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THESIS

Extraction of environmental indicators of vegetation design inside small neighborhoods: The case of Hebron

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A thesis submitted in partial fulfillment of requirements of the degree Master of Architecture-Sustainable Design

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ABSTRACT

The urban heat island effect and rising temperatures in urban areas significantly impact the standard of living and energy consumption, especially in regions like Palestine with high population density and rapid urbanization. This study explores sustainable urban solutions, focusing on enhancing microclimates and improving the thermal performance of residential buildings through strategic tree planting. Green infrastructure, such as increased vegetation, is recognized for its potential to mitigate heat islands, enhance pedestrian thermal performance, and improve air quality. However, the optimal tree typologies and configurations for these benefits remain under-researched, particularly in Palestinian urban areas. The research aim is to identify and select the optimal tree typologies that enhance microclimate and building thermal performance in residential compounds in Palestine. It includes investigating different tree configurations, green coverage ratios, and tree physical properties to determine their impact on the microclimate and thermal performance. Specific objectives include testing the ideal tree configurations for various outdoor space morphologies in which trees influence local climate conditions. The study ultimately seeks to develop urban greening tailored to the Palestinian context, promoting sustainable urban development and resilience to climate change. This study utilizes a quantitative research approach, incorporating data collection techniques such as on-site observations, field surveys, and building sample analyses. The ENVI-met software was employed to simulate microclimatic factors, including temperature, humidity, wind speed, and solar radiation. Sensors were strategically placed at various heights around the tree formations to capture microclimatic conditions and assess the influence of tree configurations on the surrounding built environment at different vertical levels. As Envi-met program is limited in its ability to simulate indoor environments, Design builder program was employed to evaluate the interior thermal comfort coefficients of the spaces and quantify the influence of the tree scenarios on these indoor conditions. The findings highlight the influence of tree characteristics, such as crown shape, density, trunk size, and height, on thermal performance. Dense tree crowns and medium-sized trunks were found to be effective in reducing temperature and increasing humidity. For closed spaces, trees with a vase-shaped crown and a height of 10 meters were found to be optimal, while cylindrical crowns and a height of 5 meters were most beneficial in open areas. The research emphasizes the crucial role of strategic tree placement, aligned with prevailing wind directions and integrated with other green infrastructure elements (Green roof and green wall), in enhancing thermal comfort within urban environments.

Keywords: Vegetation typologies, Urban heat island, Planting design, Outdoor thermal comfort, Pedestrian thermal comfort, Trees canopies.

استخلاص المؤشرات البيئية لتصميم الغطاء النباتي داخل الأحياء السكنية الصغيرة :حالة من الخليل

نزيهة عبد المطلب التميمي

الخلاصة

تؤثر ظاهرة جزيرة الحرارة الحضرية وارتفاع درجات الحرارة في المناطق الحضرية بشكل كبير على مستوى المعيشة واستهلاك الطاقة، خاصة في مناطق مثل فلسطين ذات الكثافة السكانية العالية والتحضر السريع. تستكشف هذه الدراسة الحلول الحضرية المستدامة، مع التركيز على تحسين المناخات المحلية وتحسين الأداء الحراري للمباني السكنية من خلال زراعة الأشجار بشكل استراتيجي. تُعرف البنية التحتية الخضراء، مثل زيادة الغطاء النباتي ، بقدرتها على التخفيف من جزر الحرارة، وتحسين الراحة الحرارية للمشاة، وتحسين جودة الهواء. ومع ذلك، لا يزال البحث عن أفضل أنواع الأشجار وتكوينات الأشجار لهذه الفوائد محدودًا، خاصة في المناطق الحضرية الفلسطينية. يهدف البحث إلى تحديد واختيار أفضل أنواع الأشجار التي تحسن المناخ المحلي والأداء الحراري للمباني في المجمعات السكنية في فلسطين. ويشمل ذلك دراسة تكوينات الأشجار المختلفة ونسب التغطية الخضراء والخصائص الفيزيائية للأشجار لتحديد تأثيرها على المناخ المحلي والراحة الحرارية. وتشمل الأهداف المحددة تقييم تكوينات الأشجار المثالية لأنواع مختلفة من أشكال المساحات الخارجية حيث تؤثر الأشجار على الظروف المناخية المحلية. تسعى الدراسة في النهاية إلى تطوير تصميم التشجير الحضري المصممة خصيصًا للسياق الفلسطيني، وتعزيز التنمية الحضرية المستدامة والقدرة على الصمود أمام تغير المناخ. تستخدم هذه الدراسة نهج البحث الكمي، وتدمج تقنيات جمع البيانات مثل الملاحظات الميدانية والمسوحات الميدانية وتحليلات عينات المباني. كما تم استخدام برنامج ENVI-met لمحاكاة العوامل المناخية المحلية، بما في ذلك درجة الحرارة والرطوبة وسرعة الرياح والاشعاع الشمسي. تم وضع أجهزة استشعار بشكل استراتيجي على ارتفاعات مختلفة حول تشكيلات الأشجار لالتقاط الظروف المناخية المحلية وتقييم تأثير تكوينات الأشجار على البيئة المبنية المحيطة على مستويات عمودية مختلفة. نظرًا لأن برنامج Envi-met محدود في قدرته على محاكاة البيئات الداخلية، فقد تم استخدام برنامج Design Builder لتقييم معاملات الراحة الحرارية الداخلية للمساحات وتحديد تأثير سيناريوهات الأشجار على هذه الظروف الداخلية. تسلط النتائج الضوء على تأثير خصائص الأشجار، مثل شكل التاج والكثافة وحجم الجذع والارتفاع، على الأداء الحراري. وجد أن تيجان الأشجار الكثيفة والجذوع متوسطة الحجم فعالة في خفض درجة الحرارة وزيادة الرطوبة. بالنسبة للمساحات المغلقة، وجد أن الأشجار ذات التاج على شكل مزهرية وارتفاع 10 أمتار هي الأنسب، بينما كانت التيجان الأسطوانية وارتفاع 5 أمتار أفضل للمساحات المفتوحة. يؤكد البحث على الدور الحاسم للزراعة الاستراتيجية للأشجار، بما يتماشى مع اتجاهات الرياح السائدة وتكاملها مع عناصر البنية التحتية الخضراء الأخرى (السطح الأخضر والجدار الأخضر)، في تحسين الراحة الحرارية داخل البيئات الحضرية.

DECLARATION

I declare that the Master Thesis entitled “Morpho-Strategic Guidelines for Enhanced Thermal Comfort through Tree Canopy Design: The Case of Hebron” is my own original work, and herby certify that unless stated, all work contained within this thesis is my own independent research and has not been submitted for the award of any other degree at any institution, except where due acknowledgement is made in the text.

Student Name………………………………….

Signature:———————————— Date:————————

DEDICATION

To my dearest parents, for their unwavering love and support that has always been my support. To Mustafa, my loving husband, for his constant encouragement and partnership in life's journey. To my precious daughter, Lina, you are my source of joy and inspiration. And to my brothers, Mohammad, Ahmad, Yousef, Hamza, and Omar, thank you for the bond of brotherhood and the strength we share.

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Finally, great thanks to everyone who has contributed to the success of this work.

List of Abbreviations

UHI	Urban Heat Island
PPD	Predicted Percentage Dissatisfied
PMV	Predicted Mean Vote
ISO	International Organization for Standardization
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
Tmrt	The Mean Radiant Temperature
GCR	Green Cover Ratio

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Chapter 1

Introduction

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Introduction

1.1 Preface

Urban environments significantly impact the quality of life. High outdoor temperatures often deter people from enjoying these spaces, especially during hot days. This heat disparity between indoors (usually cooled) and outdoors creates an additional burden on energy consumption. In response to the growing challenge of urban heat islands, the 'cool city' concept presents a viable strategy for achieving sustainable urban development. This approach focuses on managing urban heat by reducing heat generation.

One key strategy for achieving cool cities is incorporating green infrastructure by increasing the amount of vegetation in urban spaces. Trees and other plants play a role in mitigating the urban heat island effect by providing shade and promoting evapotranspiration, a natural cooling process. These green spaces can significantly improve thermal comfort for pedestrians by lowering both temperature and humidity.

1.2 Research problem

After more than half a century, more than 60 percent of Palestinians living in urban areas—a total of 3.8 million people—are urban residents, accounting for 77 percent of the population. With an estimated population density of 798 persons per km2 in urban areas. Rapid urbanization and high population growth rates are increasing strain on available land, infrastructure, and resources. As a result, haphazard and unplanned development has increased in cities, encroaching on nearby agricultural land and adding to the strain on the already deficient and failing infrastructure (Shaheen, 2013).Also, reports on the state of the environment in the occupied Palestinian territories are released regularly by the UNEP. These reports frequently draw attention to the disappearance of green spaces as a result of things like Israeli settlements, land confiscation, and limitations on Palestinian access to resources and land.

The loss of green public spaces in Palestine exacerbates the impacts of climate change in several significant ways. With diminishing forests, parks, and agricultural lands, the region's capacity to sequester carbon dioxide declines, intensifying greenhouse gas concentrations and accelerating global warming. Additionally, urbanization and the expansion of built-up areas create heat islands, where temperatures soar due to the absence of cooling provided by green spaces.

Rising temperatures and the urban heat island effect significantly impact building energy consumption in Palestine, particularly in urban areas. As temperatures soar, buildings require increased energy for cooling to maintain comfortable indoor conditions, leading to higher electricity demand and energy costs. In Palestine, residential and commercial buildings use 70% of the country's energy, making them the largest consumers source (Statistics, 2018).

Additionally, Palestine is primarily affected by the Israeli occupation of its territory, which prevents it from controlling its energy resources. The occupying people provide fuel, gas, and electricity. Considerable environmental risks result from a heavy reliance on traditional energy sources. Finding innovative techniques to help lower consumption and safeguard the environment is critical because of the notable increase in energy consumption as population density rises.

Choosing appropriate trees typologies and configuration is critical in mitigating climate change and reducing energy consumption, particularly in urban areas. Well-planned urban forestry initiatives can significantly impact local climate conditions by providing shade, mitigating the urban heat island effect, and improving air quality. Additionally, trees act as natural air purifiers, absorbing pollutants such as carbon dioxide and particulate matter, which helps combat climate change and improves overall air quality.

Several researchers diligently investigated the impact of trees on microclimates, revealing their significant influence on local temperature, humidity, and air quality. However, the results are still limited in part despite these efforts. Research has indicated that trees can reduce the effects of urban heat islands by providing shade and evapotranspiration, but there are still unknowns about the precise mechanisms underlying these processes. Additionally, the variability of tree species, urban layouts, and climatic conditions presents challenges in generalizing findings across diverse environments. Hence, while the evidence supporting the beneficial role of trees in shaping microclimates is robust, ongoing research endeavors are crucial to unraveling the intricacies of this complex relationship.

Many articles on the cooling effect of vegetation on thermal performance were reviewed in order to identify research gaps in the field.

Urban green spaces play a role in mitigating the Urban Heat Island (UHI) effect. Through evapotranspiration, shading, and reduced albedo, vegetation within urban environments can significantly influence local microclimates. While the importance of vegetation type, density, and spatial configuration for UHI mitigation has been established, a knowledge gap persists regarding the specific impacts of urban green spaces in Mediterranean climates. To address this deficiency, long-term studies examining the performance of urban green spaces under Mediterranean conditions are imperative. Furthermore, developing region-specific urban greening strategies is essential to optimize the benefits of vegetation within this unique ecological context.

Existing research acknowledges the benefits of urban greening but highlights the need for environmental indicators that can guide the design of green spaces for enhanced thermal comfort in Palestinian cities. These guidelines encompass strategic tree placement, spacing, canopy coverage, and suitable physical tree properties.

1.3 Research Objectives

This research aims to enhance microclimate and improve building thermal performance by identifying and selecting the optimum tree typologies in residential compound in Palestine by strategically choosing trees with characteristics that effectively mitigate heat island effects and enhance local climate conditions.

To achieve the main objective, several objectives must also be met, such as:

- Investigating and determining the impact of using different trees typologies (green cover ratio, arrangement, trees physical properties) on the microclimate and thermal comfort of residential buildings in Palestine by testing these typologies.
- Identifying the ideal trees typologies and configuration in different outdoor spaces morphologies within residential complex to enhance the microclimate.
- Quantifying Green Space Development and Maintenance Costs Based on Study Findings.

1.4 Research question

Problem identification has raised the main question: What is the optimal design of plant typologies that contain arrangement, green coverage ratio, tree crown, and vegetation types that enhance thermal performance in residential compounds in (Hebron, Palestine) with take consider axis to view and landscape design circulation?

The research sub-questions are:

- What is the organization or configuration of trees that achieves optimal thermal performance in all arrangement scenarios?
- What are the optimum tree typologies which contain tree crown shape, trees crown density, tree trunk size, and tree height that achieve the optimal thermal performance with tack consider axis to view at all configuration scenarios?
- What is the green coverage ratio that achieves optimal thermal performance in all arrangement scenarios?
- To what height can trees enhanced thermal performance (vertical temperature)?
- Is an ideal tree design sufficient to achieve optimal thermal performance for both internal and external spaces within residential spaces, or are complementary techniques necessary to support the chosen tree design and maximize its thermal impact?
- What are the construction and ongoing maintenance cost of green space development in residential complexes, as revealed by this study?

1.5 Research Significance

Tree design can occasionally reduce the effectiveness of microclimates despite being appreciated for its aesthetic qualities. Tree designs with intricate branching patterns and dense foliage can obstruct airflow, sunlight penetration, and heat and moisture exchange within a microclimate. In certain contexts, such as urban environments where optimizing microclimates for energy efficiency or agricultural productivity is paramount, prioritizing functionality over aesthetic considerations becomes critical.

In these cases, selecting tree species can help mitigate the negative impacts on microclimate efficiency without sacrificing the overall benefits of greenery. Thus, recognizing the importance of balancing aesthetic preferences with practical considerations is essential for sustainable and effective tree design in diverse environmental settings.

Most tree planting codes predominantly focus on factors such as species suitability, growth habit, and proximity to infrastructure rather than explicitly addressing the enhancement of microclimates. While these codes often prioritize considerations like root spread, canopy size, and susceptibility to pests and diseases, they may overlook the potential role of trees in shaping local climate conditions. These codes miss out on opportunities to use trees as passive climate control tools, and they do not include microclimate optimization guidelines, such as selecting species with specific canopy densities or orientations to maximize shading or wind flow.

Recognizing the influence of trees on microclimates and integrating relevant criteria into planting codes can contribute to more resilient and sustainable urban landscapes that better mitigate heat island effects, reduce energy consumption, and enhance overall environmental quality.

In the realm of research aimed at enhancing microclimates through tree typologies, a significant gap exists in the comprehensive examination of all tree typologies within a single study, particularly in Mediterranean climates.

The research initiative aims to develop a specific guideline for tree planting in Palestinian residential areas, concentrating on enhancing the building's thermal efficiency and microclimate. Even though trees are essential for reducing heat stress and improving environmental conditions, there aren't many planting guidelines that are specifically designed for the Palestinian context. With an emphasis on this area, the study aims to close this gap and provide advice with consider regional climate, cultural norms, and architectural concerns.

The guideline aims to determine appropriate tree species, planting densities, and arrangements that enhance residential buildings' thermal performance and efficiently harness the microclimatic benefits of greenery. By providing a comprehensive framework for sustainable tree-planting practices, the research seeks to empower policymakers, urban planners, and residents alike to foster greener, more resilient communities in Palestine.

1.6 Research Limits and Limitations

This study focused on the design of optimal natural spaces within residential complexes located in mountainous areas (Mediterranean climate) in Hebron, Palestine, with a focus on enhancing thermal performance.

A limitation of this study is the reliance on Envi-met Light Version software, which identifies specific project areas. So, it necessitated the subdivision of large projects into smaller zones, potentially introducing inaccuracies in the overall thermal performance evaluation. Also, the research was the limited availability and quality of climatic data.

Furthermore, computational constraints associated with simulation time in Envi-met software limited the number of tree scenarios that could be evaluated. Simulations for each scenario within the program typically require one to two days to complete.

1.7 Research structure

The study is divided into six chapters, the first of which is this one, which addresses the research approach.

- Chapter 1: Introduction, this chapter starts with the justification of this research and the research significance, aims, and objectives, and presents a summary for each chapter.
- Chapter 2: Provides theoretical background on urban heat islands and mitigation strategies. Also, it includes topics related to the effect of vegetation, such as the cooling mechanism, the benefits of trees, the role of vegetation in microclimate modification, and general codes and standards of planting design.
- Chapter 3: Provides the theoretical background on Palestine's vegetation and urban heat islands. Additional topics covered include the effects of climate change on UHI in Palestine, plant design codes specific to Palestine, and the impact of social life on planting design.
- Chapter 4: Begins with an overview of the research methods. Following that, it showed an example of the case study selection criteria. The approach for analyzing cases will be

delineated, detailing the variables scrutinized throughout the simulation process alongside the dynamic changes witnessed during this stage. Furthermore, the methodology used to simulate each case under study will be described.

- Chapter 5: Presented the simulation results of the tree matrix for each case at the microclimate and building levels.
- Chapter 6 determined a conclusion and summary of the findings and main results manifested to design a Palestinian Framework for Selecting Trees in Residential Neighborhoods". In addition, a discussion of some recommendations and suggestions for future research.

Chapter 2

Urban heat islands and outdoor thermal comfort

Chapter 2

Urban heat islands and outdoor thermal comfort

2.1 Preface

This chapter investigates the complex relationship between urbanization, UHIs, and outdoor thermal comfort. The presence of vast impervious surfaces and high-density built environments in urban regions drastically modify local climate due to the formation of UHIs. Understanding these phenomena is critical for creating long-term urban planning and development strategies. The chapter also discusses the concept of thermal comfort, which plays a crucial role in the well-being and satisfaction of urban residents. Thermal comfort is determined by various factors, including wind, thermal radiation, and vegetation's significant role in mitigating urban heat island adverse effects.

2.2 Urban heat island versus urbanization

Urban Heat Island (UHI) is a well-known phenomenon that has attracted the attention of academics and policymakers due to its significant environmental and public health implications. The natural environment has suffered significantly because of the rapid pace of global urbanization over the last few decades. Among the numerous environmental issues resulting from urbanization and industrialization, the UHI effect has emerged as a critical area of research. Studies on the heat island phenomenon began in the mid-twentieth century. As urbanization and industrialization increased, so did interest in understanding the urban heat island effect (. Santamouris, 2013). Understanding and addressing the UHI effect is critical for developing effective mitigation and adaptation plans. So, strategies seek to reduce its negative impact on the environment and human health.

Also, it is a phenomenon characterized by surface and atmospheric changes due to urbanization, leading to a warmer urban climate compared to the surrounding areas. It describes a feature of the urban area where nocturnal temperatures are higher than the surrounding landscape (Deilami , Kamruzzaman , & Liu , 2018). Warmer urban air temperatures result from various interrelated causes associated with the urban modification of natural surfaces, such as the heat and pollution released from anthropogenic activities in the urban environment (Nuruzzaman , 2015).

It has direct implications for energy efficiency, the environment, and ultimately, human comfort and health. Urban areas are characterized by high population and construction density, which leads to increased energy usage and a scarcity of green space. Hathway et al. (2012) found that Urban Heat Island is caused by the absorption of heat from building and ground surfaces, lower moisture in the air due to reduced vegetation, and large areas of traffic and pavement.

The Urban Heat Island (UHI) effect has two layers. The first layer is the Urban Boundary Layer (UBL) is the air layer directly above the urban surface. The activities and characteristics of the urban environment influence this layer, which stretches from the surface to the top of the urban canopy layer. The UBL is highly intricate, with several processes and interactions that influence urban microclimates. These characteristics help to explain phenomena such as the Urban Heat Island (UHI) effect.

The second layer is the canopy layer (atmospheric boundary layer) refers to the layer of air that is situated immediately above the surface. Several crucial factors contribute to this layer, including the urban canyon effect, heat retention, and thermal convection. Tall buildings create urban canyons that obstruct wind flow, thus reducing ventilation and trapping heat. The built environment can absorb and store heat during the day, which is then released at night, resulting in warmer nighttime temperatures. Furthermore, the urban structure hinders the movement of warm air upwards and its replacement by cooler air, which reduces the area's ability to cool down. Collectively, these factors intensify the (UHI) effect (Santamouris , et al., 2001).

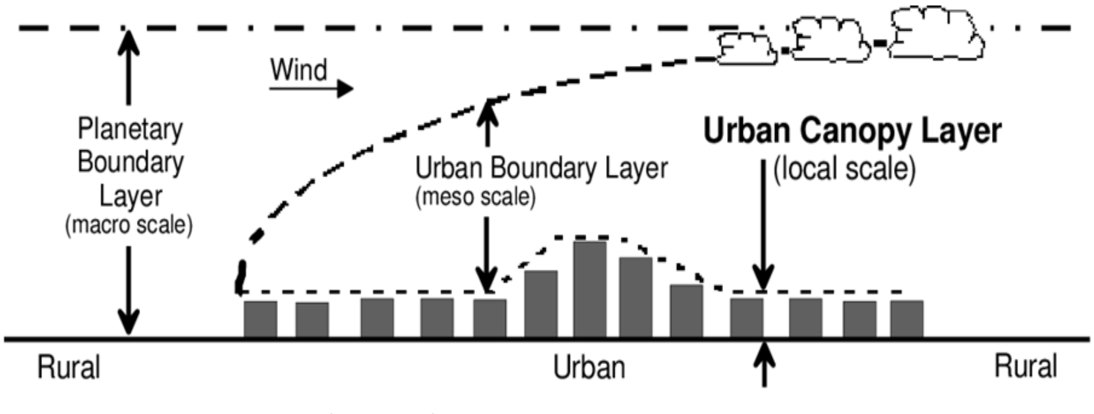


Figure 2-1: Two-layer classification of the urban atmosphere (Oke, 1976; adapted by permission).

2.2.1 Impact of urbanization on urban heat island

Over the last few decades, urbanization has been a dominant global trend. The fundamental drivers of urbanization are insufficient economic progress and a growing population. As a result, land use patterns have shifted dramatically, with natural landscapes giving way to constructed environments such as residential, commercial, and industrial regions (Angel , Parent , L. Civco , Blei , & Potere, 2011). This shift in land use coverage has far-reaching consequences for the environment, impacting biodiversity, water systems, and climate patterns (C. Setoa, Güneralpa, & R. H, 2012).

Change in land use cover is one of the environmental challenges caused by population expansion and the movement of people from rural to urban areas, which modify natural vegetation at both local and extra-local scales. The United Nations projects that there will be 6.6 billion people living in cities worldwide by 2050, up from 4.2 billion in 2019 (Junhua, 2023). The rapid population growth is putting a strain on cities, which require more space for living and working. As a result, new cities and roads will be built every day (Hamia, Abdib, Zarehaghia, & Suh, 2019). The microclimate of cities is negatively impacted by continuing urban growth and the lack of concern for the planning and design of open spaces. This leads to increases in air and surface temperatures in urban cores and the block of wind flow, ventilation, and air dryness in the urban area are additional effects of cutting back on green space and replacing it with impenetrable urban surfaces (Irfeey , et al., 2023). Rising air temperatures in cities can cause several problems, including health problems. These issues are especially concerning for vulnerable populations such as young children, elderly residents, and people suffering from chronic illnesses. Higher temperatures lead to a rise in the demand for air conditioning, putting strain on energy grids and contributing to greenhouse gas emissions (Balany , Ng, Muttil, Muthukumaran, & Wong, 2020).

2.2.2 Mitigation strategies of Urban heat island

Urban heat islands (UHIs) are becoming increasingly problematic, so cities are focusing on implementing effective mitigating strategies. The necessity of resolving UHIs has grown due to urbanization's continual modification of landscapes and the development of heat-related issues.

Various strategies and processes aim to mitigate the Urban Heat Island (UHI) effect. These strategies include implementing green roofs, high albedo roofing materials, high albedo pavements, green vegetation, shade trees, water bodies, urban planning, and pavements (Rosenzweig, et al., 2010; Rosenzweig, et al., 2010). Each strategy contributes to cooling urban environments through different mechanisms. Green roofs and vegetation promote evapotranspiration, delay runoff water, and absorb CO2. High albedo materials reflect solar radiation, while water bodies enhance wind speed through evaporation. Shade trees intercept sunlight, and urban planning can optimize wind paths and free spaces to enhance airflow. Pervious pavements facilitate cooling by allowing water infiltration. Collectively, these strategies aim to reduce urban temperatures, contributing to a more sustainable and comfortable urban environment see figure 2-2 (Nuruzzaman , 2015).

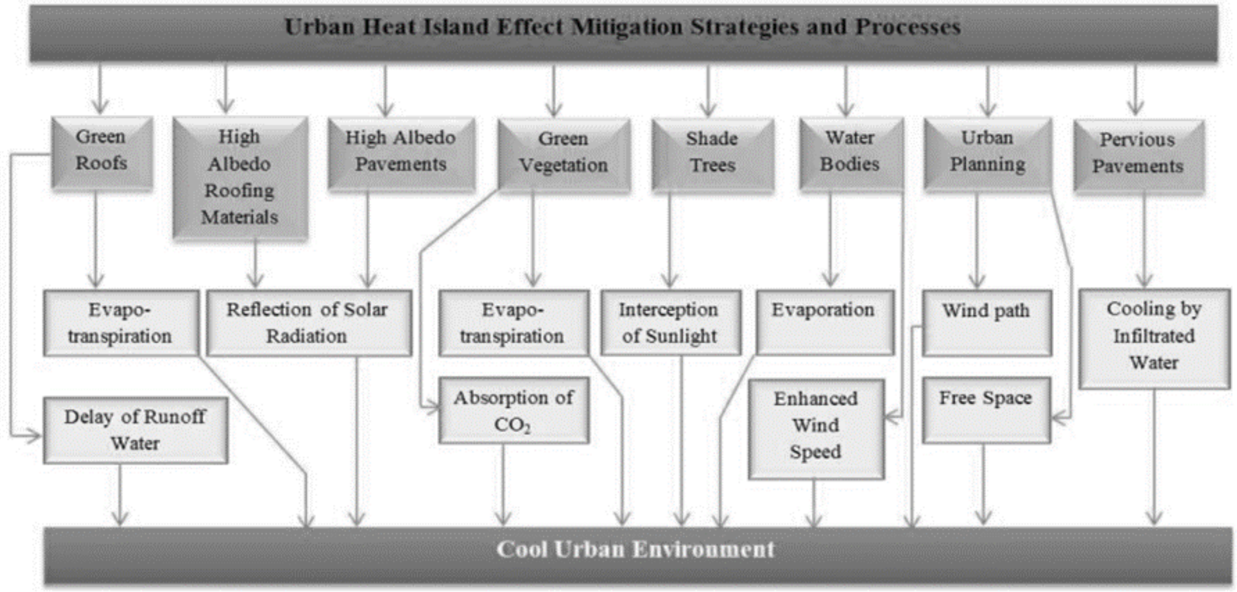


Figure 2-2: Urban Heat Island Effect Mitigation Strategies and Processes (Nuruzzaman , 2015).

2.3 Outdoor thermal comfort and vegetation effects

Many researchers described comfort as the interaction of physical, physiological, psychological, social, and cultural rights. Thermal comfort is determined by architectural design, clothes, eating habits, and climate. Discomfort can be induced by a vertical air temperature difference between the feet and the head, an asymmetric radiant field, local convection cooling, or contact with a hot or cold floor (ASHRAE Standard, 55-2012). Achieving outdoor thermal comfort is critical for well-being, particularly in metropolitan locations where heat island effects can exacerbate conditions.

Thermal comfort analysis considers a variety of parameters, including physical, physiological, and psychological components, all while noting the interdependence of environmental thermal conditions, physiological responses, and psychological phenomena. Thermal comfort is influenced by several elements, which fall into three categories.

1. Climatic factors include temperature, humidity, radiation, and velocity.
2. Personal characteristics related to metabolism and clothes.
3. Contributing elements include environmental adaptation and age.

The mean radiant temperature (Tmrt) is a crucial indicator of the radiant temperature experienced by the human body (Jamei & Rajagopalan, 2015). It encompasses all radiative fluxes, including direct, diffuse, and reflected solar radiation, as well as long-wave emissions from surfaces. Tmrt significantly influences human thermal comfort in outdoor urban areas, impacting the body's energy balance (Wang & Akbari, 2013). Research by (Peng, et al., 2012)has confirmed Tmrt's superiority over air temperature as a metric for evaluating thermal comfort. Also, have underscored Tmrt's paramount importance as a meteorological parameter governing human energy balance and thermal comfort.

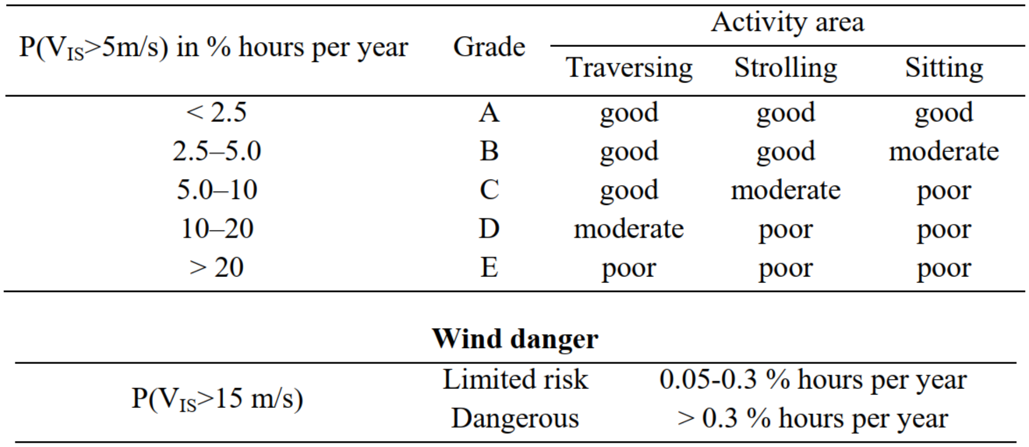
Drawing from researchers' experiments involving a uniform group of occupants, the primary standard indicators for measuring thermal comfort are the Predicted Mean Vote (PMV) and the Percentage of People Dissatisfied (PPD), as per ISO and ASHRAE standards (ISO 7730, 1994; ASHRAE, 2010). PMV offers a concise assessment of discomfort levels across a spectrum from 'cold' to 'hot,' graded on a scale from -3 to +3. Meanwhile, PPD predicts the prevalent percentage of individuals feeling 'too cold' or 'too hot.' According to Fanger's classification, responses ranging from -3 to +3 indicate discomfort, whereas those between -1 and +1 signify comfort. Ensuring accuracy necessitates applying these indices among individuals sharing similar ethnic, geographic, and age characteristics, excluding children and in good health conditions (Olesen & Parsons , 2002)

2.3.1 Wind comfort

Wind comfort is a complex interplay between wind speed, air temperature, humidity, and activity level (Stathopoulos, 2009). Studies have shown that acceptable wind speeds for outdoor activities vary depending on these factors. For instance, a light breeze (around 2 m/s) might feel pleasant on a warm, sunny day, while the same wind speed could be perceived as uncomfortably chilly in colder temperatures. Additionally, wind gustiness can significantly impact comfort, with stronger gusts causing a sensation of instability and potentially hindering movement. Understanding these relationships between wind characteristics and human perception is crucial for urban planning, designing outdoor spaces, and even developing wind chill indices for extreme weather conditions.

Unlike thermal comfort with established standards like PMV (Predicted Mean Vote) and PPD (Percentage of People Dissatisfied) defined by ISO 7730 (1994) and ASHRAE standards, wind comfort lacks a universally accepted single metric. However, several indicators are used to assess it. Wind speed is a primary factor, with comfort levels decreasing as speeds rise. Additionally, air temperature plays a role, as the wind feels colder at lower temperatures due to the wind chill effect. Local wind gustiness can significantly impact comfort by creating a feeling of instability. While no standard exists, studies suggest acceptable wind speeds vary based on activity level and these combined factors. For instance, pedestrians find wind speeds below 2 m/s comfortable for standing or sitting activities. As activity level increases, so does the tolerable wind speed. Walking briskly becomes uncomfortable around 6-8 m/s, while activities like cycling might be manageable up to 8-10 m/s. Local wind gustiness can significantly disrupt comfort by creating a feeling of instability. While no standard exists, research suggests acceptable wind speeds vary based on activity level and these combined factors (Serteser & Karadag, 2018).

The figure 2-3 provides information on wind comfort and wind danger based on the probability of wind speeds exceeding 5 meters per second (m/s) and 15 meters per second (m/s) respectively, expressed as a percentage of hours per year. For wind comfort, grades range from A to E, with each grade corresponding to different levels of comfort for activities such as traversing, strolling, and sitting. Grades are assigned based on the percentage of hours per year that wind speeds exceed 5 m/s. For example, Grade A (<2.5%) indicates good comfort for all activities, while Grade E (>20%) indicates poor comfort. The figure also addresses wind danger, categorizing it into limited risk (0.05-0.3% of hours per year) and dangerous (>0.3% of hours per year) based on the probability of wind speeds exceeding 15 m/s.



$P(V_{IS}>5m/s)$ in % hours per year	Grade	Activity area		
		Traversing	Strolling	Sitting
< 2.5	A	good	good	good
2.5–5.0	B	good	good	moderate
5.0–10	C	good	moderate	poor
10–20	D	moderate	poor	poor
> 20	E	poor	poor	poor

Wind danger

$P(V_{IS}>15\ m/s)$	Limited risk	0.05-0.3 % hours per year
	Dangerous	> 0.3 % hours per year

Figure 2-3: Criteria for wind comfort and danger in NEN 8100, *(Stathopoulos, 2009)*

The wind speed, air temperature, and relative humidity within the atmospheric boundary layer are interdependent, and their relationship is quite complex (B. Stull, 2019). Notably, there is an inverse relationship between wind speed and relative humidity. Studies have shown that high winds efficiently transport moisture, which leads to a decrease in relative humidity, while calm conditions allow moisture to accumulate near the surface, increasing relative humidity. The effect of wind speed on air temperature is less straightforward. Wind primarily affects our perception of temperature through the wind chill effect, which increases the rate of convective heat loss from the body due to wind (Nagashima , Tokizawa , & Marui, 2018). So, strong winds can make individuals feel significantly colder, even at a constant air temperature. These factors collectively influence human comfort outdoors. For example, high temperatures with high humidity can create a stifling sensation, while low temperatures with strong winds can lead to discomfort due to wind chill.

2.3.2 The vegetation effect

In urban environments, achieving thermal comfort is a significant challenge. Traditional approaches frequently rely on energy-intensive cooling systems, which add to greenhouse gas emissions and raise building operating costs. As a result, there is growing interest in exploring sustainable, passive cooling strategies. One promising approach is the strategic integration of vegetation. Plants offer a variety of biophysical processes that can modify the surrounding microclimate. Therefore, investigating the potential of vegetation as a natural cooling tool presents a compelling opportunity to create thermally comfortable urban spaces while promoting environmental sustainability.

2.3.2.1 The cooling mechanism of vegetation

Vegetation plays a vital role in cooling the environment through various mechanisms. Understanding these mechanisms is crucial for developing effective green infrastructure strategies to mitigate the impacts of climate change and create more livable urban spaces (Irfeey , et al., 2023).

A. Shading system

Shading is a technique employed by vegetation to maintain cooling surrounding environments. The cooling effect occurs by blocking sunlight from reaching the ground and reducing surface heating. Numerous studies have documented the effectiveness of shading strategies in lowering cooling demand during the summer. These studies report observed reductions ranging from 10% to 20%. This cooling is achieved through several mechanisms:

- Reduction of Solar Radiation**:** Shading intercepts and absorbs some incoming solar radiation, preventing it from reaching the ground or surfaces directly below. So, it reduces the amount of solar heat absorbed by buildings, pavements, and other surfaces, which lowers their temperatures.
- Prevention of Heat Absorption**:** Shaded areas receive less direct sunlight, which reduces solar heat absorption by surfaces like roofs, walls, and pavements. Without the intense heat absorption, these surfaces stay cooler, contributing to a cooler overall environment.

B. Evapotranspiration System

Evapotranspiration is the process by which water is drawn up from plant roots and released through pores (stomata) on the surface of leaves. This process requires energy, which comes from the surrounding environment. Water evaporates from the leaf surface, absorbing heat from the surrounding air and plant tissues. The absorption of heat lowers the temperature of the air near the plant. Evapotranspiration adds moisture to the atmosphere, increasing humidity levels near the plant. Higher humidity can lower air temperature because water vapor absorbs heat. Furthermore, increased humidity can cause a cooling sensation on human skin even when the air temperature remains constant.

C. The albedo

The albedo, or Trees with lighter-colored surfaces, such as leaves and bark, reflect more sunlight than darker surfaces. This reflection reduces the amount of solar radiation absorbed by the tree and its surroundings, thereby reducing the amount of heat absorbed by the Earth's surface (Abdi, Hami , & Zarehaghi, 2020). Moreover, vegetation can help lower the energy required to cool the building, saving energy by reducing the air temperature (by roughly 3.5 °C) during warm hours of the year under the same circumstances.

D. Vegetation ground cover effect

Vegetation ground cover significantly influences terrestrial ecosystem processes. It regulates hydrological dynamics by intercepting precipitation, attenuating raindrop impact, and enhancing infiltration rates, thereby reducing soil erosion and sediment transport (Stovin, Yuan, & Dunnett, 2017). Moreover, vegetation plays a crucial role in biogeochemical cycling by contributing to soil organic matter accumulation and improving soil fertility, structure, and water retention capacity. The complex interplay between vegetation type, density, and spatial distribution determines the efficacy of these functions. For instance, dense herbaceous cover effectively dissipates rainfall energy, while woody vegetation provides additional protection through canopy interception. Additionally, vegetation root systems contribute to soil stability, mitigating mass wasting processes (Löbmann, Wellstein, Zerbe, & Geitner, 2020). The intricate relationship between vegetation ground cover and ecosystem functions highlights its indispensable role in maintaining ecosystem health, mitigating natural hazards, and supporting biodiversity.

E. Wind breaker vegetation

Windbreaks are linear structures composed of trees, shrubs, or hedges strategically planted to diminish wind speed and its associated erosive forces. They are essential components of sustainable land management systems, particularly in arid and semi-arid environments. Windbreaks offer a multitude of ecosystem services, including soil conservation, microclimate regulation, and wildlife habitat provision. By reducing wind velocity, they safeguard crops from wind-induced damage, augment soil moisture retention, and enhance crop productivity. Furthermore, windbreaks contribute to desertification mitigation through sand dune stabilization and erosion control. The efficacy of windbreaks is contingent upon factors such as species selection, planting density, and spatial orientation (K & B. P, 2014).

2.3.2.2 The General benefits of trees and other vegetation

In rapidly urbanizing landscapes, strategically planted trees demonstrably enhance the sustainability and livability of cities. These "arboreal elements" provide several ecosystem services beyond aesthetics, including environmental risk mitigation, public health benefits, and fostering social cohesion. Scientific studies support their multifaceted contributions, making urban trees crucial for building resilient cities in a changing climate.

- Improved health and well-being

Multiple studies support the positive influence of urban trees on human health and well-being. Exposure to nature, including trees, has been linked to reduced stress hormone (cortisol) levels and improved mental health by lowering anxiety and depression (Kuo, 2003). Green spaces likely promote this effect by encouraging social interaction and a sense of community. Furthermore, trees act as natural air filters, removing pollutants and improving air quality, which can lessen the risk of respiratory issues like asthma. Additionally, trees within parks and neighborhoods encourage physical activity (walking, playing), contributing to overall health and reducing the risk of chronic diseases like obesity and heart disease (Kuo, 2003). Emerging research suggests that green environments enhance immune system function (Turner-Skoff & Cavender, 2019).

The effects of vegetation on human well-being, particularly stress reduction, have been extensively investigated. (Huang , Yang, Jane, Li, & Bauer, 2020) have contributed to this field by elucidating the complex relationship between humans and the natural environment. Their findings consistently demonstrate that exposure to green spaces can lower cortisol levels, a primary stress biomarker, and diminish physiological arousal. These stress-reducing benefits are attributed to various factors, including improved air quality, enhanced mood, and increased feelings of connectedness to nature. The incorporation of vegetation into urban environments is increasingly recognized as essential for promoting mental health and overall quality of life.

- Environmental benefits

Urban trees improve environmental conditions in several ways. Their shade and release of moisture vapor through evapotranspiration can lower summer temperatures by several degrees (Turner-Skoff & Cavender, 2019) . Also, trees act as natural filters, removing air pollutants and enhancing overall air quality. Furthermore, they provide vital habitat for urban wildlife. Beyond temperature regulation, trees offer wintertime benefits by sheltering buildings and reducing wind speed, thereby minimizing heat loss (Coder, 1996). Their presence can also significantly decrease noise pollution by reflecting and absorbing sound waves, with studies suggesting reductions of up to 7 decibels per 33 meters of trees (Coder, 1996; Dwyer et al., 1992).

- Economic benefits

Trees can raise property values in neighborhoods and help to build a strong local economy by providing resources and promoting tourism. Previous researches mentioned that One healthy public tree in its 20th year after planting generates $96 in benefits while costing only $36, for an annual net benefit of $60.Also, Over 40 years, 100 healthy yard trees provide $364,000 in benefits while costing only $92,000, resulting in a net benefit of $272,000 (McPherson, et al., Midwest community tree guide: benefits, costs, and strategic planting, 2006).

Studies have indicated that homes with mature trees might fetch 8–20% more for their real estate than those with little or no trees. This appreciation likely stems from increased curb appeal, shading for energy savings, and wind protection. Furthermore, trees significantly reduce storm water runoff by intercepting rainfall through their leaves and absorbing it through their roots (Center for Urban Horticulture, University of Washington). A single mature tree can intercept thousands of liters of rainwater annually, reducing the burden on storm drains and associated infrastructure costs (e.g., Boulder, CO example). Additionally, urban trees contribute to job creation in arboriculture, landscaping, and related fields (L. Wolf) (Song, Tan, Edwards, & Richards, 2018) . Finally, attractive urban forests can boost tourism and attract businesses, increasing revenue and economic growth (Song, Tan, Edwards, & Richards, 2018).

Urban trees improve environmental health and contribute to economic well-being. They act as natural filters, removing air and water pollutants, which reduce healthcare costs associated with respiratory and other illnesses. Furthermore, trees mitigate climate change by absorbing carbon dioxide, a significant greenhouse gas. Since climate change incurs substantial economic burdens, any efforts to lessen its impact, like urban tree planting, have long-term benefits (Turner-Skoff & Cavender, 2019)**.**

Also, edible landscapes, incorporating fruit trees as components, offer significant economic advantages to urban environments. By augmenting local food production, these systems contribute to economic resilience through reduced reliance on external food sources. Fruit trees, in particular, generate revenue through direct fruit sales, value-added product development, and tourism. Moreover, edible landscapes enhance property values and attract businesses seeking environmentally sustainable and community-oriented locations. These economic benefits underscore the potential of edible landscapes, including fruit tree cultivation, to stimulate economic growth and development in urban areas (Zheng & Chou, 2023).

- Social benefits

Green spaces such as parks and tree-lined streets act as natural gathering places, making it easier for people to interact casually and fostering a sense of belonging. Community tree planting and maintenance projects also help strengthen social bonds by encouraging shared stewardship and pride in the local environment. The presence of attractive green spaces with amenities like seating and shade increases social interaction by encouraging residents to spend time outdoors and connect with their neighbors. Trees also contribute to place making, giving a community a unique identity and enhancing its aesthetic appeal, which entices residents to linger and socialize. Additionally, green spaces provide crucial benefits for children and young people, offering opportunities for play, exploration, and the development of social skills while fostering a connection to nature (

Kuo, 2003).Also, strategically planted trees can significantly enhance privacy in residential areas. Their dense foliage acts as a natural barrier, visually blocking unwanted views from neighboring properties. This creates a secluded and sheltered outdoor space where residents can relax and unwind without feeling exposed. Trees also provide a sound-dampening effect, reducing noise pollution from traffic or nearby activities. This can contribute to a more peaceful and tranquil atmosphere within the residence.

2.3.2.3 Vegetation Typologies

A multitude of studies have investigated vegetation typologies across diverse spatial scales and employing a variety of methodologies. These studies have grouped vegetation types based on factors, such as methodological approaches, spatial extent, and thermal indices like wind speed, air temperature, relative humidity, and average radiant temperature. Micro-scale investigations often incorporate more specific parameters, such as the crown size of individual plants, while large-scale studies typically rely on broader indicators like overall vegetation cover (Zhang, et al., 2022).

The reviewed studies on various scales and types of sites used a variety of vegetation parameters, such as green coverage ratio, tree configuration, and individual Characteristics of trees.

- The effect of green cover ratio on microclimate

The green cover ratio (GCR) is a metric used in urban design to quantify the amount of vegetation in a specific area. It's essentially a way to measure how much of a space is covered by plants. The green cover ratio significantly influences urban heat island (UHI) mitigation and energy consumption. Increasing vegetation cover, particularly through tree and grass planting, effectively reduces ambient air temperatures, lowering building cooling energy demand. Research across diverse climatic regions demonstrates a correlation between higher green cover ratios and enhanced cooling efficiency, with corresponding reductions in energy consumption. However, the efficacy of green cover in mitigating UHI is modulated by urban density and local climatic conditions. See table 2-1

Table 2-1: Literature addressing the percentage of green cover

Ref	Climate	Research aim	Variables	Method	Results
(Aboelataa & Sodoudic, 2019)	Hot and humid climate	The study seeks to find the best urban vegetation ratio in order to reduce the buildings' energy demand through mitigating UHI and enhancing thermal performance in high and low-density built-up areas Measure air temperature, relative humidity, wind speed, energy consumption	30% trees, 50% trees and 70% trees scenarios High-density built-up district and low density	ENVI-met model Design builder to calculate the energy consumption	Trees are effective at lowering air temperature and reducing energy usage in very high-density built-up areas, but ineffective in low-density built-up areas. The study 421 recommends using 50% trees in both urban environments in hot and humid climate if the 422 objective is enhancing thermal performance.
(Xi & Cao, 2023)	Tropical climate	The paper designed the trees-grass area ratio (TAR) and explored its effect on the benefits at the community scale The paper measure Air temperature (T), energy consumption €, and carbon emission (Ce)	0–90% trees-grass area ratio three building heights	ENVI-met model	The TAR was 90%, the maximum reduction of T, E, and Ce were 6 ◦C, 17.3%, and 20%, respectively The average air temperature reduction rate increased with the increase in TAR and building height
(Ouyang , Morakinyo, Ren, & Ng, 2020)	subtropical climate	The study discusses the cooling efficiency by measuring the relationship between greenery coverage ratio and the cooling effects of greenery	- Urban densities (Low, Mid, and High) - Tree coverage ratios (TCR) (30%, and 56%	ENVI-met model	TCR reached 20–30%, the optimal cooling efficiency of trees were achieved, irrespective of building densities and temporal periods
(Teshnehdel , Di Giuseppe, & D. Brown, 2020)	Arid and semiarid	The impact of urban greening on microclimate and pedestrian comfort in a residential district Measure air temperature and relative humidity	Four scenarios with different trees species and ratio Low Tree Cover, Moderate Tree Cover, and High Tree Cover Deciduous vs. Evergreen Trees, Broadleaf vs. Needleleaf Trees See Appendix B (figure2-1)	ENVI met v4	The study found that higher tree cover ratios, particularly when using broadleaf or deciduous species, are most effective in reducing temperatures and improving pedestrian comfort in the residential district studied. However, the optimal tree cover ratio and species selection would depend on the specific climate, urban density, and desired balance between shading, ventilation, and overall environmental comfort.

- The effect of vegetation types on microclimate

Terrestrial plant types can be broadly categorized into three dominant growth forms: trees, grasses, and shrubs. Trees are the perennial woody plants of greatest stature, possessing a single main trunk supporting a crown of branches and leaves. Grasses, in contrast, are herbaceous with non-woody stems that die back seasonally. These low-growing plants with slender leaves are characteristic of expansive grasslands. Shrubs occupy a size class between trees and grasses. They are also woody perennials, but with multiple stems branching from the base and reaching a height less than that of trees (Zhang, et al., 2022).

Table 2-2: Literature addressing the vegetation types

Ref	Climate	Research aim	Variables	Method	Results
(DR, TK, RN, & PJ, 2020)	Tropical climate	Compared the cooling effect of five vegetation types Measure Ambient air temperature	grass, shrub, managed trees, managed trees over shrub, and secondary forest	Monitoring over 18 months at 88 locations	Urban vegetation could be designed to be more “forest-like” in structure, by combining multiple layers of shrubs and small trees beneath larger tree canopies
(Liao , Tan , & Li , 2021)	Tropical climate	The Study evaluate the vertical cooling performance of different vegetation species (grass, shrubs, trees) in the residential quarter.	Grass, shrubs, trees	ENVI-met model	The cooling effect of trees is the most significant, and the vertical cooling performance is the best, followed by shrubs
(Tana, Liaoa, Bedrab , & Li, 2022)	Tropical climate	The study evaluates the 3D (horizontal and vertical) cooling performances of the three vegetation combination scenarios in the urban area Measure air temperature and relative humidity	tree-grass (TG) combination, tree-shrub-grass (TSG) combination, shrub grass (SG)	ENVI-met model	Study recommends the tree-shrub-grass combination rather than TG or SG combination in urban areas to effectively improve the thermal environment. The study also shows that the relationship between increasing tree coverage and the resulting cooling effect is not linear
(Rui , Buccolieri, Gao, & Ding, 2018)	Tropical climate	Investigates the influence of different vegetation types and layouts on microclimate and air quality in residential districts	Green cover ratio: Total vegetated area compared to the whole residential district. Grass and shrub cover ratio: Area covered by grass and shrubs composition: Types of trees, shrubs, and other vegetation present.	Computational Fluid Dynamics and the microclimate model ENVI-met	Under the same green cover ratio (i.e., the same quantity of all types of vegetation), the reduction of grass and shrub cover ratio (i.e., the quantity of grass and shrubs), replaced by trees, has a little impact on thermal comfort, wind speed and air pollution, in addition to increasing the leisure space for occupants.
(Choi, Kim , Kim, & Lee, 2021)	Humid climate	The study aims to investigate the impact of different paving and planting strategies on microclimate conditions and thermal comfort within apartment complexes	Types of plants (trees, shrubs, grasses, etc.) Density and distribution of vegetation Plant species diversity Planting location (e.g., on rooftops, along	ENVI -met model	The results indicate that grass paving was more effective than stone paving in lowering air temperature and improving thermal comfort at the near-surface level. Coniferous trees were found to be more

			sidewalks, in courtyards)		
(Binabid & Anteet, 2023)	Arid climate	Quantifying the impact of vegetation on thermal comfort in outdoor spaces at a public school situated in a hot and arid climate the research aims to assess how vegetation affects microclimate conditions, including air temperature, humidity, and wind patterns	Type of vegetation (trees, shrubs, grasses, etc.) Density of vegetation (number of plants per unit area) Height and canopy coverage of vegetation Species-specific characteristics (leaf size, canopy shape, water use efficiency)	ENVI-met 5.5	Trees proved most effective in improving thermal comfort. Compared to the base case, trees 10m high with 3.5m spacing reduced: •Air temperature by 1.4-3.2°C with maximum reduction in August. •Mean radiant temperature by 7.13-64.73°C with maximum reduction in October. •UTCI by 3.00-17.95°C with maximum reduction in April.

- The effect of vegetation configuration on microclimate

Vegetation configuration refers to the spatial arrangement of plant species within a particular area. It describes how different vegetation types (trees, shrubs, grasses, etc.) and individual plants are distributed and organized in a landscape.

Table 2-3: Literature addressing the vegetation configuration

Ref	Climate	Research aim	Variables	Method	Results
(Lai, Liao, & Yu, 2023)	Tropical climate	The study compared the microclimate and thermal comfort of green space with 17 different layouts on a typical summer day	Squared corners, arrowed corners, canopy's gaps, determinant planting, evenly distributed	ENVI-met (version 4.4.5)	The suggested to arrange the trees downstream of wind to avoid low winds at the site.
(Abdi, Hami , & Zarehaghi, 2020)	Arid and semiarid	The study examines the effect of various plant arrangements, plant type, and the direction of the rows of trees against the prevailing wind on micrometeorological conditions and thermal comfort The study examines the effect of trees located front of the building	Plant arrangements, plant type, and the direction of the rows of trees against the prevailing wind See Appendix B (figure 2-2)	ENVI-met model	The results indicated that the rectangular planting of evergreen trees in the outer rows and deciduous trees in the inner rows in a direction perpendicular to the prevailing wind produced the most optimal condition in improving outdoor thermal comfort (1.3 Predicted Mean Vote (PMV) reduction)

(Lu, Gao , Jiang, Chen, & Hao, 2023)	Tropical	This study investigated different greening cases for residential buildings in hot summer–cold winter zones.	See Appendix B(figure 2-3)	ENVI-met software	Results indicate that the greening design for determinant layout should give priority to ensuring the greening area and shortening the distance from the sidewalk. In cases where the distribution of arbors and shrubs covers a ratio of 7:4, constituting 30% of the overall green space, there is a reduction in environmental temperature by 1.4 ◦C and in PET by 4.8 ◦C.
(Yang, et al., 2022)	Humid climate	analyzes the impact of tree species and planting layout on the outdoor thermal environment in the squares	See Appendix B (figure 2-4)	Field measurements, ENVI-met software	Increasing planting density improved thermal comfort, with larger reductions in PET observed at closer tree spacing (up to 1.14°C in summer). Arranging trees perpendicular to prevailing winds enhanced ventilation and cooling.
(Zhang , Bae, & Kim, 2019)	Humid climate	This study aimed to examine how layouts of vegetation space and wind flow affect microclimate air temperature, which directly affects city dwellers' thermal comfort in summer, in a real apartment housing complex	See Appendix B (figure 2-5)	Reynolds-averaged Navier–Stokes model	when the total area of vegetation was the same, it was more effective To reduce air temperature by placing it in small units rather than concentrating it in one place, and placing small vegetation spaces close to buildings was better than locating them between buildings.

- The effect of trees physical properties on microclimate

Tree physical properties encompass a range of characteristics that define their structure, form, and material.

Table 2-4 : Literature addressing the individual trees (Physical properties)

Ref	Climate	Research aim	Variables	Method	Results
(Wang, et al., 2021)	Tropical	The study investigates the relationship between tree crown geometry and its effectiveness in mitigating heat stress.	Tree characteristics: tree crown radius (TCR), ratio of TCR to trunk height (R/TH), sky view factor (SVF), leaf area index (LAI) See Appendix B (Figure2- 6)	Field measurements were conducted on ten trees in a park during five sunny summer days in China.	R/TH was the most significant factor influencing thermal comfort. Increasing R/TH by 1 led to a PET reduction of approximately 2.5°C and 2.65°C in the morning and afternoon, respectively.

(de Abreu-Harbich , Labaki , & Matzarakis, 2015)	Tropical	Investigates how different tree planting strategies and species selection can influence thermal comfort in tropical environments, it highlights the significant impact of shading on mitigating heat stress and creating more comfortable outdoor spaces.	See Appendix B (Figure 2-7)	Field measurements	Species selection matters: Caesalpinia pluviosa emerges as the most effective species, offering significant PET reductions (12-16°C for individual trees and 12.5-14.5°C for clusters).
(Liu , Lim , Hnin Thet, Lai , & Shing Koh, 2022)	Tropical	evaluate the impact of tree morphologies and planting densities on outdoor thermal comfort in tropical residential precincts in Singapore.	Two residential precincts: A matured one with established trees (MRP) and a new one with open spaces (NRP). Four tree morphologies: Umbrella, oblong, round, and inverted cone. Varied planting densities	On-site measurements	Umbrella and oblong trees with larger canopies provide the most significant PET reduction (up to 4.35°C)

2.3.2.4 General Codes and standard of planting design

Scientific research, best practices, and local knowledge are all used to inform these tree-planting codes and guidelines. Organizations like the Arbor Day Foundation, the International Society of Arboriculture, and government forestry agencies offer valuable resources and recommendations for tree planting projects. Collaboration with local arborists, landscape architects, and community stakeholders can also help tailor guidelines to specific planting site needs and conditions. Tree planting codes and guidelines can vary depending on location, climate, soil type, and project goals (Watson, 2014).

Crucial factors influence successful and sustainable urban tree-planting initiatives. Species selection is paramount, prioritizing diversity to prevent widespread disease outbreaks that can devastate monocultures. Native species are favored due to their adaptation to local environments and their role in supporting biodiversity. Planting plans should actively promote a variety of species, typically limiting any single species to no more than 15% of the total (London, 2015). Additionally, aesthetic considerations such as tree shape and size create a cohesive and visually appealing streetscape. Planting large or messy fruit trees, excessively thorny trees, poplars, willows, or ash (Fraxinus) species is generally discouraged due to potential hazards like tripping hazards from fruit or safety concerns from thorns. Infrastructure damage and disease susceptibility are also considerations when choosing trees. Minimizing allergenic pollen production and selecting trees with appropriate branching heights for pedestrian and vehicle clearance is essential for responsible tree planting (Department of Public Works, 2011).

Several codes and standards highlight the scientific basis for strategic tree placement to optimize building energy efficiency. Key considerations include avoiding evergreen trees near south-facing elements, utilizing deciduous trees for summer shade and winter solar gain, positioning windbreaks to maximize passive solar heating, selecting shade trees for balanced light transmittance, and employing space-saving tree varieties in confined areas. Coniferous trees are preferred for windbreaks due to their year-round foliage and superior wind protection capabilities (McPherson, R. Simpson, J. Peper, & Xiao, 1999).

Appropriate tree spacing is crucial for healthy urban tree canopies and minimizing resource competition. Several factors guide optimal placement:

- Infrastructure clearance: Maintaining minimum distances from building entrances (unspecified distance) and underground utilities (minimum 0.9 meters) (Department of Public Works, 2011). Specific clearances may vary by regulation.
- Species-specific spacing: Planting trees with appropriate spacing for their mature size. Large trees require the most space (minimum 9 meters), followed by medium (minimum 6 meters), and small trees (minimum 3 meters) (Code, 2018).
- Utility line avoidance: Strictly prohibiting planting directly beneath utility lines for safety and maintenance reasons (Code, 2018).
- Adequate root space: Providing ample space for root and crown development through larger tree pits (ideally 3 meters x 1 meter or 1.5 meters) (Peper, McPherson, R. Sim, N. Albers, & Xiao, 2010).
- Planter considerations: Allowing a minimum spacing of 2 meters from the curb for trees in raised planters with proper soil and mulch containment.

- Shrub and perennial spacing: Following established guidelines for spacing shrubs (1 meter) and perennials (0.5 meters) to ensure healthy growth (McPherson R. , 2022).
- Tree clustering: Permitting closer clustering (minimum 9 meters) for large trees of the same species to create a grove effect where canopies merge (McPherson R. , 2022).
- Long-term planning: Considering future growth by planting trees with sufficient space to maintain visual distinction from neighboring trees even at maturity ("design in the fourth dimension") (McPherson R. , 2022).

Also, many criteria mentioned that urban landscapes can be optimized for rainwater interception through a focus on strategic tree selection and promoting healthy root systems. Species with morphological characteristics that enhance interception should be prioritized. These characteristics include evergreen foliage for year-round interception potential, large leaf surface area to capture more rainwater, and rough leaf textures that retain water droplets and minimize evaporation. Furthermore, planting larger trees is recommended due to their increased capacity to intercept rainfall volumes. Finally, preserving the natural state of street-side planting strips is crucial. Paving over these areas for weed control is counterproductive, as it impedes rainwater infiltration and can harm tree health, ultimately compromising their role as natural interception buffers.

2.3.2.5 Literature Review on the Effects of Vegetation

(Zou1 & Zhang, 2021) reviews on Urban Heat Island (UHI), thermal comfort, microclimate, and urban planning from the previous ten years. Also, it focuses on using landscape design strategies to mitigate the effect of the (UHI). It highlights the significance of taking particular features like canopy density, water body form, and material texture into account for the best cooling effect. Future studies should investigate their synergistic effects in different urban layouts.

Also, mentioned that (There is general agreement that natural solutions (i.e., green spaces with a tree-dominated canopy) should take precedence over other strategies for increasing urban thermal comfort due to their greater cooling intensity and range. Nevertheless, since plant species, sizes, and placements can significantly affect how well they cool, plant strategy—one of the most important tactics for enhancing thermal comfort—must be properly thought through and chosen.).

(Hamia, Abdib, Zarehaghia, & Suh, 2019) argued that the systematic review investigates the thermal comfort effects of green spaces to gain a comprehensive understanding of their impact on human comfort. The study examines existing literature to determine the impact of various green space characteristics, such as vegetation type, density, and layout, on thermal comfort results.

Green Space Configuration and Microclimate Interactions: While previous research has looked at the impact of individual green space characteristics on thermal comfort, more research is needed to understand how the configuration and spatial arrangement of green spaces within urban areas affect local microclimates and thermal comfort levels. Understanding how the size, shape, and distribution of green spaces affect temperature gradients and air movement can help urban planners and designers make more informed decisions.

Long-term Effects and Seasonal Variability: Many studies concentrate on short-term assessments of thermal comfort in green spaces, typically during specific seasons or weather conditions. Future research should look into the long-term effects of green spaces on thermal comfort during different seasons and climates. This could include long-term studies that track thermal sensations and physiological responses to capture seasonal variability and trends in thermal comfort.

The thesis by (Hamdan ElHissi, 2012) investigates the microclimatic effects of trees on the thermal performance of residential buildings in the Gaza Strip, aiming to elucidate the potential benefits of urban greening for mitigating heat stress and enhancing indoor comfort. Through a combination of field measurements, numerical simulations, and data analysis, the study examines how the presence of trees influences local microclimate conditions, including air temperature, humidity, and wind patterns, and evaluates their impact on the thermal behavior of residential structures., The findings have implications for urban design and planning strategies in the Gaza Strip, emphasizing the importance of integrating trees and green spaces into residential neighborhoods to improve microclimate conditions and enhance human well-being.

