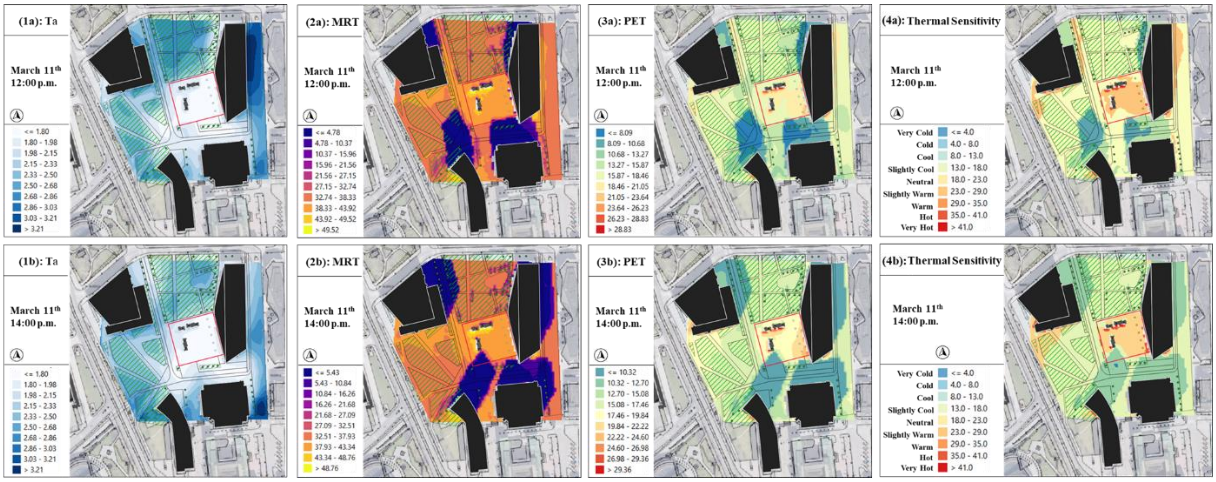
Successful implementations of similarly designed modular cubes in Helsinki validate the practicality of this approach (Figure 31). The concept emphasises modularity for easy assembly and portability, enabling seasonal adjustments, relocation for events, and reconfiguration of units. Key seasonal changes include incorporating vegetation in planters during summer and the option to open or close the sides of the cubes for temperature control.

Figure 31. Simulation design concept inspired by Helsinki Innovation Center's modular public furniture project

5.2.4.1. Proposal Simulations for Late Winter (March 11th)

A second round of microclimate simulations is conducted on two selected days: one in late winter (March 11th, Table 22) and one in early summer (June 2nd) at 12:00 and 14:00. The receptor points (Figure 10) in the existing condition and the proposed designs will be compared.

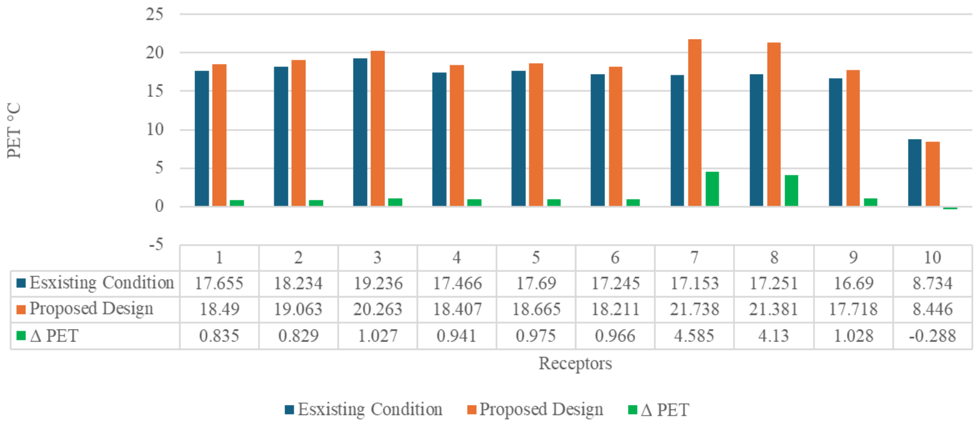
Table 22. Simulated T_{air} (1), MRT (2), PET (3c), and Thermal Sensitivity (4) of the proposed design on March 11th at 12:00 (a) and 14:00 (b) (Own elaboration)



Physiological Equivalent Temperature (PET) is a key measure of thermal comfort in outdoor environments. It considers both air temperature and radiant heat exchange to provide a comprehensive evaluation of human heat balance. This analysis compares PET values simulated for the existing condition and the proposed design across ten receptor points within Oodi Plaza on March 11th at 12:00 and 14:00. The existing condition on this date shows a PET range indicative of slightly cold to neutral conditions (around 13°C to 23°C).

