Doctoral Thesis

Shibaura Institute of Technology

CLIMATE-LED URBAN LANDSCAPE PLANNING:

A SIMULATION DATA-DRIVEN ANALYTICS, DESIGN AND DECISION-MAKING PROCESS FOR IPOH, MALAYSIA.

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TEOH MEI YEE

Other than my beloved parent (Teoh Chai Hock and Lim Yen Chin)
and maternal grandfather (Lim Hoo Cheong),

this thesis is specially dedicated to …

My dearest late maternal grandmother
- Loo Kam Ying (1931- 5th April 2021) -

My most respected late paternal grandfather
- Teoh Lan Hup (1915 – 29th April 1993) –

and also,
My late paternal grandmother
- Kow Him (1924 - 2001) -

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Sadhu… Sadhu… Sadhu…

MeiYee Teoh
Tokyo, August 2021

ABSTRACT

Designing urban landscapes for climate change adaptation and mitigation has been highly promoted in contemporary urban development. However, the knowledge gap between urban design and climatology have often put the agenda into an impasse during implementation in practice. This research, therefore, aimed to develop a climatology data-driven design framework for landscape planning and design. This design-based research has formulated four objectives based on the design process: analysis, design, evaluation, and decision-making. The entire framework was laid on the basis of scenario modelling and simulation. In terms of thesis structure, there was a total of nine chapters in this study. It began with the Introduction, introducing prospects of urban landscapes in facilitating urban heat and climate change. This chapter also explored the issues and problems in integrating climate considerations into urban landscape planning and design, giving a practical motivation for this research. It was followed by the study goal and objectives, scope of study, site introduction, and structure of thesis. Chapter 2 was about a literature review on outdoor thermal comfort, covering the history and trend in thermal comfort studies, the thermal comfort implications between indoors and outdoors, and the parameters, indices, methods and tools used for thermal assessment. The last part of this chapter looked at the past thermal researches conducted in Malaysia to define the novelty and significance of the research. Chapter 3 was to develop an assessment framework to study outdoor thermal resilience and comfort in tropical regions. Taking a case study of Ipoh downtown, Malaysia, a model was built and simulated in ENVI-met and RayMan.

This research suggested integrating the GIS tool to evaluate and analyze thermal-spatial relationships. As a result, the integrated outcomes and insights became the guidelines during the planning and design phases. In Chapter 4, nine street greening prototypes were developed and screened based on green coverage ratios. The selected prototypes were then replicated into a pilot model for simulation testing. Two scenarios were created in this process: one focused on maximum greening, and another considered heritage visibility in the downtown. The latter scenario was selected after comparison in thermal performance and design integrity. Finally, the pilot model design concept was applied to the full-scale model in Chapter 5. In short, Chapter 5 was the resulting outcomes of previous chapters. Similarly, two scenarios were created based on different design considerations in practice. They were assessed and compared in terms of degrees of improvement in microclimate and thermal comfort. Both scenarios resulted in significant microclimate and thermal comfort improvement. In the process, the cooling magnitude was correlated with the green coverage ratio (GCR) and tree coverage ratio (TCR), enhancing greening significance in urban thermal improvement. Chapter 6 was the extension study of Chapter 5, focusing on sub-models thermal analysis at a micro-scale in order to determine zoning differences and their development priorities. Although most of the thermal sensation improvement was associated with vegetation, especially trees, the zoning comparison found that urban microclimate and thermal comfort performance actually also depend largely on the nature of site contexts. In this case, the main findings included:

- GCR / TCR was not definitely proportional to OACR (open area coverage ratio). However, a high OACR has adverse effects on thermal performance and reduced greening effectiveness.

- ΔGCR (also known as the degree of implementation) was always correlated to Δ measured parameter indexes (the degree of improvement). However, the correlation was not in a proportional relationship.
- The highest GCR did not definitely lead to the greatest improvement. The same/similar GCR/TCR would not definitely have proportional effects. Likewise, the same/similar effects could be achieved by using different GCR/TCR.

Chapter 7 explored the significance of buffer greening in urban cooling. It mainly investigated whether greening created at the buffer zone did have thermal effects on the core area of the study area. The result showed that both buffer greening and core greening were necessary in order to achieve the optimal degree of thermal improvement. Chapter 8 was the final discussion on the so-called climate-led design, a new concept proposed mainly for landscape redevelopment. This chapter mainly elaborated its ideas, framework, approaches, as well as its discrepancies and advantages compared to other similar concepts used in existing urban design and planning. Finally, the conclusion chapter ended with a summary, research significances and key lessons, study limitations, and suggestions for actual implementation and future studies. Overall, this research has demonstrated a complete roadmap and quick-start guide on how the thermal consideration to be integrated into urban design and planning from a design point of view. Such an approach has four significances. First, it acts more precisely in capturing the existing thermal condition of a particular model, identifying site problems and problematic locations, and deriving specific insights to improve such a situation. Second, the integrated scenario modelling and simulation can better explore the thermal effects in urban design, assist in testing hypothetical designs, and provide evidence-based explanations for any design decisions. Third, the loop evaluation is result-oriented, and this can minimize design failures in implementation. Lastly, the framework can be integrated with non-thermal objectives, such as pedestrian-oriented development, to enforce the landscape position in urban design. In conclusion, the climate-led approach is multi-dimensional, integrated and flexible in implementation. It is far-reaching, not only in urban thermal improvement but also in urban resilience and sustainability.

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CHAPTER 1
INTRODUCTION

1.1 BACKGROUND AND MOTIVATION

Urban landscape design and planning is one of the professions of urbanism that started in the 20th century. As a branch of landscape architecture, the discipline evolved from private domestic gardens to public spaces and expanded from neighbourhood to urban design today (Vroom, 2006:9). With the evolution of cities, urbanists have come up with different views on the nature and scope of landscape design and planning. The design concepts and ideas are constantly renewed by bringing new implications for urban landscapes in relation to contemporary urban issues and demands.

Taking the last century as the outset, the improved living standards and public health awareness biased the early urban landscape projects more to human recreational models (Pauleit et al., 2017), allowing people to unwind, leisure, and reconnect to nature in cities. Meanwhile, many planners treated landscape areas as remaining reserves to protect natural and cultural resources from being destroyed in urbanisation. This offsetting concept has created another mainstream in landscape discipline, focusing more on ecology, especially wildlife protection or biodiversity conservation (e.g., Leedy et al.,1978; Adams & Dove,1989; Adams, 1994; Rookwood,1995). Their new terminology was usually related to green. For example, 'greenbelt', a popular term officially used in the Greenbelt Act 1938 in the United Kingdom (the term originated from the garden city initiated by Ebenezer Howard in 1898). Another seminal example was the 'greenways', derived from Little (1995) 's book named "The Green Way in America". There are many other examples, such as 'green corridor', 'green lung', 'urban oasis', and so on.

Coming to the 21st century, the intensive move toward urbanisation and industrialisation resulted in a sharp rise in the urban population. The increased population density and industrial agglomeration have pushed cities to continue growing and expanding at an unprecedented pace. The massive urban sprawls and heavy vehicle use in and around the cities continue to exacerbate environmental degradation, accelerating the urban heat island phenomenon (Manley, 1958; Oke, 1973). Nowadays, urban warming accelerates human-induced climate change and gives rise to a series of hazards, including extreme weather like heat waves, natural disasters like wildfires, and the rapid sea-level rise. These kinds of climate-based hazards are not temporary or occasional anymore. The Intergovernmental Panel on Climate Change (IPCC) (2018) has proclaimed that "*Warming from anthropogenic emissions from the pre-industrial period to the present will persist for centuries to millennia and will continue to cause further long-term changes in the climate system"*. In view of the overwhelming threats and destruction caused by changing climate, more countries are now willing to take climate issues seriously at the global and national agenda to reduce the potential risks and losses. As of 2020, a total of 196 countries have signed the Paris Agreement of United Nations Framework Convention on Climate Change (UNFCCC), committed to reducing global warming by minimising greenhouse gas (GHG) emissions in their homeland (UNFCCC, 2015a &2015b).

Various schools of thought on climate change mitigation and adaptation have put forward diverse suggestions on green technologies, management practices, and consumer practices (Hendrickson et al., 2016). On the other hand, many climate change professionals believed climate change solutions rooted in the city itself, placing urban growth models in a decisive position to tackle global warming (Dodman, 2009; Rosenzweig et al., 2011; Balaban and Oliveira, 2013; Tapias & Schmitt, 2014; Carter et al., 2015; Mehaffy, 2019). Such a viewpoint is increasingly endorsed and mentioned by many contemporary urban scholars. For example, as mentioned in Corfee-Morlot et al. (2009, page 12):

"The fate of the Earth's climate and the vulnerability of human society to climate change are intrinsically linked to the way the cities develop over the coming decades and century."

In this context, new urbanism presented itself as the most permanent resolution to diminish GHG emissions. Such a concept continued to expand the notion of urban landscapes. Turner (1996) suggested viewing the city as a landscape: "the city of the future will be an infinite series of landscapes: psychological and physical, urban and rural, flowing apart and together. They will be mapped and planned for special purposes……" (Turner,1996: v). Different from being simply regarded as ornaments and allocated to left-over areas of the city (Steiner, 2011), the landscape in new urbanism has pertained to either position in the spatial planning and policies. The coverage includes but is not limited to promoting compact cities, green spaces and water bodies, and non-motorised public transports use.

The change thus gives impetus to another transformation of urban landscapes. In addition to the synergy between buildings, between man-made and nature, and between people, social-economy, and cultures, urban landscape and its green components now are also regarded as key measures for mitigating and adapting to climate change (Lenzholzer and Brown, 2013; Klemm et al., 2017; Pauleit et al., 2017; Yang et al., 2018). Their significance on urban thermal variations is primarily reflected in shading potential, thermal reflectivity, and ventilation characteristics (Lin et al., 2017). The natural components, especially the trees, can cold down the air by evapotranspiration and shade and impede the undesirable airflow by redirecting the wind direction (Lee et al.,2016; Gunawardena et al., 2017; Kong et al., 2017). Massive tree canopies can block a substantial amount of incoming short-wave radiation and intercept long-wave radiation into the atmosphere (Louafi et al., 2017; Zhao et al., 2018).

With the rise of new urbanism that focuses on pedestrian-oriented development, a higher standard has also been put forward on the quality of urban landscapes. Human thermal comfort is increasingly being considered when designing urban outdoor environments because it could affect walkability and other human-powered mobility, i.e., biking (Rakha, 2015; Zhen et al., 2020). A more thermally comfortable walking environment is generally expected to promote walking in cities as a daily urban travel mode. From a sustainable perspective, the revival of pedestrian communities would change urban mobility from auto-dependency to walking, biking, and transit, reducing the reliance on cars. In other words, it is expected that urban landscapes can help to inhibit the car-led growth in the cities, alleviating the in-town automobile emissions into the urban atmosphere (Mehaffy, 2019). Other than that, a thermally comfortable outdoor environment can strengthen the initial intention of urban landscapes in providing people with amenities for recreation, exercise, socialisation and relaxation. An increasing willingness to walk and participate in outdoor activities is also conducive to urban development. It can increase the pedestrian flow in the city, improve the service efficiency of public spaces, and ultimately bring positive returns to urban vitality and economic growth (Jacobs, 1961; Reiter & Herde, 2003; Litman, 2004; Nikolopoulou and Lykoudis, 2007; Lunecke & Mora, 2018; Zhang et al., 2020; Zhen et al., 2020).

All kinds of urban changes continue to shape and expand the scope and purpose of urban landscape development. From ecology to public health, socio-economy and tourism, it showed that climate change and the subsequent new urban concepts, such as new urbanism, drive urban landscape design and planning to more convincing prospects. At the same time, its scope becomes more multifaceted and intertwined with other professional fields. For example, as shown in Figure 1.1, we could find that at least two-thirds of the actions initiated by the United Nations to cope with climate change mitigation and adaptation involve urban landscape design and planning directly and indirectly. Other than providing nature, it strengthened the position of urban landscapes in changing cities to be more people-centred, green and resilient.

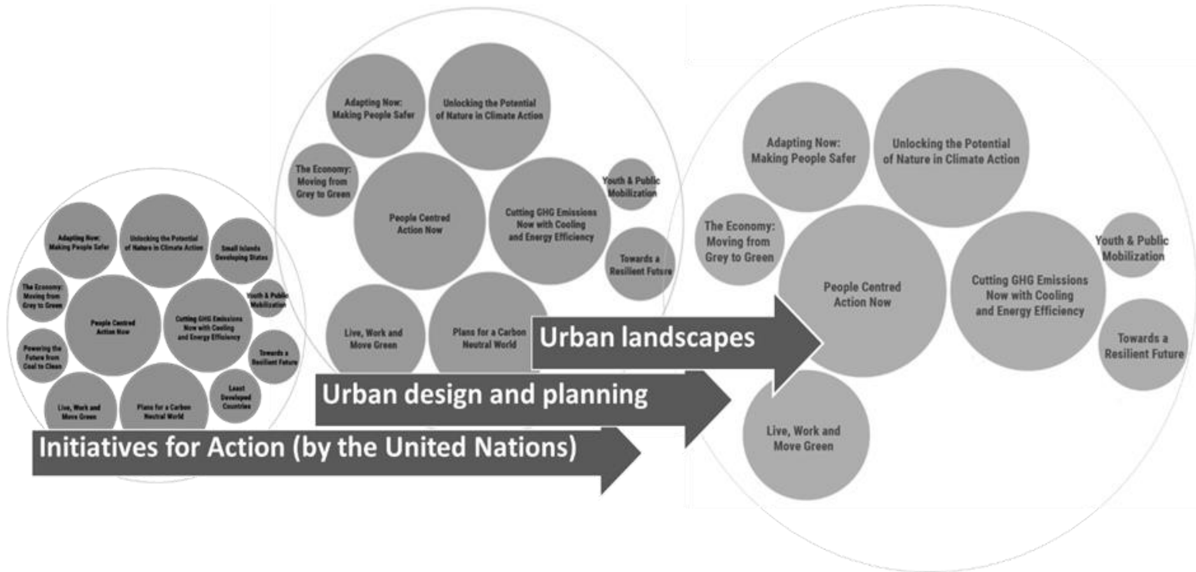


Fig.1.1. The position of urban landscapes in climate action.

In principle, taking climate actions and thermal comfort considerations into landscape planning will undoubtedly optimise the efficiency of landscape functions in the modern urban system. Therefore, it is the turn to talk about the execution. The proposition for climate-based landscape planning is relatively new and complex in city planning. In addition, the climate-based landscape is not a standalone concept in design and planning but a latent and auxiliary idea embodied in contemporary landscape plans. This idea made it different from other tangible approaches that typically have a clear subject user or target (e.g., human, wildlife, heritage, and pollution) to deal with. Hence, how to mastermind climate-based landscape design and planning in a systematic and integrated modus operandi become the primary motivation of this study. The related issues, the position of research, and the tasks to be carried out in this dissertation, are discussed further in the following sections.

1.2 PROBLEM STATEMENT AND EXPECTATIONS

Multiple measures have been carried out regarding the trend of climate change. In this regard, some countries have started to mandate landscape and urban design to deal with the adverse impacts of climate change. Their initiative, as expected, had been presented in some national landscape policies or strategies, i.e., the Malaysia National Landscape Policy (NLD, 2011), the Hungarian National Landscape Strategy 2017-2026 (HMA, 2017), and National Landscape Strategy for Ireland 2015 – 2025 (DAHG, 2015). In these cases, urban landscapes have been "politically" expected to play a role in climate change mitigation and adaptation plan, consolidating with other economic, social and environmental development goals. However, despite an increasing consensus on promoting landscape or urban design approaches for climate change improvements, in most cases, there is no effective spatial countermeasure against climate change, nor any concrete plans to incorporate climate considerations into any local landscape development. The weak execution was unexpected and disappointing.

In view that urban landscape can offer a solution for urban microclimate improvement and achieve the ultimate goal of sustainable development (Reiter & Herde, 2003; Nikolopoulou and Lykoudis, 2007), it is necessary to understand the key barriers in the current modus operandi. Therefore, in this section, it discussed several issues and challenges in implementing landscape-based climate change measures. They are respectively elaborated and analysed, as followed:

a) The rookie's attitude and the weak bond between climatology and planning

"Urban climatology in city planning is in its infancy" - this is a common but wrong assumption in the field of urban planning (Herbert, 2014). Based on the history review of Herbert (2014), many efforts had been made in applying urban climatology into city planning over the last century. Several long-established organisations are authoritative in the promotion of climate-aware concepts in urban planning, such as the International Meteorological Organization (WMO - active since 1951, the relaunch of the World Meteorological Organization founded in 1873) and the International Association for Urban Climate (ICUC - active since 1989). So why are climate-aware designs still not a prevalent practice in current city planning? It is a fact that most previous efforts had limited impacts on local practices. Several scholars had explained this impasse by adopting the viewpoint of Chandler (1976), claiming there is a "*weak communication link that presently exists between climatology and planning*" (Eliasson, 2000; Herbert, 2014).

For more than half a century, climatology has been long accounted for meteorological purposes, working most on weather forecasting and disaster warning. The neglect of climatology in urban spatial planning has led to a scarcity of understanding and competence in handling a climate-aware urban design and planning today (Wamsler et al., 2013; Zölch et al., 2016). In most cases, the so-called climate-responsive landscape design looked dubious, and the process was haphazard. According to Zhao et al. (2018), it lacked climate-based justification in allocation or arrangement. The worst was that many planners have mistakenly or simply regarded it as just a matter of adding more trees to the cities. The absence of climatology underpinnings made the landscape-led climate change agenda being questioned, relegated and easily overridden by other political, social and economic decisions. This situation has formed a vicious circle: the low acceptance in practices continued to reduce the motivations to study climatology from a city planning perspective; and in turn, the incomprehension on climatology reduced the willingness and confidence of urban decision-makers to kick-off in practices, eliminating the climate-based proposal in the decision-making process. To enable the connection between climatology and planning, the driving force must be bilateral.

It is similar happening to the landscape-led approach in urban planning for climate change mitigation and adaptation. Based on an advocacy statement of AILA (Australian Institute of Landscape Architects) in 2017, they claimed that: (i) there is "inadequate awareness and acceptance of the role and importance of the landscape as living infrastructure for adaption and resilience"; and (ii) the "existing sustainability rating tools do not include landscape elements in the assessment of design and development proposals." (AILA, 2017). In Malaysia, the National Policy in Climate Change has been enacted to "ensure climate-resilience development to fulfil national aspirations for sustainability", which included "the incorporation of climate change considerations in implementation of development programs at all level" (MNREM, 2009). However, it is ironic that several keywords related to climate-aware physical planning, such as "spatial", "landscape", or "greening", are not mentioned at all in the principles and action plan of the policy. In the domain of climate change adaptation and resilience, the low appreciation of landscapes at the national and local levels would continue to deepen the gap between climatology and landscape planning.

To play an influential role in mitigation and adaptation plans, the existing fragmented landscapes on the left-over plots must be assessed, improved and integrated as a whole from a climatology perspective. Again, the efforts, as well as the driving force, are always bilateral.

First, decision-makers should remove the doubts on landscape-led urban design and kick off the climate-based landscape planning system at the national and local levels. On the other hand, urban planners and designers should upscale the landscape capacities in combating climate issues. The second part requires a reliable planning framework to integrate climate considerations into the local landscape design. Urban planners and designers must strengthen their capabilities by conducting intensive climate-related research and justification during the design and planning phase.

b) **The gap in scholar-practitioner's perspective: lack of alternation between urban climate theory and practice**

Climate-responsive design is a knowledge-to-action process, which requires communication between experts, researchers and practitioners to span their knowledge and perspective in response to the complex challenges in climate change (Rosenzweig et al., 2011). However, the theory-practice exchange is relatively low in urban design and planning compared to other climate-aware disciplines in the urban context, such as building energy and green architecture. In Taylor & Hurley (2016), they highlighted that many urban policies, assumptions and decisions did not have solid research evidence as a basis. Their simple headline, "not many people have read these things", had clearly outlined the reality of urban research in planning practice, disclosing the gulf between urban scholars and practitioners.

Sharing a joint climate change goal between scholars and professional planners is apparently not enough. In Goodman et al. (2017), it pointed out that academics usually were somewhat optimistic and "unaware or insensitive to the realities of working life in the planning profession". This implied that there was a growing irrelevance between research works and urban design and planning. The viewpoint has some parallels to Durning (2004) and Hurley et al. (2017), which mentioned that many academic studies did not reflect the "local context-specific needs of practice". Furthermore, the overuse of academic jargon and obscure language in academic papers has widened the communication gap between the academic and professional groups (Goodman et al., 2017; Hurley et al., 2017). In some cases, the esoteric scholarly findings are also another barrier for some practitioners in professional practices, just as illustrated by Ng (2012):

"Overly detailed and precise meteorological information, and excessively sophisticated climatic explanations and knowledge presentation do not help planners; information overload makes planners feel discouraged and ill-equipped."

At present, the subject of urban microclimate has been increasingly explored piecemeal under all sorts of academic interests, but most only focused on analysis and assessment. The studied topics included urban heat island effects (e.g. Oke, 1976; Giridharan et al., 2005; Li et al., 2011; Shahmohamadi et al., 2011; Rajagopalan et al., 2014; Sachindra et al., 2016); microclimate effects of urban canyon and geometry (e.g. Bärring et al., 1985; Eliasson, 1996; Sakakibara, 1996; Andreou, 2013; Unger, 2004; Ali-Toudert & Mayer, 2006; Johansson, 2006; Krüger et al., 2011; Chen et al., 2012; Klemm et al., 2015); vegetation effects in urban microclimate (e.g. Wong & Yu, 2005; Bowler et al., 2010; Oliveira et al., 2011; Susca et al., 2011; Shishegar, 2014; Kong et al., 2014; Zupancic at al., 2015; Lee & Mayer, 2018). These studies were also conducted in fragmentation: in the park, square or courtyard, inside a particular institution, or on the street. They did have high scholarly significance, but from an urban planning perspective, they also need professional insights and methods to expand their horizons for practical needs. In short, being in a practice-oriented field, it is essential to note that research should be a complementary response to the limitations of existing urban planning models. A higher consensus between the practitioners and researchers is necessary.

Regarding this, Hurley et al. (2016) redefined the interface of research with urban policy and practice by suggesting that "the issue of how research knowledge and evidence is used is more critical to effective knowledge transfer". In other words, it suggested a shift of research paradigm from an academic or laboratory setting to a professional setting, reconnecting the research field with professional practices. This innovation will be a new pioneering role for current urban planning researchers working on urban climate, in accordance with the advocation of Herbert (2014):

> *" The science of urban climatology should not only be pursued intellectually but applied in the practice of city planning 'to mitigate or eliminate the undesirable climatic modifications brought about by urbanisation' - Landsberg (1981, p. 255)."*

c) **The capacity deficit and technical challenges in implementation**

Given that the complex cities-climate nexus is built on the basis of physical science and beyond the existing knowledge and abilities of urban practitioners, it is important to take initiatives to figure out the "stuck point" and strengthen the existing planning capabilities and mechanisms in practices. Several constraints have been identified, as follows:

- <u>The lack of design analysis and decision support tools and methods:</u> Most designers or planners usually do not understand the climate information, make them failed to determine what kind of design is most effective for a particular urban setting (Bowler et al., 2010; Zölch et al., 2016). It is necessary to seek professional but simple tools and means to help urban professionals digest climate information or data and translate it into design and planning, and vice versa. In addition, Srivanit & Hokao (2013) and Sun et al. (2017) also explained that the application of relevant tools could provide convincing evidence to support implementation at the local level, such as the extent of heat stress reduction in those proposals (Lee & Mayer, 2018).

- The complexity and friendliness of current modelling tools: the Organization for Economic Co-operation and Development (OECD) (2011) has first called attention to the disconnection between the expert-led model makers and non-expert model users. With the aid of advanced computational tools, there have been many efforts to develop modelling and simulation techniques for climatology study purposes. They mainly were designed based on the theory of computational fluid dynamics (CFD) and remote sensing, used to generate virtual climate performance for visualisation, analysis and prediction. The use of modelling and simulations tools so far most remain in the academic domains as they are too complicated for non-scientists, in this case, the urban designers and planners (Jusuf et al., 2012).

- The integration and interconnection of climate objectives in overall city planning: Urban climate is always expressed in multi-dimension, which can be individually modelled and assessed in fragments according to the fields of interests, such as thermal comfort, wind, heat energy, etc. The unintegrated assessment could not comprehensively explain the interconnection or interdependencies of urban components with urban climate (Mauree et al., 2019). At the same time, urban design and planning are never built on a single aspect. As mentioned in Section 1.1, the climate consideration in urban planning should always be compatible with other physical, economic and social objectives within the same geographical context. Urban landscape areas should play multiple roles in the city, including but not limited to recreational amenities, tourist attractions, social-economic development, etc. (Steiner, 2011). While targeting to make the urban landscape an effective option to mitigate and adapt to urban heat stress and climate change, how to balance it with other objectives is another challenge under this topic.

It is a fact that most current urban professionals so far do have insufficient substantive knowledge and skills in combating climate impacts. Generally, most constraints were originated from technical gaps. Therefore, the technical underpinnings and supports (in the forms of tools and methods) occupy a core position to integrate climate considerations into urban design development programs. To bridge the gap, it suggested strengthening the climate-based insights and planning capabilities of urban planners by leveraging more systematic computer-based methods in the design process. Meanwhile, an integrated, simpler and clear operational framework should be formulated to minimise technical issues within the process.

In summary, this section clearly illustrated the impasse of climatology in urban design and planning. Several key initiatives were recommended to break the impasse in practices, depending on the acceptance in decision-making chains, the knowledge transfer, and the improvement of frontline capacities. Applied climatology should be advocated at every scale of urban development. The position of urban design and planning in addressing climate change should also be reinforced at all levels of the decision-making chain. Besides, the efficiency of urban design and urban landscape response to climate change will finally depend on the level of knowledge and competence throughout the chain of planning and decision making. Regarding this, Abd Elrahman & Asaad (2020) has expressed a vital thought on urban design, that is:

"Questioning the capacity of urban design to control the built environment is a two-sided issue; first, it might acknowledge the necessity for a pluralistic approach in shaping the city due to the need of multidisciplinary partnership; or doubting the applicability of future urban design proposals extending the doubts to the discipline itself."

In summary, prior to the design and planning, it is necessary:

- to understand the urban-climate nexus from both climatology and city planning perspectives;
- to establish an interdisciplinary theoretical framework for implementation.
- to explore more relevant tools and methods to overcome the technical gaps.

1.3 RESEARCH GOAL AND OBJECTIVES

In response to climate change adaptation and mitigation, the study aims to develop a climatology data-driven design framework in the field of landscape design and planning. It is expected to comprehensively cover the scope of works existing in the actual design and planning process: the analysis, design, evaluation and decision making. In other words, it is designed from an urban design perspective and is result-oriented. In most of the previous literature, it can be found that climate-related concepts or ideas are often referred to as 'climate-responsive', mostly related to traditional architecture in building design and highlighted the adaptation to the local climatic context. The term sounds relatively passive when applied to climate-based landscape design because landscapes instead have the initiative to dictate urban microclimate conditions, less to be placed in the passive position like buildings.

Besides, other than decoding climate information for urban design and planning, the study associates with the concept of new urbanism, linking landscapes to the blueprint of pedestrian-oriented development. In this case, it works beyond the creation of landscape cooling, not only responding to the local climate. The scope of works is extended to develop a systematic and thermally comfortable pedestrian network in the study area to promote walking activities, thereby reducing local dependence on cars and restoring the vitality of downtown. Therefore, this research suggested using "climate-led" for climate-based landscape designs instead of "climate-responsive". The term "climate-led" implies an active response to climate-related issues as well as an initiative in design and planning that is oriented with climate-based knowledge.

The climate-led approach seeks a relative balance between theoretical knowledge and practical knowledge. Combining the considerations of both academic research and professional research, there are four objectives designed to achieve the study goal, as shown in the following:

a) Analysis: To formulate the roadmap of thermal analytic in the current site analysis process, based on modelling and simulation;
b) Design: To evaluate and convert the thermal findings into integrated urban design recommendations;
c) Evaluation: To examine and analyse the experimental design plans through scenario testing;

d) Decision making: To assist and support landscape development, such as priority of development, procedures and guidelines

1.4 SCOPE OF STUDY

The research demonstrated a new area of inquiry for landscape design analysis by using modelling and simulation to investigate site performance in the aspect of climatology. Within a simulation study framework, the research developed a scenario modelling-based operational framework to assist design analysis and decision-making in tropical climate-led landscape planning. The case study method was adopted. As explained by Dargusch and Lacher (n.d.), researchers who used a case study can "bound the scope of climate change problems", which "can effectively capture this complexity (the problems) and better understand the associated challenges and opportunities". The study was conducted in Ipoh, Malaysia, aiming to develop a landscape-led climate change adaptation and mitigation plan at the local level.

According to the Malaysia National Policy in Climate Change (MNREM, 2009), climate change adaptation and mitigation measures should be incorporated into development plans. It should be balanced and harmonised with existing legislation, policies, and plans by considering public health, transportation, human settlement and livelihood, etc. Urban landscapes can be well-positioned to increase urban capacity in this context, but on the premise that the constitution factors and configuration must be sufficiently verified during the planning stage (Lee and Mayer, 2018; Sodoudi et al., 2018). Given that, there was a total of three main phases proposed for the entire study. The first stage was to demonstrate a quantitative evaluation of existing climate performance using modelling and simulation tools. Next, several scenario designs were proposed for the Ipoh landscape redevelopment plan to cope with the undesirable thermal conditions (based on the feedback obtained from the first stage). At this stage, some other design considerations were taken into account to comply with local tourism-based regeneration plans and heritage conservation (refer to Ipoh Special Area Plan 2020, p. 2- 4) (MBI, 2006). Lastly, all proposed design plans were tested, compared, and verified thermal performance through simulation again. With the support of computational tools, this approach enabled a loop analysis of design ideas and integrated thermal considerations with other non-thermal design concerns until a desirable design can be achieved (Figure 1.2).

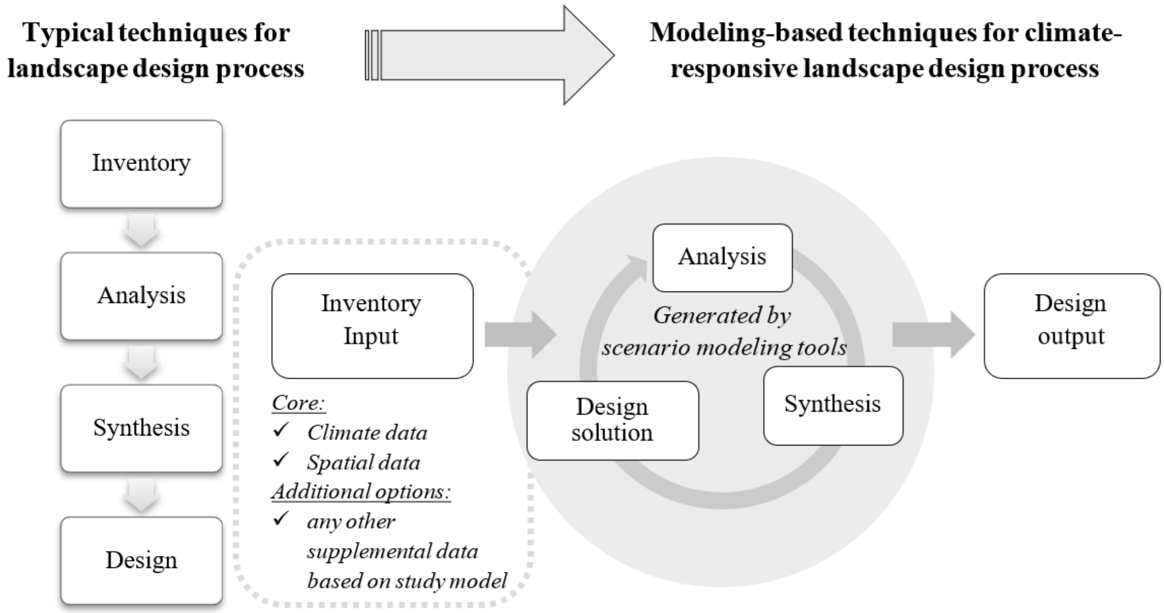


Fig.1.2. The schematic diagram demonstrated the use of scenario modelling and simulation in the landscape design process.

1.5 STUDY AREA: IPOH, MALAYSIA

1.5.1 Reasons of Study

Malaysia was selected in this study because the hot condition has created a high level of thermal discomfort for pedestrians (Thani et al., 2013), greatly reducing the willingness of people to walk or having outdoor activities during the day. This situation is detrimental to the implementation of pedestrian-oriented development for new urbanism and transit-oriented development (TOD) in Malaysian cities. In selecting the case study area, this study considered the applicability, compatibility and contribution of the study. Finally, Ipoh was selected, mainly because of:

a) Its high applicability.

Urban and town planning in Malaysia began during the British colonial period in the early last century. The rise of new towns at that time was typically related to socio-political and economic activities. It was mainly led by the British governance in the Straits Settlements (Penang, Malacca and Singapore) and the Federated Malay States (Perak, Selangor, Pahang and Negeri Sembilan). Many cities and towns in the Federated Malay States were built due to the discovery of tin mines, giving them the identity of tin towns. These colonial townships were similar in history, architecture and town planning.

As the central tin-mining hub as well as the second main British administration centre during the colonial period, Ipoh was planned more complex, comprehensive and inclusive than other tin towns. At present, most of these former mining townships remain active. More importantly, this kind of physical structure has also been adopted by post-colonial town planning and later modified in the current urban planning of Malaysia. In this case, as one of the most representative town models in Malaysia, studying Ipoh would be essential and practical to formulate a standard climate-led landscape planning indicator for most of Malaysia existing towns and cities.

b) Its high physical compatibility with the new urbanism concept and pedestrian-oriented development.

A historic urban context was preferred as the historic cities and towns usually have been built before the widespread adoption of automobile use. These existing mixed-use and walkable neighbourhoods are relatively more compatible with the new urbanism concept and pedestrian-oriented development. Regarding this, among the existing cities in present Malaysia, only the city centre of Malacca, Penang and Ipoh meet the conditions the most. Their overall layout is relatively well-preserved and less undermined by modern car-led settings. Among these three areas, Ipoh has an advantage over others: it is not restricted by UNESCO heritage preservation commitments, making it relatively more optimistic and flexible for redesign and planning.

c) The necessity of thermal and landscape improvement in Ipoh.