The study suggested that the future research should focus on the development of urban greening guidelines tailored specifically in Palestine context. These guidelines could provide recommendations for the strategic placement of trees and green spaces in residential neighborhoods to optimize their microclimatic effects and enhance thermal comfort for residents. Moreover, the guidelines could address factors such as tree spacing, canopy coverage, and maintenance practices to ensure the long-term viability and effectiveness of urban greening initiatives.

Also, Future studies could investigate how urban greening can help mitigate heat waves, reduce urban heat island effects, and enhance resilience to extreme weather events such as heat waves and droughts. This could involve scenario-based modeling to assess the effectiveness of different tree planting scenarios in mitigating future climate risks and informing adaptive planning and design strategies for the built environment (Hamdan ElHissi, 2012) .

2.4 Summary

This chapter explored the critical link between urbanization and the detrimental urban heat island (UHI) effect. Unchecked urban sprawl replaces natural landscapes with heat-absorbing materials, leading to significantly higher temperatures in cities compared to rural areas. This decline in outdoor thermal comfort poses a health risk, particularly during heatwaves.

Also, it focused on mitigating UHI through strategic planting design. Vegetation plays a key role by providing shade, promoting evapotranspiration (water vapor release), and creating wind corridors for improved air circulation. While specific planting design codes may vary by region, general principles regarding vegetation selection remain crucial. These principles often extend beyond cooling strategies and encompass the physical properties of trees in the urban environment. For example, some codes may specify considerations like mature tree height, root structure, and potential for interference with underground utilities.

Finally, the chapter emphasized the importance of wind comfort when designing green infrastructure. Carefully arranged vegetation can channel prevailing winds, further enhancing air circulation. Beyond UHI mitigation, trees offer numerous benefits, including improved air quality through pollutant filtering, increased biodiversity by providing wildlife habitat, and enhanced aesthetics for a better overall quality of life.

Chapter 3

Urban heat island and thermal comfort in Palestine

Chapter 3

Urban heat island and thermal comfort in Palestine

3.1 Preface

Studying Palestine's urban heat island (UHI) phenomena and thermal comfort is now essential to understanding the complex relationships between urbanization, climate dynamics, and human welfare. These studies are dedicated to quantifying temperature variances between urban and rural locales while scrutinizing influential factors like land use patterns, building materials, and socio-economic indicators that impact the intensity of UHI effects.

This chapter seeks to elucidate the impact of urbanization on the formation of urban heat islands (UHIs) and its subsequent effects on thermal comfort within Palestine. It aims to delineate the intricate relationship between rapid urban development, elevated temperatures in urban areas, and their implications for human comfort and well-being. Additionally, this chapter will investigate the efficacy of planting initiatives as a mitigation strategy against UHI effects in Palestine.

3.2 Urban heat island versus urbanization in Palestine

Palestinian cities are grappling with the challenges of rapid urbanization, driven by a high population growth rate estimated at around 3% – exceeding global averages. This surge, coupled with limitations on land availability due to the ongoing occupation (Shaheen, 2013), presents a complex scenario for sustainable development. Consequently, urban sprawl often occurs at the expense of valuable agricultural land. Studies report a concerning conversion rate, with agricultural land being transformed into urban areas at a rate exceeding 27% within ten years (Nassar, Levy, Keough , & N. Nassar, 2017).

Employing Geographic Information Systems (GIS) data, (Nassar, Levy, Keough , & N. Nassar, 2017) investigated land-use cover changes within Tulkarm City, Palestine. Their analysis revealed a substantial transformation in land use patterns. Over ten years (1999-2009), urban and built-up areas exhibited a significant expansion of 54%. This growth coincided with a decrease in agricultural land cover of 27%, suggesting a primary source for urban development. These results demonstrate the tendency of Tulkarm City's fast conversion of agricultural land to urban sprawl.

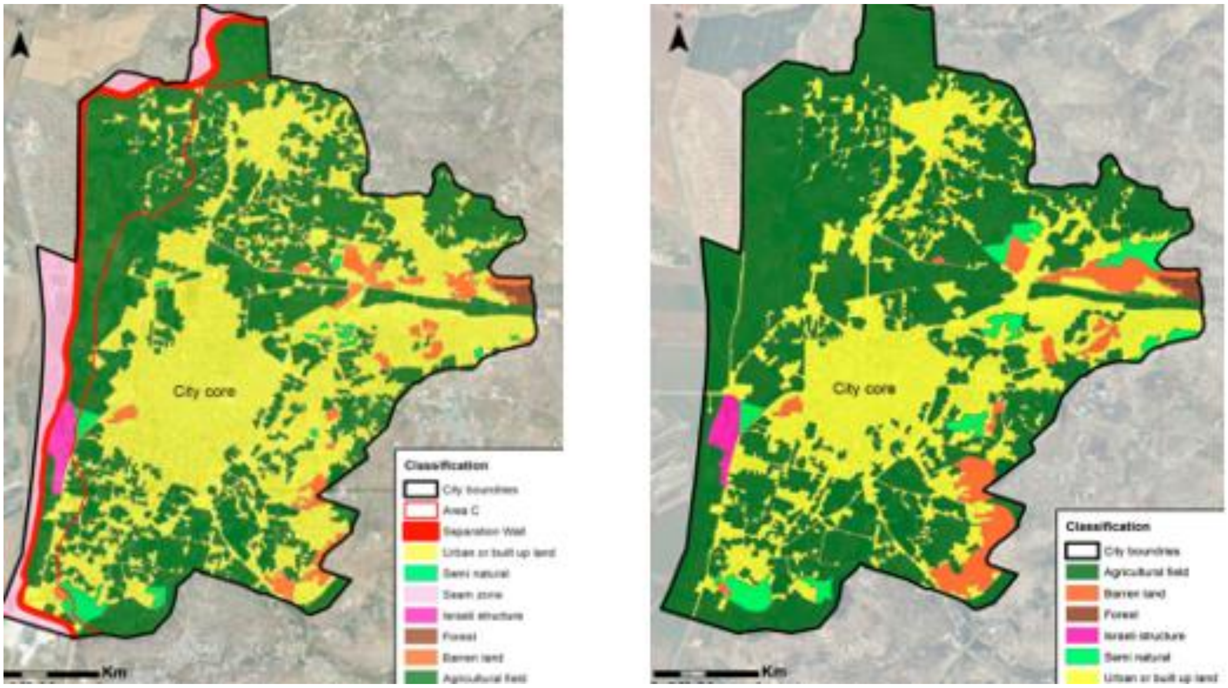


Figure 3-1 : Classified Image Showing LUCC Categories of Tulkarm- 2009-1999 *(Nassar, Levy, Keough , & N. Nassar, 2017)*.

Also, a study was conducted to assess land-use cover changes in the Ramallah region of Palestine using aerial images from 1994 and 2014. The study revealed a significant shift towards urbanization, with over 52% of the area experiencing noticeable urban development. This process had an impact on the landscape, in particular, after 1993. Agricultural lands, such as olive groves and grasslands, decreased considerably, while urban surface areas increased sharply by over 140%. These findings indicate a trend of landscape fragmentation caused by land-use changes associated with urban expansion in the Ramallah area (Nazer, Abughannam, & Khasib, 2018).

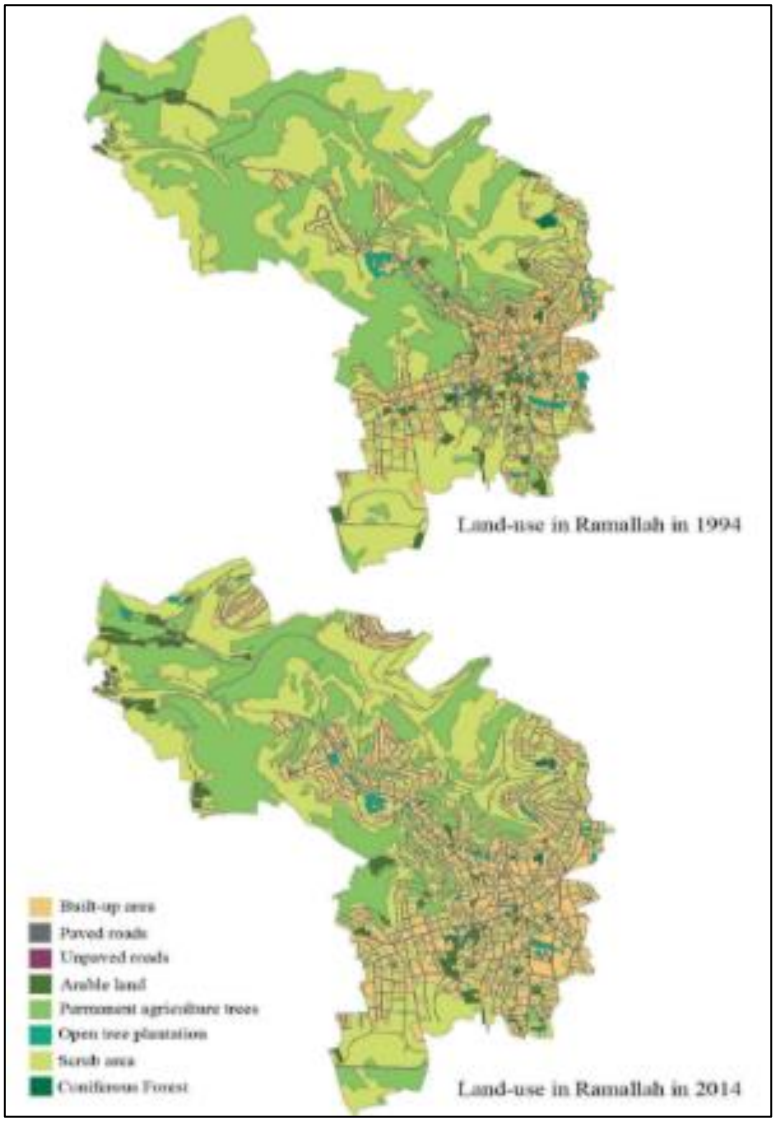


Figure 3-2:. Landscape change between the years 1994 and 2014 in Ramallah *(Nazer, Abughannam, & Khasib, 2018)*

Additionally, a study examining land-use/land-cover change within the Jenin Governorate, a vital agricultural region of Palestine, (Thawaba, Abu-Madi, & Özerol, 2017) identified a concerning trend. Their research suggests a significant conversion of agricultural land for urban development. This finding is particularly noteworthy considering the dominance of rain-fed agriculture in the West Bank, where it constitutes approximately 87% of cultivated land. While the specific percentage of land-use cover change towards urbanization isn't explicitly stated in the study, it emphasizes the urgency of addressing this issue for the future of Palestinian agriculture.

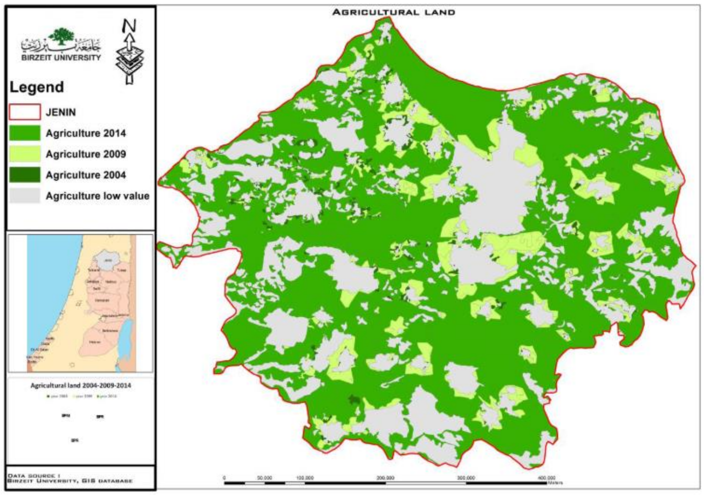


Figure 3-3: Agricultural land changes in Jenin Source: Birzeit University, GIS database

This trend disrupts natural cooling mechanisms within cities. The decline in green spaces and the corresponding increase in built-up areas with high heat absorption capacity, such as concrete and asphalt (Shaheen, 2013), which are up to 60% of urban land cover in some Palestinian cities disrupts natural cooling mechanisms. The transformation of the urban landscape is likely to exacerbate the urban heat island (UHI) effect, potentially leading to temperature differentials of up to 10°C between urban and rural areas during peak summer months (Al Abadla, Schlink, Abdel Wahab, & Robaa, 2020).

These studies provide empirical evidence of the accelerating loss of green spaces and concomitant expansion of streets and built-up areas throughout the West Bank. This trend exacerbates climate change and rising temperatures, underscoring the critical need for comprehensive research to assess the impacts of urban expansion in the region. The findings emphasize the imperative of implementing green infrastructure solutions, such as tree planting, to mitigate these challenges.

3.3 Thermal Comfort in Palestine

A key concern associated with the urban heat island (UHI) effect in Palestinian cities is its negative impact on outdoor thermal comfort for residents. Studies like the one conducted by (Al Abadla, Schlink, Abdel Wahab, & Robaa, 2020) in Tulkarm provide a quantitative assessment of this impact. Their research employed established thermal comfort metrics such as Physiologically Equivalent Temperature (PET), Thermal Discomfort Index (DI), and Universal Thermal Climate

Index (UTCI). These data provide a full assessment of the human thermal experience, considering air temperature, humidity, wind speed, and solar radiation. The findings from Tulkarm revealed a significant decrease in comfortable outdoor conditions during the summer months, with over 50% of the urban population experiencing thermal discomfort according to the applied metrics (Al Abadla, Schlink, Abdel Wahab, & Robaa, 2020). The study highlights the urgency for developing mitigation strategies to address the UHI effect and create a more thermally comfortable outdoor environment for Palestinian residents, particularly during the extended hot summer periods.

3.3.1 Planting design in Palestine

Throughout millennia, trees in Palestine have played a central role in cultural development and economic well-being, serving as essential sources of sustenance, shade, and raw materials. The enduring olive groves and meticulously maintained orchards on terraced landscapes exemplify the profound influence of arboreal elements on agricultural practices and cultural identity. However, geopolitical conflicts and environmental pressures have resulted in significant challenges, such as deforestation and biodiversity loss. (Fernley-Pearson, 2010) research emphasizes the necessity of implementing sustainable agroforestry practices to conserve Palestine's arboreal heritage and promote resilience against emerging environmental threats.

Figure 3-4: Orchards of Battir, Palestine shows the terrace and natural agriculture *(Fernley-Pearson, 2010)*

(Fernley-Pearson, 2010) extensive research on agroforestry in Palestine illuminates the intricate design methodologies and cultivation techniques utilized in the region. Leveraging both traditional wisdom and modern innovations, Palestinian farmers have devised refined strategies to enhance the productivity and sustainability of their ecosystems. One noteworthy design approach is the incorporation of trees in agricultural landscapes, a practice deeply entrenched in Palestinian heritage and historical practices. This integration serves manifold purposes, including soil preservation, regulation of microclimates, and augmentation of agricultural diversity. Additionally, Fernley-Pearson emphasizes the significance of selecting "favorable trees" – species adept at local conditions, resilient to environmental pressures, and offering valuable ecosystem services.

Also, techniques such as terracing, mulching, and intercropping are utilized by farmers to optimize land use efficiency and enhance soil fertility. Terracing enables cultivation on steep slopes while minimizing soil erosion and water runoff. Intercropping trees with annual crops promote biodiversity and provides additional income sources for farmers. Fernley-Pearson emphasizes the importance of agroforestry for enhancing food security, mitigating climate change impacts, and preserving cultural heritage in Palestine.

Photo: Terraced slope, Beit Jala

Figure 3-5: Olives cultivated on a terraced slope, Ayn il-Hawiyah, Husan *(Fernley-Pearson, 2010)*

Also, Fruit stone planting, a traditional agricultural technique, offers a sustainable pathway for regenerating agroforestry systems in Palestine. This method entails the propagation of fruit trees from seeds extracted from stone fruits, including peaches, plums, cherries, and apricots. Seed viability is carefully assessed before cleaning and stratification, a cold treatment that overcomes seed dormancy. Subsequently, the prepared seeds are sown in fertile, well-drained soil for germination and subsequent tree development. Given the scarcity of agricultural land and water resources in Palestine, fruit stone planting emerges as a viable strategy for enhancing biodiversity, bolstering food security, and supporting local livelihoods within agroforestry frameworks (Fernley-Pearson, 2010).

Moreover, ornamental plants hold significant cultural, aesthetic, and ecological value in Palestinian landscape design. The incorporation of locally adapted species enriches public and private spaces while preserving regional heritage. These plants, selected for their suitability to the Mediterranean climate, offer multiple benefits including shade provision, erosion control, and microclimate amelioration in urban and rural settings. Notably, the preference for native and drought-tolerant ornamental plants aligns with water conservation strategies, promoting sustainability in a water-scarce region (Fernley-Pearson, 2010).

3.3.2 Planting design codes and standards in Palestine

Despite the pivotal role of Palestinian building regulations in construction practices, it is noteworthy that there are no specific guidelines and standards addressing planting design. However, existing resources offer insights for integrating sustainable planting strategies. An example is the "Green Buildings Guidelines – State of Palestine," which, while primarily focused on promoting sustainable construction practices, often includes sections dedicated to landscaping. While not strictly comprising planting design codes, these sections address essential considerations such as plant selection and soil health.

3.3.3 Social life versus Planting design

Within Palestinian culture, strong social bonds are highly esteemed and typically nurtured within communal spaces such as marketplaces and majlises (Khalidi, 2008). Leveraging biophilic design principles, which underscore the importance of connecting with nature, can bolster the prevailing social fabric (R. Kellert & F. Calabrese, 2015). Thoughtfully planned public gardens and parks, guided by these principles, have the potential to emerge as vibrant centers for social engagement.

Research suggests that proximity to green spaces facilitates social cohesion by facilitating casual interactions and encouraging community gatherings (Frumkin et al., 2017).

Furthermore, incorporating elements that resonate with Palestinian cultural heritage can strengthen the place attachment between residents and these green spaces, planting fragrant herbs traditionally used in Palestinian cuisine or incorporating native trees referenced in folklore can foster a sense of ownership and cultural identity (Yaghmour, 2019). By creating aesthetically pleasing and culturally relevant green areas, planting design has the potential to serve as a tool for cultivating a more vibrant and socially connected Palestine.

In Palestine, trees like olive, fig, poplar, carob, and mulberry are integral to both the ecosystem and the cultural fabric of the region. The olive tree is particularly sacred, symbolizing peace, resilience, and connection to the land, and it plays a crucial role in the economy through olive oil production. Figs provide essential nutrition and have been cultivated for generations. Poplars are valued for their wood and shade, while carob and mulberry trees contribute to biodiversity and sustainable agriculture, offering fruit and supporting wildlife. These trees collectively enhance environmental stability and cultural heritage in Palestine (Nazer S. , 2008).

3.4 Summary

This chapter focused on the issues of growing urbanization in Palestine, where fertile land is transformed for building, disrupting natural cooling and reducing outdoor comfort. Planting design stands out as a possible approach. Traditional agroforestry techniques, such as planting trees save soil and control microclimates.

While there are no formal planting design rules, publications such as the "Green Buildings Guidelines" offer advice on plant selection, water saving, and soil health, which can be used in planting designs, and Public green areas constructed with biophilic principles can promote social interaction and community by promoting meetings. Furthermore, adding parts of Palestinian cultural history increases inhabitants' connections to these locations.

Chapter 4

Research methodology

Chapter 4

Research methodology

4.1 Research type and process

This chapter details the methodological framework employed in this study. It outlines the data collection procedures and simulation protocols utilized to evaluate the thermal performance of existing outdoor spaces within a residential context. This evaluation serves as a baseline for the subsequent investigation into the thermal performance of optimal tree typologies within residential building outdoor spaces, which forms the core objective of this thesis.

Also, it elaborates on the data acquisition methodology, providing a comprehensive overview of the rationale and techniques employed. It details the selection process and justification for the chosen simulation model, along with a description of the thermal modeling procedure and the specific simulation engines utilized.

This study employs a quantitative research approach to investigate the potential for mitigating outdoor temperatures through the strategic integration of optimal tree typologies. Data gathering involves on-site observation techniques, physical surveys, and the collection of building samples. Subsequently, this data informs the evaluation of the impact of various tree typology scenarios within the building samples on thermal comfort.

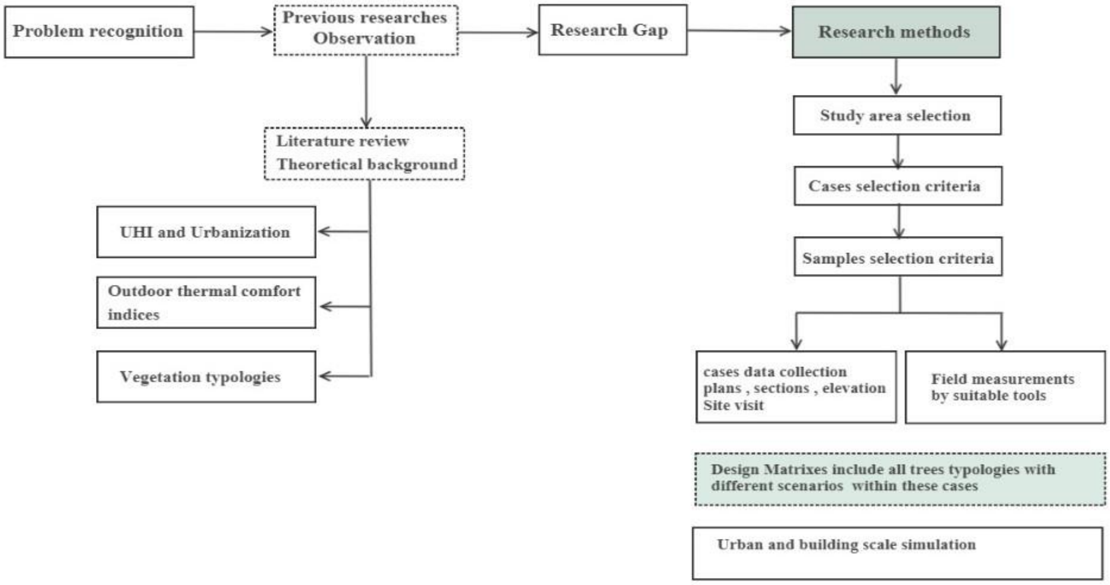


Figure 4-1 : Research process

4.2 Study area selection

Hebron City in Palestine was selected as the study area for several reasons. The researcher lives nearby, making it easy to visit and collect data. Additionally, there isn't much information regarding how to use trees to improve temperatures in outdoor public spaces.

According to building on the established variation in climatic conditions across Palestinian topographical regions documented by Dear et al. (2013), this study has the potential for replication so as to generalize to Hebron City and other Palestinian cities sharing similar topographical and geographical characteristics.

Figure 4-2:Palestine map

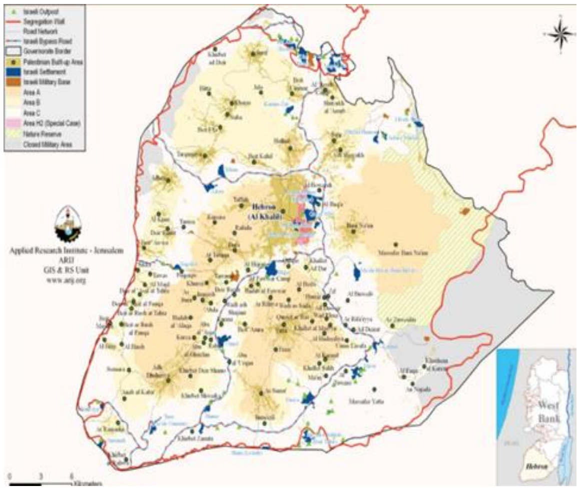


Figure 4-3:Hebron government map

(https://www.worldatlas.com/maps/palestine)

4.3 Cases selection criteria

According to (Palestinian Central Bureau of Statistics, 2023), Palestine's population, numbering 5.48 million as of mid-2023, predominantly dwells in urban areas, with 78% residing in cities. This urban concentration manifests in a notable national population density of 910 people per square kilometer, revealing significant differences between regions; the West Bank registers 575 people/km². This urbanization trend has spurred the dominance of apartments as the primary housing type, accounting for over 54% of housing in 2023. This shift is driven by the need for space-efficient solutions in these densely populated areas compared to detached houses, which constitute 43% of housing.

Informed by the findings of (Sabrin, Karimi, Nazari, Pratt , & Bryk, 2021), this study focuses on residential buildings as the context for examining tree typology scenarios. This selection is driven by several key factors. Firstly, residential areas constitute a significant portion of urban landscapes, exerting a substantial influence on overall microclimate dynamics. Secondly, residential buildings typically encompass diverse outdoor spaces, such as courtyards, gardens, and parks, offering ideal locations for strategic tree integration to provide shade and mitigate heat. Finally, residential communities represent a broad spectrum of demographic and socio-economic backgrounds. Investigating tree typologies within these settings allows for a comprehensive understanding of their effectiveness in enhancing canopy-level thermal comfort and cooling benefits across diverse urban populations.

A purposive sampling approach was implemented which involved an initial reconnaissance survey of residential complexes containing apartments. Based on this survey, common case studies were identified based on several criteria:

- Common Palestinian buildings in Hebron have a limestone as the dominant material for external cladding.
- Common Palestinian buildings typically incorporate windows sized 1-2 meters wide and 1-1.5 meters high.
- The average setback of 3-4 meters between buildings.
- Floor height of 3 meters.
- The type of housing is apartments with floor levels typically range from 4 to 8 meters

4.4 Samples selection criteria

Three residential complexes were selected from Hebron for this study. The selection process employed several criteria to ensure the chosen cases represent common typologies within the city.

- The location must be situated within urban areas, distinct from rural area.

- The space should be encircled by residential buildings ranging from four to eight floors in height, which represent the typical numbers of floors in Hebron.
- The compound's space must be bordered by two to four blocks.

By the aforementioned criteria, three outdoor spaces were chosen within two common cases of residential compound in Hebron City (King Abdullah residential neighborhood and Housing orphans in Duer Ban) for the evaluation of various tree typology design scenarios.

Outdoor spaces were chosen with consideration for variances in area sizes and architectural morphologies. The selection method considers the quantity and spacing of residential buildings that surround the spaces.

Both cases are situated within the urban fabric of Hebron City, Palestine, within an urban zone distinct from rural areas.

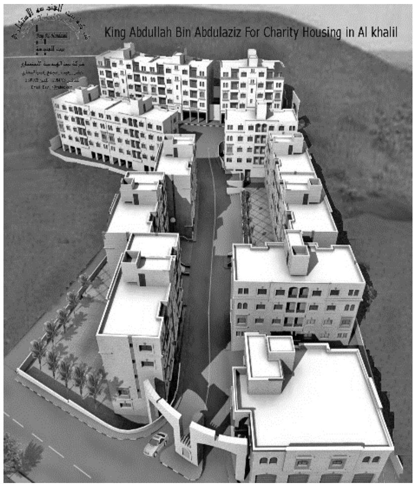


Figure 4-4: King Abdullah residential neighborhood

Figure 4-5: Housing orphans in Duer Ban (Source from the researcher)

4.5 Data collection and analysis criteria

Data about the two residential neighborhoods were obtained from the relevant administrative offices. This involved gathering architectural plans and general details about each neighborhood, such as material and construction details.

A comprehensive field study was conducted in all cases, involving bi-monthly visits throughout March, April, and May. During these visits, temperature and humidity data were collected on days characterized by high temperatures. Subsequently, thermal comfort indicators were calculated using the collected data. An assessment of occupant thermal satisfaction in the study area was conducted by calculating thermal comfort indices, specifically the Predicted Mean Vote (PMV) and the Predicted Percentage of Dissatisfaction (PPD).

Average temperature and relative humidity readings were measured by using wireless weather station as a measurement tool for each case. Notably, observations in the King Abdullah bin Abdulaziz neighborhood revealed high levels of occupant dissatisfaction with the thermal performance of the outdoor spaces on most days. These findings are presented in the following table 4-1.

Table 4-1 : Thermal comfort indicators in King Abdullah bin Abdulaziz neighborhood outdoor spaces

Date	27-March	31-March	3-April	25-April	21-May	10-May
Operative temperature ©	27	31	29	37	27	35
Relative humidity %	34	22	40	37	58	39
PMV	0.73	1.74	1.34	3.64	0.85	3.09
PPD	16.3	64	42.3	100	20.3	99.5

Furthermore, field measurements were collected in the orphanage housing outdoor space. The collected data is presented in the table below. Thermal comfort indicators were subsequently calculated using a thermal comfort calculator.

Table 4-2 : Thermal comfort indicators in orphanage housing outdoor spaces

Date	27-March	31-March	3-April	25-April	21-May	10-May
Operative temperature ©	28	31	31	38	29	35
Relative humidity %	40	30	43	40	58	40
PMV	1.07	1.83	1.96	4	1.52	3.11
PPD	29	68.7	75.1	100	51.7	99.5

After calculating the thermal comfort indices for the outdoor areas in both cases, it was found that the occupants' thermal perception ranged from hot to very hot on most of the measurement days. Additionally, the percentage of dissatisfied occupants exceeded 20%, highlighting the study's significance and the potential of trees to mitigate thermal discomfort.

Contrary to expectations, despite the presence of green spaces and tree elements in the orphanage’s, measured temperatures were higher compared to the King Abdullah neighborhood, which lacked green spaces. This observation emphasizes the importance of the study in understanding the optimal composition and selection of trees for maximizing thermal comfort.

Figure 4-6 : Green space in orphanage) Source from the researcher)

Figure 4-7: The lack of green spaces in King Abdullah bin Abdulaziz neighborhood(Source from the researcher)

4.6 Trees typologies scenarios design

Tree typology scenarios were developed depending on the standards and codes outlined in the theoretical background. These scenarios prioritize appropriate spatial arrangements between trees, acknowledging the critical role of size-dependent spacing. This emphasis on size reflects the codified understanding within the referenced standards that tree morphologies, particularly crown spread and root system dimensions, are crucial determinants of optimal placement.

Deciduous trees were employed as a constant variable in the study due to their demonstrated efficacy in regulating temperature during both summer and winter seasons. These trees effectively reduce temperatures during the summer months while exhibiting minimal impact during winter.

The scenario design incorporated several variables, including:

- Green coverage ratio (Cr): Vegetation cover was referred to by various names in some studies, including vegetation cover fraction, vegetation cover ratio, and vegetation coverage, all of which measured the percentage/ratio of vegetation cover. In all studies, vegetation cover was calculated by dividing the area of vegetation by the total site area, which could be a district, a street, a park, etc. Two green coverage ratios have been established: 20% and 40%, the green space percentages within the study were determined based on the design criteria for pedestrian pathways within each outdoor space.
- Arrangement(A): Plant spacing strategies were evaluated based on several key factors: wind direction relative to planting, horizontal spacing between plants, and vertical spacing between planting layers. Three specific arrangements were adopted for the study: one aligned with the wind direction, another perpendicular to the wind direction, and a third employing clustered planting patterns.
- Crown shape (Cs): Tree crown shape refers to the overall outline or silhouette formed by the branches and foliage of a tree when viewed from a distance, such as conic, spherical, cylindrical, or Irregular.

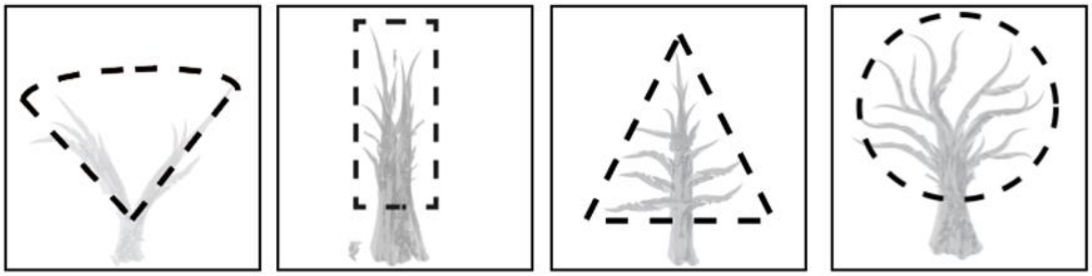


Figure 4-8 : Trees crown shapes variables (Heart, cylindric, conic, spherical)

- Crown density (D, S): quantifies the degree of foliage occupancy within the upper canopy of a tree. This metric exhibits substantial variation attributable to several factors, including species, tree age, health status, and environmental conditions. Classifications of crown density encompass high density, indicative of a thick and luxuriant canopy, and low density, signifying sparse foliage cover.

- Trunk size (Ts): In trees, trunk diameter or circumference, typically measured at breast height (DBH), serves as a proxy for overall tree size. The study investigated trees across a spectrum of size classes, including small, medium, and large.
- Trees height (H): Tree height classification typically categorizes trees based on their ultimate mature height. While classifications can vary slightly depending on the source,
  - Low (L): Like grassland (<1 m)
  - Medium (M): Like shrubs (1-2 m)
  - High: (h): h1: 2-10 m, h2: >10 m

The scenario design incorporates several matrices containing various variables. The first matrix focuses on the interplay between green coverage percentage and spatial arrangement due to the relationship between these variables influencing tree-to-tree spacing and the distance between trees and open spaces. Notably, the tree is kept constant within the matrix to study the effects of green space coverage and spatial arrangement.

Subsequent matrices incorporate variables about the diverse physical characteristics of trees. This approach aims to identify the optimal outcome from each matrix while isolating the influence of each tree characteristic on the building's thermal performance, encompassing both internal and external environments.

Deciduous trees were the primary selection for this study, leveraging their documented advantages in both summer and winter. However, to isolate the influence of crown shape within courtyards, evergreen trees with conical canopies were employed for specific investigations focused on this factor. Moreover, the grass was included in every scenario because, as the theoretical basis explains, it works well to protect root systems and encourage precipitation drainage.

A constant distance was maintained between trees and building across all scenarios and study cases. This standardization facilitates the isolation and precise evaluation of the impact of scenario design on the overall outcomes.

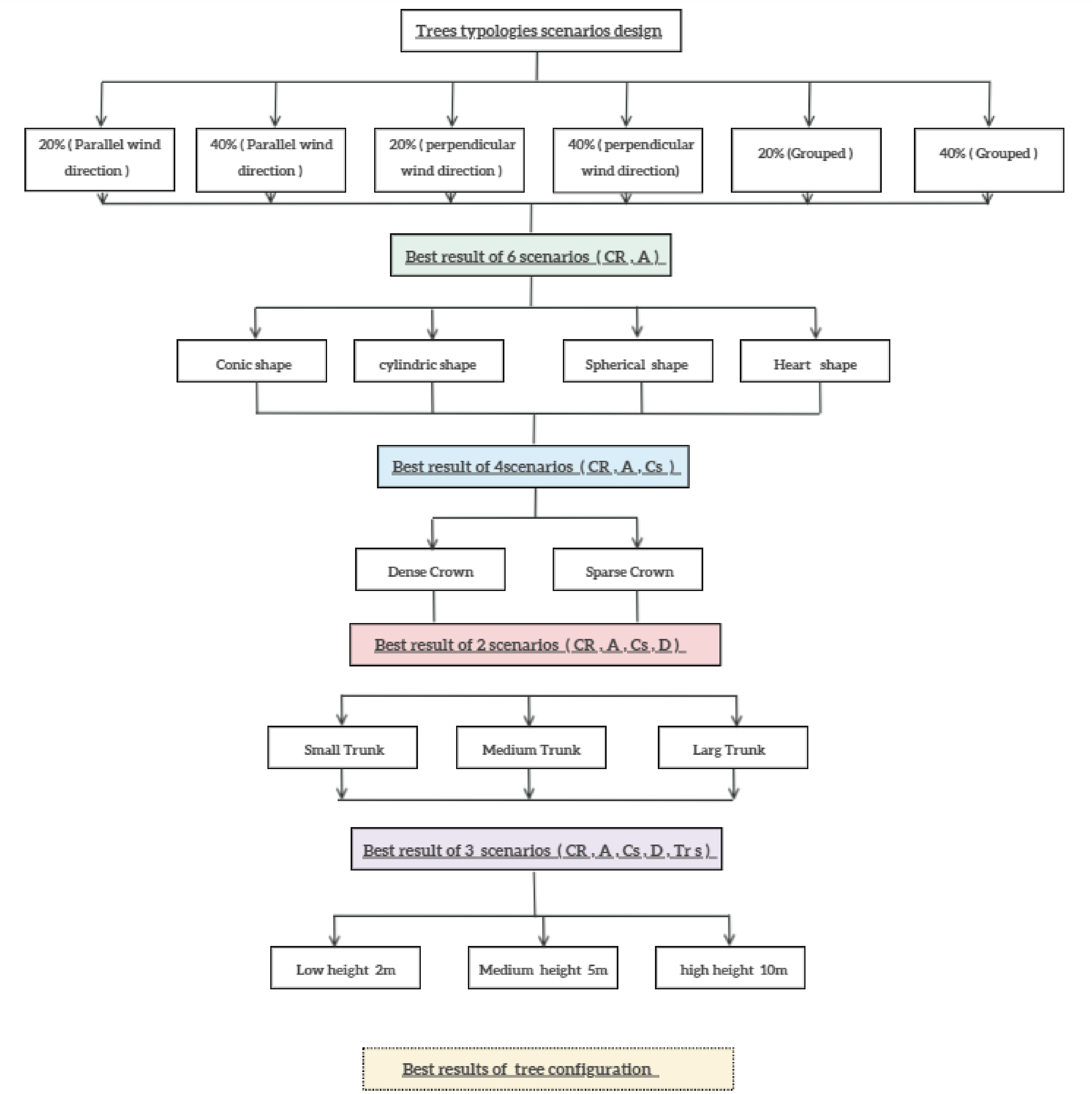


Figure 4-9: Tree typologies scenarios stages

4.7 Model simulation process

Employing the Envi-met software, the urban and building scale simulation modeled various microclimatic aspects, including temperature, humidity, wind speed, and solar radiation distribution. Envi-met further incorporates the intricate interactions between buildings, vegetation, and other urban elements. This capability facilitates the investigation of how urban greening strategies, such as parks and trees, influence local climates. The software additionally offers functionalities to assess mitigation strategies for heat islands, evaluate measures to improve air quality and enhance urban resilience to climate change impacts.

Sensor placements were strategically selected to cover areas adjacent to building facades and open spaces. Every sensor data point accurately represents the microclimatic conditions of its immediate vicinity, facilitating subsequent analysis of spatial fluctuations in thermal comfort across the outdoor space.

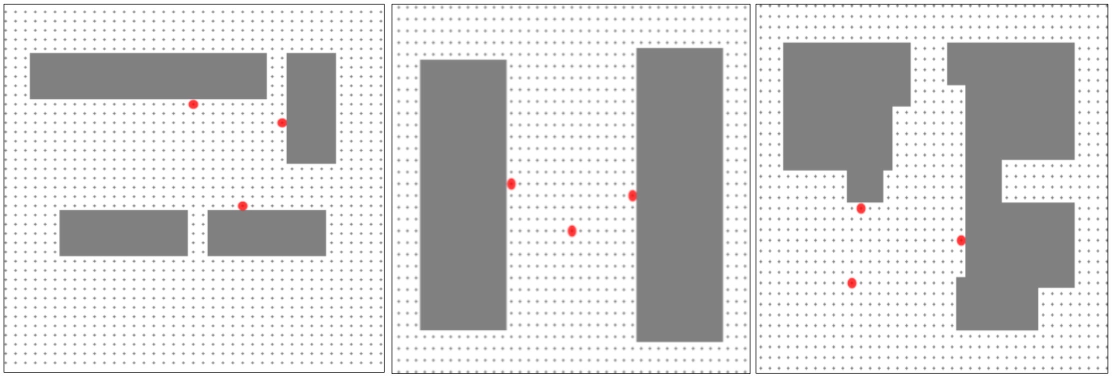


Figure 4-10 : Cases site plan shows the sensors location point

A three-sensor was established within the outdoor space to investigate the vertical profile of thermal comfort conditions. Sensor placement heights were selected to represent occupant experience zones: 1.8 meters corresponding to the typical standing height of an adult, 7 meters aligning with the third-floor pedestrian level, and 13 meters coinciding with the fifth-floor pedestrian level. This approach allows for the comprehensive assessment of thermal comfort variations across different occupant positions within the outdoor space.

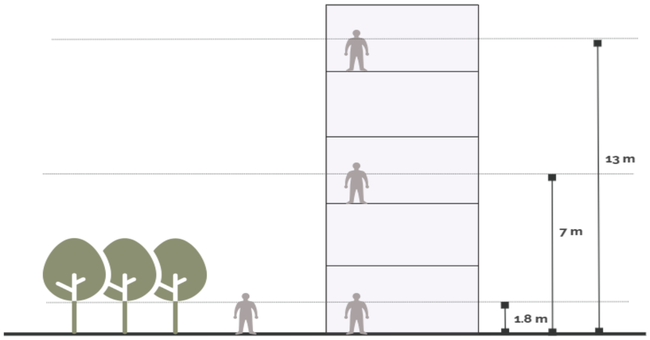


Figure 4-11 : Sensor’s height level (Ground, third and fifth floors)

A computational simulation was conducted to establish a baseline for thermal conditions within an outdoor space of a residential complex. The scenario simulated an open space devoid of natural elements and trees during summer (12:00 pm/16-7-2-2021) and winter (12:00 pm/ 21-12-2021). The selection of dates and days for the study was informed by historical weather data, identifying July 21, 2021, as the years warmest day and December 21 as the coldest. The initial simulation serves as a control for subsequent simulations that incorporate various tree typologies. By comparing the thermal conditions of the baseline scenario with those featuring different tree types, the study aims to quantify the influence exerted by vegetation on the outdoor thermal environment.

As Envi-met program is limited in its ability to simulate indoor environments, Design builder program was employed to evaluate the interior thermal comfort coefficients of the spaces and quantify the influence of the tree scenarios on these indoor conditions.

A single case study was chosen for a focused simulation to evaluate the effectiveness of tree scenarios in influencing internal space conditions.

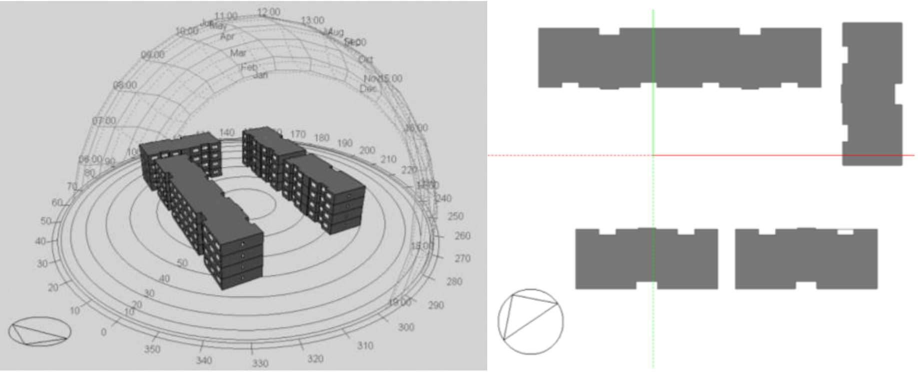


Figure 4-12: case 1 simulation model by design builder program

The simulation employed weather data from Jerusalem due to the absence of a weather file specifically for Hebron City. According to Weather-Spark (2019), 67% of Hebron's climatic data aligns with Jerusalem.

To validate the model's accuracy, an on-site evaluation was conducted within the indoor space. This evaluation involved collecting temperature measurements using a wireless weather station.

4.8 Model validation process

A simulation approach was employed at both the urban and building scale to assess and compare scenarios involving various tree types. For model validation purposes, a field visit was conducted within the outdoor space. This on-site evaluation involved the collection of temperature and humidity measurements using a wireless weather station. The data collection process itself was carried out on April 2, 2024.

Figure 4-13: Wireless weather station (Measurement tool) (Source from researcher)

4.8.1 Urban scale validation process

Leveraging existing case studies, the simulation process incorporated comprehensive weather data, location information, and detailed building specifications. These specifications included building layout, construction materials, and outdoor space materials. The Envi-met software was used in this stage.

On April 3, 2024, at 15:00 hours, simultaneous field measurements of outdoor space temperatures were conducted across all case studies. Measurement points were established throughout the spaces. Weather data for that specific date and time was incorporated into the Envi-met program to simulate space temperatures. The resulting simulations were compared with the field measurements to assess the program's accuracy.

- Validation results of area (1) in King Abdullah Ben Abdul-Aziz residential complex

Figure 4-14 depicts the spatial arrangement of temperature measurement stations within the outdoor environment. Furthermore, a corresponding simulation of temperature distribution for that day is presented and generated using the Envi-met program.

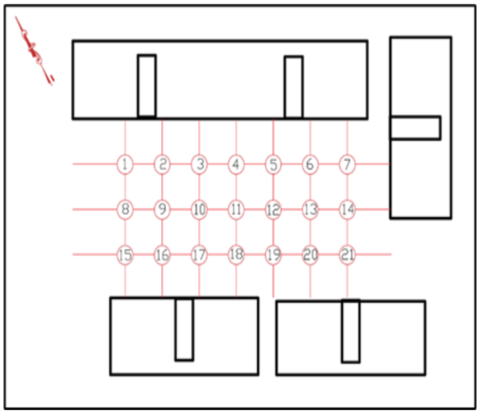


Figure 4-14: Area (1) in King Abdullah Ben Abdul-Aziz residential complex showed measurement point

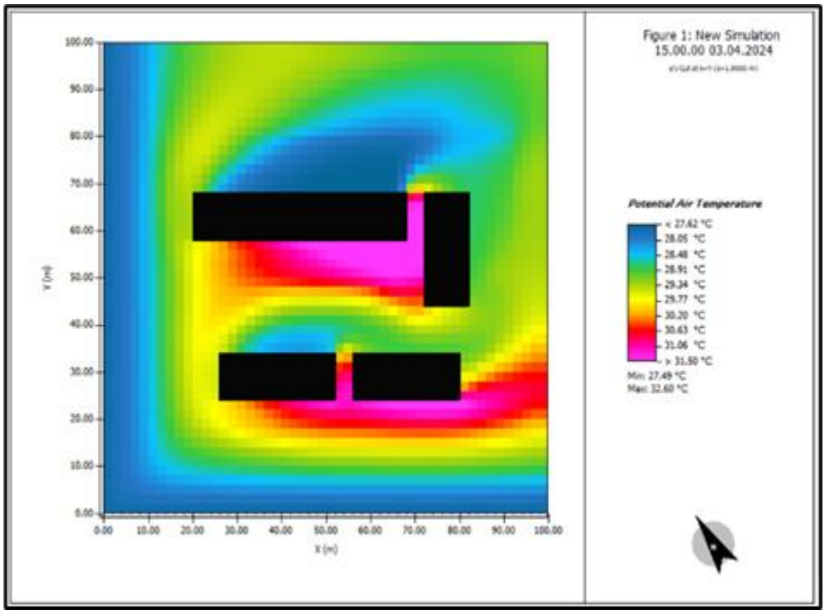


Figure 4-15: Area (1) in King Abdullah Ben Abdul-Aziz residential complex model validation

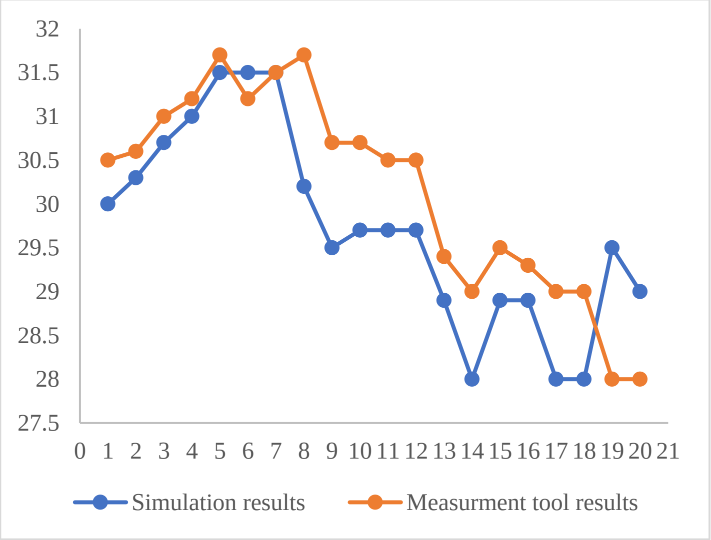


Figure 4-16: Chart show the deviations between the simulated temperature distribution and the field data.

Discrepancies of up to 1-0.5 degrees Celsius were observed between the device (weather data station) readings and the simulation program at most data points. Field measurements consistently yielded higher temperatures compared to the simulated results. These deviations may be attributed to several factors.

Incomplete Model: The simulation program might not have encompassed the entire residential complex due to limitations in handling large areas. It could have resulted in a less detailed representation of the environment, potentially leading to underestimates in temperature. A single outdoor space model was created within the program, suggesting that other external spaces were simplified as open areas.

External Influences: The presence of elements within the outdoor space, such as parked cars and concrete structures, could have introduced thermal variations not accounted for in the simulation. These elements can absorb and radiate heat, influencing the local temperature profile.

Figure 4-17: area (1) in King Abdullah Ben Abdul-Aziz residential complex showed parked cars and concrete structures (Source from researcher)

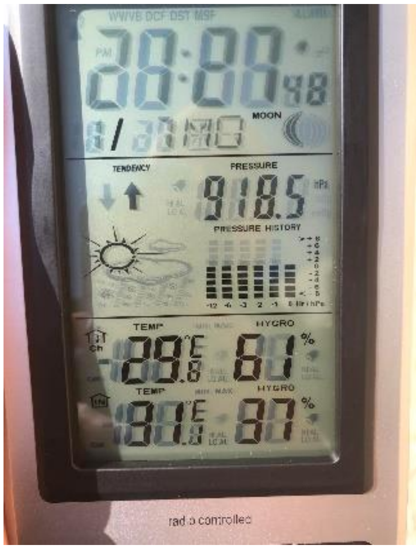


Figure 4-18: Wireless weather station shows temperatures reading (Source from researcher)

- Validation results of area (2) in King Abdullah Ben Abdul-Aziz residential complex

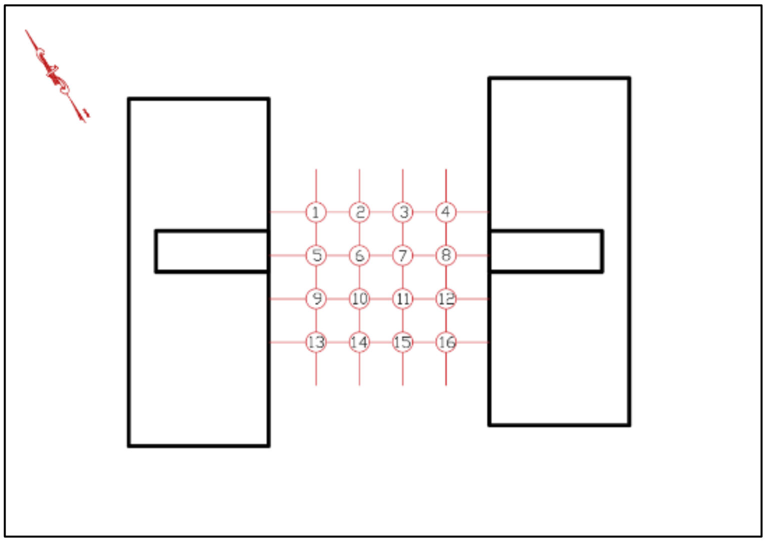


Figure 4-19 :Area (2) in King Abdullah Ben Abdul-Aziz residential complex showed measurement point

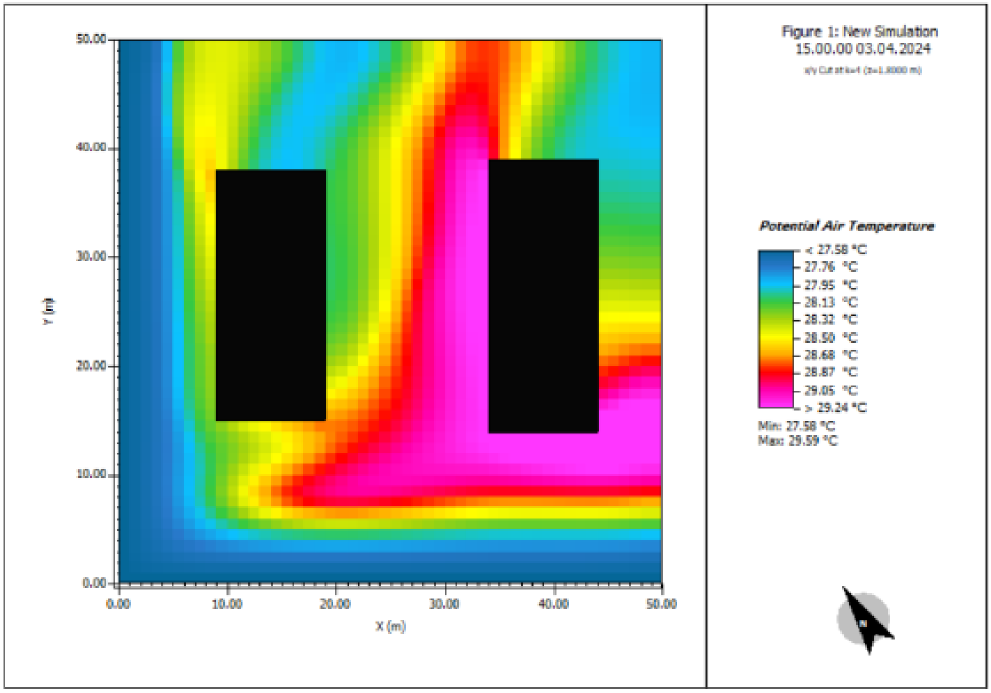


Figure 4-20: Area (2) in King Abdullah Ben Abdul-Aziz residential complex model validation

Figure 4-19 depicts the spatial arrangement of temperature measurement stations within the outdoor environment. Furthermore, a corresponding simulation of temperature distribution for that day is presented and generated using the Envi-met program.

Consistent with prior observations, discrepancies were again identified between the field measurements and the simulation results obtained on the same date (Figure 4-21). The reasons for these deviations are likely the same as those postulated previously (refer to previous section for details).

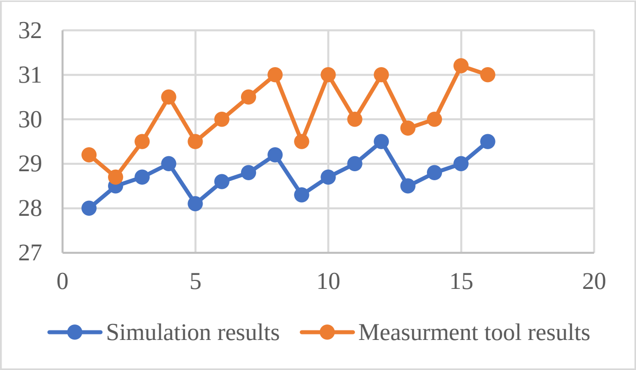


Figure 4-21: Chart show the deviations between the simulated temperature distribution and the field data.

- Validation results of outdoor area in Orphan housing

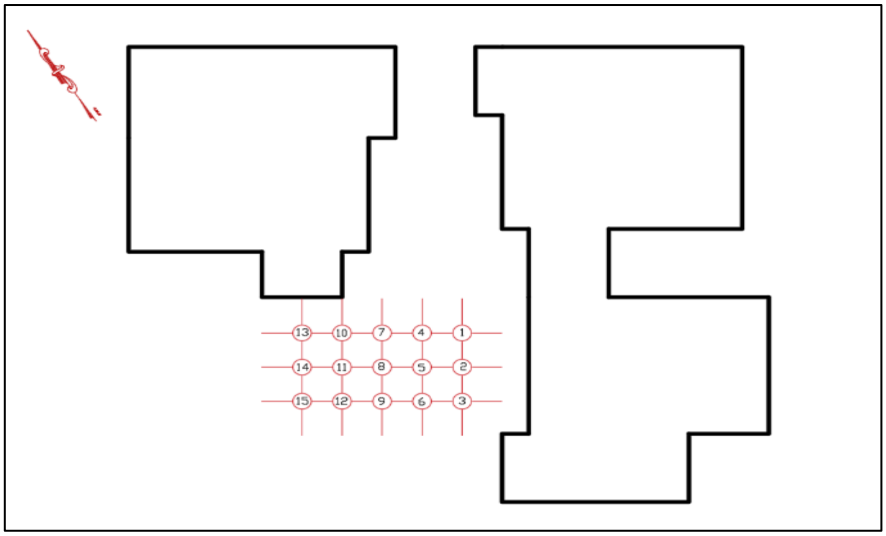


Figure 4-22 : Outdoor area in Orphan housing site shows measurement points

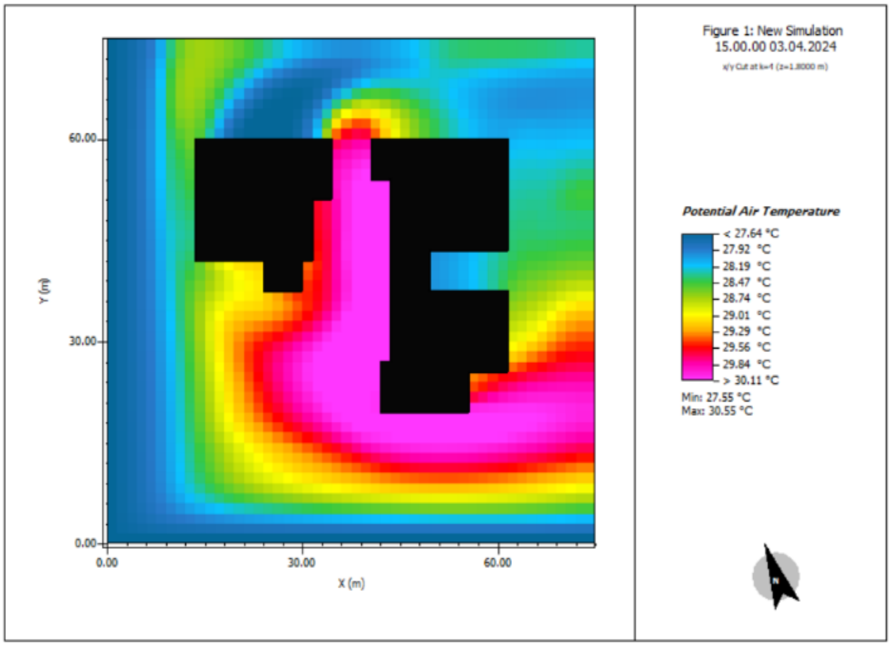


Figure 4-23: Outdoor area in Orphan housing site shows validation results

Field measurements indicated temperatures 1-1.5 °C higher than expected, despite the natural elements in the outdoor space. This difference can be attributed to the higher proportion of asphalt compared to green spaces in the outdoor space, resulting in increased heat absorption compared to the simulation program. Furthermore, field measurements revealed higher relative humidity compared to the simulation results, likely due to the influence of natural elements.

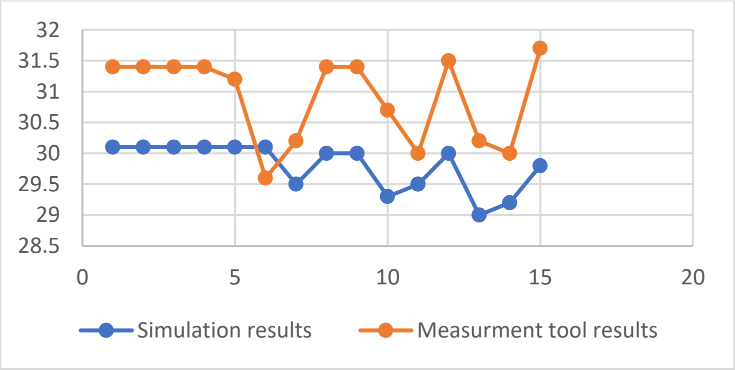


Figure 4-24 : Case 3 chart show the deviations between the simulated temperature distribution and the field data.

For model validation purposes, a discrepancy of 10-15% between field measurements and simulation outputs is deemed acceptable across all comparisons. This tolerance accounts for the influence of factors specific to each case.

4.8.2 Building scale validation process

On April 3, 2024, at 15:00 hours, simultaneous field measurements of temperature were conducted within a second-floor residential apartment located in the King Abdullah bin Abdulaziz residential complex. These measurements were taken at designated points within the living area facing the outdoor space. Subsequently, a simulation was performed using a builder program to model the temperature within the living space. The results obtained from this simulation were then compared to the field measurements to assess the software's accuracy.

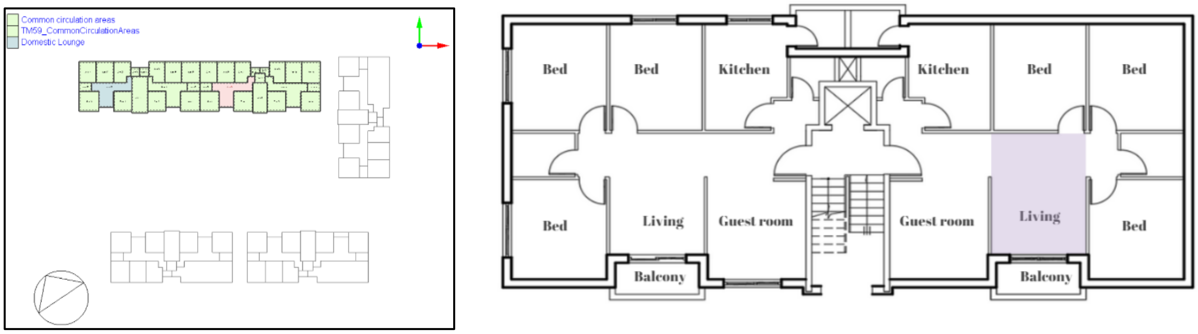


Figure 4-25 : Case 1 shows the residential apartment layout for validation

The simulation yielded a uniform temperature of 25.5 °C for the entire living area. However, field measurements revealed a more nuanced temperature distribution with an average of 27 °C. This discrepancy can be attributed to several factors, including furniture within the living space.