The proposed design improves thermal comfort by creating pockets of mostly neutral or comfort zone conditions (around 18°C to 23°C) in the Plaza. Due to the design's influence, some areas might even experience warm or slightly warm spots next to the design elements (around 23°C to 29°C).

Graph (15) shows the differences in PET between the existing condition and the proposed design at ten designated locations within Oodi Plaza, as illustrated in Figure 10 (Section 3.3.3). The time period is 14:00, which typically experiences peak solar radiation and influences outdoor thermal comfort. The proposed design generally enhances the microclimate conditions in winter by increasing PET values, which suggests better thermal comfort for users in most areas of the plaza.



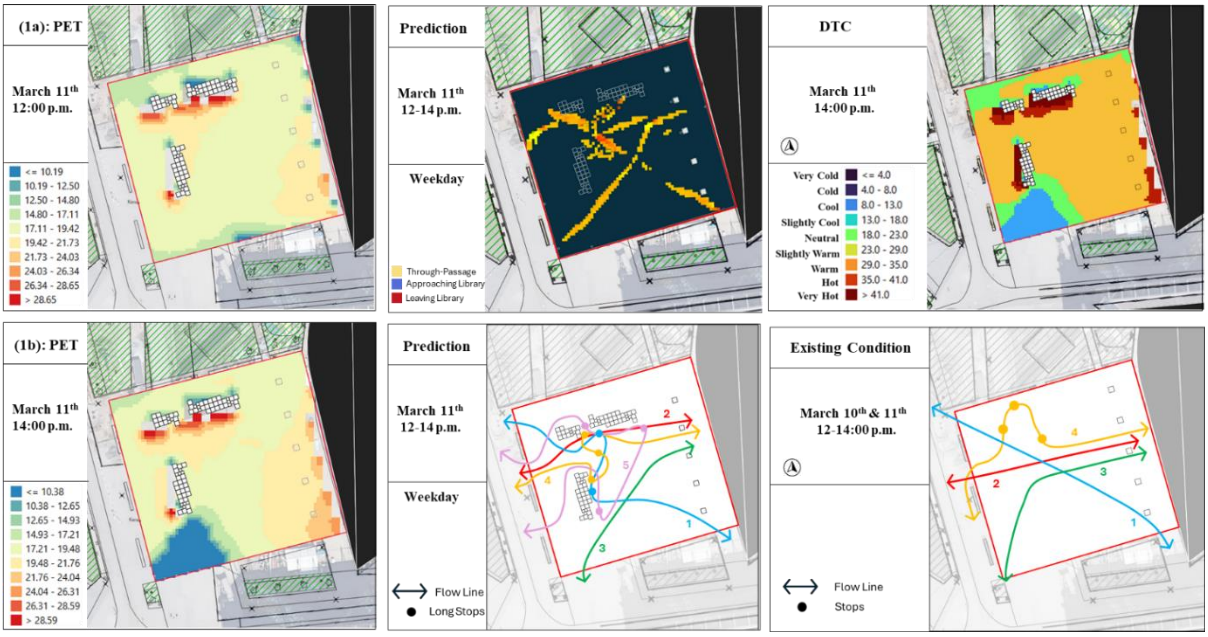
Graph 15. The difference in PET between the existing condition and the proposed design at each receptor point on March 11th at 14:00

The comparison of receptor points PET reveals a general trend of increased PET under the proposed design for most receptors. This indicates improved thermal comfort for users in these areas of the plaza. Notably, Receptors 7 and 8 show the most significant increases in PET (4.585°C and 4.13°C, respectively), suggesting a substantial positive impact of the proposed design in areas influenced by the design elements. Moderate increases in PET, ranging from 0.829°C to 1.028°C, are observed at Receptors 1 to 6 and 9. However, Receptor 10 exhibits an anomalous result with a slight decrease in PET (-0.288°C) compared to the existing condition in the cold zone. This could be due to factors such as shading or wind patterns in the cold zone of the plaza.

The design of successful public open spaces hinges on understanding how people will interact with the environment. Predicting human behaviour before design and construction remains a challenge, as a multitude of factors influence individuals' perceptions, emotions, and needs.

This analysis proposes to address this challenge by leveraging existing pedestrian flow patterns. By analysing observed behaviour under existing conditions, the probability of people interacting with objects and elements in the redesigned plaza was. Subsequently, the Dynamic Thermal Comfort (DTC) for the dominant pedestrian flows can be calculated (Table 23).