It has been acknowledged that the Malaysian government has closely looked at the prospects of landscape development in the nation in recent years. They ratified a Landscape National Policy in 2011, defining the landscape development not only as a "medium to address issues of global and microclimate change" but also "the nation's economic resource that contributes to the tourism section" (NLD, 2011).

At the local level, Ipoh downtown began to decline after the tin industry faded out in the 1980s. The decline was then accelerated by the emergence of new development zones in Ipoh. Since the 2010s, the historic downtown has finally regained recognition as a tourist destination full of colonial characteristics, traditional shophouses, and tin-mining heritages.

It has even been regarded as one of the most recommended destinations by Lonely Planet in the "Best in Travel 2017: top 10 regions".

However, there are several issues to be solved to achieve long-term positive growth in Ipoh downtown. First, the growing number of tourists and walking activities in the town have led to an increasing conflict between pedestrians and traffic today. It is mainly because most current sidewalks are small, disconnected and cannot accommodate the increasing number of visitors. Second, the lack of public open space for social, economic, and cultural activities at the street level has limited the development potential in the tourism sector. In this situation, a landscape-led strategy would be appropriated to create a new appearance for Ipoh downtown, by not only upgrading the pedestrian amenities for tourism development but also improving the local microclimate and thermal comfort. Such an approach is recommended for the redevelopment of Ipoh downtown.

d) Other aspects.

I also considered the study feasibility based on (i) the urban scale, context, background and history; (ii) the access to the local climate and planning data; (iii) the communication with the local authority; (iv) the accessibility to the city. More importantly, the rich physical characteristics of the site.

1.5.2 Site Inventory and Preliminary Analysis

Ipoh (4.5975° N, 101.0901° E) is the capital city of Perak state with a population of over 434,000 (Department of Statistics Malaysia, 2010). It is a valley city located on the western coast of Peninsular Malaysia (Figure 1.3). It grew from a Malay village in the 1870s to a tin-mining centre that thrived until the 1980s. There are several nicknames for Ipoh, most derived from the booming tin mining activities in the 20th century. For example, the Town Built on Tin and the City of Millionaires. In the past, the locals would rather call Ipoh Paloh (坝罗). The old name is closely related to the tin ore extraction in the old times in which "坝罗" referred to the transliteration from "Palong". Palong, where the tin ore was saved, was the most important structure in the tin mines using the gravel pump method (Yap, 2006). Other than that, Ipoh is also commonly known as the Hill City, mainly refer to the majestic spectacle of the mountain range, limestone hills and caves around Ipoh.

Fig. 1.3. The location of Ipoh in Malaysia (Source from: https://en.wikipedia.org/wiki/Ipoh, accessed 9 October 2020)

Located in the equatorial region, Ipoh has a distinctive tropical climate featured by high temperature, abundant rainfall and heavy precipitation throughout the year. Ipoh's climate showed little variations, subject to an average of 26 - 27 °C in mean temperature, 75 – 85% in mean relative humidity, and mean surface wind speed in 1.5 to 1.8 m/s, except for January and August (Malaysian Meteorological Department, 2018). January had the lowest mean temperature at 25.7 °C and the highest mean relative humidity at 86.2%. In contrast, August had the highest mean temperature at 28.2 °C and the lowest mean relative humidity at 71.2%. The mean annual trend of climate was summarised in Table 1. According to Ibrahim et al. (2012 & 2017), the warming trend in Ipoh was detected throughout 1970 - 2010 due to the substantial increase in population and the expansion of industrial and commercial areas.

Table 1.1 The mean annual trends of air temperature, relative humidity, and wind speed of Ipoh in 2018 (Source from: Malaysian Meteorology Department, 2018)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Mean Temperature (◦C)	25.7	27.3	27.4	27.6	27.3	27.9	27.7	28.2	26.8	26.6	27.1	26.6
Average Relative Humidity (%)	86.2	75.4	78.8	82.3	84.7	76.9	76.3	71.2	80.8	84.5	82.7	84.1
Average Surface Wind Speed (m/s)	0.4	0.5	0.5	0.5	0.4	0.4	0.5	0.5	0.5	0.5	0.4	0.4

Ipoh acted as the second administration centre after Kuala Lumpur, indicating its importance during the British rule in Malaya. Ipoh was once destroyed by The Great Fire of Ipoh in 1892, and then was rebuilt by the colonist in the form we see today, mainly to accommodate the arrival of thousands of Chinese miners at that time (Tam, 2012). During the colonial period in the early last century, the British had enormously integrated their town planning ideas and practices into the towns they created in British Malaya (Harun and Jalil, 2014). As one of the key cities developed during the British occupation, Ipoh has strong colonial characteristics in terms of urban morphology and building architecture style. It is rearranged in a way similar to other British colonial cities like Singapore, in a more orderly grid pattern by "straightened the road network, redrew the land boundaries and issued new title deeds" (Tate and Chai, 1962, p. 13,18).

Ipoh downtown was separated by the Kinta River and divided into Old Town and New Town (Figure 1.4). Today, the bold quarters were still active, and the local authority regards them as the core zone of Ipoh Special Area for heritage conservation. Both areas are mainly occupied by blocks of traditional shophouses, but they are slightly different in details in terms of usage, layout, orientation and size. These shophouses combined residential and commercial uses in the past, allowing people to reside on the upper floors while the ground floor remained for business activities (Wagner, 2017).

Fig. 1.4. The Ipoh centre layout (adapted from: Google Earth, accessed 9th July 2019).

Old Town is the oldest part of Ipoh, where the British colonial government started the rule of Perak around 1877. The layout context is quite diverse, which included public transportation hubs like bus terminal and railway station, governmental institutions like the town hall and courthouse, some public facilities like schools and *padang* (a common open space used for public events and sports in Malaysia), and the clusters of shophouses. In Old Town, shophouses were clustered into blocks with various forms and sizes, and separated by streets. The streets have different widths and lengths to serve multiple functions. Each block presented unique typological characteristics by the size and orientation of buildings. Some alleys are intertwining inside these clustered blocks in forms similar to a straight line, 'T' or 'H' pattern (Figure 1.5).

The booming of mining towns had driven the New Town development from 1905 to 1914, and the development continued throughout the 1920s and 1930s following the city's expansion (Myheritage Technovation Sdn Bhd, 2009). It is mainly occupied by shophouses, with a few public amenities, such as markets and theatres, to fulfil the local demand at the old time. New Town's configuration is relatively simple but more standard compared to Old Town. The majority of the blocks encompassed two rows of shophouses uniformly lying in a linear direction, in either an East-West or North-South orientation (Figure 1.6). The building layout and size were uniform, with a wider straight service lane running in the middle of the block for vehicle access. The streets between the blocks are almost all the same in size and width. This kind of model has been continued into the current urban planning structure of Malaysia.

Fig. 1.5. The layout pattern of Ipoh Old Town (Source from: Google Earth , accessed 9 July 2019).

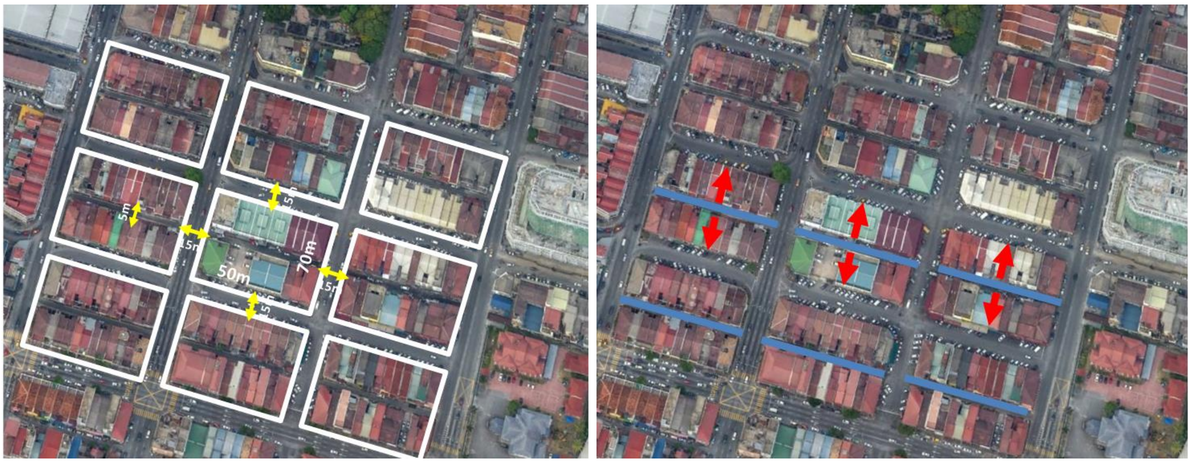


Fig. 1.6. The layout pattern of Ipoh New Town (Source from: Google Earth, accessed 9 July 2019).

1.6 STRUCTURE OF STUDY

This section explained the chapter organisation of this dissertation. It was mainly comprised of nine chapters and illustrated in the following diagram (Figure 1.7). The first chapter was the introduction of this research, followed by the literature review chapter (Chapter 2), the methodology including baseline model creation and assessment (Chapter 3), the climate-led pilot study (Chapter 4), the application of climate-led approach into full-scale landscape design and planning (Chapter 5), and two extension studies of climate-led landscape model in Chapters 6 and 7. Chapter 8 was about the discussions on the final framework representing the climate-led concept and approach, and its integration into the current urban design and planning context. The last chapter was the concluding chapter that summarised all the main findings and outcomes of the research. Each chapter had a particular theme designed for different objectives. At the same time, they were interrelated and organised in sequence. The composition mainly showed the diverse possibility of study objectives under the subject of climate-led urban landscape planning. It also shows that the climate-led approach can be applied in different stages of development in urban design and landscape planning.

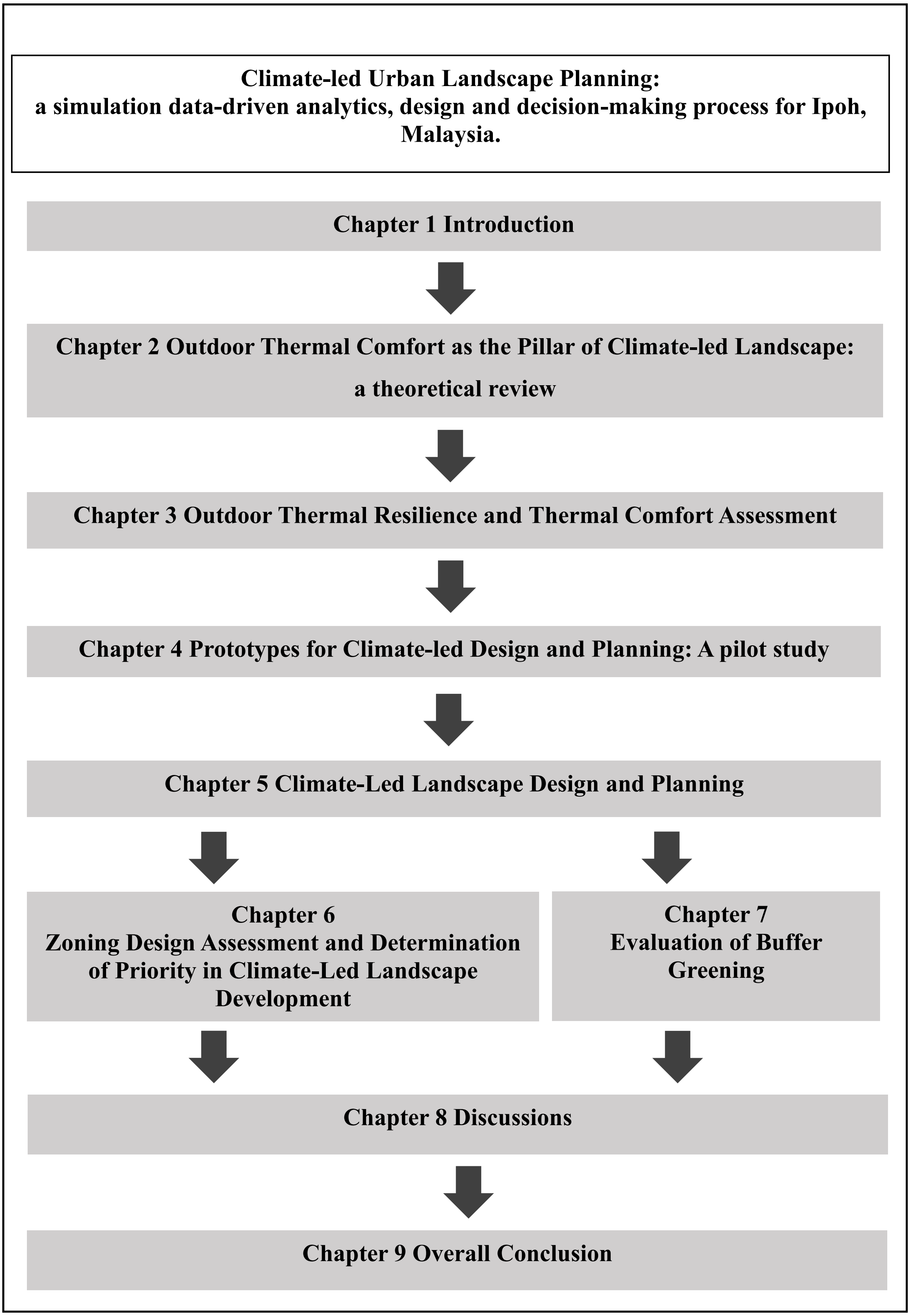


Fig. 1.7. The structure of the study

CHAPTER 2
OUTDOOR THERMAL COMFORT AS THE PILLAR IN CLIMATE-LED LANDSCAPE DESIGN AND PLANNING: A THEORETICAL REVIEW

2.1 INTRODUCTION

The urban microclimate is a complex subject involving different professions and disciplines; however, it is hard to be annotated without reference to its impacts on human thermal comfort. Thermal comfort is somehow an evaluation index for determining a comfortable environment. It is most commonly expressed as “a condition of mind which expresses satisfaction with the thermal environment”, as stated in ANSI/ASHRAE Standard 55 published by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE, 2004).

The growing urban warming and climate change have prompted thermal comfort to be studied under urban quality and sustainability. However, the piecemeal approaches and standards from various disciplines, coupled with their respective set of parameters, drive thermal comfort to be somehow elusive. This chapter, therefore, reviewed a series of relevant papers and discussed outdoor thermal comfort in a more holistic view.

The review started with the trend of thermal comfort studies, which explored the evolution of thermal comfort concepts. In this section, the discussion was mainly based on seminal scholar works in the field and their disciplines used to define human thermal comfort. Next, it was to differentiate the thermal comfort between indoors and outdoors, ranging from human-level control to time of exposure, physical and psychological perception, spatial efficiency, etc. After that, this chapter reviewed and summarised the parameters, indices, methods and tools used in environmental thermal research. Lastly, it was to find out the urban microclimate studies trend and topics that have been conducted in Malaysia in order to consolidate the novelty of this research.

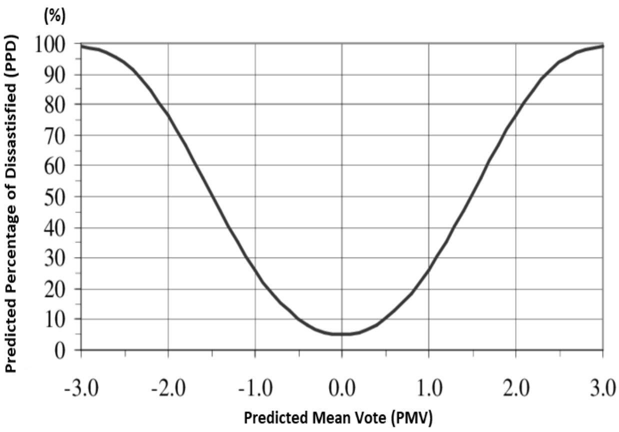
2.2 TRENDS IN THERMAL COMFORT STUDIES: EVOLUTION, SEMINAL SCHOLARS AND THEIR DISCIPLINES

The early idea of thermal comfort stemmed from the indoor context due to the growing demand for human health and comfort inside buildings (Shoorshtarian, 2015). It was developed with the rise of heating, ventilation, and air conditioning (HVAC) industry at the beginning of last century, which initially used to establish an acceptable (or comfortable) thermal range for occupants inside those mechanically conditioned spaces (Fabbri, 2015; Nicol & Roaf, 2017). With the aim to improve thermal comfort, there was intense interest in understanding the influence of the thermal environment on the human body since the early twentieth century. Particularly in the developed region like the United States and Europe, numerous indices and models have been developed to analyse thermal comfort.

Thermal comfort is generally assessed through three approaches (Höppe, 2002; Andreou, 2013): the heat balance of the human body, the thermo-physiological properties, and the psychological and behavioural factors. The heat balance model is the earliest approach used for investigating human thermal comfort. As the pioneer, Gagge & Bazett (1941) focused on the thermal state of the human body heat exchange with the environment. They proposed a "two-node model" that underlined the principles of thermodynamics in the thermal exchange of the human body and environment. Under this model, the heat loss to the environment was assumed to be equal to heat production in the human body. While recognising that there are many other variables in thermal comfort analysis, Gagge & Bazett (1941) claimed that "comfort is dependent largely upon skin temperature".

Regarding that, they identified three main factors to describe thermal exchange: the rate of heat production of the body (*met*), the insulating value of the clothing (*clo*) and the environmental temperature (^{o}F). In short, Gagge & Bazett (1941) studied thermal comfort from a pure physics viewpoint, viewed it as an outcome of heat and mass exchanges between a static man and physical environment. Other than establishing a practical system of units ("*clo*" and "*met*") for thermal comfort analysis, Gagge & Bazett (1941) has also provided a precedent case that applying the concept of thermodynamics to physiology, which became the foundation for the subsequent thermal comfort researches. Gagge and the latter scholars continued creating indices for thermal comfort assessment, e.g., Gagge et al. (1967); Gagge et al. (1972); and Gagge, Fobelets & Berglund (1986). The most common-used indices developed by Gagge's team is SET* (Gagge et al., 1972)

P.O. Fanger contributed another seminal work in the 1960s. He introduced a "rating scale of the perceived sense of wellbeing" (Fanger, 1967), which allow people to judge and express their sense of thermal comfort. From his works from 1967 to 1973 (Fanger 1967; Fanger, 1970 & Fanger, 1973), Fanger investigated the relationship between environmental parameters, the human physiological parameters, as well as the people thermal perception (in the form of scores and voted by the subjects on the ambient temperature condition) in the context of confined spaces (climatic chamber). By referring to four environmental parameters (air temperature, mean radiant temperature, air velocity, and relative humidity) and two human physiological parameters (metabolic rate and clothing insulation), Fanger proposed a new thermal sensation index, called Predicted Mean Vote (PMV). To allow people to access the acceptability of the condition of comfort, Fanger also developed Predicted Percentage of Dissatisfied (PPD) to enable an adverse judgment in the evaluation of an environment thermal condition (Figure 2.1).



PMV	Thermal perception	Grade of physiological Stress
−3	Very cold	Extreme cold stress
−2.5	Cold	Strong cold stress
−1.5	Cool	Moderate cold stress
−0.5	Slightly cool	Slight cold stress
0	Comfortable	No thermal stress
0.5	Slightly warm	Slight heat stress
1.5	Warm	Moderate heat stress
2.5	Hot	Strong heat stress
3	Very hot	Extreme heat stress

Fig. 2.1. Relationship between the predicted mean vote (PMV) and the percentage of dissatisfied (PPD).

Closed to the end of the last century, Mayer & Höppe (1987) proposed another thermal index and named it "physiological equivalent temperature" (PET) (Table 2.1). Considering the human thermo-physiological regulatory process, Mayer & Höppe used Munich Energy-balance Model for Individuals (MEMI) as the basis to calculate PET (Höppe, 1999). Based on Höppe (1999) and Matzarakis et al. (1999), PET functioned as a real climatic index. It evaluated the meteorological parameters (air temperature, mean radiant temperature, air velocity and vapour pressure) in a thermo-physiological weighted way that resulted in both thermal state and regulatory process of the human body. One of the significant PET features is that a more widely known unit (^{o}C) was adopted (Matzarakis et al., 1999). At the same time, PET's neutral sensation can be modified and adapted to more specific weather and human behaviour (clothing and activities), made it more applicable for diverse study contexts. In other words, the PET thermal scale can be varying from region to region throughout the year (Höppe, 1999; Lin et al., 2010).

Table 2.1. The categorisation of PET.

PET	Thermal perception	Grade of physiological Stress
<4	Very cold	Extreme cold stress
4–8	Cold	Strong cold stress
8–13	Cool	Moderate cold stress
13–18	Slightly cool	Slight cold stress
18–23	Comfortable	No thermal stress
23–29	Slightly warm	Slight heat stress
29–35	Warm	Moderate heat stress
35–41	Hot	Strong heat stress
>41	Very hot	Extreme heat stress

All models developed in the last century were so-called “steady-state models”, also known as traditional or conventional comfort theory (Baker & Standeven, 1996; Nikolopoulouet al., 2001). They are primarily experimental and conducted in a confined climate chamber with high control on the parameters. For example, the respondents were situated in a seated and quiet position to avoid any controversy about the metabolic effect during the experiment (Fanger, 1970). These steady-state models continued to be adopted as the contemporary universal standard for evaluating and prescribing thermal comfort in different contexts and climates, e.g., PMV and PET, with or without modification.

Despite that, some scientists started to ponder what criterion to add or change for the thermal comfort measurement when there was always some discrepancy between these theoretical models and the actual comfort condition (Brager & de Dear, 1998; Andeau 2013). They also tried to explain the gap in different aspects. In Brager & de Dear (1998), it was summarised as the technical limitation in models input, mainly due to: (a) the difference of clothing ensemble insulation values observed in the laboratory compared to in situ measurement; (b) the overestimation of thermal neutralities when neglecting thermal effect by some other thermal insulation factors during field study; (c) the low accuracy on estimating the people’s activity pattern with associated met levels by using least-developed standards; (d) the baffle happened during physical spot measurement, which might not reflect the actual thermal condition experienced by the occupants on-site; (e) the major model assumption based on steady-state condition, which is opposite to the dynamic thermal environment in reality; and (f) the influences caused by other non-thermal factors that are not covered in the models.

On the other hand, Brager and de Dear (1998) had also viewed the gap resulting from the thermal adaptation of occupants in our built environment. They re-examined the relationship between people and their thermal environment and challenged the heat-balance-based models derived from laboratory research, highlighting a 'real world' model setting. Different from Gagge & Bazett (1941) and Fanger (1970), Brager & de Dear (1998) acknowledged place as "a multi-variate phenomenon" and viewed people as "an active agent interacting with the person-environment system via multiple feedback loops". This principle drove them to look more at thermal perception and adaptation – a non-thermal extent linked to a person's experience and expectation. This new concept was beyond the physics of the human body heat balance. As the pioneer of thermal adaption studies, Brager & de Dear (1998) defined thermal adaptation based on three modes: physiological, behavioural adjustment of the body heat-balance, and psychological.

a. Physiological adaptation refers to all physiological responses to heat or cold stress. It can be divided into two subcategories: genetic alteration and physiological acclimatisation. Genetic alteration refers to the genetic heritage of particular individuals or tribes in the subject of genetics. As for physiological acclimatisation, it is more about how to maintain a reasonably constant deep body temperature that can be balanced with the environment (Fanger, 1973). This process involved the changes mediated by the autonomic nervous system in response to thermal environmental stressors, such as sweating and various cardiovascular responses in heart rate, blood pressure, etc.

b. Behavioural adjustment of the body heat balance refers to all conscious and unconscious corrective actions that people react to maintain thermal comfort. It is explained as active feedback of human physical response to the thermal environment through (i) personal adjustment, in which changing personal variables like clothing, position or drinking water; (ii) environmental adjustment, in which modifying the surrounding thermal condition, such as opening the window or turning on a fan; or (iii) cultural adjustment, such as adapting dress codes.

c. Psychological adaptation, also referred to as perceptual adaptation, is an extent to which individual habituation and expectation can directly affect the human thermal sensory and the associated physiological response. Most leading scholars in the 20th century, including Brager, de Dear and Nikolopolou, advocated that psychological adaptation is probably the most reasonable explanation to describe the divergence between model prediction and field observation (Brager & de Dear, 1998; Nikolopoulou et al. 2001; Nikolopoulou and Steemers, 2003; Nikolopoulou and Lykoudis, 2006; Lin & Matzarakis 2008; Lin 2009; Middel et al., 2016; Lucchese & Andreasi, 2017). This is because people might evaluate their environment based on a 'benchmark' created by their past and current thermal exposure. Such cognition and memory can be varied in different time scales and contextual factors (Brager & de Dear, 1998), and last form their thermal sensation and thermal acceptability. In other words, individual experience and expectation can alter thermal perception and response to an environment.

The above paragraphs gave a clear fundamental concept of thermal comfort and its disciplines. In the HVAC industry, digitising comfort into specific numeric index values was undoubtedly a direct and satisfying outcome in terms of applicability when the quantitative measures did have merits for the plant sizing calculation. Both objective and subjective thermal comfort are complementary rather than contradictory.

Coming to the 21st century, the growing awareness of urban warming and climate change have further shifted the subject of thermal comfort toward the mainstream of the adaptive comfort model (de Dear et al., 2013). Contrary to the initial purpose of creating thermal comfort, adaptive thermal comfort was established to reduce the high dependence on the mechanical-based cooling or heating system, promoting more passive energy strategies in building services. The change has extended the studies on thermal comfort from indoor to outdoor environment quality, making outdoor thermal comfort gradually become the dominant subject in contemporary thermal comfort research. The evolution of thermal comfort studies and the disciplines involved were summarised and illustrated in Figure 2.2, showing a clear trend shift of thermal comfort subjects from indoors to outdoors. Compared with indoors, the scope of research on outdoor thermal comfort is broader. In addition to studying the impact of the urban thermal environment on the human body, it also covers the physical, social and economic impacts on local communities and cities.

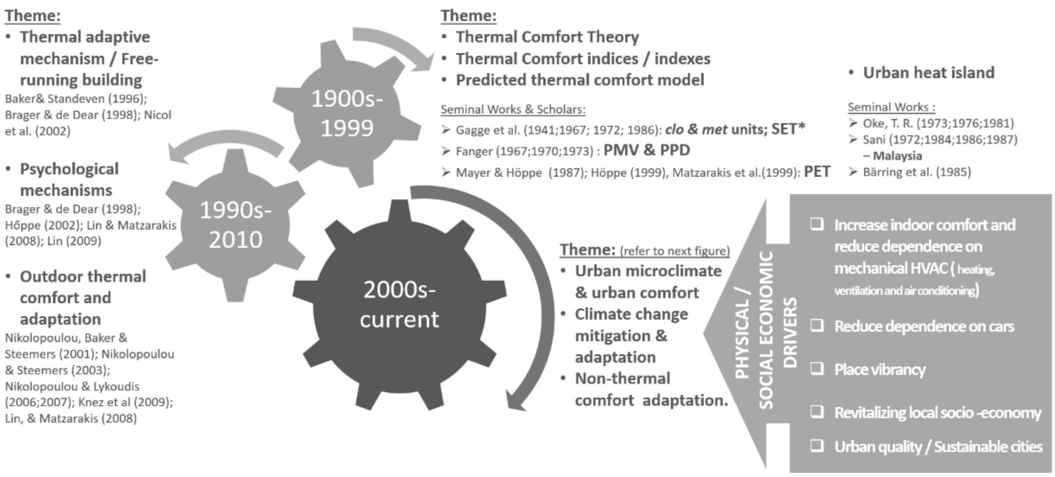


Fig. 2.2. The evolution of thermal comfort studies and the main disciplines.

Finally, as summarised in Figure 2.3, it can be seen that the exploration of the urban thermal environment in the 2000s has become more comprehensive, ranging from the environment itself to human physiology and psychological perceptions. In the scope of environmental aspects, the research trend was mainly placed on assessing the impacts of studied subjects on the local microclimate and thermal comfort. These environmental assessment-based research could be further divided into two major subjects: the study on urban structures and the study on landscapes and greenery. Nevertheless, it also found a small but growing trend of research on seeking urban design solutions to improve the urban thermal environment, sharing a common philosophy with this research. Although the design-based topic is also getting more and more attention with an increasing reference, it remains room for explorations in terms of approach, techniques and scopes. Particularly when connecting to a specific regional context, level of development or local policy, the outcomes may become significant and new, filling the gap of knowledge in the field.

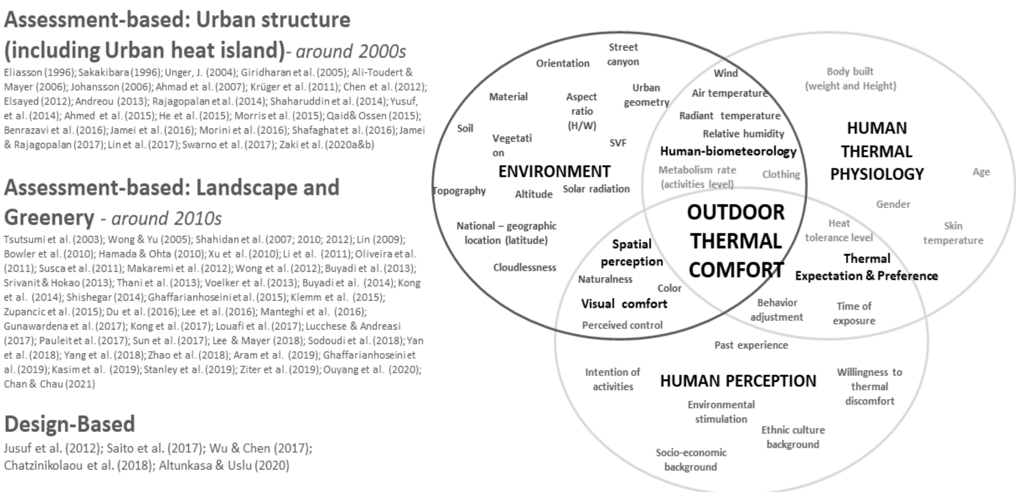


Fig. 2.3. The relevant themes and subjects of thermal comfort studies: a summary.

2.3 THE COMFORT DISCREPANCY IN BETWEEN INDOORS AND OUTDOORS

Studying outdoor thermal comfort is relatively more challenging. The outdoor thermal environment is always dynamic and more diverse than indoors in terms of climate, human's activities and clothing. However, they share the same indices, methods, and approaches in thermal comfort assessment: based on the heat balance of the human body, thermo-physiologically and psychologically (Nikolopoulou & Steemers, 2003). According to Chen & Ng (2012), the use of indoor comfort indices for outdoor thermal assessments laid on two principles: (i) simplifying the complex outdoor thermal conditions into simpler indoor thermal scenarios; and (ii) assuming thermal equilibrium or physiological equivalence is reached

However, in fact, people generally perceive outdoor comfort differently than indoor comfort, leading to a multi-dimensionally defined thermal comfort in indoor and outdoor environments, respectively (Nicol & Humphreys, 2002; Reiter & De Herde, 2003). The most apparent difference between indoors and outdoors is human-level control over the thermal environment. In contrast to the active manipulation of the thermal condition in buildings, people are more inclined to adjust themselves adapting to the outdoor climate through different behavioural adjustments or psychological adaptations (Höppe, 2002; Lin et al., 2010; Lin et al., 2011). The viewpoint was similar to what has been mentioned by Nikolopoulou et al. (2001): people have stronger thermal adaptability outside the buildings, which enables them to accept more diverse thermal circumstances at outdoors.

Another common factor that causes the difference between indoors and outdoors is about the times of exposure (Höppe 2002; Nikolopoulou & Steemers, 2003; Ali-Toudert & Mayer, 2006). People usually stay outdoors for a short time, often within a few minutes. It was not the same as the comparable long stay in a stable indoor thermal environment. Höppe (2002) indicated that short exposure to outdoor climate would be hard for the human body to reach thermal equilibrium. In this case, the use of underestimated exposure time in the steady-state thermal model may lead to deviations in assessing human actual thermal comfort level.

Besides, despite the fact that human senses play a vital role in both indoor and outdoor thermal sensation, human sensory reactions can be not the same due to the diverse ways of our sensory interfacing with the environment. In architecture or building sciences, our environment is typically evaluated separately using a single sense, namely thermal for tactile, visual for sight, acoustic for sound, and air quality. These physical parameters help architects and engineers' control and manage the indoor conditions to ensure a stable and comfortable environment for the building occupants. In contrast, human comfort in the outdoor context is somewhat a form of multisensory phenomenon (Boduch & Fincher, 2009), involving the range of time, places and seasons (Chappells & Shove, 2005; Nicol & Roaf, 2017). It was mainly evaluated through human interaction with the environment (Strang, 2005). Furthermore, the sensory interaction at outdoors can be beyond physical. For example, sight and hearing can be described in more depth and humanised. They are not only about luminance and sound frequency but also the psychological impacts of landscape images and sound on a human, which affects the individual's perception or feeling. The multisensory resulted in a subjective and changeable perception of outdoor comfort depending on individual experience (Reiter & De Herde, 2003).

Höppe (2002) also found that psychological expectancy and thermal history affect subjective outdoor thermal comfort. Personal outdoor memory and expectation could dominate thermal perception and create thermal preference. Under such a condition, even if the outdoor temperature conditions are beyond the range of physical comfort, personal motivation can still sustain the individual's willingness to stay outdoors (Lin et al., 2010; Lin et al., 2011). Taking an example, people are willing to do sunbathing on the beach during summertime in a temperate zone.

The perception difference, in turn, created a discrepancy in the interpretation of ideal thermal comfort between indoors and outdoors as well. Based on Fanger (1970), the ideal thermal comfort is that someone neither feels warm nor cool under a particular thermal condition, also known as thermal neutrality. This idea has been long accepted and used for indoor thermal studies. However, it is not difficult to find that people primarily seek thermal pleasure in outdoor environments, rather than thermal neutrality. In this case, it is more appropriate to regard the user's preferred thermal state as ideal comfort (Rupp, et al., 2015). The standard and range of ideal outdoor thermal comfort, thus, may be varied with site context and season.