For model validation purposes, a discrepancy of 10-15% between field measurements and simulation outputs is deemed acceptable across all comparisons. This tolerance accounts for the influence of factors specific to each case.

Also, consistency was ensured by evaluating the convergence of the wind speed predictions from DesignBuilder and Envi-met software by measuring the external wind speed of the residential complex in both software programs and verifying the accuracy of the findings.

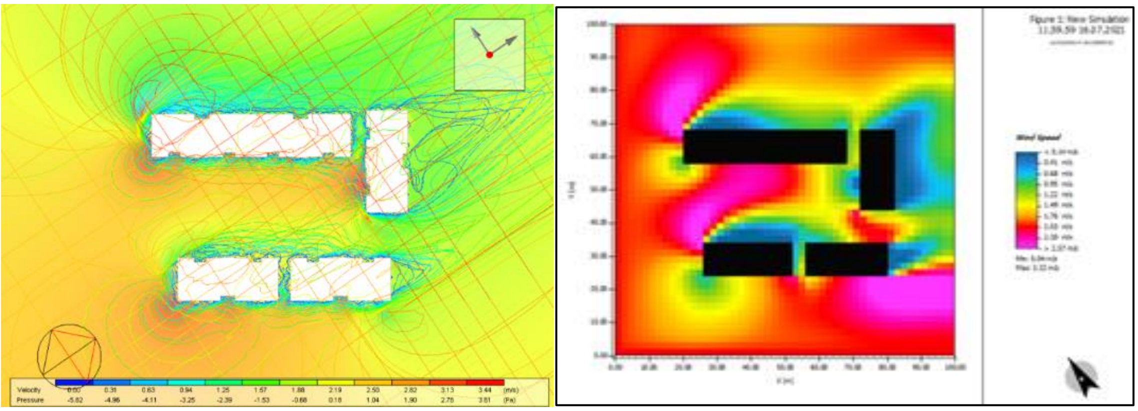


Figure 4-26 : Case 1 wind speed validation in Design builder and Envi-met programs

The figure 4-26 illustrate the degree of convergence between wind speed simulations from both softwires. The correlation between the outside thermal performance data from the Envi-met software and the inside thermal performance findings from the Design-Builder software depends on this convergence. Ultimately, the goal is to develop a relationship or equation that links these results, enabling the identification of key performance indicators.

The simulations focused on temperature, humidity, and wind speed within living spaces across various floors (ground, third, and fifth). The aim was to quantify the impact of the external tree design on enhancing thermal comfort conditions inside the building.

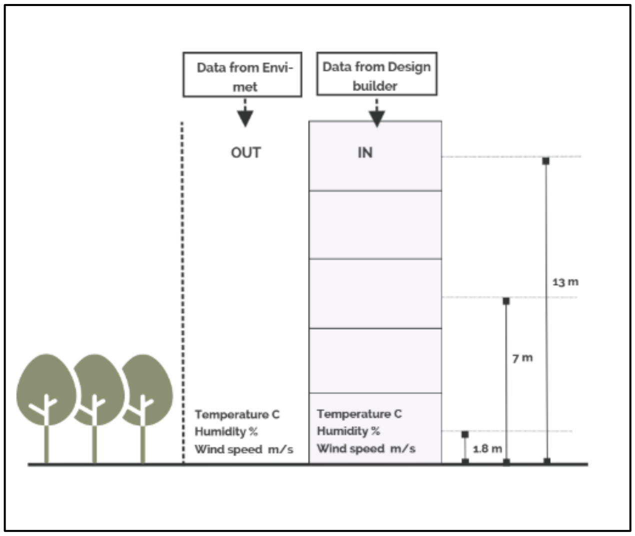


Figure 4-27 : A section outlining the procedures followed to get data from both software

4.9 Summary

This chapter details the research methodology employed to evaluate the thermal performance of outdoor residential spaces and investigate the effects of optimal tree typologies. This study utilizes a quantitative research approach, incorporating data collection techniques such as on-site observations, field surveys, and building sample analyses. These methods inform simulations that assess various tree typology scenarios aimed at enhancing thermal comfort.

The study area selected for this research is Hebron City in Palestine. Also, the research focuses on residential buildings due to their significant impact on urban microclimate dynamics. To ensure a comprehensive evaluation of tree typology designs, three outdoor spaces within the selected residential complexes were chosen based on specific criteria. The chosen spaces exhibit variations in area sizes and architectural morphology, providing a diverse set of conditions for analysis.

The Envi-met software was employed for urban and building scale simulations, modeling microclimatic aspects such as temperature, humidity, wind speed, and solar radiation distribution. Sensors were strategically placed to capture accurate microclimatic conditions at different vertical levels (the ground, third, and fifth floors). Initial simulations were conducted for spaces devoid of natural elements to establish baseline conditions, which served as controls for subsequent simulations incorporating various tree typologies.

Model validation was a critical component of the methodology. A field visit was conducted on April 2, 2024, to collect temperature and humidity measurements using a wireless weather station. These measurements were then compared with simulations produced by the Envi-met software, which integrated detailed weather data, building specifications, and outdoor material characteristics. The validation process aimed to ensure the accuracy of the model in representing thermal conditions, thereby providing a reliable basis for evaluating the impact of tree typologies on outdoor thermal comfort.

Chapter 5

Results and findings

Chapter 5

Results and findings

5.1 Preface

This study investigated the effect of tree typologies on outdoor thermal comfort. Analysis of various tree characteristics explored the connection between tree morphology and its capacity to improve microclimates and enhance human comfort in exterior spaces. The results revealed a statistically significant influence of tree typologies on thermal regulation. Specifically, canopy density, tree arrangement, and crown shape were identified as factors impacting air temperature, mean radiant temperature, and relative humidity. These findings suggest that strategic selection and planting of trees based on their typologies can be a tool for mitigating urban heat island effects and promoting the creation of thermally comfortable outdoor environments.

The model's applicability is geographically restricted due to documented variations in Palestinian climates across different topographical regions. Nevertheless, cities like Hebron, which share similar topographical and geographical characteristics with the study site, could potentially experience similar benefits from its implementation. Evaluating the model's performance in these diverse climatic contexts is crucial to determine its broader effectiveness.

Employing micro-scale and building-scale simulations, this study investigated the influence of tree typologies on the thermal comfort of various building complex morphologies. This multi-scale approach allowed for a comprehensive understanding of how different tree characteristics interact with building configurations to impact outdoor thermal conditions. The simulations focused on environmental parameters affecting human comfort, such as, (PMV) and (PPD).

5.2 Study context description

Hebron City, situated in the central region of Palestine south of Jerusalem, serves as the location for this study. The city experiences a Mediterranean climate characterized by hot summers and cool, wet winters (Meteoblue Weather, 2019). Summer temperatures typically peak around 29°C, while winter temperatures rarely fall below 0°C, with a minimum of around 3°C. Data from 2018 indicates a maximum air temperature of 21.9°C, a minimum of 13.7°C, and an average of 17.3°C. The average relative humidity in Hebron from 2010 to 2018 hovered around 65% (PCBS, 2018).

Table 5-1 : Average annual temperatures in Hebron (2020) (Weather-Spark, 2020)

	Summer			Winter		
Hebron city	Avg. daily temperature	Avg. Min. temperature	Avg. Max. temperature	Avg. daily temperature	Avg. Min. temperature	Avg. Max. temperature
	25 c	18 c	29 c	15 c	3 c	11 c

Table 5-2: Average annual humidity rate in Hebron (2012-2018) (Weather-Spark, 2020)

Year	2012	2013	2014	2015	2016	2017	2018
Average humidity (%)	61	63	65	66	64	64	69

Hebron exhibits a seasonal variation in solar radiation. The peak occurs on June 21st, with an average daily value of 8.6 kWh/m² and a coincident daily average daylight duration of 14 hours. Conversely, winter months experience a significant decrease in solar radiation, averaging around 4.2 kWh/m².

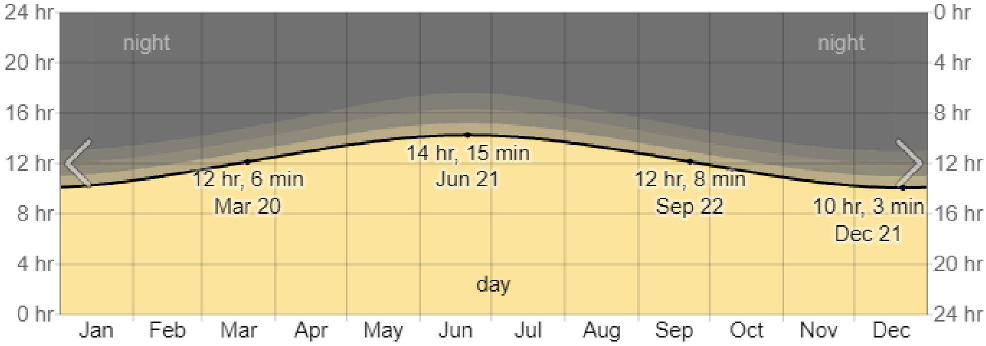


Figure 5-1 : Hours of Daylight and Twilight in Hebron (Weather-Spark, 2020)

[Online: https://weatherspark.com/y/98840/Average-Weather-in-Hebron-Palestinian-Territories-Year-Round]

Hebron experiences a seasonal variation in wind patterns. Northwesterly and westerly winds are predominant, as evidenced by Figure 4-6. Their average speed surpasses 3.2 m/s from May to September, reaching a maximum of 3.6 m/s in July. Conversely, wind speeds decrease to around 3.0 m/s between December and February. The remaining months exhibit intermediate wind speeds, as illustrated in Figure (Weather-Spark, 2020).

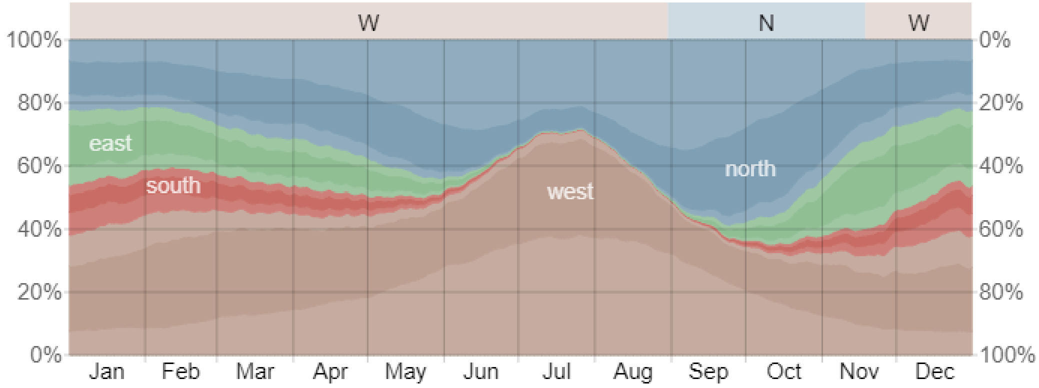


Figure5-2 : Wind direction in Hebron (Weather-Spark, 2020).

[Online: https://weatherspark.com/y/98840/Average-Weather-in-Hebron-Palestinian-Territories-Ye.ar-Round]

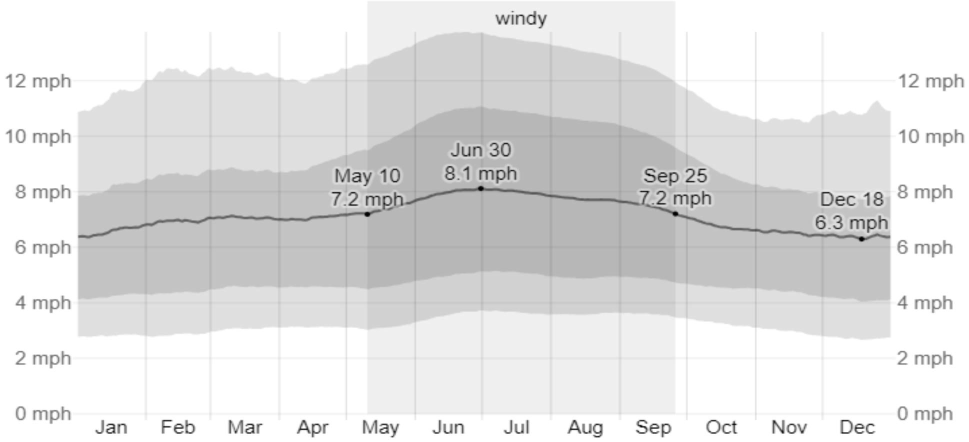


Figure 5-3 : Average Wind Speed in Hebron (Weather-Spark, 2020).

The preceding figures presented the climatic profile of Hebron City, encompassing temperature, relative humidity, solar radiation, wind speed, and wind direction. This data served as the foundation for creating a simulation model using the Envi-met and DesignBuilder software. To facilitate model development, the data from these figures was summarized into an average annual weather profile for the city.

Table 5-3 : Hebron city climatic averages (Weather-Spark, 2020)

	Temperature (°C)		Wind speed (m/s)		Wind direction	Humidity (%)
	Average minimum	Average maximum	Average speed	Maximum speed		
Summer	17	29	3.2	6	225° North-Western wind	45%
Winter	4	12	2.8	5	270° Western wind	65%

5.3 cases description and urban scale simulation results

To quantify the influence of tree typologies on outdoor pedestrian thermal comfort, simulations were conducted using the Envi-met program encompassing a range of scenarios with varying tree characteristics. These scenarios incorporated diverse temperature, wind speed, and relative humidity conditions. Following simulation execution, key physiological parameters affecting thermal comfort, including air temperature and established thermal comfort indices, were measured at the pedestrian level for each scenario. This systematic approach enables the isolation and analysis of the specific influence exerted by different tree typologies on pedestrian thermal comfort while controlling for the confounding effects of ambient temperature, wind speed, and relative humidity.

5.3.1 Case 1 and 2: The description and simulation results of area (1, 2) in King Abdullah Ben Abdul-Aziz residential complex

The King Abdullah neighborhood is located within the Abu Katila area in Hebron. It comprises a cluster of residential structures, each building four to five stories, with an average height of approximately three meters. These buildings incorporate central outdoor spaces distributed among them. The residential units within these buildings encompass an average area of 150 square meters.

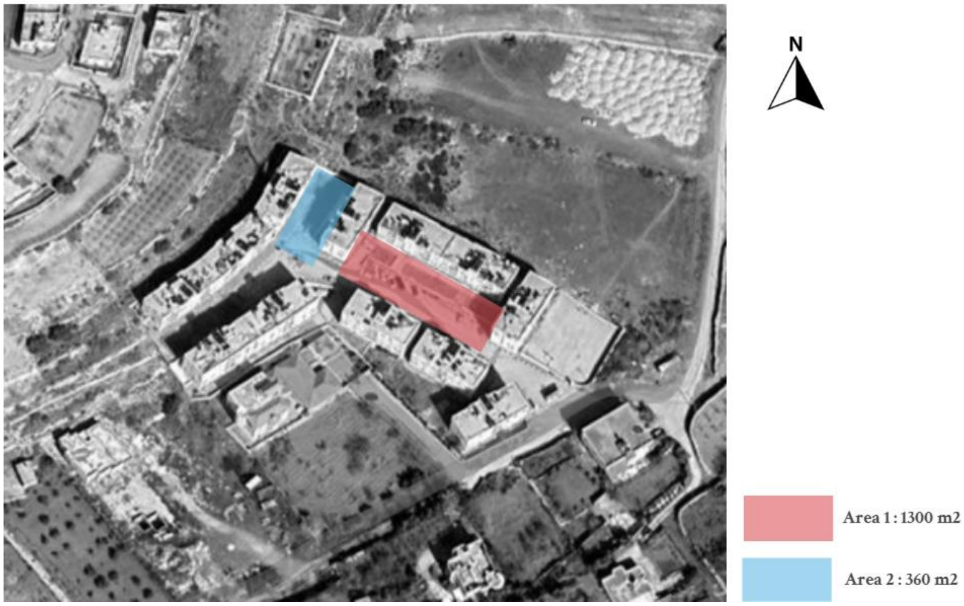


Figure 5-4 : King Abdullah neighborhood site plan shows area 1,2

(https://earth.google.com/)

The research was carried out on two external areas within the residential locality, the first measuring 1,300 m2 and the second 360 m2.

The architectural blueprints for the residential complex were sourced from Al-Bayt Engineering Company.

The typical floor plan of an apartment includes three bedrooms, accommodating 6 to 8 residents. This design is commonly observed in apartment models in Hebron.

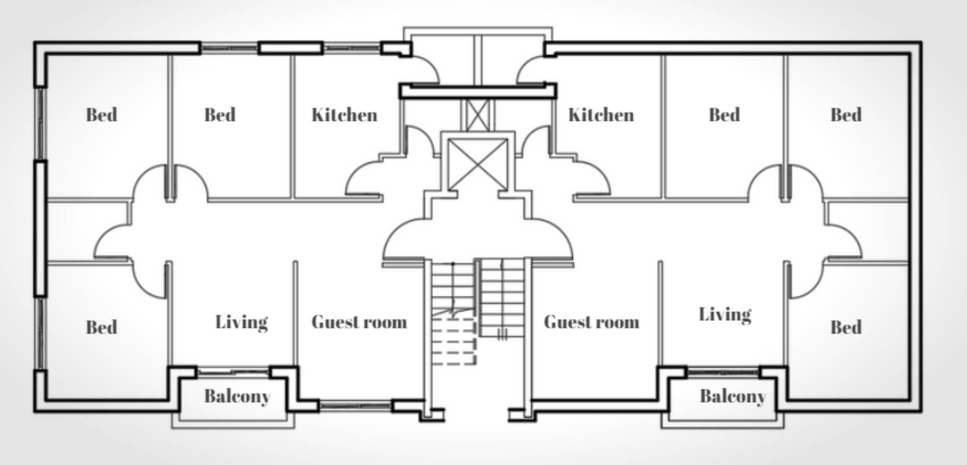


Figure 5-5 : Typical apartment design (Engineering House Consulting Company)

The facade design incorporates windows measuring between 1 to 2 meters in width and 1 to 2 meters in height. Limestone is utilized as the cladding material for the building.

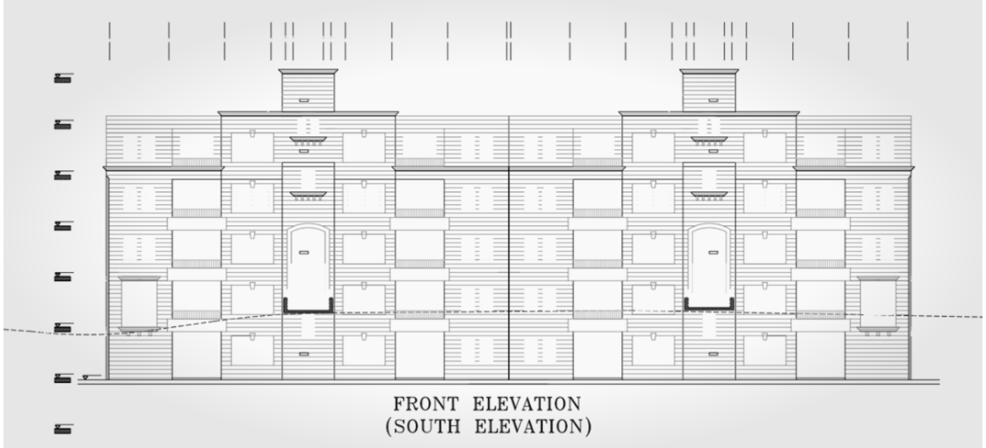


Figure 5-6 : Elevation design (Engineering House Consulting Company)

The construction materials utilized in the building process were characterized for input into Envi-met and DesignBuilder programs. This characterization included both the insulating value and thickness of each structural element.

Table 5-4 : Apartments construction material detail

Element	Material and thick(cm) Out-in	Thickness(cm)	U-value (W/ (m2.k))
Exterior wall	-Stone (5cm) -Concrete(20cm) -Plaster(2cm)	27	2.413
Celling and floor	-Tile (3cm) -Mortar (2cm) -Sand (8cm) -Reinforce concrete slap(25cm) -Hollow block(17cm) -plaster (2cm)	25	2.2
Glazing type	- Double Glazing	1.9	2.71
Internal partition	-Plaster(2cm) -Hollow block(10cm) -Plaster(2cm)	14	4.957

The external space exhibits an absence of natural elements. The entire area is paved with asphalt, prioritizing its functionality as a parking lot. This design approach eliminates the incorporation of landscaping features or designated play areas for children.

Figure 5-7 : photos show the external spaces within the neighborhood (Source from researcher)

5.3.1.1 Case 1: Simulation results of area (1) in King Abdullah Ben Abdul-Aziz residential complex

A computational simulation was conducted to establish a baseline for thermal conditions within an outdoor space of a residential complex. The scenario simulated an open space devoid of natural elements and trees during summer (12:00 pm/16-7-2-2021) and winter (12:00 pm/ 21-12-2021). The initial simulation serves as a control for subsequent simulations that incorporate various tree typologies. By comparing the thermal conditions of the baseline scenario with those featuring different tree types, the study aims to quantify the influence exerted by vegetation on the outdoor thermal environment.

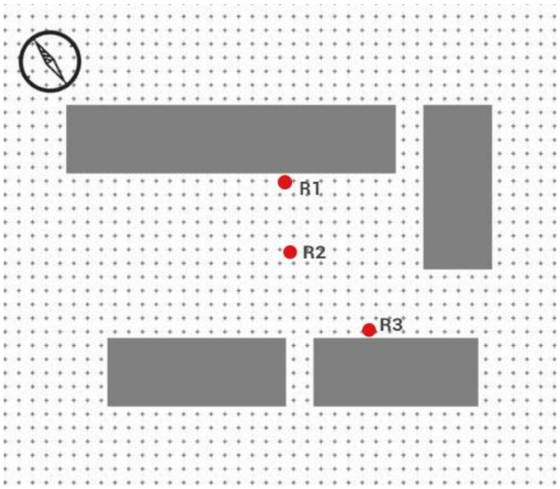
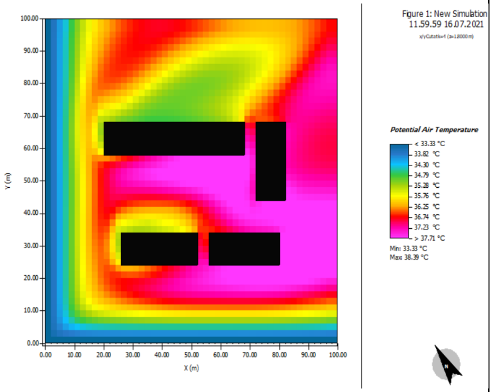
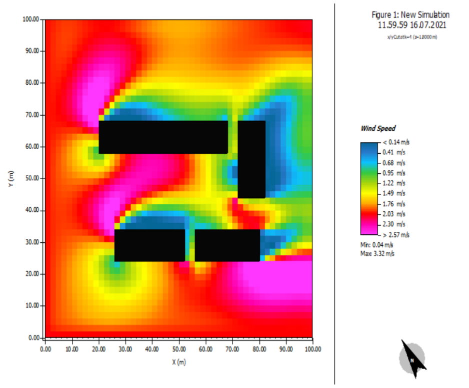
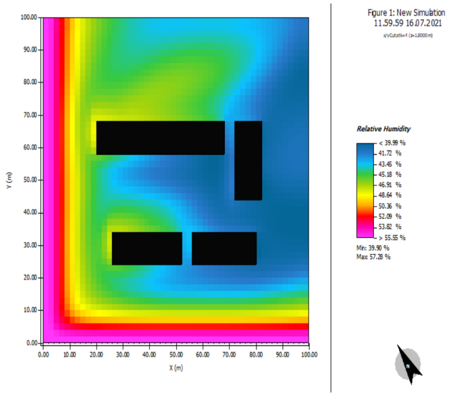
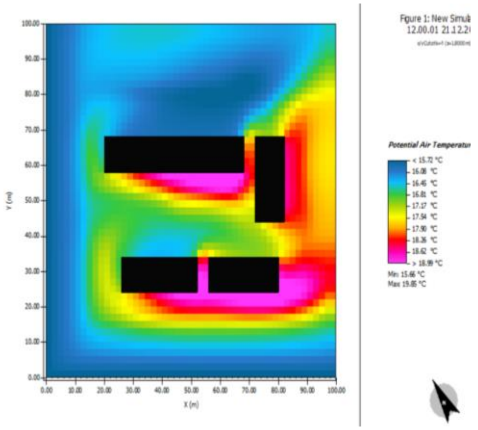
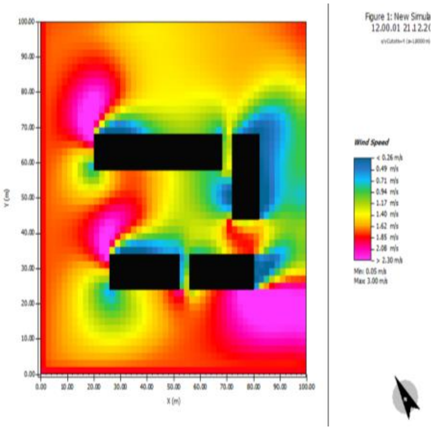
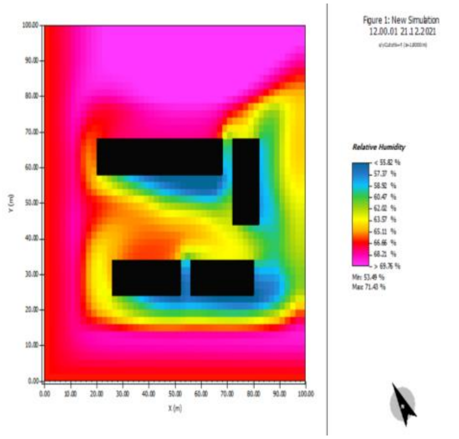


Figure 5-8 : Area (1) in King Abdullah Ben Abdul-Aziz residential complex site plan shows sensors location

Summertime measurements within the outdoor space revealed that approximately 80% of the area experienced temperatures around 37.5°C. Wind speeds exhibited spatial variability across the space, as (Table 5-5). Additionally, relative humidity is estimated at 41% across roughly 85% of the outdoor space area. Thermal comfort analyses conducted for the space environment indicated that 100% of occupants were likely to experience thermal discomfort.

Wintertime measurements within the outdoor space revealed that approximately 50% of the area experienced temperatures around 17°C. Wind speeds exhibited spatial variability across the space, as detailed (Table 5-5). Additionally, relative humidity is estimated at 50% across roughly 65-63% of the outdoor area. Thermal comfort analyses conducted for the space environment indicated that 30% of occupants were likely to experience thermal discomfort.

Table 5-5 : (Base case1) Urban scale simulation (At pedestrian level 1,8 m)

(Base case) Urban scale simulation (At pedestrian level 1,8 m)						
Case	Description	Operative temperature ©	Wind speed(m/s)	Relative humidity	PPD	PMV
Summer	Base case (summer time at 12:00 pm) 16-7-2-2021	 	 	 	100%	5.1-5.3
Winter	Base case (Winter time at 12:00 pm) 21-12-2021	 	 	 	30%	-1.35

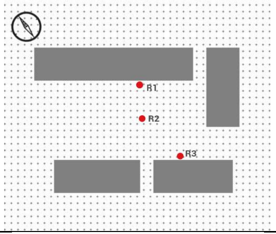
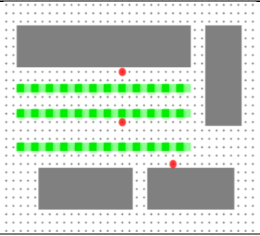
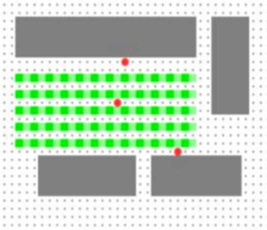
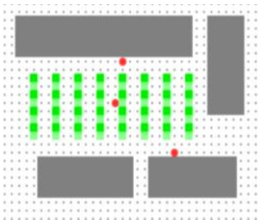
Following the establishment of a baseline scenario through computational simulation, subsequent simulations incorporated various tree typologies as variables. These tree-related variables include:

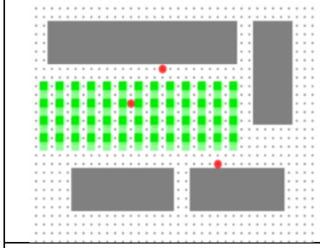
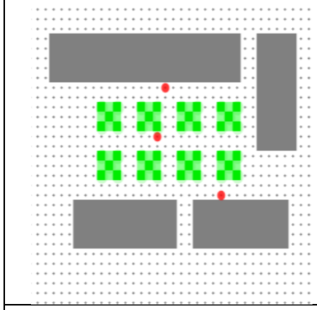
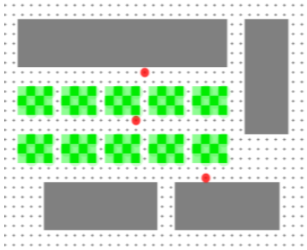
- Vegetation cover ratio and arrangement simulation results

The first investigation focused on the combined influence of green cover percentage and tree spatial arrangement on outdoor thermal performance. This phase encompassed six distinct scenarios (detailed in the accompanying table) that systematically varied these variables. The subsequent analysis elucidates the effects of green cover percentage and tree arrangement on the thermal environment.

- Summer case simulation

Table 5-6 : Case 1 (Vegetation cover ratio and arrangement simulation results)

Cases	Description	Operative temperature ©	Wind speed(m/s)	Relative humidity
	Base case (summer time at 12:00 pm) 16-7-2-2021	Appendix C (Figure 5-1)	Appendix C (Figure 5-2)	Appendix C (Figure 5-3)
	• Cr1: 20% • A1: Row horizontal • Grass, Tree constant	Appendix C (Figure 5-4)	Appendix C (Figure 5-5)	Appendix C (Figure 5-6)
	• Cr 2: 40% • A1: Row horizontal • Grass, Tree constant	Appendix C (Figure 5-7)	Appendix C (Figure 5-8)	Appendix C (Figure 5-9)
	• Cr1: 20% • A2: Row Vertical • Grass, Tree constant	Appendix C (Figure 5-10)	Appendix C (Figure 5-11)	Appendix C (Figure 5-12)

	• Cr2: 40% • A2: Row Vertical • Grass, Tree constant	Appendix C (Figure 5-13)	Appendix C (Figure 5-14)	Appendix C (Figure 5-15)
	• Cr1: 20% • A3: Grouped • Grass, Tree constant	Appendix C (Figure 5-16)	Appendix C (Figure 5-17)	Appendix C (Figure 5-18)
	• Cr2: 40% • A3: Grouped • Grass, Tree constant	Appendix C (Figure 5-19)	Appendix C (Figure 5-20)	Appendix C (Figure 5-21)

Base case simulation: Temperature was found to be 37–38 degrees Celsius in most spaces with the eastern and southern sides and 36–35 degrees Celsius in the western and northern areas.

Similar effects on temperatures were observed across all scenarios, with the temperature reduction ranging between one to two degrees Celsius. From the maps, a consistent distribution of temperatures was noted in the case (H20%), leading to the arrangement of trees almost parallel to the direction of the wind, with wide paths between them.

It was noted that temperatures uniformly decreased around all sides of the buildings, with no significant variation in temperature reduction observed on any particular side.

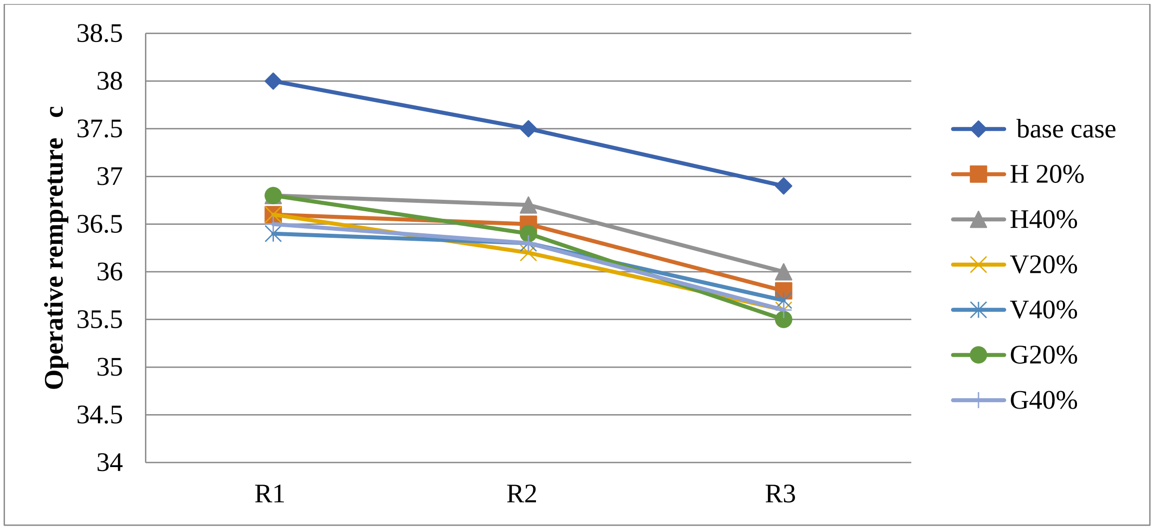


Figure5-9 : Case 1 (The effect of vegetation coverage and Arrangement on operative temperature in summer)

(H20%): The green cover percentage is 20% and it is planted in rows parallel to the wind direction, (H40%): The green cover percentage is 40% and it is planted in rows parallel to the wind direction,(V20%): The green cover percentage is 20% and it is planted in rows perpendicular to the wind direction, (V40%): The green cover percentage is 40% and it is planted in rows perpendicular to the wind direction,(G20%): The green cover percentage is 20% and it is planted in groups, (G40%): The green cover percentage is 40% and it is planted in groups.

In all scenarios except Case (H 20%), a uniformly decrease in relative humidity ranging from 5% to 10% was observed. Conversely, in Case (H20%), there was a 5% increase in humidity.

Planting trees in rows parallel to the prevailing wind direction can lead to an increase in local humidity levels due to several factors. Firstly, the rows act as a wind barrier, reducing wind speed and allowing for a longer residence time of water vapor in the air, facilitating its evaporation from leaves and soil.

Planting trees perpendicular to the wind direction can have different effects on humidity. Perpendicular planting exposes the trees to higher wind speeds, leading to increased evaporation from leaves and soil, potentially resulting in lower humidity.

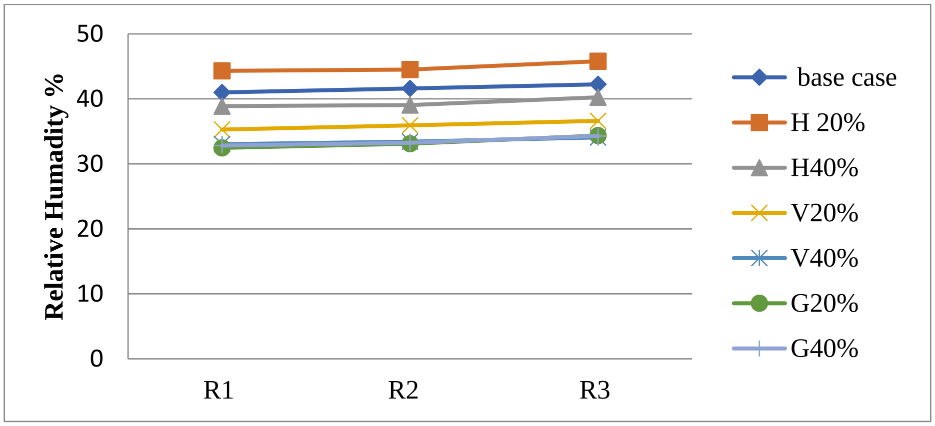


Figure 5-10 : Case 1 (The effect of vegetation cover ratio and arrangement on Relative humidity)

In all scenarios, a reduction in wind speed was observed. However, sensor 2 displayed a more substantial percentage decrease compared to sensor 1. At all points, there was a greater reduction in wind speed observed in Case (H20%) ranging from 2m/s to 0.7m/s

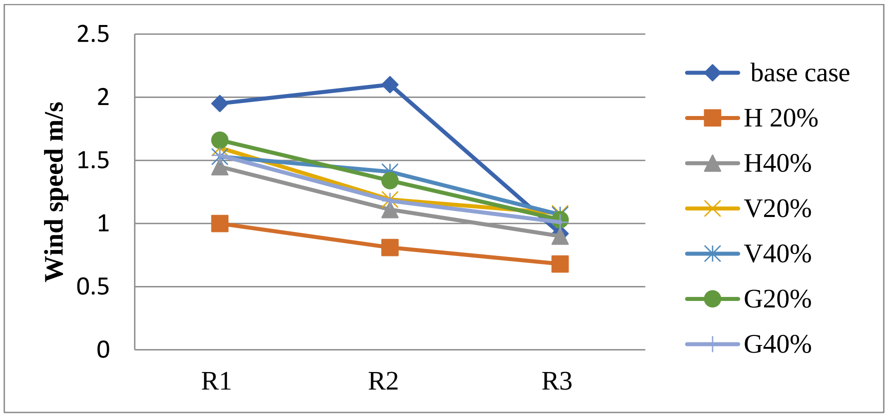


Figure 5-11 : Case 1 (The effect of vegetation coverage and arrangement on wind speed)

Planting trees in rows parallel to the wind direction offers several advantages compared to groups or perpendicular planting:

- ✓ Creates a continuous barrier that significantly reduces wind speed.
- ✓ Increased residence time of water vapor**:** Lower wind speeds allow more time for water vapor to evaporate, leading to higher humidity.
- ✓ Enhanced transpiration: Stable boundary layer around leaves facilitates efficient transpiration, further increasing humidity.

- Winter case simulation

During winter, deciduous trees with grass have a minimal impact on temperature and wind compared to other seasons due to the lack of leaves on the trees. Without leaves, the trees have significantly reduced surface area, diminishing their ability to intercept solar radiation and provide shade, which would otherwise contribute to cooler temperatures under the canopy. Additionally, the absence of leaves reduces wind resistance, allowing more air movement through trees, and minimizing the wind-blocking effect.

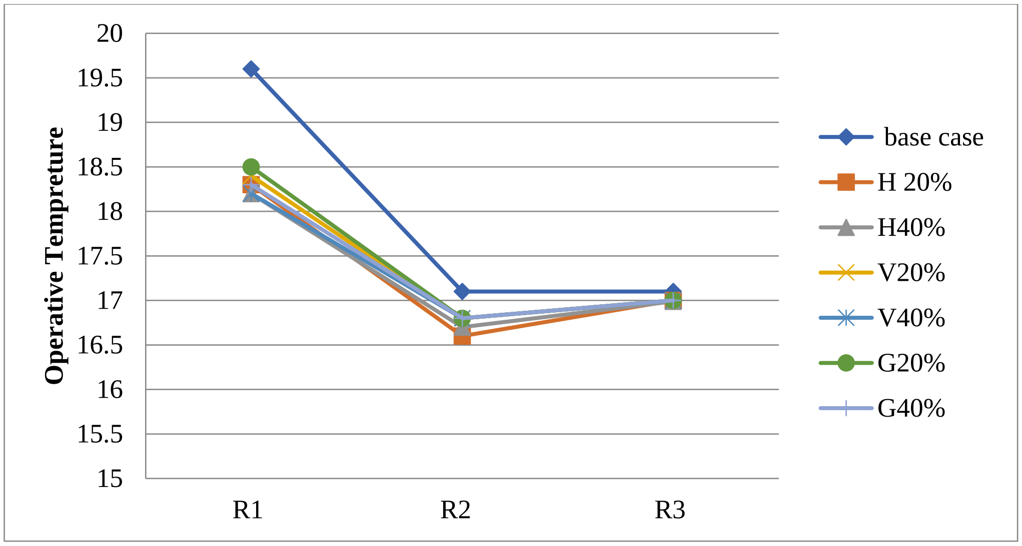


Figure 5-12 : Case 1 (The effect of vegetation cover and arrangement on Operative temperature in winter)

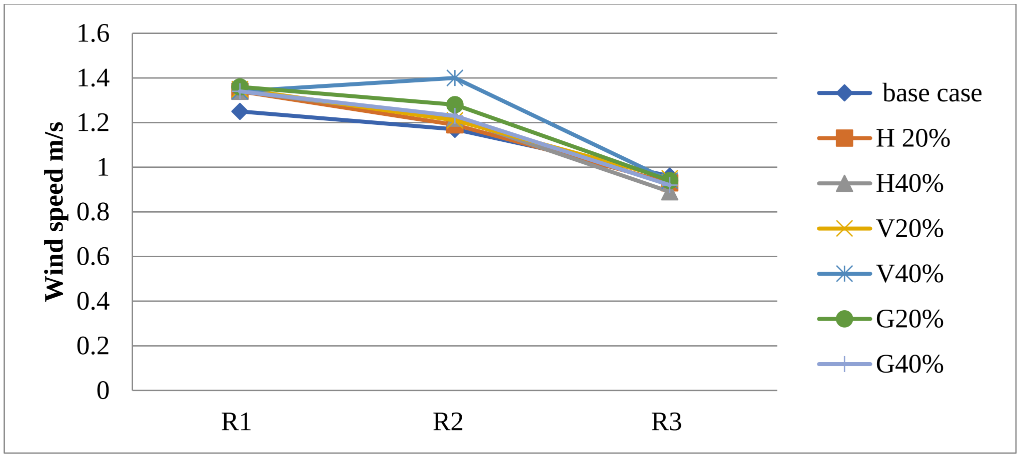


Figure 5-13 : Case 1 (The effect of vegetation coverage and arrangement on wind speed in winter)

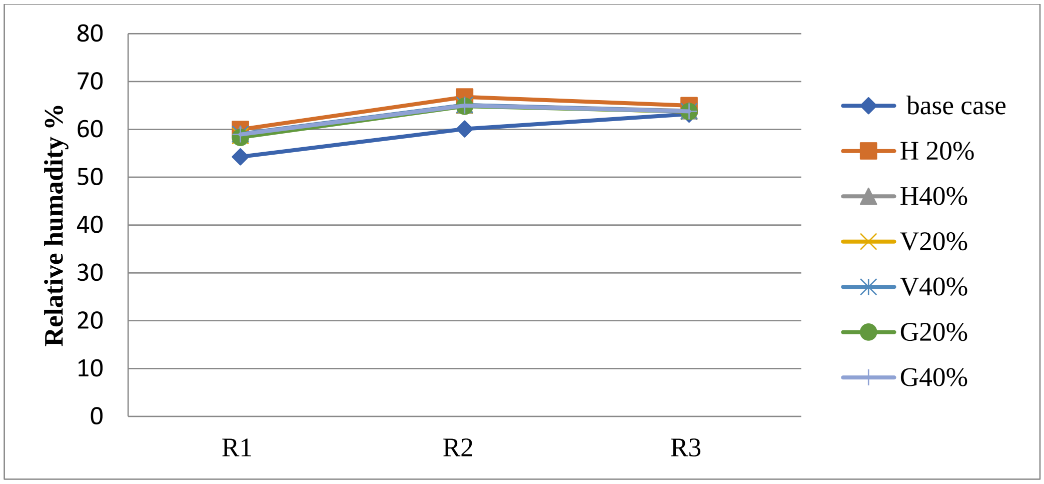


Figure 5-14 : Case 1 (The effect of vegetation cover and arrangement on relative humidity in winter)

Winter simulations across all scenarios yielded comparable results, closely resembling those of the base case. This observed consistency can be attributed to the grass, a constant element across all simulations, in conjunction with the selection of deciduous trees. Deciduous trees shed their leaves in winter, thus offering minimal influence on thermal performance during this season. Consequently, the observed minor deviations in temperature, wind speed, and relative humidity likely stem from the inherent properties of the grass cover.

- Crown shape scenarios simulation results

Following the selection of optimal vegetation cover percentage and tree spatial arrangement (H20%) through prior simulations, a subsequent analysis focused on the influence of tree crown morphology. This phase involved fixing the previously optimized variables (cover percentage and arrangement) while introducing crown shape as a new variable. The specific crown shapes included are:

Targeted simulations were used to accurately measure the impact of crown morphology on outdoor thermal performance. All other pertinent tree properties, such as crown diameter, overall tree height, trunk dimensions, and canopy density, were kept unchanged during these simulations.

Across all simulated tree crown shapes, comparable thermal performance was observed, with a consistent temperature reduction ranging from 1.5°C to 2°C.

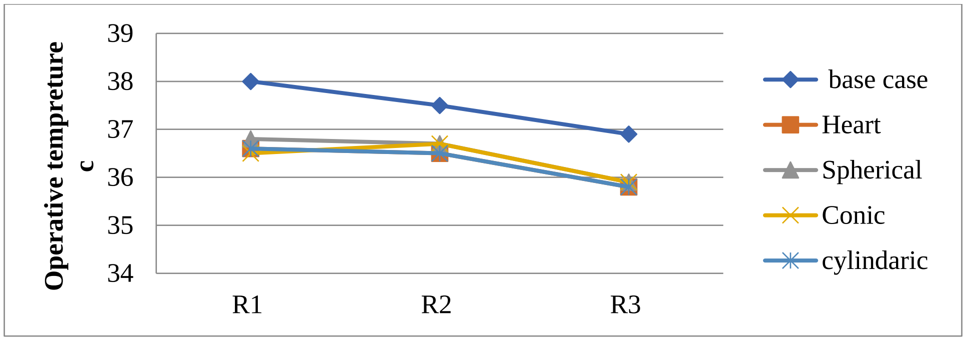


Figure 5-15 : Case 1 (The effect of crown shape on operative temperature in summer)

The simulations revealed a consistent decrease in wind speed across all sensors, except sensor number 3. This sensor exhibited an increase in wind speed, potentially due to the specific influence of crown shape. Notably, crown shape (Heart shape) represented the most significant reduction in crown area compared to the baseline scenario (2-1) m/s.

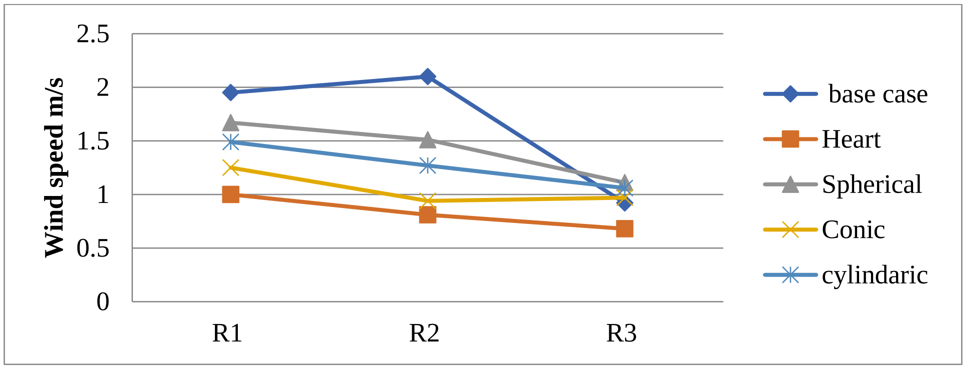


Figure 5-16 : Case 1 (The effect of crown shape on operative temperature in summer)

The simulations revealed a trend of decreased relative humidity across most tree crown shape scenarios. The observed reductions ranged from 10% to 5%. However, heart shape deviated from this trend and exhibited an increase in relative humidity by 5%.

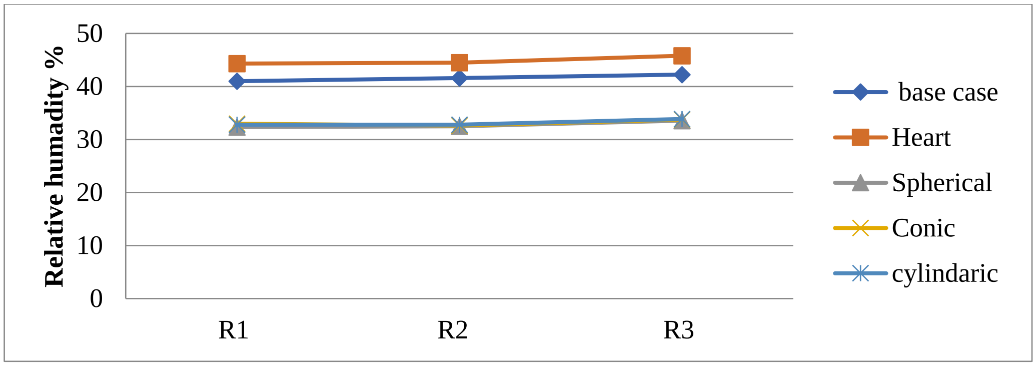


Figure 5-17 : Case 1 (The effect of crown shape on relative humidity in summer)

The simulations consistently identified the crown shape (Heart) as the most effective configuration for improving the thermal performance of the outdoor space. The crown shape (Heart) consistently reduced wind speeds compared to other crown shapes. Wind speed reduction creates a more comfortable outdoor environment, especially during extreme temperatures. Also, unlike some scenarios, the crown shape (Heart) did lead to an increase in relative humidity.

- Crown density scenarios simulation results

Following the implementation of crown shape (Heart, Vase), The study investigated the relationship between the density of the crown leaves and its impact on the thermal performance of the residential complex's outdoor space.

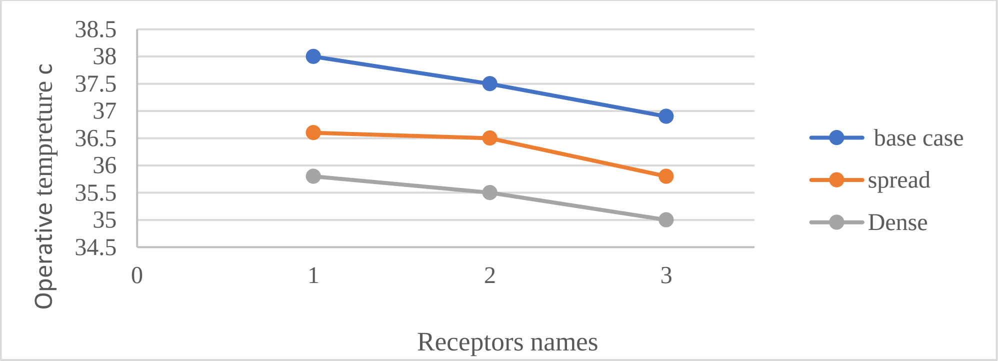


Figure 5-18 : Case 1 (The effect of crown density on operative temperature in summer)

Planting trees with dense crowns resulted in a temperature decrease of about 2.5-3 degrees Celsius. In contrast, planting trees with sparse crowns led to a temperature decrease of about 1.5-2 degrees Celsius.

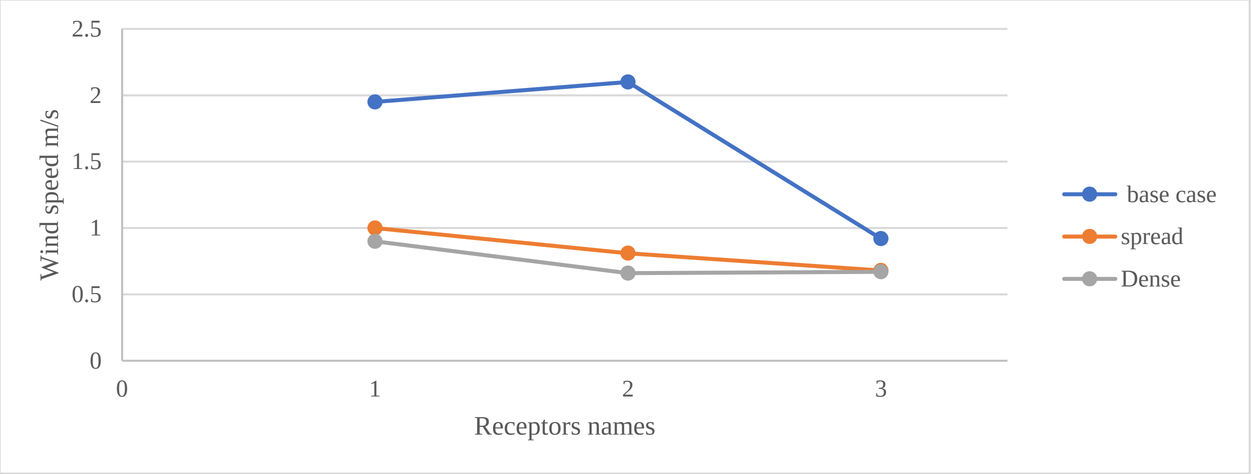


Figure 5-19 : Case 1 (The effect of crown density on wind speed in summer)

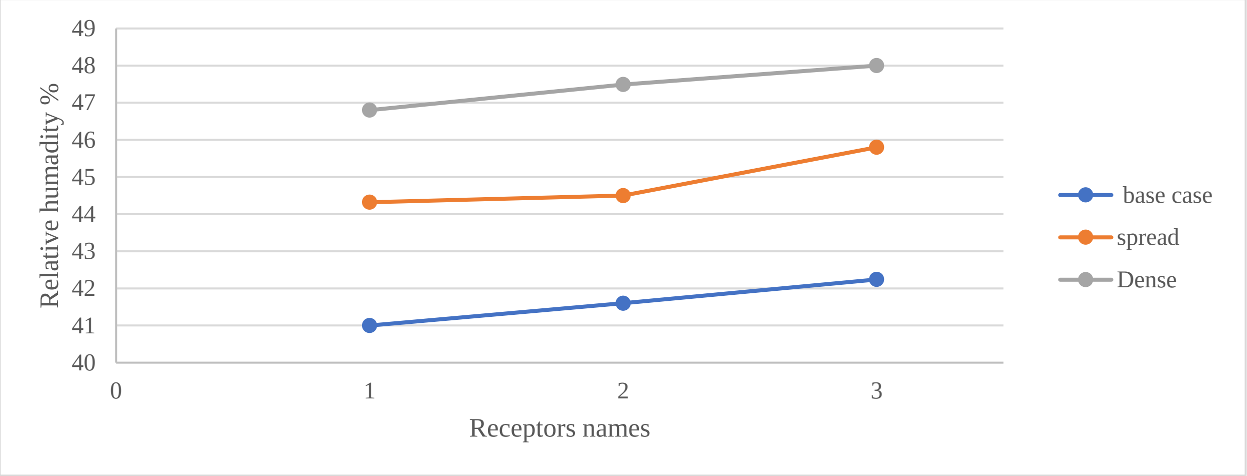


Figure 5-20 : Case 1 (The effect of crown density on relative humidity in summer)

Dense crowns generated readings approximately double those of sparse crowns, with the latter registering between 8-10%. Dense crowns typically have a larger surface area of leaves compared to widespread crowns. This allows for greater transpiration, the process by which plants release water vapor into the air. Increased transpiration leads to higher humidity levels in the surrounding area, which can be particularly beneficial in the Mediterranean climate.

Trees with dense crowns can create a distinct microclimate characterized by:

- ✓ Cooler temperatures: Due to the shade and reduced wind chill.
- ✓ Higher humidity: Due to enhanced transpiration.
- ✓ Reduced wind speed: Due to the wind-blocking effect of the dense foliage.

- Trunk size scenarios simulation results

Following the examination of previous variables, this section explored how variations in tree trunk size (Small, Medium, Large), affect temperature, wind speed, and relative humidity.

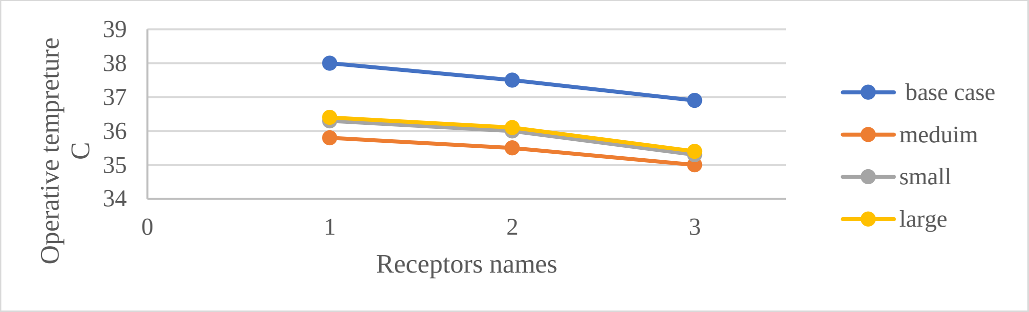


Figure 5-21: Case 1 (The effect of trunk size on operative temperature in summer)

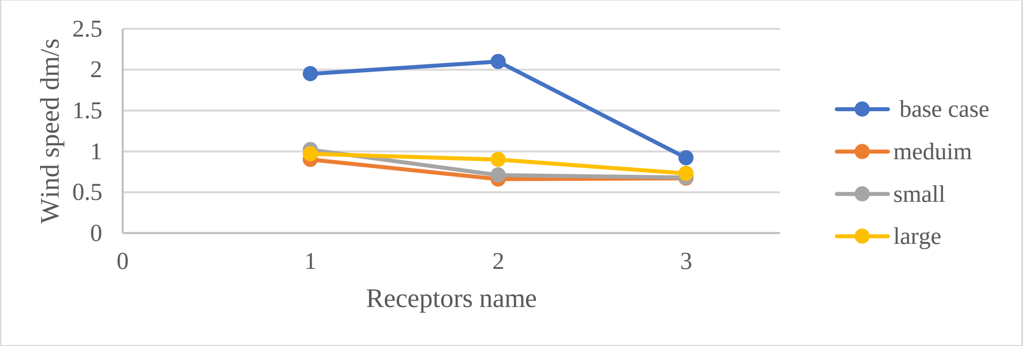


Figure 5-22: Case 1 (The effect of trunk size on wind speed in summer)

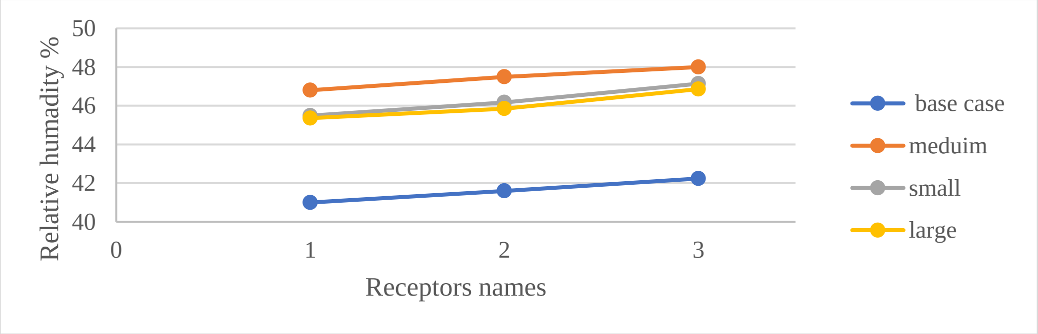


Figure 5-23: Case 1 (The effect of trunk size on relative humidity in summer)

The study investigated the impact of tree trunk size on the thermal performance of the outdoor courtyard. Interestingly, medium-sized tree's trunk exhibited the most significant improvement. Compared to other sizes, medium tree trunks resulted in:

- ✓ Temperature reduction of approximately two degrees Celsius.
- ✓ Moderate increase in relative humidity, ranging from 6-8%.
- ✓ The reduction in wind speed, with a similar effect observed for both large and small tree trunks.

- Trees height scenarios simulation results

Informed by the outcomes of prior variable analyses, this section utilized simulations to examine the impact of tree height on thermal performance. The simulations specifically investigated how temperature variations within the building and the external courtyard are influenced by tree height at different floor levels.