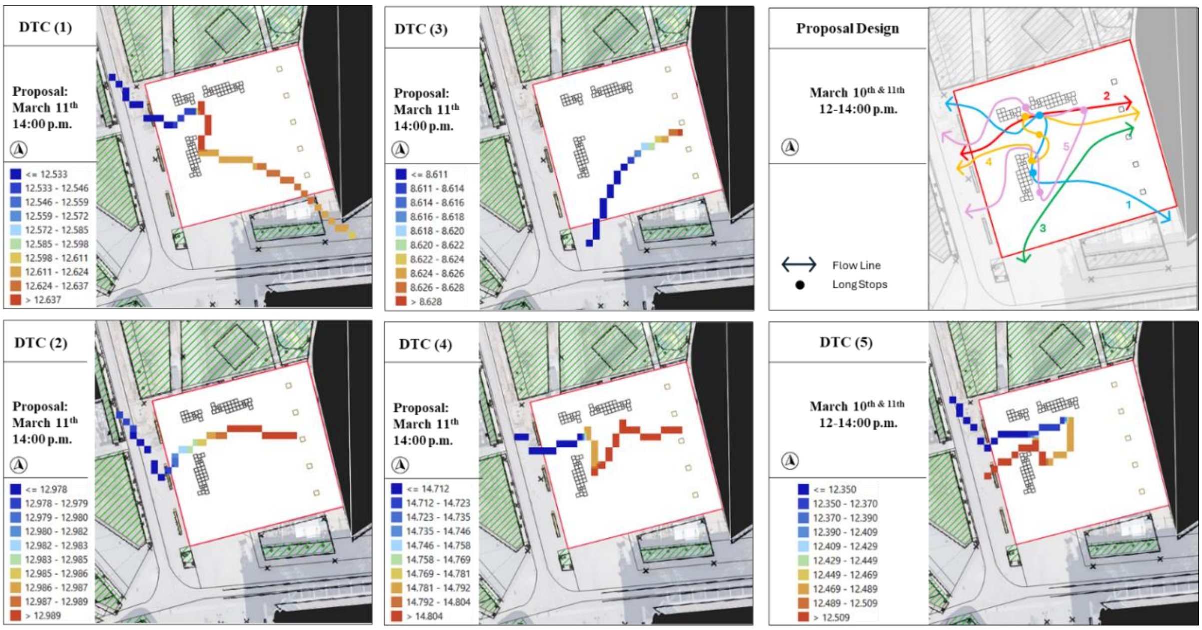
Table 23.Dominant Pedestrian Flow Patterns of the Design Scenario on March 11th and Simulated PET (1) at Midday (12:00-14:00) (Own elaboration)



Following the analysis of existing pedestrian flow, an additional flow category, "Plaza engagement," will be introduced. This category will represent the potential flow of people who are not currently visiting the library or simply passing through but who might be drawn to the Plaza by engaging activities. Examples of such activities could include pop-up events or programming specifically designed to encourage people to stay and interact within the space.

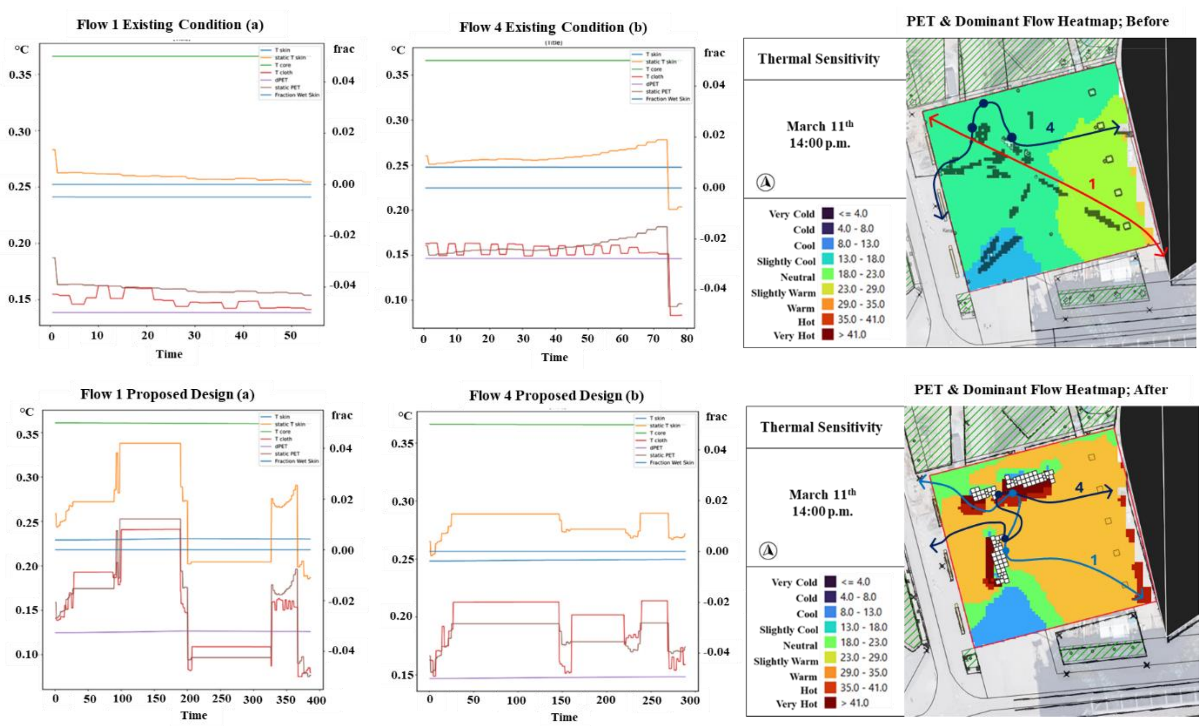
Building upon this concept of plaza engagement, an analysis of current pedestrian patterns would allow for the identification of areas where design interventions could be implemented to encourage visitor lingering and extended enjoyment of the plaza.