Lastly, for spatial efficiency, indoor thermal comfort mainly affects the building energy efficiency, but outdoor comfort instead significantly impacts public space's service efficiency (Höppe 2002; Nikolopoulou & Steemers, 2003; Ali-Toudert & Mayer, 2006). In this context, it also implied a non-unidirectional link between outdoor thermal comfort, outdoor activities and the use of outdoor spaces. That is, the promotion of outdoor activities and the efficiency of public spaces always correlate to outdoor thermal comfort, but at the same time, the outdoor thermal comfort perception can also be altered based on the attributes of outdoor activities and public spaces. The differences in thermal comfort implications between the indoors and outdoors context were finally summarised in Table 2.2 and Figure 2.4.

Table 2.2. Comparisons of thermal comfort between indoors and outdoors context.

INDOOR	**vs**	**OUTDOOR**
Steady/Stable	**Context**	Dynamic
Started around the 1900s	**History**	Started around the 2000s
HVAC development: Spatial energy efficiency	**Intention**	Outdoor use and quality: Spatial service effectiveness
• Heat balance of human body • Thermo-physiological properties • Psychological and behaviour factors	**Theory/mechanism models**	Generally, refer to indoors
• Air temperature • Mean radiant temp. • Air velocity • Relatively humidity • Clothing • Metabolism (activities)	**Variable / Indicator used**	Generally, refer to indoors
• Physiological • Behavioural adjustment of the body heat-balance • Psychological	**Approaches of thermal sensation & adaptation**	Generally, refer to indoors
• Thermal neutrality; Comfort range	**Ideal**	Thermal Pleasure
• Single sensory	**Sensory experience** *(*refer to Figure 2.4)*	Multisensory

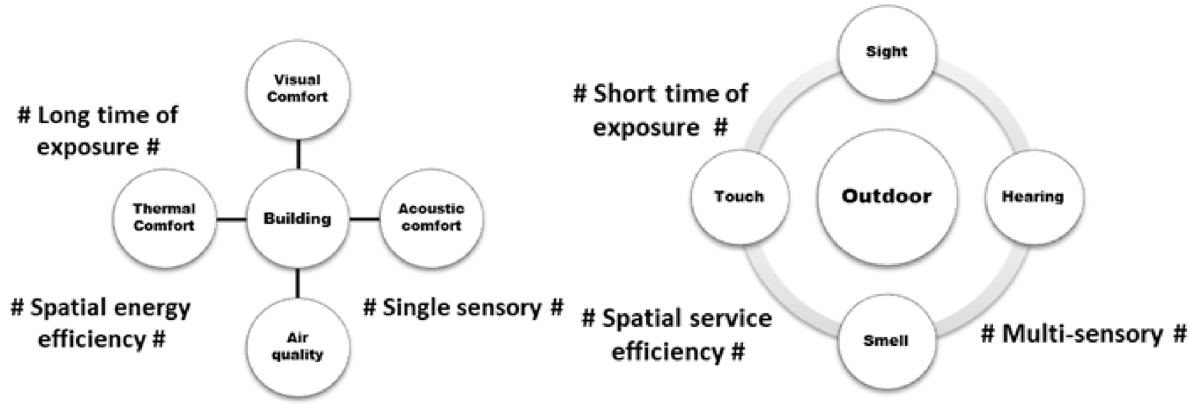


Fig. 2.4. The implication of thermal comfort between indoors and outdoors context.

2.4 THE PARAMETERS, INDICES, METHODS AND TOOLS INVOLVED

2.4.1 The Microclimate Parameters that Associated with Natural and Urban Factors

The urban thermal environment determines the outdoor comfort level of city users. It is usually classified by natural and urban factors and assessed in diverse scales and contexts of analysis ranging from macro to micro scale, from urban geometry to single landscape elements, etc. On a macro scale, the microclimate of a specific environment is dominated by climate and geographical parameters. The latitude determines the availability and distribution of solar energy generated by the incoming solar radiation, which would affect the atmosphere's thermodynamic and dynamic state, resulting in diverse radiation, temperature, humidity, wind speed, and pressure (density) on Earth (Rotac & Calanca, 2003).

The implications of land on regional climate variation are most manifested in elevation or altitude, topography, soil and vegetation. In IPCC 2019 special report, their effects on climate were mainly explained through their "biophysical and biogeochemical land forcing and feedbacks to the climate system" (Jia et al., 2019, p.133). Generally, as the altitude increases, the air pressure would drop relatively due to the decrease in gravity and air density. The air molecules become less dense and hold less heat, making the area colder than the lower altitudes. Topography refers to landforms such as mountains, plateaus, ridges, canyons, etc. These topographical features create convective processes and influence the moisture-bearing air distribution at the near-surface layer, giving distinct impacts on climate in terms of regional wind and precipitation. As for the soil and vegetation, they are the key factors that affect land moisture, surface emissions (e.g., carbon dioxide, methane and nitrous oxide) and surface albedo, which all have a decisive impact on evapotranspiration and sensible heat flux.

Within the Urban Canopy Layer, the atmospheric state is relatively described on a micro-scale. It is highly influenced by the local surface properties, most discussed in terms of land cover and land use (LCLU) (Jia et al., 2019, p.135). The local atmospheric condition, including air temperature, mean radiant temperature, relative humidity, and air velocity in the urban context, are strongly governed by land cover change (LCC). The LCC or land modification can be ranged from the minor modification of the landscape characters to a full land-cover type (or land use) conversion through anthropogenic or natural forces (Mölders, 2011).

Nowadays, rapid urbanisation has dramatically changed the albedo, roughness, thermal and hydrological characteristics of urban land surfaces by eliminating a huge amount of natural environment (Lin et al., 2017). The massive land conversion induced distinctive climate variation in urban areas, namely urban heat islands (UHI). Under this subject, there are more diverse and complex interactions between soil-vegetation-atmosphere. Their relationships are primarily reflected in ecosystem dynamics, biodiversity, carbon storage, emissions of trace gases and particles (pollutants), and energy cycles (Mölders, 2011). In urban thermal studies setting, the urban impacts are usually assessed using different descriptors and parameters.

For example, in the viewpoint of building and energy science, materials used for urban surfaces (including walls, roofs, and pavements) play a vital role in urban thermal balance. Urban surface properties can markedly determine the total heat amount they absorbed from incoming solar radiation as well as their efficiency in dissipating the absorbed heat into the atmosphere, affecting the ambient temperature (Morini et al., 2016). In this context, scientists mainly consider albedo effects as it is a crucial measure of the reflectivity of a surface. A higher albedo is preferred because more incoming sunlight can be reflected into space, allowing less radiation from the Sun absorbed by the Earth surface.

Besides, urban geometry and greenery are two main urban descriptors that most affect the micro-scale microclimate and human comfort, primarily because they determine the solar radiation availability and wind flow pattern (He et al., 2015). Their influences on microclimate variation are usually assessed in shading potential, ventilation (or wind characteristics) and thermal reflectivity (Lin et al., 2017). The effects of street orientation and building aspect ratio have been most discussed in analysing the correlation between urban geometry and microclimate. While the street orientation plays a significant role in the variation of solar access and air circulation in an urban canyon, the aspect ratio has an essential function in controlling the amount of solar radiation and wind entering the urban canyon (Jamei & Rajagopalan, 2017).

Besides, the sky view factor (SVF) has long been used to reflect urban geometry, density, and land-use characteristics (Lin et al., 2017). It represents the ratio of sky hemisphere visible from the ground (Oke 1981). In thermal studies, SVFs are most used to characterise the thermal balance and correlate with surface temperature. The amount of radiation that reached a certain point on the ground can be calculated and analysed by fisheye photos (He et al., 2015; Jamei et al., 2016). In this case, both building and vegetation are considered, which helps to present an integrated thermal condition in an urban context.

Greenery and vegetation affect microclimate in several ways. First, tree canopies provide shading, which not only blocks a substantial amount of incoming shortwave radiation by reflection and transmission through their leaves but also intercept the dissipation of longwave radiation from the ground to the atmosphere (Lee et al., 2016; Louafi et al., 2017; Kong et al., 2017). Simultaneously, the evapotranspiration of the leaves helps reduce the surrounding temperature by converting sensible heat into latent heat (Kleerekoper et al., 2012). Moreover, trees possess a wind resistance characteristic, not only impeding the airflow and decreasing wind speed but also altering wind direction in some cases (Kong et al., 2017). The microscale cooling effects of vegetation through evapotranspiration and shade provision made it the most popular measure to counterbalance built density in hot and humid regions (Duarte et al., 2015; Stanley et al., 2019).

Other than that, urban blue surfaces, including river, lake, fountain, pool, or any surface waters within a city, are also being studied regarding their impacts on urban microclimate (e.g., Xu et al., 2010; Wong et al., 2012; Theeuwes et al., 2013; Du et al., 2016). Similar to urban green spaces, water possesses an evapotranspiration-based cooling influence on our urban canopy (Gunawardena et al., 2017). The high thermal capacity of water also helps to keep the air temperature lower on the water surface and its adjacent surroundings (Manteghi et al., 2015). Other than that, the open water bodies, especially those flowing rivers, act as air lanes and induce the cool breeze into the heated urban area (Völker et al., 2013).

2.4.2 The Indices Used in Outdoor Thermal Comfort (OTC) Studies

Empirical thermal indices have been long used as indicators for assessing the thermal environment. More than 100 indices have been created and introduced for thermal evaluation over the last century (Blazejczyk et al., 2012; de Freitas & Grigorieva, 2017; Kumar & Sharma, 2020). According to De Freitas & Grigorieva (2017), the evaluation of thermal indices relied upon six criteria: comprehensiveness, scope, sophistication, transparency, usability, and validity. Different from indoor thermal studies, the indices used for outdoor thermal comfort studies (OTC) were relatively few and consistent. Based on the comparative review of OTC studies by Kumar & Sharma (2020) for 2001-2019, PET was the most common indices used in OTC studies, followed by the sequence as UTCI-PMV-SET* (PET-PMV-SET* in Honjo (2009)). The basis and principles of these indices were as explained in Table 2.3.

Table 2.3. Comparison of OTC indices.

Indies	Name	Definition, Basics & Principles
PET	Physiological Equivalent Temperature (developed by P. Hoppe,1999)	• It is defined as "the air temperature at which, in a typical indoor setting (without wind and solar radiation), the heat budget of the human body is balanced with the same core and skin temperature as under the complex outdoor conditions to be assessed" (Höppe,1999). • It is based on Munich Energy- Balance Model for Individuals (MEMI), which physiologically models the human thermal comfort conditions (Höppe 1984,1994). • It considers the impacts of all thermally relevant climate parameters (air temperature, radiant temperature, air velocity, air humidity) in a thermo-physiologically relevant way, evaluating their real effect on the regulatory processes and the thermal state of the body.
UTCI	Universal Thermal Climate Index (developed by International Society of Biometeorology,2005-2009)	• It is defined as "the air temperature (Ta) of the reference condition causing the same model response as actual conditions" (Błażejczyk et al., 2013). • The offset, i.e. the deviation of UTCI from air temperature, depends on the actual values of air (*Ta*) and mean radiant temperature (*Tmrt*), wind speed (*va*) and humidity,

		expressed as water vapour pressure (*vp*) or relative humidity (*RH*); or in mathematical terms as: UTCI = f (*Ta; Tmrt; va; vp*) = *Ta* + Offset (*Ta; Tmrt; va; vp*) • It is based on the Fiala multi-node model of human thermoregulation by taking into account the total heat budget of the human body and human physiological response (Fiala et al., 2012). • It is a physiological response-based assessment model. A total of 187 human tissue nodes (based on 12 spherical or cylindrical body compartments: head, face, neck, shoulders, thorax, abdomen, upper and lower arms, hands, upper and lower legs, and feet) are used as thermophysical and thermophysiological parameters.
PMV	Predicted Mean Vote (developed by P.O. Fanger, 1970) Now also known as "Klima-Michel-Modell"	• It is an empirical fit to the human sensation of thermal comfort. • It predicts the average response of the large group on a seven-point thermal sensation scale (Refer to Figure 2.1)
SET*	Standard Effective Temperature (developed by Gagge et al., 1986)	• It is defined as "the temperature of an imaginary environment at 50% [relative humidity], less than 0.1 meters per second air-speed, and [the mean radiant temperature equals the air temperature], in which the total heat loss from the skin of an imaginary occupant with an activity level of 1.0 met and a clothing level of 0.6 *clo* is the same as that from a person in the actual environment, with actual clothing and activity level" (ANSI/ASHRAE Standard 55, 2010). • It is based on human energy balance and a two-node model (Gagge et al., 1971).

PET has been recognised as applicable to a wide range of real outdoor conditions. It is the index and method recommended by the German Association of Engineers (Verein Deutscher Ingenieure, VDI) to evaluate climate for urban and regional planning in Germany (VDI, 1998). In principle, PET is formulated under the MEMI model with three equations (Höppe,1999), as elaborated in the following (and Figure 2.5 is showed as an example):

a. **The energy balance of the total body: $M+W+R+C+E_D+E_{Re}+E_{Sw}+S = 0$**

where M is the metabolic rate, W is the physical work output, R is the net radiation of the body, C is the convective heat flux, E_D is the latent heat flux diffusing through the skin (imperceptible perspiration), E_{Re} is of heat flux by the respiration, E_{Sw} is the heat flux due to evaporation of sweat, and S is the storage heat flow for heating or cooling the body mass. These terms in this equation have positive signs if they gain energy for the body (M is always positive, W, E_D and E_{Sw} are always negative). The unit of all heat flow is in Watt. Under this equation, the sub-equations for each component are showed in the following (Höppe,1993):

i. $C = A_{Du} \cdot f_{cl} \cdot h_c \cdot (Ta - Ts)$

where A_{Du} is the surface area of the unclothed body, f_{cl} is the surface enlargement factor for the clothed body, h_c is the heat transfer coefficient depending on the air velocity, Ta is the temperature of the ambient air, and Ts is the surface temperature of the body (skin or/and clothing surface temperature)

ii. $R = A_{Du} \cdot f_{cl} \cdot f_{eff} \cdot \varepsilon_p \cdot \delta \cdot (Tmrt^4 - Ts^4)$

where f_{eff} is the factor giving the relation between the body surface and the effective surface for radiative exchanges ($f_{eff} = 0.7$ for standing persons), ε_p is the emission coefficient for the human surface, δ is the Stefan-Boltzmann constant and Tmrt is the mean radiation temperature of the environment.

iii. $E_D = m \cdot r \cdot (VP_a - SVP_{sk})$

where m is the permeance coefficient of the skin for water vapour, r is the vaporisation heat of water, VP_a is the ambient water vapour pressure, and SVP_{sk} is the saturation vapour pressure at skin temperature.

iv. $E_{Re} = E_{res} + E_{Rel}$

E_{res} ***= heating of respired air =*** $RTM \cdot c_p \cdot (Ta - Tex)$

E_{Rel} ***= humidification of respired air =*** $RTM \cdot r \cdot (VP_a\sim - SVP_{Tex})/p$

where RTM is the mass of air respired per second, c_p is the specific air heat, Tex is the expired air temperature, SVP_{Tex} means the saturation vapour pressure at expiration temperature, and p is the air pressure.

v. $E_{sw} = SW \cdot r$

Used when the body produces less sweat than can evaporate from the body surface, where SW is the sweat rate m kg/s.

$E_{sw} = (A_{Du} \cdot r \cdot ho \cdot 0.622/p) \times (VP_a - SVP_{Tsk})$

Used when the potential evaporation from the body is lower than the amount of sweat produced.

b. **The heat flux from the body core to skin surface:** $F_{CS} = v_b \times \rho_b \times c_b \times (T_c - T_{sk})$

where V_b is the blood flow from the body core to skin (in Is^{-1} m^{-2}), ρ_b is the density of blood (in kgl^{-1}), c_b is the specific heat capacity of blood (in $W_sK^{-1}kg^{-1}$). T_c is the core temperature, and T_{sk} is the mean skin temperature (in °C).

c. **The heat flux from the skin through the clothing layer to the outer surface of the clothing:** $F_{SC} = (1/I_{cl}) \times (T_{sk} - T_{cl})$

where I_{cl} is the heat transfer resistance of the clothing, T_{sk} is the mean skin temperature, and T_{cl} is the mean surface temperature of the clothing

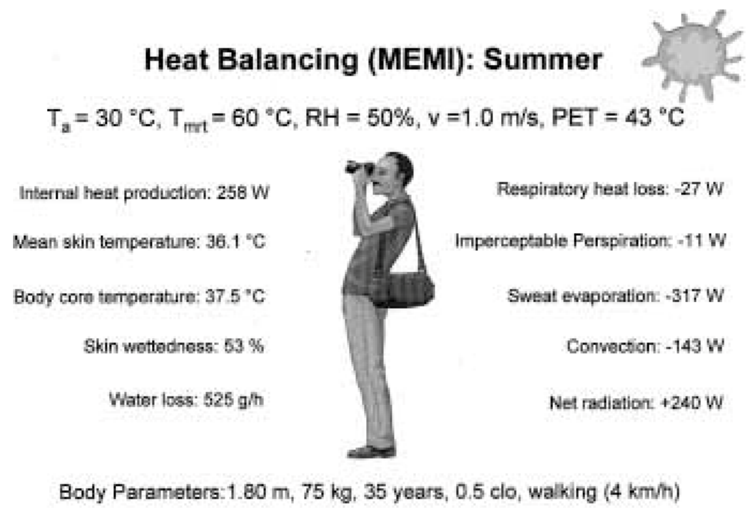


Fig. 2.5. Sample heat-balance calculation using the MEMI for the warm and sunny conditions in summer (Source: Höppe,1999).

Based on the equations in (a) i-v, it can be found that the meteorological parameters primarily influence heat flow. C and E_{Re} are affected by air temperature; E_D, E_{Re}, E_{Sw} are affected by humidity; C and E_{Sw} are affected by wind velocity; R is affected by Tmrt, the mean radiant temperature, calculating the exchange between the environment and human body by short wave and longwave radiation.

With the development of user-friendly software by Matzarakis et al. (2007 & 2010), named RayMan, nowadays PET has been commonly used in urban thermal studies. Based on Matzarakis and Amelung (2008), Tmrt and PET can be calculated using the RayMan model based on the input parameters. The calculation of PET in RayMan involved:

- calculation of thermal conditions of the human body based on MEMI (with a given database of meteorological parameters).
- insertion of the calculated values for mean skin temperature and core temperatures into the MEMI model.
- solving the energy balance equation system for the air temperature (the resulting air temperature is equivalent to PET).

The resulting PET values finally would be transformed into corresponding thermal perception based on climate region, as shown in Table 2.1 for tropical regions.

2.4.3 The Assessment Methods and Tools Used in Outdoor Microclimate and Thermal Comfort Studies

There are three main methods in assessing microclimate and thermal comfort: in-situ field measurements, remote sensing-based, and modelling and simulations. Fong et al. (2019) demonstrated that in situ field measurement was critical to producing precise and detailed site reports on the microclimatic conditions. In contrast, modelling and simulations were most used for scenario forecasting purposes and future planning. There were two types of measurement in the field study: (i) the objective measurement using primary or secondary data and (ii) the subjective measurement using survey questionnaires. The primary data involved the on-field observation using meteorological instruments, whereas the secondary data could be directly obtained from the national meteorological department.

Bherwani et al. (2020) have explained another approach other than in-situ field measurements and modelling and simulations, that is, remote sensing and GIS-based assessments. Multiple data could be obtained from the various sensors and satellites, including temperature, albedo, humidity, roughness and the planetary boundary. However, the authors claimed that this approach was still limited to measurements and observations, even though it has been used for prediction and decision making in conjunction with GIS tools.

The development of the modelling and simulation approach was a result of evolution in the field of microclimate studies. In the mainstream of early on-site observations and measurement, researchers attempted to understand theories and principles embedded in urban climate phenomena (such as UHI effects and flux patterns) through simple modelling techniques. However, with the increase of computational resources, the modelling and simulation approach has become more favourable in contemporary research. The main reason was that the numerical simulation approaches have advantages in performing comparative analyses based on designated scenarios (Kanda, 2007; Blocken, 2015; Toparlar et al., 2017).

Most simulation modelling software was developed under the concept of Computational Fluid Dynamics (CFD) (Toparlar et al., 2017). Its high applicability was most demonstrated in analysing wind flow, pedestrian wind comfort and thermal comfort, wind-driven rain, pollutant dispersion and other topics. Temperature and wind were the earliest key model parameters in the CFD-based model development, and then only other parameters were added to later models, as shown in Figure 2.6 (Bherwani et al., 2020).

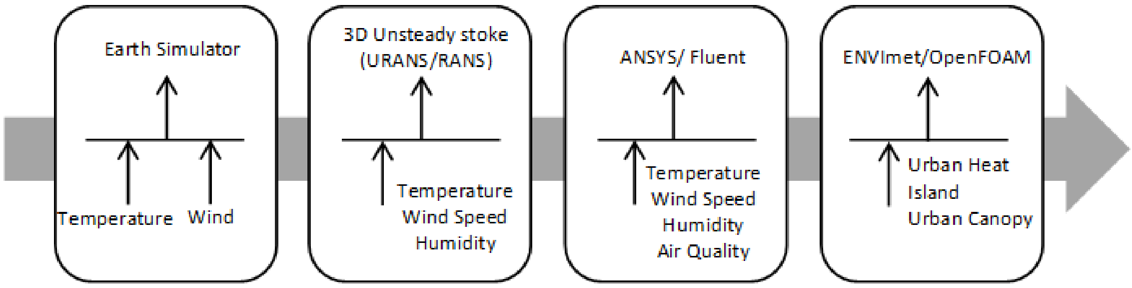


Fig. 2.6. The evolution of the use of CFD in urban microclimate research. (Source from: Bherwani et al., 2020).

2.4.3.1 The basics of microclimate simulation in ENVI-met

The use of ENVI-met has been widely reported in recent UHI and thermal comfort studies around the world (e.g., Salata et al., 2016; Chatzinikolaou et al., 2018; Elwy et al., 2018; López-Cabeza et al., 2018; Tsoka et al., 2018; Rui et al., 2019; Altunkasa et al., 2020; Xiong et al., 2020; Chan & Chau, 2021; Yilmaz et al., 2021). ENVI-met model is a three-dimensional (3D) microclimate model used to calculate the dynamics of surface-plant-air interactions of urban environments, using the fundamental laws of fluid dynamics (CFD) and thermodynamics in atmosphere physics (Bruse & Fleer, 1998). The turbulence model applied is the so-called 2-

equation Turbulence Kinetic Energy (TKE) Model, based on the distribution of kinetic energy (advection-diffusion-production-destruction) and the dissipation rate.

ENVI-met model consists of three main components: a 3D atmospheric model, a 1D atmosphere boundary layer model, and a 1D soil model, where the area of interest must be modelled into grid cells. The schematic overview and the data flow over the ENVI-met model are illustrated in Figures 2.7 and 2.8, respectively.

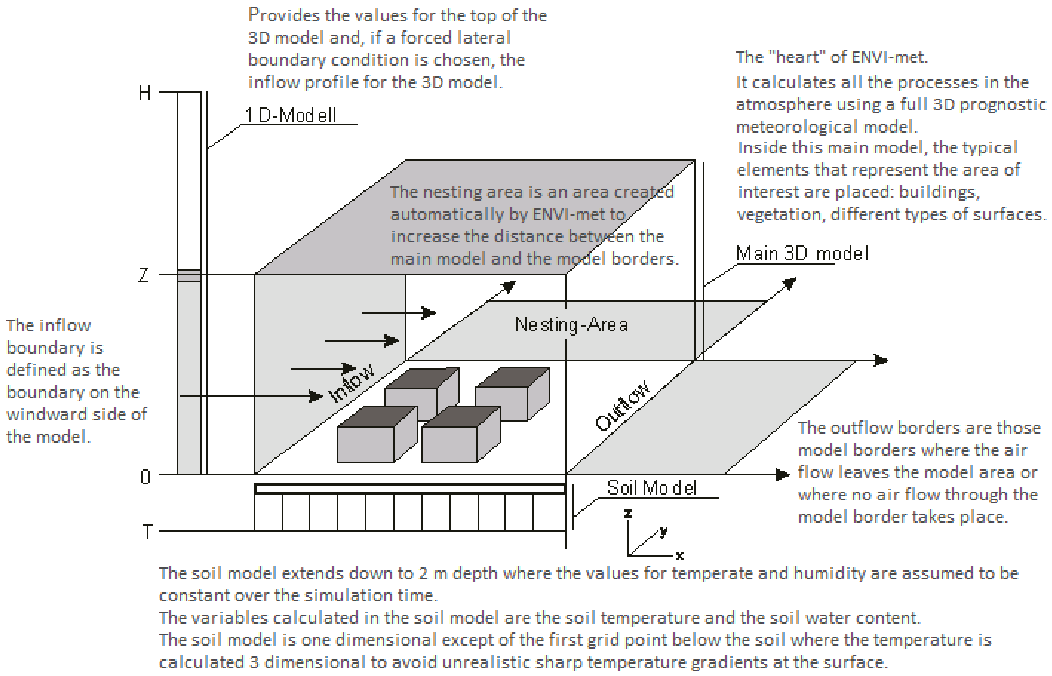


Fig.2.7. Schematic overview over the ENVI-met model layout (Source: ENVI-met manual).

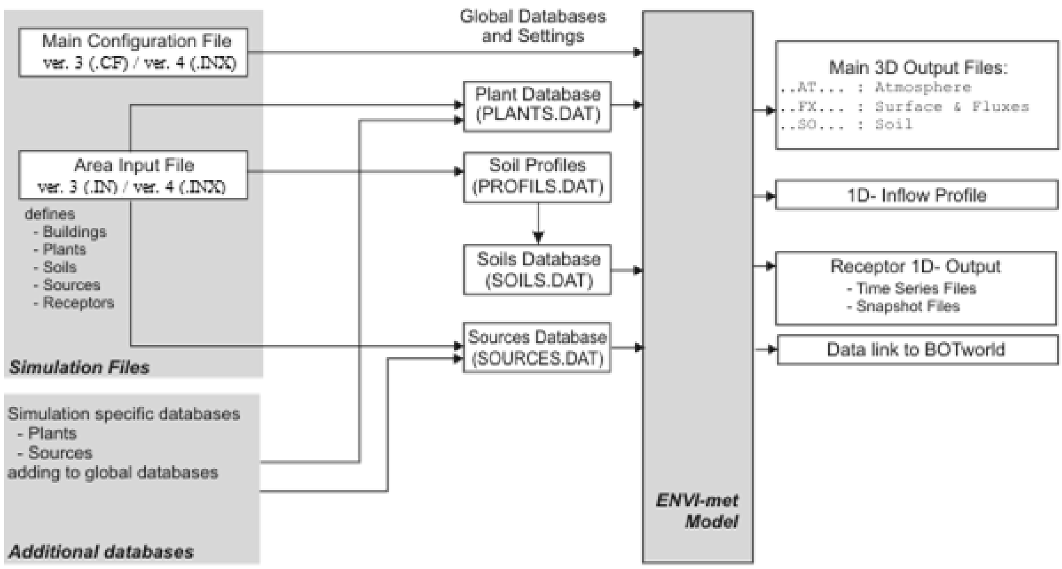


Fig.2.8. Data flow over the ENVI-met model layout (Source: ENVI-met manual).

Based on the ENVI-met website, the model covers the calculations of:

- shortwave and longwave radiation fluxes with respect to shading, reflection and re-radiation from building systems and the vegetation;
- transpiration, evaporation and sensible heat flux from the vegetation into the air, including full simulation of all plant physical parameters (e.g. photosynthesis rate);
- dynamic surface temperature and wall temperature calculation for each facade and roof element;
- water- and- heat exchange inside the soil system;
- 3d representation of vegetation including dynamic water balance modelling of the individual species;
- dispersion of gases and particles.

In order to simulate fluxes (including CO_2 and water vapour) from vegetation layers into the atmosphere, Bruse (2004a) implemented the Jacobs' A−gs stomata model into the development of ENVI-met. The A−gs model mainly takes into account the link between the stomatal conductance (g_s) and the photosynthetic rate (An) by considering the ratio of leaf internal CO_2 concentration (C_i) to external CO_2 concentration (C_s), as written in the following basic hypothesis:

$$g_s = 1.6 \frac{A_n}{C_s - C_i}$$

Since then, the ENVI-met model has been continuously developed for more than 20 years (initial version in 1994). The current ENVI-met system database covers the CO2 fixation type, leaf type, albedo, light transmittance, plant height, root zone depth, LAD profile, RAD Profile and seasonal profile for plants, enabling more dynamic interaction between the vegetation and the atmosphere.

In summary, the main prognostic variables influencing the ENVI-met simulation model include: (Bruse, 2004b)

- mean wind flow, temperature, humidity, atmospheric turbulence, and radiative fluxes in the atmospheric model;
- soil properties, such as thermodynamic and hydraulic conductivity or albedo, in the soil model;

- turbulent fluxes of heat and vapour, stomatal resistance, energy balance of the leaf, water balance of the plant/soil system in the vegetation model;
- radiative fluxes, turbulent fluxes of sensible heat and vapour, soil heat flux and heat flux through building walls on the ground surface and building surfaces;
- computational domain and grid structure, and other numeric aspects.

Also, lastly, as calibrated by Maleki et al. (2014), the quality and accuracy of ENVI-met in evaluating and predicting urban microclimate scenarios is depending heavily on the input data (the weather data and geometry/materials on the ground) and initial/boundary conditions used in the simulation.

2.5 URBAN MICROCLIMATE STUDIES IN MALAYSIA: THE TREND AND TOPICS

Malaysia, located in the tropical climate region, is featured with intensified sun radiation, high air temperature and relative humidity, and insignificant wind velocity (Ghaffarianhoseini et al., 2019). The interest in studying urban microclimate in Malaysia was started as early as in the 1970s when Sani (1972) investigated whether the phenomenon of urban heat islands occurred in the capital of Malaysia. His studies primarily focused on traverse survey (in-situ measurement) and continued from 1972 to 1987 (Sani,1972; Sani, 1984; Sani, 1986; Sani, 1987), becoming the earliest research literature about urban microclimate in Malaysia. The main finding of Sani's works included:

a. The city centre is generally warmer and drier than the rural and large open area.
b. The physiological temperatures followed the patterns of air temperatures and reached their highest values in the city streets.

However, based on Ramakreshnan et al. (2018), there was a research hiatus in urban microclimate studies in the 1990s. Until the 2000s, with an increasing concern on global warming and climate change issues, urban microclimate studies gradually regained the attention of local researchers with more diverse climate-relevant subjects in Malaysia. For example, the multiple works of Shahidan on the effects of trees (Shahidan et al., 2007; Shahidan & Jones, 2008; Shahidan et al., 2010; Shahidan et al., 2012). More advanced tools were used in their study, such as the use of remote sensing tools to examine the impacts of soil moisture on urban heat islands (Ahmad & Hashim, 2007).

In particular, starting in 2010, there are more regular and systematic research works published internationally. Based on the authors' details, it was found that most of them worked under the fixed research groups led by the local universities. This also explained why many works were conducted on the university campus. Each research group worked on different study areas and subjects under the theme of urban microclimate, as described in the following:

a. Group I, including Syahidah et al. (2015), Swarno et al. (2017) and Zaki et al. (2020a & 2020b), focused on in-situ measurement and observation of urban microclimate and the effects of urban morphology.
b. Group II, including Makaremi et al. (2012), Ramakreshnan et al. (2018) and Ghaffarianhoseini et al. (2015 & 2019), worked on urban heat and outdoor thermal comfort.
c. Group III, including Rajagopalan et al. (2014), Ahmed et al. (2015), Qaid & Ossen (2015), Manteghi et al. (2016) and Shafaghat et al. (2016), most investigated urban factors that could influence local microclimate.
d. Group IV, including Nasir et al. (2012 & 2015) and Buyadi et al. (2013 & 2014), studied the thermal effects of urban greenery.

Based on the summary of Table 2.5 regarding the trend of microclimate studies in Malaysia, most studies in Malaysia highlighted urban heat island (UHI), thermal comfort, shading and vegetation. The majority of research works were conducted in Klang Valley, included Kuala Lumpur, Shah Alam and Putrajaya, also known as the Greater Kuala Lumpur. The air temperature and land surface temperature (LST) were among the most common parameters to measure the thermal condition in local cities. Although the surface temperature was not considered in determining human thermal comfort, its variation was highly concerning since it was the most direct indicator representing the effects of LCLU change.

In terms of procedure, except for Saito et al. (2015 & 2017), most studies ended in the evaluation stage, commonly completed with site-based findings that can be used as references for urban design and planning. For those scenario studies, ENVI-met simulation software became the only tool for non-buildings-based thermal study, suggesting it as the most appropriate software tool for contemporary simulation-based thermal study in Malaysia. Most of them are based on a 24-hour simulation, which would also become a duration index for the simulations conducted in this research. As for the objective thermal comfort assessment, Rayman was used for all cases. Besides, some local studies showed that the GIS modelling tool could help analyse the thermal data.

Lastly, it is worth mentioning that Shahidan and Mustafa (2005) have identified four tropical microclimate indicators for the Malaysian urban landscape to achieve a sustainable outdoor comfort zone: solar and terrestrial radiation, wind, air temperature and humidity. These indicators explained the functions of landscape elements in modifying urban microclimate, as summarised in Table 2.4.

Table 2.4. The character of urban landscape elements in tropical microclimate modification.