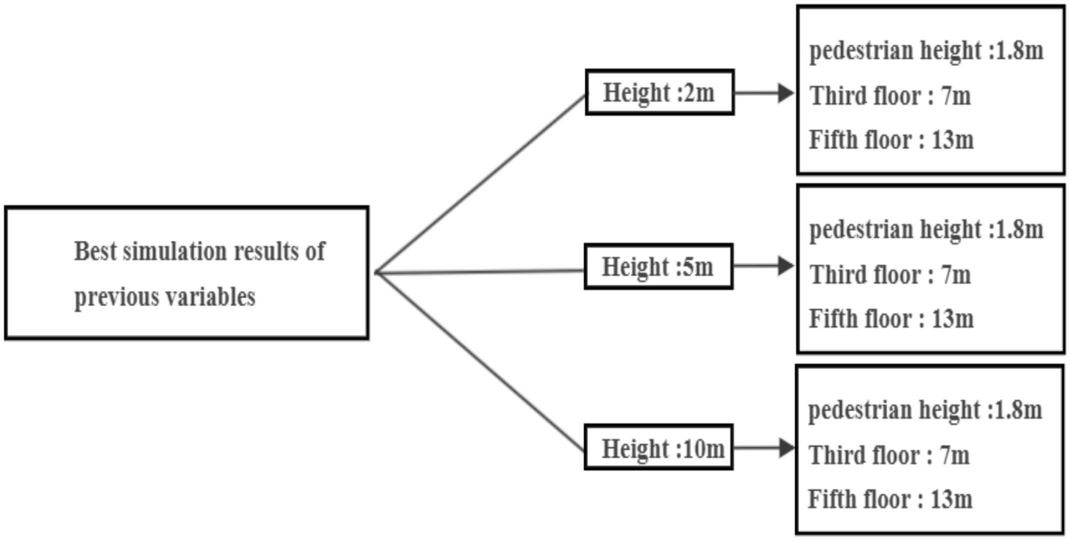


Figure 5-24: chart show height scenarios process

- Trees height scenarios simulation results at 1.8 m

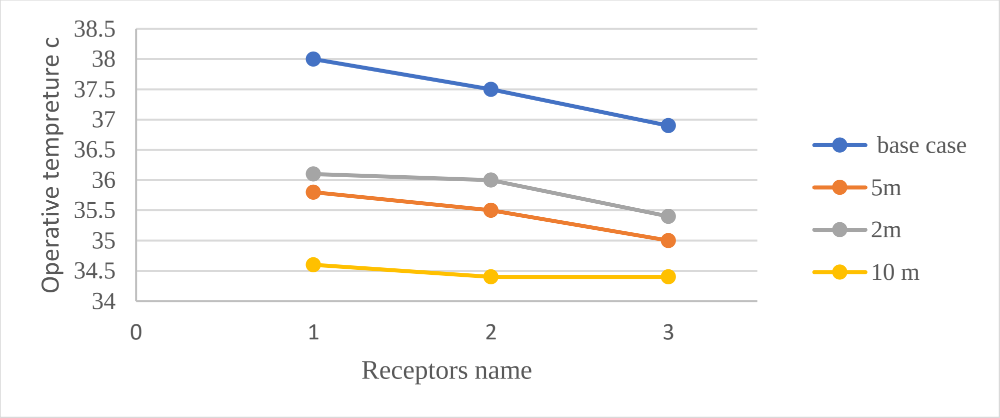


Figure 5-25: Case 1 (The effect of tree height on operative temperature at 1.8m in summer)

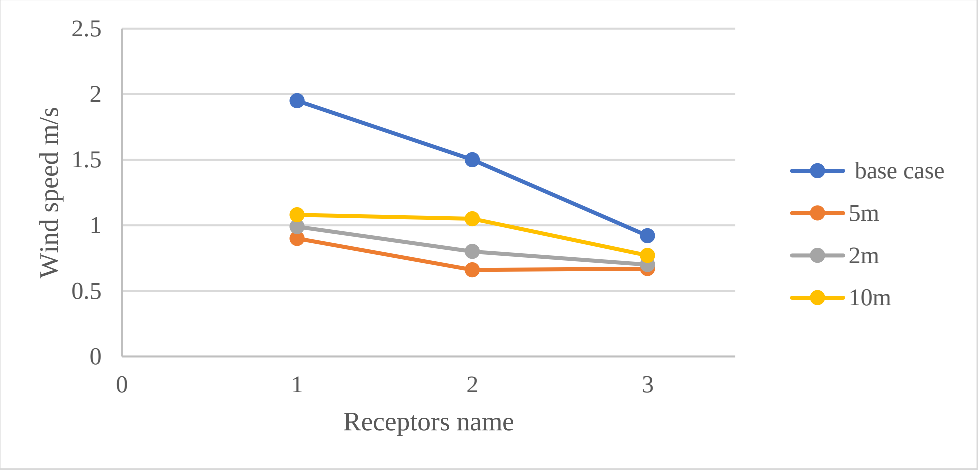


Figure 5-26: Case 1 (The effect of tree height on wind speed at 1.8m in summer)

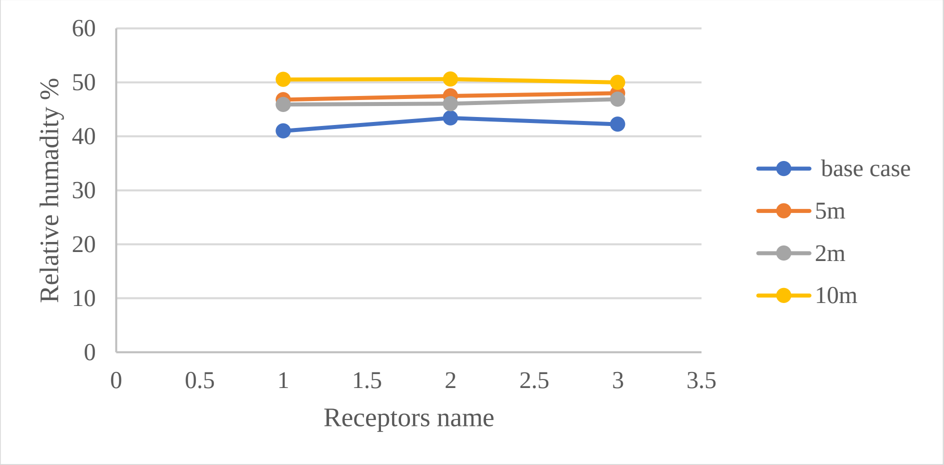


Figure 5-27 : Case 1 (The effect of tree height on relative humidity at 1.8m in summer)

The simulations revealed that 10-meter-tall trees provided the most significant thermal improvement. Compared to trees of other heights, these trees achieved:

- A temperature reduction of approximately 3.5-4 degrees Celsius at a measurement height of 1.8 meters.
- An increase in relative humidity of around 10%.
- The reduction in wind speed is 1 m/s.

✓ Trees height scenarios simulation results at 7 m

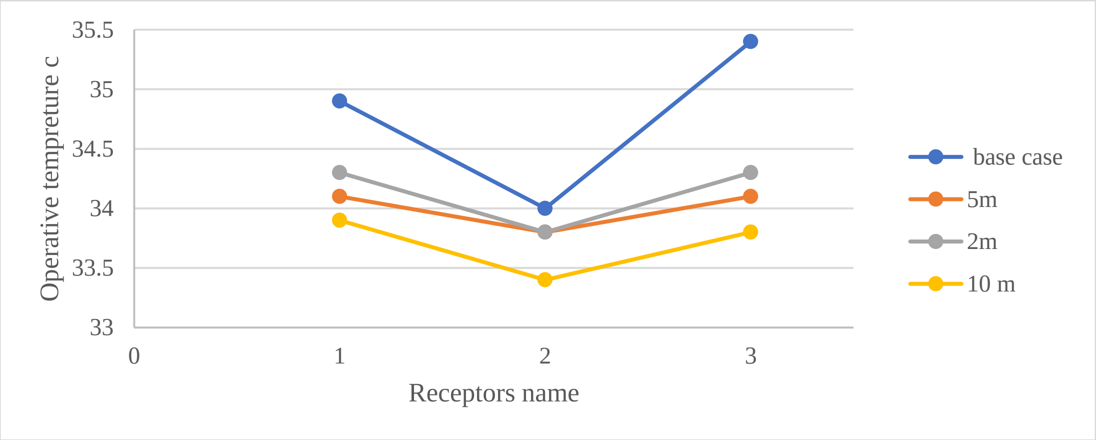


Figure 5-28 : Case 1 (The effect of tree height on operative temperature at 7m in summer)

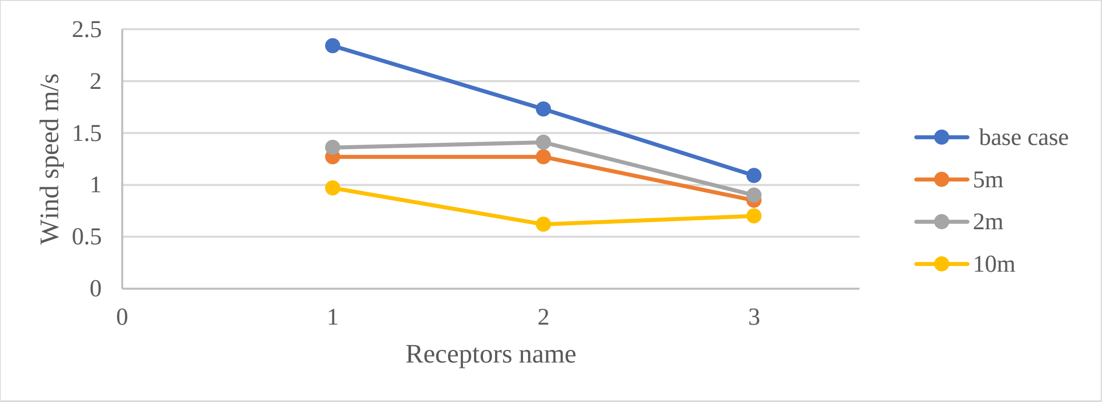


Figure 5-29 : Case 1 (The effect of tree height on wind speed at 7m in summer)

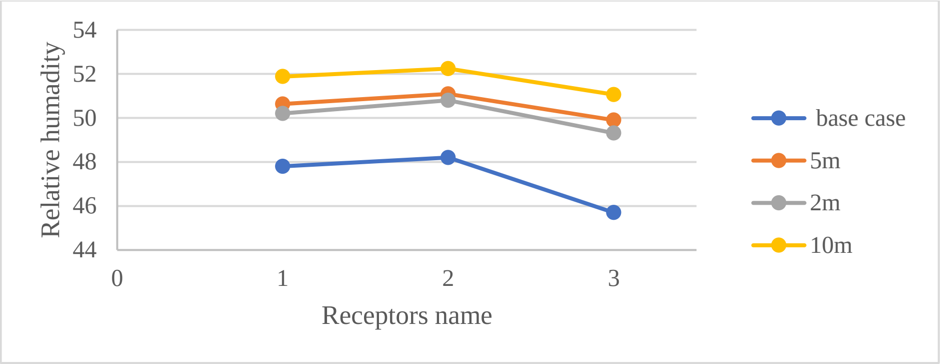


Figure 5-30 : Case 1 (The effect of tree height on relative humidity at 7m in summer)

The simulations identified trees with a height of 10 meters, measured at a reference height of 7 meters, as the most effective configuration for improving thermal performance. These trees achieved a reduction in temperature of approximately 1-2 degrees Celsius, an increase in relative humidity of around 5%, and a reduction in wind speed by 1.5 m/s.

✓ Trees height scenarios simulation results at 13 m

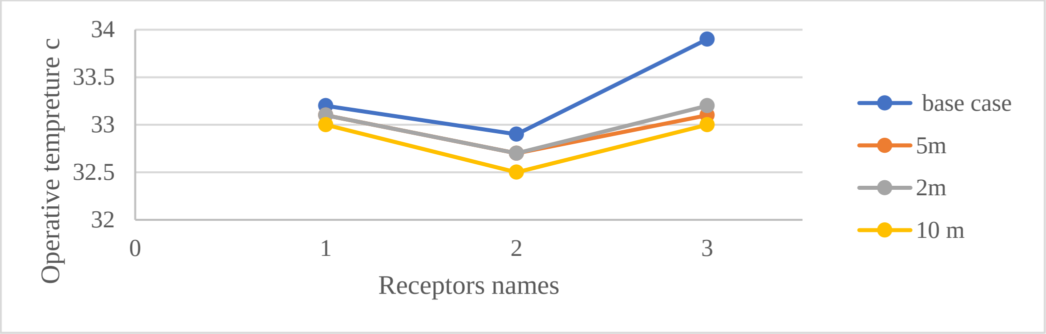


Figure 5-31 : Case 1 (The effect of tree height on operative temperature at 13m in summer)

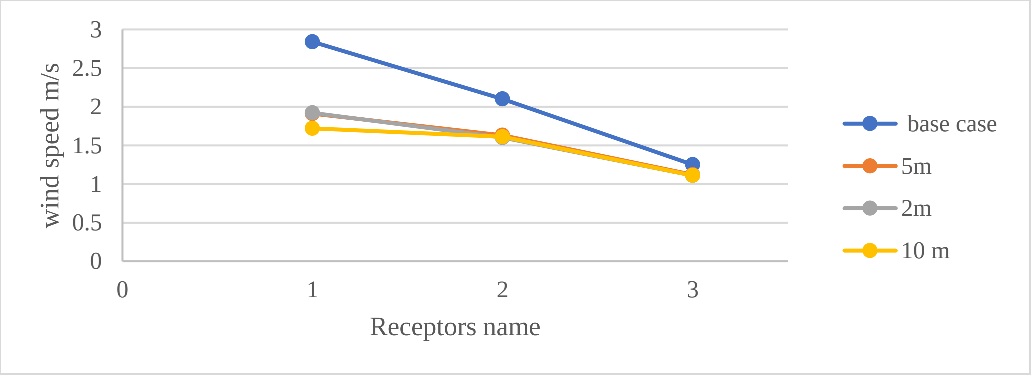


Figure 5-32 : Case 1 (The effect of tree height on wind speed at 13m in summer)

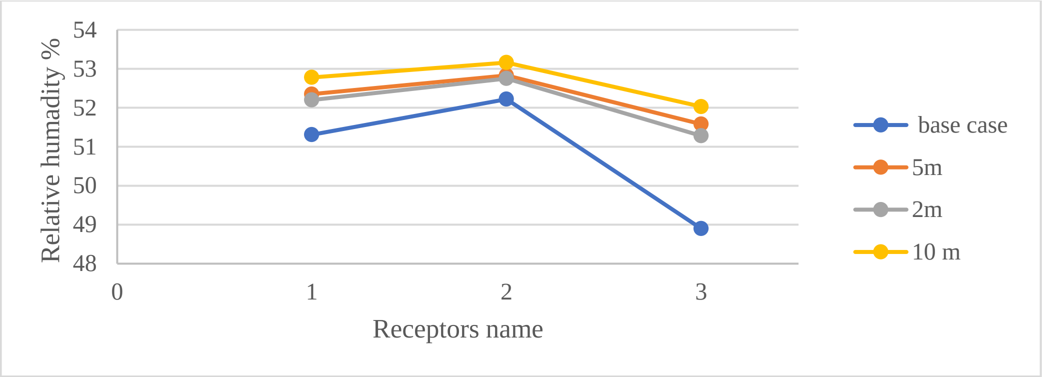


Figure 5-33 : Case 1 (The effect of tree height on relative humidity at 13m in summer)

The simulations revealed that the scenario with 10-meter-tall trees has the most enhancement in reducing temperature, wind speed, and increasing humidity. However, compared to the effects observed at measurement heights of 1.8 meters and 7 meters for 10-meter trees, the impact at a reference height of 13 meters was minimal.

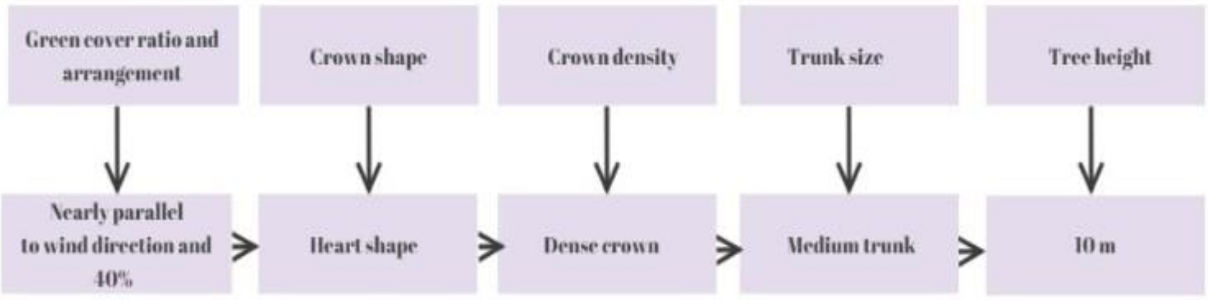


Figure 0-34 : Case 1 (The optimal green typologies)

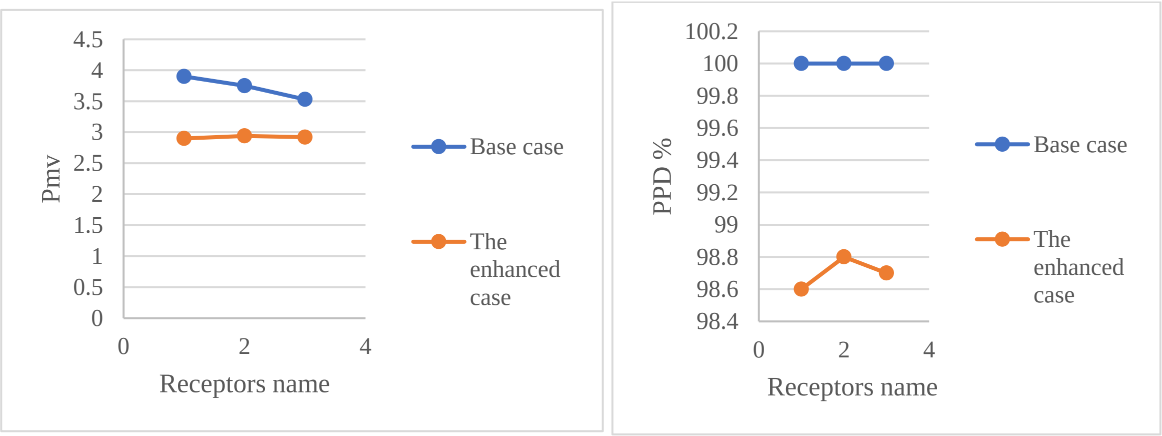


Figure 5-35 : Case 1 (Thermal comfort indicator calculation)

The figure shows the best choice for each variable based on earlier analysis of the scenarios. Thermal comfort indicators, including Predicted Mean Vote (PMV) and Predicted Percentage Dissatisfied (PPD), were evaluated for the outdoor space at a 1.8-meter height. While the results demonstrate an improvement in both PMV and PPD, the extent of this change is limited. It implies that the presence and optimal design of trees, while favorable, are insufficient to provide ideal thermal comfort conditions. It was suggested that additional features, such as green roofs and walls, may be required to support strategic tree placement for optimal thermal comfort.

5.3.1.2 Case 2: Simulation results of area (2) in King Abdullah Ben Abdul-Aziz residential complex

The case is a separate area within the same residential complex. This selection was driven by two factors: the difference in orientation between this case and the previous case and the variation in building distances between the two locations.

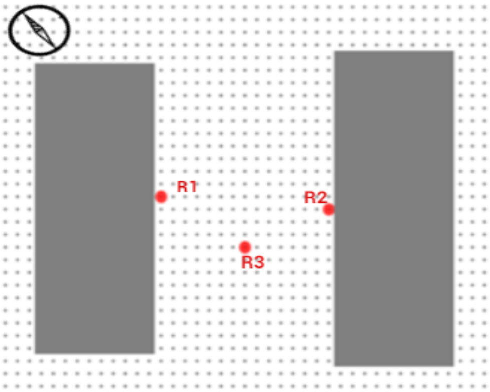


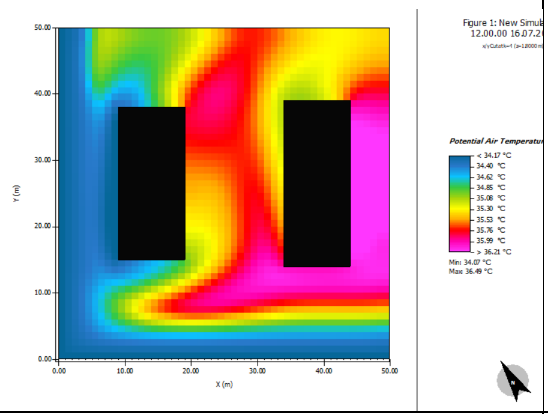
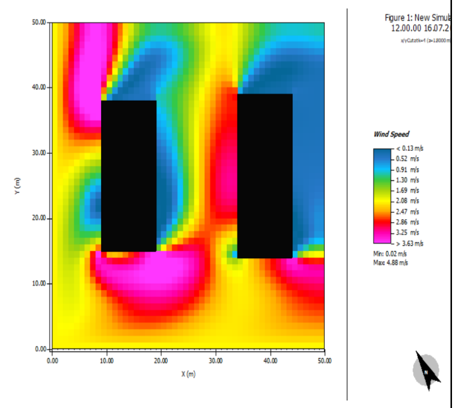
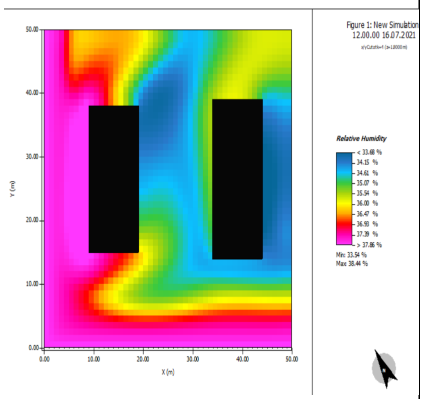
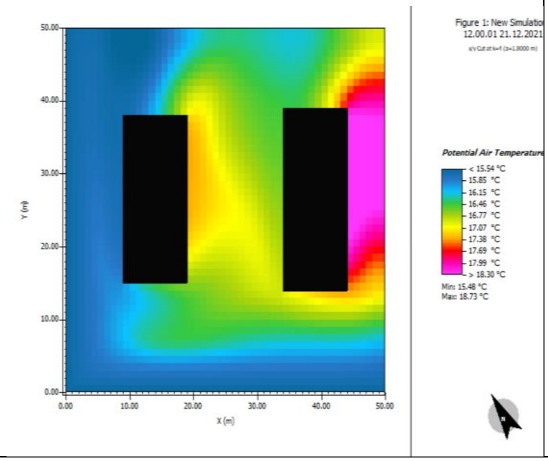
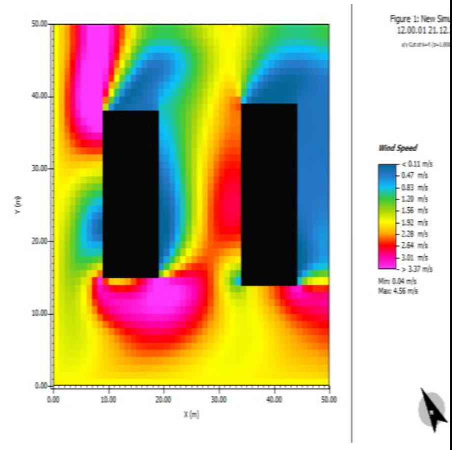
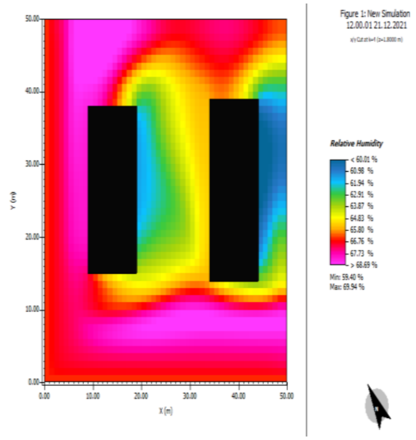
Figure 5-36 : case 2 site plan showed the receptors location

A computational simulation was conducted to establish a baseline for thermal conditions within an outdoor space of a residential complex. The scenario simulated an open space devoid of vegetation or other natural elements during peak summer (12:00 pm, July 16, 2021) and peak winter (12:00 pm, December 21, 2021) conditions.

Summertime measurements within the outdoor space revealed that approximately 80% of the area experienced temperatures around 35°C. Wind speeds exhibited spatial variability across the space, as (table). Additionally, relative humidity is estimated at 35% across roughly 85% of the outdoor space area. Thermal comfort analyses conducted for the space environment indicated that 100% of occupants were likely to experience thermal discomfort.

Wintertime measurements within the outdoor space revealed that approximately 50% of the area experienced temperatures around 17°C. Wind speeds exhibited spatial variability across the space, as detailed(table). Additionally, relative humidity is estimated at 50% across roughly 65-63% of the outdoor area. Thermal comfort analyses conducted for the space environment indicated that 30% of occupants were likely to experience thermal discomfort.

Table 5-7 : Case 2: base case simulation

(Base case) Micro climate scale simulation (At pedestrian level 1,8 m)						
Case	Description	Operative temperature ©	Wind speed(m/s)	Relative humidity	PPD	PMV
Summer	Base case (summer time at 12:00 pm) 16-7-2-2021				100 %	5.1-5.3
Winter	Base case (Winter time at 12:00 pm) 21-12-2021				30%	-1.35

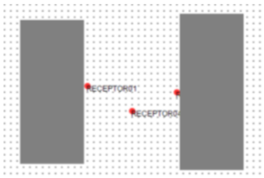
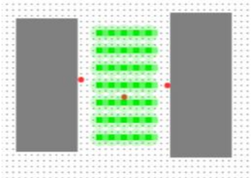
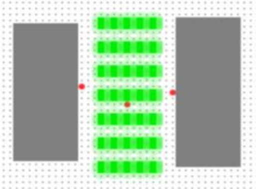
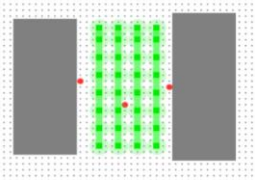
Following the establishment of a baseline scenario through computational simulation, subsequent simulations incorporated various tree typologies as variables. These tree-related variables include:

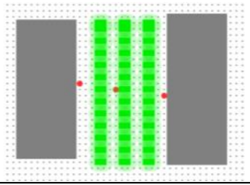
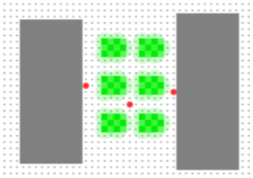
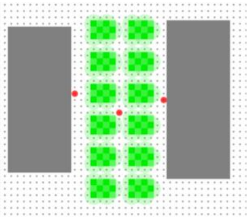
- Vegetation cover ratio and arrangement simulation results

The section centered on how vegetation cover percentage and tree spatial arrangement interact to influence outdoor thermal performance. This phase included six different scenarios that systematically impacted these variables. The subsequent analysis delves into the impact of both green cover percentage and tree arrangement on the thermal environment.

- Summer case simulation

Table 5-8: Case 2 (Green ratio and arrangement simulation results)

Cases	Description	Operative temperature ©	Wind speed(m/s)	Relative humidity
	Base case (summer time at 12:00 pm) 16-7-2-2021	Appendix c (Figure 5-22)	Appendix c (Figure 5-23)	Appendix c (Figure 5-24)
	• Cr1: 20% • A1: Row horizontal • Grass, Tree constant	Appendix c (Figure 5-25)	Appendix c (Figure 5-26)	Appendix c (Figure 5-27)
	• Cr 2: 40% • A1: Row horizontal • Grass, Tree constant	Appendix c (Figure 5-28)	Appendix c (Figure 5-29)	Appendix c (Figure 5-30)
	• Cr1: 20% • A2: Row Vertical • Grass, Tree constant	Appendix c (Figure 5-31)	Appendix c (Figure 5-32)	Appendix c (Figure 5-33)

	• Cr2: 40% • A2: Row Vertical • Grass, Tree constant	Appendix c (Figure 5-34)	Appendix c (Figure 5-35)	Appendix c (Figure 5-36)
	• Cr1: 20% • A3: Grouped • Grass, Tree constant	Appendix c (Figure 5-37)	Appendix c (Figure 5-38)	Appendix c (Figure 5-39)
	• Cr2: 40% • A3: Grouped • Grass, Tree constant	Appendix c (Figure 5-40)	Appendix c (Figure 5-41)	Appendix c (Figure 5-42)

The simulations yielded consistent results across all scenarios except Scenario (Grouped 40%), which displayed a cooling effect, with a temperature decrease of 0.5-1 degree Celsius, except at sensor 1where there was no observed change. Additionally, Scenario (Grouped 40%) reduced wind speed by 1 m/s, except for sensor 1, where it had no effect. Finally, Scenario (Grouped 40%) increased relative humidity by 3-4%.

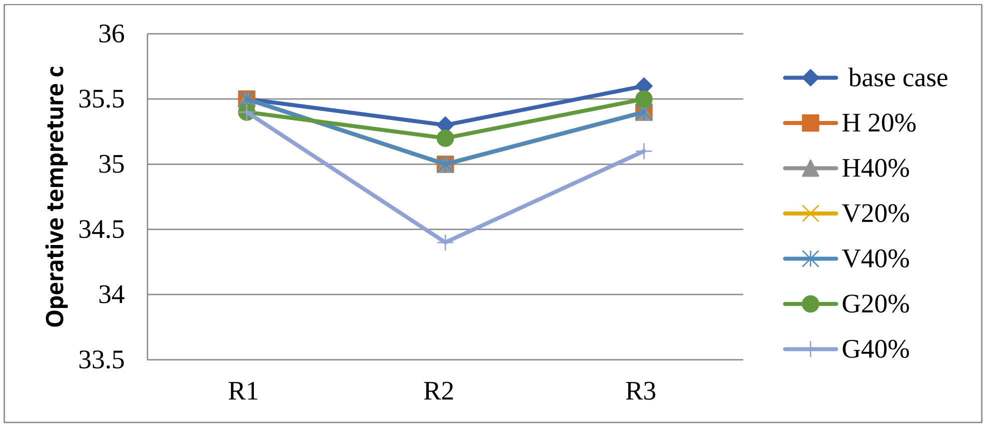


Figure 5-37 : Case 2 (The effect of green cover ratio and arrangement on operative temperature in summer)

(H20%): The green cover percentage is 20% and it is planted in rows perpendicular to the wind direction, (H40%): The green cover percentage is 40% and it is planted in rows perpendicular to the wind direction,(V20%): The green cover percentage is 20% and it is planted in rows Parallel to the wind direction, (V40%): The green cover percentage is 40% and it is planted in rows Parallel to the wind direction,(G20%): The green cover percentage is 20% and it is planted in groups, (G40%): The green cover percentage is 40% and it is planted in groups.

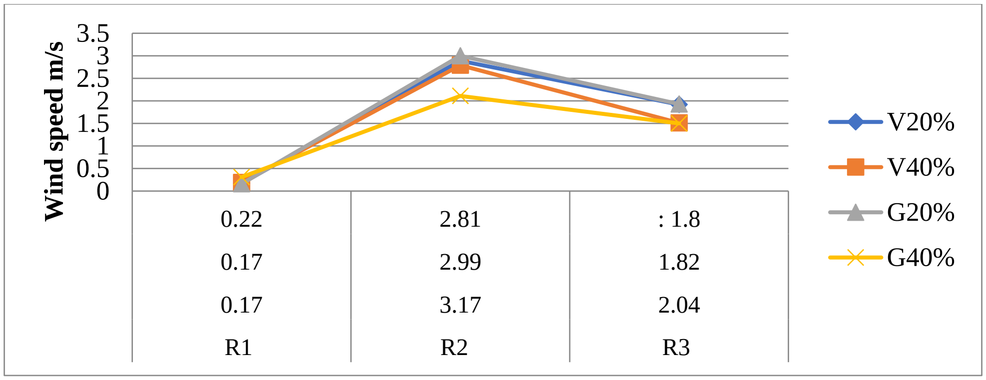


Figure 5-38:Case 2 (The effect of green cover ratio and arrangement on wind speed in summer)

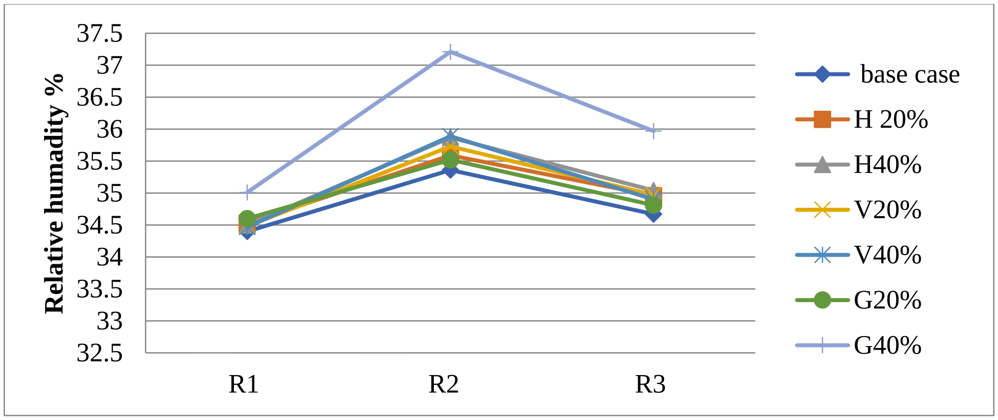


Figure 5-39 : Case 2 (The effect of green cover ratio and arrangement on relative humidity in summer)

- Winter case simulation results

Across all scenarios, winter temperatures exhibited a slight decrease of 1 degree Celsius. Additionally, the wind speed increased slightly (0.2-0.4 m/s), except for sensor 1, which showed no change. Relative humidity also saw a modest increase of 3-2%. Similar to the previous findings, winter simulations involving deciduous trees yielded minimal to no reductions in temperature, wind speed, and relative humidity. However, it's important to note that the consistent presence of grass in all scenarios might have contributed to these slight decreases.

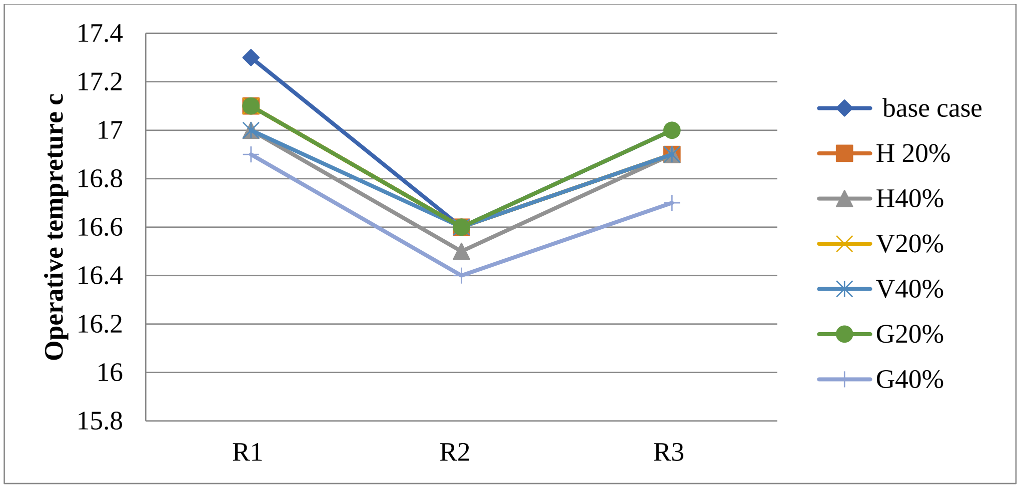


Figure 5-40 : Case 2 (The effect of green cover ratio and arrangement on operative temperature in winter)

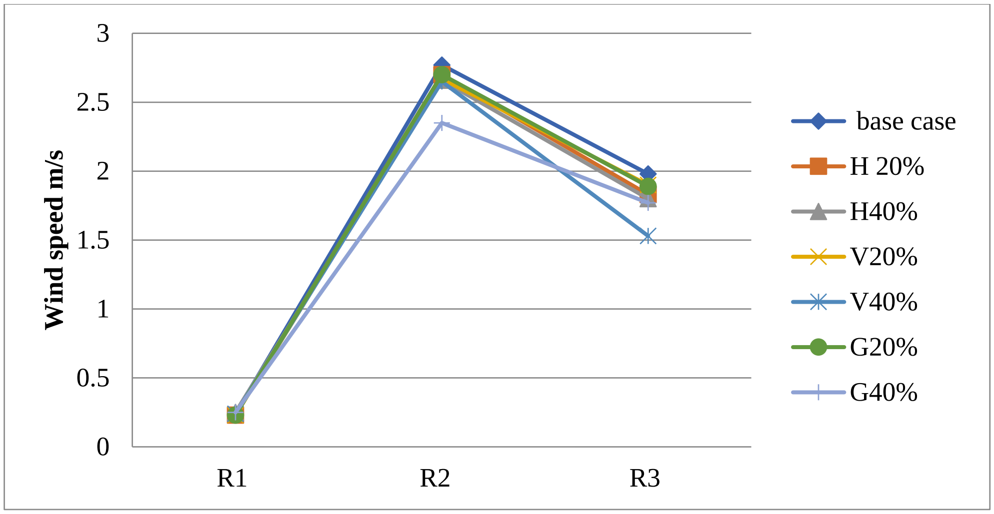


Figure 5-41 : Case 2 (The effect of green cover ratio and arrangement on wind speed in winter)

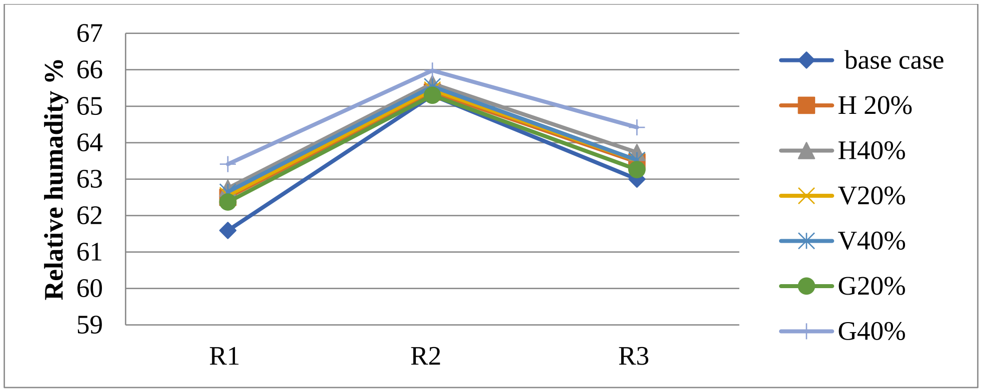


Figure 5-42 : Case 2 (The effect of green cover ratio and arrangement on relative humidity in winter)

- Crown shape scenarios simulation results

Following the selection of optimal vegetation cover percentage and tree spatial arrangement (Grouped 40%) through prior simulations, a subsequent analysis focused on the influence of tree crown morphology. This phase involved fixing the previously optimized variables (cover percentage and arrangement) while introducing crown shape as a new variable. The specific crown shapes included are cylindric, conic, spherical, and (heart, vase).

The simulations identified the cone-shaped tree scenario as most effective for summer cooling, reducing temperature, wind speed, and increasing relative humidity (except at sensor 1, which exhibited the opposite effects). However, cone-shaped trees are often evergreen, which reduces winter temperature – especially when planted on eastern and western building facades.

Overall thermal performance for the outdoor space, cylindrical and vase-shaped trees provided similar positive impacts compared to the cone-shaped scenario.

Cylindrical and vase-shaped crown scenarios displayed a positive impact on thermal performance. These shapes resulted in a temperature decrease of 0.5-0.7 degrees Celsius, a reduction in wind speed by 1 m/s, and a minimal increase in relative humidity.

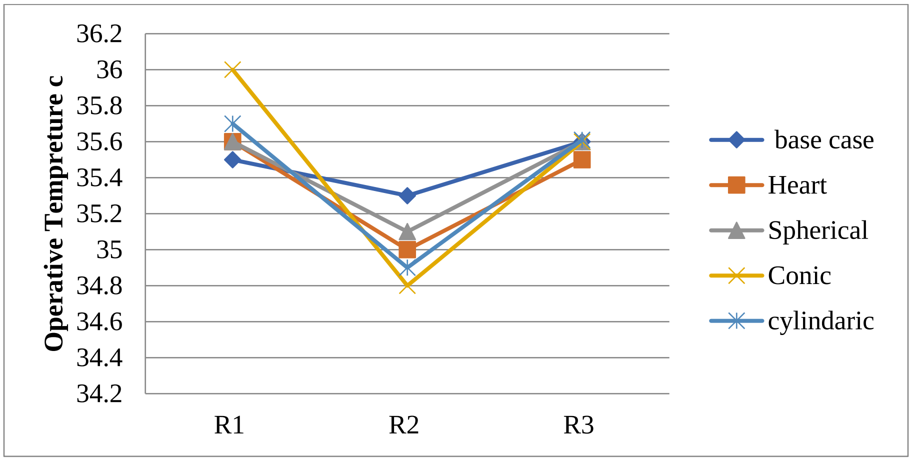


Figure 5-43: Case 2 (The effect of crown shape on operative temperature in summer)

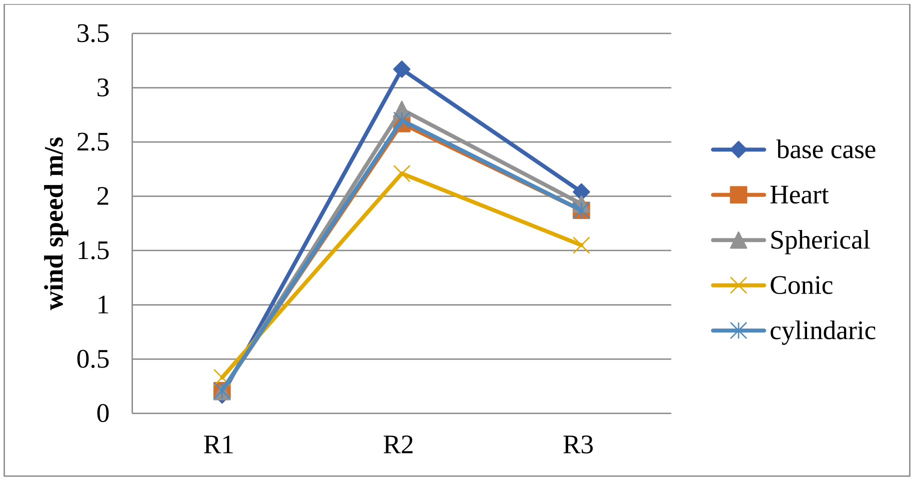


Figure 5-44 : Case 2 (The effect of crown shape on wind speed in summer)

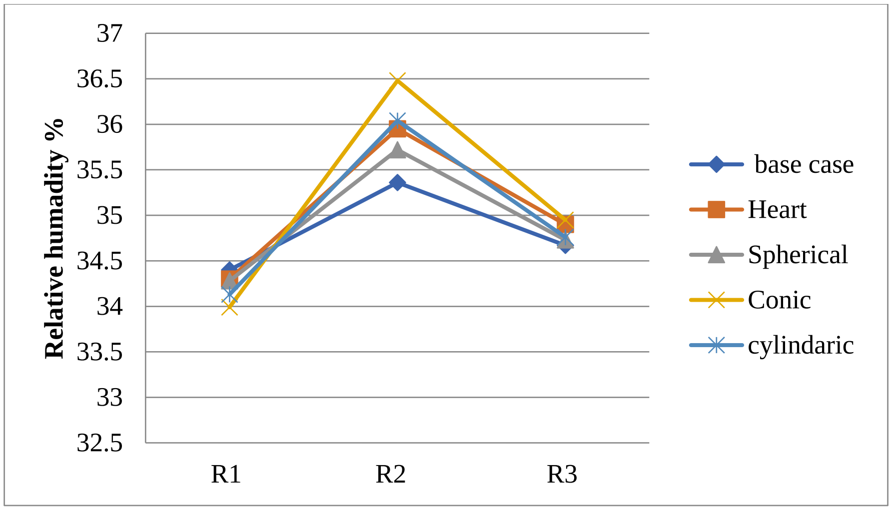


Figure 5-45: Case 2 (The effect of crown shape on relative humidity in summer)

- Crown density simulation results

Dependent on the findings from the previous scenarios, the investigation focused on the crown density of cylindrical and vase-shaped trees. The goal was to determine if optimizing density could further enhance their thermal performance compared to the previously explored conical shape, which exhibited some positive results. This section investigates the optimal crown density for cylindrical and vase-shaped trees in terms of thermal performance. The findings will inform the selection of these shapes in subsequent simulations involving various scenario variables.

Both cylindrical and vase-shaped tree crowns exhibited superior thermal performance when they have dense crowns, compared to sparser crowns. This section compared these dense configurations (dense cylindrical vs. dense vase-shaped) to identify the one with the most optimal thermal benefits.

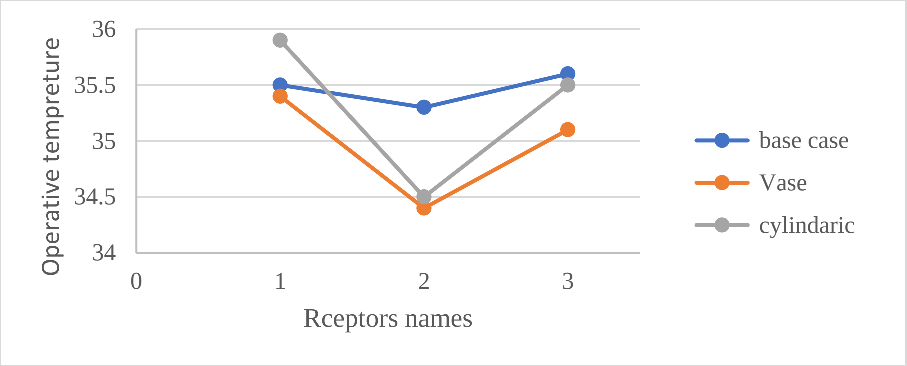


Figure 5-46 : Case 2 (The effect of crown shape and density on operative temperature in summer)

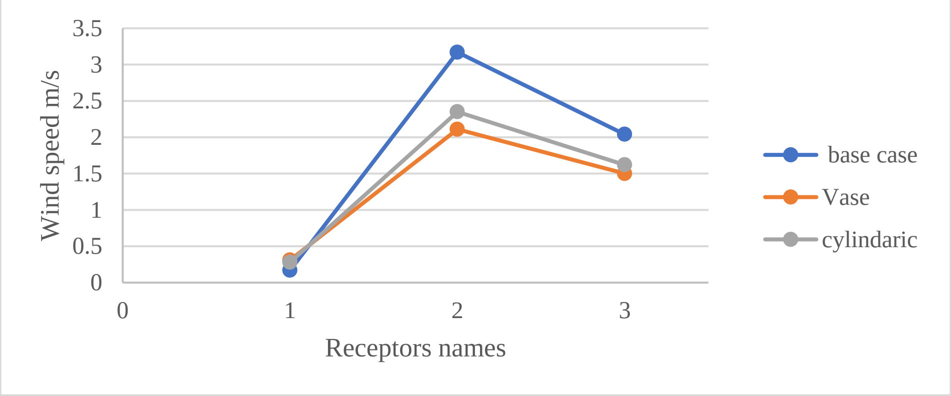


Figure 5-47 : Case 2 (The effect of crown shape and density on wind speed in summer)

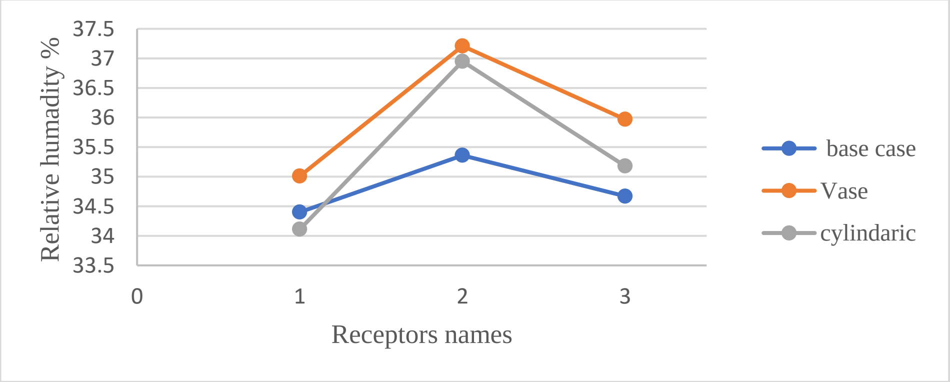


Figure 5-48 : Case 2 (The effect of crown shape and density on relative humidity in summer)

The charts identified the dense vase-shaped crown as more effective in optimizing thermal performance than its dense cylindrical crown. The vase-shaped crown decreases by 0.5-1 degrees Celsius, reductions in wind speed, and increases in humidity levels. Notably, this advantage was most significant in the open central area of the courtyard, where unobstructed airflow could maximize the vase crown's influence.

- Trunk size scenarios simulation results

Following the examination of previous variables, this section explored how variations in tree trunk size (Small, Medium, Large), affect temperature, wind speed, and relative humidity.

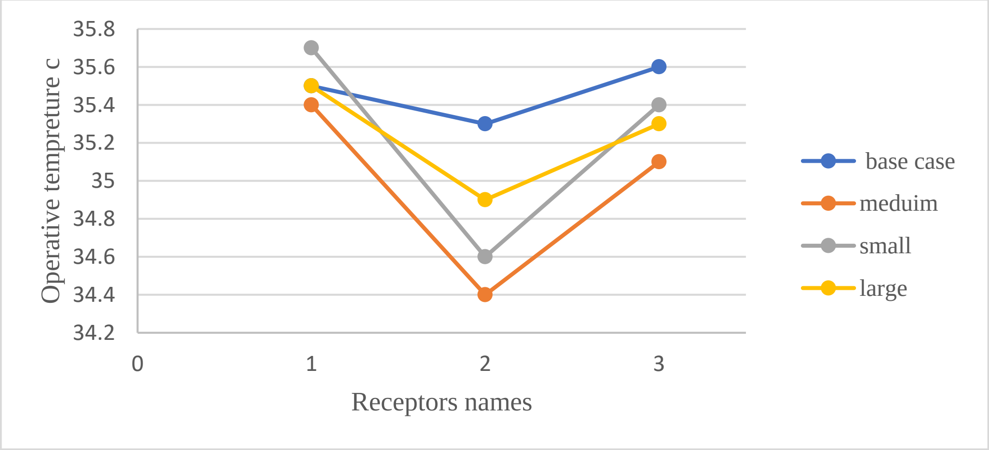


Figure 5-49: Case 2 (The effect of trunk size on operative temperature in summer)

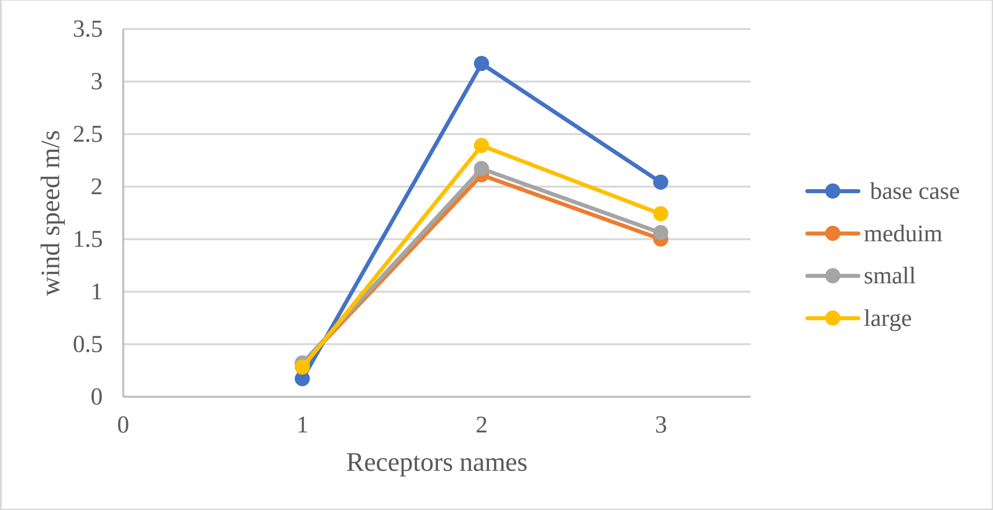


Figure 5-50: Case 2 (The effect of trunk size on wind speed in summer)

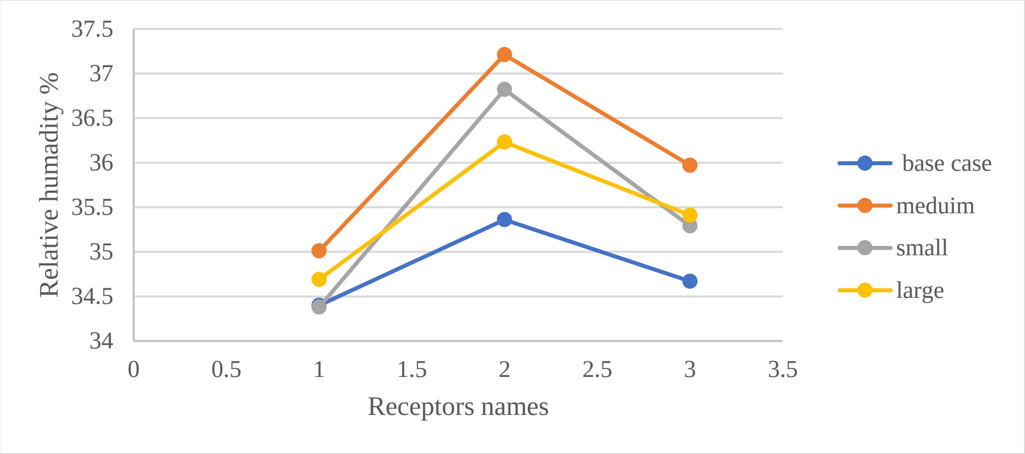


Figure 5-51: Case 2 (The effect of trunk size on relative humidity in summer)

The simulations revealed that medium-sized tree trunks delivered the most significant thermal improvement. Compared to large and small tree trunks, medium-sized tree trunks resulted in:

- ✓ Temperature reduction of 1-5 degrees Celsius.
- ✓ An increase in relative humidity (although the percentage increase was low compared to large and small trees).
- ✓ The reduction in wind speed (with a similar effect observed for large and small trees).

- Trees height scenarios simulation results

Dependent on the findings from the previous variables, this section utilized simulations to examine the impact of tree height on thermal performance. The simulations specifically investigated how temperature variations within the building and the external courtyard depend on tree height (2m, 5m, and 10m) at different floor levels (1.8m, 7m, and 13m).

✓ Trees height scenarios simulation results at 1.8 m

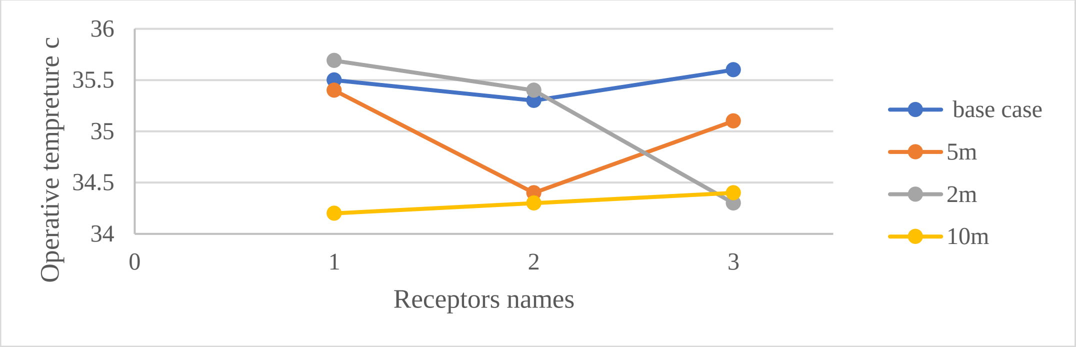


Figure 5-52 : Case 2 (The effect of tree height on relative humidity at 1.8m in summer)

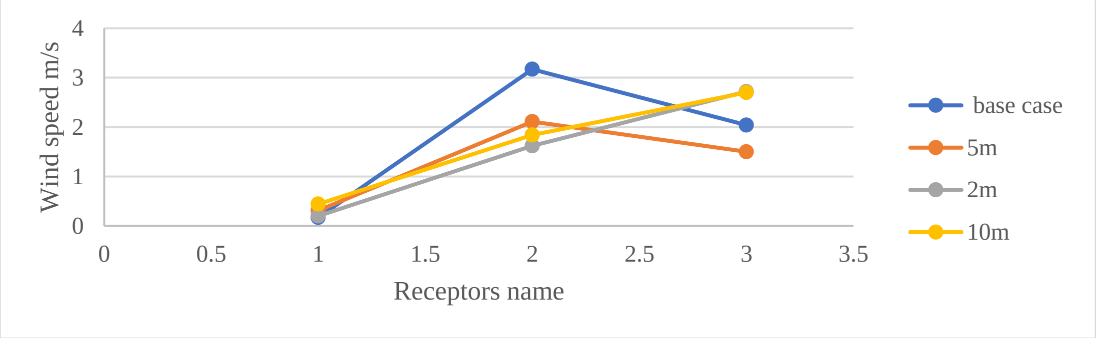


Figure 5-53 : Case 2 (The effect of tree height on wind speed at 1.8m in summer)

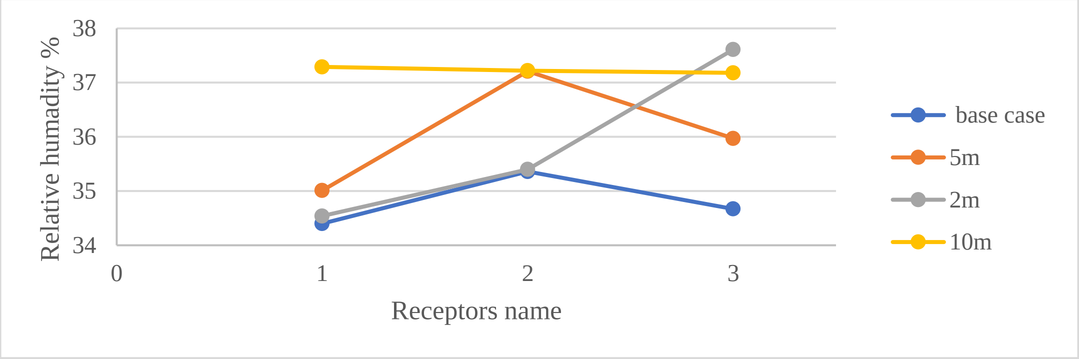


Figure 5-54: Case 2 (The effect of tree height on relative humidity at 1.8m in summer)

Pedestrian-level measurements across the various height scenarios (2-10 meters) revealed inconsistent thermal performance at sensors, particularly within the open area. This inconsistency manifested as increased wind speed at sensor 3, located in the central zone. Conversely, the 5-meter scenario exhibited a consistent and modest decrease in temperature and wind speed, accompanied by a slight increase in humidity.

✓ Trees height scenarios simulation results at 7 m

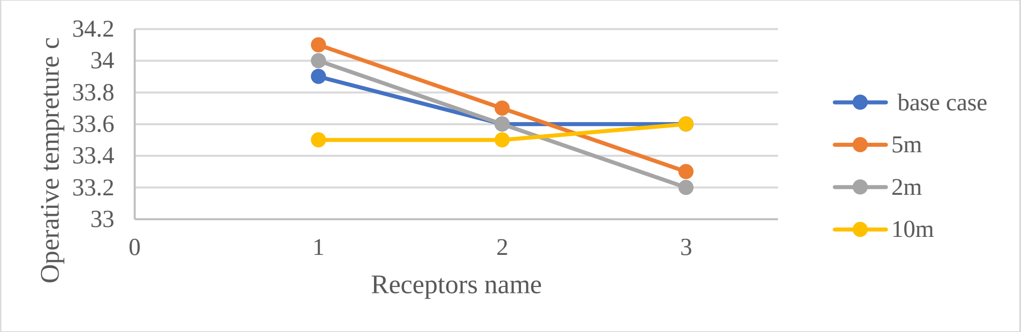


Figure 5-55: Case 2 (The effect of tree height on operative temperature at 7m in summer)

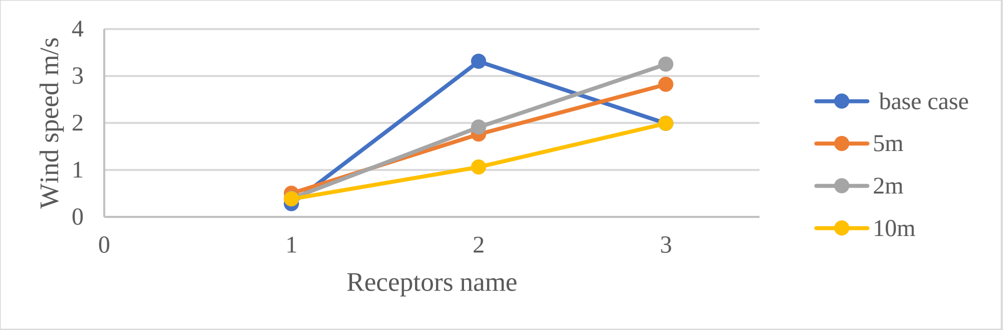


Figure 5-56: Case 2 (The effect of tree height on wind speed at 7m in summer)

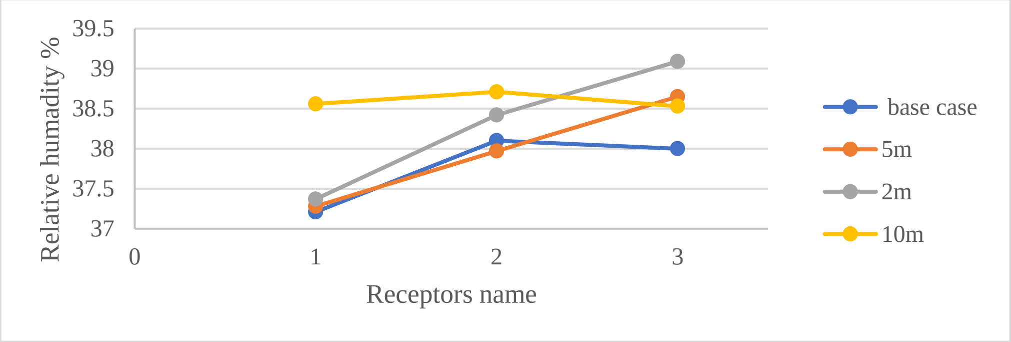


Figure 5-57: Case 2 (The effect of tree height on relative humidity at 7m in summer)

Simulations for various tree heights revealed inconsistent results at a measurement height of 7 meters:

- Across all scenarios, temperatures increased near building sensors. In contrast, sensors positioned within the open area of the outdoor space consistently displayed a decrease in temperature.

- The wind speed simulations exhibited consistent results across all scenarios, with readings near the building 1 sensor remaining close to the base case. Conversely, a decrease in wind speed was observed near sensor 2, which led to an increase in wind speed within the open area of the space. However, this effect was not observed for the 10-meter tree height scenario.

- The relative humidity simulations revealed an increase at sensor heights of 2 meters and 10 meters across all scenarios. Conversely, the 5-meter scenario exhibited a decrease in relative humidity.