Table 24.DTC for predicted dominant pedestrian flows in proposed design in late winter (March 11th; 12-14:00)



Calculating the dynamic thermal comfort for the identified dominant pedestrian flows (including the potential 'plaza engagement' flow) helps to understand how thermal comfort might change based on how people use the redesigned plaza. These findings suggest that the design interventions implemented in the plaza have demonstrably improved thermal comfort for pedestrians during winter.

The observed increase in DTC values (Table 24) indicates a warmer microclimate compared to the existing conditions. These results indicate that the proposed interventions have successfully addressed thermal concerns and contributed to a more thermally balanced and user-friendly environment during the winter season.



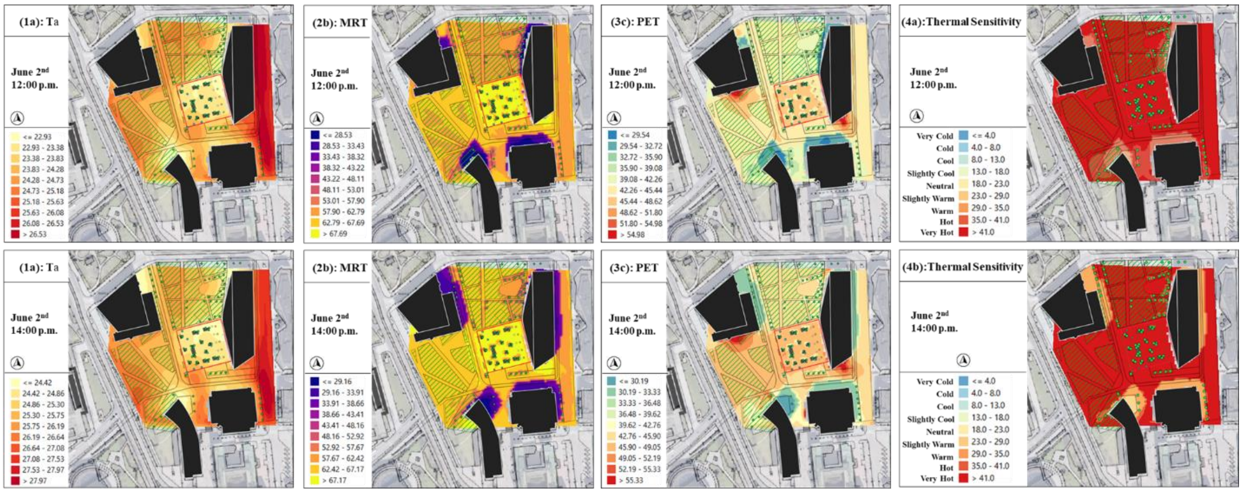
Graph 16. Static T-skin, Static PET, and Dynamic PET (dPET) for Walking Paths: Flow 1 & 4 in two scenarios

A consistent pattern emerged across all five dominant flow paths: dynamic thermal comfort (DTC) values increased slightly as pedestrians approached the library, with an average increase of 0.1°C (maximum change of 0.2°C). This aligns with the results showing higher static PET values inside the plaza compared to outside (existing static PET values inside the plaza were -2°C to 4°C higher than outside). For example, Graph (16) compares the existing condition and the proposed design's T-skin, DTC, and static PET for Flow 4 and Flow 1. In both cases, the designed scenario with T-skin shows an increase in DTC of up to 5°C compared to the existing condition.

5.2.4.1. Proposal Simulations for Early Summer (June 2nd)

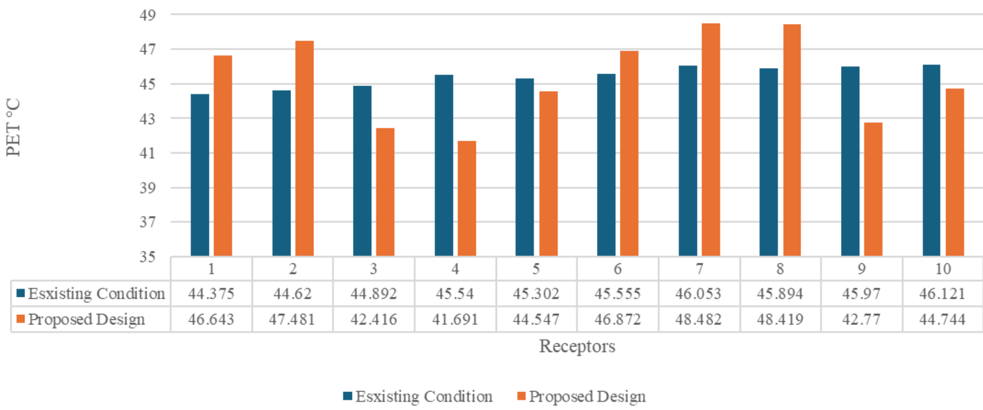
As with winter, summer simulations (June 2nd) compare PET at ten receptor points (Figure 10) for existing and proposed designs (Table 25).