Microclimate modification	**Soft landscape**	**Hard landscape**
Radiation modification	The density of tree canopy (the density of woody plants' twigs, branches and leaf cover) determined: (i) the amount of radiation absorbed, reflected and transmitted (Figure 2.9); and (ii) the degree of reduction in downward energy flow, which indicated by tree shade.	The albedo, emissivity and thermal conductivity of solid structure surfaces determined the total radiation partitioned into the energy budget.
Wind modification	• Landforms determined the speed, direction and turbulence of wind (Figure 2.10a). • The size, location, orientation, porosity, and proximity of landscape elements (trees and buildings) determined the speed, direction and turbulence of wind (Figure 2.10b).	
Temperature modification	The dense shade of trees and abundant water sources could slightly reduce temperature through radiation and wind modification (Figure 2.11a).	The temperature differences can slightly be achieved by the dense shade created by solid walls (Figure 2.11b).
Humidity modification	The water sources, such as ponds or transpiration from plants, could slightly increase the humidity through water evaporation.	The humidity differences can slightly be achieved by reducing or eliminating air movement

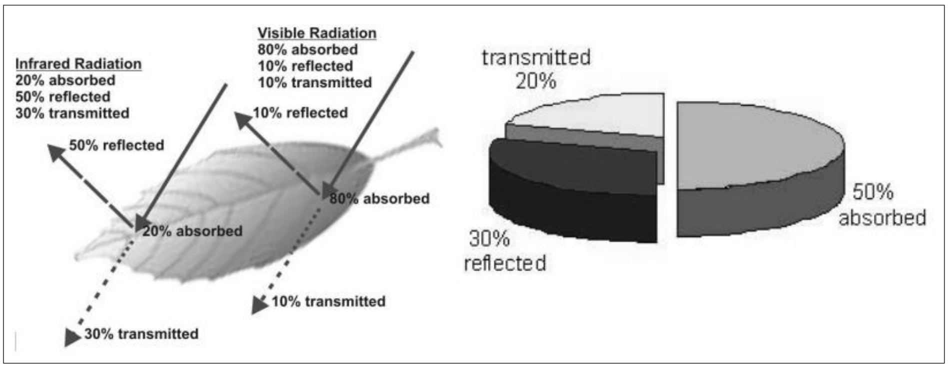


Fig. 2.9. The function of vegetation in solar radiation modification. (Modified from: Shahidan and Mustafa, 2005).

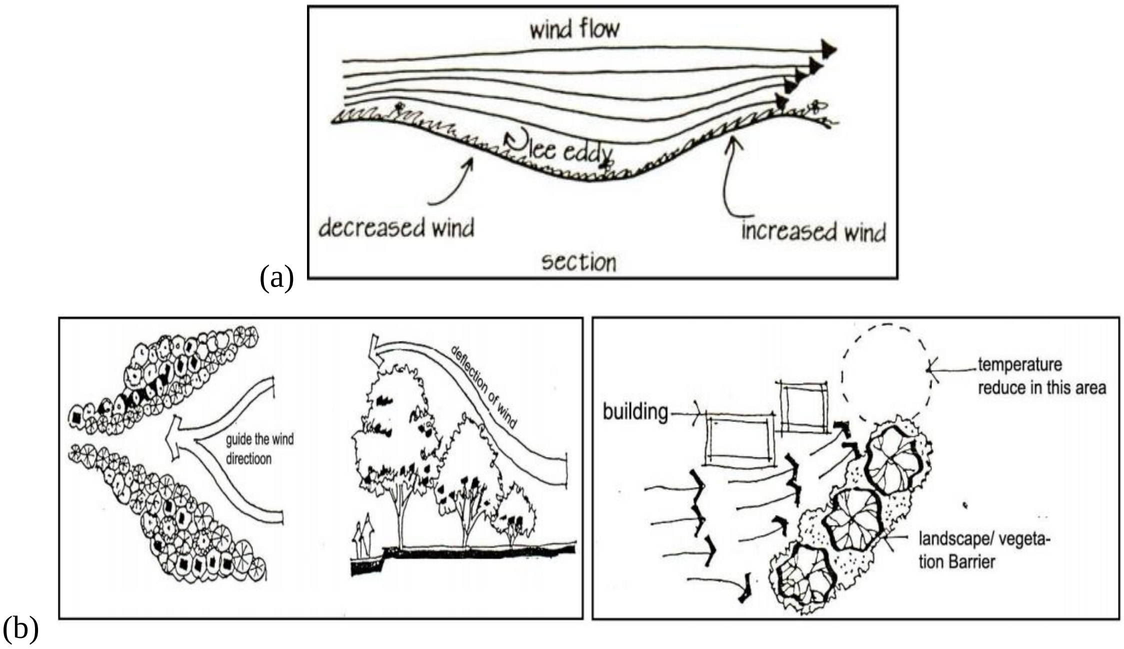


Fig. 2.10. The function of natural landforms and landscape elements in wind modification. (Source from: Abdul Chalim in Shahidan and Mustafa, 2005).

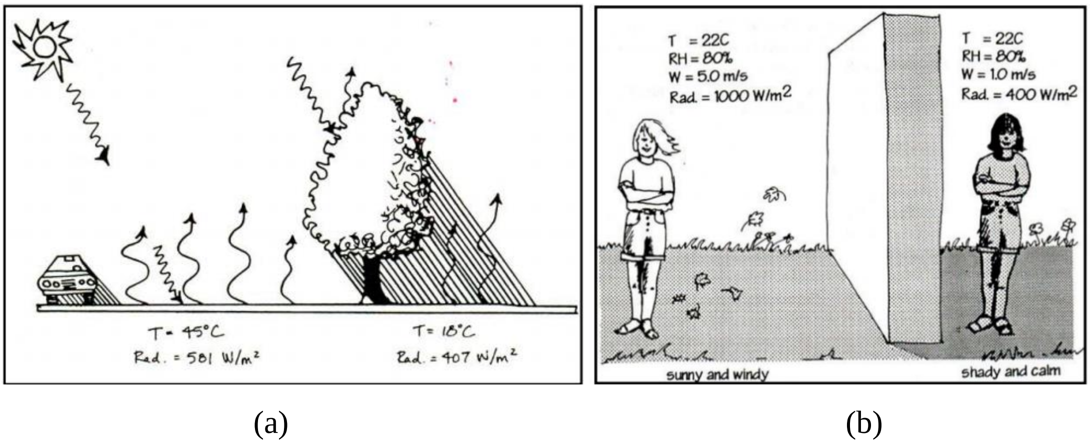


Fig. 2.11. The function of landscape elements in temperature modification (Source from: Brown and Gillespie in Shahidan and Mustafa, 2005).

Among the above-discussed indicators, Shahidan and Mustafa (2005) put more emphasis on the impacts of landscapes on solar and terrestrial radiation and wind. They also explained that the prevailing atmospheric system would usually quickly dissipate the air temperature and humidity differences through air movement (wind). The feature of atmospheric neutralisation has both advantages and disadvantages, ultimately determining whether the wind plays a positive or negative role in the local microclimate and thermal comfort. On the one hand, it could draw the cool and humid ambient air into the city to ameliorate UHI effects. On the other hand, it could also dissipate or minimise the cool island effects produced by greenery created at certain locations in the city (parks and green spaces).

In conclusion, the past thermal studies in Malaysia have provided basic viewpoints in response to urban microclimate improvement in the tropical region. Different from the international literature commonly derived from temperate and arid zones, Malaysia studies provided specific insights into urban thermal environments in hot and humid regions. The consistency in study methods and tools also gave high validation and reliability in terms of research significance, which would consolidate the foundation and methodology of this research in the next chapter. However, the scope of studies, as well as the methods and tools used in Malaysian studies, were limited and not comprehensive in general, which could not provide holistic design guidelines in practices. Last but not least, the microclimate or thermal studies conducted in Malaysia less considered the improvement through a local design planning perspective, opening up a new inquiry in the scope of the study.

Table 2.5. The latest trend of urban microclimate studies in MALAYSIA: from 2010 to current.

Author / Year	**Context and Location**	**Method & Duration**	**Study subject**	**Parameter**	**Key findings/ Highlights**
Zaki et al. (2020a)	University Campus / Kuala Lumpur	In-situ measurement (7 days)	Urban morphology: green cover ratio, height-to-width (H/W) ratio, and sky view factor (SVF).	Air temperature, relative humidity	• The optimum cooling effect was achieved through the larger green area and tree shading, denser building condition (lower H/W ratio) and higher SVF. • Without trees, green coverage such as grass and shrubs could also effectively lower the ground surface temperature.
Zaki et al. (2020b)	Kampung Baru - an urban residential area / Kuala Lumpur	1. In-situ measurement (6 days) 2. ArcGIS	Building morphology	Air temperature, urban heat island intensity (UHII)	• The UHI effect in Kampung Baru was found at the average building with a height of six to ten metres. • A low-rise compact residential area surrounded by high-rise buildings has increased the tendency of the area to trap warmer air during the daytime, resulting in the highest temperature and lower relative humidity compared to other surrounding places.
Ghaffarianhoseini et al. (2019)	University Campus / Kuala Lumpur	1.In-situ measurement 2.Modelling and simulation tool: ENVI-met and IES-	Outdoor thermal comfort	Air temperature, relative humidity, solar radiation, wind speed	• Outdoor spaces that encompassed shading potentials due to the existence of trees and adjacent building blocks would provide more acceptable thermal comfort conditions. • Greeneries such as trees did not guarantee a positive effect on the outdoor thermal

		VE (5:00 to 19:00)			performance unless their number, type, size, and location have been efficiently designed to provide sufficient shading. • The highest temperatures and PMV/PET values embraced several similar characteristics, i.e. openness to the sky with no possibility of shading; relatively far from the surrounded trees and considerably less vegetated; and covered by low albedo surface materials such as asphalt. • There was no constancy with wind movement, as well as unpredictable wind direction and weak wind velocity
Kasim et al. (2019)	University Campus / Kuala Lumpur	1. In-situ measurement 2. Modelling and simulation tool: Rayman	Landscape Environmental Settings for Pedestrian (LESP)	Air temperature, surface temperature, wind velocity, relative humidity, MRT, PET	• Pedestrian walkways with shading, either artificial shades or shading by trees, provided better microclimate in terms of air temperature, surface temperature, relative humidity, mean radiant temperature, and thermal comfort. • A continuous and wider shade can increase pedestrian comfort.
Ramakreshnan et al. (2018)	Greater Kuala Lumpur	Review	Urban Heat Island (UHI)		• The rise of UHII was associated with a decrease in vegetation cover and land-use change. • The authors promoted the utilisation of advanced modelling and simulation technologies as a basis for more informed decision-making

Kei et al. (2015 & 2017)	Heritage site/ Melaka	Modelling and simulation tool: 1. ENVI-met (24hr) 2. ArcGIS 3. Rayman 4. DepthmapX	Improvement of urban heat environment	PET	• The authors proposed an efficient method for extracting potential areas for future neighbourhood greening, which accounted for pedestrian's thermal comfort, visibility and movement. • An average reduction of PET on the pedestrian walkway: up to 4.6 °C with a GCR increase by approximately 2%; and up to 11.5 °C with a GCR increase by approximately 7%. • The high building-coverage ratio and narrow streets have reduced the heat radiated from the surrounding buildings and road surface.
Swarno et al. (2017)	University Campus / Kuala Lumpur	Weather station (1 year)		Air temperature, relative humidity, solar radiation, wind speed and direction, rainfall	• The trend of microclimate parameters (hourly, daily, monthly) was measured. • Urban microclimatic parameters were influenced by monsoon seasons and the urban surface.
Benrazavi et al. (2016)	Putrajaya	In-situ measurement (28 days)	Pavement materials	Air temperature, land surface temperature (LST)	• The surface temperature of AS was significantly higher than Fontana concrete (54.6◦C), Blue Impala polished granite (46.5◦C), and Rosa Tanggo polished granite (44.9◦C) in the "open space" location. • The surface temperatures of all pavement materials tested in the "under shade" location

					were the lowest as compared to those in the "open space" and "near water" locations. • The surface temperature increased at the "near water" location for granite pavement materials because they have lower porosity and water-repellent characteristics, resulting in less heat exchange.
Manteghi et al. (2016)	River / Melaka	Modelling and simulation tool: ENVI-met (24hr)	Waterbody and vegetation (Scenario study)	Air temperature	• The cooling effects of water and greenery upon the surrounding areas were strongly correlated to the distance between the greenery area and the water body with the area • The best cooling effect on the surrounding area was achieved via greenery.
Shafaghat et al. (2016)	Tropical Coastal Cities	Review	Street geometry		• The street factors that impacted the microclimate was identified: geometry factors (aspect ratio, street orientation, sky view factor), meteorological factors (air temperature, surface temperature, relative humidity, and wind speed) and streetscape factors (thermal comfort).
Ahmed et al. (2015)	Putrajaya	In-situ measurement (3 days)	Urban surface and heat island effect	Building & land surface temperatures, wind velocity	• Higher surface temperatures were found at the (1) main boulevard due to direct solar radiation incident, (2) street orientation in the direction of northeast and southwest, and (3) low building height-to-street width ratio. • There was a strong positive relationship between the intensity of solar radiation and surface temperatures during the daytime.

					• Compared to scattered and isolated trees, clustered trees along the street were more effective in reducing surface temperatures. • The design of buildings located beside the street influenced wind speeds, and the surface temperatures on the streets were associated with wind speed.
Ghaffarianhoseini et al. (2015)	Kuala Lumpur	Modelling and simulation tool: 1. ENVI-met (14–48hr) 2. Rayman	Courtyard design (Scenario study)	PMV, PET	• Proper selection of the location and orientation of courtyards (facing North) could maximise wind speed and increase efficient shading. • Increasing the height of wall enclosures in courtyards could block the intense solar radiations and provide more shaded areas • Increasing the albedo of wall enclosures in courtyards could reduce outdoor thermal comfort. • The efficiency of trees and the limitations of grass in improving thermal comfort was showed.
Morris et al. (2015)	Putrajaya	Modelling and simulation tool: Weather Research and Forecasting (WRF) Model + Noah land surface model + urban canopy model (UCM)	Surface material	Urban heat island intensity (UHII)	• Model validation. • UHI intensity varied temporally and spatially. • It showed the influences of landcover type on the magnitude of UHI, in which the reserved total land area for vegetation has influenced the overall magnitude of UHII in Putrajaya.

Nasir et al. (2015)	Lake Garden / Shah Alam	1. In-situ measurement 2. Modelling and simulation tool: ENVI-met (24–48hr)	Vegetation (Scenario study)	Air temperature, relative humidity, wind velocity, MRT	• Plants had functions in controlling the microclimate, including decreasing air temperature, increasing humidity, and modulating wind ventilation. • Trees were the most beneficial mitigation strategy for the optimisation of the area.
Qaid & Ossen (2015)	Putrajaya Boulevard	1. In-situ measurement 2. Modelling and simulation tool: ENVI-met (24hr)	Asymmetrical street aspect ratios (Scenario study)	Solar radiation, air temperature, surface temperature, wind velocity	• High surface and air temperatures were caused by the street orientation, the low aspect ratio and the high sky view factor. • When tall buildings confronted wind direction or solar altitudes, the asymmetrical street performed better than the low symmetrical street to enhance wind flow and block solar radiation.
Syahidah et al. (2015)	University campus / Kuala Lumpur	1. Weather station (1 year) 2. In-situ measurement (7 days) 3. ArcGIS	• Land cover (Greenery coverage) • Aspect ratio (Morphological characteristics)	1. Air temperature, relative humidity, solar radiation (method no.1) 2. Air temperature (method no.2)	• A lower air temperature was recorded within building canyons and where with a high greenery percentage. • A lower height-to-width ratio showed a higher air temperature.
Rajagopalan et al. (2014)	Muar	Modelling and simulation tool: IES Virtual Environment	Urban canyon: city configuration and building layouts (Scenario study)	UHI, wind flow	• Towers should be placed on the windward side to gain maximum ventilation. • Areas with low wind velocity should be shaded and covered with trees.

					• The formation of narrow streets and tall buildings tended to entrap heat and reduce airflow, resulting in high temperatures. • Step up configuration was most effective in distributing the wind evenly, enabling the wind to reach the buildings' leeward side.
Shaharuddin et al. (2014)	Klang Valley	Remote sensing tool: TERRA /MODIS satellite	Land cover	Land surface temperature (LST)	• Those areas with high urban imperviousness coverage had the most notable UHI gradient. • Urban cool islands were associated with the occurrences of urban green patches.
Yusuf et al. (2014)	Greater Kuala Lumpur	Remote sensing tool: Landsat TM/ETM (1997 and 2013)	Land use land cover (LULC)	Land surface temperature (LST)	• The decrease of forest and water bodies resulted in the loss in low-and-intermediate-temperature classes. Meanwhile, there was a gain in moderate-and-high-temperature classes due to increased built-up area and farmland.
Buyadi et al. (2013, 2014)	Green spaces / Shah Alam	1.Remote sensing tool: Landsat 5 TM (1991 and 2.2009) 3.ArcGIS	Vegetation: normalised difference vegetation index (NDVI)	Land surface temperature (LST)	• Urbanisation significantly increased the LST. • They found a strong negative correlation between LST and NDVI.
	Parks / Petaling District				• Urban green spaces could reduce the high radiant temperatures of the surrounding developed areas, but only until 500 m. • The cooling effects of parks depended on the composition of land use/land cover profile (water body, high-density trees, mixed vegetation, built-up area and open spaces) and also the distance from the park boundary.
Elsayed (2012)	Kuala Lumpur	1.Weather station network - Malaysian Meteorological Services (MMS)	Urban Heat Island (UHI)	UHII, number and location of cool and heat islands, and the location of the nucleus of such UHI.	• The temperatures varied from a workday to a nonworking day in the city, related to traffic intensity. • The only recognised cool island inside the city centre was located in the park.

		2. Traverses survey (1 week)			• The UHI's nucleus was located within the city centre, but it could be shifted due to the land use and human activity changes.
Makaremi et al. (2012)	University campus / Kuala Lumpur	1. In-situ measurement 2. Rayman 3. Questionnaire	Outdoor thermal comfort	Air temperature, relative humidity, wind velocity, MRT	• There was a considerable difference between actual sensations of individuals (human subjective assessment) in outdoor spaces and the outcome of calculated thermal comfort values based on the climatic parameters (objective measurement). • **"Warm" (PET<34ºC) was an acceptable thermal condition.** • Other than environmental factors, thermal adaptation and psychological parameters also strongly affected the human thermal comfort level in outdoor spaces. • There was a significant difference between the local and international subjects' responses regarding the climatic conditions.
Nasir et al. (2012)	Lake Garden / Shah Alam	1. In-situ measurement 2. Rayman 3. Interview sheets and observation	Outdoor thermal comfort	Air temperature, relative humidity, wind velocity, solar radiation, apparent temperature, MRT	• They affirmed the existence of adaptive thermal comfort when they found that most respondents perceived better microclimatic conditions than what was measured. • **The subjects adapted to the "warm" rather than the "comfortable" range of Physiological Equivalent Temperature (PET).** • The personal factors did not affect the comfort level, and there must be other factors impacting the preferences.

CHAPTER 3
URBAN OUTDOOR THERMAL RESILIENCE AND THERMAL COMFORT ASSESSMENT

3.1 INTRODUCTION

Understanding urban thermal resilience is essential in creating a resilient landscape design. It involves climate knowledge and capacities in interfacing a given urban model with local thermal characteristics and vice versa. Indeed, the thermal analytical capabilities of urban microclimate simulation tools have been greatly improved nowadays. However, there are still many technical challenges in interpreting or visualising the interaction between local climate and cities, making it difficult to transfer climate considerations into urban design practice. To fill the technical gap, this chapter firstly developed a practical approach to study outdoor thermal resilience and thermal comfort in tropical cities. The relationship between urban morphology and thermal performance was explored using integrated computational modelling and simulation tools. After that, microclimate and thermal comfort simulation data would be assembled into a GIS platform. The new platform was mainly used to conduct comprehensive climate-spatial analysis and transform the findings into thermal resilience insights. In the end, this chapter provided explicit design suggestions for thermal resilience improvement in Ipoh downtown. It is expected that these thermal insights could be compatible with other considerations in urban design. Given that, this integrated outdoor thermal resilience assessment framework was built on three premises, as follows:

a. it was evidence-based and result-oriented;

b. it was compatible with current urban design spatial analysis, as well as the design and planning tools and methods;

c. all thermal insights were complied with the local development context and practical for urban landscape design.

3.2 CHALLENGES: THE SHORTCOMINGS OF ENVI-MET APPLICATION AND ITS SOLUTIONS

The reliability of the ENVI-met model in simulating urban thermal performance for different climate regions has been extensively reported and accepted in recent urban climate studies (e.g., Song et al., 2014; Zölch et al., 2016; Saito et al., 2017; Sodoudi et al., 2018; Bande et al., 2019).

However, for this research, using only the ENVI-met tool would have at least three shortcomings. These problems not only occurred in the path of model setup, but also in the climate-spatial analysis and subsequent design process, as explained below:

a. ENVI-met is designed based on CFD (Computational Fluid Dynamics) theory applied in environmental engineering that typically use raster models to produce high-resolution climatic maps for each time step (Hien et al., 2012). On the contrary, spatial-related design and planning is always a vector-based representation presented by lines, points and polygons. Compared to the vector models, it is relatively less flexible to change and amend the shape of raster models. This attribute made it incompatible with the spatial design interface (see the difference in Figure 3.1).

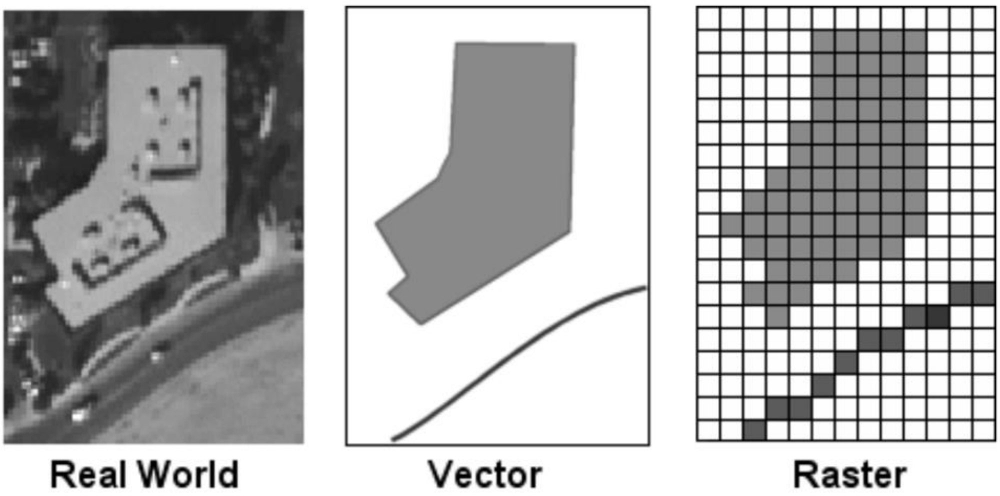


Fig. 3.1. A typical example showing the difference between vector and raster techniques in the geographic data model (Adopted from Albrecht, 2021)

b. Building a city-scale raster model in ENVI-met is time-consuming and challenging. The SPACE feature in ENVI-met "allows users to create model areas and resulting input files (.INX) needed to run a simulation" (Bruse, n.d.). However, the input was based on the modelling element layers, such as buildings, vegetation, and surfaces. Such a one-to-one input mode using SPACE would make the input workloads extremely heavy (Figure 3.2). Also, raster modelling is pixel-based and resolution-dependent. Retaining the high-resolution data fidelity of large models will additionally cost a lot of processing time and storage capacity (Hogland et al., 2013). Moreover, the software does not support resampling, so the pixels cannot be flexibly enlarged or reduced to different grid sizes or resolutions. It is also difficult to extract any partial area from the raster model for further simulations, limiting the range of study in analysis. To overcome the shortcomings, the latest ENVI-met Version 4.4 introduced a new module called MONDE, trying to ease the input process by direct importing OSM data or shapefiles for model simulation. However, the complexity of use is still a certain challenge for beginners, especially when it has only released some expert lessons for professional users since 2019.

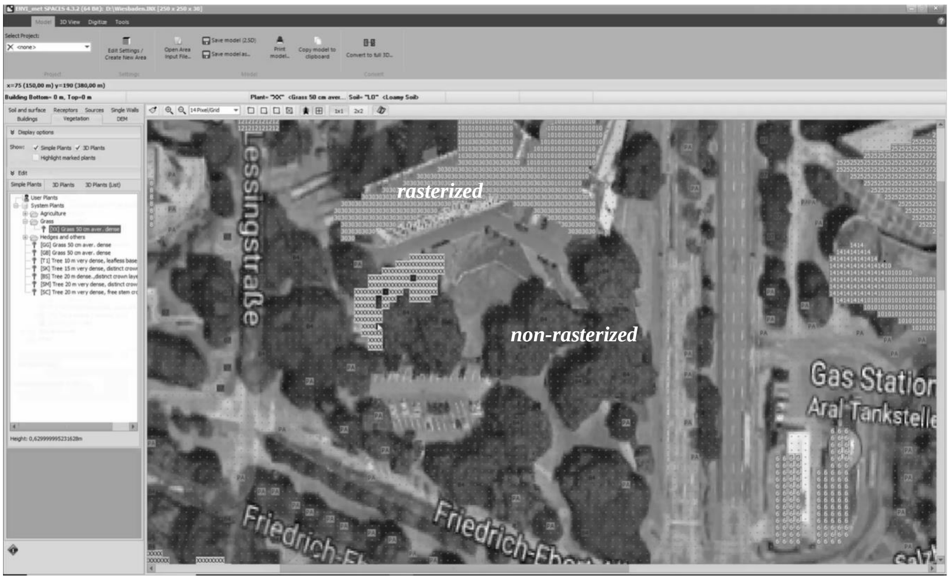


Fig. 3.2. The typical SPACE interface in ENVI-met: The modelling elements have to be digitised one by one. (Adopted from online tutorial in ENVI-met website: envi-met.com/learning-support/spaces/#video-5ff342b401859)

c. ENVI-met is a monofunctional modelling tool working solely on microclimate simulation. It does not support data synthesis, comparison, management or retrieval between parameters and models, creating limitations for further analysis. Also, the ENVI-met output interface, LEONARDO, has limited the output visualisation at a time (Figure 3.3). Without reading the simulation results in a holistic picture, it is hard to understand the interrelationship between the parameters as well as their cause and effect on the environment.

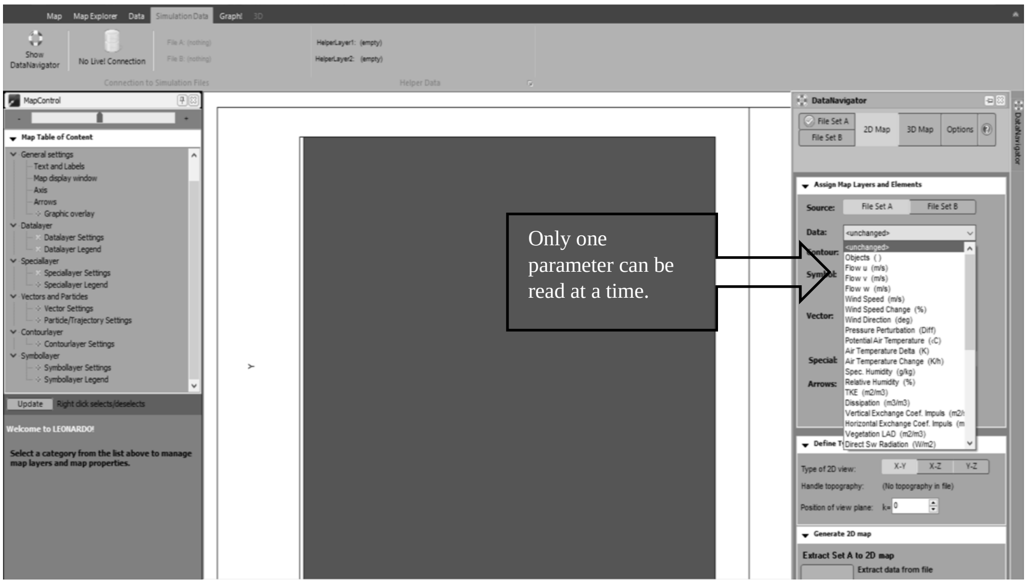


Fig. 3.3. The typical LEONARDO interface in ENVI-met: The simulated data cannot be read all-in-one or across models (a screenshot image from ENVI-met).

In view that ENVI-met software alone is insufficient to support and achieve the research objectives, it is necessary to minimise the shortcomings of ENVI-met by coupling the tool with other modelling tools in the pre- and post-simulation stages. Therefore, it is suggested to link ENVI-met with GIS spatial modelling tool, mainly because of:

a. Its coexistence of vector and raster formats can avoid duplicate works in the model setup.

b. Its functions of file interchange and extension conversion allow the alternation of prototypes between different modelling platforms. This function also enables the simulated data from other modelling tools to be incorporated and reconnected to the same environment for integrated analysis.

c. Its editable database system can cover a wide range of attribute information. In this case, it will be not only the data required for microclimate simulation but also other urban planning and design information (such as land-use, ownership, heritage significance and the relevant details).

It was expected that their interconnection throughout the study would help to incorporate microclimate consideration into current urban planning and design analysis. In turn, the integrated viewpoint would also provide more comprehensive insights to understand the outdoor thermal resilience of the city.

3.3 MODEL SCALES, SIZES AND BOUNDARIES

The research model focused on the Special Area Plan of Ipoh, particularly the existing and potential walking areas in the Ipoh downtown. Due to the consideration of simulation time used, the model area was finally fit into an area of approximately 2000m x1500m in size, which covered the core area of downtown for pedestrian-oriented development. The selected area has presented diverse land-use patterns, built layout, and greenery, giving the context worthy of study. In addition, there was a total of 4 sub-zoning in the model for detailed studies. Each model's shape, size, and boundaries were determined by their characteristics in spatial layout, built form pattern, featured uses, and activities (see Figure 3.4).

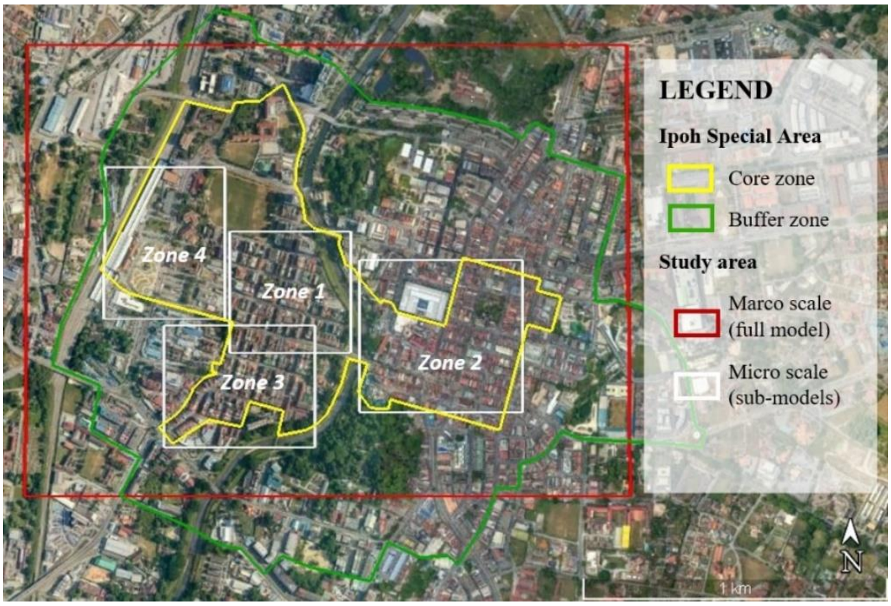


Fig. 3.4. The overall study zoning and sub-zones (adapted from: Google Earth, accessed 9th July 2019).

Zone 1 locates in the upper part of the shophouse zone in the Old Town. Its boundary is physically defined by the Kinta River, the primary road (*Jalan Sultan Iskandar*), and where the fabric texture is clearly different from the neighbouring area. The main feature of Zone 1 was the diverse frontage orientation pattern in this area. Also, compared to others, Zone 1 is relatively more compact. Its roads vary in size, and similarly, the size and shape of the building clusters in the area are not uniform.

The overall layout pattern in New Town is relatively more uniform and simpler than Old Town, which has been explained in Chapter 1.5.2. Particularly at Zone 2, it was the core of New Town. The boundary was mainly bounded by the Kinta River and the border where its urban fabric is divided from the adjacent area. Despite the differences, Zone 1 and Zone 2 also have two characteristics in common. First of all, they both have a clear boundary edge, and we can clearly distinguish them from neighbourhood areas. Secondly, compared with other adjacent areas, Zone 1 and 2 show a very rigid grid form, where the buildings are placed exactly in either East-West or North-South orientation.

Zone 3 is also a shophouse area, but its layout is completely more complex but unique than other areas. It is the only area in the town having a curved layout. At the same time, it also contains certain layout features of Zone 1 and 2, respectively. It can be found that the cluster layout is similar to that of Zone 1, which is arranged in multiple sizes and shapes, but the buildings are more constructed in the orientation pattern of Zone 2. The boundary is mainly featured by the Kinta River and where the fabric texture is clearly different from the neighbouring area.

Lastly, Zone 4 represented the non-shophouses area of Old Town, where many large institutional buildings and open spaces were located. It mainly focused on the heritage buildings along the primary road (Jalan Panglima Bukit Gantang Wahab). The area is ranged from Royal Ipoh Club (Padang Ipoh) to Ipoh Station, covering all heritage assets in the area.

Besides their physical characteristics, Zones 1-4 are also distinct in their activities, heritage values, and attractions, summarised in Table 3.1. For modelling and simulation purposes, all zonings are specifically shaped into rectangles, and the size of each area depended on the coverage area required for the study.

Table 3.1. The basic information of sub-models in this research.

Zone	**Description**	**Characteristics**	
		Heritage value	**Attractions**
1	Old town heritage and shophouse area	High	• Concubine Lane shopping street • Plenty of heritage buildings and murals spots to visit
2	New town business and shopping area	Medium-low	• Gerbang Malam night market • Mural street • Local food hunting and shopping area
3	Old town business and shopping area	Medium-low	• Little India shopping district • Traditional Chinese trading zone: grocery and coffee shops
4	Old town heritage and institutional area	High	• Full of colonial-style architecture: Ipoh Royal Club, Ipoh Railway Station, Town Hall, High Court, Clock Tower, etc.

3.4 METHODOLOGY

3.4.1 Model Building in ArcGIS

In this study, the map and building footprint used in the simulation were mainly imported from the existing resources provided by Ipoh local authority. After importing the model layout built by the CAD (computer-aided design) tool, there were three fundamental steps to build a climate area input model in the ArcGIS platform, as follows:

3.4.1.1 The creation or update of the database

The necessary input data for climate simulation included building height, landcover materials and vegetation types - most obtained from Google Earth and field survey. From there, two main layers were created: the above-ground layer (building and vegetation) and the ground layer (surface material). They were respectively coded in the category named: Elevation and LC_code (see some extracted examples, as shown in Figure 3.5). Buildings were coded based on their height in meters (m), whereas vegetation and land cover were coded based on their respective types. Table 3.2 shows the types of vegetation and land cover based on the coding given. Figure 3.6 showed the final vector layers, which served as the baseline model throughout the research process.