✓ Trees height scenarios simulation results at 13 m

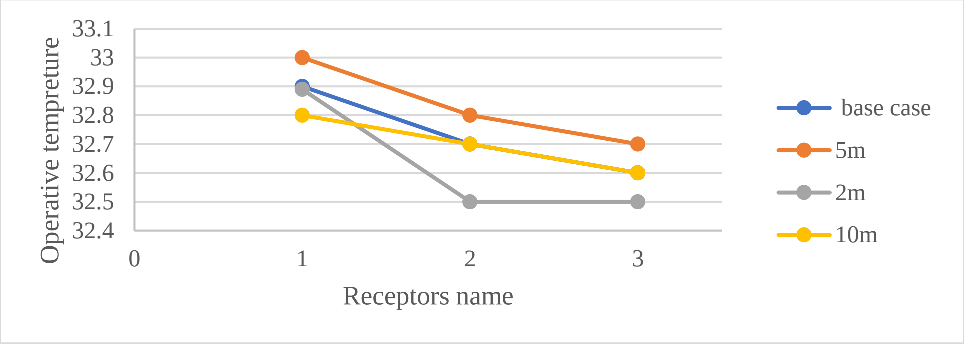


Figure 5-58: Case 2 (The effect of tree height on operative temperature at13m in summer)

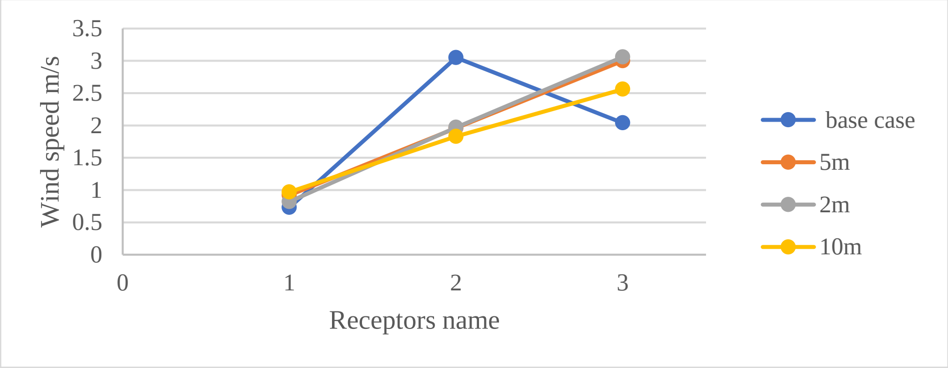


Figure 5-59: Case 2 (The effect of tree height on wind speed at13m in summer)

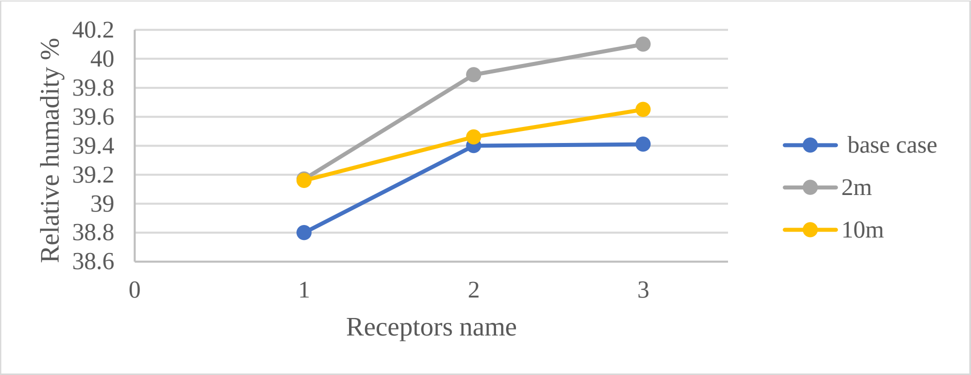


Figure 5-60: Case 2 (The effect of tree height on relative humidity at13m in summer)

The simulations for 10-meter-tall trees consistently yielded positive thermal performance improvements at a measurement height of 13 meters compared to other scenarios. However, it's important to note that these improvements were relatively modest.

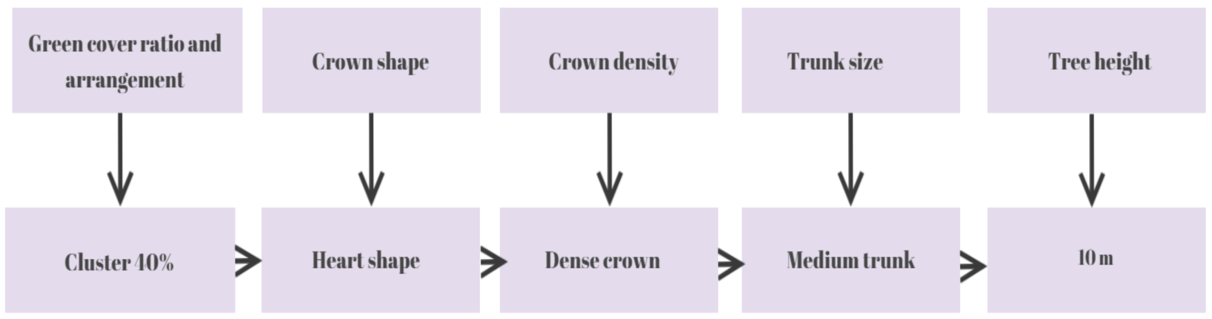


Figure 5-61: Case 2 (The optimal green typologies scenarios)

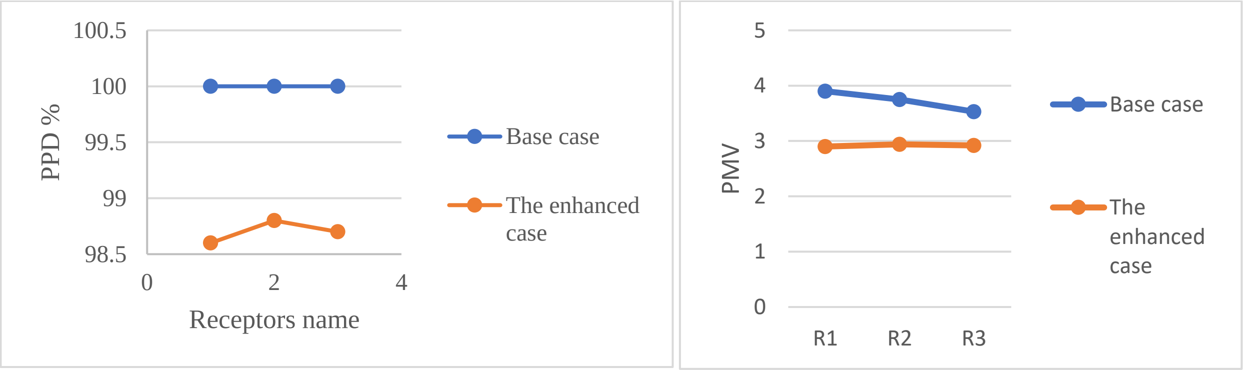


Figure 5-62: Case 2 (Thermal comfort indicator calculation)

analyses, the figure depicts the optimal selection for each variable. Thermal comfort metrics, including predicted mean vote (PMV) and predicted percentage of dissatisfaction (PPD), were evaluated at a height of 1.8 meters within the outdoor space. While both PMV and PPD exhibit improvement, the magnitude of this change remains modest, particularly compared to the previous case. It was suggested that strategically placed trees, even when optimally designed, are not sufficient for achieving ideal thermal comfort. The findings imply that incorporating additional elements, such as green roofs and walls, might be necessary to complement the strategic use of trees for optimal thermal comfort conditions.

5.3.3 Case 3: The description and simulation results of outdoor area in Housing orphan's complex

A housing complex for orphans is situated in the Duer Ban area of Hebron, it consists of three clustered buildings, each with five floors. The average floor height is approximately three meters. Each building includes outdoor spaces adjacent to it. The housing units within these buildings have an average floor area of 330 square meters.

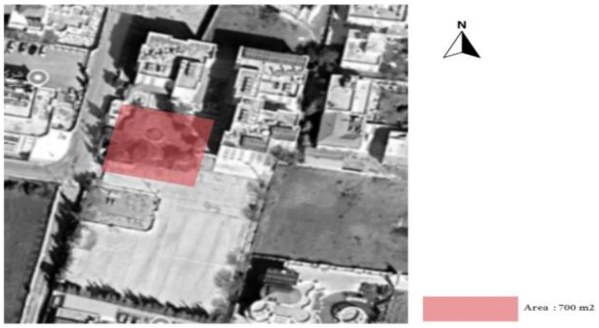


Figure 5-63 : Housing orphans site plan show the outdoor spaces (https://earth.google.com/)

The housing features a variety of outdoor playgrounds designed for children. These playgrounds include a designated exercise area with an asphalt surface. Additionally, natural elements with pavement material are incorporated within the playgrounds to facilitate learning and provide opportunities for practicing various activities.

The study area is approximately 700 square meters and is situated directly adjacent to the main residential buildings.

Figure 5-64: Exterior spaces in Housing orphans (Source from resercher)

The Typical housing model within the complex incorporates four individual bedrooms. Each bedroom has a designed capacity to accommodate six residents. (Figure 5-65)

Figure 5-65 : Typical housing floor design (Engineer of the Charitable Society for Orphan Housing)

As in the previous case, the facade incorporates fenestration elements with dimensions ranging from 1 meter to 2 meters in width and 1 meter to 2 meters in height. Limestone serves as the primary cladding material for the building envelope.

Figure 5-66 : Photos show the exterior façade design with material (Source from researcher)

In the absence of documented design specifications for the facades, field studies and observations were employed to establish the facade details and dimensions.

The structural elements and construction materials exhibit similarities between the two case studies in the King Abdullah neighborhood and the orphan housing.

Orphan housing was chosen as the third case study to examine the influence of tree typologies on building and space configuration on thermal performance. This case differs from the previous ones as the orphan housing features an open courtyard on two sides, with buildings positioned side-by-side in a specific area. This design allows for the analysis of the effect of trees on open-space thermal efficiency and the comparison of results between earlier research and various building compositions.

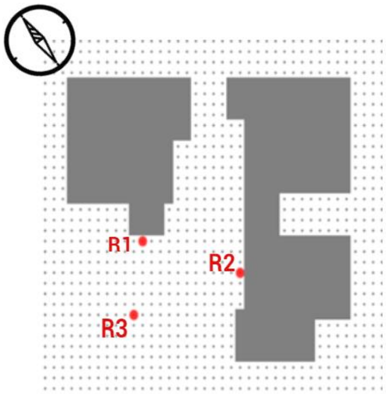


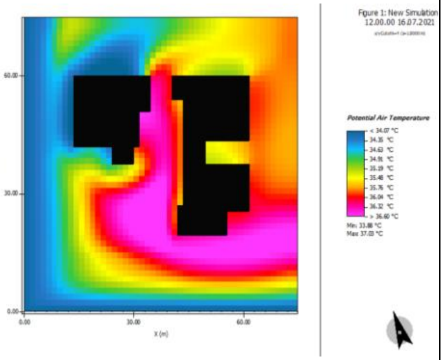
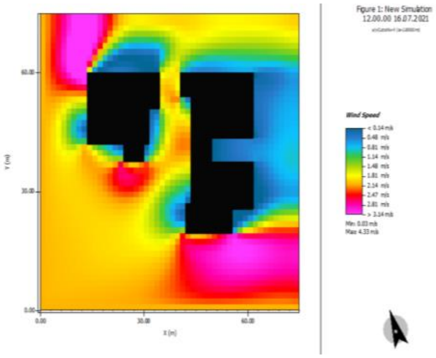
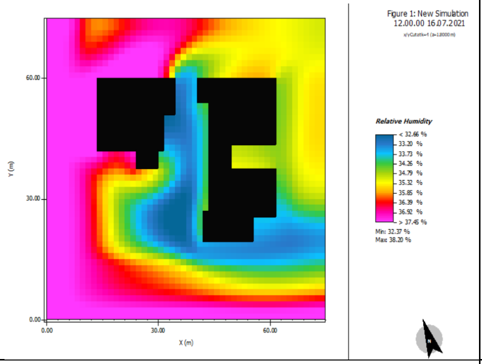
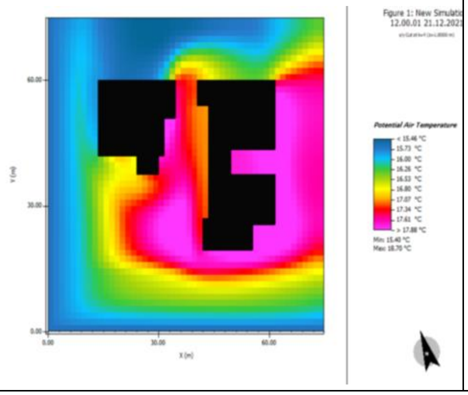
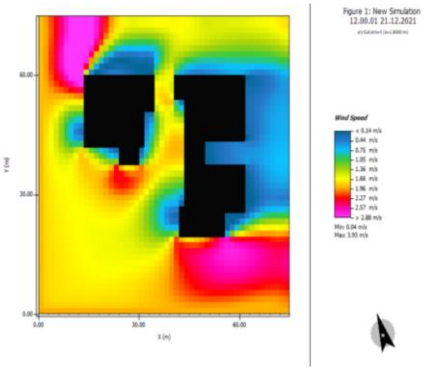
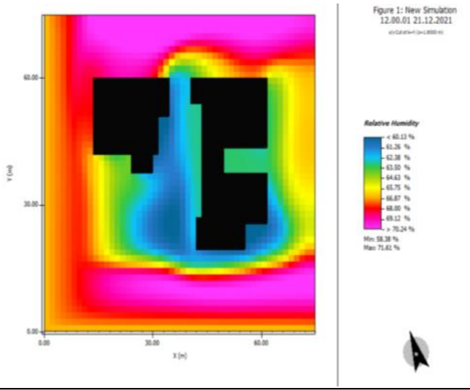
Figure 5-67 : Orphan housing site plan shows receptors location

A computational simulation was conducted to establish a baseline for thermal conditions within an outdoor space of a residential complex. The scenario simulated an open space devoid of vegetation or other natural elements during peak summer (12:00 pm, July 16, 2021) and peak winter (12:00 pm, December 21, 2021) conditions.

Summertime measurements within the outdoor space revealed that approximately 70% of the area experienced temperatures around 35°C. Wind speeds exhibited spatial variability across the space, as (table 5-9). Additionally, relative humidity is estimated at 33% across roughly 65% of the outdoor space area. Thermal comfort analyses conducted for the space environment indicated that 100% of occupants were likely to experience thermal discomfort.

Wintertime measurements within the outdoor space revealed that approximately 50% of the area experienced temperatures around 17°C. Wind speeds exhibited spatial variability across the space, as detailed(table 5-9). Additionally, relative humidity is estimated at 40% across roughly 65-63% of the outdoor area. Thermal comfort analyses conducted for the space environment indicated that 30% of occupants were likely to experience thermal discomfort.

Table 5-9 : Case 3: Base case simulation result (summer, winter)

(Base case) Micro climate scale simulation (At pedestrian level 1,8 m)						
Case	Description	Operative temperature ©	Wind speed(m/s)	Relative humidity	PPD	PMV
Summer	Base case (summer time at 12:00 pm) 16-7-2-2021				100 %	5.1
Winter	Base case (Winter time at 12:00 pm) 21-12-2021				30%	-1.35

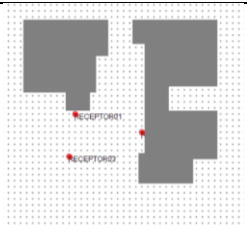
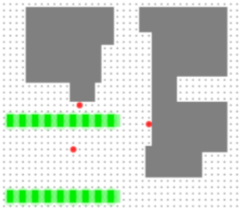
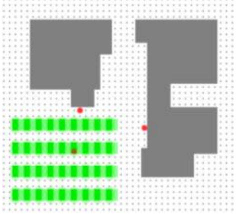
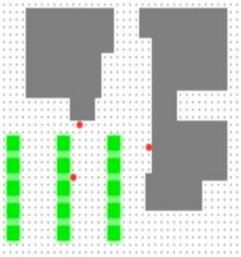
Following the establishment of a baseline scenario through computational simulation, subsequent simulations incorporated various tree typologies as variables. These tree-related variables include:

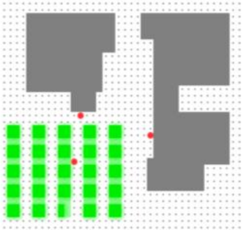
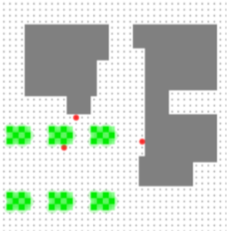
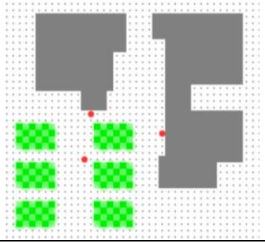
- Green cover ratio and arrangement simulation results

The section centered on how green cover percentage and tree spatial arrangement interact to influence outdoor thermal performance. This phase employed six distinct scenarios (described in the accompanying table) that systematically manipulated these variables. The subsequent analysis delves into the impact of both green cover percentage and tree arrangement on the thermal environment.

- Summer case simulation

Table 5-10 : Case 3 (Green ratio and arrangement simulation results)

Cases	Description	Operative temperature ©	Wind speed(m/s)	Relative humidity
	Base case (summer time at 12:00 pm) 16-7-2-2021 Three receptors	Appendix c (Figure 5-43)	Appendix c (Figure 5-44)	Appendix c (Figure 5-45)
	• Cr1: 20% • A1: Row horizontal • Grass, Tree constant	Appendix c (Figure 5-46)	Appendix c (Figure 5-47)	Appendix c (Figure 5-48)
	• Cr 2: 40% • A1: Row horizontal • Grass, Tree constant	Appendix c (Figure 5-49)	Appendix c (Figure 5-50)	Appendix c (Figure 5-51)
	• Cr1: 20% • A2: Row Vertical • Grass, Tree constant	Appendix c (Figure 5-52)	Appendix c (Figure 5-53)	Appendix c (Figure 5-54)

	• Cr2: 40% • A2: Row Vertical • Grass, Tree constant	Appendix c (Figure 5-55)	Appendix c (Figure 5-56)	Appendix c (Figure 5-57)
	• Cr1: 20% • A3: Grouped • Grass, Tree constant	Appendix c (Figure 5-58)	Appendix c (Figure 5-59)	Appendix c (Figure 5-60)
	• Cr2: 40% • A3: Grouped • Grass, Tree constant	Appendix c (Figure 5-61)	Appendix c (Figure 5-62)	Appendix c (Figure 5-63)

Simulations investigating various vegetation cover percentages and tree arrangements yielded comparable results in temperature reduction. Scenario (vertical 40%) demonstrated the most effective performance, achieving a one-degree Celsius decrease in temperature. Notably, all scenarios for this case exhibited similar wind speed reductions and improvements in relative humidity. Scenario (vertical 40%) outperformed the others, promoting a 2-3% increase in relative humidity. However, none of the scenarios have any improvements in temperature, wind speed, or humidity at sensor 1.

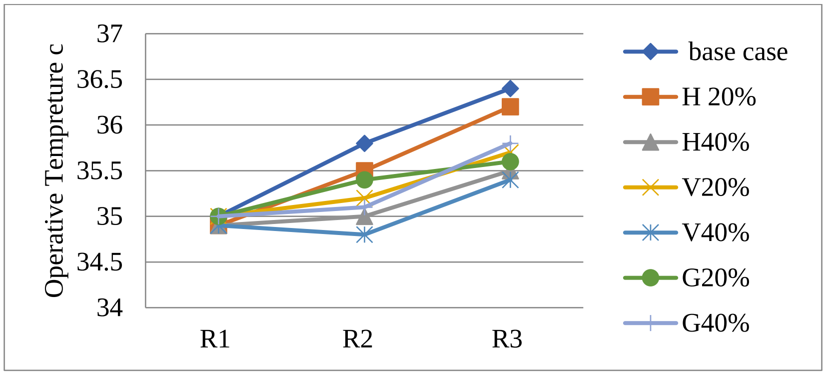


Figure 5-68: Case 3 (The effect of green cover ratio and arrangement on operative temperature in summer)

(H20%): The green cover percentage is 20% and it is planted in rows parallel to the wind direction, (H40%): The green cover percentage is 40% and it is planted in rows parallel to the wind direction,(V20%): The green cover percentage is 20% and it is planted in rows perpendicular to the wind direction, (V40%): The green cover percentage is 40% and it is planted in rows perpendicular to the wind direction,(G20%): The green cover percentage is 20% and it is planted in groups, (G40%): The green cover percentage is 40% and it is planted in groups.

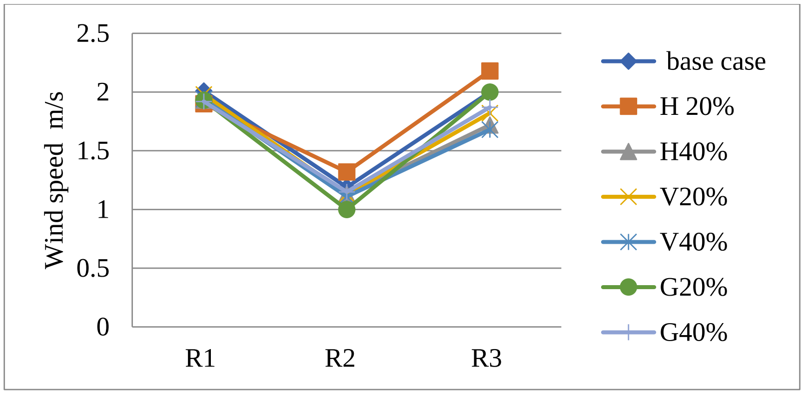


Figure 5-69: Case 3 (The effect of green cover ratio and arrangement on wind speed in summer)

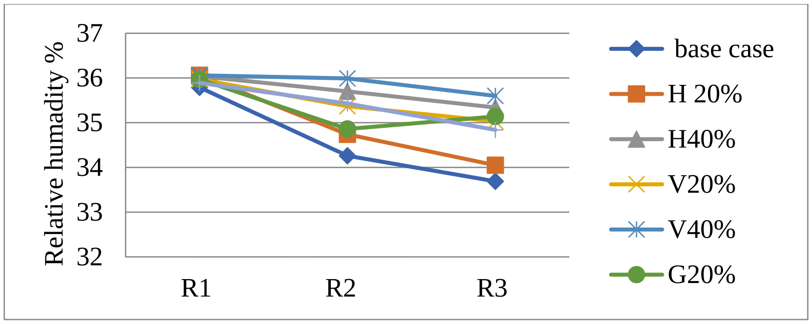


Figure 5-70: Case 3 (The effect of green cover ratio and arrangement on relative humidity in summer)

- Winter case simulation results

Across all scenarios, winter temperatures decreased slightly by 1 degree Celsius. Wind speed also exhibited a modest increase (0.1-0.3 m/s) except at sensor 1, which remained unchanged. Relative humidity followed a similar trend, with a slight increase of 3-2%. Consistent with prior findings, winter simulations involving deciduous trees showed minimal to no reductions in temperature, wind speed, and relative humidity. However, the presence of grass in all scenarios might have played a role in these minor wintertime improvements.

- Crown shape scenarios simulation results

Simulations for various tree crown shapes in open spaces yielded similar results, particularly between cylindrical and conical shapes. Both achieved comparable temperature reductions of 1-1.5 degrees Celsius. Additionally, wind speed improvements were observed, especially in the open area of the courtyard (sensor 3). However, the positive impact on thermal performance near building sensors was minimal to negligible.

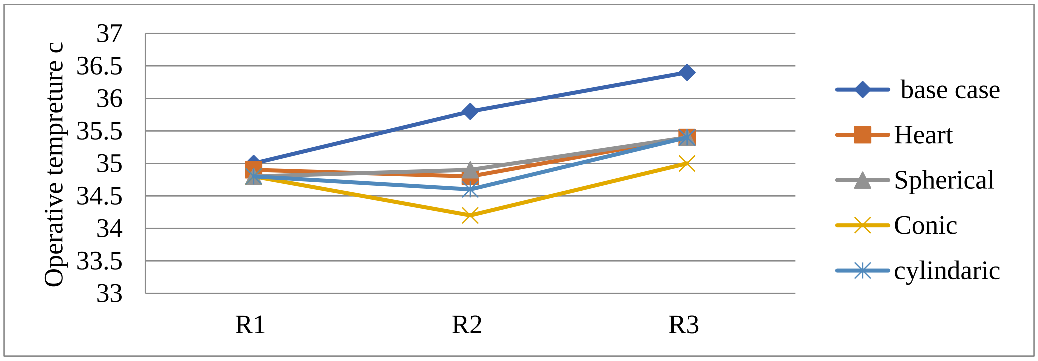


Figure 5-71: Case 3 (The effect of crown shape on operative temperature in summer)

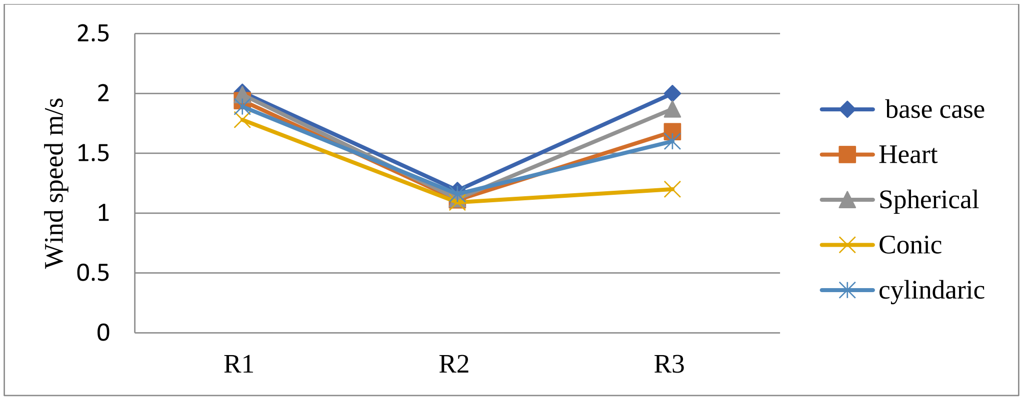


Figure 5-72: Case 3 (The effect of crown shape on wind speed in summer)

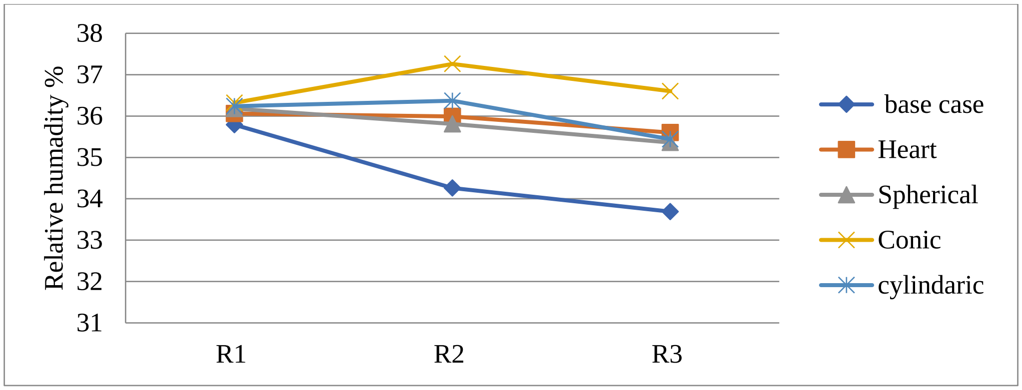


Figure 5-73: Case 3 (The effect of crown shape on relative humidity in summer)

- Crown density scenarios simulation results

The study focused on deciduous trees but investigated the influence of conical shapes, typically associated with evergreen trees. This investigation aimed to evaluate their effectiveness in various layouts of open squares to compare their performance with nearby cylindrical trees. The initial simulations explored both shapes, and the focus subsequently shifted to optimizing the density of cylindrical trees based on the findings, considering their superior performance near buildings alongside the presence of deciduous trees in the overall landscaping plan.

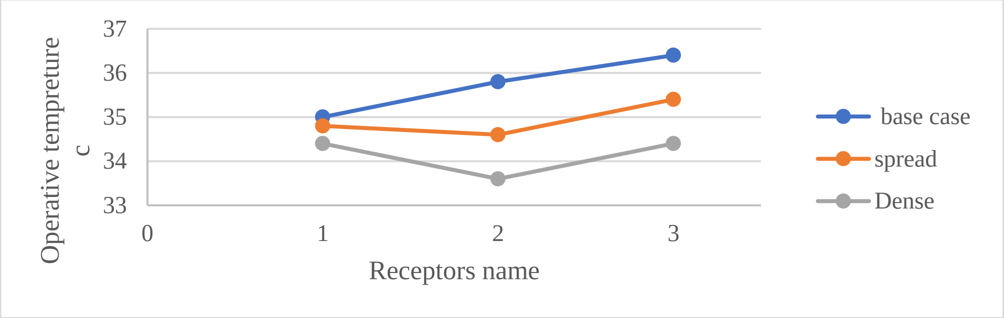


Figure 5-74: Case 3 (The effect of crown density on operative temperature in summer)

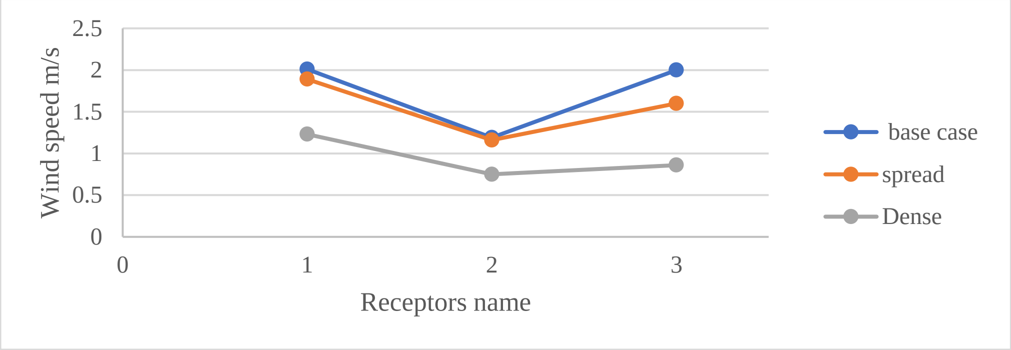


Figure 5-75: Case 3 (The effect of crown density on wind speed in summer)

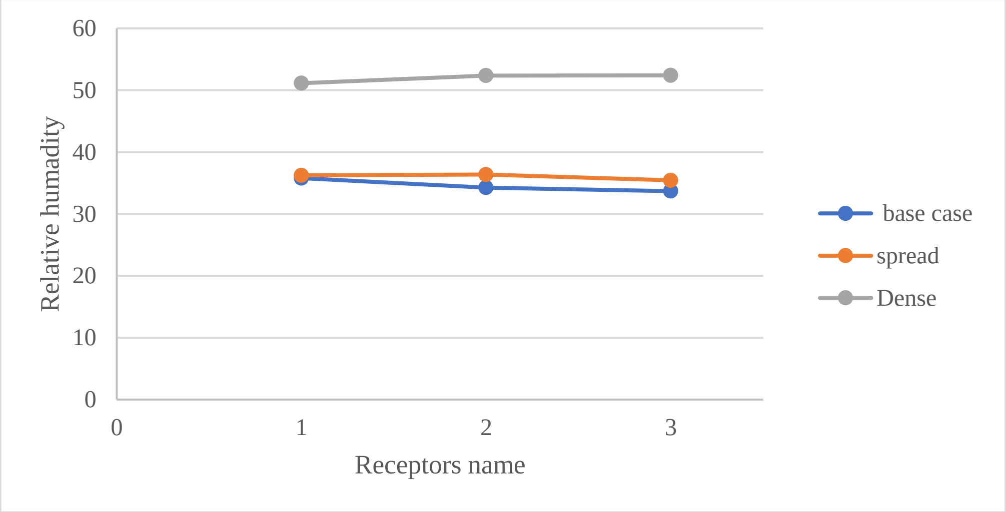


Figure 5-76: Case 3 (The effect of crown density on relative humidity in summer)

Consistent with prior findings, simulations for various crown density scenarios revealed that dense crowns yielded the most significant improvements in thermal performance. In contrast, sparse crown scenarios exhibited performance in relative humidity similar to the base case, indicating no enhancement.

- Tree’s trunk size scenarios simulation results

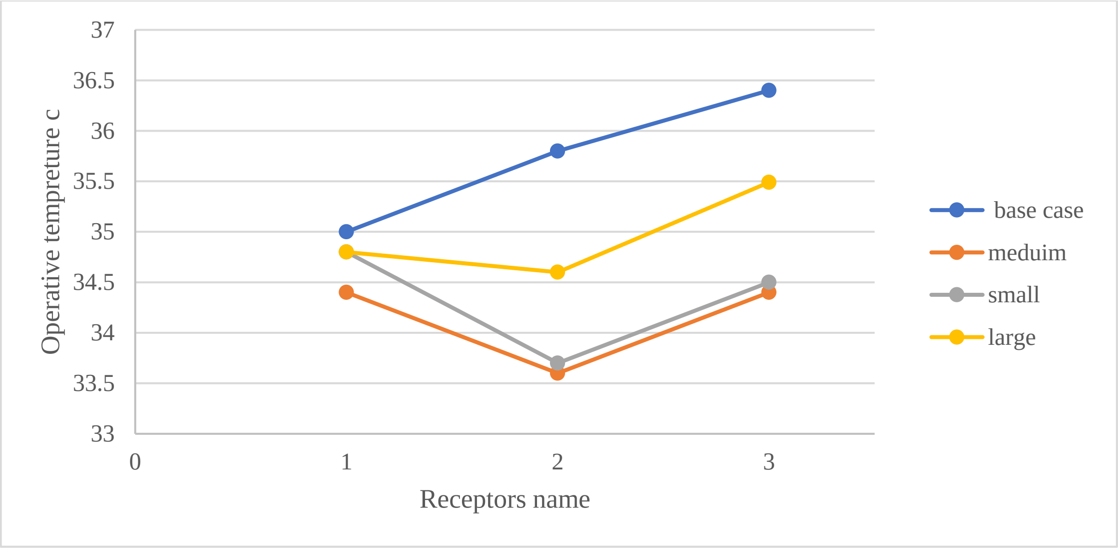


Figure 5-77: Case 3 (The effect of trunk size on operative temperature in summer)

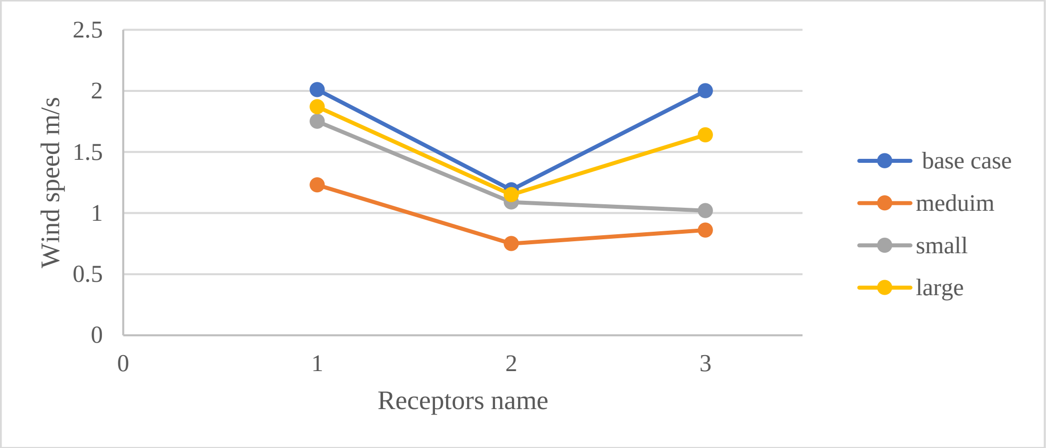


Figure 5-78: Case 3 (The effect of trunk size on wind speed in summer)

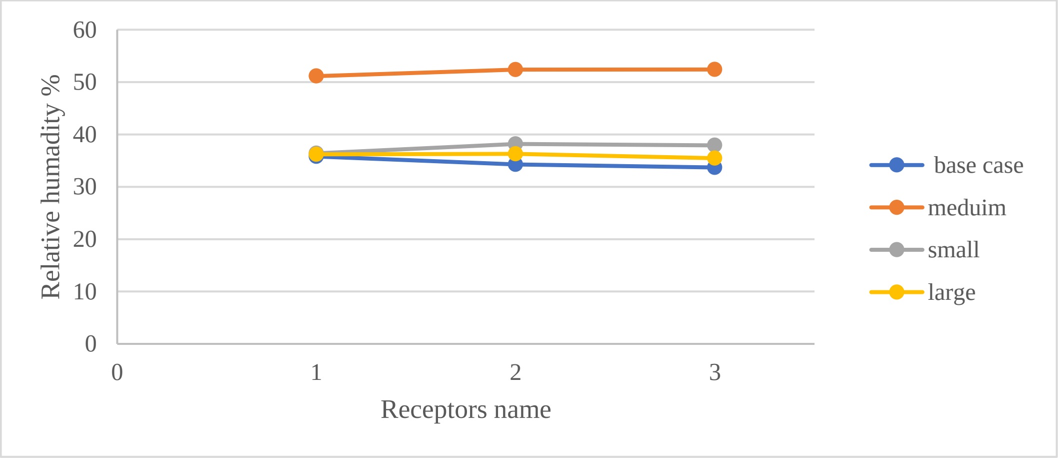


Figure 5-79: Case 3 (The effect of trunk size on relative humidity in summer)

Simulations investigating various tree trunk sizes revealed their impact on the outdoor space's thermal performance. Notably, trees with an average trunk size emerged as the most effective, achieving a 2-degree Celsius reduction in temperature, a 1 m/s decrease in wind speed, and a 10% increase in relative humidity.

- Trees height scenarios simulation results

Dependent on the findings from the previous variables, this section utilized simulations to examine the impact of tree height on thermal performance. The simulations specifically investigated how temperature variations within the building and the external courtyard depend on tree height (2m, 5m, and 10m) at different floor levels (1.8m, 7m, and 13m).

✓ Trees height scenarios simulation results at 1.8 m

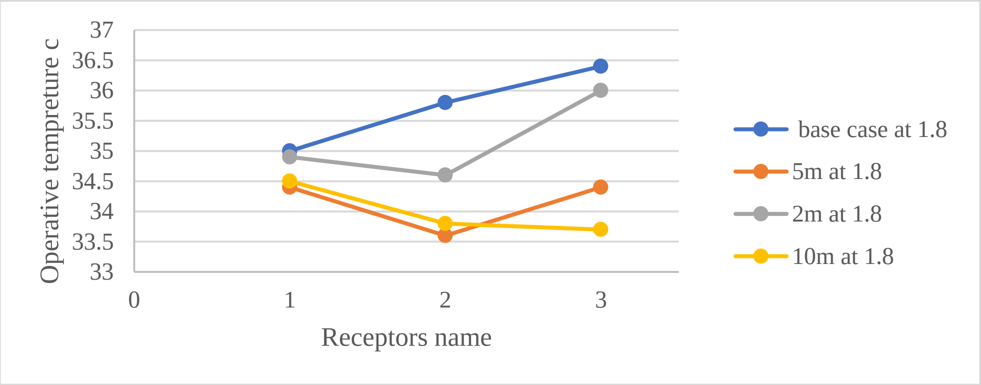


Figure 5-80: Case 3 (The effect of trees height on operative temperature at 1.8m in summer)

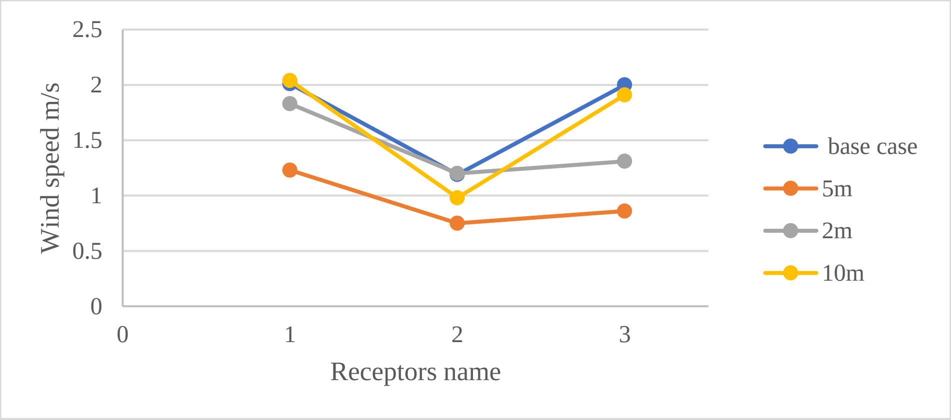


Figure 5-81: Case 3 (The effect of trees height on wind speed at 1.8m in summer)

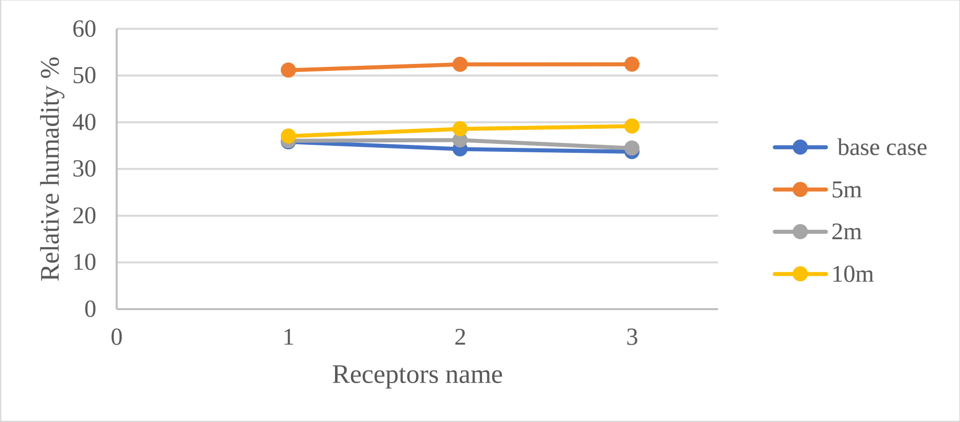


Figure 5-82: Case 3 (The effect of trees height on relative humidity at 1.8m in summer)

- ✓ Trees height scenarios simulation results at 7m

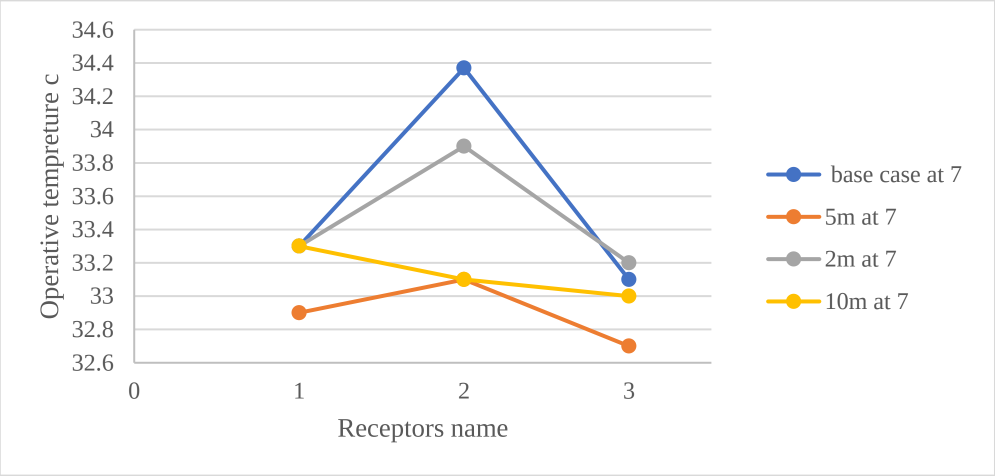


Figure 5-83: Case 3 (The effect of trees height on operative temperature at 7m in summer)

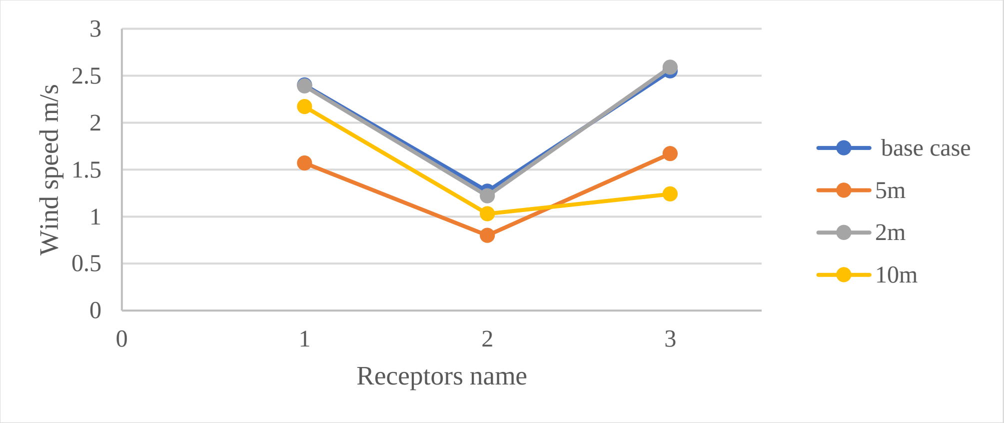


Figure 5-84: Case 3 (The effect of trees height on wind speed at7 m in summer)

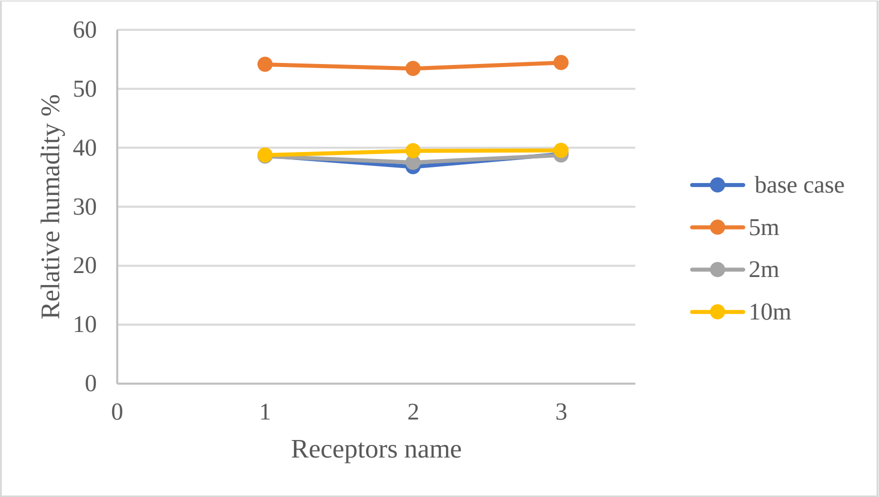


Figure 5-85: Case 3 (The effect of trees height on relative humidity at 7 m in summer)

- ✓ Trees height scenarios simulation results at 13 m

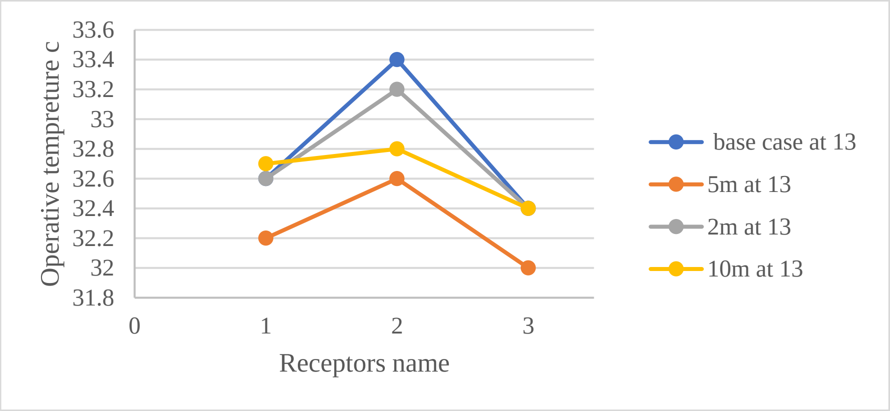


Figure 5-86: Case 3 (The effect of trees height on operative temperature at 13 m in summer)

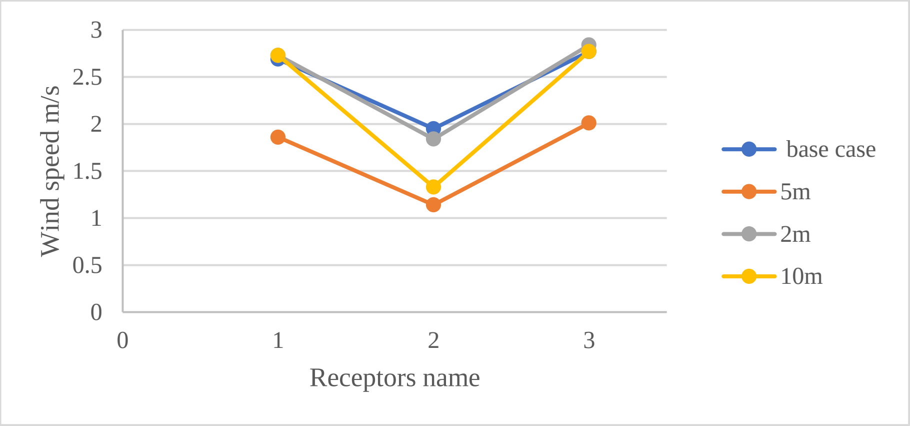


Figure 5-87: Case 3 (The effect of trees height on wind speed at 13 m in summer)

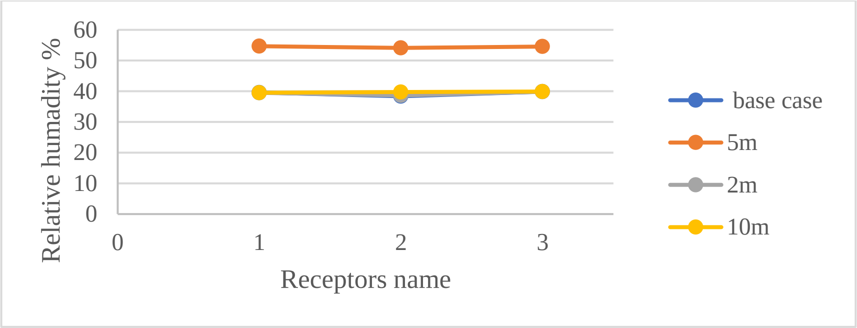


Figure 5-88: Case 3 (The effect of trees height on relative humidity at13 m in summer)

Across all three height scenarios, simulations consistently identified the 5-meter height configuration as the most effective. This scenario yielded the most significant improvements in temperature, wind speed reduction, and humidity increase at all measurement levels. Notably, these enhancements were observed uniformly across the various sensor locations.

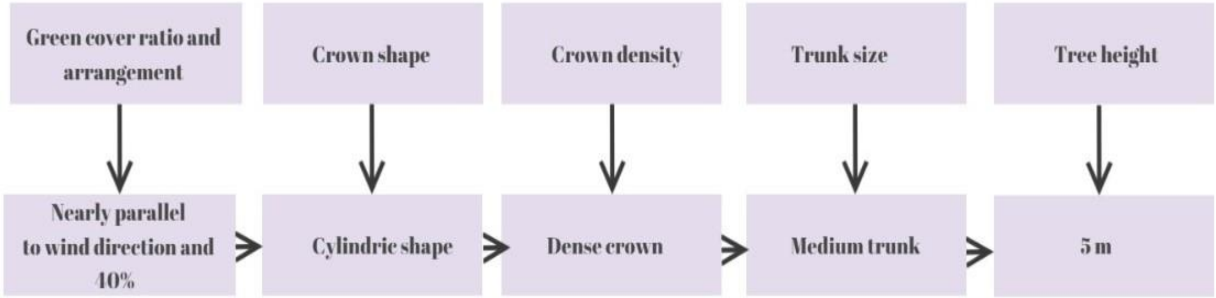


Figure 5-89: Case 3 (The optimal vegetation typologies scenarios)

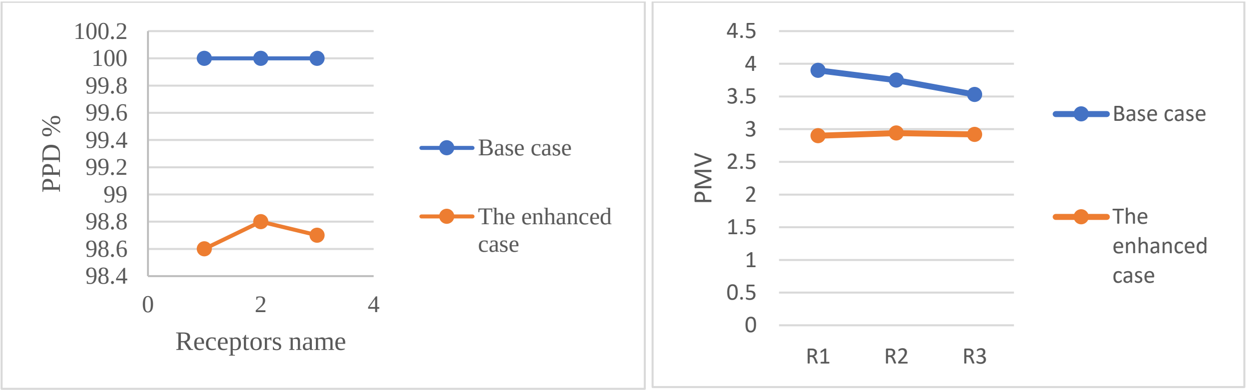


Figure 5-90: Case 3 (Thermal comfort indicators calculation)

The figure shows the best choice for each variable based on earlier analysis of the scenarios. Thermal comfort indicators, including Predicted Mean Vote (PMV) and Predicted Percentage Dissatisfied (PPD), were evaluated for the outdoor space at a 1.8-meter height. While the results demonstrate an improvement in both PMV and PPD, the extent of this change is limited. It implies that the presence and optimal design of trees, while favorable, are insufficient to provide ideal thermal comfort conditions. It was suggested that additional features, such as green roofs and walls, may be required to support strategic tree placement for optimal thermal comfort.

5.4 Building scale simulation results

An evaluation of the simulation results ensured that temperature, wind speed, and relative humidity matched between the indoor and outdoor environments across all vertical levels. This comparison is detailed in the provided table.

Table 5-11: Case 1 indoor and outdoor measurement data (Base case)

Base case (Indoor)	Ground Floor	Third floor	Fifth floor
Operative Temperature(c)	30.29	30.65	30.85
Wind speed (m/s)	0.1	0.1	0.1
Relative humidity %	30.8	30.32	30.04
PMV	1.76	1.83	1.87
PPD %	65	68.6	70.6
Base case (Outdoor)	Ground Floor	Third floor	Fifth floor
Operative Temperature(c)	37	34.9	33.2
Wind speed (m/s)	2.2	2.34	2.84
Relative humidity %	40	47.8	51.3

After optimization by comparing several tree scenarios for each of the three vertical levels, the optimal scenario informed the development of an equation incorporating ratios and proportions. This equation serves to quantify the impact of the chosen tree scenario on thermal comfort within the interior spaces.

Table 5-12: Case 1 indoor and outdoor measurement data (Enhanced case)

Enhanced case (Indoor)	Ground Floor (1)	Third floor (2)	Fifth floor (3)
Operative Temperature(c)	28.2	29.7	30.6

Wind speed (m/s)	0.1	0.1	0.1
Relative humidity %	38.5	33.11	30.9
PMV	1.36	1.64	1.82
PPD %	38.5	58.7	68.2
Enhanced case (Outdoor)	Ground Floor	Third floor	Fifth floor
Operative Temperature(c)	34.5	33.9	33
Wind speed (m/s)	0.9	1	1.7
Relative humidity %	50	52.2	52.9

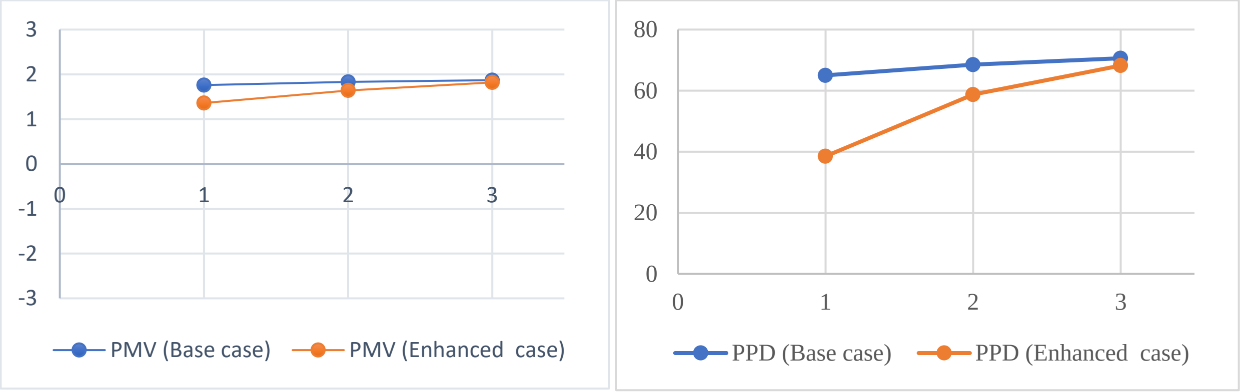


Figure 5-91: PMV and PPD charts of indoor space shows the enhancement of thermal comfort

Thermal comfort indicators were evaluated within the building's interior space across all three levels (ground floor, third floor, and fifth floor) for the optimal tree scenario. The results revealed an improvement rate of 26.5% for the ground floor and 9.9% for the third floor. However, the improvement on the fifth floor was minimal, at only 2.9%. These findings suggest that despite the optimal design of the trees, their impact on thermal comfort diminishes with increasing building height.

5.5 Vegetation calculation costs

In collaboration with agricultural experts in Palestine, a cost analysis was conducted for greening the study cases. This analysis utilized the following data points:

Table 5-13 : Vegetation calculation costs

Construction costs	
Type	Cost
Trees	28-40 $/One tree
Grass area	14$/ 1m2
Irrigation systems	Nearly 6$/ 1m2
Periodic maintenance costs	
Pruning and fertilizers	6$ for 1m2 / Month

Utilizing the data presented in Table 5-13, greening costs for the case studies were determined based on the number of trees and greening area per meter

Table 5-14: Case 1 vegetation calculation costs

Case 1 vegetation calculation costs	
Total trees costs= Trees No*Cost	36*28$ = 1000$
Total grass cost = Green area* Cost	270m2*14$=3780$
Total irrigation systems cost	270*6$=1500$
Total construction cost: 6400$	
Total maintenance cost: 1500$/Month	

Maintenance and irrigation costs were calculated in collaboration with an agricultural engineer, resulting in a monthly expenditure of $1,500. While this cost can be apportioned among the residential complex's households, the economic viability of the project is enhanced through the utilization of drought-resistant plant species.

Within the first case study, green space creation costs were determined based on a per-unit (apartment) basis. This methodology was selected due to the findings of the calculations, which are presented.

Green area / No of units (apartment) = Green space for each apartment

270m2 /40 units = 7m2

Table 5-15 : Case1 vegetation cost/one unit

Case 1 vegetation calculation costs / One unit	
Total trees costs= Trees No*Cost	2*28$ = 56$
Total grass cost/unit = Green area* Cost	7m2*14$=98$
Total irrigation systems cost	7*6$=42$
Total construction cost: 200$	
Total maintenance cost: 42$/Month	

As evidenced by the table 5-15 results, the initial cost of establishing green space per residential unit is approximately $200. This cost is factored into the base price of the apartment. Additionally, the table indicates an ongoing monthly maintenance cost of roughly $42, presumably reflected in monthly fees for residents (buyers or tenants).

Table 5-16: Case 2 vegetation calculation costs

Case 2 vegetation calculation costs	
Total trees costs= Trees No*Cost	36*28$ = 1000$
Total grass cost = Green area* Cost	144m2*14$=2000$
Total irrigation systems cost	144*6$=865$
Total construction cost: 3860$	
Total maintenance cost: 800$/Month	

Table 5-17: Case 3 vegetation calculation costs

Case 3 vegetation calculation costs	
Total trees costs= Trees No*Cost	50*28$ = 1400$
Total grass cost = Green area* Cost	200m2*14$=2800$
Total irrigation systems cost	200*6$=1200$
Total construction cost: 5400$	
Total maintenance cost: 1200$/Month	

5.6 Discussion

(DR, TK, RN, & PJ, 2020) suggested that urban vegetation could be designed to be more “forest-like” in structure. The results of this study, however, showed that a high percentage of vegetation cover did not always have a substantial impact on the thermal efficiency of the space.

(Liao , Tan , & Li , 2021) has suggested that taller trees provide the highest vertical cooling effect, followed by shrubs. The current study did not observe a clear correlation between tree height and the extent of the vertical thermal improvement. So, the finding suggests that the influence of tree height on thermal performance may be contingent upon specific space configurations, as evidenced by the case study results, a medium-height tree exhibited the most pronounced cooling effect, highlighting the potential dependence of optimal height on the space layout.

Research conducted in tropical climates has documented the potential for trees to reduce temperatures by 8-10°C (Teshnehdel , Di Giuseppe, & D. Brown, 2020), while the current study focusing on optimal tree design observed a temperature reduction of 3-4°C. So, this highlights the significant influence of climatic context on the efficacy of tree planting for thermal performance improvement.

Chapter 6

Conclusion and recommendation

Chapter 6

Conclusion and recommendation

6.1 Preface

In modern building design, thermal comfort for occupants is crucial, especially for residential buildings. While existing planting and landscaping codes offer valuable guidance, they may not fully address the need for enhanced thermal performance in exterior and interior spaces. This study emphasizes the critical role of strategic tree design and selection in developing effective strategies for planners and landscape designers. The research focuses on tree characteristics influencing thermal performance, including arrangement, green cover percentage, crown shape and density, trunk size, and height. The goal is to equip professionals with the knowledge to select and design tree placements that optimize thermal comfort within outdoor squares and residential buildings.

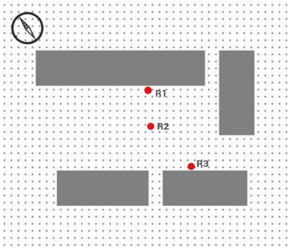
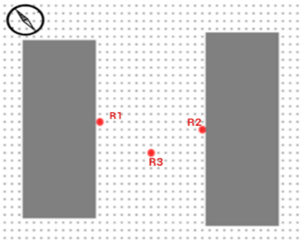
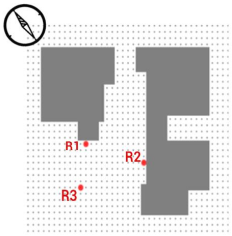
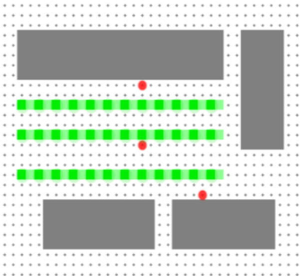
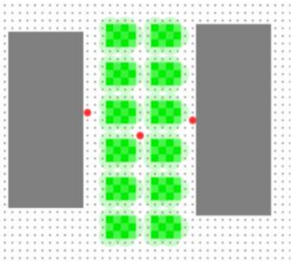
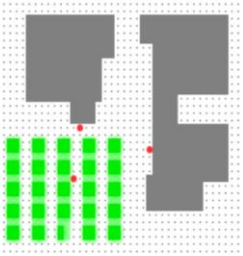
This study analyzes three case studies of exterior spaces within a residential complex in Hebron. These spaces exhibit variations in their spatial configuration, including the number of adjacent buildings, total area, solar orientation, and the layout of open spaces, to investigate the influence of various tree planting configurations on the surrounding urban environment and to elucidate the relationships between tree characteristics and the resulting urban form.