Table 25. Simulated T_{air} (1), MRT (2), PET (3c), and Thermal Sensitivity (4) of the proposed design on June 2nd at 12:00 (a) and 14:00 (b) (Own elaboration)



Despite the significant improvements in winter thermal comfort, the summer design focuses on mitigating heat stress through targeted interventions. While the Plaza remains outside the ideal thermal comfort zone, the design elements demonstrably improve the conditions next to them. Notably, these areas transition from heat stress zones to "hot" and even "warm" zones in close proximity to vegetation and water mist features.

The PET analysis reveals a cooling effect of up to 3.5°C in areas influenced by the design elements and vegetation, compared to unshaded open areas. This translates to a total temperature difference of 2°C. While there is still room for further improvement, especially considering the potential for high density and longer user engagement during summer events, these findings demonstrate the effectiveness of the proposed design in mitigating heat stress (Graph 17).



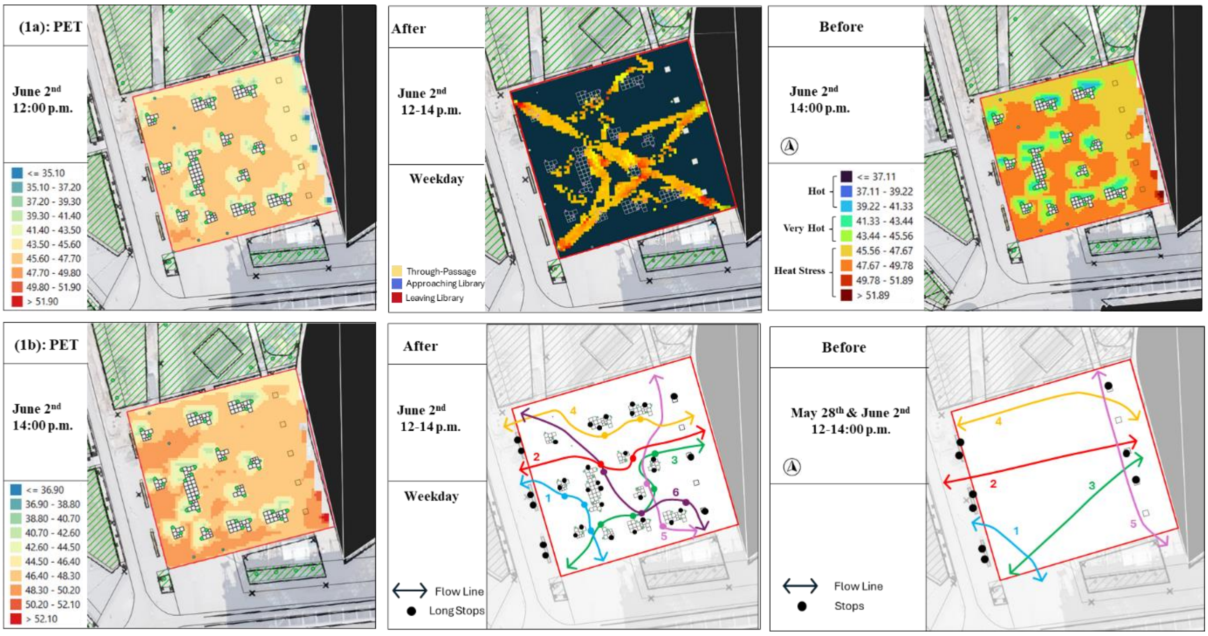
Graph 17. The difference in PET between the existing condition and the proposed design at each receptor point on June 2nd at 14:00

The existing plaza exhibits a consistently high thermal stress environment, with PET values ranging from approximately 44.3°C to 46.1°C across all receptors. The proposed design shows mixed results, with PET values ranging from 41.6°C to 46.6°C. While some receptors (3 to 10) experience reductions in PET (up to -3.85°C), others (1 and 2) show increases (up to 2.8°C). These inconsistencies highlight the need for further design refinement.

Currently, the Plaza falls far outside the comfort zone (18-23°C), with static PET values significantly exceeding that range. The proposed design offers some improvement, with the lowest PET value (Receptor 8 at 39.9°C) showing a reduction. However, even this value remains considerably above the comfort zone.