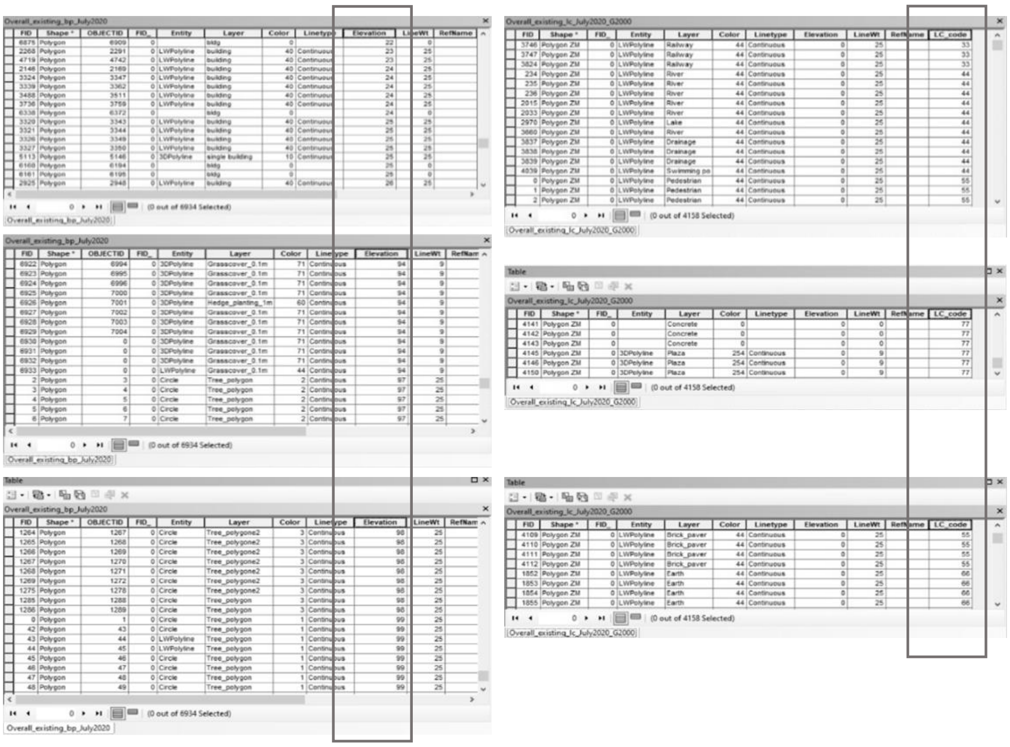


Fig. 3.5. The input of modelling elements for microclimate simulation based on their attributes (a screenshot image from ArcGIS).

Table 3.2. Coding list of vegetation and landcover used for this research.

VEGETATION		LANDCOVER	
Type	**Code**	**Type**	**Code**
Grasscover	94	Railway	33
Hedge	95	Water	44
10m_Tree	97	Brick paver	55
15m_Tree	98	Earth	66
20m_Tree	99	Concrete	77
		Asphalt	88*

*(*not presented in vector form.)*

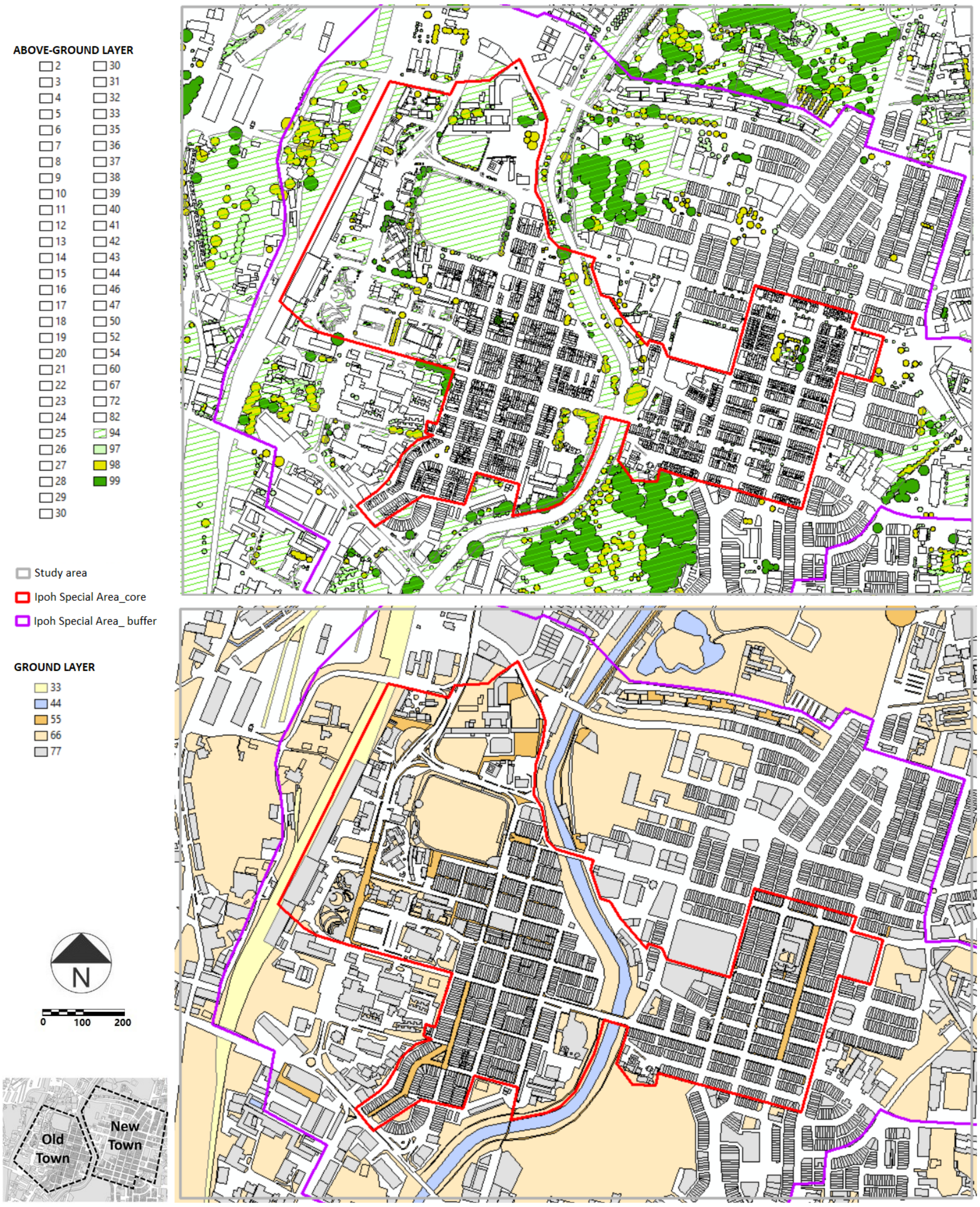


Fig. 3.6. The vector image of the entire study area in Ipoh downtown.

3.4.1.2 The model mode conversion: Vector to Raster

The grid resolution pixel size mainly relied on the extracted area size, computer capacity and simulation time. There was a premise that a 24-hour simulation should be completed within one month (this situation considered the limitations of time and computer hardware specification used for the research). After several trials and errors to optimise the data fidelity of the large model for this research, it was finally discovered that a 5-meter grid most fitted the entire study area, which was about 2000m x 1500m. Further, in order to obtain high-resolution output data, four sub-models have been extracted from the baseline model according to the zoning explained in Section 3.3 (Figure 3.7). A 2-meter grid was applied to this case. The conversion tool used for this step was Polygon to Raster.

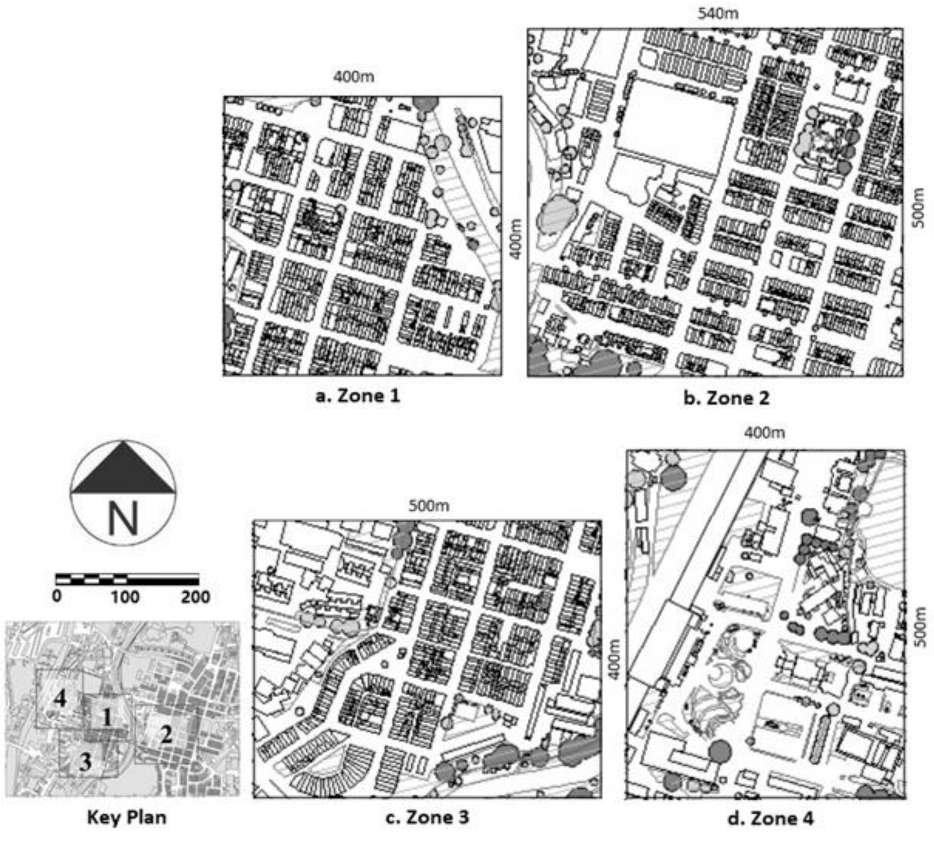


Fig. 3.7. The location and extracted layout of sub-models.

After being converted to raster mode, it was found that some grid cells were "NoData". These "NoData" cells represented the following conditions:

- Above-ground layer: without any elements above the ground. It should be coded as "0" (equal to 0m in building height).
- Ground floor: the asphalt surface of alley, lanes and roads. It should be coded as "88" (refer to Table 3.2).

In order to avoid the existence of "NoData" cells in the later simulation model, the rasterised layers were all reclassified through the Reclass tool. It was to change "NoData" to the values mentioned above accordingly. (Figure 3.8). After this, the reclassified layers (above-ground and ground layers) were ready to export from ArcGIS.

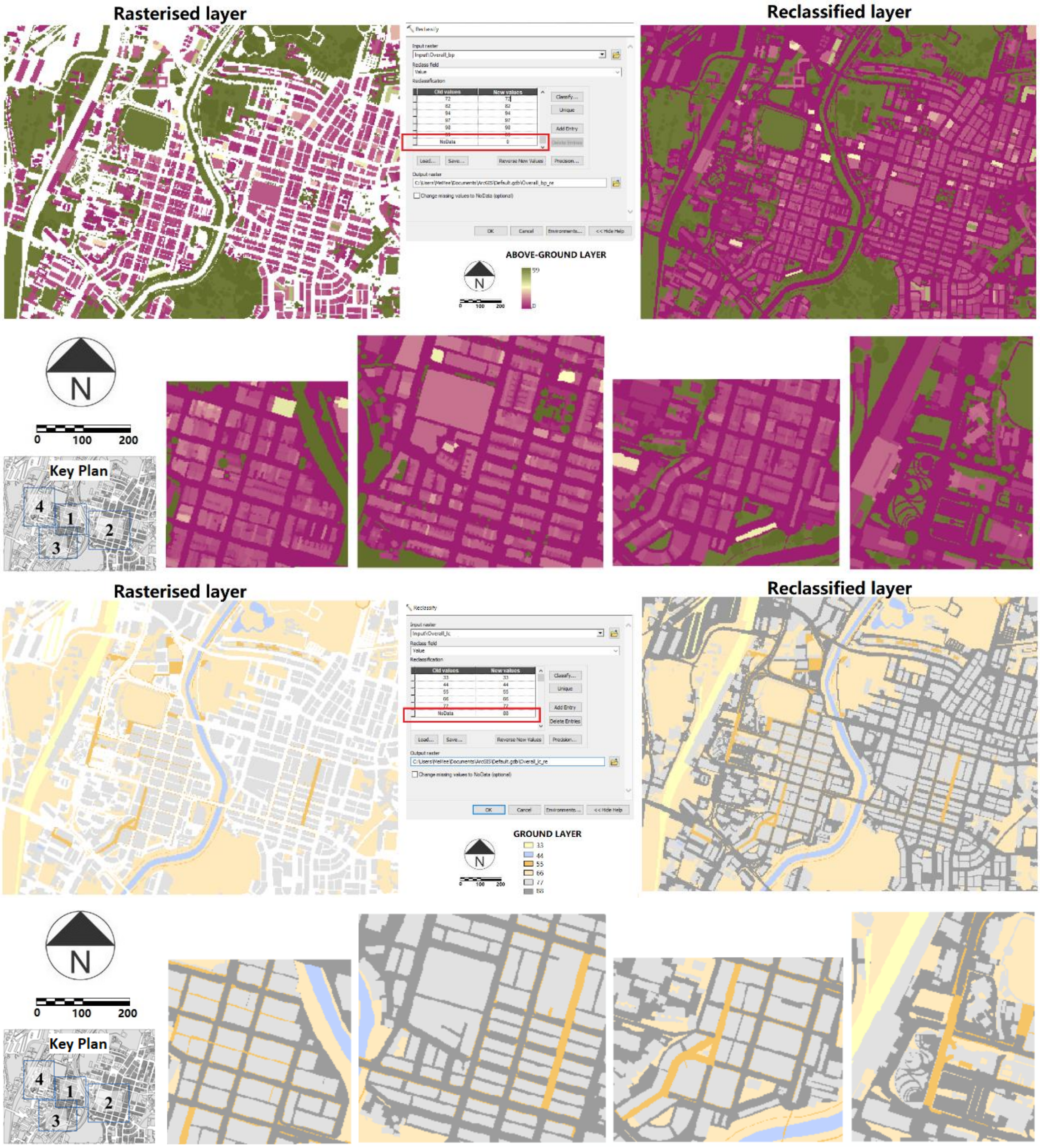


Fig. 3.8. All raster layers are reclassified through Reclassify tool in ArcGIS.

3.4.1.3 The model extension conversion: Raster to ASCII

The raster model was finally exported to ASCII files through the conversion tool, i.e., Raster to ASCII. The buildings and vegetation, and the ground surface materials, were composed as above-ground and ground layers, respectively. ASCII was the final extension in the ArcGIS interface. From Figure 3.9, it can see that the raster images have been converted to digital files. At the top of these two files, it consisted of the summary of the model area as well, which including the total amount of grids in X (ncols) and Y (nrows) axis, coordinate of X (xllcorner) and Y(yllcorner) axis, and cell size.

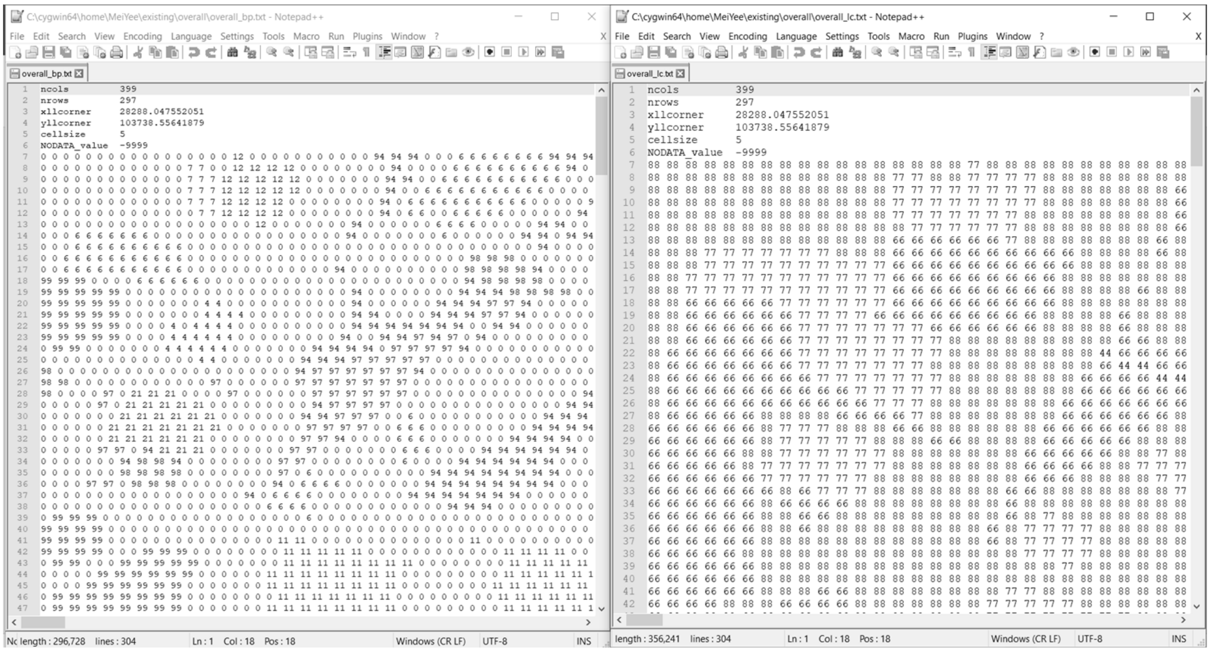


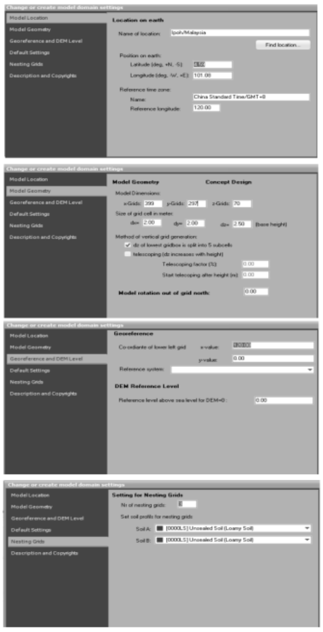
Fig. 3.9. An example showing the raster model was finally exported in digital form (ASCII) for simulation purposes.

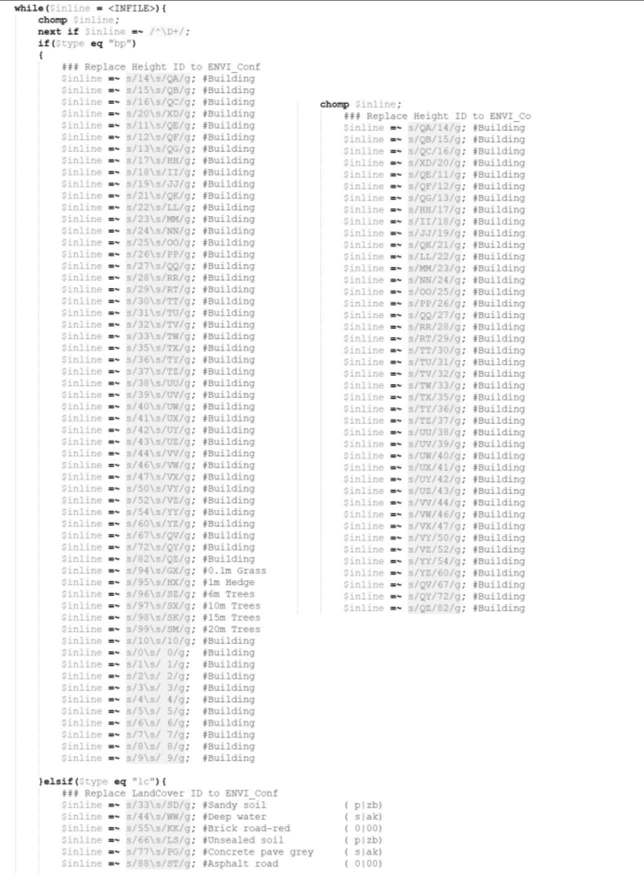
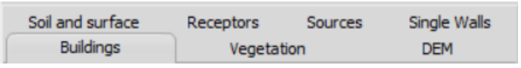
3.4.2 An Intermediate Medium between GIS and ENVI-met Tools

It should be noted that the latest ENVI-met has improved their model building and offered the possibilities to directly import a GIS shapefile, a CAD file or even a Streetmap file through Monde (Bruse, n.d.). However, the use of Monde in creating a model input area remains time-consuming and challenging for most non-expert users. In view of that, this research provided another alternative applicable to extending the GIS model to the ENVI-met platform.

ASCII files cannot be directly imported into the ENVI-met platform. The model exported from ArcGIS must be modified and converted to the format and extension compatible with ENVI-met, i.e., IN or INX (the extension of area input file used in ENVI-met). At the same time, the coding built in the ArcGIS needed to be decoded, re-processed and synchronised with the coding in the ENVI-met database. A relevant Perl script was obtained through personal communication with the authors who previously conducted a similar study in Malaysia (Saito et al., 2017). In this study, the script has been modified and fitted to the study context accordingly. The script editing works were mainly done using Notepad++. Table 3.3 presents the modification of the script formulated for this research.

Table 3.3. The script used to convert the ASCII files to ENVI-met input files.

<table>
<tr><th>Script content</th><th>Function or purpose</th></tr>
<tr><td>$workdir="/home/MeiYee/existing";
$datdir=$workdir."/overall/";
$envdir=$workdir."/overall/";
$inline;</td><td>To determine workspace to extract and store the files</td></tr>
<tr><td>our @arrModel = ("overall"); #ModelName
our @arrType = ("bp","lc"); #GIS layer(Height|Landcover)
our @arrRes = (5); #Raster cellsize</td><td>To determine the input files and cell size</td></tr>
<tr><td>#-------------------------------------
my $zdirection = 75; #z direction
my $vgridsize = 2.5; # Vertical Gridsize
#-------------------------------------</td><td>To determine the 3D Z-axis margin and cell size</td></tr>
<tr><td>$inline=<INFILE>;
@list = split(/\s+/,$inline);
if($i == 0){$ncol = $list[1];}
elsif($i == 1){$lows = $list[1];}
elsif($i == 2){$xll = $list[1];}
elsif($i == 3){$yll = $list[1];}
elsif($i == 4){$size = $list[1];}</td><td>Refer to the summary of the model area that has been listed in ASCII text files. They included the total amount of grids in X (ncols) and Y (nrows) axis, coordinate of X (xllcorner) and Y(yllcorner) axis, and cell size.</td></tr>
<tr><td>print OUTFILE "% Number of grids in x, y and z direction\n";
print OUTFILE $ncol."\n";
print OUTFILE $lows."\n";
print OUTFILE $zdirection."\n";
print OUTFILE "% Base Horizontal Gridsize dx, dy\n";
print OUTFILE $size."\n";
print OUTFILE $size."\n";
print OUTFILE "% Vertical Gridsize\n";
print OUTFILE $vgridsize."\n";
print OUTFILE "% Telecoping vertical Grid? 0= No 1= Yes\n";
print OUTFILE "0\n";
print OUTFILE "% Model rotation out of grid north in deg\n";
print OUTFILE "0.0\n";
print OUTFILE "% Number of nesting grids\n";
print OUTFILE "3\n";
print OUTFILE "% Soil Profile ID for Nesting Grid A\n";
print OUTFILE " LS\n";
print OUTFILE "% Soil Profile ID for Nesting Grid B\n";
print OUTFILE " LS\n";
print OUTFILE "% Geographical Projection System\n";
print OUTFILE "GK\n";
print OUTFILE "% Real world coordinate lower left grid x and y\n";
print OUTFILE $xll."\n";
print OUTFILE $yll."\n";
print OUTFILE "% Name of location (city,..)\n";
print OUTFILE "Ipoh/Malaysia\n";
print OUTFILE "% Position on earth (latitude and longitude\n";
print OUTFILE "4.59\n"; #Ipoh
print OUTFILE "101.08\n";
print OUTFILE "% Name of reference time zone\n";
print OUTFILE "China Standard Time/GMT+8\n";
print OUTFILE "% Definition longitude of time zone\n";
print OUTFILE "120.00\n";
print OUTFILE "% Define where area data are located\n";
print OUTFILE "[INTERNAL]\n";
print OUTFILE "% Model-Domain: z- of Building Top, Plants\n";</td><td>This section contained all the information that must be included in the ENVI-met area input file, synchronised with the model domain setting in ENVI-met SPACE.
</td></tr>
</table>

	Separated the building and vegetation layers, and replaced all coding with relevant input values synchronised with SPACE input layers. 

The edited Perl script was then needed to be executed using the Cygwin application (Figure 3.10). Cygwin is "a distribution of popular GNU and other Open-Source tools running on Microsoft Windows" (Cygwin FAQ, n.d.). Once the script was completed, a new.IN (the extension of area input file used in ENVI-met) file would be found in the working folder (Figure 3.11).

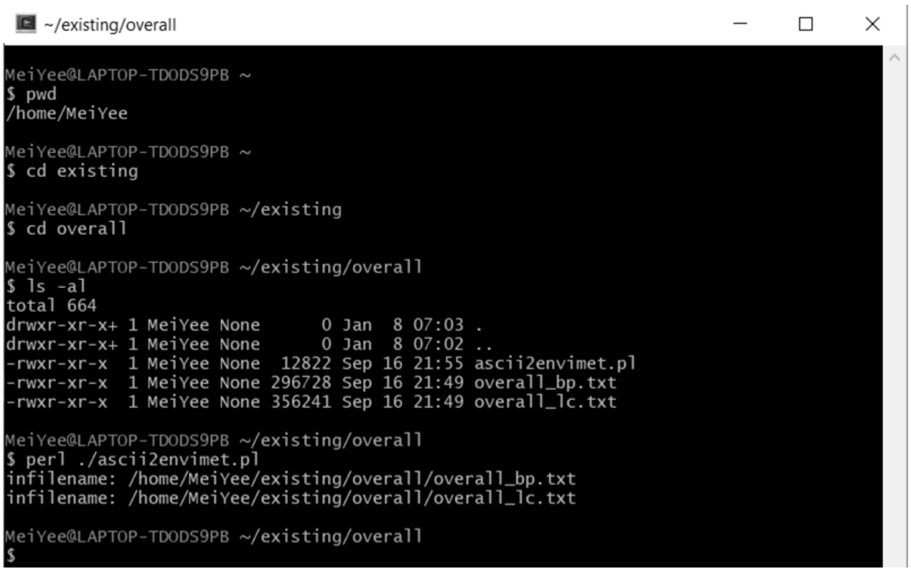


Fig. 3.10. The Cygwin interface: running a Perl script.

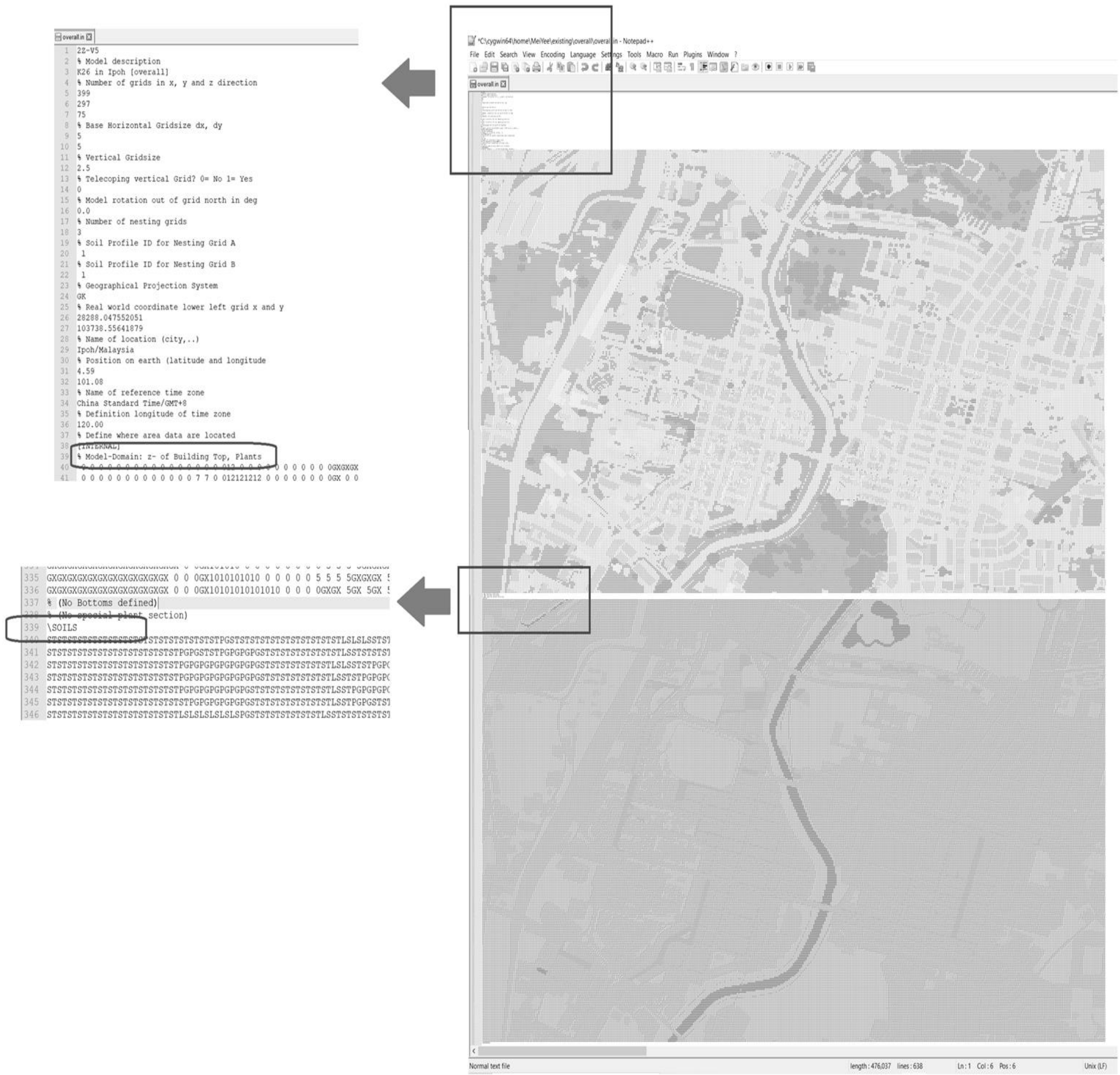


Fig. 3.11. An example of the area input file (IN.) for ENVI-met simulation.

3.4.3 Microclimate Simulation in ENVI-met

ENVI-met version 4.4.5 was used in this study. In ENVI-met, we imported the input model area extracted from GIS in SPACE. The entire model area was approximately 400m x 300m x 75m, with the model grid resolution of 5m x 5m x2.5m in dx, dy and dz directions, respectively. Each pixel cell integrated all physical properties depicted in layers, ranged from the building, vegetation to soil and surface. Several vegetations used in this research did not exist in the existing planting specifications of the ENVI-met system database (see Table 3.4). So they were added to the system by importing the user database through Database Manager tool (Figure 3.12).

Table 3.4. The introduced vegetation (modified from existing species in the system database) used for the simulation.

Vegetation	Script
10-meter-height dense tree	<PLANT> <ID> 0000SX </ID> <Description> Tree 10 m very dense, distinct crown layer </Description> <AlternativeName> (None) </AlternativeName> <Planttype> 0 </Planttype> <Leaftype> 1 </Leaftype> <Albedo> 0.20000 </Albedo> <Transmittance> 0.30000 </Transmittance> <rs_min> 400.00000 </rs_min> <Height> 10.00000 </Height> <Depth> 2.00000 </Depth> <LAD-Profile> 0.15000,0.15000,0.15000,0.15000,0.65000,2.15000,2.18000,2.05000,1.72000,0.00000 </LAD-Profile> <RAD-Profile> 0.10000,0.10000,0.10000,0.10000,0.10000,0.10000,0.10000,0.10000,0.10000,0.00000 </RAD-Profile> <Season-Profile> 1.00000,1.00000,1.00000,1.00000,1.00000,1.00000,1.00000,1.00000,1.00000,1.00000,1.00000,1.00000 </Season-Profile> <Group> - Legacy | Hedges and others </Group> <Color> 56576 </Color> </PLANT>
6-meter-height dense tree*	<PLANT> <ID> 0000SZ </ID> <Description> Tree 6 m very dense, distinct crown layer </Description> <AlternativeName> (None) </AlternativeName> <Planttype> 0 </Planttype> <Leaftype> 1 </Leaftype> <Albedo> 0.20000 </Albedo> <Transmittance> 0.30000 </Transmittance> <rs_min> 400.00000 </rs_min> <Height> 6.00000 </Height> <Depth> 1.00000 </Depth> <LAD-Profile> 0.15000,0.15000,0.15000,0.15000,0.65000,2.15000,2.18000,2.05000,1.72000,0.00000 </LAD-Profile> <RAD-Profile> 0.10000,0.10000,0.10000,0.10000,0.10000,0.10000,0.10000,0.10000,0.10000,0.00000 </RAD-Profile> <Season-Profile> 1.00000,1.00000,1.00000,1.00000,1.00000,1.00000,1.00000,1.00000,1.00000,1.00000,1.00000,1.00000 </Season-Profile> <Group> - Legacy | Hedges and others </Group> <Color> 56576 </Color> </PLANT> *(*not used in this stage. Refer to the following chapters)*
1-meter-height dense hedge	<PLANT> <ID> 0000HX </ID> <Description> Hedge dense, 1m </Description> <AlternativeName> (None) </AlternativeName> <Planttype> 0 </Planttype> <Leaftype> 1 </Leaftype> <Albedo> 0.20000 </Albedo> <Transmittance> 0.30000 </Transmittance> <rs_min> 400.00000 </rs_min> <Height> 1.00000 </Height> <Depth> 0.30000 </Depth> <LAD-Profile> 2.50000,2.50000,2.50000,2.50000,2.50000,2.50000,2.50000,2.30000,2.20000,1.50000 </LAD-Profile> <RAD-Profile> 0.10000,0.10000,0.10000,0.10000,0.10000,0.10000,0.10000,0.10000,0.10000,0.00000 </RAD-Profile> <Season-Profile> 1.00000,1.00000,1.00000,1.00000,1.00000,1.00000,1.00000,1.00000,1.00000,1.00000,1.00000,1.00000 </Season-Profile> <Group> - Legacy | Hedges and others </Group> <Color> 56576 </Color> </PLANT>
10cm-height grass	<PLANT> <ID> 0000GX </ID> <Description> Grass 10 cm aver. dense </Description> <AlternativeName> (None) </AlternativeName> <Planttype> 0 </Planttype> <Leaftype> 1 </Leaftype> <Albedo> 0.20000 </Albedo> <Transmittance> 0.30000 </Transmittance> <rs_min> 200.00000 </rs_min> <Height> 0.10000 </Height> <Depth> 0.10000 </Depth> <LAD-Profile> 0.30000,0.30000,0.30000,0.30000,0.30000,0.30000,0.30000,0.30000,0.30000,0.30000 </LAD-Profile> <RAD-Profile> 0.10000,0.10000,0.10000,0.10000,0.10000,0.10000,0.10000,0.10000,0.10000,0.00000 </RAD-Profile> <Season-Profile> 1.00000,1.00000,1.00000,1.00000,1.00000,1.00000,1.00000,1.00000,1.00000,1.00000,1.00000,1.00000 </Season-Profile> <Group> - Legacy | Hedges and others </Group> <Color> 56576 </Color> </PLANT>

Fig. 3.12. Importing user database into the model system through Database Manager interface.