Moreover, The examination of Three outdoor space typologies within the residential complex yielded strategies for crafting more inclusive and varied tree-planting configurations. This examination further allowed for the discernment of tree-related factors specific to each urban layout while concurrently uncovering factors applicable across all case studies.

6.2 Urban scale conclusion

The analysis revealed consistent trends in the impact of tree characteristics across all case studies, suggesting the potential for generalizability to open squares with comparable configurations. Conversely, other tree characteristics exhibited variations between case studies, likely attributable to the unique spatial composition of each outdoor space. The analysis yielded a comprehensive set of findings.

Table 6-1 : Optimal tree typologies in all cases

Residential Complex	Area 1 in (King Abdullah bin Abd- alazizi residential complex	Area 2 in (King Abdullah bin Abd- alazizi residential complex	Orphan housing
Residential Complex layout			
Optimal green cover ratio and arrangement	Gr%: 20% , A:horizantial 	Gr%:40%, A:cluster 	Gr%:40%, A:Vertical 
Optimal tree crown shape	Hear shape (Vase)	Hear shape (Vase)	Cylindaric shape
Optimal tree crown density	Dense	Dense	Dense
Optimal tree trunk size	Meduim	Meduim	Meduim
Optimal tree height	10m	10m	5m

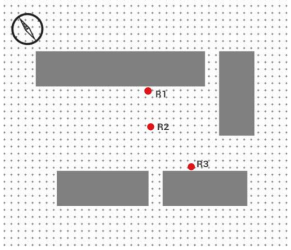
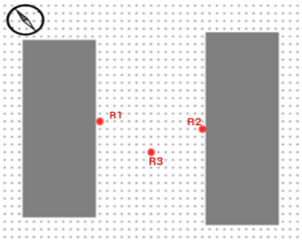
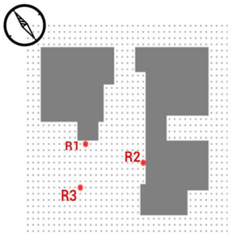
- Trees should be strategically planted roughly parallel to the direction of the prevailing wind to attain maximum thermal efficiency and encourage desired heat distribution inside the space. Rows of trees should be spaced at a maximum of 3-6 meters apart to facilitate wind channeling and maximize shading effects.
- Generalizing a vegetation cover percentage for outdoor spaces is not feasible due to the absence of a clear correlation between outdoor space variations and this metric. Instead, the analysis

suggests that the configuration of plantings, specifically the arrangement of plants and spacing between rows, emerges as the variable influencing thermal performance.

- The area of open space and vegetation's impact on thermal performance was found to be negatively correlated. In the second case study, with a smaller open area, vegetation resulted in a modest improvement of 0.5-1°C decrease in temperature and a 1-2% increase in humidity. According to these results, vegetation's ability to improve thermal comfort may be less effective in smaller areas.
- The effectiveness of the tree crown shape (vase or heart) in closed or semi-open urban areas has been proven to improve thermal performance, as it reduced the temperature by 1.5-2 degrees Celsius, reduced the wind speed significantly, especially in the open area of space, and increased the humidity level by 10%.
- The efficiency of conical tree crowns in open metropolitan environments necessitates a comprehensive evaluation, particularly during winter. While they excel in the summer by providing shade and boosting thermal comfort, their evergreen nature may reduce solar heat gain in the winter. So, this element should be considered when choosing tree species to balance summer cooling and winter passive heating effects.
- Cylindrical tree crowns exhibited thermal performance effectiveness comparable to conical shapes within open courtyard areas. These shapes achieved a temperature reduction of 2°C, contributing to enhanced thermal comfort in the outdoor space.
- The analysis indicates that trees with dense crowns and medium-sized trunks provide a promising strategy for enhancing thermal performance within outdoor spaces. However, it may be possible to generalize this result to all Hebron courtyards and similar climates.
- An inverse relationship emerged between tree height and cooling effectiveness in closed and semi-open spaces. While taller trees demonstrated the highest overall temperature reduction (4°C), their impact diminished progressively with increasing height. It suggests an optimal height range for maximizing thermal comfort across all vertical levels within the space.
- Trees with a height of 5 meters demonstrated optimal thermal performance across all levels (ground, third, and fifth floors) within open spaces. This finding translates to a temperature reduction of 3-4°C, with a gradual decrease in effectiveness observed at higher elevations. Consequently, the impact on upper floors ranged from 1-0.5°C.

- Analysis of the tree height scenarios revealed the most significant influence on thermal performance compared to other tree variables. The table demonstrates the impact of tree height on both temperature and humidity. Conversely, the tree crown density scenarios indicated a significant reduction in wind speed compared to other scenarios.

Table 6-2: Trees typologies impact

	Case 1			Case2			Case 3		
									
	Operative temperature	Wind speed	Relative humidity	Operative temperature	Wind speed	Relative humidity	Operative temperature	Wind speed	Relative humidity
Vegetation ratio and arrangement	Middle	High	Middle	Low	Middle	Low	Low	Low	Low
Crown shape	Middle	Low	Low	Low	Middle	Low	Middle	Low	Low
Crown dense	High	Middle	High	Low	Middle	Low	High	High	High
Trunk size	Low	Low	Low	Low	Middle	Low	Low	Low	Low
Tree height	High	High	High	Low	High	Low	Middle	Middle	Low

The table 6-2 presents a comprehensive analysis of how tree design characteristics influence the microclimate. Each scenario is evaluated against the baseline case study, revealing the extent of its impact on various climatic parameters. The table categorizes the tree's typologies and configuration based on their impact.

Table 6-3 : case 1 (trees scenarios effects in thermal performance)

	Receptors	base case	Gr%, A	Crown shape	Crown dense	Trunk size	Tree height
Operative temperature c	R1	38	36.6	35.6	35.8	35.8	34.6
	R2	37.5	36.5	35	35.5	35.5	34.4
	R3	36.9	35.8	35.5	35	35	34.4
Wind speed m/s	R1	1.95	1	0.21	0.9	0.9	1.08
	R2	2.1	0.81	2.67	0.66	0.66	1.05
	R3	0.92	0.68	1.87	0.67	0.67	0.77
Relative humidity%	R1	41	44.32	34.3	46.8	46.8	50.55
	R2	41.6	44.5	35.95	47.49	47.49	50.61
	R3	42.24	45.8	34.9	48	48	49.99

- The analysis revealed a diminished influence of trees on thermal conditions near building facades compared to open spaces areas. So, it suggests a potentially limited impact of tree planting on the indoor environment across various building levels.
- While tree planting improves thermal performance within outdoor courtyards, the impact appears modest. Observed reductions in the PMV index (shifting the thermal sensation from "very hot" to "hot") or (4-3) and the percentage of dissatisfied people (PPD) from 100% to 98% suggest a limited influence on achieving optimal comfort levels. ASHRAE standards recommend PMV values between 0-1 and PPD values below 20%. Therefore, additional strategies with tree planting may be necessary to attain these desired comfort conditions.

6.3 Building scale conclusion

Sensor data from various elevations near buildings (ground, third, and fifth floors) were collected using the Envi-met program and compared with results obtained from the Design Builder program. This analysis revealed a correlation between external and internal temperatures, allowing for the evaluation of how different tree-planting scenarios influenced the indoor building environment.

Thermal performance information was gathered for a single case study to know how different tree-planting scenarios might affect the interior environment. This data provides a preliminary indication of how different tree designs affect internal comfort levels. The results revealed an improvement rate of 26.5% for the ground floor and 9.9% for the third floor. However, the improvement on the fifth floor was minimal, at only 2.9%. These findings suggest that despite the optimal design of the trees, their impact on thermal comfort diminishes with increasing building height.

6.4 Recommendations

Informed by the outcomes of comprehensive simulations, this study offers recommendations for optimizing thermal comfort within outdoor spaces. These recommendations, derived from the most impactful simulation results, focus on strategic tree selection and design considerations. The following recommendations are:

- ✓ Strategic tree placement is roughly parallel to the direction of the prevailing wind to maximize thermal performance. Aim for a maximum distance of 3-6 meters between rows of trees to optimize shade effects and aid in wind channeling.
- ✓ For outdoor spaces, high-dense built-up areas, and closed spaces, vase- or heart-shaped tree crowns are recommended to enhance thermal performance within the outdoor space. These crown shapes promote improved air circulation and shading.
- ✓ For open spaces, cylindrical tree crowns may offer a strategic selection to improve thermal performance. These crown shapes can provide effective shading throughout the day.
- ✓ Across various outdoor spaces configurations, trees with dense crowns and medium-sized trunks emerge as a promising strategy for enhancing outdoor thermal performance. These characteristics promote effective shading and potential evapotranspiration.
- ✓ In closed or semi-open courtyards, strategically planting trees with a height of 10 meters may be an effective strategy to enhance thermal performance across all building levels.
- ✓ In open spaces, strategically planting trees 5 meters height may be an effective strategy to enhance thermal performance at all levels of the building.
- ✓ Optimizing thermal performance within outdoor spaces necessitates a holistic approach that transcends solely planting trees. Combining complementing methods, such as green wall systems and vegetated roofs, can produce synergy.
- ✓ Strategic tree placement informed by airflow simulations and thermal comfort assessments can transform outdoor spaces into spaces conducive to sitting and strolling. This approach aims to achieve wind speeds within a comfortable range, promoting the utilization of these outdoor environments.

In conclusion, the simulations and analyses presented in this study are expected to serve as valuable guidelines for landscape designers, residents, and local municipality planners seeking to create more thermally responsible and occupant-centric residential complex outdoor spaces. The findings can be effectively disseminated through a user-friendly manual to aid landscape design for gardens and open areas. Also, local municipalities and related associations could consider generalizing such manuals to promote widespread implementation.

6.5 Future work

This thesis depends on existing planting design codes by conducting an in-depth analysis of tree characteristics and design scenarios. Future research could expand upon this work by exploring tree arrangement configurations, including diagonal and other non-standard shapes. Additionally, investigations into various outdoor space layouts within residential complexes would be valuable. While this study focused on common urban conditions, future efforts could integrate these findings into a more comprehensive framework. This framework could encompass research on combined tree shapes (e.g., cone-vase, cylindrical-vase) with varying proportions, alongside investigations into different tree types. Finally, a comprehensive study could explore how green roof and wall techniques can be implemented synergistically with trees to enhance thermal performance.

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APPENDICES

APPENDIX A

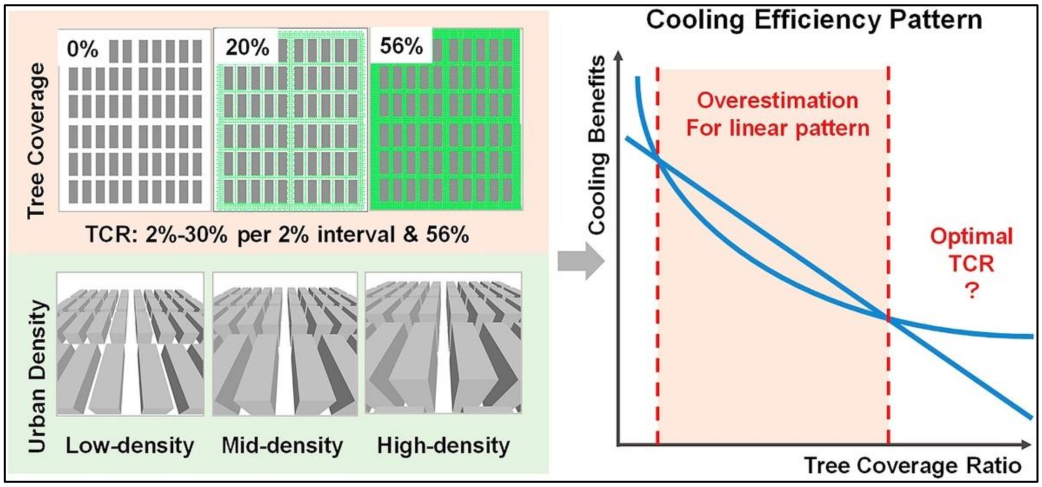
Trees species diversity in Palestine

Name	Form	Height (m)	Trunk Diameter (m)	Canopy Spread	Foliage	Longevity (year)	Fruits & Flowers
Silk Oak (Grevillia robusta)	Conical or oval	15-20	0.6	10-15	Ever green	50-150	Orange Yellow flowers, Brown Pondlike with Winged Follicles
Holly Oak (Quercus ilex)	round or umbrella a	21	0.55	28-30	Evergreen	Greater than150	Unclear flower, Brown Acorn
Sycamore Maple (Acer pseudoantanus)	round or oval	18-21	0.4-0.5	12-18	Decid - uous	50-150	Green Yellow flowersunclear fruits
Carob (Ceratonia siliqua)	round or umbrell a	10	0.6	20	Evergreen	Greater than150	Red flowers, Prolific, Brown Pod
Oriental Plane (Plantanus orientalis)	Rounded, umbrella or oval	21-30	0.6	12-30	Deciduous	50-150	Unclear flower, Prolific, Brown Mostly Green Achene
Black Locust (Robinia pseudoacacia)	Oval	20	0.6	10-20	Deciduous	Greater than150	Showy, Fragrant, White flowers, Brown Pod
Idaho Locust (Robinia ambigua)	Oval	12-15	0.6	6	Deciduous	50-150	Showy, pink, purple rose, Brown Pod
Japanese Pagoda Tree (Sophora japonica)	Rounded, umbrella or vase	7-15	0.5	6	Deciduous	50-150	Showy, Fragrant, White Brown Green Pod
Horse Chestnut (Aesculus hippocastanum)	Rounded	15-20	0.55	10-12	Deciduous	50-150	Showy, Fragrant, Cream flowers, Brown Capsule fruits
California Fan Palm (Washingtonia filifera)	Fan Palm	15-20	0.45	4	Evergreen	50-150	Unclear flowers, Black Drupe fruits
Norway Maple (Acer platonoides)	Rounded	6-20	0.4-0.5	15	Deciduous	50-150	Green Yellow flowers, Brown Winged Seed

Wild Pistachio (Pistacia atlantica)	round or oval	10	0.6	7	Deciduous	50-150	Unclear flowers, Purple Mostly Blue Drupe
Palestine Live Oak (Quercus calliprinos)	Rounded	15-20	0.45	10	Evergreen	50-150	Green flowers, Acorn ovoid
Red Gum (Eucalyptus camaldulanisis)	Rounded or oval	12-45	0.45	15-30	Evergreen	50-150	Yellow, White flowers, Brown, or Green Capsule
Cypress (Cupressus sempervirens)	Column	15	0.3	15	Evergreen	50-150	Unclear flowers, Brown Cone
Aleppo Pine (Pinus hallepensis)	Conical	20	0.8	25	Evergreen	Greater than150	Unclear flowers, Brown, Yellow, Green Cone
Poplar (Populus nigra italica)	Column	12-30	0.8	4-9	Deciduous	40-150	Unclear flower, Brown Capsule
Populus alb (White Poplar)	Rounded, umbrella or vase	20	0.4	12	Deciduous	40-150	Unclear flower, Brown Capsule
Weeping Willow (Salix babylonica)	Oval, rounded or umbrella	10-15	0.6	5-20	Deciduous	Less than 50	Unclear flower, Brown Capsule
Tree of Heaven (Ailanthus altissima) (Not recommended)	Oval, rounded or umbrella	15	0.8	15	Deciduous	Less than 50	Prolific, Red or Yellow Winged Seed
Pepper Tree (Schinus molle)	Rounded or umbrella	15	1.4	22	Evergreen	50-150	Fragrant, yellow white flower, Prolific, Rose Drupe
Judas Tree (Cersis siliquastrum) (Hihly recommended)	Oval, rounded or umbrella	10	0.4	12-15	Deciduous	50-150	Showy, Purple or Rose flower, Brown Pod
Olive tree (Oleo europaea)	Rounded, umbrella or vase	10	0.6	10-15	Evergreen	Greater than 150	Green Drupe
Apricot (Prunus armeniaca)	rounded, umbrella or vase	7	0.4	10	Deciduous	50-150	Pink or White flowers Orange Drupe
Jacaranda (Jacaranda Mimosifolia)	Oval, rounded, umbrella or vase	12-15	0.4	20-22	Deciduous	40-150	Unclear flower, Brown Acorn

Crape myrtle (Lagerstroemia Indica)	Oval, rounded, umbrella or vase	7-10	0.3-0.4	12	Deciduous	50-150	Lavende r, Pink, Red, Rose or White flowers
Chinaberry (Melia azedarach)	Oval, Rounded or Umbrella	10-15	0.6-0.7	18	Deciduous	40-150	Fragrant, Lavende r, flowers Yellow Berry
Azadirachta indica (neem tree)	rounded	20-45	3	spread widely	Evergreen	200 years or more	Produces white, fragrant flowers in large clusters. The fruit is a greenish-yellow drupe, similar in size and shape to an olive.
Weeping fig (Ficus benjamina)	Oval	10	0.35	10-15	Evergreen	40-150	Unclear flower, Red Follicle
Rubber Tree (Ficus Elastica)	Oval	7	0.60	10-15	Evergreen	40-150	Unclear flower, green fruits
Indian Laurel (Ficus Microcarpa Var. Nitida	round or oval	7	0.60	10-12	Evergreen	50-150	Unclear flower, Green Follicle fruits

APPENDIX B
Figures appendices for chapter 2



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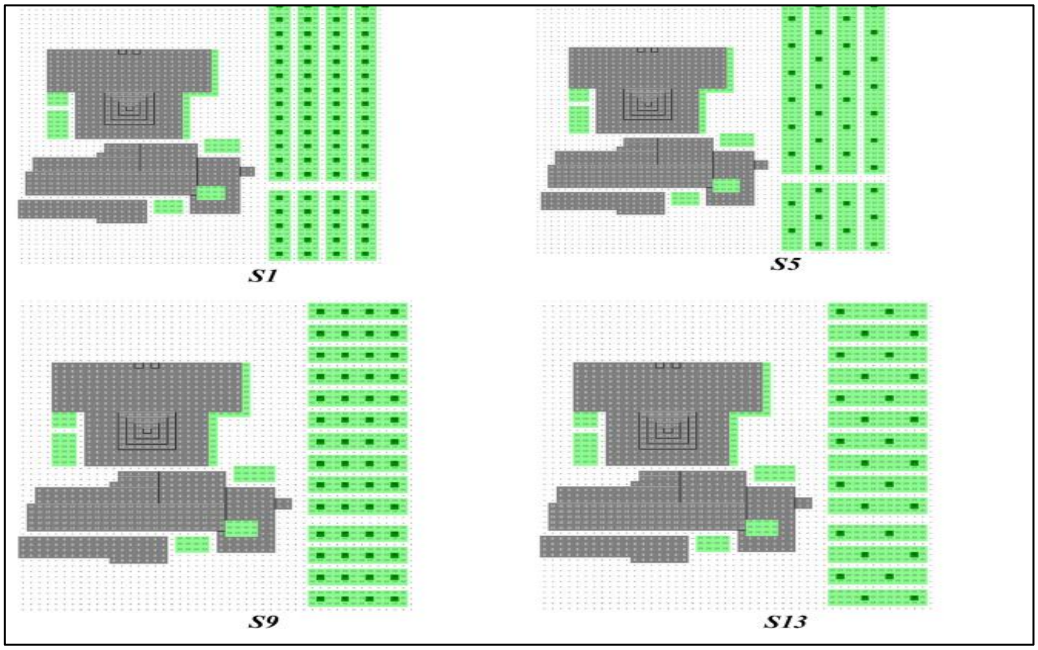

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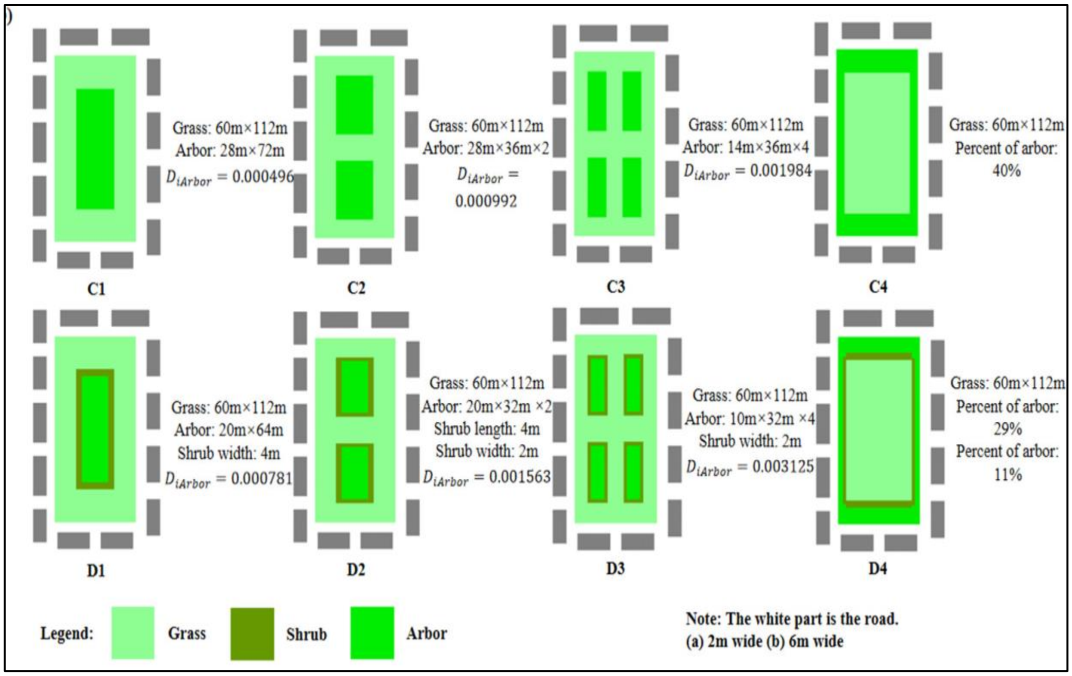

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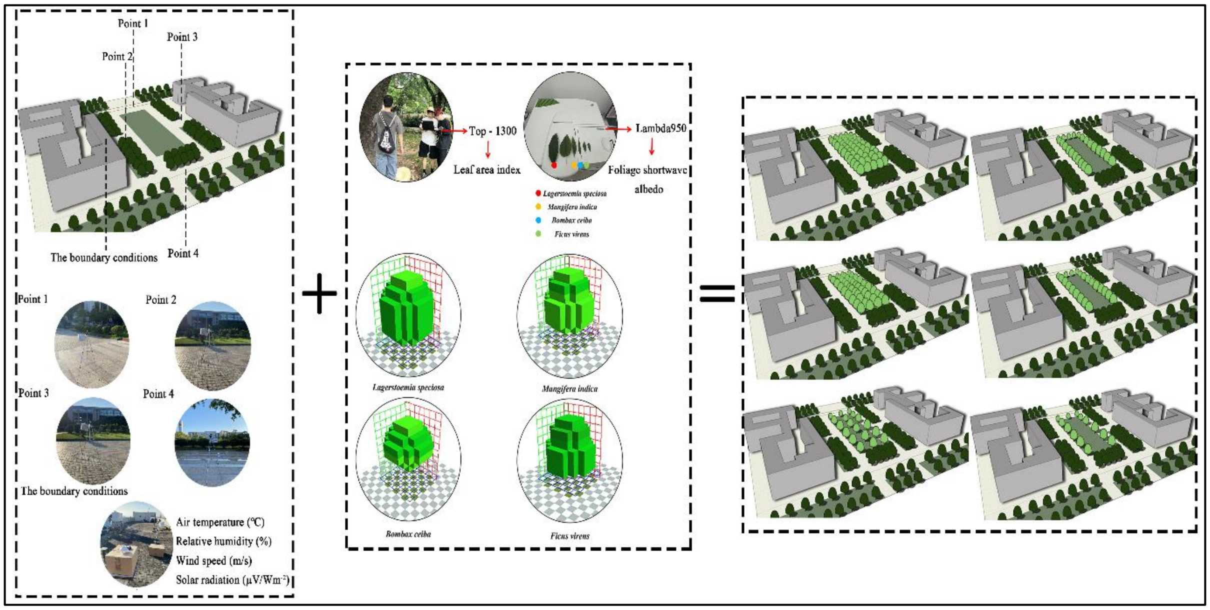

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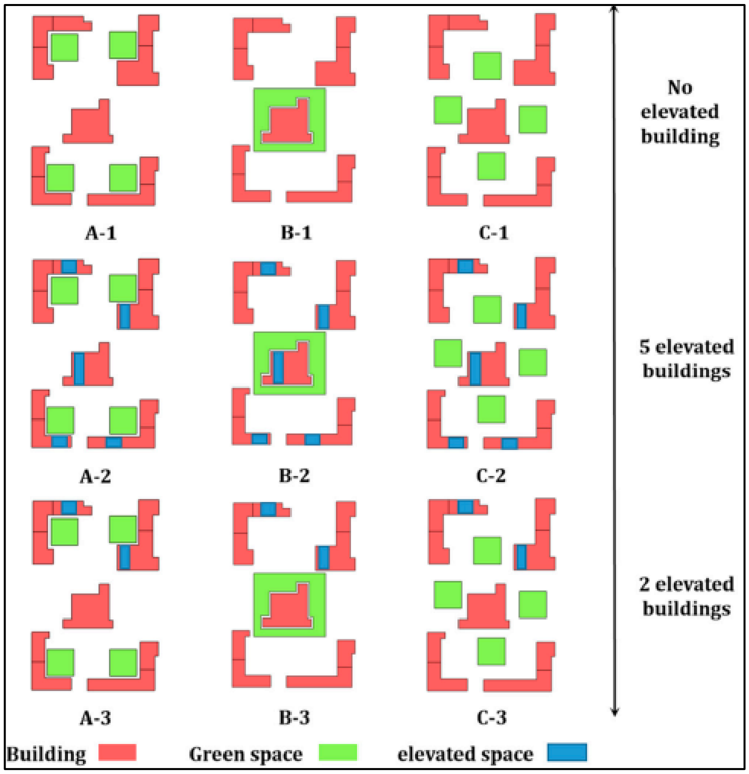

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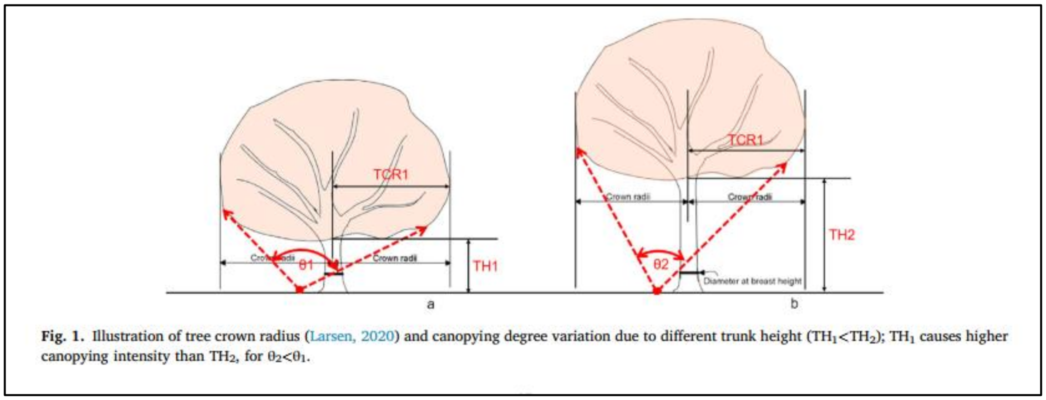


Fig. 1. Illustration of tree crown radius (Larsen, 2020) and canopying degree variation due to different trunk height ($TH_1 < TH_2$); TH_1 causes higher canopying intensity than TH_2, for $\theta_2 < \theta_1$.

Figure 2-6

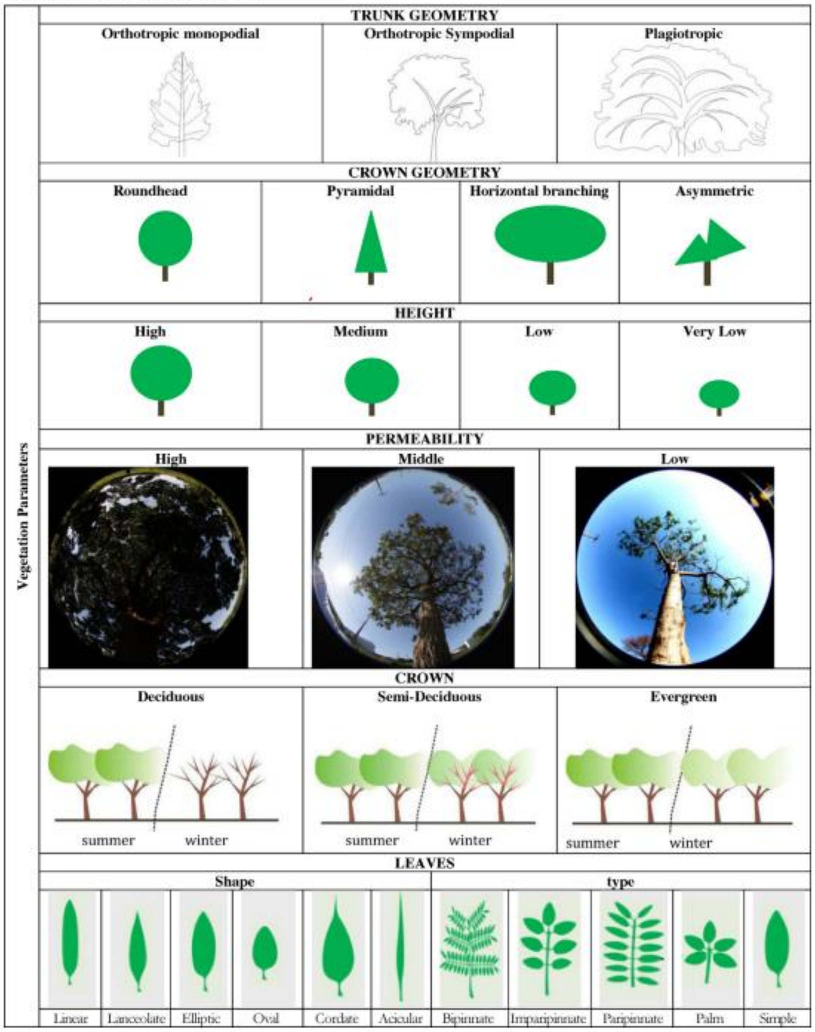
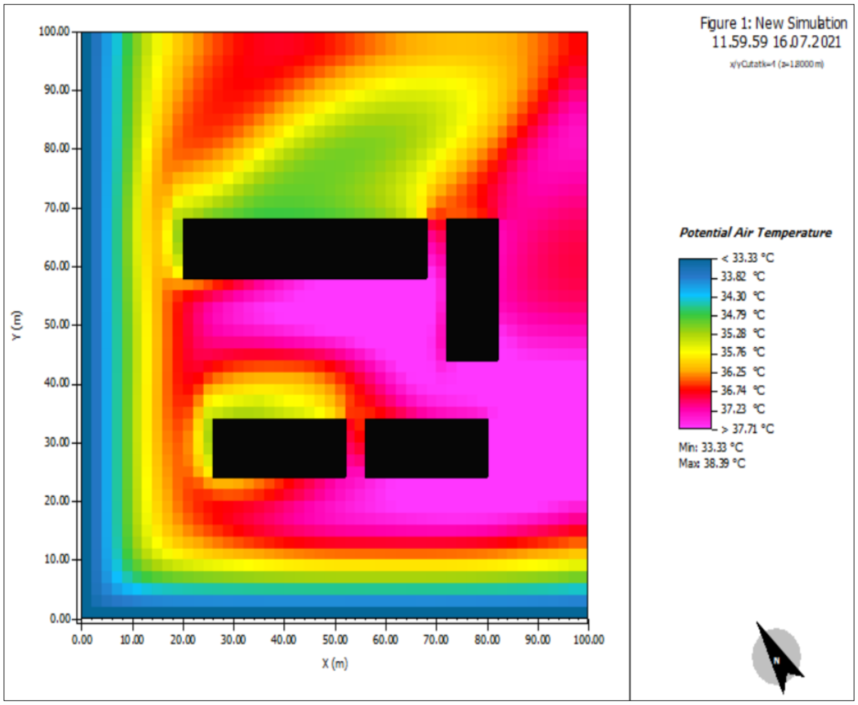

Vegetation Parameters
TRUNK GEOMETRY
Orthotropic monopodial
Orthotropic Sympodial
Plagiotropic
CROWN GEOMETRY
Roundhead
Pyramidal
Horizontal branching
Asymmetric
HEIGHT
High
Medium
Low
Very Low
PERMEABILITY
High
Middle
Low
CROWN
Deciduous
Semi-Deciduous
Evergreen
summer
winter
summer
winter
summer
winter
LEAVES
Shape
type
Linear
Lanceolate
Elliptic
Oval
Cordate
Acicular
Bipinnate
Imparipinnate
Paripinnate
Palm
Simple

Figure 2-7

APPENDIX c

Figures appendices for chapter 5



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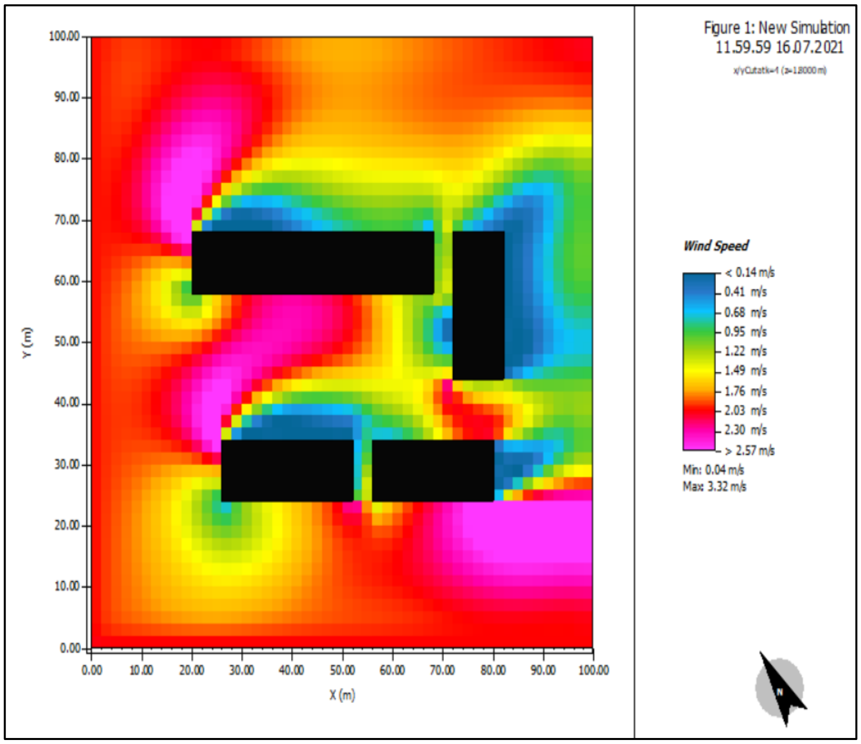

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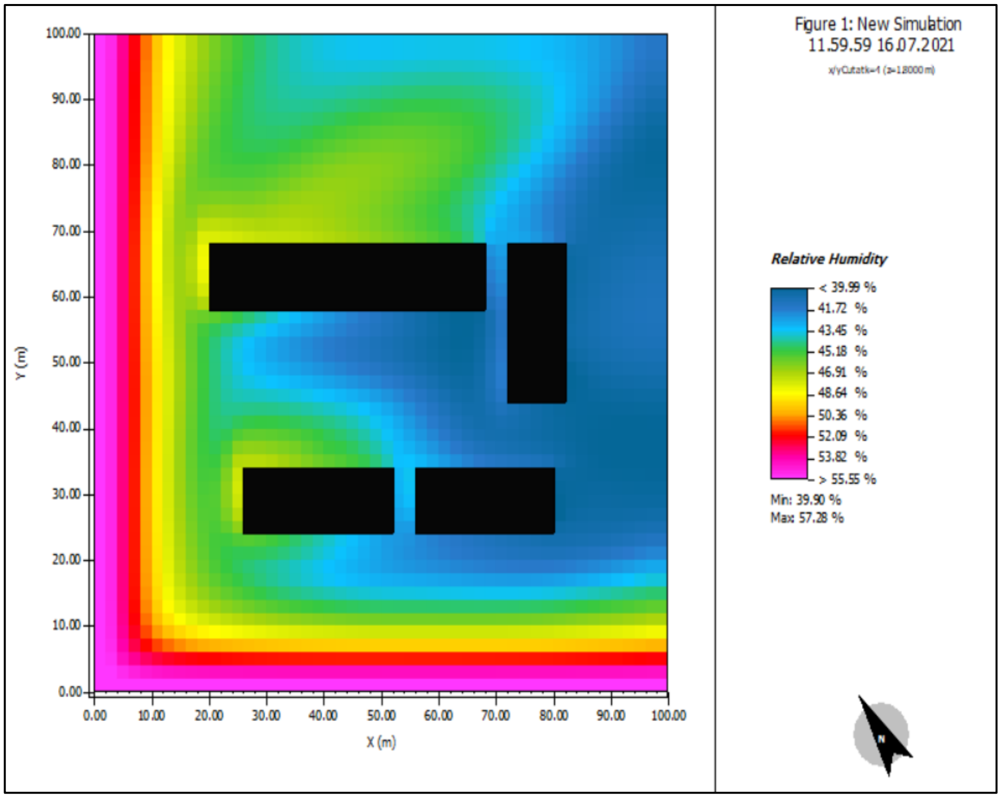

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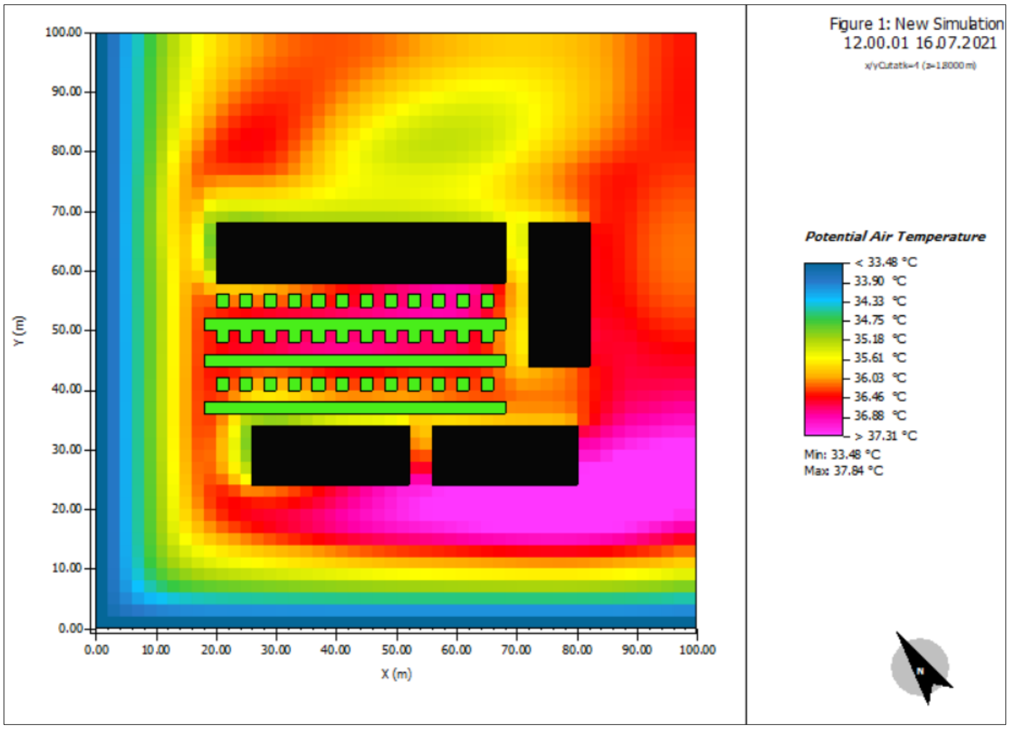

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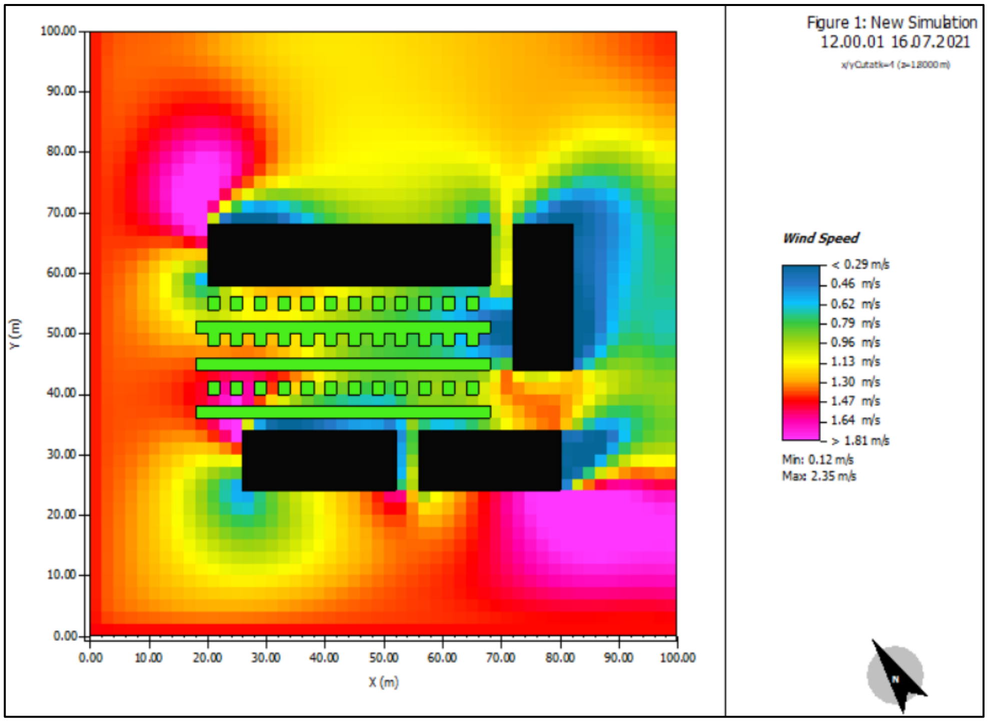

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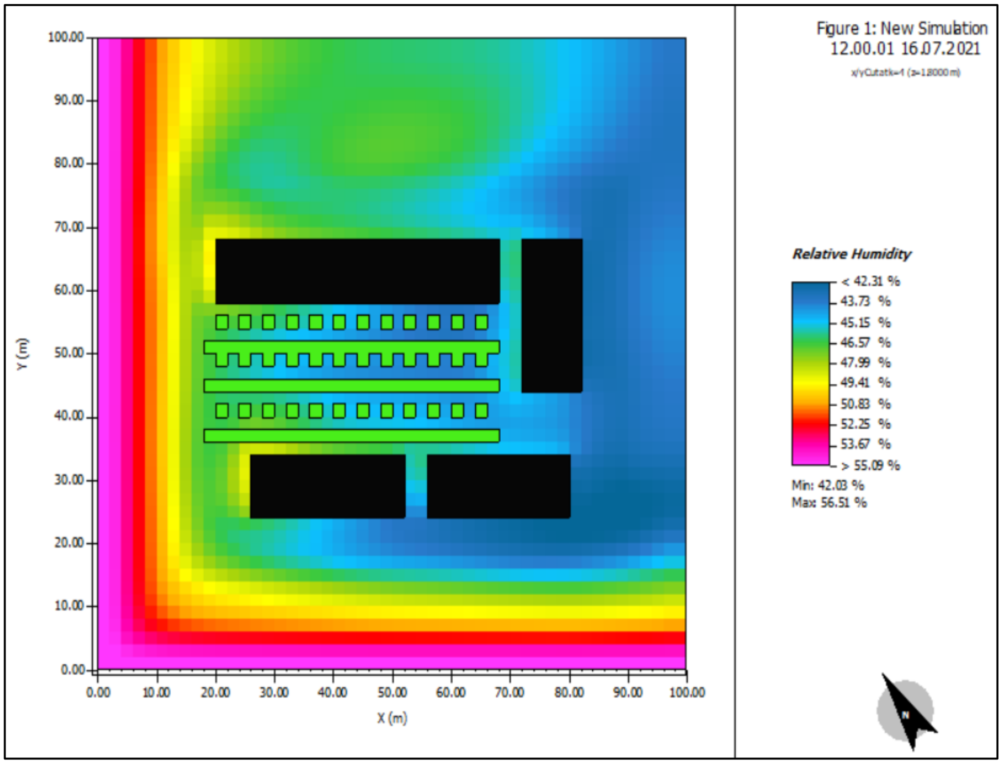

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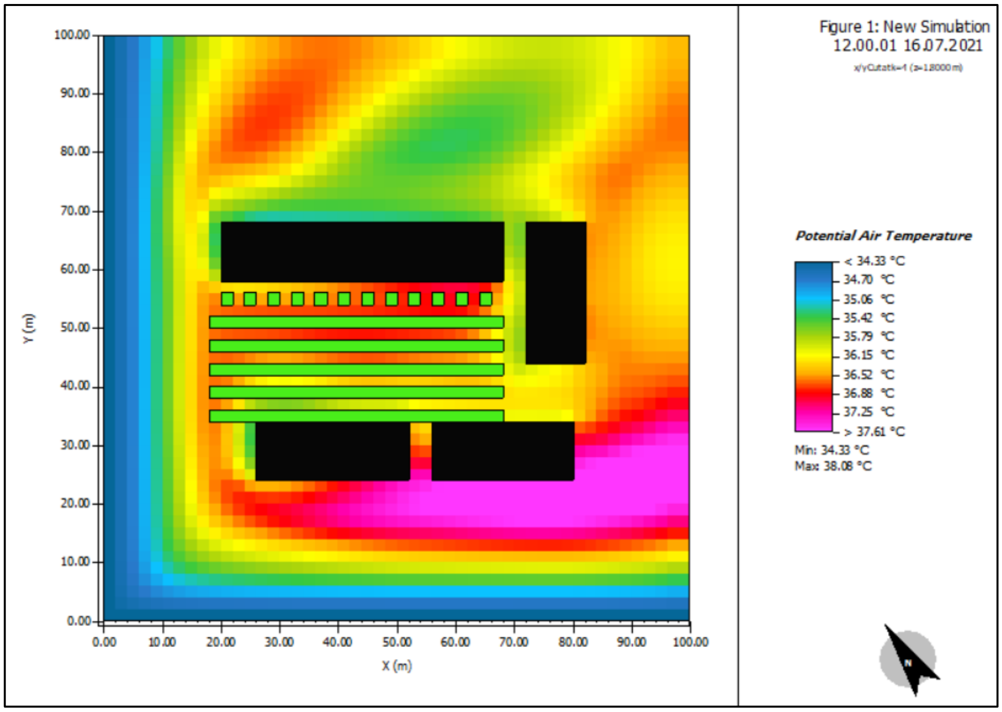

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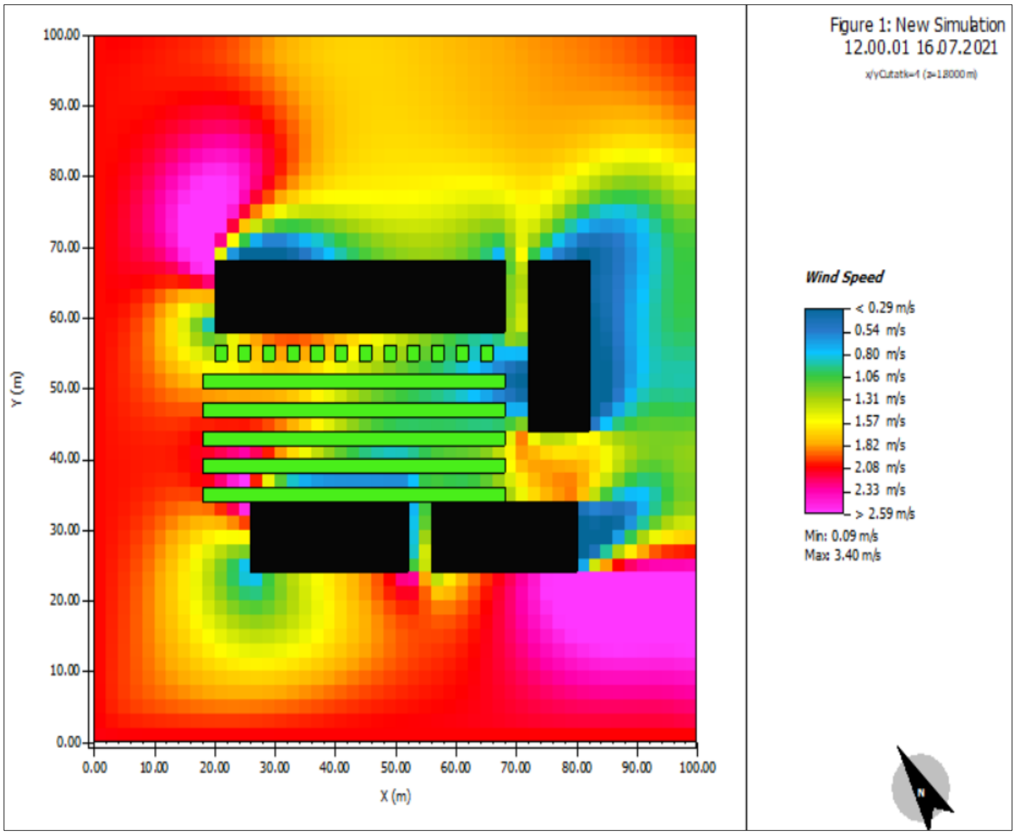

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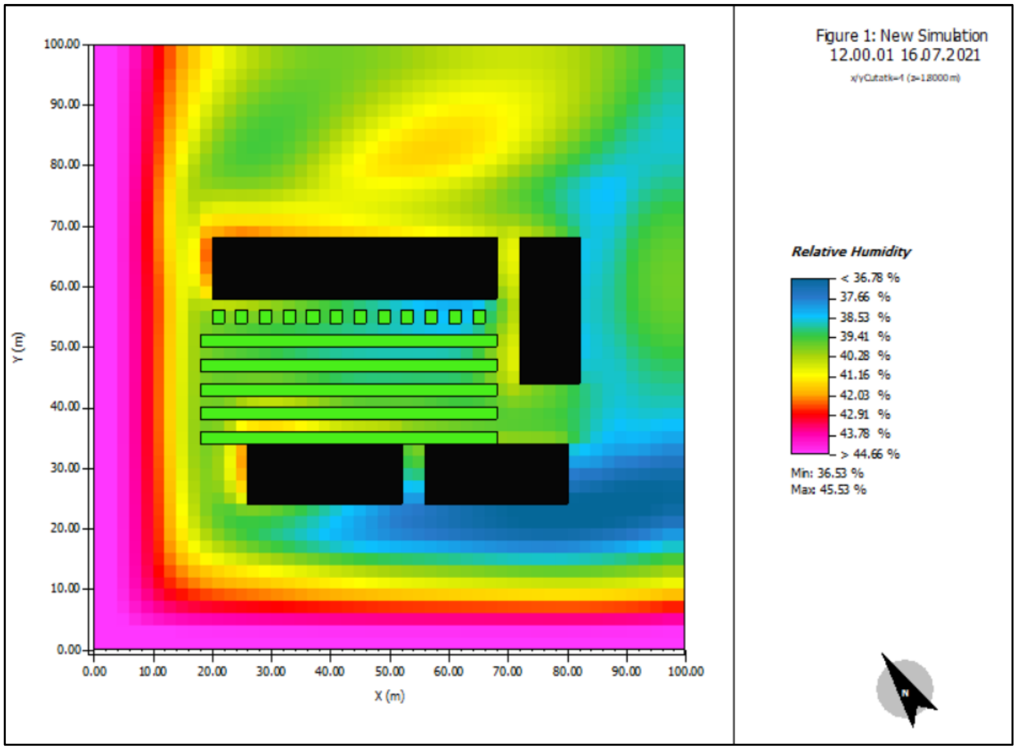

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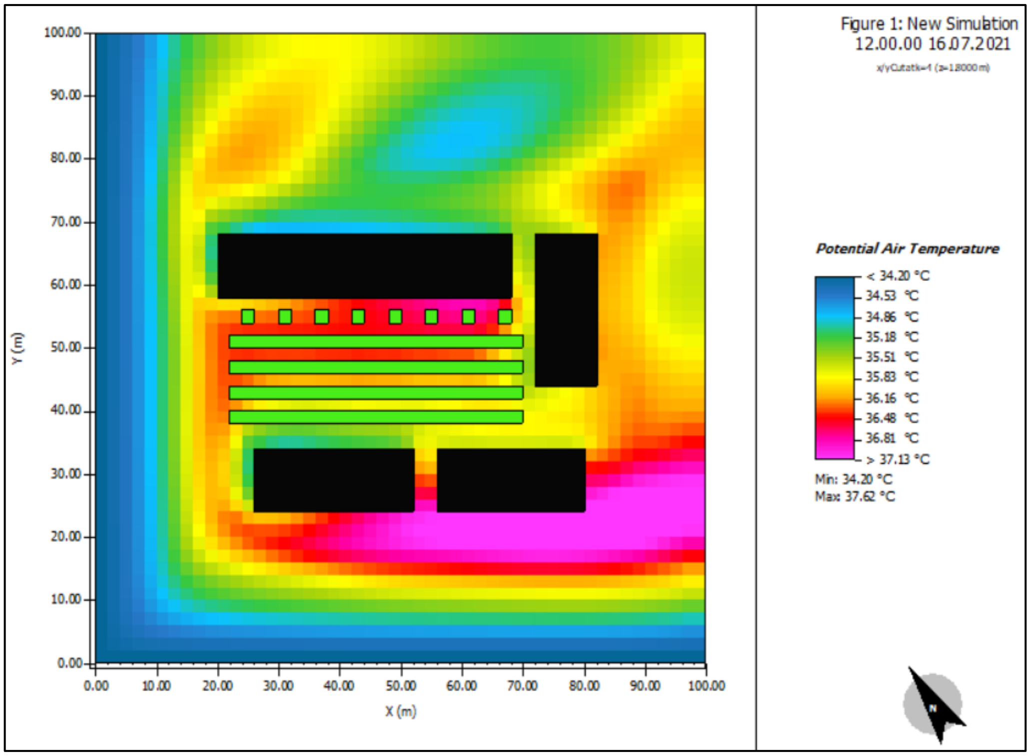

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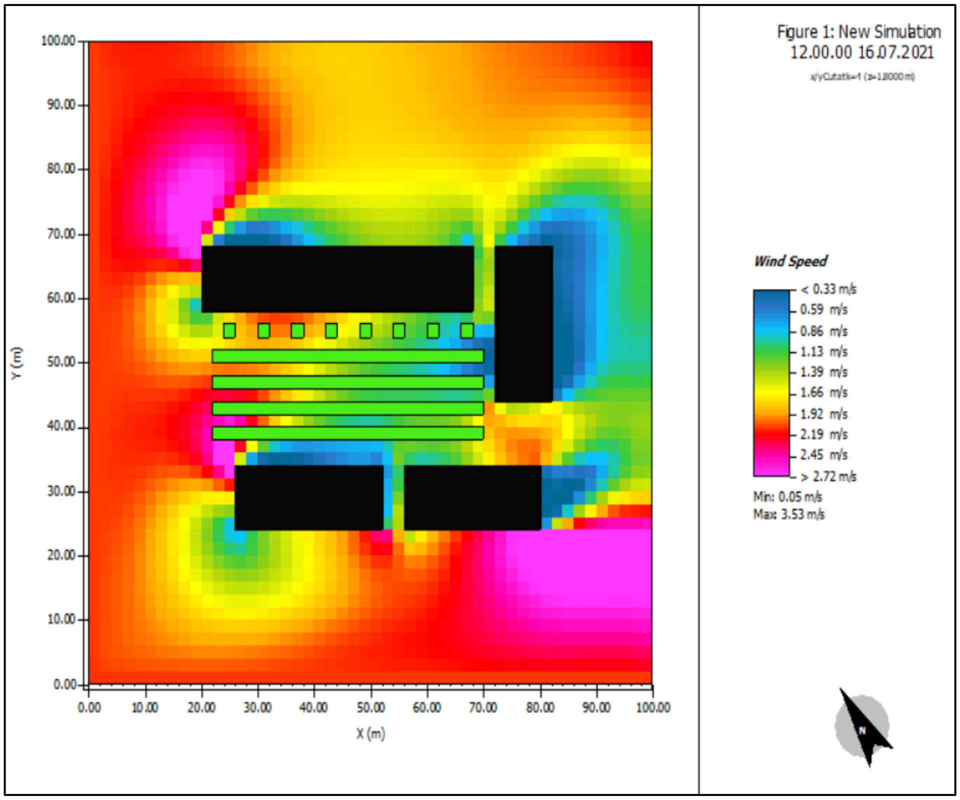

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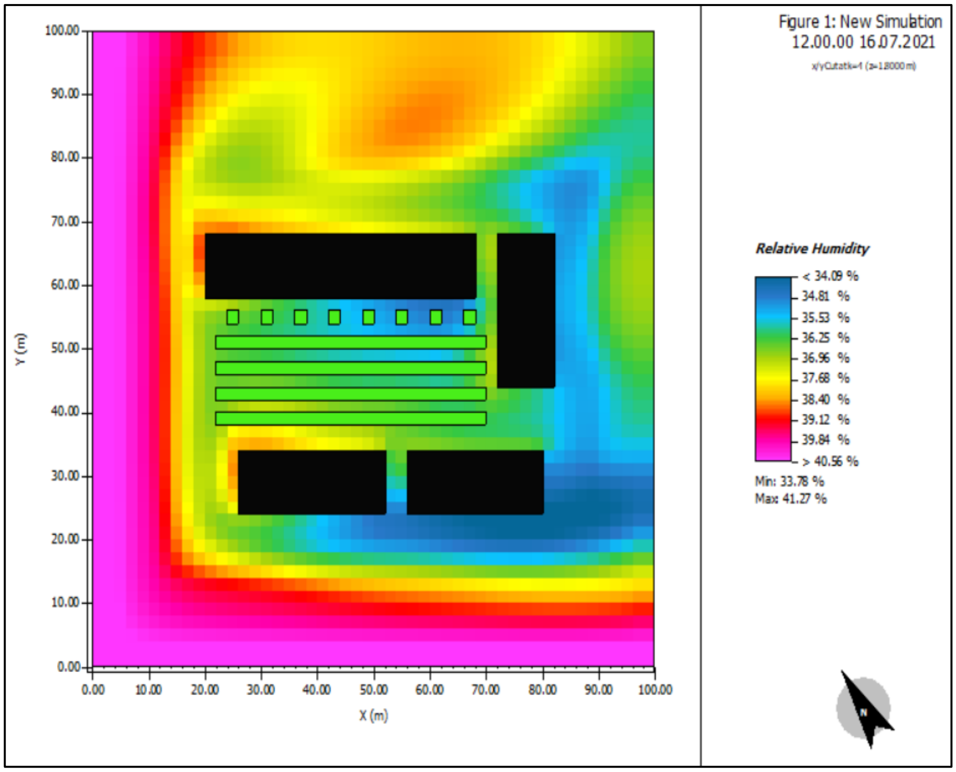

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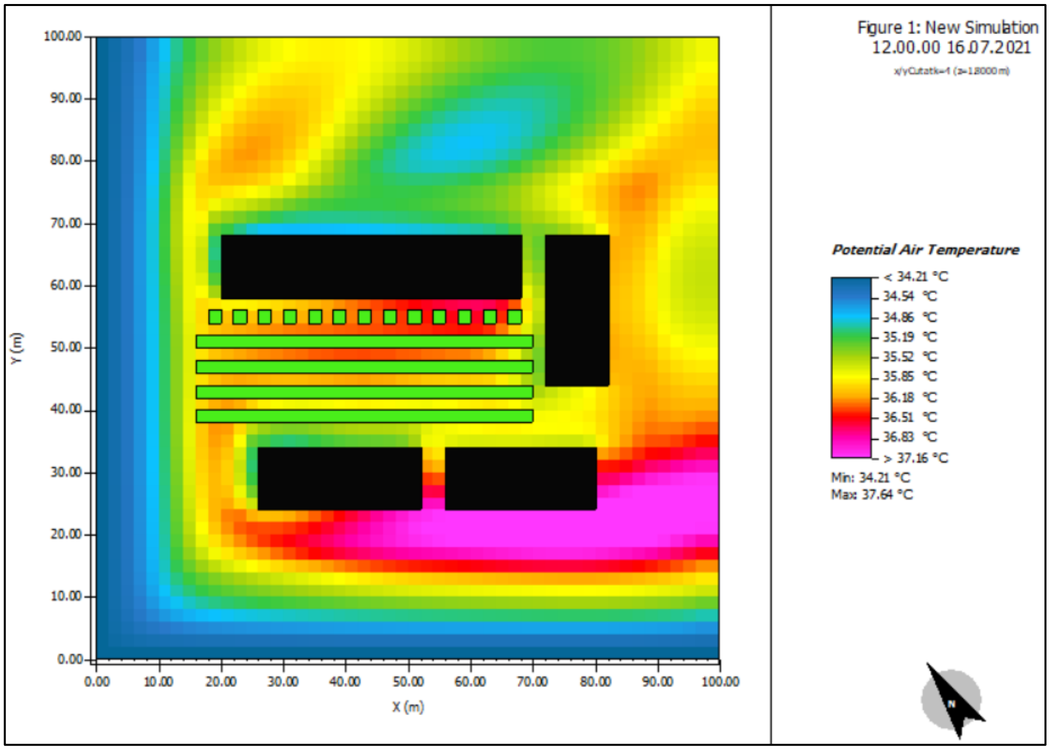