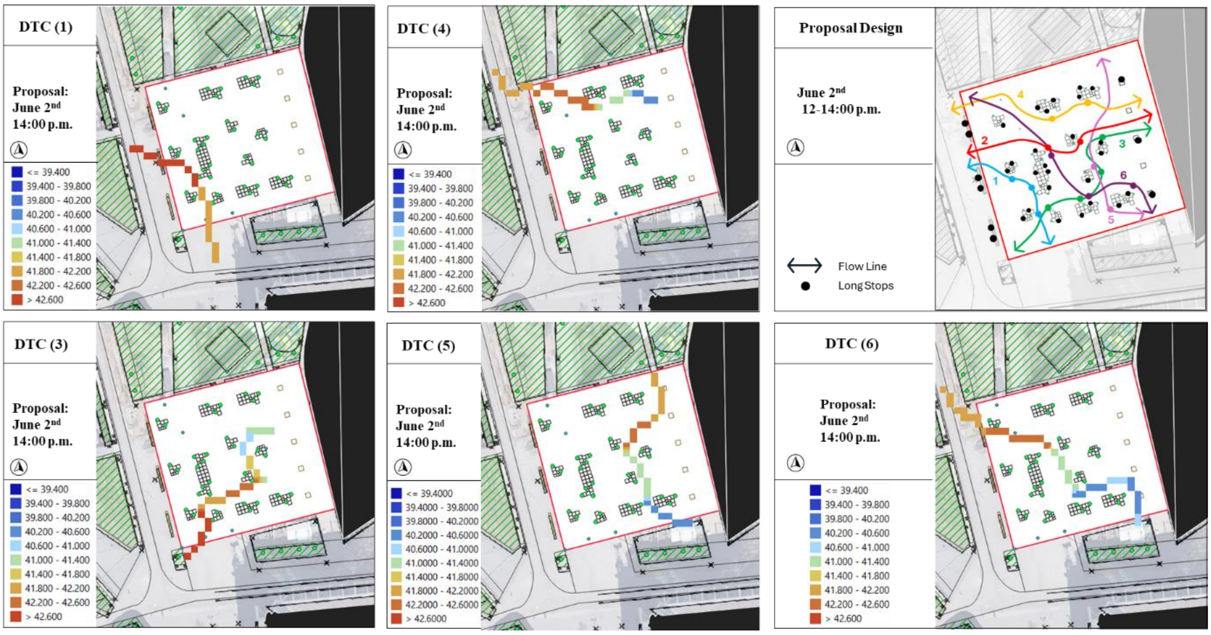
While the proposed design demonstrates the potential for localised thermal comfort improvements, its inconsistency necessitates further modifications. A more holistic approach that incorporates shading, ventilation, and potentially cool materials could significantly reduce overall PET values and bring them closer to the comfort zone.

Table 26.Dominant Pedestrian Flow Patterns of the Design Scenario on June 2nd and Simulated PET (1) at Midday (12:00-14:00) (Own elaboration)