In ENVI-met, to run a simulation, it was necessary to build up the simulation configuration using ENVI-guide, namely ‘simulation file’ (.SIMX) (Bruse, n.d.). The simulation configuration was created to define a simulation task, including a 3-D model (.INX file- see an example in Figure 3.13), the meteorological settings, and other simulation details such as the naming of input and output files, time duration, and starting time. The microclimate simulation was carried out on June 21st, 2018. It was the summer solstice, representing the longest daytime of the year. The overall initial and boundary conditions used for simulations were summarised and shown in Table 3.5.

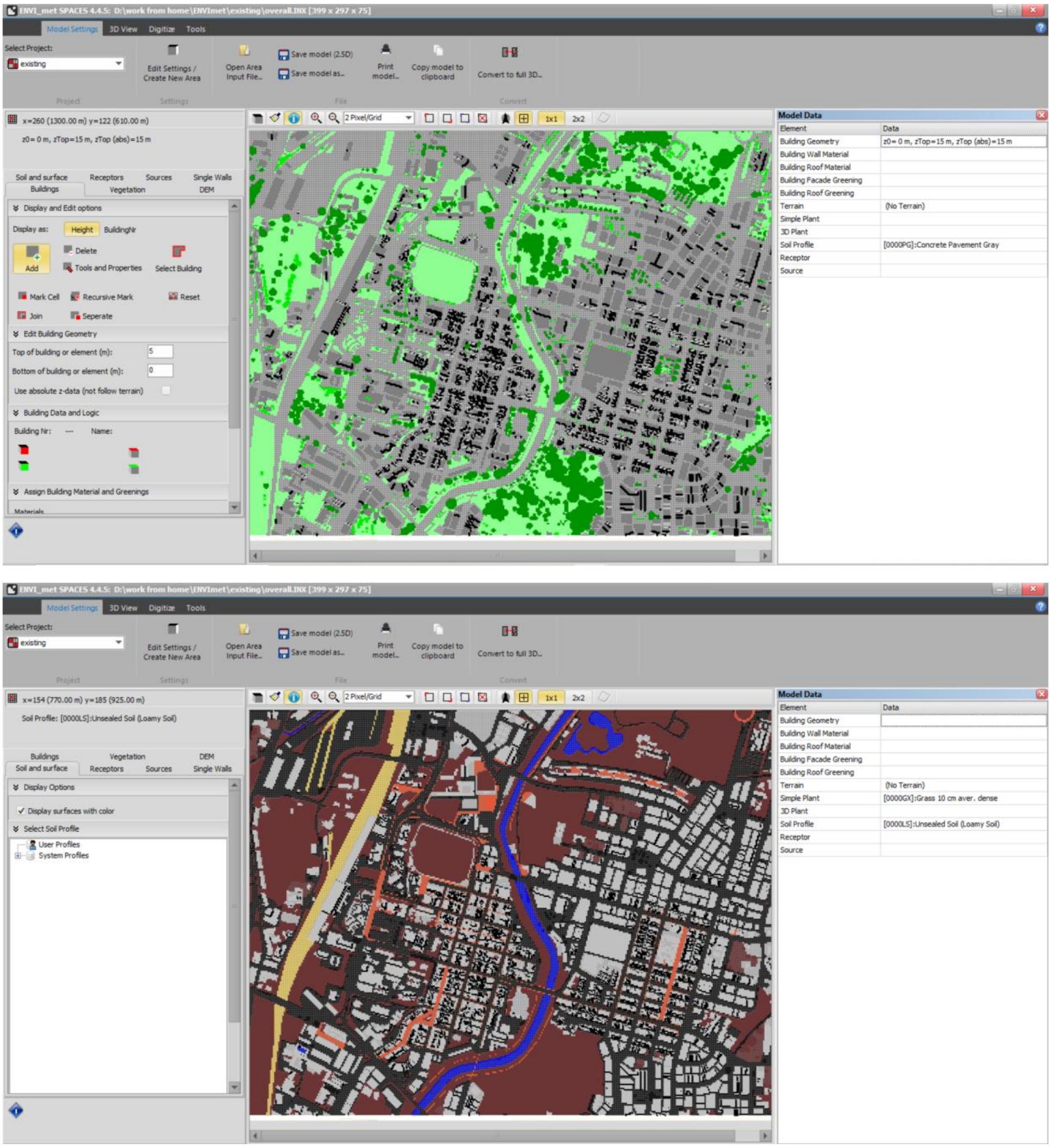
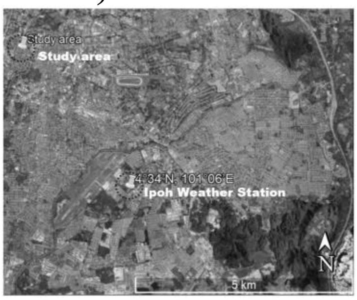


Fig. 3.13. The model area displayed in the ENVI-met Space interface.

Table 3.5. Initial and boundary conditions used in the ENVI-met simulations.

SETTING	INPUT DATA	
Time and date	Starting date and time	20.6.2018;18:00
	Duration	24h
Model	Location (Latitude & Longitude)	Ipoh (4.59N, 101.08E)
	Reference time zone	GMT+8
	Model size (m)	*-varied-*
	Model area (no. of grid)	*-varied-*
	Size of grid cell (m)	2 x 2 x 2.5 (micro models) 5 x 5 x 2.5 (macro models)
Initial meteorological and boundary conditions ** meteorological data observed at the Ipoh Weather Station. (see the location below: 4°34'N, 101°06'E).*  	Wind speed in 10m ht.	1.7m/s
	Wind direction (0 = from North;180 = from South)	45°
	Roughness length at measurement site	0.1
	Initial temperature of atmosphere	28.1 22.8°C (minimum) – 32.8°C (maximum)
	Relative humidity in 2m	57% (minimum) – 97% (maximum)
	Boundary condition	Forced (simple forcing) **only the humidity and temperature can be forced in this 24-hours setting*
	Nesting grid	3
	Cloud setting	*default setting:* 0.00 *(clear sky)*
	Turbulence model	*default setting:* Standard Turbulence Kinetic Energy (TKE) Model (Bruse / ENVImet 2017)
Dynamic time step	For solar angle ≥50°	*default setting:* 1s
	For solar angle < 50°	*default setting:* 2s
Initial soil and plant conditions	Initial temperature of soil	*default setting:* 19.85°C
	Soil humidity	*default setting:* • 70% - for upper layer (0-20cm) • 75% - for middle & deep & bedrock layers (20-50cm; 0-200cm; below 200cm)
	CO2 background level	*default setting:* 400ppm *(based on A-g_s model: calculates the photosynthesis rate of plants and concludes from that to the CO_2 demand and finally to the state of the stomata)*

Solar radiation	Adjustment factor for solar radiation	*default setting:1.00*
Initial indoor conditions	Building temperature	*default setting:* 19.85℃
OTHER INPUT: MATERIALS USED IN SIMULATION MODELS		
Default setting for Wall and Roof	System database: *default setting:* Default wall-moderate insulation [000000] *<Materials> 0100PL,0100IN,0100CO* *<ThicknessLayers> 0.01000,0.12000,0.18000* *<RoughnessLength> 0.02000*	
Soil and surface	System database: a. Unseal soil (loamy soil) [0000LS] *<z0_Length> 0.01500* *<soilprofil> 0000LE,0000LE,0000LE,0000LE,0000LE,0000LE,0000LE,0000LE, 0000LE,0000LE,000LE,0000LE,0000LE,0000LE,0000LE,0000LE,0000LE,0000LE,0000LE* *<Albedo> 0.20000* *<Emissivität> 0.98000* b. Asphalt road [0000ST] *<z0_Length> 0.01000* *<soilprofil> 0000AB,0000AB,0000AB,0000AB,0000AB,0000AB,0000AB,0000AB, 0000AB,0000LE,0000LE,0000LE,0000LE,0000LE,0000LE,0000LE,0000LE,0000LE,0000LE* *<Albedo> 0.20000* *<Emissivität> 0.90000* c. Concrete pavement gray [0000PG] *<z0_Length> 0.01000* *<soilprofil> 0000ZB,0000ZB,0000ZB,0000ZB,0000SD,0000LE,0000LE, 0000LE,0000LE, 0000LE,0000LE,0000LE,0000LE,0000LE,0000LE,0000LE,0000LE,0000LE,0000LE* *<Albedo> 0.50000* *<Emissivität> 0.90000* d. Deep water [0000WW] *<z0_Length> 0.01000* *<soilprofil> 0000WW,0000WW,0000WW,0000WW,0000WW,0000WW,0000WW,0000WW,0000WW, 0000WW,0000WW,0000WW, 0000WW,0000WW,0000WW,0000WW,0000WW,0000WW,0000WW* *<Albedo> 0.00000* *<Emissivität> 0.96000* e. Brick road [0000KK] *<z0_Length> 0.01000* *<soilprofil>0000BR,0000BR,0000BR,0000SD,0000LE,0000LE,0000LE,0000LE,0000LE,000LE, 0000LE,0000LE,0000LE,0000LE,0000LE, 0000LE,0000LE,0000LE,0000LE* *<Albedo> 0.30000* *<Emissivität> 0.90000* f. Sandy soil [0000SD] *<z0_Length> 0.05000* *<soilprofil>0000SD,0000SD,0000SD,0000SD,0000SD,0000LE,0000LE,0000LE,0000LE,0000LE,0000LE,0000LE,0000LE,0000LE, 0000LE,0000LE,0000LE,0000LE,0000LE* *<Albedo> 0.00000* *<Emissivität> 0.90000*	
Trees & vegetation	System database: a. 20m_trees: Tree 20m, very dense, distinct crown [0000SM] * b. 15m_trees: Tree 15m, very dense, distinct crown [0000SK] * ** The plant model database entry includes CO2 fixation type, leaf type, albedo, transmittance, plant height, root zone depth, LAD profile, RAD profile and season profile.*	
	User database: c. 10m_trees: modified based on [0000SM] and [0000SK] in system database d. 1m_hedge: modified based on hedge dense, 2m [0000H2] in system database e. 10cm_grass: modified based on Grass 50cm aver, dense [0000XX] in system database	

The climate data used in the simulation was referred to as the actual monthly records done by the Ipoh weather station in 2018. The total simulation time was 24 hours, starting from 18:00 on the previous day (June 20th). However, only the last 12-hours of data, from 06:00 until 18:00 on June 21st, were accepted as valid for study. The first 12 hours were used to spin up the model (Middel et al., 2014), allocating to stabilise and increase the overall performance of the model, and so not being counted in this research (Figure 3.14).

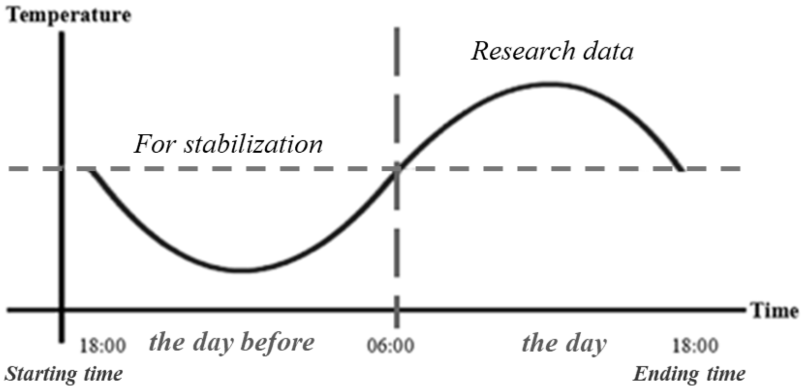


Fig. 3.14. The numeric simulation data can be more accurate if the calculation followed the atmospheric process in advance and started at night (ENVI-met 3.1 Manual Contents, n.d.), assuming that the tested environment has been completely stabilised before sunrise.

After completed the simulation configuration, the simulation model would be loaded, checked and run in ENVI-core. After the simulation was done, it can be found that a vast amount of hourly data (the output interval can be edited in configuration setting as well) were generated, organised, and stored in different files, automatically.

In LEONARDO, the output data was displayed one-by-one using DataNavigator. To examine thermal resilience, this study only extracted the 2-dimensional data at the time of 14:00, the hottest hour of the day recorded in measured data. Five parameters were studied in this research: air temperature, mean radiant temperature, wind speed, relative humidity, and surface temperature. The first four were extracted from the atmosphere output, explicitly at 1.75m above the ground (=3k in the position of view plane), which is the level closest to a typical pedestrian's height. The surface temperature was separately obtained from the surface output. These extracted map layers were then exported in text format (CSV extension) for further analysis (Figure 3.15).

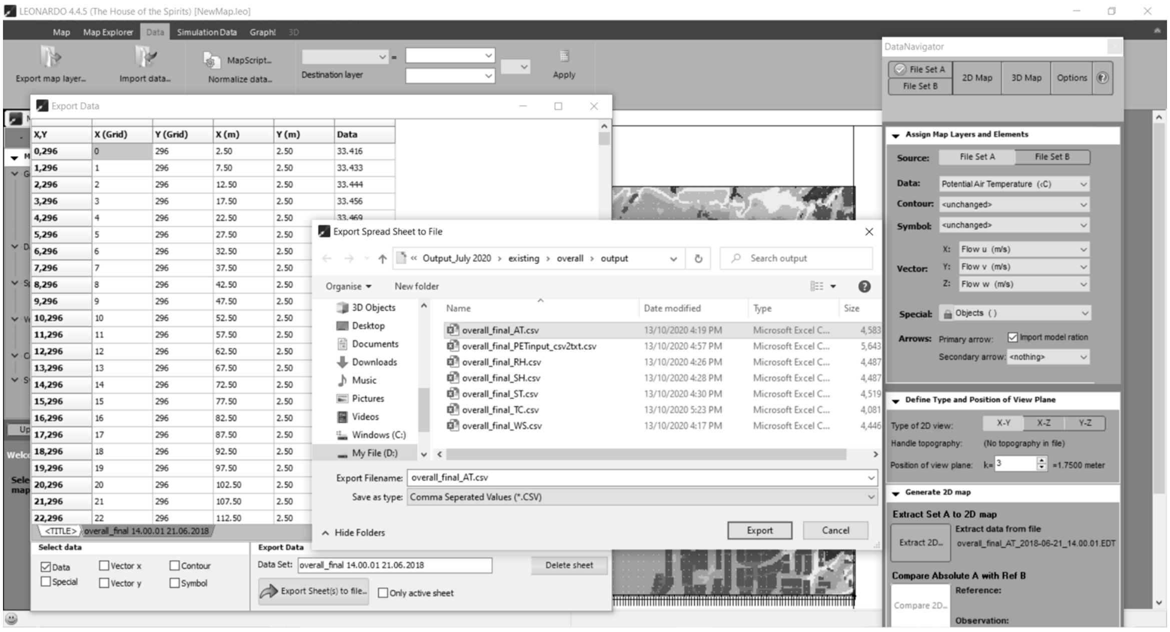


Fig. 3.15. An example of extracting and exporting the final output (the air temperature) in the ENVI-met system.

3.4.4 Calculation of Physiological Equivalent Temperature (PET)

To comprehensively assess the thermal performance, we have also considered the human comfort aspect using Physiological Equivalent Temperature (PET) evaluation. PET has been widely adopted in many relevant studies, as summarised in Deb and Ramachandraiah (2010). In this study, we calculated PET in Rayman, a software tool introduced by Matzarakis et al. (2007 & 2010). The Rayman simulation required date, time, geographic location, personal setting, and climate datafile. The climate data (in text files) included the information of date, time, air temperature (^{o}C), surface temperature (^{o}C), mean radiant temperature (^{o}C), wind speed (m/s) and relative humidity (%), which extracted from the simulated output of ENVI-met. As for the personal setting, this study referred to the index used in the previous study in Malaysia (Saito et al., 2017), setting the metabolic rate and clothing insulation to 93(W) and 0.3(*clo)* in, respectively. Table 3.6 summarised all input information required on the Rayman main page. After obtaining the output from RayMan, we evaluated the thermal comfort level based on the tropical thermal comfort classification modified by Lin and Matzarakis (2008) (refer to Table 3.7). In order to visualise and further analyse the PET, we modified the output file mode (same as those CSV files created in ENVI-met) so that it could be converted back to ArcGIS along with other files in the next stage.

Table 3.6. Input parameters required for PET calculations.

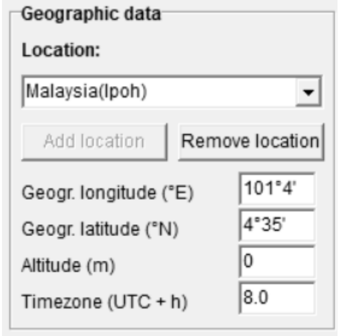
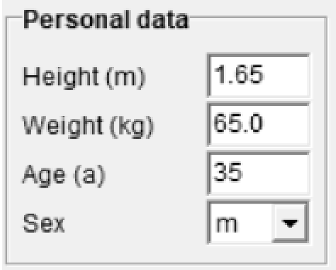
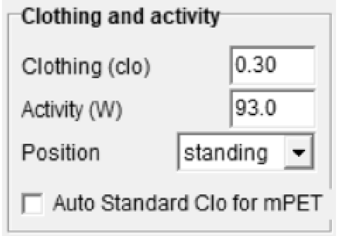
<table>
<tr><th colspan="2">Parameters</th><th colspan="2">Input</th></tr>
<tr><td colspan="2">Date</td><td>June 21st, 2018</td><td rowspan="2">
</td></tr>
<tr><td colspan="2">Time</td><td>14:00</td></tr>
<tr><td colspan="2">Location</td><td>Malaysia (Ipoh)</td><td>
</td></tr>
<tr><td rowspan="4">Personal data</td><td>Height (m)</td><td>1.65</td><td rowspan="4">
</td></tr>
<tr><td>Weight (kg)</td><td>65</td></tr>
<tr><td>Age</td><td>35</td></tr>
<tr><td>Sex</td><td>male</td></tr>
<tr><td rowspan="3">Clothing and activity</td><td>Clothing (clo)</td><td>0.3</td><td rowspan="3">
</td></tr>
<tr><td>Activity (W)</td><td>93</td></tr>
<tr><td>Position</td><td>Standing</td></tr>
</table>

Table 3.7. Thermal comfort classification used for the tropical region. (Source: Lin and Matzarakis, 2008)

Thermal perception	Index	Temperature range [ºC]
Very cold	-4	<14
Cold	-3	14-18
Cool	-2	18-22
Slightly cool	-1	22-26
Neutral	0	26-30
Slightly warm	1	30-34
Warm	2	34-38
Hot	3	38-42
Very hot	4	>42

3.4.5 Output Models Conversion to GIS Platform

After completing all simulations in 3.3.3 and 3.3.4, the climate and thermal comfort data needed to be redirected to the GIS platform for further spatial-climate analysis. The data were reorganised and conducted in a reverse process. Another Perl script was used to run in the Cygwin program for this step. It should be noted that the master copy of the Perl script running at this stage was also given by the same author mentioned in 3.3.2. After modifying the script accordingly (see the content in Table 3.8), all CSV files were successfully developed into ASCII extension (Figure 3.16).

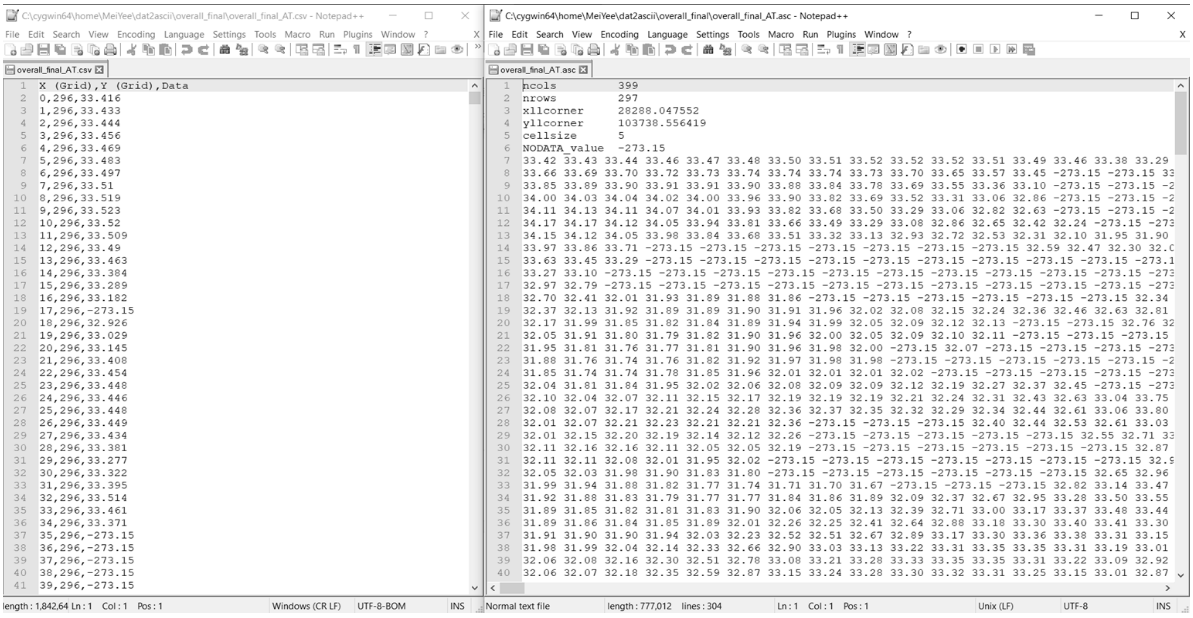


Fig. 3.16. Example of conversion from an ENVI-met CSV output (left) to an ASCII file (right) used in the GIS platform.

Table 3.8. The script used to convert the output CSV files to ASCII input files.

Script content	Function or purpose

`our $workdir="/home/MeiYee/dat2ascii/";`
`our $datdir=$workdir."overall_final/";`
`our @files=();`
`our $inline;`
	To determine workspace to extract and store the files

`our $resX = 399;`
`our $resY = 297;`
`our $cellsize = 5;`
	To determine the total amount of cells and cell size (refer to the input or output files of ENVI-met)

`my($base_name,$dir,$suffix) = fileparse($filename,'.csv');`
 	
`our $infile=$datdir.$base_name.".csv";`
`our $outfile=$datdir.$base_name.".asc";`
	To determine the extension of input file and output file (from CSV to ASCII)

`print OUTFILE "ncols ".$resX."\n";`
`print OUTFILE "nrows ".$resY."\n";`
`print OUTFILE "xllcorner 28288.047552\n";`
`print OUTFILE "yllcorner 103738.556419\n";`
`print OUTFILE "cellsize ".$cellsize."\n";`
	Refer to the input files of ENVI-met. They included the total amount of grids in X (ncols) and Y (nrows) axis,

<table>
<tr><td></td><td>coordinate of X (xllcorner) and Y(yllcorner) axis, and cell size.</td></tr>
<tr><td><code>if($index eq "RH"){</code>
<code>   print OUTFILE "NODATA_value -999\n";</code>
<code>}elsif($index eq "AT"){</code>
<code>   print OUTFILE "NODATA_value -273.15\n";</code>
<code>}elsif($index eq "ST"){</code>
<code>   print OUTFILE "NODATA_value 19.85\n";</code>
<code>}elsif($index eq "SH"){</code>
<code>   print OUTFILE "NODATA_value -999\n";</code>
<code>}elsif($index eq "TC"){</code>
<code>   print OUTFILE "NODATA_value 9999\n";</code>
<code>}else{</code>
<code>   print OUTFILE "NODATA_value 0\n";</code>
<code>}</code></td><td>To determine NoData values for each parameter. The abbreviations were explained in the following:

RH = relative humidity
AT = atmospheric temperature
ST = surface temperature
SH = mean radiant temperature
TC = PET</td></tr>
</table>

After Cygwin, the ASCII files were finally converted to raster mode in ArcGIS for integration and analysis purposes. The conversion tool used for this step was ASCII to Raster. The overall workflow in Section 3.4 is presented in Figure 3.17.

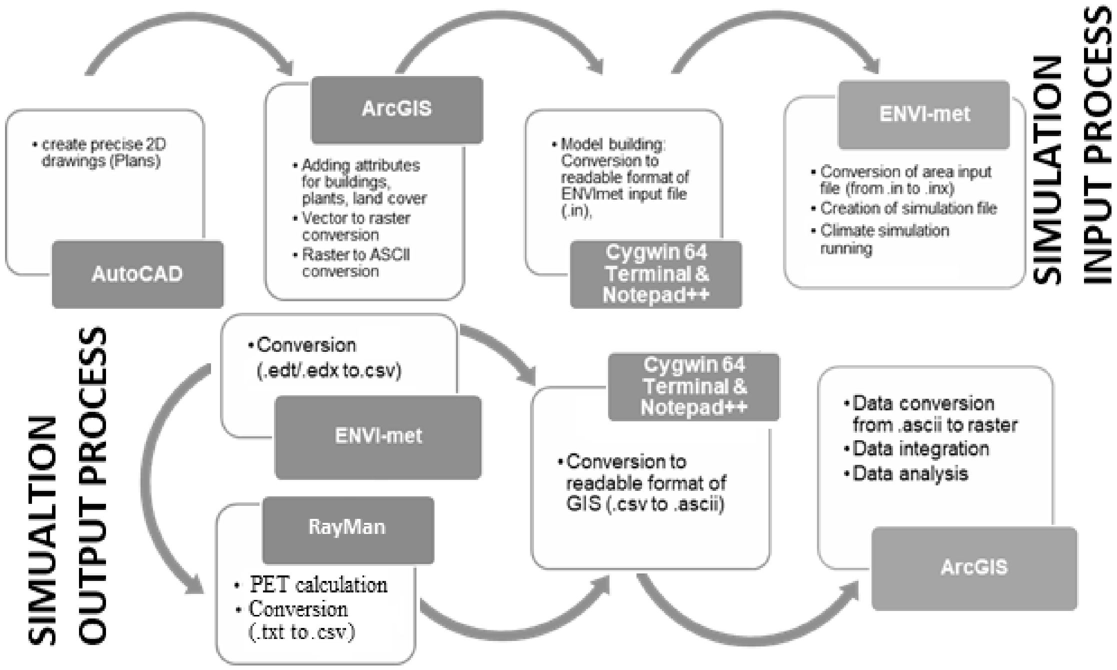


Fig. 3.17. The diagram presents the model data flowing before and after simulations.

3.5 VALIDATION OF SIMULATION MODEL

To support the ENVI-met model's validation, some part of simulated output data from the baseline model was extracted and compared with actual data measured by the nearest governmental weather station on the same day. There were three basic sets of actual weather data used for simulations: the daily air temperature, the daily relative humidity, and the annual wind rose of Ipoh.

Prior to the result, as shown in Table 3.5, it should be noted that the simple forcing mode limited the definition of diurnal variations, in which only air temperature and relative humidity can be forced manually in the 24-hours data. Wind speed and direction was set at a fixed value of 10m height. In this case, wind speed is not eligible for comparison as the simple-forcing method did not allow more additional profiles for wind speed and direction in the microclimate model. Hence, to a certain extent, it should be acknowledged that there are still some drawbacks in using simple forced domains to simulate imaginary scenarios accurately. Also, given that the boundary conditions for the simple forcing in this research were typically derived from reference data measured at the weather station, the conditions might slightly deviate from actual conditions within the study area.

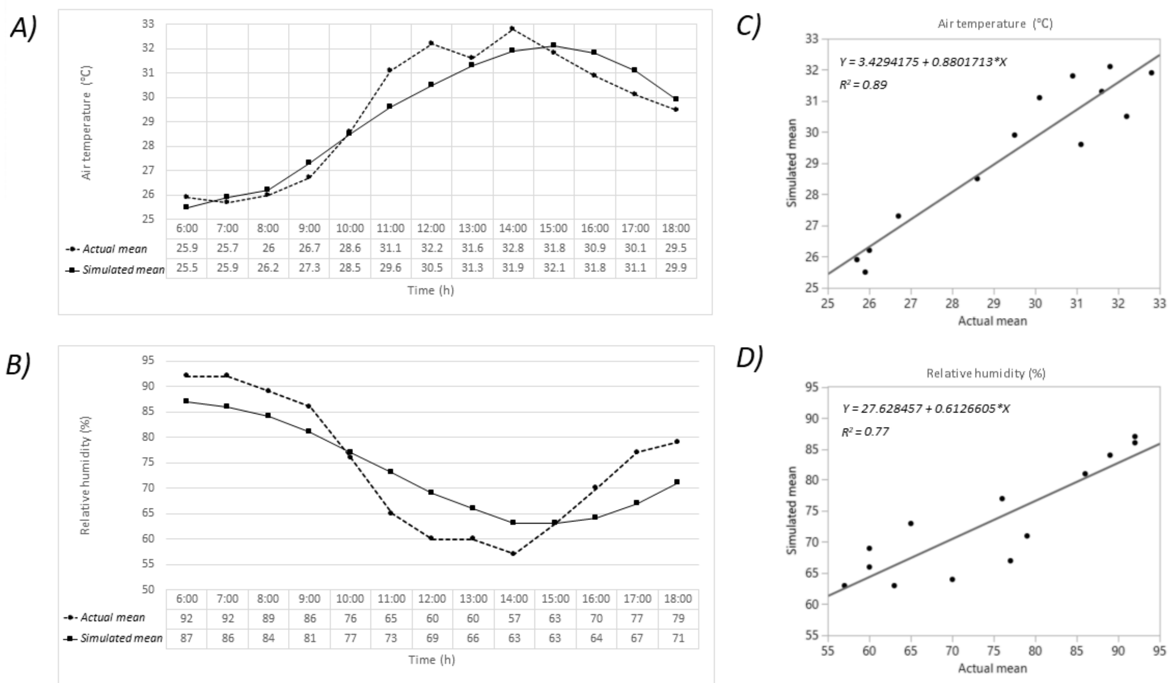


Fig. 3.18. Validation of ENVI-met model by comparing measured and simulated data in Ipoh for June 21st, 2018.

All the results were presented in Figure 3.18. Figure 3.18 (C & D) showed the corresponding linear fitting and correlation coefficient of air temperature and relative humidity, respectively. We found a strong positive correlation between the simulated and measured temperature trend, where R^2 is 0.89 in air temperature and 0.77 in relative humidity. Both indexes were close to 1, strongly affirming the validity of the model used in this research.

Nevertheless, it found some discrepancies in the diurnal air temperature and relative humidity trend pattern between simulated and measured data, as shown in Figure 3.18 (A and B). It can be seen that there was a sharp drop/increase at a particular period in actual air temperature and relative humidity variation. By contrast, simulated data presented relatively smooth and consistent increasing/decreasing trends for air temperature and relative humidity. This situation was mainly because the simulation was carried out in a clear-sky setting, but the actual situation could be affected by cloud cover changes in the atmosphere of the measured day. Similarly, the actual and simulated trends provided peak points at different times, which might also be affected by actual on-site wind effects. Wind speed and direction in the actual condition changed rapidly, with intervals of minutes or seconds. These additional factors led to further inaccuracies of simulations, making the trend pattern inconsistent with the actual situation. Finally, on the whole, the credibility and reliability of using the ENVI-met model for this research were still satisfactory.

3.6 RESULTS AND DISCUSSION

In this section, we mainly analysed the simulation outcomes of five climate factors and the human thermal comfort: air temperature (Ta), surface temperature (Ts), mean radiant temperature (MRT), wind speed (WS), relative humidity (RH), and Physiological Equivalent Temperature (PET), assessing the existing thermal resilience of urban design in Ipoh downtown. This section specifically studied the hottest condition of the day (2 p.m.), focusing on the height of 1.75m from the ground, similar to the height of a typical Asian male. The study model was evaluated in two dimensions: the overall study area (hereinafter referred to as macro- or full model) and based on four zonings described in Section 3.3 (hereinafter referred to as micro- or sub-model).

3.6.1 Air Temperature

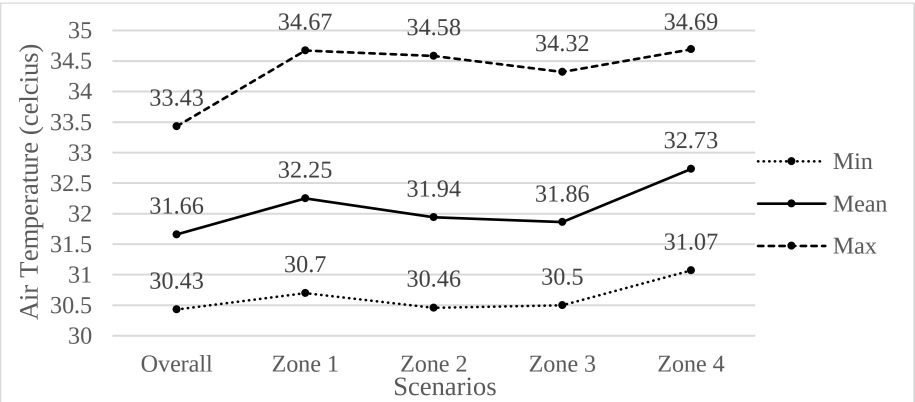


Fig. 3.19. Mean, minimum and maximum values on air temperature performance.