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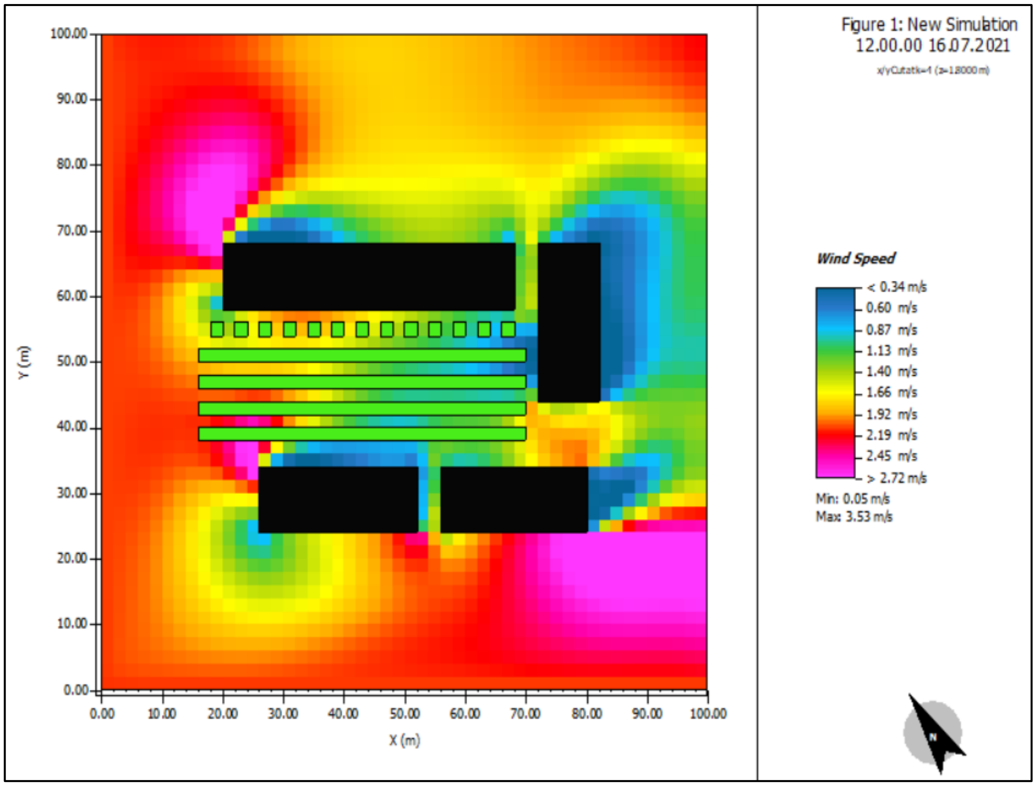

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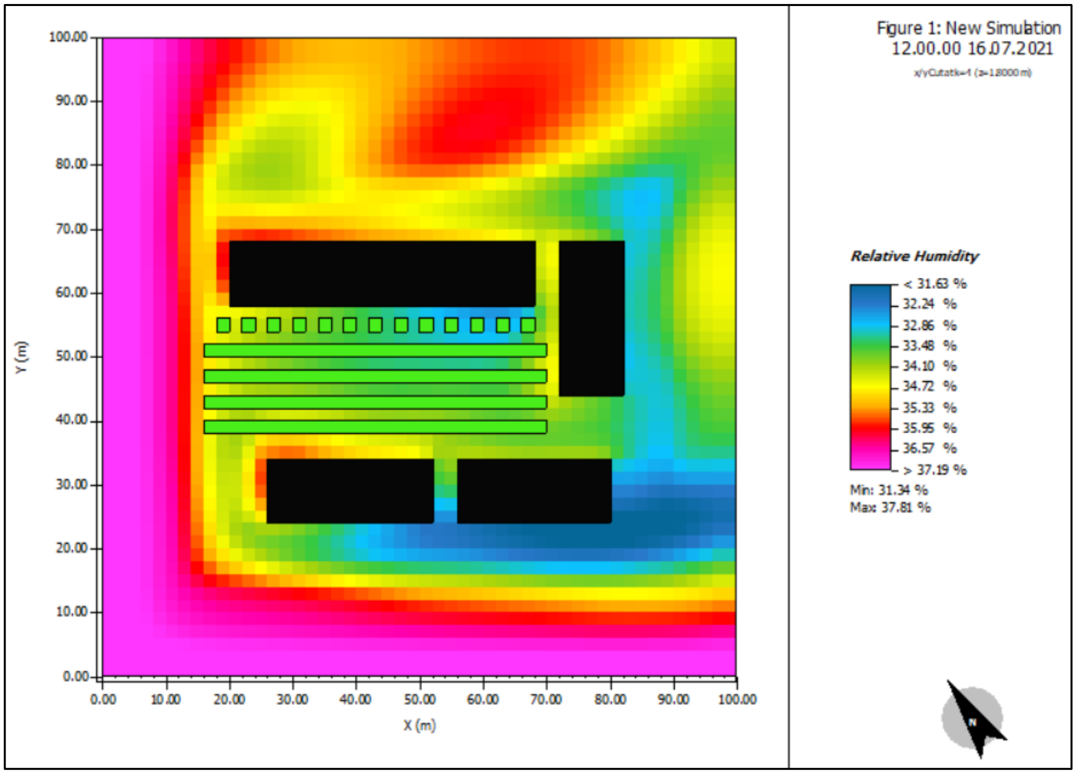

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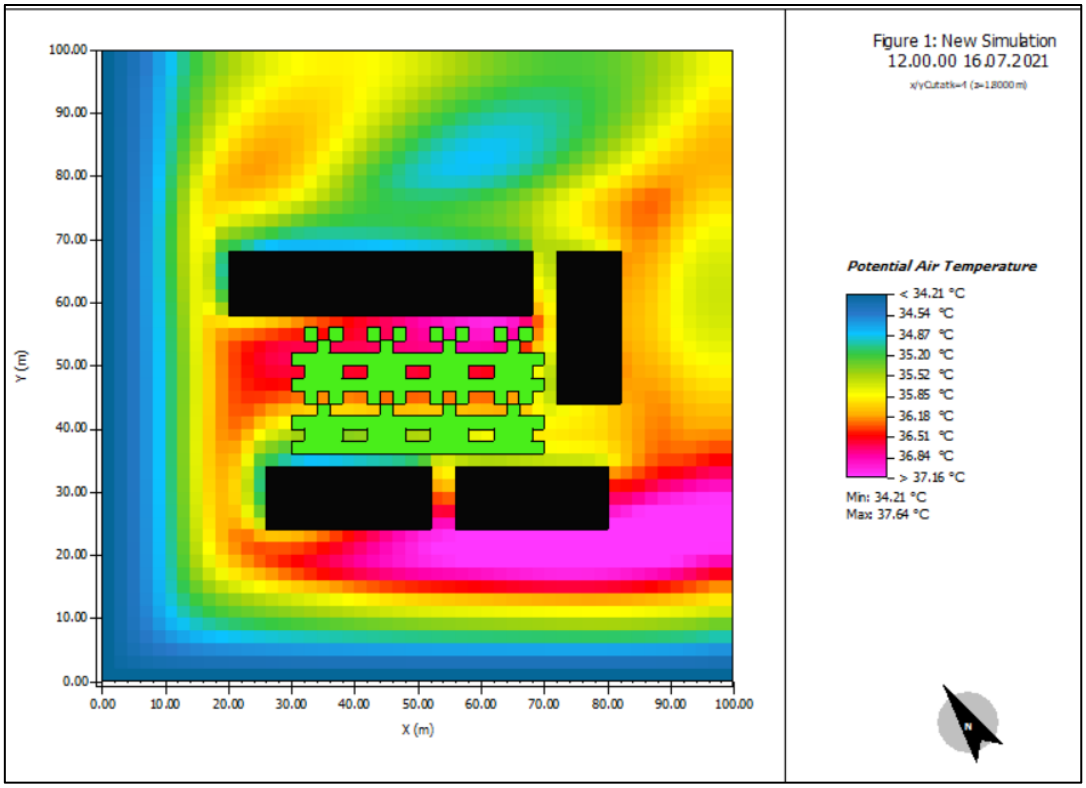

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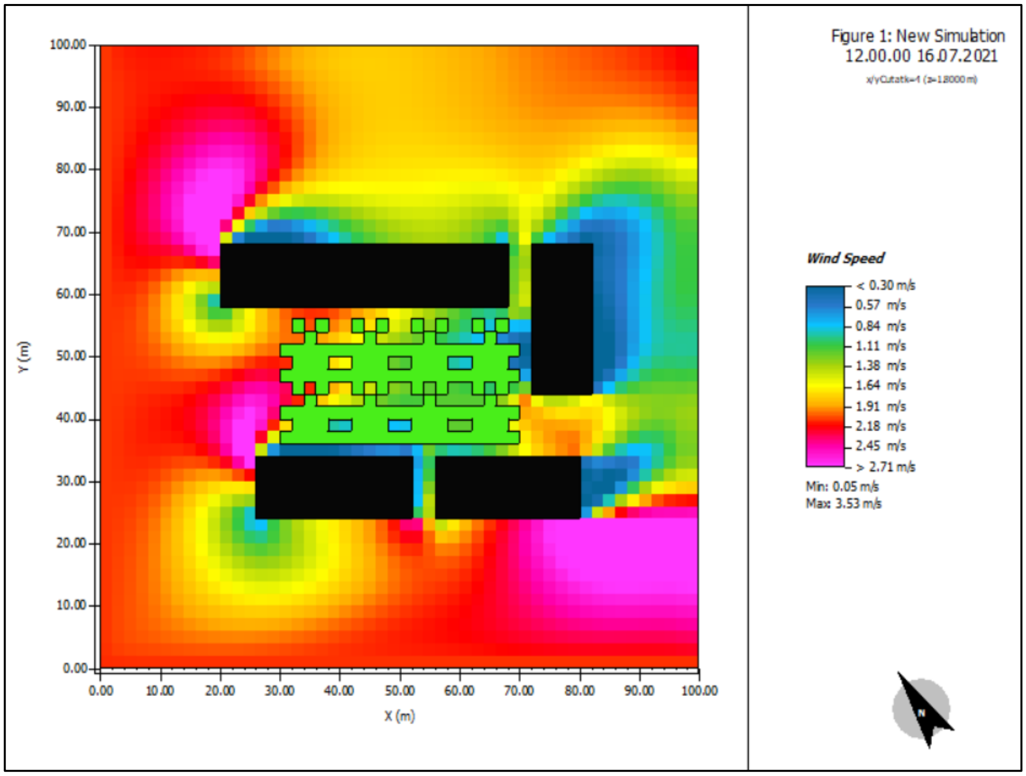

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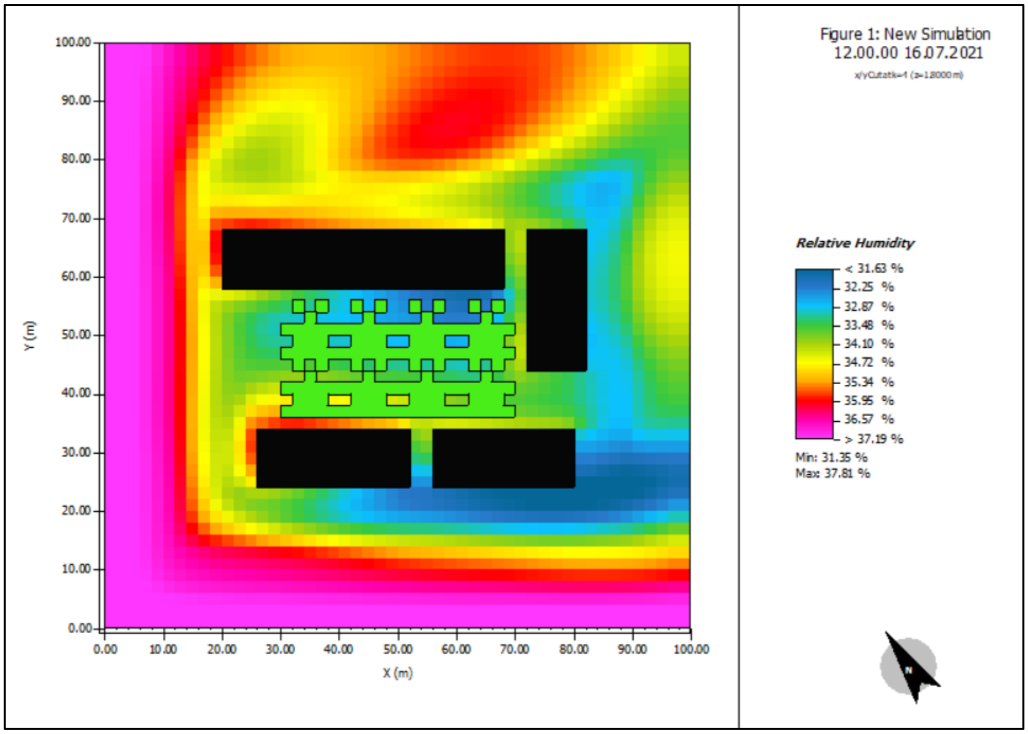

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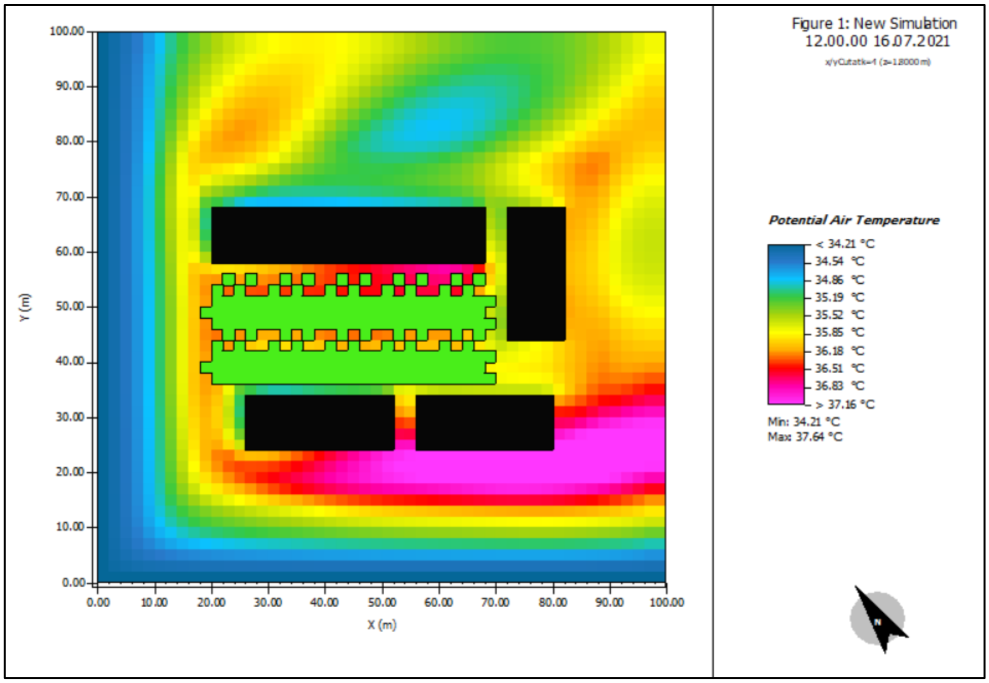

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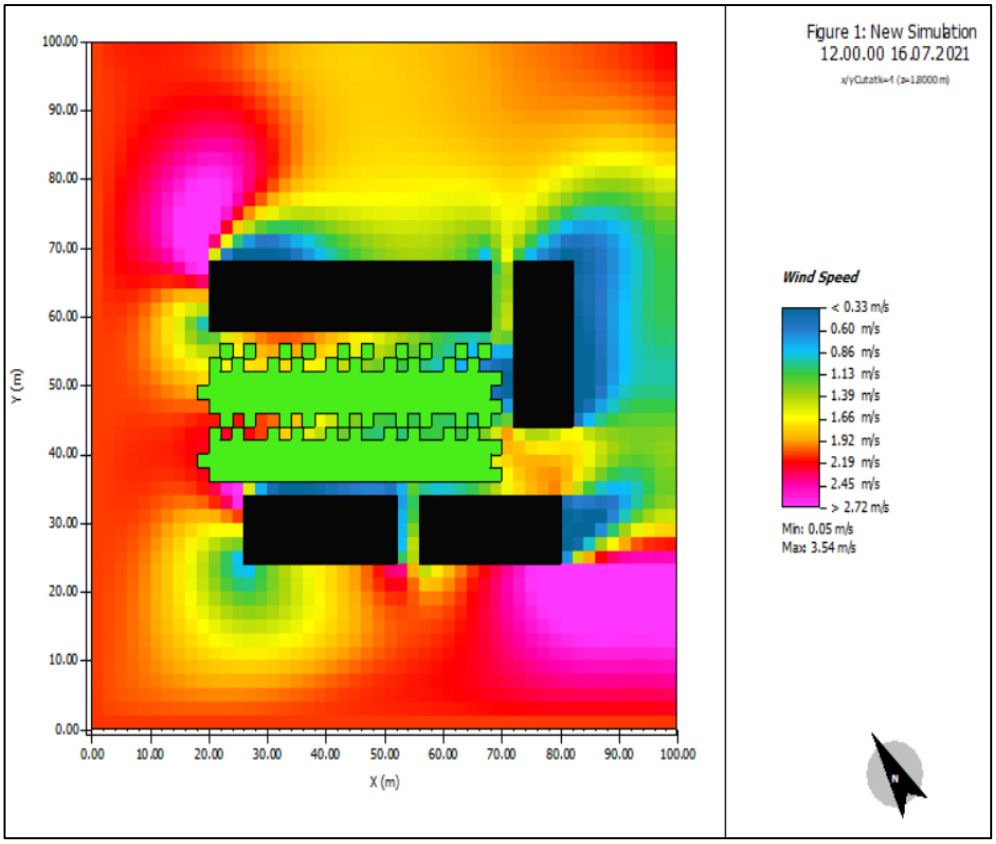

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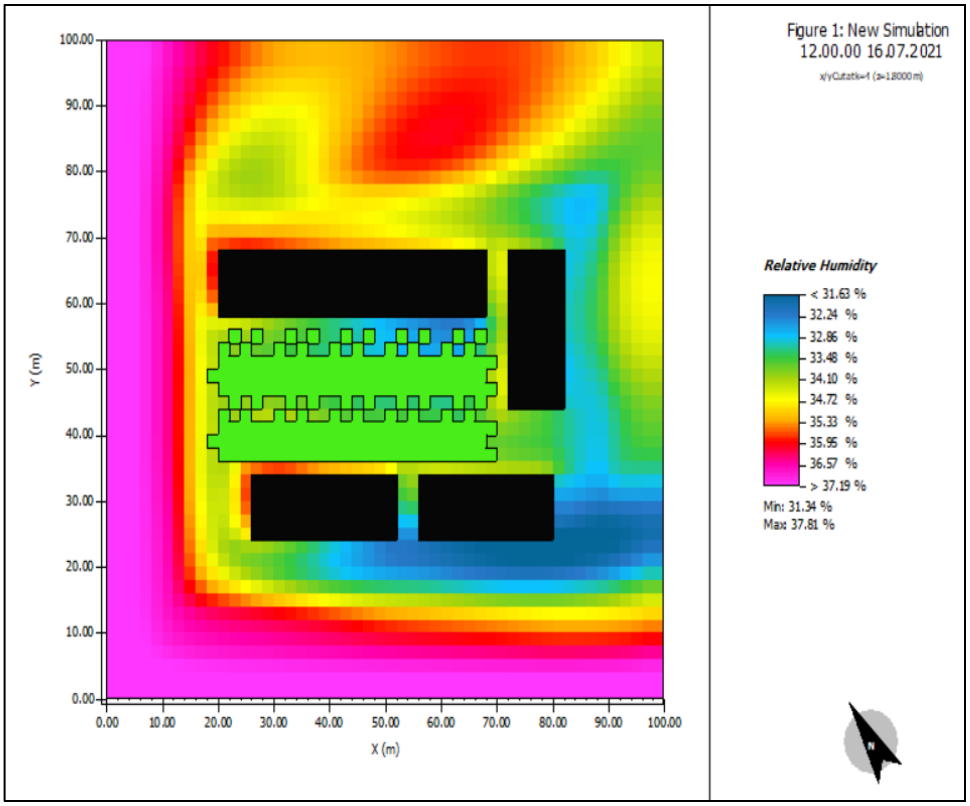

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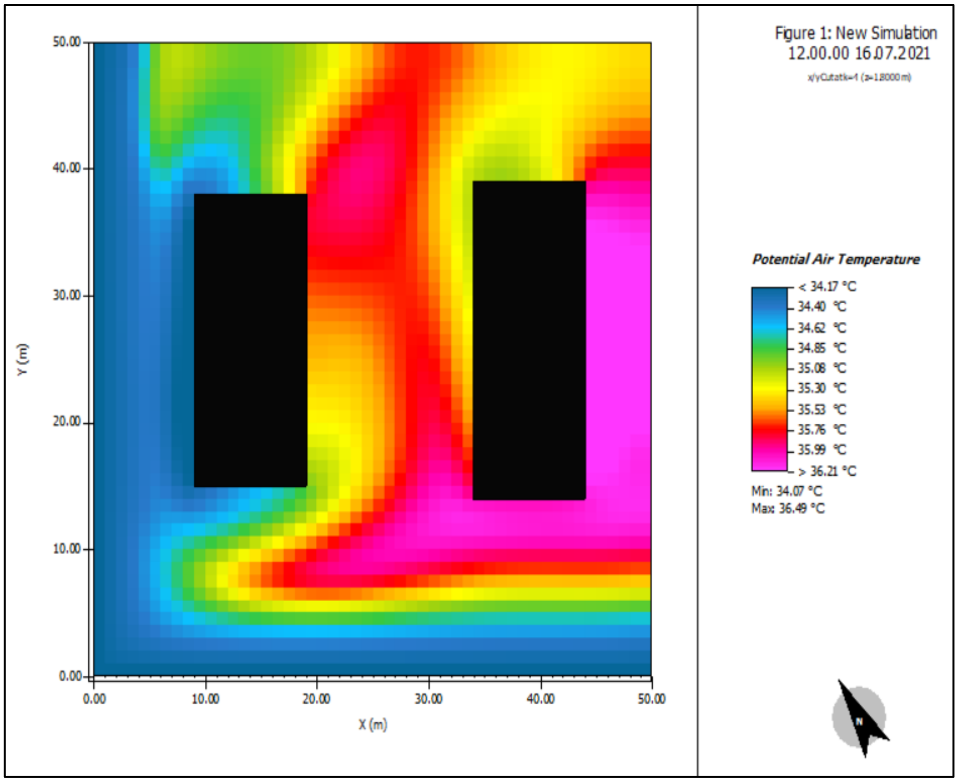

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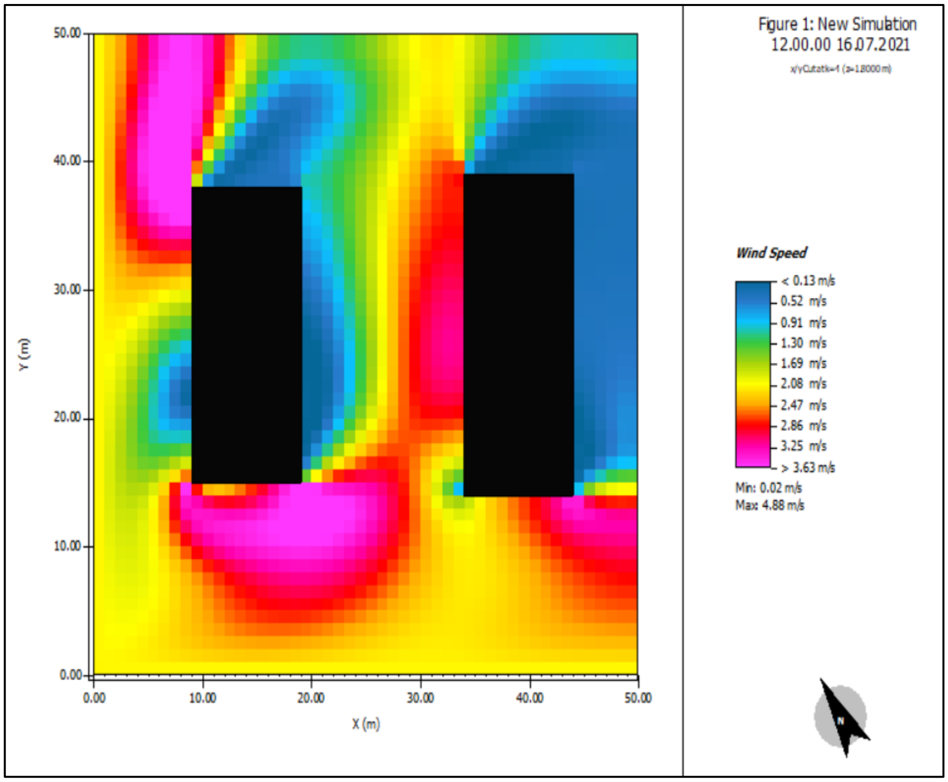

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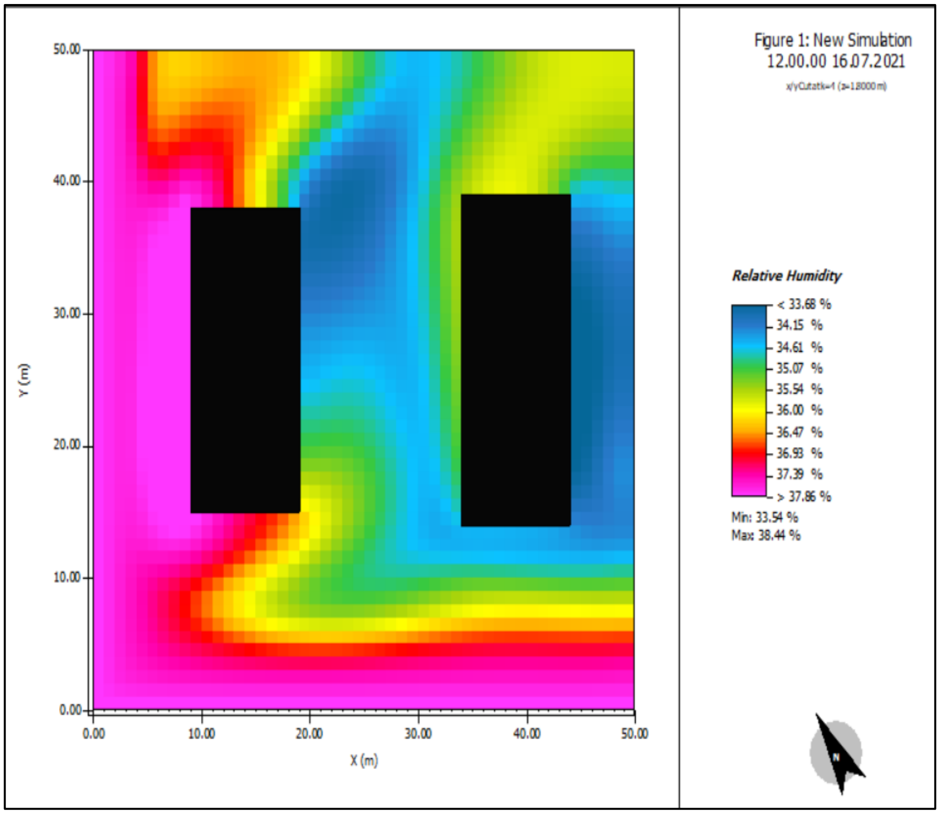

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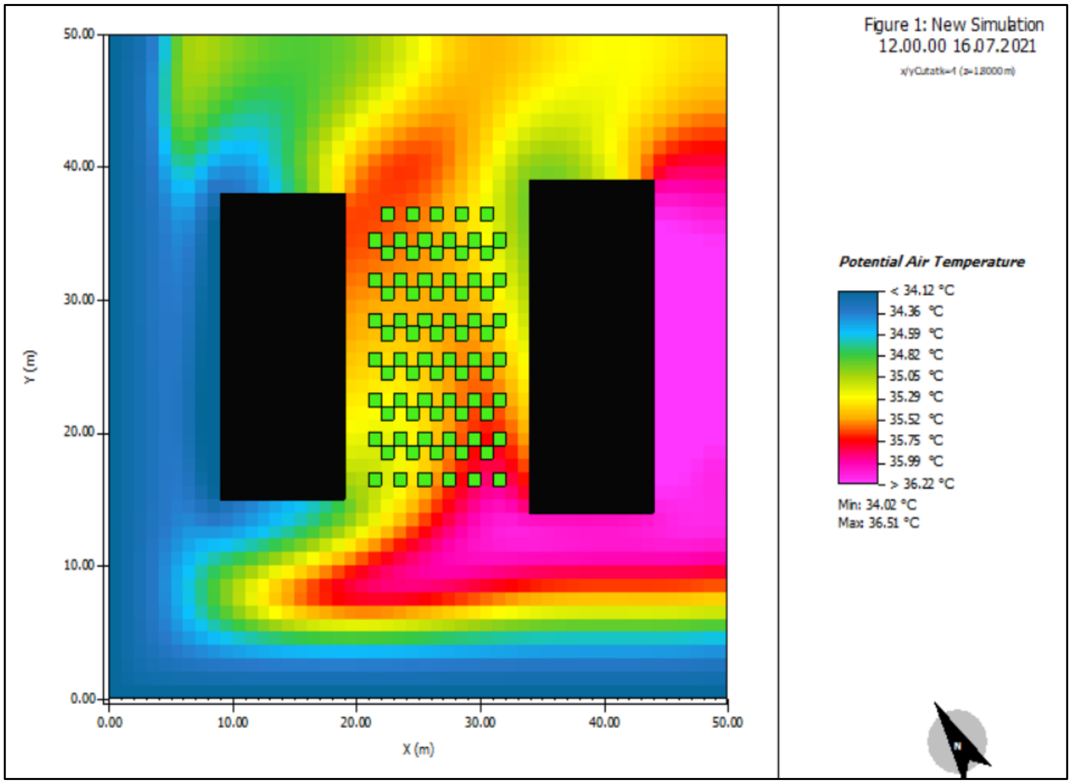

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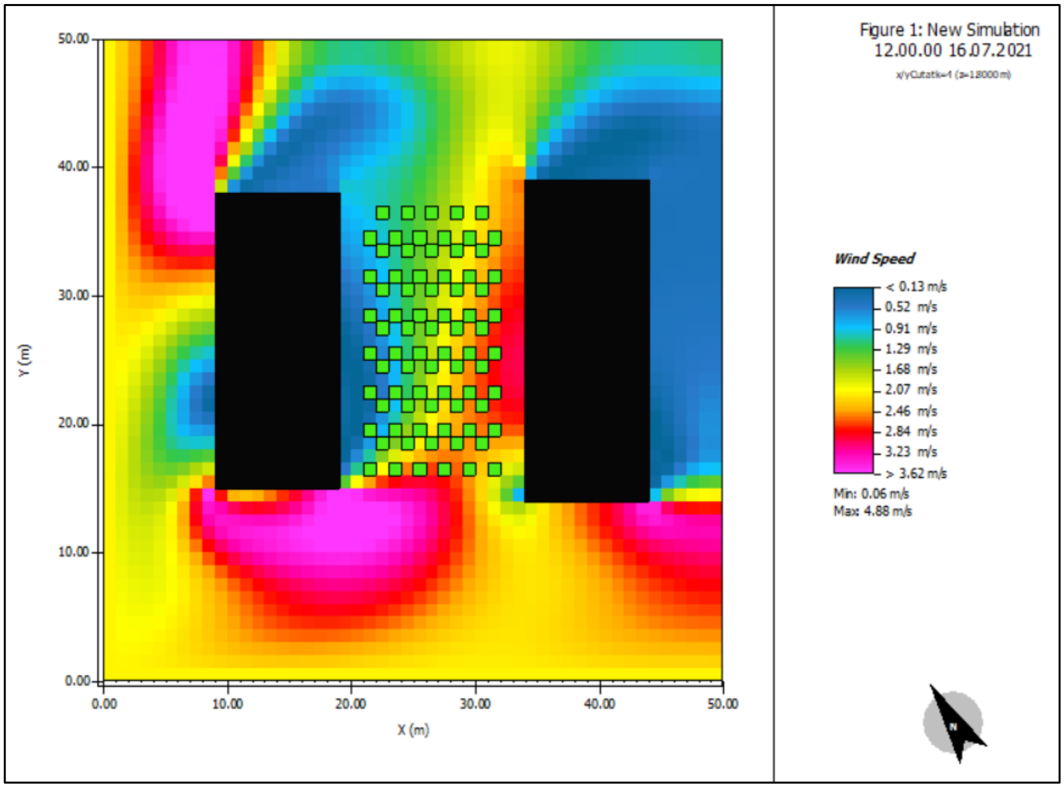

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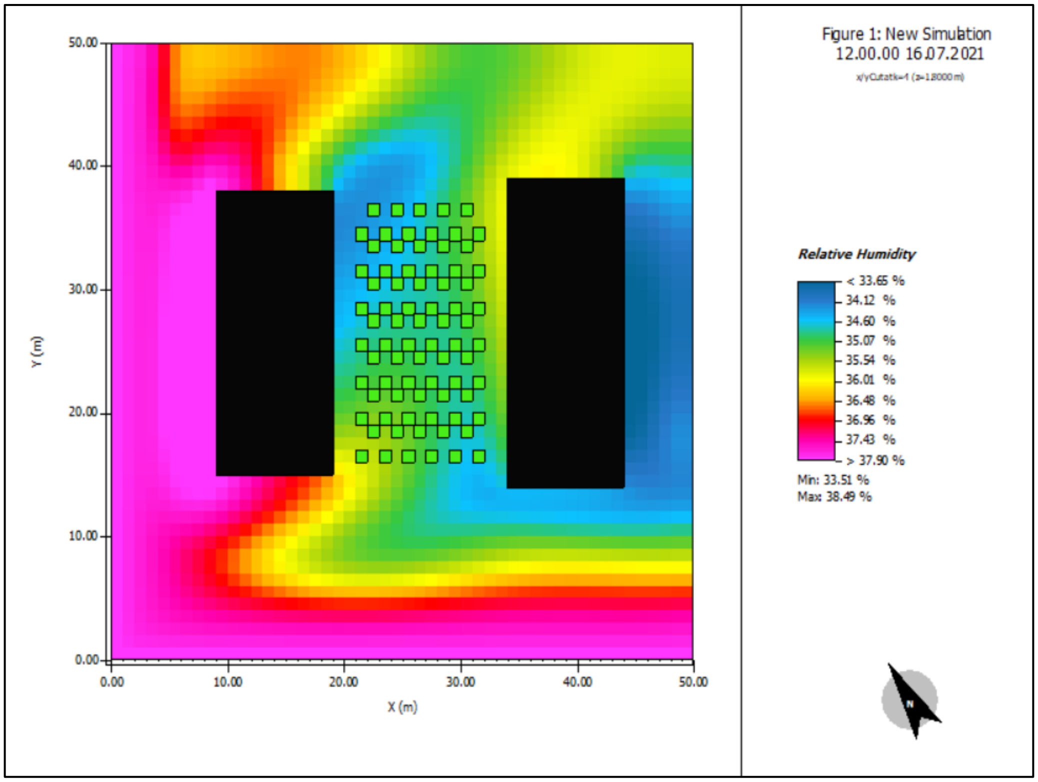

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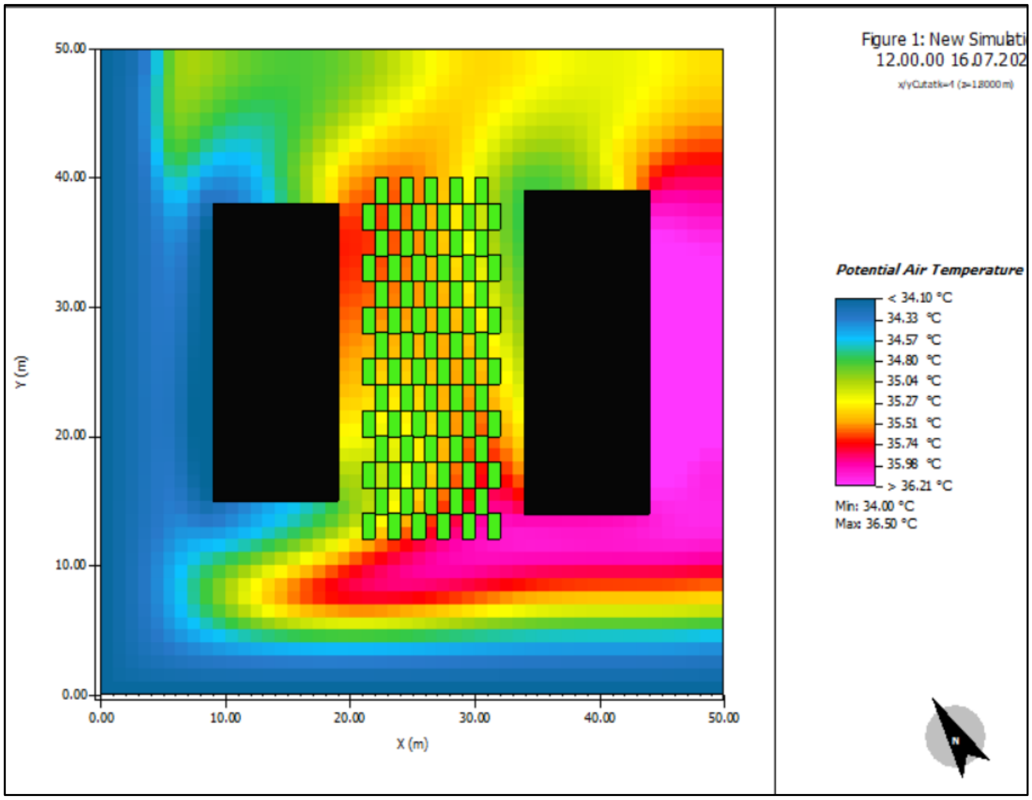

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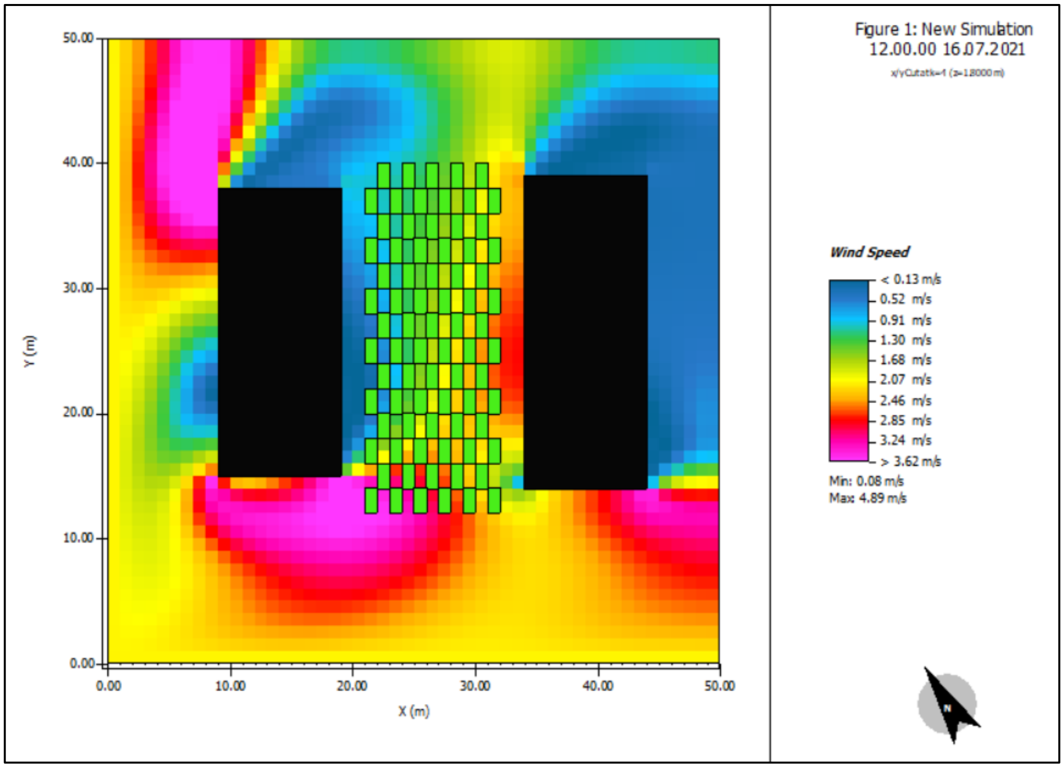

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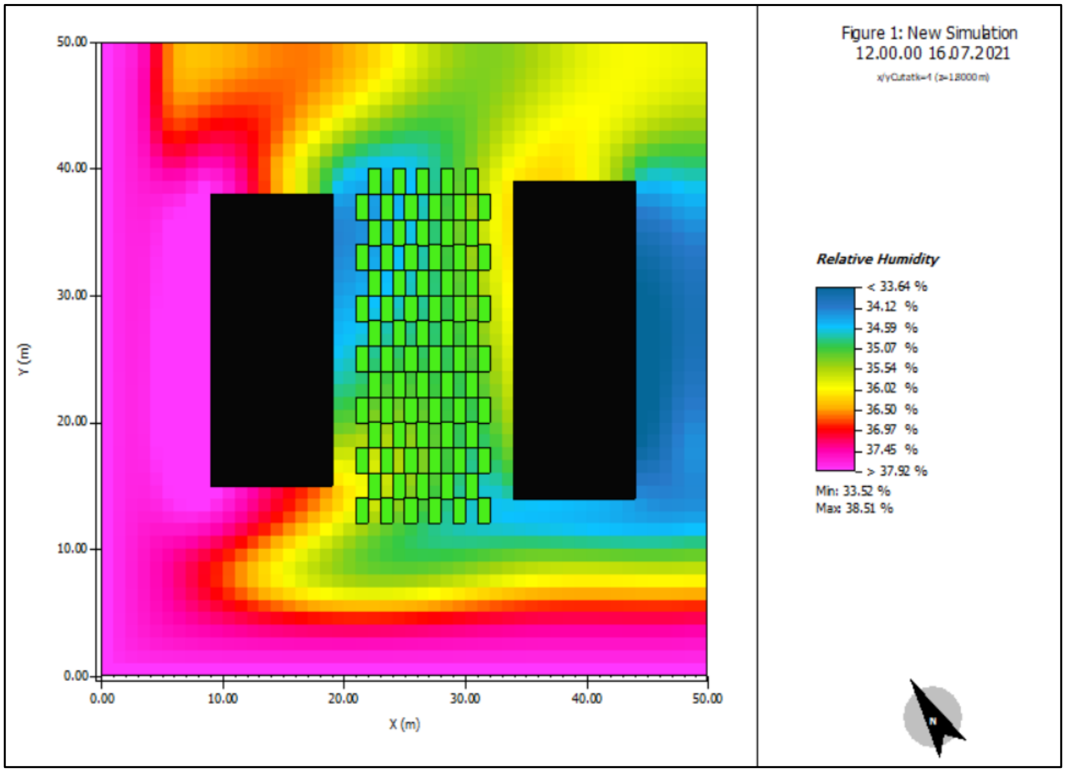

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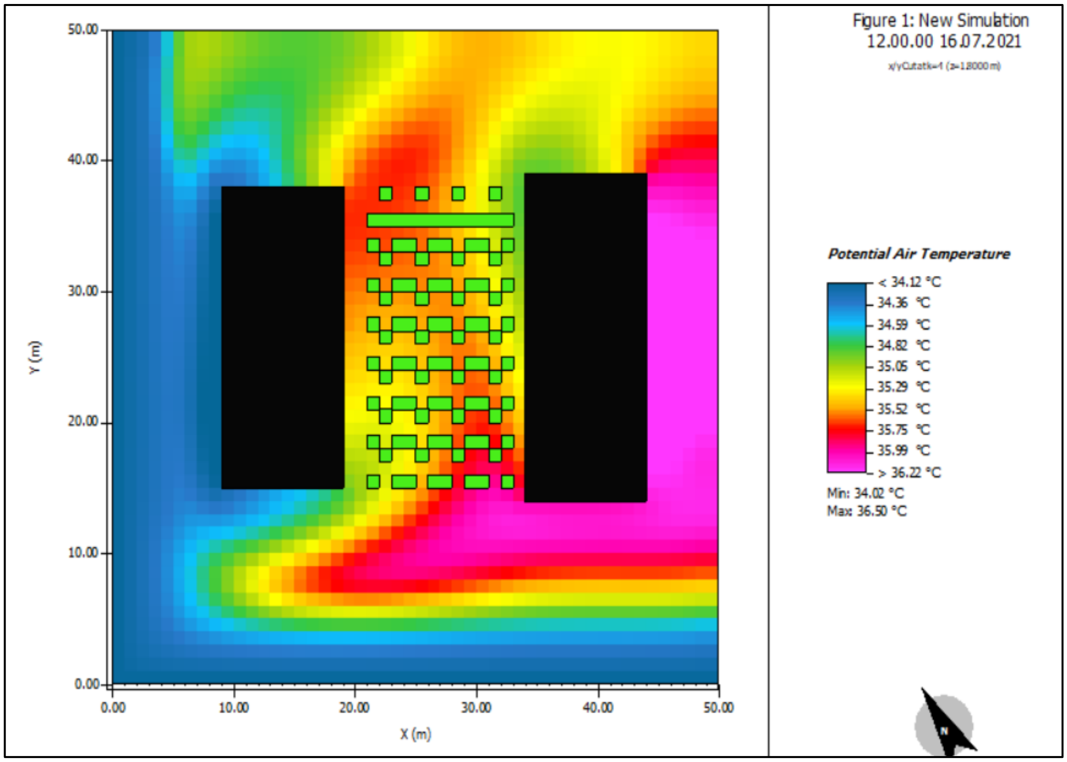

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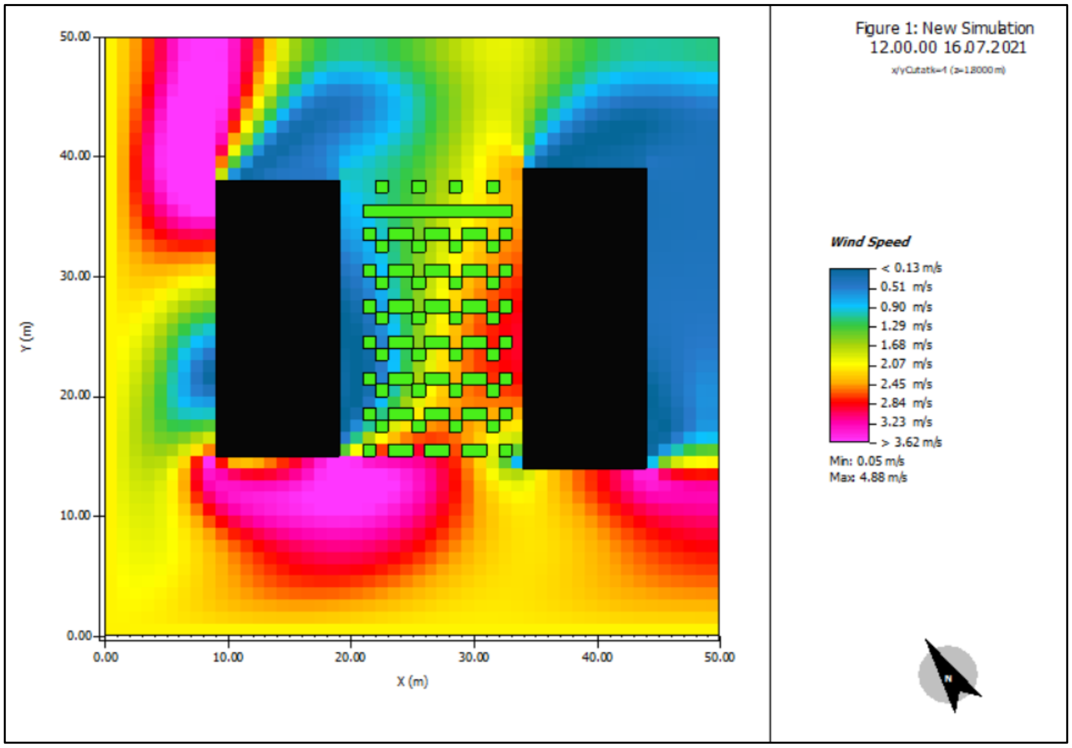

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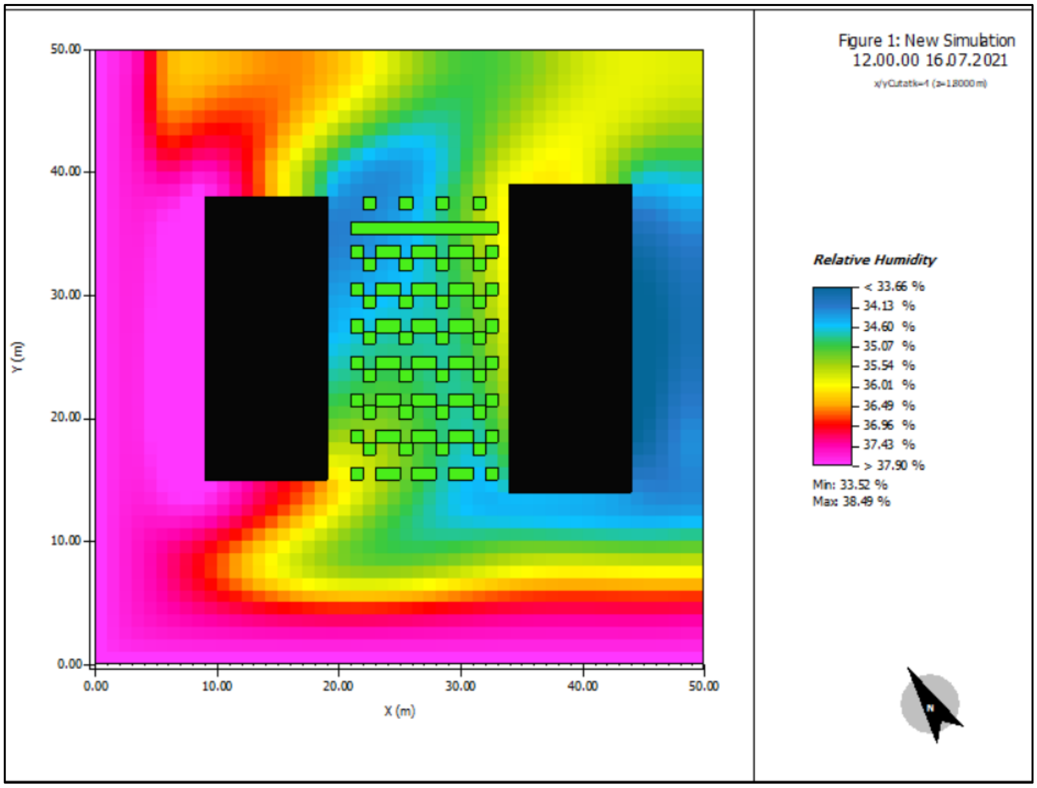

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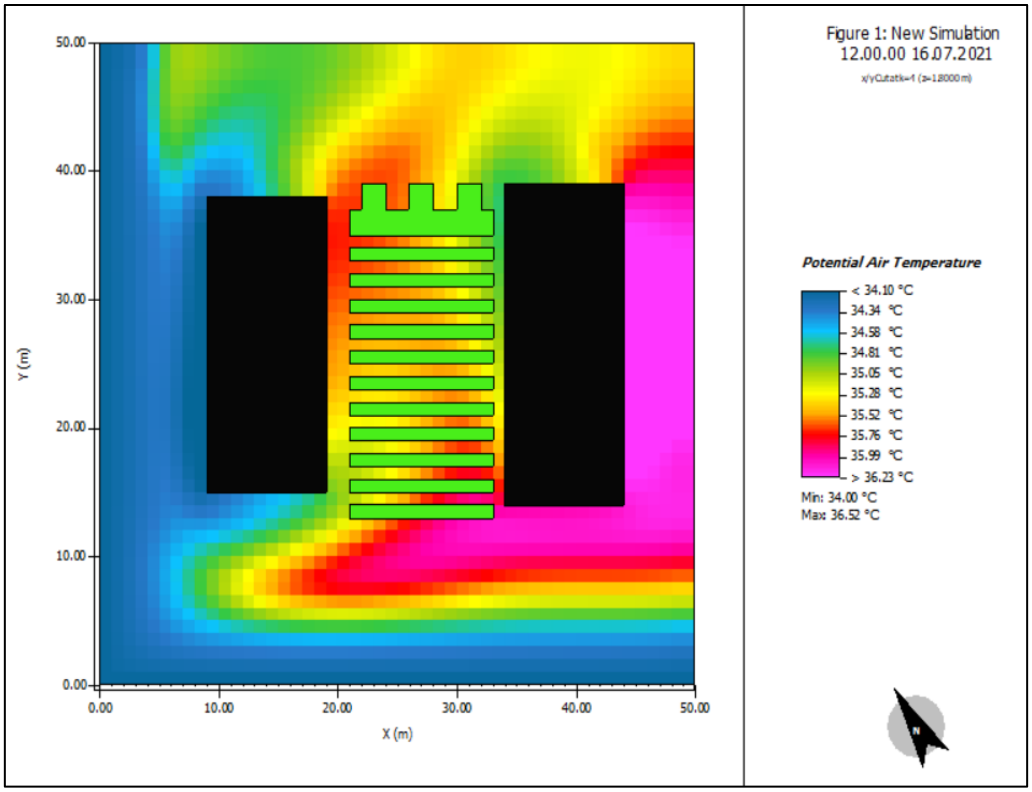

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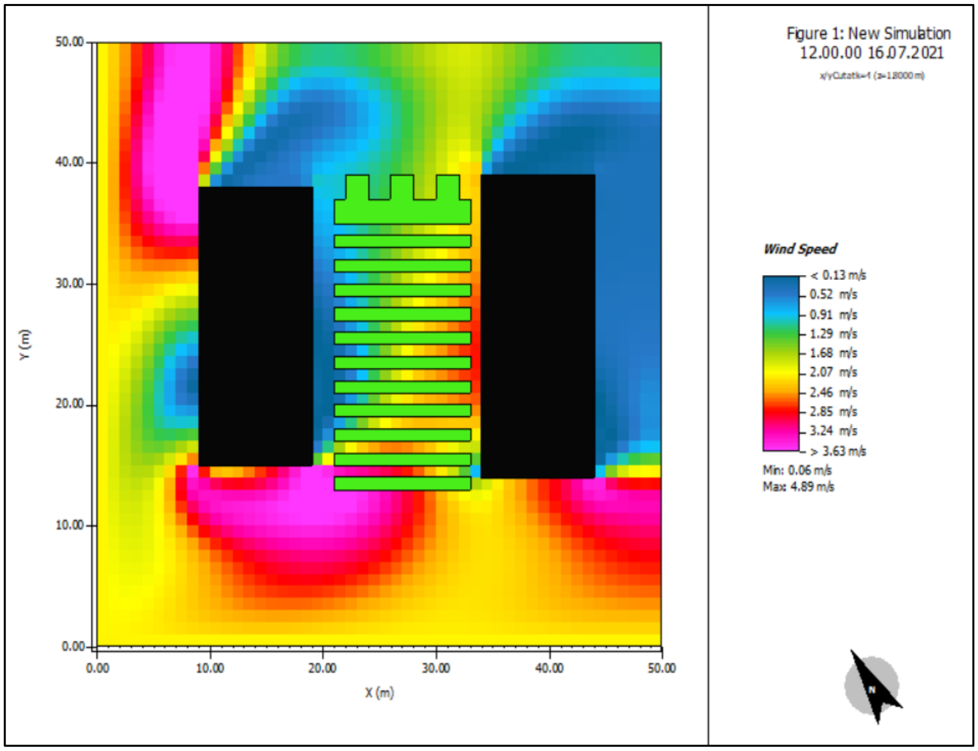

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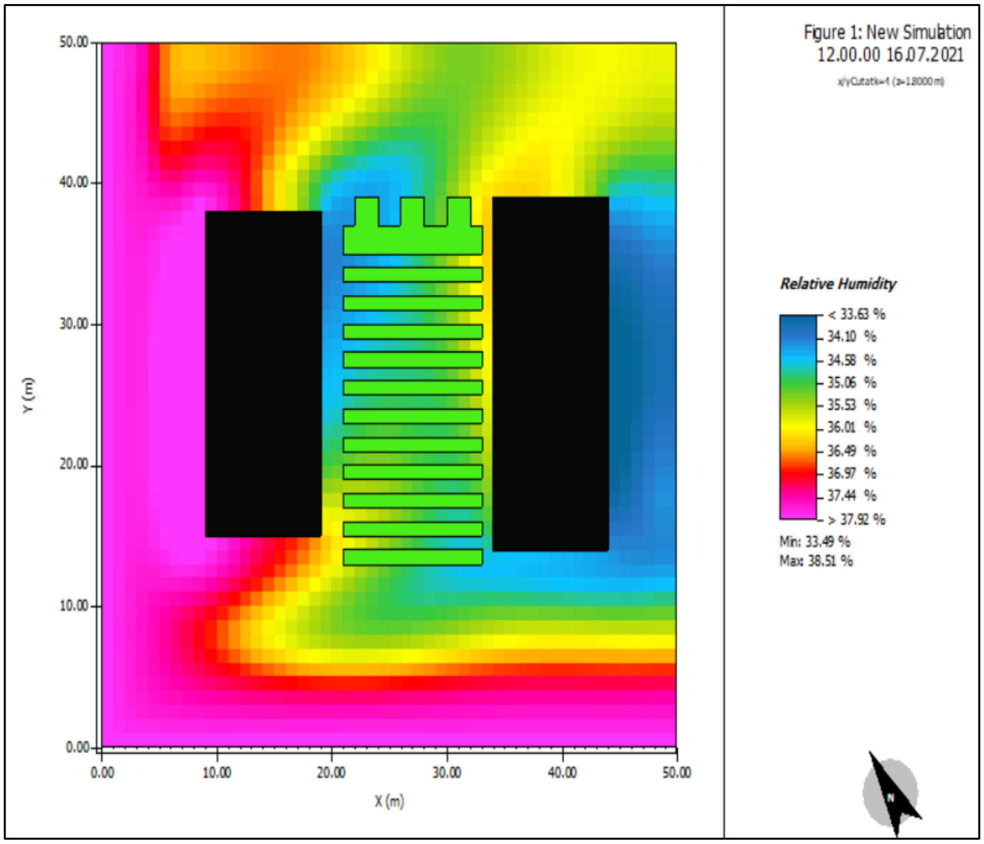

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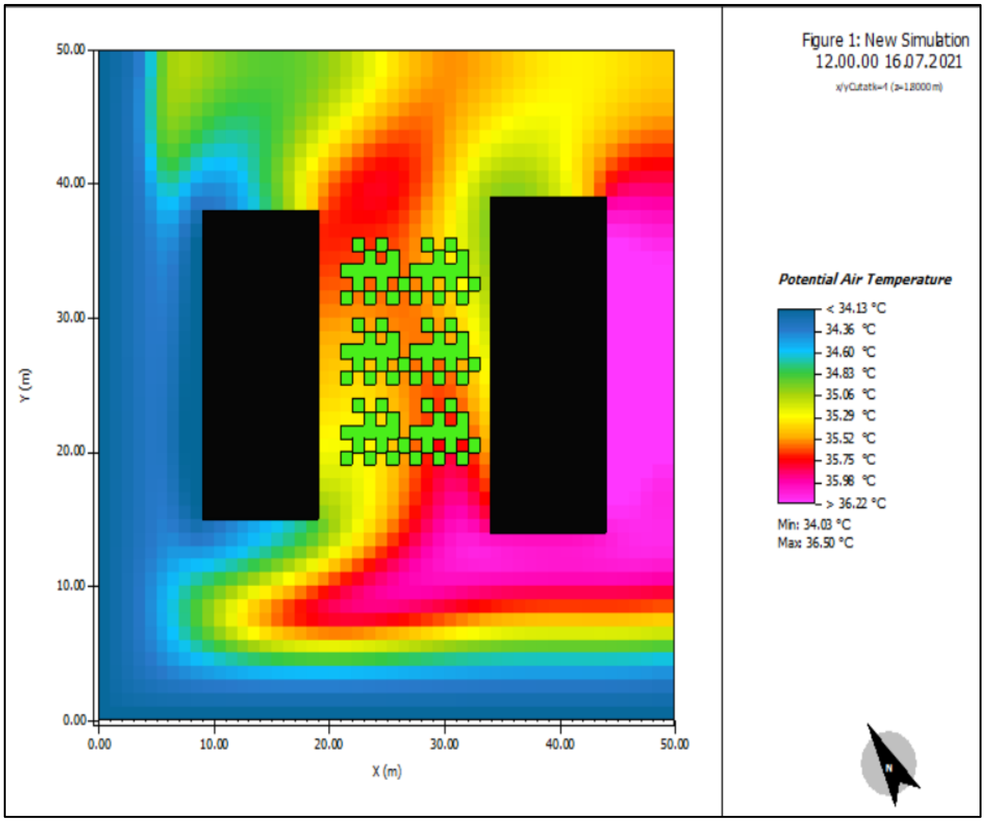