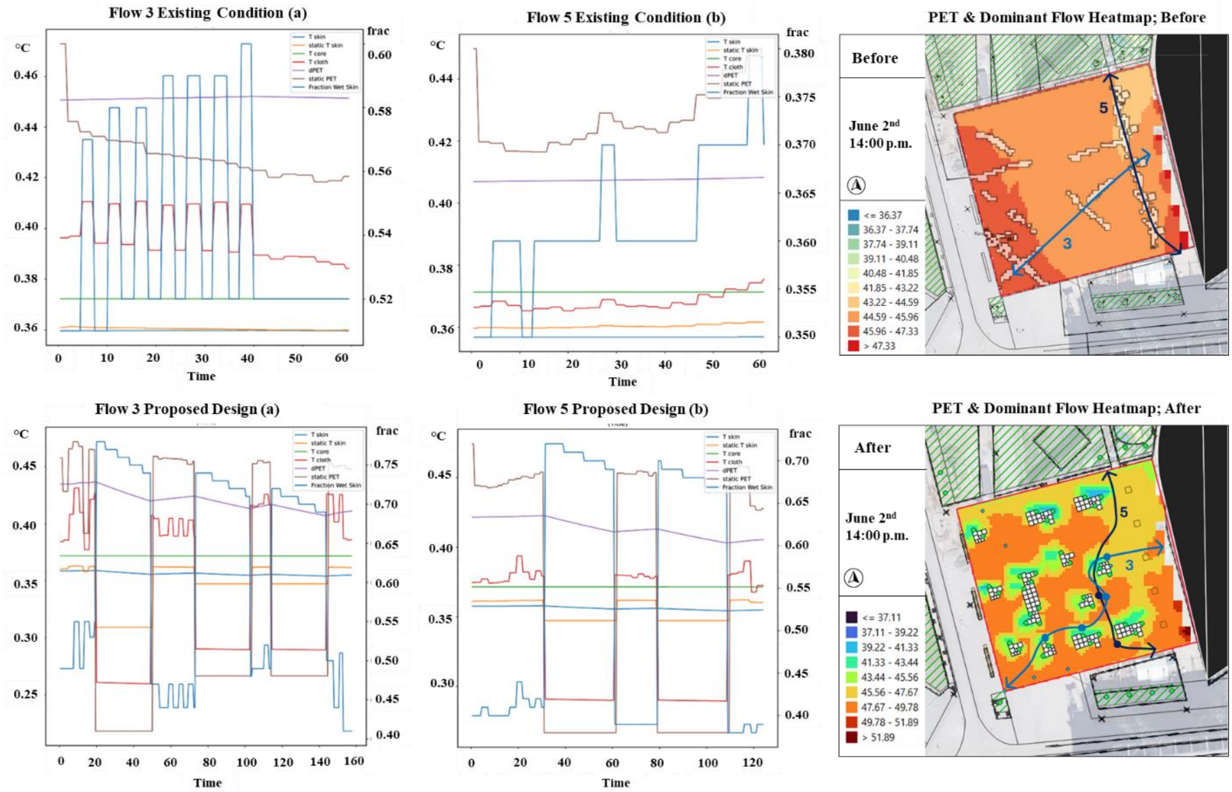


Similar to the approach employed for winter, the analysis of existing pedestrian flow patterns will be complemented by the introduction of a new category: "Plaza engagement" flow (Table 26). It represents the anticipated increase in pedestrian activity drawn to the plaza by engaging activities. Examples of such activities could include pop-up events or programming specifically designed to foster social interaction and extended stays within the space.

Table 27.DTC for predicted dominant pedestrian flows in proposed design in early summer (June 2nd; 12-14:00)



Dynamic thermal comfort (DTC) was calculated for the identified dominant pedestrian flows, including the potential "Plaza engagement" flow. The results (presented in Table 27) suggest that the design interventions implemented in the Plaza have demonstrably improved thermal comfort for pedestrians during summer, with observed decreases in DTC values of around 3°C. This decrease indicates a cooling effect achieved by the design elements. However, despite transitioning the area from heat stress to a state of warm thermal sensitivity, the summer design may benefit from further refinement to achieve a more pronounced cooling effect and reach the desired comfort zone.



Graph 18. Static T-skin, Static PET, and Dynamic PET (dPET) for Walking Paths: Flow 3 & 5 in two scenarios

Graph (18) illustrates that dynamic thermal comfort (DTC) exhibits a clear spatial variation. Users who spend more time in areas with lower PET values, particularly those near vegetation, shadows and water features incorporated into the design, experience demonstrably lower DTC values. This suggests that the design elements effectively create microclimates with improved thermal comfort. Furthermore, the observed fluctuations in DTC correspond to user behaviour, with individuals seeking refuge from the sun in shaded areas and vegetation zones. This dynamic interaction between user behaviour and the designed environment ultimately contributes to decreased overall dPET across the dominant pedestrian flows.

CHAPTER 6: Conclusion and Future Research

6.1.Key Findings

This thesis investigated the interplay between microclimate, social engagement, and pedestrian behaviour within the Plaza in Helsinki. The key findings of the research offer valuable insights for optimising plaza design to encourage year-round utilisation and enhance user comfort.

- People are drawn to spaces offering engaging features and interactive elements, regardless of the prevailing microclimate. This echoes the principle of social magnetism and "people attract people", highlighting the importance of social presence and stimulating elements in promoting plaza activity. Design strategies that encourage interaction and social engagement are crucial for fostering a vibrant and year-round active plaza (pp. 58, 61).
- Late winter observations depict increased activity and dwell time on sunny days compared to summer. Further research is needed on plaza usage in overcast, snowy, or windy winter conditions. The presence of sunlight zones during winter emerged as a significant factor in attracting users. These findings suggest design solutions that maximise sun exposure during colder months, coupled with features that encourage social interaction (p. 57).
- During summer, pedestrian behaviour shifts towards avoiding the plaza's centre and utilising shorter paths, leading to decreased activity. Design solutions like shaded seating areas, strategically placed trees, and water features could mitigate heat stress and encourage users to linger and explore the space during hot weather (p. 60).
- The study demonstrates that temporary interventions, such as art installations or events, positively influence outdoor thermal comfort. The benefits were more pronounced in late winter than in early summer. This reinforces the effectiveness of these interventions in enhancing user comfort, particularly during colder seasons. Future research could explore optimising temporary interventions for summer (pp. 81, 84).
- The successful execution of proposed Plaza improvements necessitates collaboration among stakeholders. Creative young artists could play a key role by proposing temporary interventions and documenting user behaviour and acceptance, particularly in winter, to foster increased engagement during colder months (pp. 71-78).
- Integrating climate-sensitive strategies into the Plaza design is crucial for creating a more comfortable and diverse public space and encourages year-round use (p.p 82, 85).