Fig. 3.20. Overall air temperature distribution of 1400 LT at 1.75m above the ground.

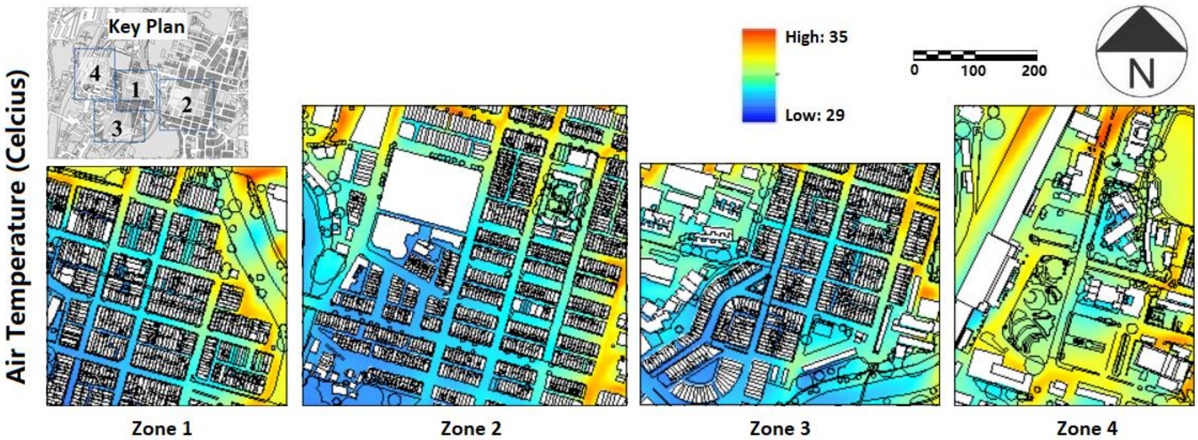


Fig. 3.21. Zoning air temperature distribution of 1400 LT at 1.75m above the ground.

Figures 3.20 - 3.21 presented the air temperature distribution maps in Ipoh downtown, with mean, minimum and maximum values shown in Figure 3.19. The result showed that there was a significant thermal variation from the North/East to Southwest direction. On macro-scale, air temperatures varied around 3°C, with the highest degree at 34.43°C. The air temperatures in the shophouses area were significantly lower than the surrounding, where the minimum degree could be as low as 30.43°C. Such index value was lower than 32.8°C – the lowest average temperature recorded at the nearest meteorological station for June 21st, 2018, 14:00. In open spaces, it found that the green space of the recreational park in the northern part of New Town was much cooler than the paved area of the Ipoh Cargo Terminal and adjacent parking spaces in the northwest of Old Town. Also, the greens have much blocked the heat diffusing into the shophouse area while the heat from paved areas continued to spread to other areas in Old Town through the wide-open railway and main road. Overall, the results showed that the more open the area, the higher the temperatures, indicating that the openness of the urban layout did affect the air temperature performance in Ipoh downtown.

Based on Figure 3.19, Zone 4 was the hottest on average, followed by Zone 1, 2 and 3. The ranking markedly corresponded to the site openness as well. Fewer buildings were found in Zone 4, and the buildings were far apart from each other. Simultaneously, there were relatively large open areas in Zone 4, including the open square, open field (*padang*), sizeable open car parks, railway, and those primary roads. This condition has highly exposed most areas in Zone 4 to the sun, resulting in higher air temperature on average than in other areas. Similar to Zone 4, the high average temperature in Zone 1 was also related to the presence of the open field (*padang*) and open car parks next to the river. The big but sparse trees in these two zones did not seem to help lower the temperature. The lowest temperatures index values were found along the East-West small lanes and alleys in Zone 1 and the dead corners of majestic buildings in Zone 4, indicating that buildings can significantly cool down the air through shading. In this case, it also explained the lower average temperature in Zone 3 and Zone 4 as there was a large tract of land occupied by shophouses. The shade provided by massive buildings has reduced direct solar radiation at the outdoor pedestrian level and avoided the air being warmed up adequately during hot hours. Those small and sparse trees in Zone 3 and Zone 4 also had no significant effect on cooling down the atmosphere.

3.6.2 Surface Temperature and Mean Radiant Temperature (MRT)

The outcomes of surface temperature and mean radiant temperature (MRT) had several similarities. Compared with the air temperature distribution, they had relatively large variations in the entire model, with a difference of about 30^{o}C. They have best explained the influence of urban design elements on microclimate. By comparing Figures 3.22 and 3.23, it can be found that MRTs were higher than surface temperatures, indicating a significant heat released by the ambient buildings during hot hours. Overall, both MRT and surface temperature changed depend on the urban configuration, including the presence of trees, building effects, street pattern, as well as the properties of land surface materials, which to be explained as follows:

a. Trees

The distribution maps showed that all treed areas hold significant low temperatures, regardless of the tree's size and height. The results proved that trees are the most efficient elements in cooling urban MRT and land surfaces in the tropical region. The result also supported that tree effects are most identified in shading potential, evaporative cooling and thermal reflectivity, highly corresponding to most previous relevant studies (He et al., 2015; Lee et al., 2016; Louafi et al., 2017; Kong et al., 2017; Lin et al., 2017).

b. Building aspect ratio: the building height and the gap distance between buildings

Buildings provided cooling mainly through shading. The shadow created by the building could effectively cool down the land and building surface, leading to a lower degree in MRT and surface temperature. Especially the large high buildings (see the circled areas in Figures 3.26 and 3.27), they did provide large shadows at the pedestrian level, effectively reducing MRT and surface temperature. Besides, lower index values were also found along the narrow lanes and alleys. As explained in Section 3.6.1, it was because the solar radiation that could reach these areas was extremely limited due to the closely-spaced buildings. The MRT and surface temperature under shade were thus merely undisturbed and remained cool during hot hours.

c. Street pattern: size and orientation

It found that the temperatures were lower at the North side of East-West oriented streets and the West side of North-South oriented streets. These areas had lower temperatures, mainly because the buildings have highly blocked the direct solar radiation at the moment, and the heat could not be transferred to the shaded building surfaces and ground. Street's size also played a regulating role for both MRT and surface temperature in this case: the smaller the road, the lesser area was exposed to direct solar radiation, thereby decreasing the heat absorbed by the ground and adjacent buildings.

d. Land surface materials

Natural land surfaces like water, grasscover, unsealed soil, and sandy soil had more prominent effects on cooling land surfaces. However, by comparing Figures 3.24 and 3.25, the natural land surfaces could not simultaneously reduce MRT. As for artificial surface materials, asphalt surfaces absorbed the most heat, having a higher temperature than paver and cement surfaces. The thermal level of each land surface in Ipoh was clearly illustrated in Figure 3.28.

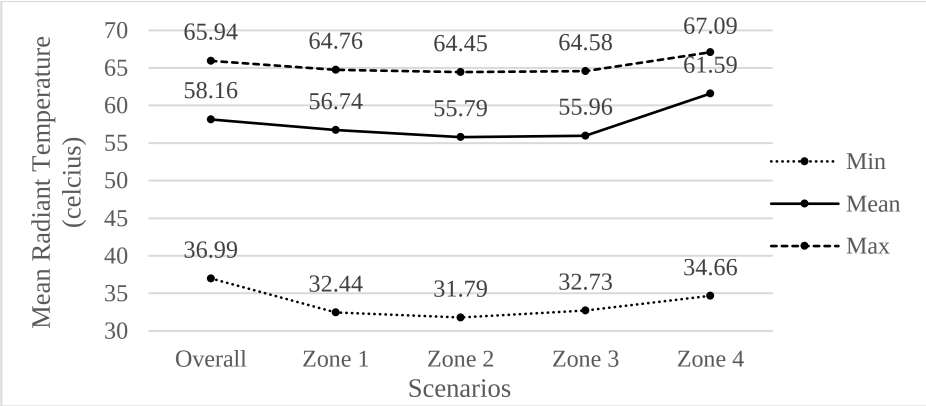


Fig. 3.22. Mean, minimum and maximum values on MRT performance.

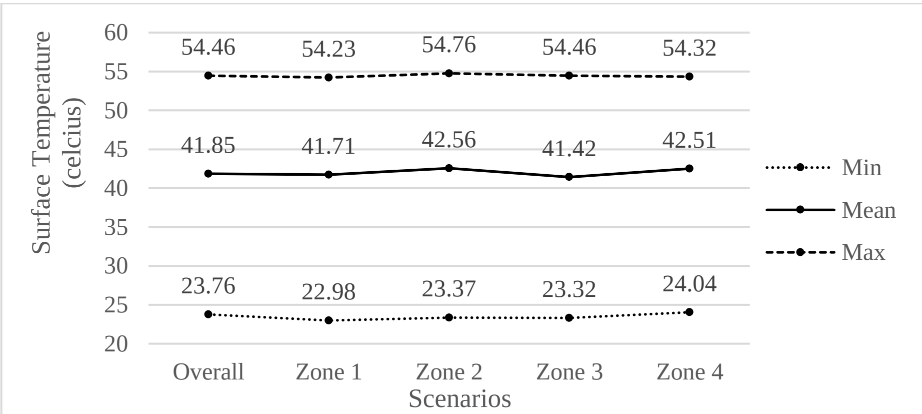


Fig. 3.23. Mean, minimum and maximum values on surface temperature performance.

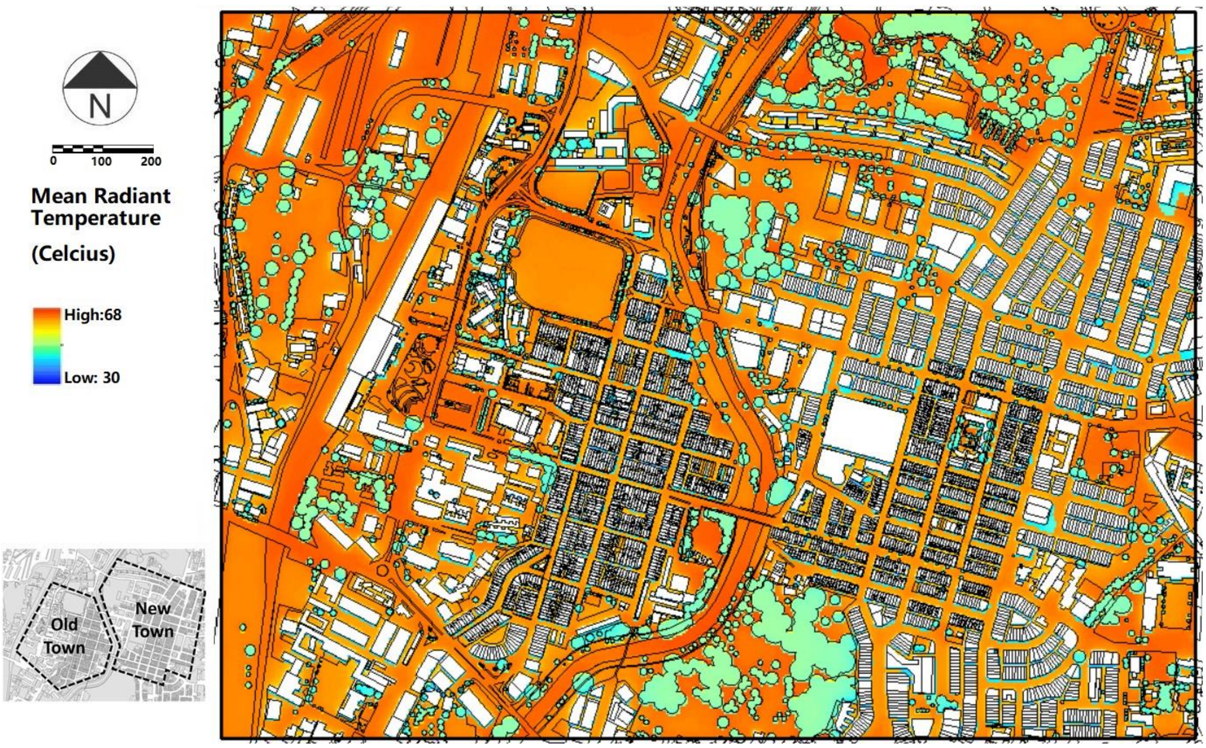


Fig. 3.24. Overall MRT distribution of 1400 LT at 1.75m above the ground.

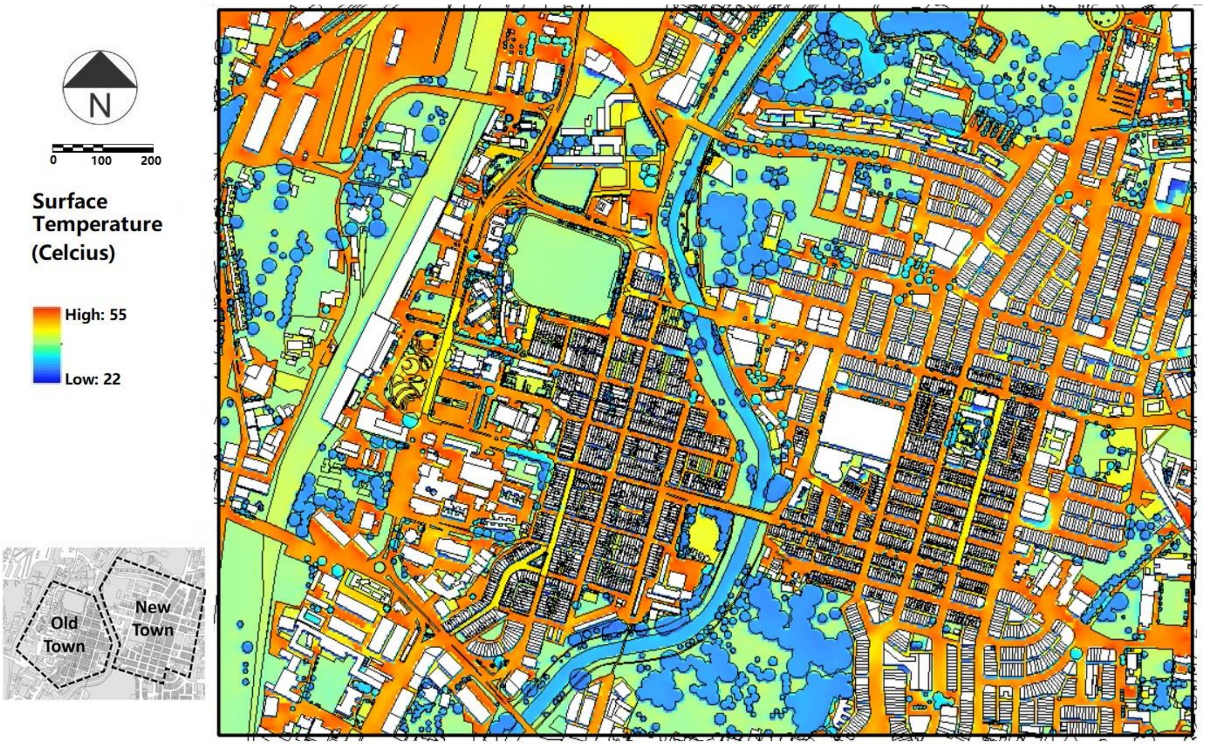


Fig. 3.25. Overall surface temperature distribution of 1400 LT at 1.75m above the ground.

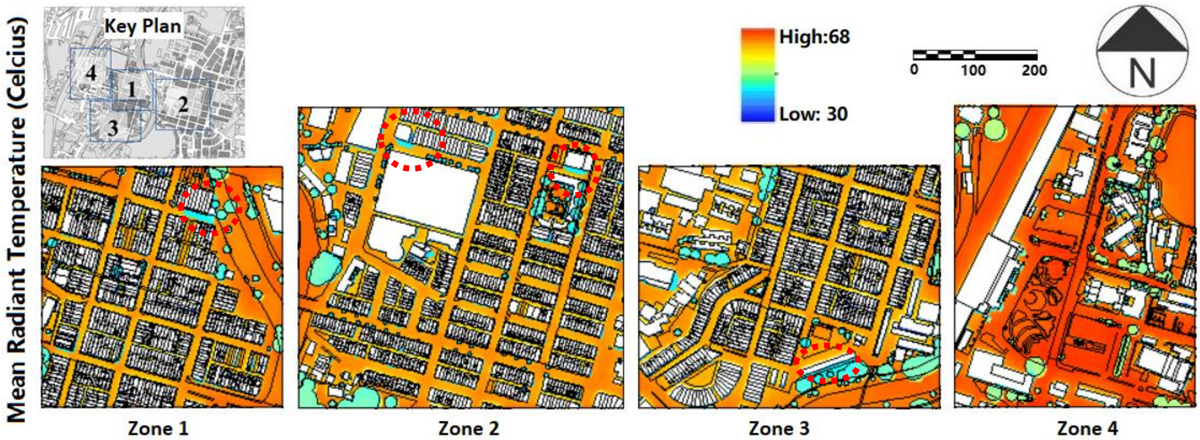


Fig. 3.26. Zoning MRT distribution of 1400 LT at 1.75m above the ground.

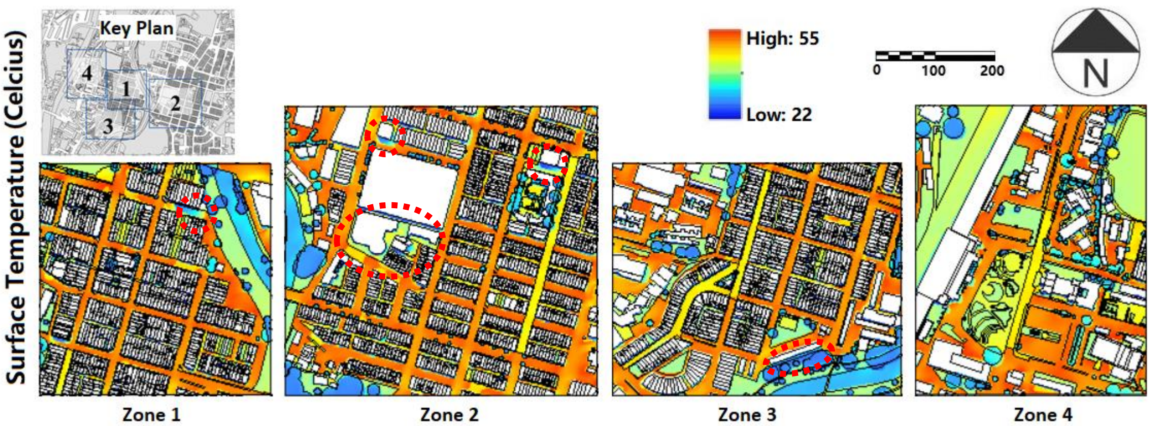


Fig. 3.27. Zoning surface temperature distribution of 1400 LT at 1.75m above the ground.

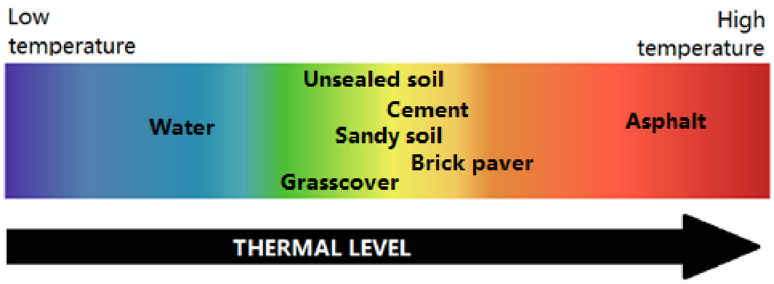


Fig. 3.28. Thermal level of land surface materials

3.6.3 Relative Humidity

Based on Figures 3.30 and 3.31, it was significant that green areas, especially with large treed compounds, had the highest relative humidity (RH) and helped increase the RH of their adjacent areas as well. Also, as shown in Figure 3.29, the presence of vast greenery outside the compound of Zones 1-4 gave a relatively higher maximum value to the full model (73.27%). However, the mean RH of the full model was much lower than that of sub-models, with only 53.6%, indicating that the green /tree coverage ratio was still averagely low on the macro scale.

On the micro-scale, the highest mean RH was found in Zone 3 (61.87%) and followed by Zone 2 (61.18%), Zone 1 (60.62%) and Zone 4 (59.64%). The result has strongly illustrated the capability of urban layout patterns in capturing and dissipating air moisture that cooling the city. Regarding this, the small lanes and alleys within the building clusters of Old Town performed in high RH. The results show that air moisture could be trapped in a compact building layout with relatively low temperatures and wind speeds. Comparatively, open areas were less effective in RH regulation unless being associated with trees. In terms of surface materials, grass and natural soil surface did have advantages over artificial hard surfaces like paver and asphalt. However, their effect was far weaker than that of trees.

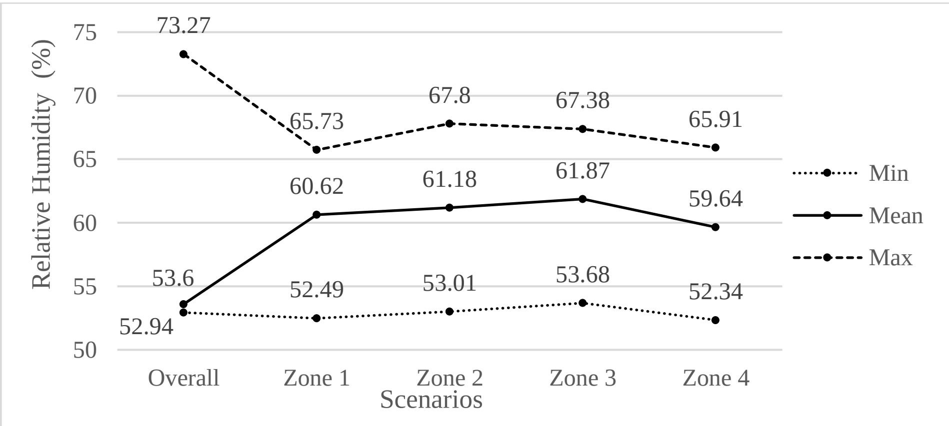


Fig. 3.29. Mean, minimum and maximum values on relative humidity performance

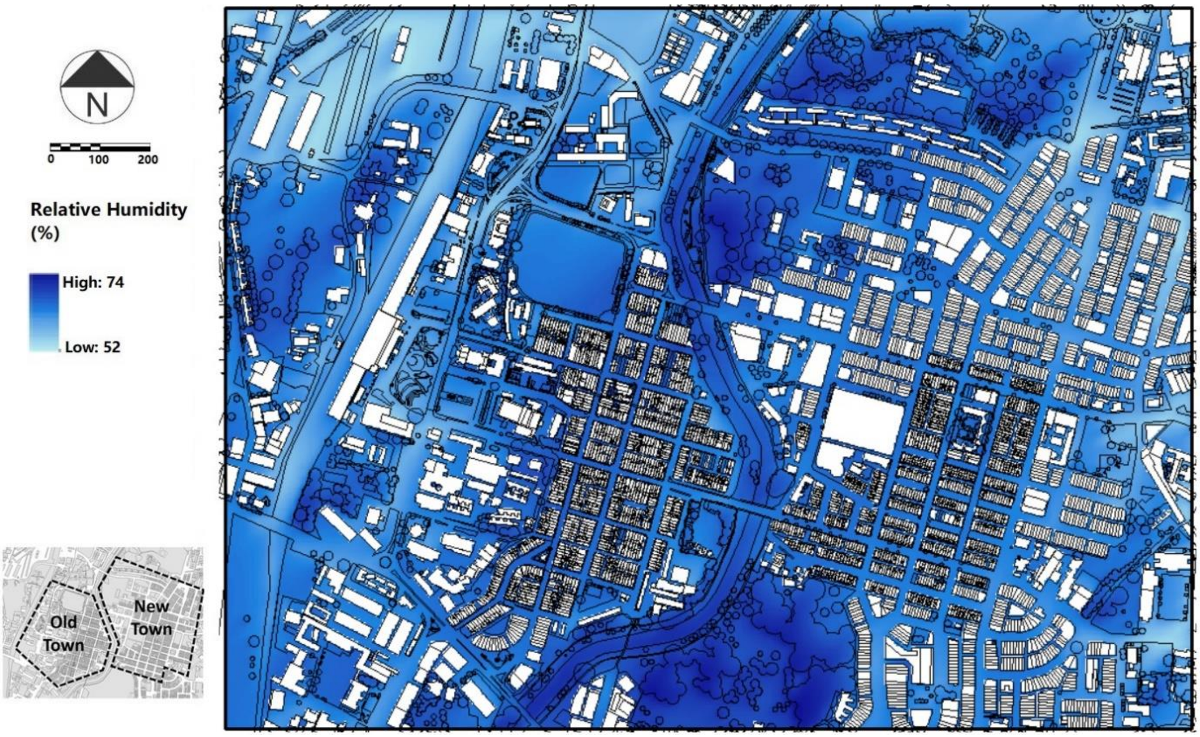


Fig. 3.30. Overall relative humidity distribution of 1400 LT at 1.75m above the ground.

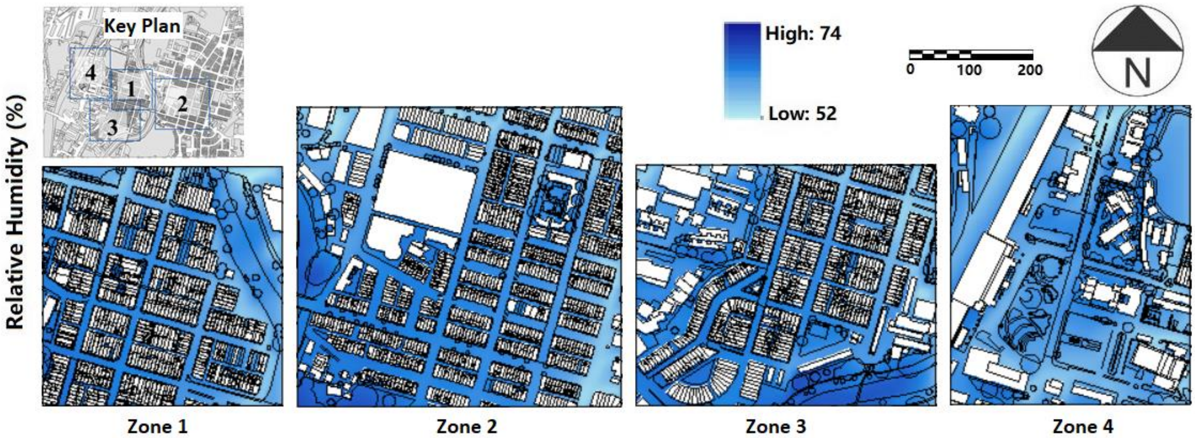


Fig. 3.31. Zoning relative humidity distribution of 1400 LT at 1.75m above the ground.

3.6.4 Wind Speed

First of all, Figure 3.32 showed that the wind speed range decreased from Zones 1 to 4. Zone 4 had the highest mean but also had the lowest maximum value. However, the wind performance between zonings was not so significant due to the low wind speed value, with an average range of 0.59-0.96m/s and less than 1m/s.

However, based on Figures 3.33 and 3.34, it can be seen that the North-South oriented roads, the river, and the railways acted as air tunnels and reached the highest wind speed than other areas in the model. The site openness has accelerated the airflow and subsequently increased the wind speed of their adjacent area, particularly the open spaces like open squares, the open field (*padang*), large carparks, and the green area without tree canopies.

On the contrary, building clusters have effectively blocked and trapped the wind in this case. Lower index values were most found at the East-West streets in the shophouse zone. The narrow lanes laid in the closely-spaced building clusters experienced the calmest air. This situation has two-sided effects. At shaded lanes (found at those small lanes in Old Town), it prevented hot air outside the lanes from being directed into these areas by winds, helping them maintain lower temperatures during hot hours. On the other hand, the low wind speed became a threat for those open-wide lanes or streets exposed to extreme heat radiation, because the hot air was remained in the area and exacerbated the warming condition.

It was also found that the existing trees highly manipulated the wind pattern on site. It was clearly shown along the river in the model. Compared to the sparse trees planting at the middle part of the riverside (see A in Figure 3.33), the big and dense trees along the lower part of the riverside (see B in Figure 3.33) have successfully prevented the air from flowing from the river to its adjacent areas. The wind was less dissipated and maintained at a higher speed on the river.

Besides, it found high-rise buildings would create a "downdraught effect", accelerating winds near these buildings at pedestrian level (see the circled areas in Figure 3.34). According to Nada Piradeepan, the phenomenon occurred when "the air hits a building and, with nowhere else to go, is pushed up, down and around the sides. The air forced downwards increases wind speed at street level. There is also an acceleration of wind around the side of the buildings if it has completely square corners." (Figure 3.35) (Parkinson, 2015).

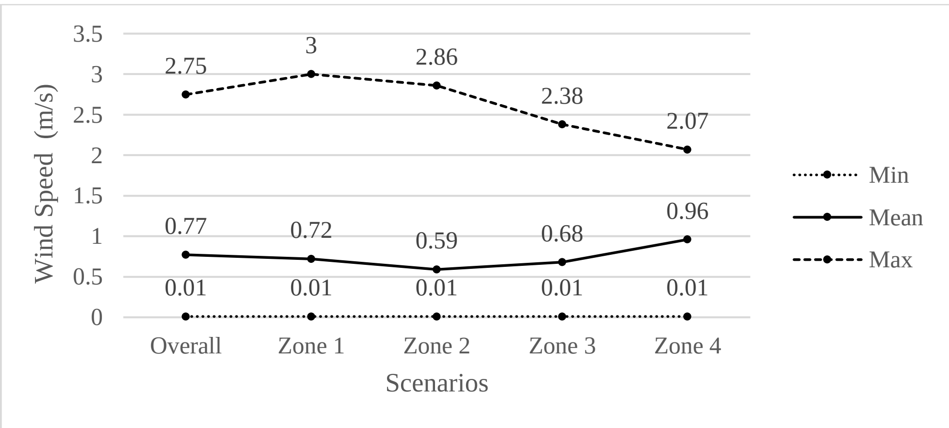


Fig. 3.32. Mean, minimum and maximum values on wind speed performance.

Figure 3.33. Overall wind speed distribution of 1400 LT at 1.75m above the ground.

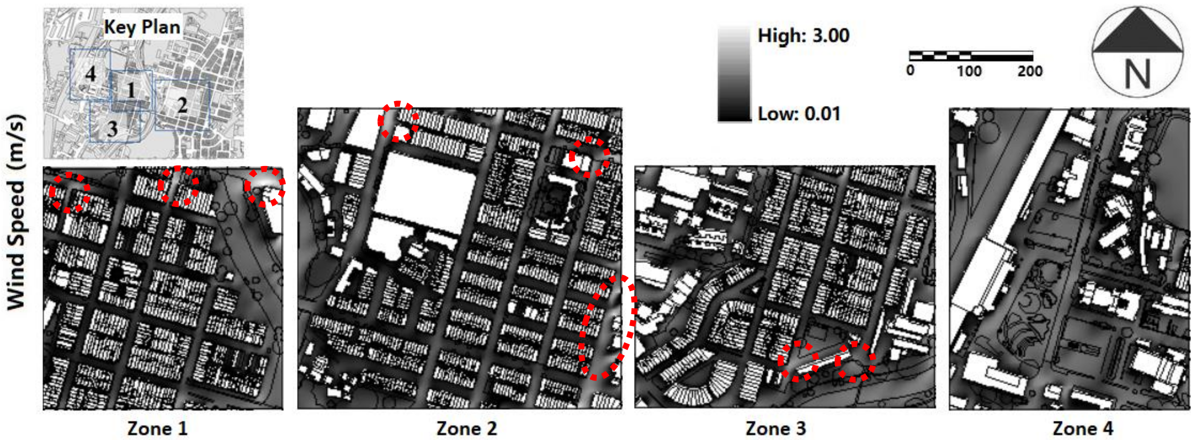


Fig. 3.34. Zoning wind speed distribution of 1400 LT at 1.75m above the ground.

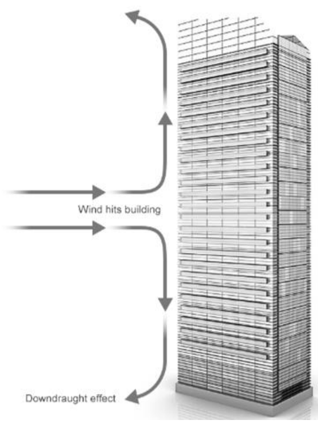


Fig. 3.35. A typical downdraught effect happened nearby high-rise buildings. (Source from Parkinson, 2015).

3.6.5 Thermal Comfort: Physiological Equivalent Temperature (PET)

According to Figures 3.36-3.37, the PET distributed in full model fall at an average of 45.27ºC (very hot), even though under a wide thermal comfort range between 34ºC (slightly warm) and 51.5ºC (very hot). So it was difficult for pedestrians to stay long outdoors during 14:00. It was the same in most sub-model areas when they are averagely above 44 ºC (very hot). The degree of thermal discomfort in Zone 4 was much higher than in other zones. Again, it was related to site openness, indicating that a wide-open urban layout would indeed become a weakness in providing human thermal comfort in tropical regions.

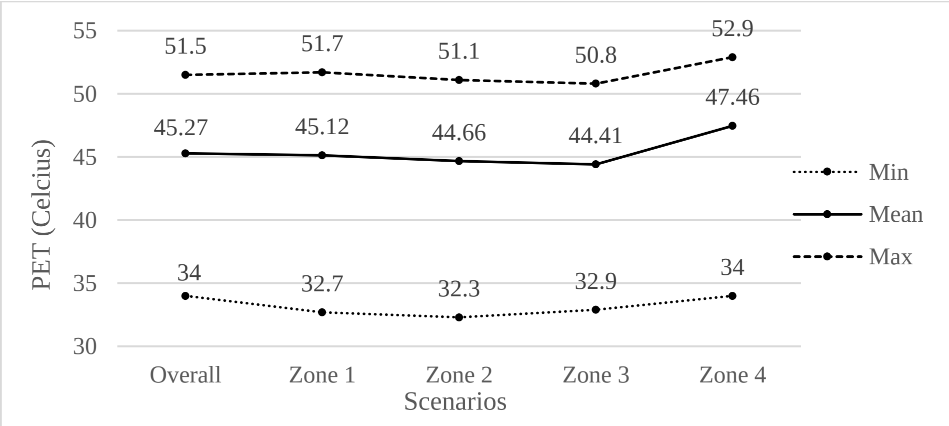


Fig. 3.36. Mean, minimum and maximum values on PET performance.