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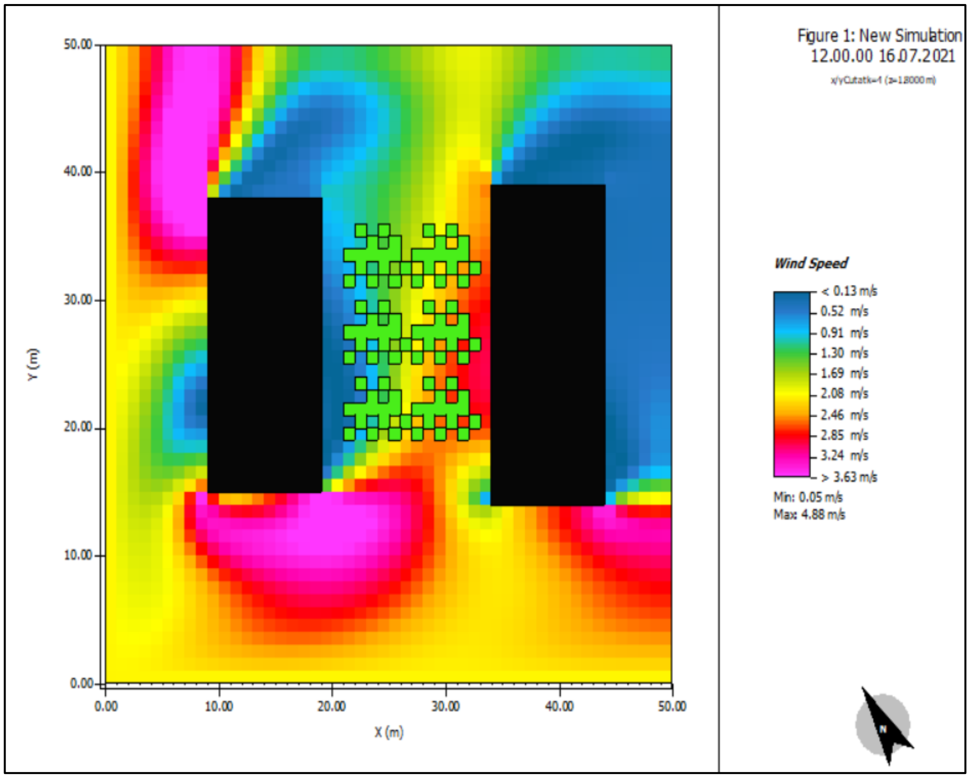

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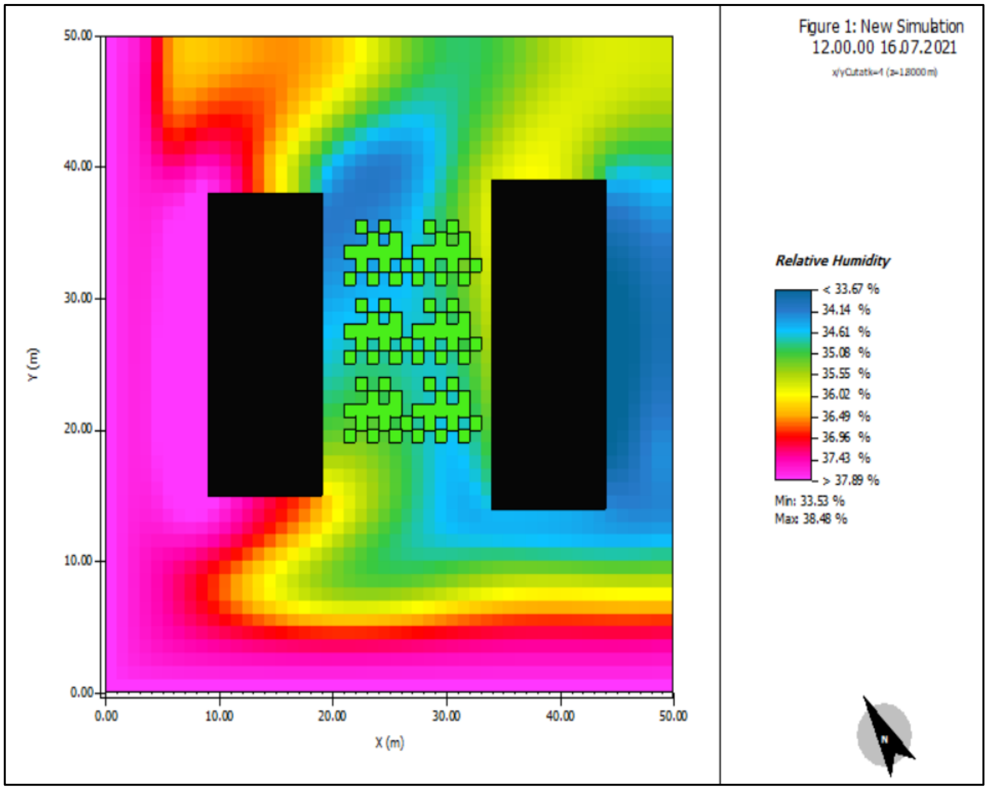

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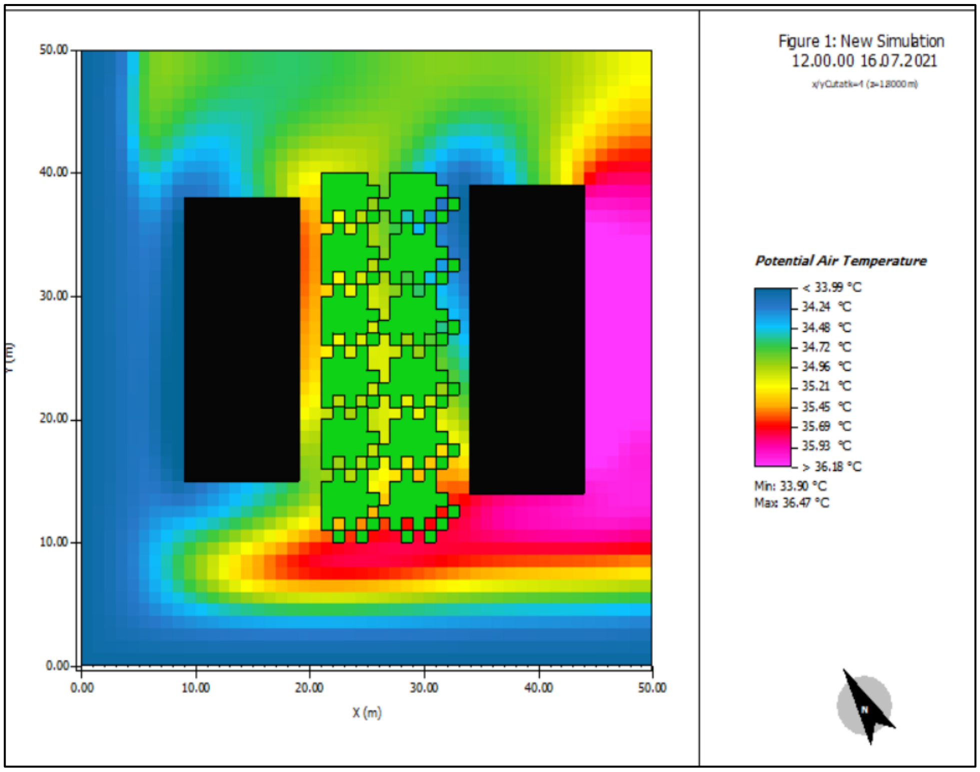

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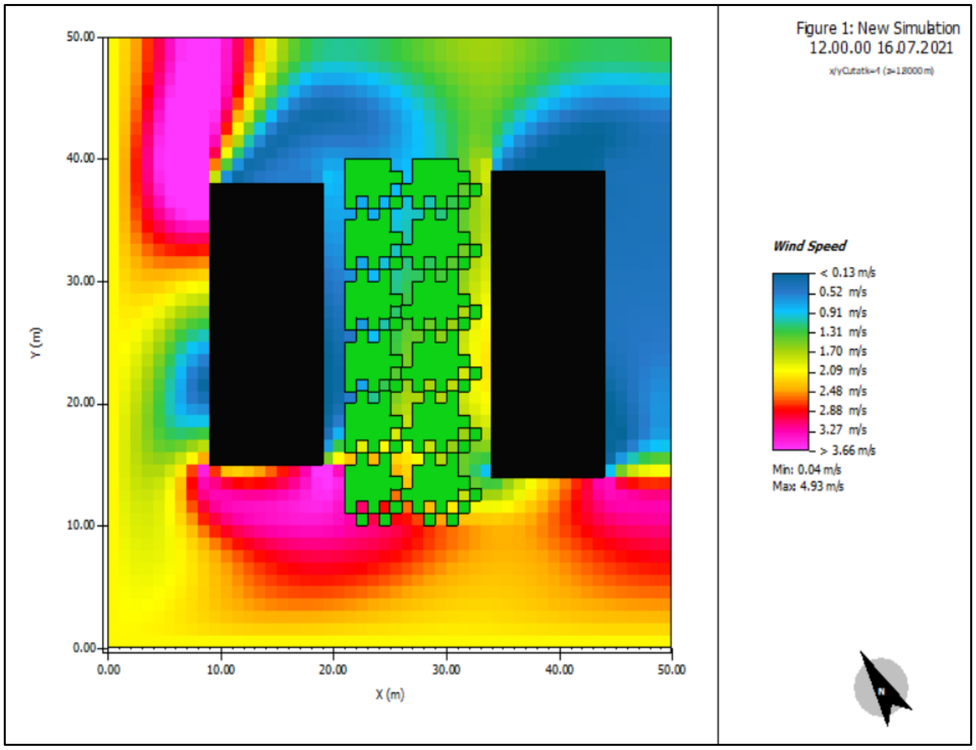

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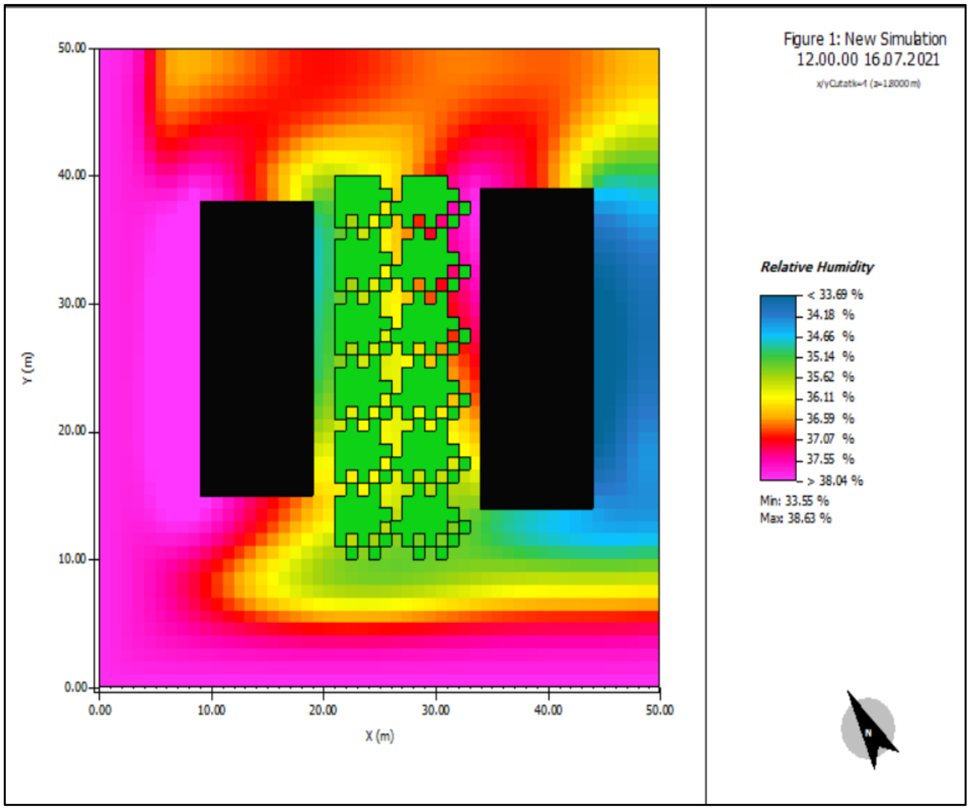

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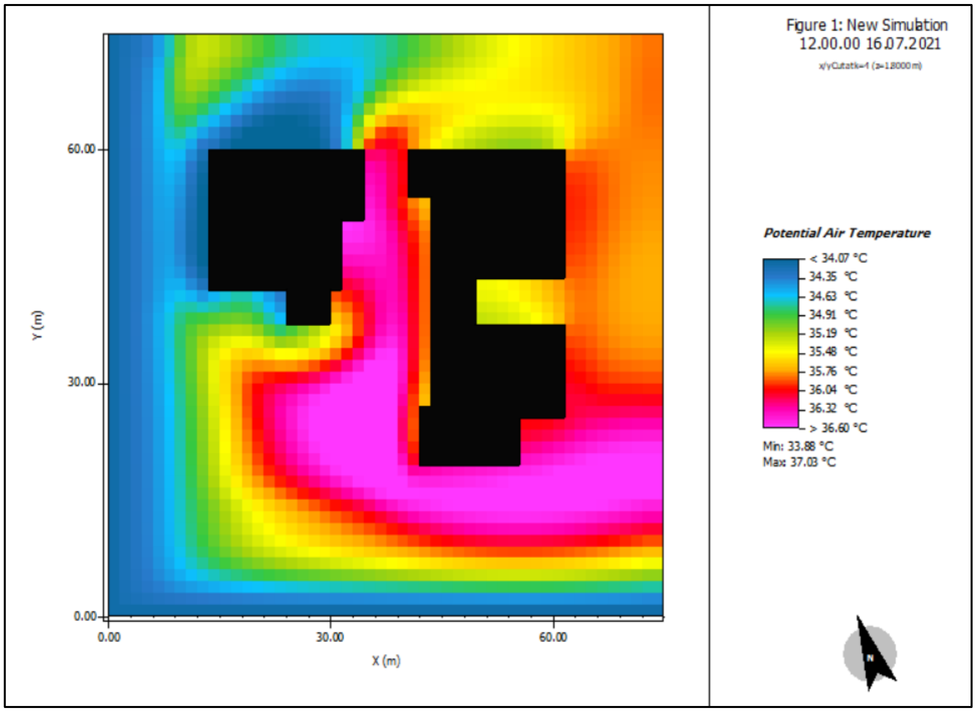

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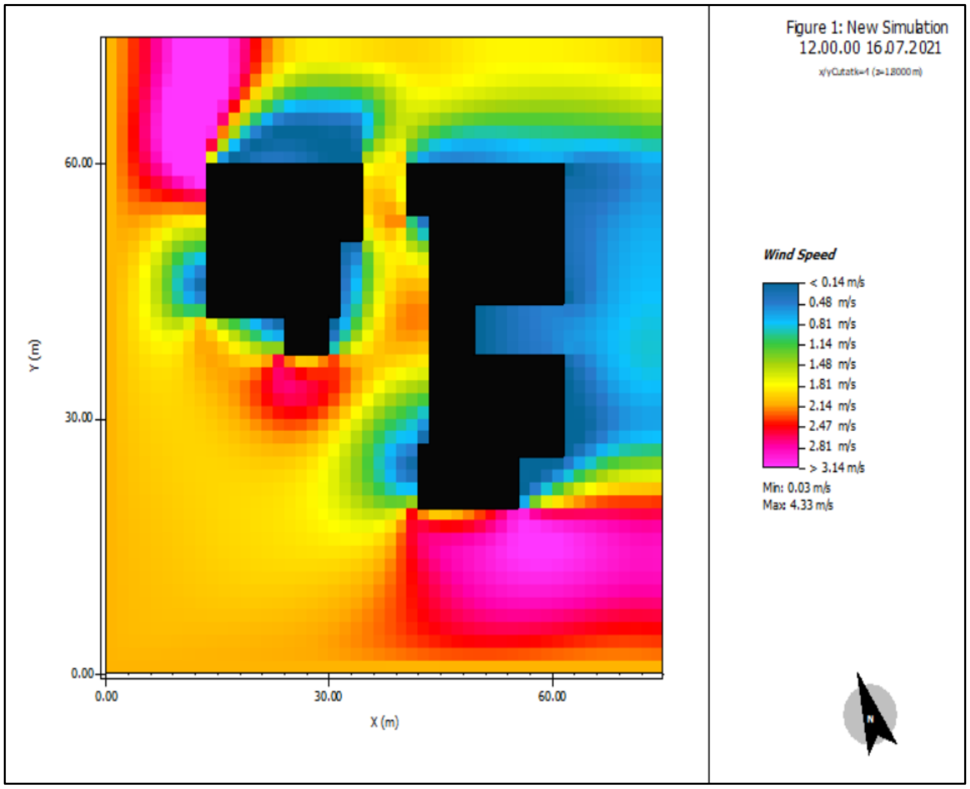

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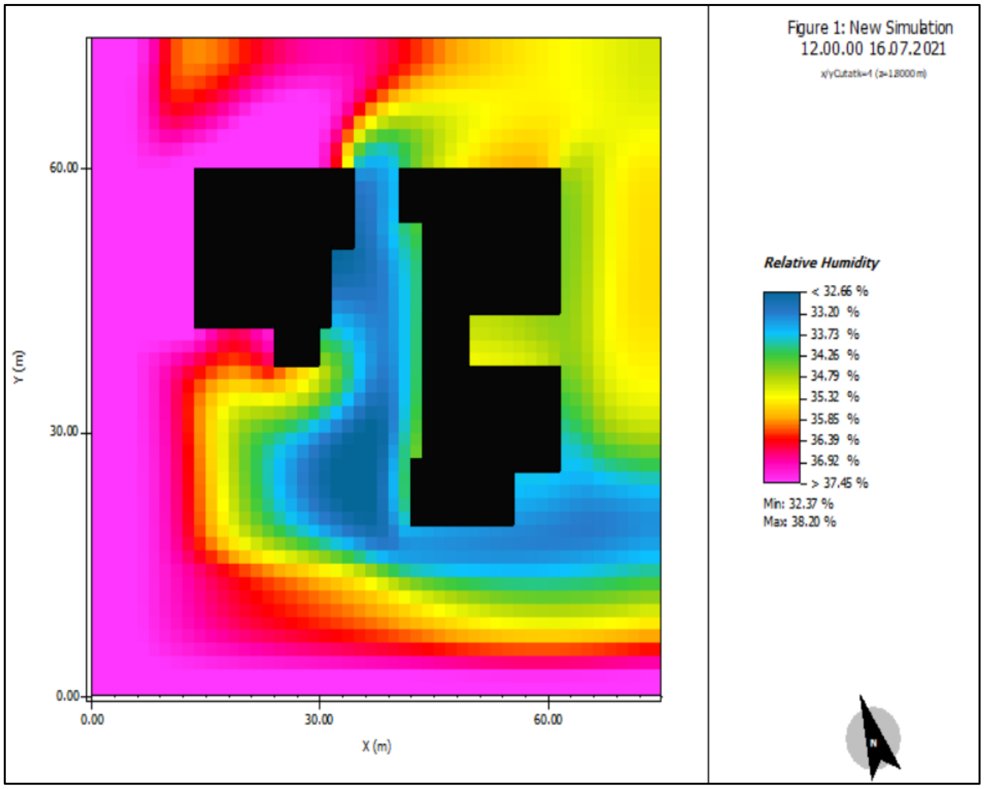

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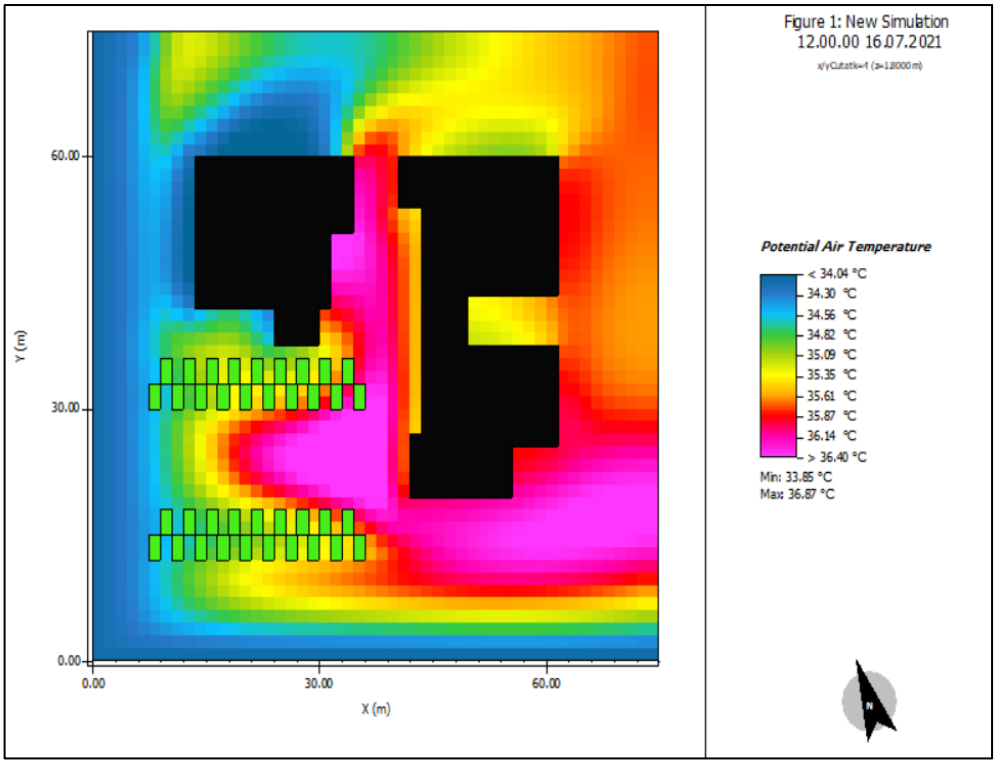

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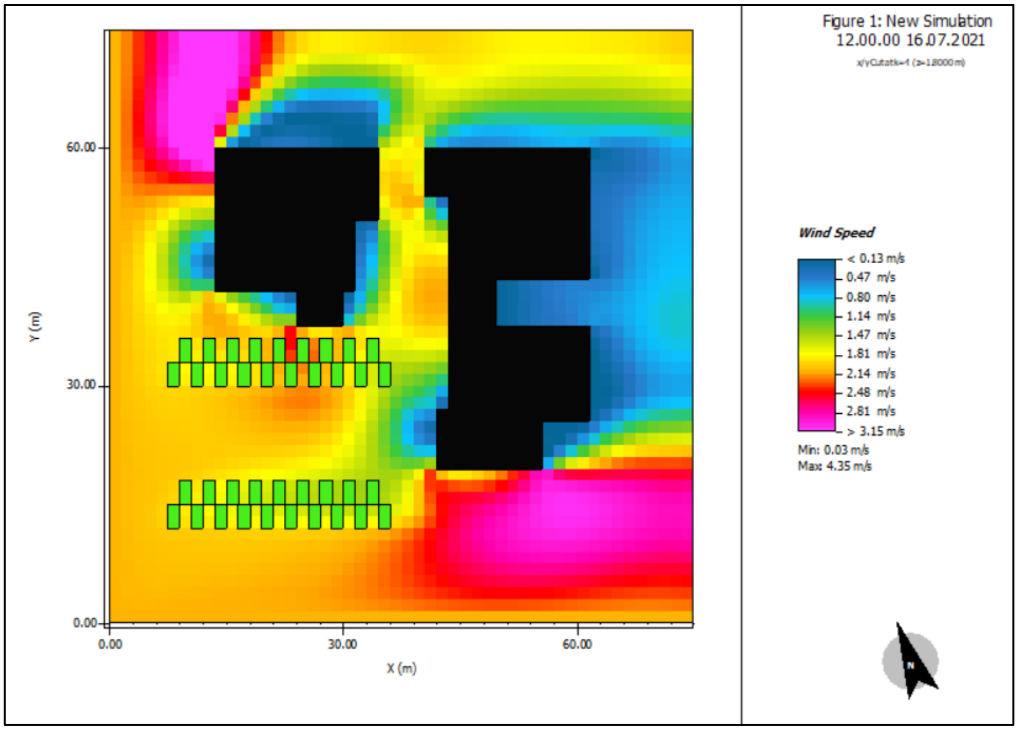

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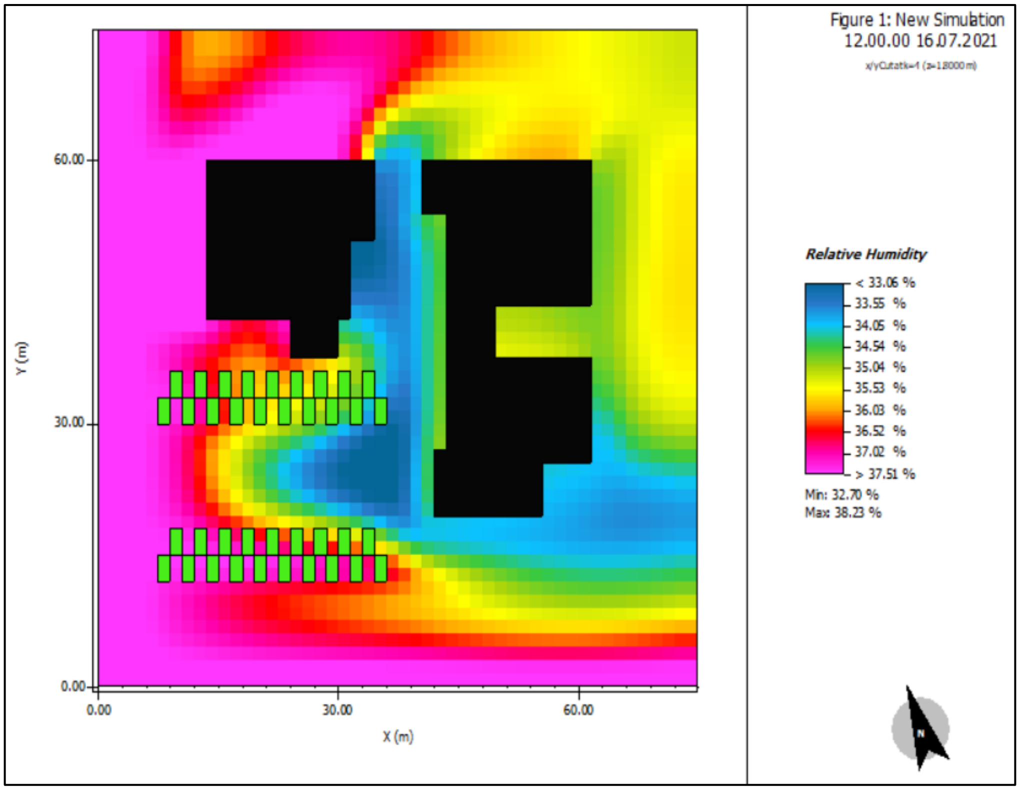

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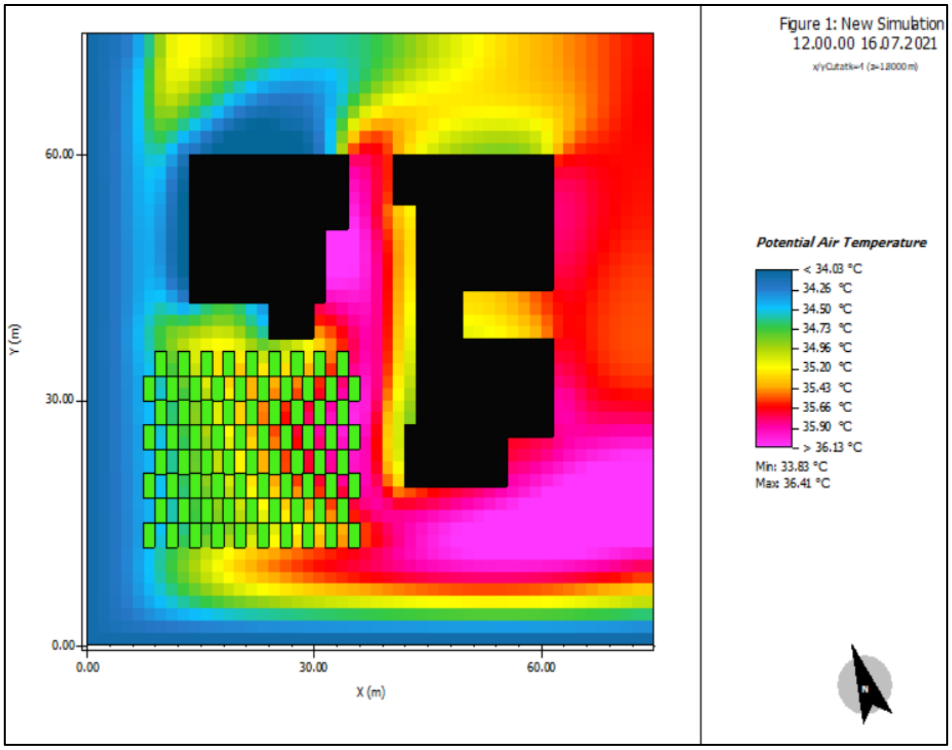

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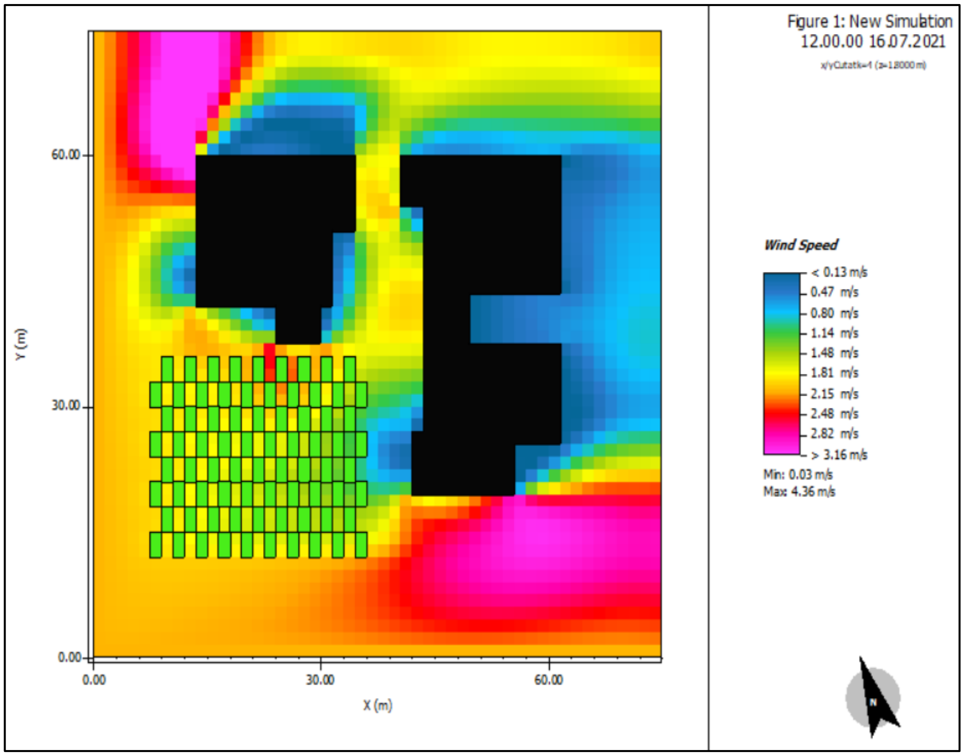

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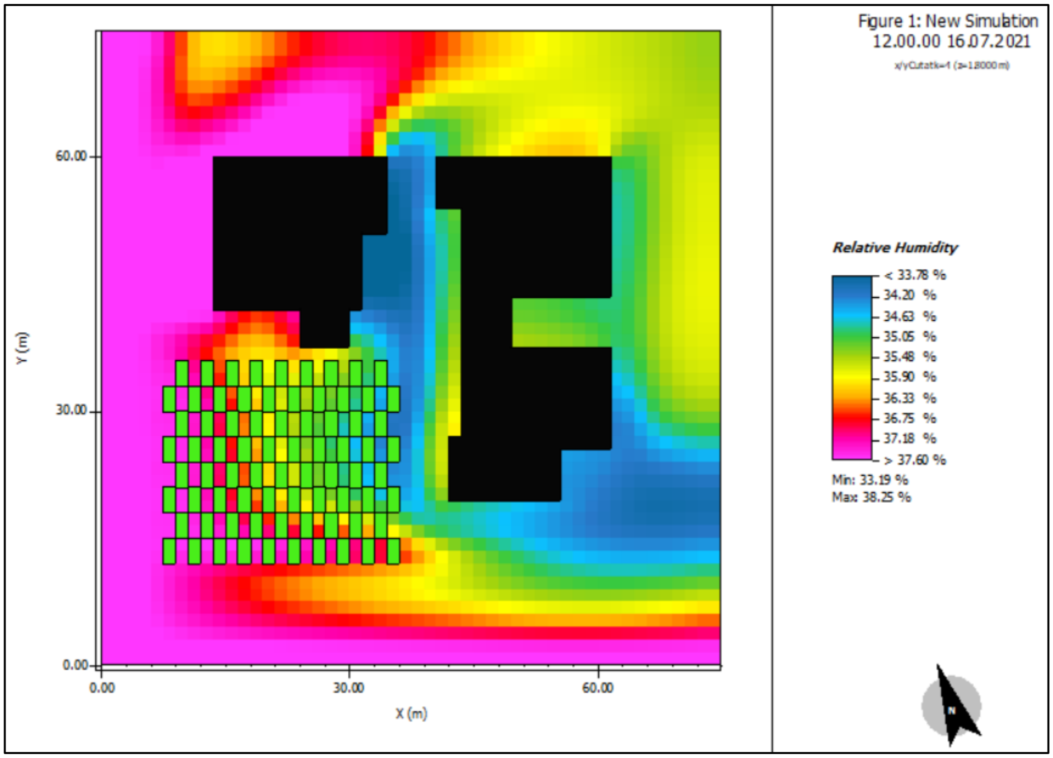

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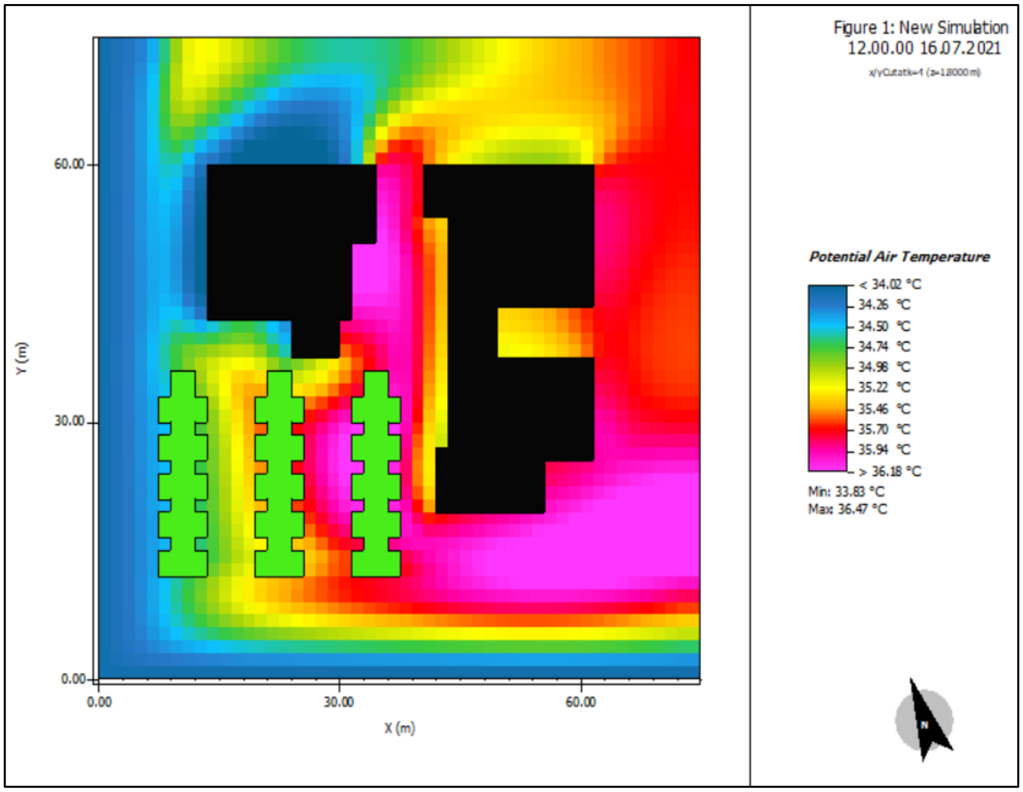

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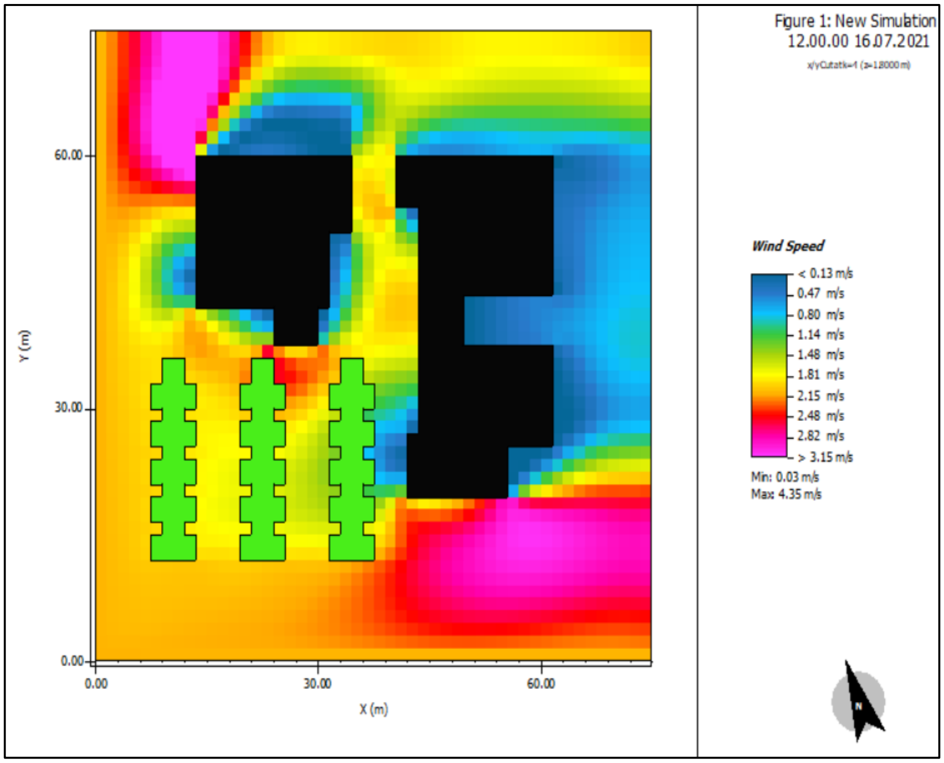

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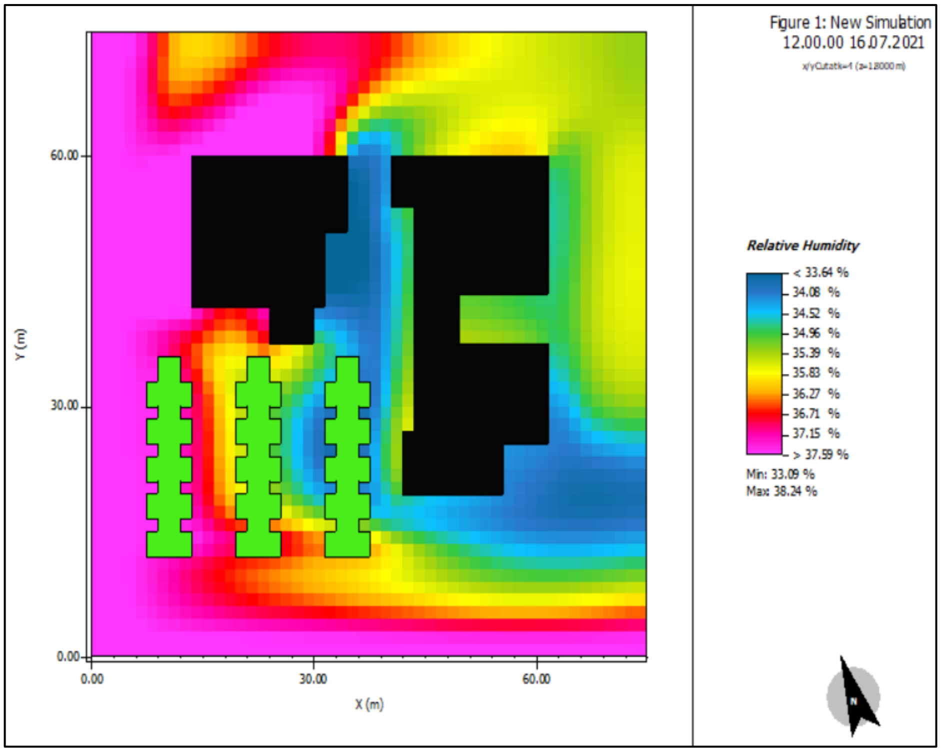

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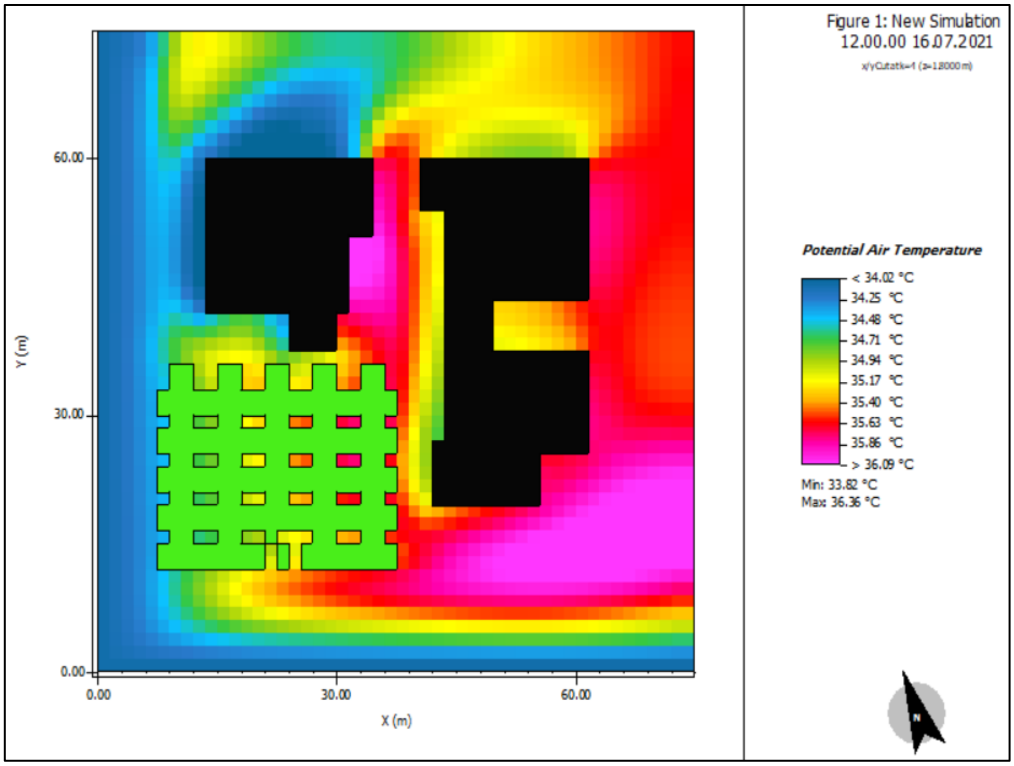

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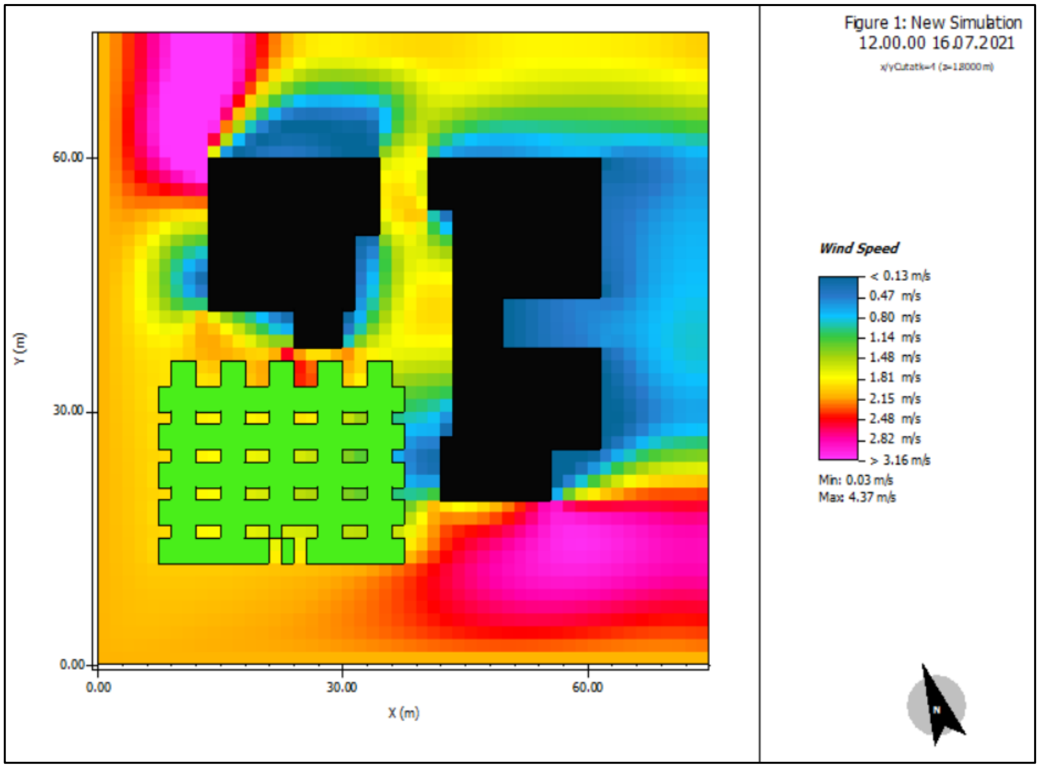

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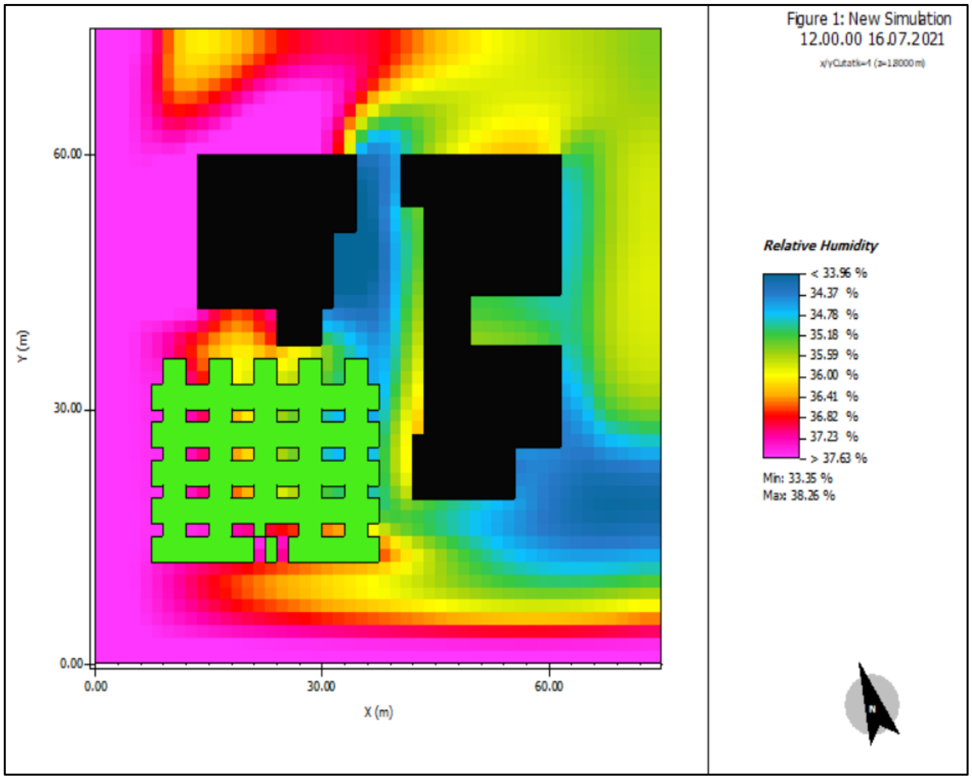

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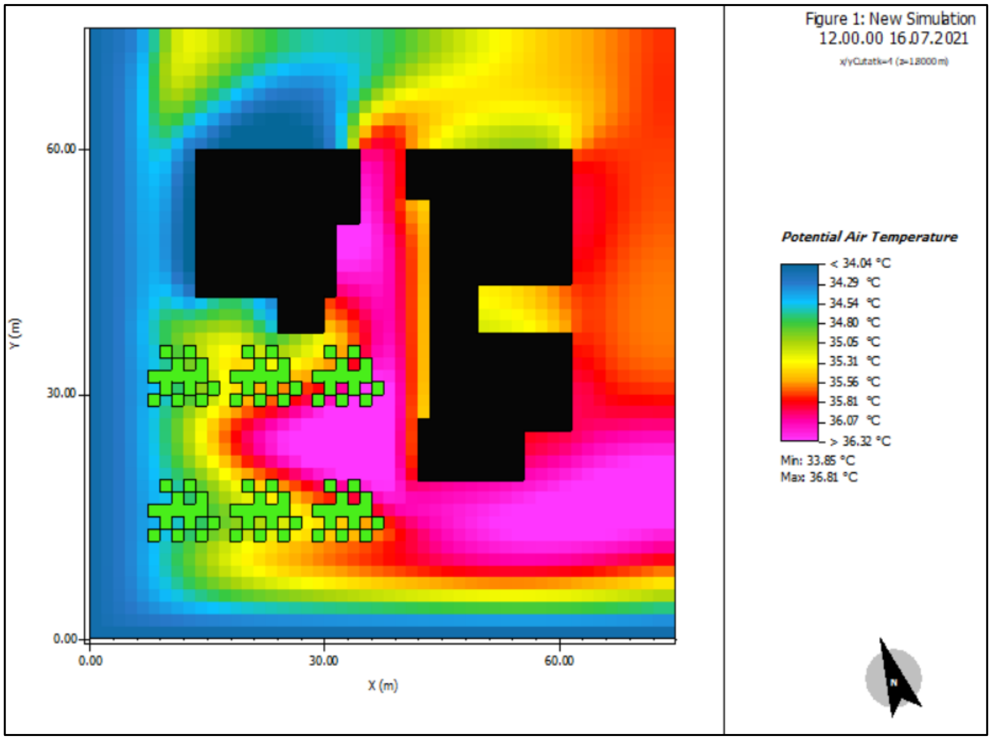

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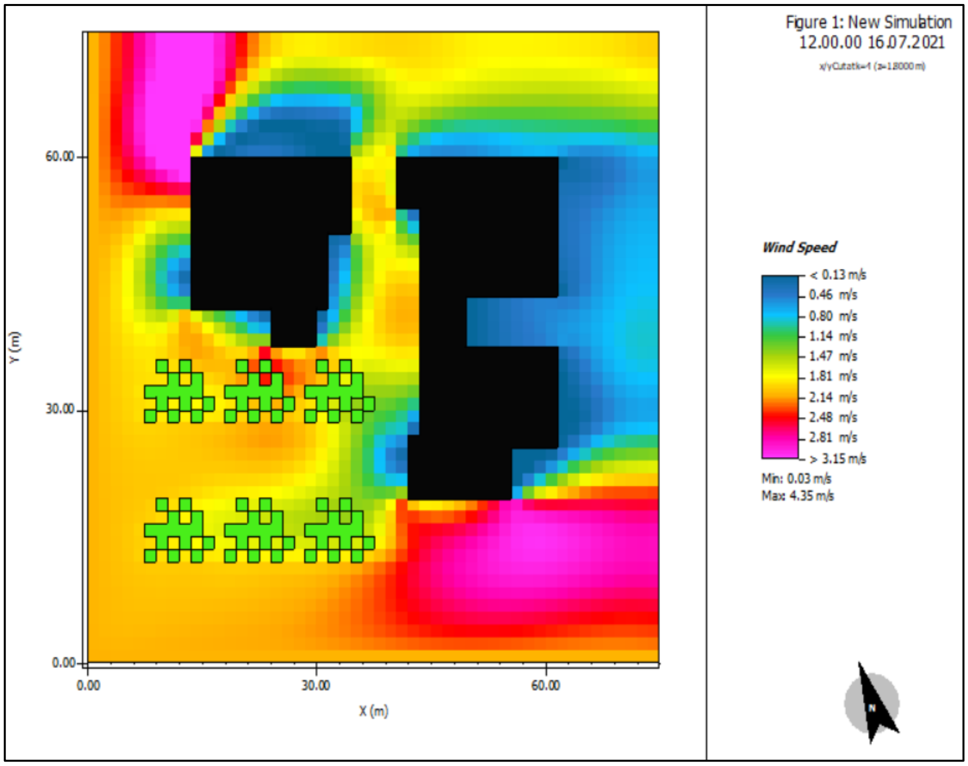

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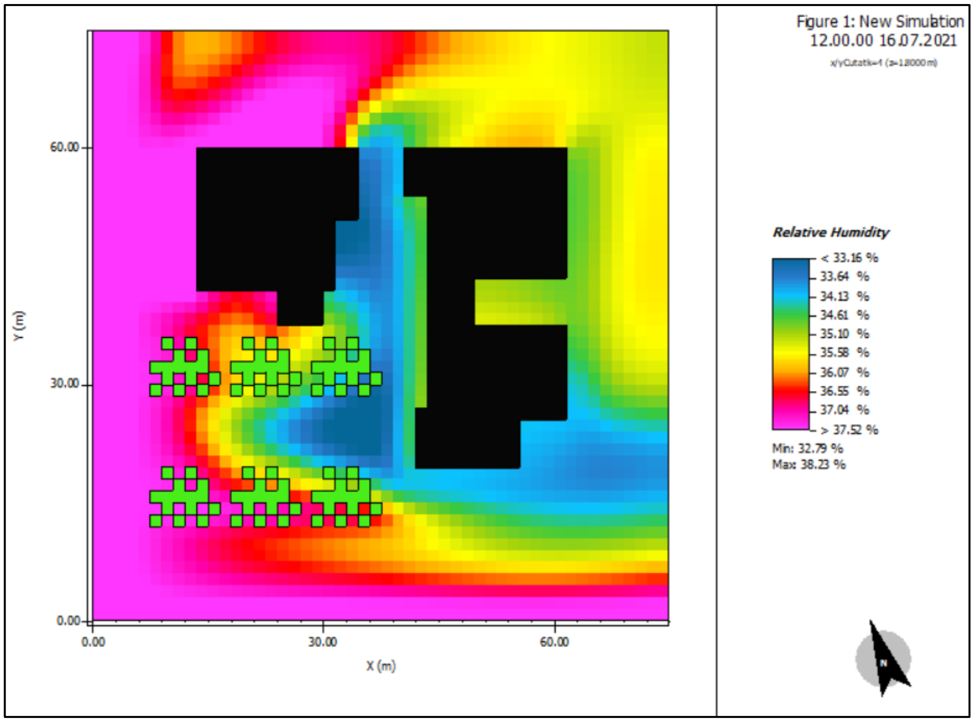

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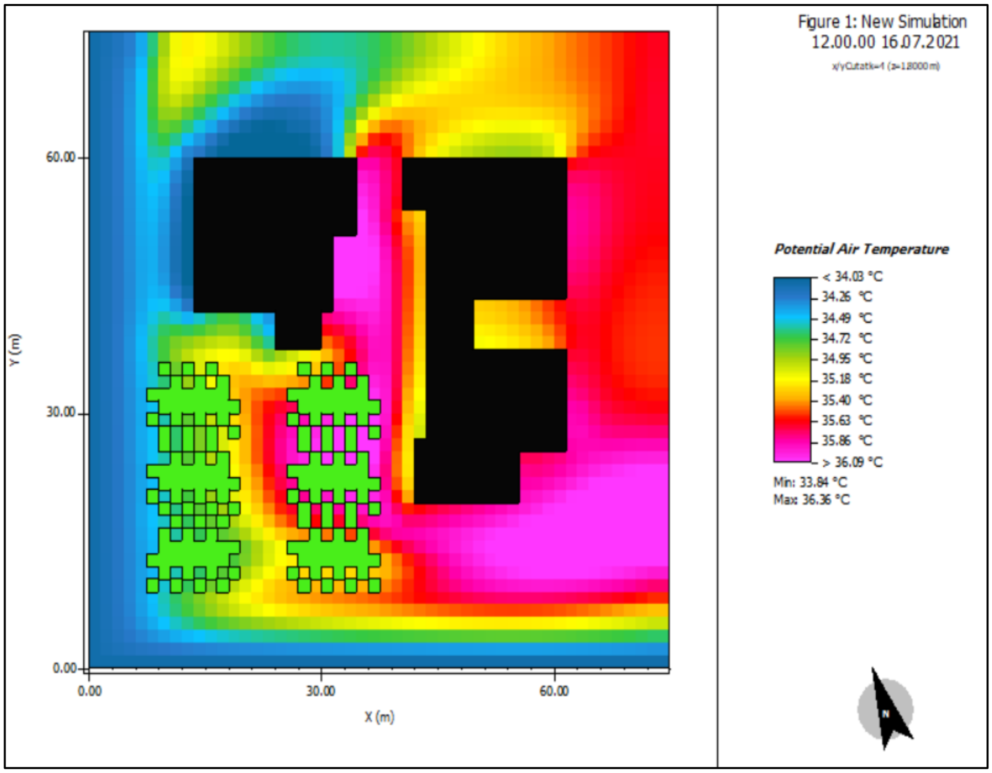

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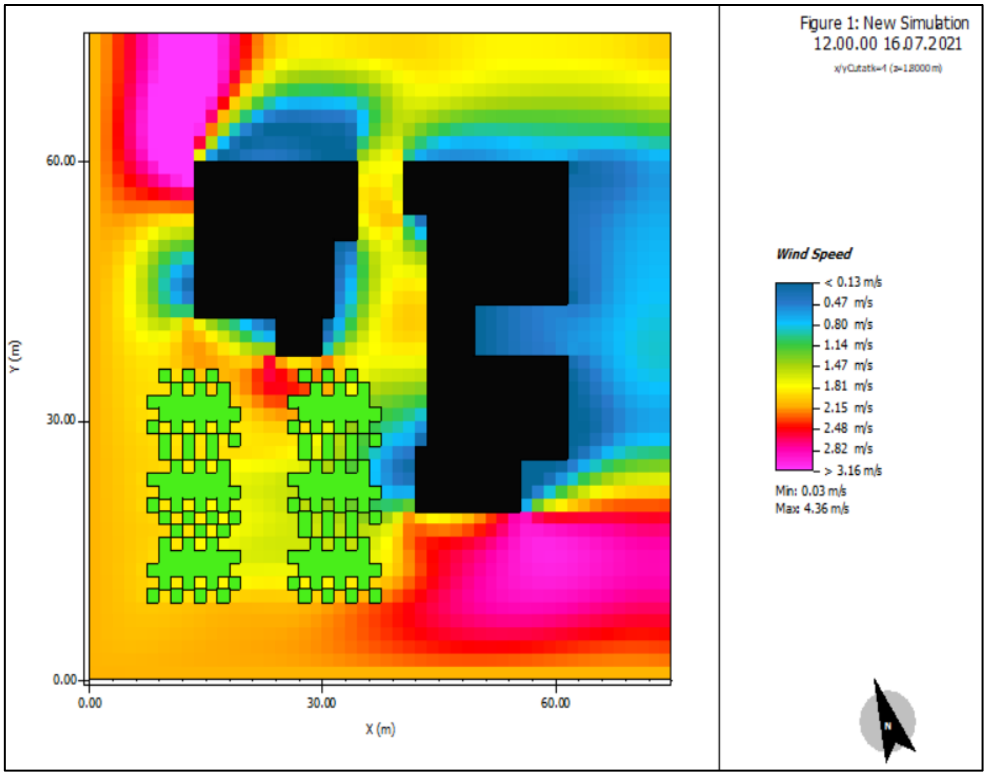

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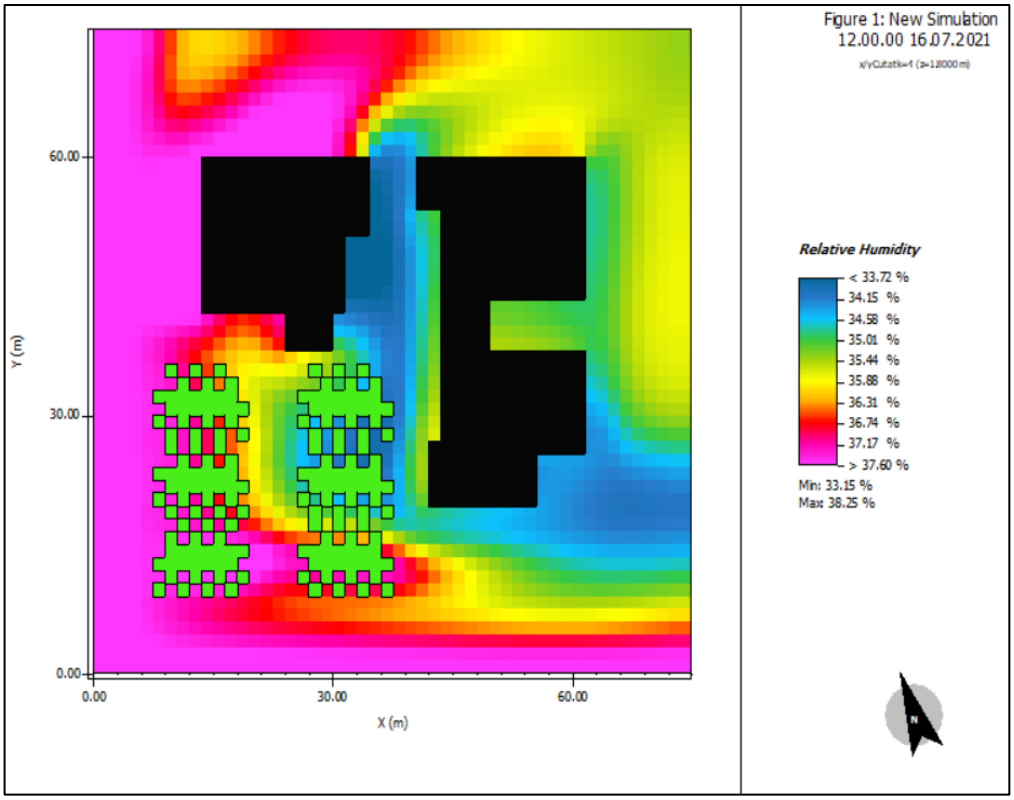
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12.00.00 16.07.2021
x/y Cut at k=4 (z=1.8000 m)
Relative Humidity
< 33.72 %
34.15 %
34.58 %
35.01 %
35.44 %
35.88 %
36.31 %
36.74 %
37.17 %
> 37.60 %
Min: 33.15 %
Max: 38.25 %
60.00
30.00
0.00
Y (m)
0.00
30.00
60.00
X (m)
N

Figure 5-63