These key findings provide a foundation for optimising the Plaza design and contribute to a broader understanding of creating usable and engaging public spaces in cold climates year-round. While interventions in individual public spaces are beneficial, creating a vibrant urban environment requires a comprehensive approach. This involves integrating climate-sensitive design principles into citywide planning. Existing design and planning frameworks should be revised to ensure interconnected and functional public spaces. Moving beyond a focus on simply avoiding discomfort zones and initiatives that promote active space utilisation is crucial for fostering a vibrant cityscape. Creating a network of comfortable and engaging public spaces throughout the city will encourage year-round use and contribute to a healthier and more vibrant urban environment.

6.2. Limitations

The following limitations encountered during the study should be acknowledged to ensure a comprehensive understanding of the research findings.

1. Microclimate Modeling

- *Software Capabilities*: Current microclimate simulation software, particularly ENVI-met, has limitations in winter conditions. Overcast days and precipitation can restrict the model's ability to accurately capture the full diurnal cycle (daytime variations) of thermal comfort.
- *Wind Speed Exclusion*: The exclusion of wind speeds exceeding 8-10 m/s, common in Helsinki winters, omits a key factor affecting thermal comfort and user behaviour (e.g., pedestrian comfort, route selection, wind shelter design).
- *Snow Cover Approximation*: ENVI-met's inability to directly simulate snow cover necessitated using adjustments to ground roughness, soil moisture, and humidity. This may not fully capture the impact of snow on thermal comfort, especially on days with significant snow cover.

2. User Behavior Observation

- *Resource Constraints*: Timeframe, finances, organisational limitations, and the lack of advanced technology (e.g., Wi-Fi signals, GPS tracking, CCTV) limited the options for user behaviour data collection.
- *Observer Effect*: Relying on a single observer (the author) limited the selection of observation locations. As participants might alter their behaviour if aware of being observed, this method may not be suitable for all areas of the plaza.
- *Limited Data Collection Method*: While valuable, the qualitative approach to user behaviour observation could benefit from including quantitative data collection methods (e.g., people counting, location tracking) in future studies.

3. Plaza Design Flexibility

- *Focus on Temporary Elements*: The plaza's role as a flexible space for events and its seasonal usage necessitated focusing on temporary interventions. Proposals such as installing lawns, changing ground materials, and adding large water bodies for cooling effects in the summer were not feasible and were thus limited in this study.

4. Static and Dynamic Thermal Comfort Evaluation

- *PET vs. dPET*: The differences between PET and dPET results suggest potential influences of initial conditions or user clothing options within the software. Furthermore, the simulations only considered short walks within the Plaza area, whereas actual user journeys may involve longer distances, such as those between transportation stations and the library. While the observed differences in thermal sensitivity between PET and dPET for short paths require further investigation, the directional changes in thermal comfort (increasing or decreasing) captured by dPET are likely valid, especially when considering these longer walking distances encountered in reality.

6.3.Future Research Directions

This research sets the stage for further investigation into user behaviour and microclimate interactions within public spaces. Here are some potential areas for future exploration:

- *User Diversity*: A deeper understanding of user behaviour variations across different demographics, such as gender, age groups, and ability levels, can be achieved through surveys and targeted observation.
- *Subarctic Climate Context*: Investigating user experiences in a subarctic climate context (cities located at higher latitudes) with significant snowfall can provide valuable insights into winter pedestrian movement patterns and user preferences for navigating such environments.
- *Advanced User Behavior Analysis*: Advanced techniques like CCTV cameras (subject to ethical and privacy considerations) could provide a detailed analysis of user path choices across various public spaces – plazas, streets, and sidewalks – particularly during winter when snow cover influences pedestrian movement.
- *Transitional Month Observations*: Including observations during spring and autumn months to strengthen the research validity. Examining user behaviour and microclimate interactions throughout the year provides a more comprehensive picture of public space utilisation.
- *Summer Comfort Optimisation*: Further microclimate simulations can be conducted to assess the effectiveness of different temporary interventions in achieving optimal thermal comfort during the summer season.
- *Extended Observation Periods*: A limitation of this study is the focus on daytime user behaviour. Future research could extend observation periods to evenings and nighttime, especially in winter, to provide a more holistic understanding of how users interact with the plaza throughout the day.
- *Investigating Sustainable Cooling Strategies*: Building upon the understanding of user behaviour and microclimate interactions, future research could explore integrating sustainable cooling strategies for public spaces. One promising approach involves snow cooling systems. Successful implementations in Sundsvall, Sweden, and Sapporo Airport, Japan, demonstrate the potential of harvesting snow during winter and storing it in insulated reservoirs for summer cooling (InterregEurope, 2018). Further research could examine the feasibility and effectiveness of adapting this approach for public open spaces, such as plazas.

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