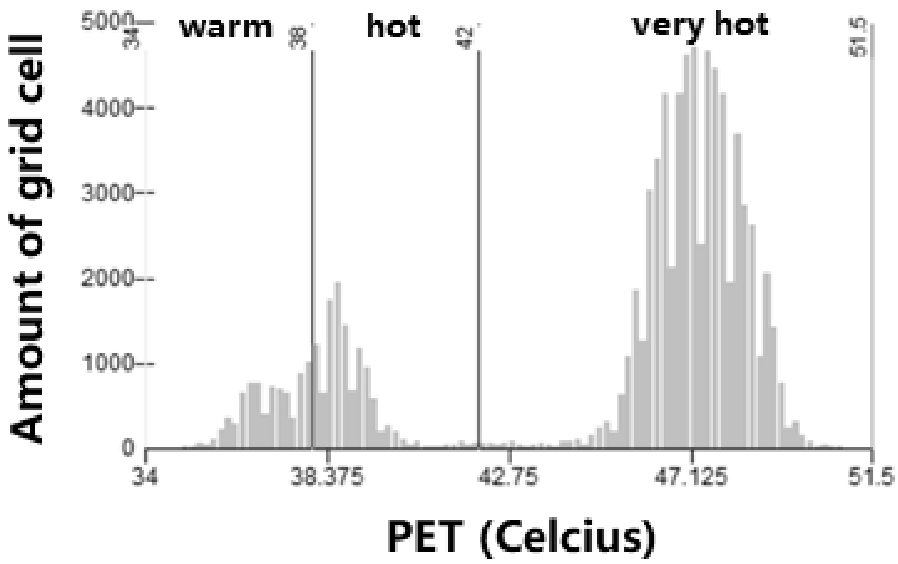


Fig. 3.37. Overall PET distribution chart of 1400 LT at 1.75m above the ground.

While assessing the distribution maps (Figures 3.38-3.41), it could find that PET had a significant decline in those areas shaded by trees or high-rise buildings. These shades have significantly helped to relieve pedestrians' thermal discomfort during hot hours. In this case, it showed that even though the presence of trees might not much help improve the atmospheric temperature on site, they still have a core position in alleviating thermal stress. This finding is essential to affirm the importance of trees in urban microclimate and human thermal comfort regulation. Besides, it showed that land surface properties and street patterns did affect PET values (as shown in Figures 3.38 and 3.39). However, unfortunately, the thermal variations caused by these factors were not enough to change the thermal comfort perception (see Figures 3.40 and 3.41).

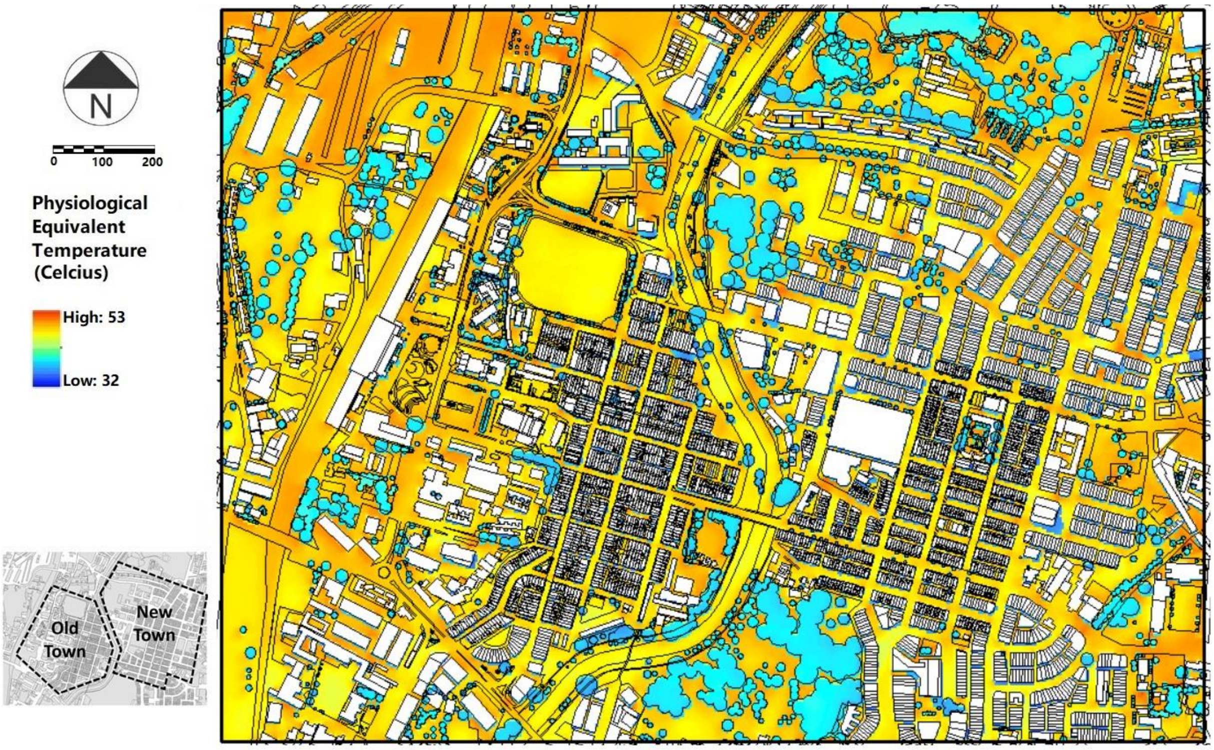


Fig. 3.38. Overall PET distribution of 1400 LT at 1.75m above the ground.

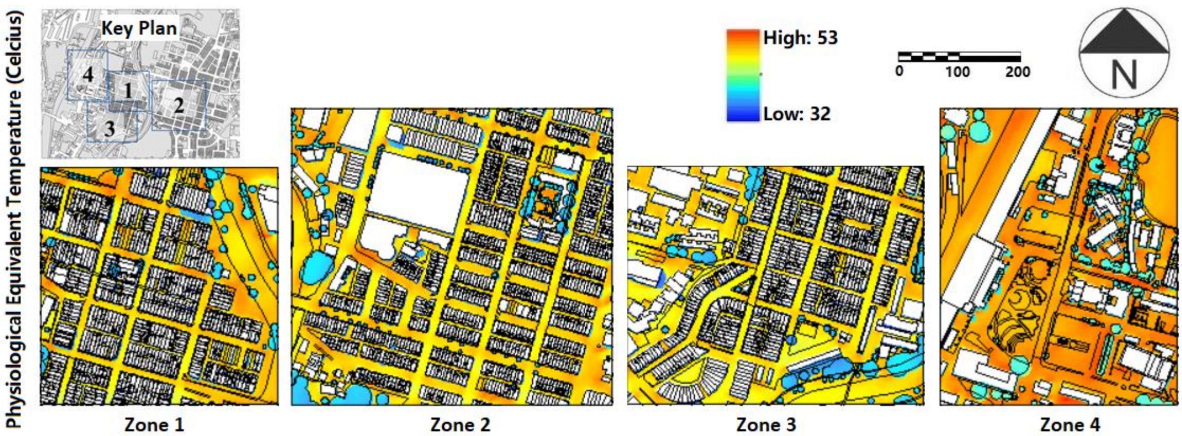


Fig. 3.39. Zoning PET distribution of 1400 LT at 1.75m above the ground.

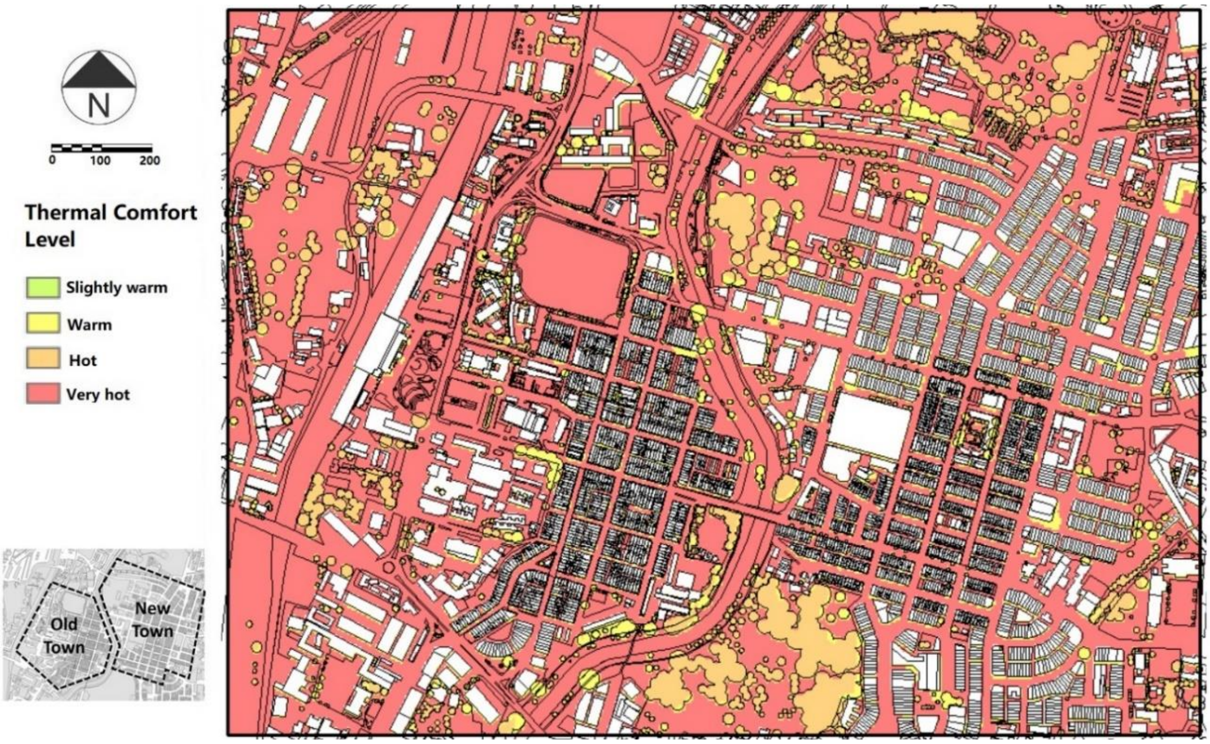


Fig. 3.40. Overall thermal comfort distribution of 1400 LT at 1.75m above the ground.

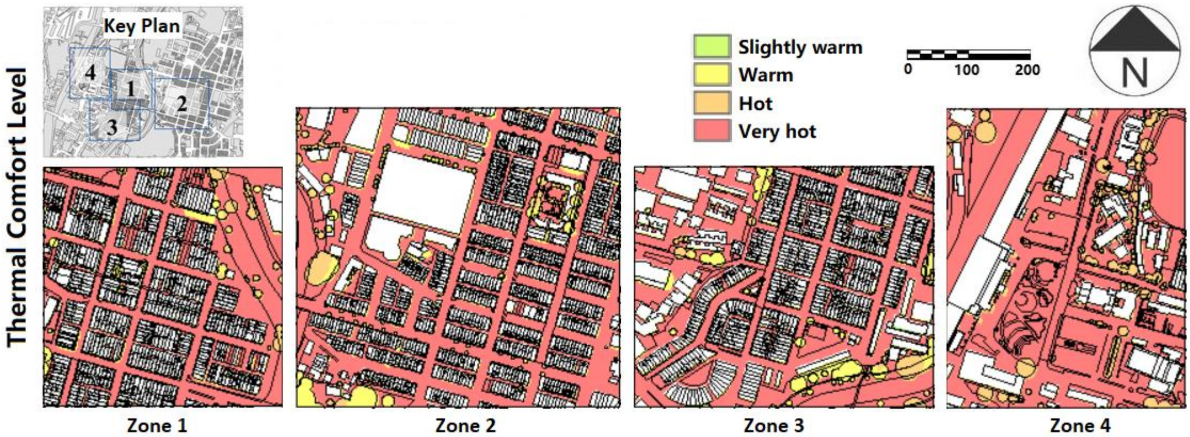


Fig. 3.41. Zoning thermal comfort distribution of 1400 LT at 1.75m above the ground.

3.6.6 Correlations between climatic factors and PET

To determine the weight of each climatic parameter correlated to PET in Ipoh downtown, the baseline model output was also assigned for a multivariate correlation analysis using JMP statistical software. The analysis used linear correlation coefficients to quantify the strength to which two different variables are linearly associated. It should be acknowledged that correlations analysis does not explain cause and effect and cannot accurately describe any curvilinear relationship. On the basis of Pearson product-moment correlation, the results were described in the range of -1 to1, where the closer the correlation coefficient is to 0, the weaker the linear relationship; the value of 0 signified no relationship. The sample correlation coefficient (r) was represented using the following formula:

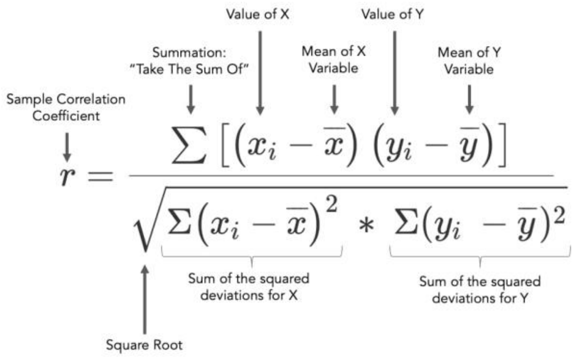
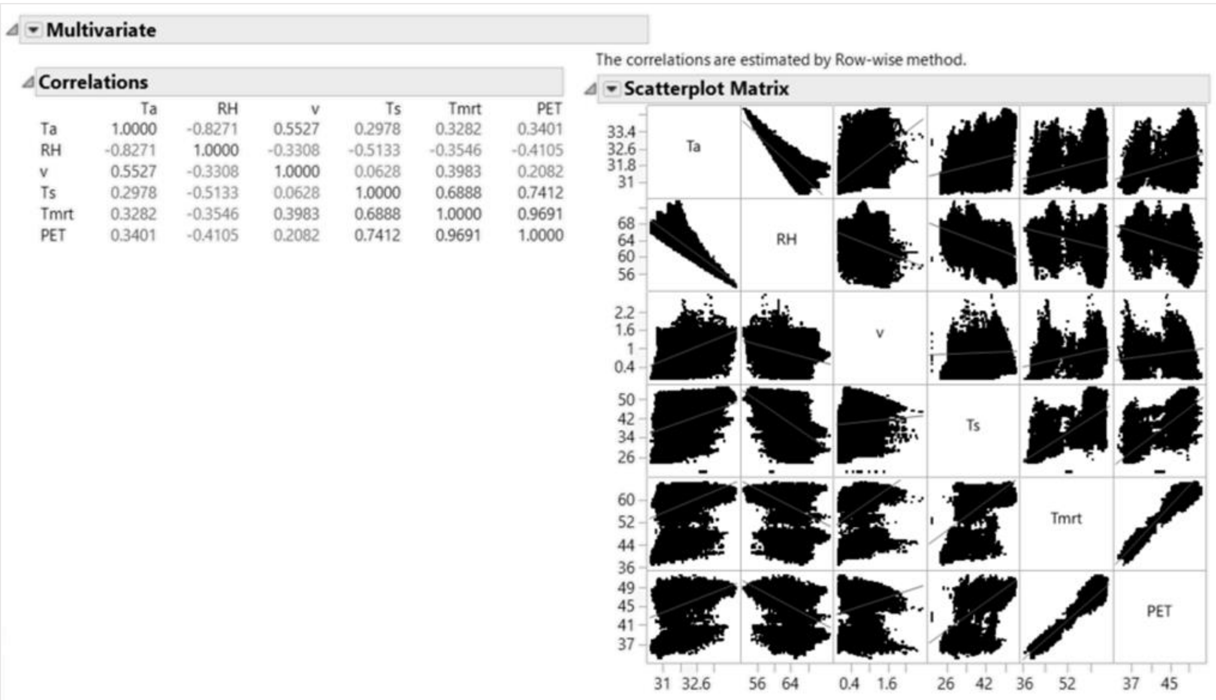


Figure 3.42 presented the overall outcomes of multivariate correlation analysis for Ipoh thermal studies. It showed that MRT correlated with PET the most, as high as 0.9691, indicating the significances of MRT in monitoring PET performance in Ipoh. We can also see that there was a high negative correlation between air temperature and relative humidity (r = -0.8271), as well. Overall, all climate parameters were positively correlated to thermal comfort (PET), except for relative humidity (RH).



	Ta	RH	v	Ts	Tmrt	PET
Ta	1.0000	-0.8271	0.5527	0.2978	0.3282	0.3401
RH	-0.8271	1.0000	-0.3308	-0.5133	-0.3546	-0.4105
v	0.5527	-0.3308	1.0000	0.0628	0.3983	0.2082
Ts	0.2978	-0.5133	0.0628	1.0000	0.6888	0.7412
Tmrt	0.3282	-0.3546	0.3983	0.6888	1.0000	0.9691
PET	0.3401	-0.4105	0.2082	0.7412	0.9691	1.0000

Fig. 3.42. The output of multivariate correlation analysis.

Besides, also as shown in Figure 3.42, it was worth mentioning that two distinct sets of distribution appeared in each correlation related to MRT and PET (in air temperature, relative humidity and wind speed). To find out the reason, the data was divided into two sets according to their distribution in the chart. These two datasets were then exported and re-examined in the ArcGIS platform.

The result showed that Group I represented the climatic conditions exposed to the direct solar radiation while Group II referred to those under the trees and building shade (Figure 3.43). These findings undoubtedly solidified the essential role of shading in manipulated MRT and PET in Ipoh downtown. In addition, Group II result indicated that the correlation of relative humidity to PET would become insignificant (r = 0.0895, close to 0) when people are under the shade. On the other hand, in areas exposed to direct solar radiation, wind speed would change from positive correlation (r=0.2082) to negative correlation (r=-0.1442), even though the strength was still relatively weak.

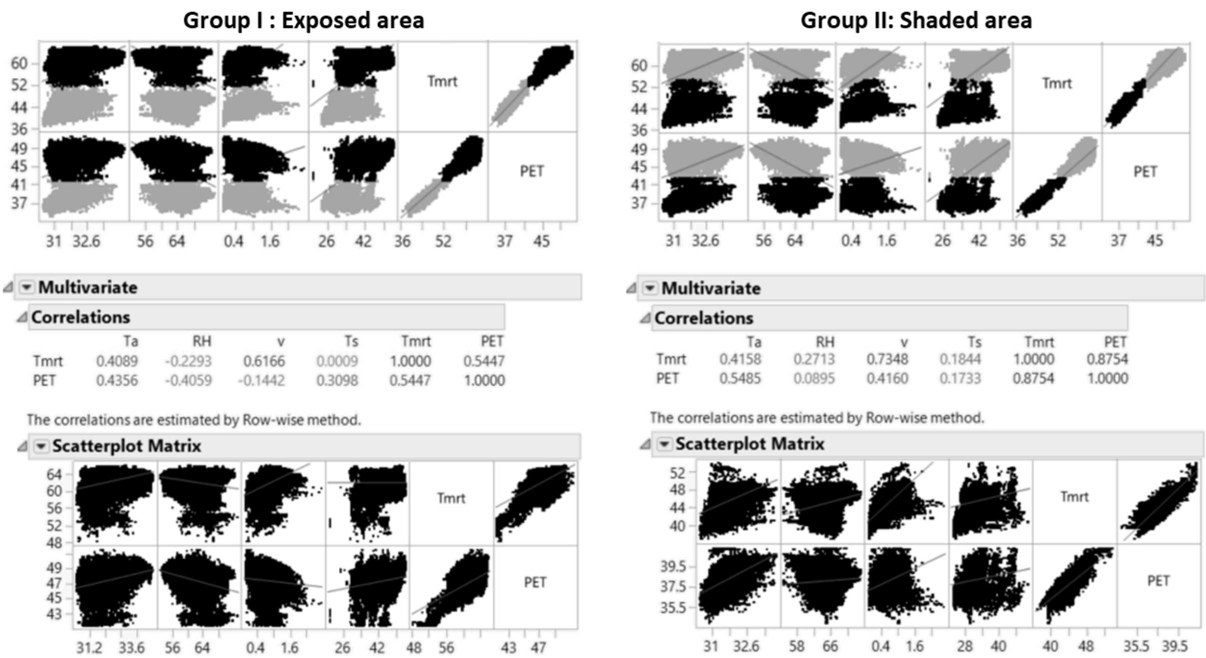


Fig. 3.43. The shading effect in multivariate correlation analysis.

Lastly, it is necessary to discuss the correlation between wind and PET. In view that sea breeze or mountain breeze usually brings moisture-bearing air to cool the environment, most researchers assumed that wind and thermal comfort level have a strong positive correlation, that is, a strong negative correlation with PET. However, in this study area, its correlation with PET was relatively weak (within the r ranged from -0.1442 to 0.2082) during hot hours. Some more, it has a positive correlation with PET, especially when under shade (r=0.4160). In this case, the higher the wind speeds, the higher PET, increasing pedestrian thermal discomfort in Ipoh.

Multiple phenomena might explain this situation. First, the data was based on the hottest hour of the day, in which most air molecules in the incoming wind have been highly heated by the sun. Second, the site was located at the centre of the city, surrounded by a massive built-up area within a few kilometres. In such a situation, the moisture-bearing air molecules might have been heated and evaporated when they moved along the near-surface layer in the city. Based on these phenomena, it could be assumed that the incoming air directed by the prevailing wind was not necessarily cooler than those inside the study area. This assumption was logical with the following references. According to Buyadi et al. (2013 & 2014), the cooling effect induced by urban greenery was only within 500m from the cooling source. Also, as stated in Shahidan and Mustafa (2005), the prevailing atmospheric system would usually dissipate the differences in air temperature and humidity through air movement (wind) quickly, so the cool incoming air might have already been dissipated before entered the study area.

In summary, this section concluded that the relationship between climatic parameters and PET is not absolute or fixed, depending on the local structure and vegetation pattern, their efficiency in shading potential, and the climate condition at the period measured/simulated. The conclusion stressed the necessity of thermal resilience and comfort assessment before the stage design and planning to justify thermal correlations before any design idea or decision is made. Overall, to improve thermal comfort in Ipoh downtown, attention should be paid to increasing relative humidity and reducing other parameters, especially the mean radiant temperature. This analysis provided explicit instructions for the coming design stage.

3.6.7 Thermal Resilience Evaluation: Summary and Comparison

Throughout the study, we found that each sub-model presented different climatic characters, affecting their ranking in thermal resilience and human comfort (see Table 3.9). The strength of Zone 1 was mainly contributed by its compact shophouses layout and a large number of small lanes and alleys in the area. Many land surfaces in this area were highly shaded and maintained at a lower index on average. With the supports of vegetation and uniform layout, Zone 2 performed well in most aspects, especially in terms of average radiation temperature and wind speed, except for surface temperature. It is the worst-performing model in terms of surface temperature, indicating that wide-open streets without shade tended to increase urban surface temperature significantly. Zone 3 performed the most in this chapter. It was mainly because the model had combined the first two models' advantages: a compact layout with a large number of alleys and trees. Lastly, based on the existing condition, Zone 4 was far worse than the other three zonings. The site was too open and less protected by trees, which made it highly exposed to high average temperatures and wind speed, resulting in low relative humidity and thermal comfort.

Table 3.9. The comparison between the sub-models (micro-scale) and their findings regarding thermal resilience and thermal comfort.

Area \ Factors		**Thermal resilience level** *(ranking started from high to low)*					
		Air temp.	**Surface temp.**	**MRT**	**Wind speed**	**Relative humidity**	**PET**
Micro	**Zone 1**	3	2	3	3	3	3
	Zone 2	2	4	1	1	2	2
	Zone 3	1	1	2	2	1	1
	Zone 4	4	3	4	4	4	4

According to Table 3.10, Old Town and New Town shophouses area had their own merits in providing thermal resilience and thermal comfort. New Town's resilience was mainly constructed by greenery, while Old Town's resilience most relied on its compact morphology. However, based on the existing microclimate and thermal comfort indexes as summarised in Table 3.11, the whole Ipoh downtown still needs much physical improvement to achieve an ideal thermal resilience and thermal comfort level during hot hours. Before the conclusion and recommendation, herein summarised that thermal resilience and thermal comfort of Ipoh downtown were mainly influenced by the following factors:

a. Site openness and compactness
b. The ratio of trees and vegetation
c. The building aspect ratio
d. The street pattern and orientation
e. The ratio of natural and artificial land surface

These influencing factors were highly in accordance with the key findings of previous studies in Malaysia (comparable to Table 2.5).

Table 3.10. The findings summary for practical implications in urban design planning and landscape planning.

Area	**Findings**	
	Old Town	**New Town**
Strength	• The compact shophouse clusters have offered effective cooling to the site through shading. These buildings were closely spaced and sufficient to intercept direct solar radiation from reaching these areas. • The weak airflow along the small lanes and alleys has blocked the inflow of hot air and prevented the cool air and moisture from flowing out from the lanes during hot hours.	• Site openness was relatively low outside the shophouse zone. The shophouse area was surrounded by a large treed compound (buffer greening), effectively reducing the temperature and wind speed. These treed areas also increased the moisture in the air and filtered a substantial amount of hot air before the air was directed into New Town • New Town has relatively more street planting than Old Town, even though most were small and planted sparsely. • The road and building layout were relatively larger and more uniform, offering a stable airflow between the buildings in New Town. In this case, the hot and dry air in the shophouse zone could also be uniformly removed and replaced with the cool breeze air coming from the surrounding vegetated area.

Disadvantages	• Site openness was relatively high outside the shophouse zone. The open areas were less treed and overexposed to direct solar radiation. • There are relatively few trees in and around the area with uneven distribution. • High wind speed inside Old Town would accelerate the diffusion of hot and dry air coming from outside, exacerbating the undesirable thermal conditions of the site.	• The car-prone road system design has resulted in the expansion of streets and service lanes in New Town, increasing the gap distance between the buildings, making the road surface more exposed to direct solar radiation.
Conclusion	• The urban configuration of Old Town – openness and compactness –manipulated its thermal performance. • Irregular road sizes and building forms have generated different wind speeds in the area, giving different impacts to the site.	• The large treed area of New Town positively manipulated its thermal performance.

Table 3.11. Summary and comparison of microclimate and thermal comfort indexes.

	Mean					**Minimum value**					**Maximum value**				
	Macro	**Zone 1**	**Zone 2**	**Zone 3**	**Zone 4**	**Macro**	**Zone 1**	**Zone 2**	**Zone 3**	**Zone 4**	**Macro**	**Zone 1**	**Zone 2**	**Zone 3**	**Zone 4**
Ta (°C)	31.66	32.25	31.94	31.86	32.73	30.43	30.7	30.46	30.5	31.07	33.43	34.67	34.58	34.32	34.69
Ts (°C)	41.85	41.71	42.56	41.42	42.51	23.76	22.98	23.37	23.32	24.04	54.46	54.23	54.76	54.46	54.32
MRT (°C)	58.16	56.74	55.79	55.96	61.59	36.99	32.44	31.79	32.73	34.66	65.94	64.76	64.45	64.58	67.09
WS (m/s)	0.77	0.72	0.59	0.68	0.96	0.01	0.01	0.01	0.01	0.01	2.75	3.00	2.86	2.38	2.07
RH (%)	53.6	60.62	61.18	61.87	59.64	52.94	52.49	53.01	53.68	52.34	73.27	65.73	67.8	67.38	65.91
PET (°C)	45.27	45.12	44.66	44.41	47.46	34	32.7	32.3	32.9	34	51.5	51.7	51.1	50.8	52.9

3.7 CONCLUSION AND RECOMMENDATIONS

Studying a baseline model is mainly used to capture the existing thermal condition, identify the problematic locations, and derive insights to improve such a situation. It was undoubtedly that shading indeed plays a dominant role in providing thermal resilience and thermal comfort in Ipoh downtown. Through the results and discussion, it proved that dense vegetation, especially the trees, played a determinant role in urban climate regulation in the tropical region. Street pattern and building clusters layout also jointly impacted the aspect ratio and the subsequence performance of all studied parameters in this study. They were essential to determine:

a. The degree and amount of solar radiation that could reach the ground and people at outdoor.

b. The speed and flowing pattern of wind; and

c. The capacity to capture air moisture and maintain the relative humidity.

In order to enhance the outdoor thermal resilience and thermal comfort in Ipoh downtown, several recommendations were formulated, as followed:

a. The thermal comfort of the shophouses zone in New Town was mainly contributed by the surrounding green spaces, indicating that buffer greenery is significant for improving thermal resilience in Ipoh. A similar strategy, therefore, should be applied to Old Town and other surrounding areas as well. The local authority should enhance the greening along the railway, river, and open spaces adjacent to Old Town.

b. Street tree planting was recommended to increase the green coverage ratio in the limited open spaces within the shophouse zones. The high exposure of primary and secondary roads to direct solar radiation should be reduced by replacing the current small and slow-growing trees with moderate fast-growing species. In addition, the roadside trees should be planted continuously to create efficient shading for pedestrians and land surfaces, avoiding scattered or clustered tree planting. An additional tree row should be considered for wide-open streets to maximise the green coverage area on streets.

c. In the small lanes and alleys in Old Town, the shade created by the closely-spaced buildings has significantly cooled down the land and building's surface, positively regulating pedestrians' temporal thermal comfort during hot hours. Their overall performance in the climate aspects was also satisfied. The advantages of traditional narrow alleys in providing pedestrian thermal comfort and resilience during the hot time were similar to the findings of Majima et al. (2007). In Ipoh, the strategic locations of these alleys gave themselves the opportunity to be developed into full or semi pedestrian zones to accommodate the increasing number of visitors in the downtown area. Other than having advantages over thermal comfort, developing these alleys was promising for urban redevelopment. First, these areas would reduce human-vehicle conflicts, giving pedestrians a safe walking environment in Old Town. Second, for those double-facade shophouses that are mostly found in Old Town, this suggestion would help revitalise their abandoned rear facade to comply with pedestrian zone development.

d. Semi-outdoor conditions provided a better comfort sensation than outdoor conditions in Malaysia (Othman et al., 2021). The combination of covered walkway and vegetation, or other semi-outdoor designs, was highly recommended to maximise the shading in those highly open areas. This idea originated from the typical “five-foot way” found at the front of shophouses. It is a continuous roofed corridor, but at the same time, it is also part of the shophouse used for business activities. It should be further explored on the pattern and ratio of design to determine their efficiency in providing thermal comfort.

e. It should strengthen the redevelopment regulation in controlling the size and height of buildings in the Ipoh downtown. The policy was initially used to maintain the historic skyline of the downtown from a heritage preservation perspective. However, in this study, this policy would be advantageous to minimise the deep canyon effects in the study area.

CHAPTER 4
PROTOTYPES FOR CLIMATE-LED DESIGN AND PLANNING: THE PILOT STUDY

4.1 INTRODUCTION

There have been many kinds of literature supporting the cooling functions of trees and vegetations, promoting urban heat mitigation and adaptation through greening strategy. However, it remains uncertain between greenery coverage and urban cooling magnitude (Aram et al., 2019; OuYang et al., 2020). In other words, how much green do we need and how cool it can be? The above question asked about the green coverage threshold, and so far, many researchers were keen to give a standard on this subject based on the green coverage ratio (GCR). The green coverage ratio is a common index used to determine greenery abundance, which refers to "the ratio of the summation of trees, grasses and other plants areas to the area of a certain space" (Tsutsumi et al., 2003).

There is a wide variety of opinions and controversies on this topic. Firstly, there are different feedbacks on the cooling magnitude provided by a 10% increase of greenery, as elaborated in OuYang et al. (2020). While some studies have ascertained that the relationship between cooling magnitude and greenery abundance is built on a linear correlation, there are other studies that have found that it is instead laid on a non-linear relationship. In short, it is not easy to obtain a conclusive reference index to be the greening threshold, remaining at an impasse.

Beyond that, the threshold concept is less presentable and far from holistic in practice due to numerous climate and urban limitations. This is because the urban thermal performance is never solely manipulated by the greenery coverage, likewise urban cooling magnitude. Moreover, vegetation will not be able to become the central element of existing cities. Hence, instead of obsessing about a standard green coverage threshold, this study suggested looking more at the feasibility and coverage of greening in design and planning. Let's take an urban street as an example. How much green can a street hold at most in reality? To what extent can the street be changed to cooperate with effective greening? If it reached the expected greening, to what extent can it be achieved in terms of microclimate and thermal comfort? All of these uncertainties give high motivation for this chapter.

Furthermore, the greenery in the urban area is relatively complex than in natural and rural regions. There is often no clear separation on land cover changes at the fine-scale level, nor any defined transition between vegetated coverage and artificial coverage in the outdoor environment. The combination between vegetation structure and built features, as well as between vegetation cover and impervious surfaces, are diverse among and within cities. The thermal interaction is dissimilar when combined in different compositions and configurations, giving different thermal effects to the site and surrounding areas within the city. In other words, each city would have its greening limits due to the land-use pattern and density, affecting the urban greenery coverage and the possible cooling magnitude achieved in landscape strategies. It is essential to recognise the greening limitations and possibilities, especially in landscape space allocation, composition, and configuration.

This chapter conducted a pilot study in two parts before implemented the full-scale model study. The first part was to identify the optimum greening prototypes and to demonstrate what is coming with a climate-led landscape design and planning. The prototypes design mainly referred to the findings and recommendations presented in the previous chapter in the design and development process. This process mainly focused on the maximum greening strategy, and it was expected that the greenery coverage would reach the greatest possible extent in the model. To achieve the objective, a series of greening schemes were constructed and executed as prototypes for screening.

In the second part, it tested the design by embedding the selected greening prototypes into a pilot model. The pilot model was simulated in different scenarios based on the study situatedness to determine the most appropriate design scheme for the full-scale model study. Empirically, this study also tried to analyse the regression relationship between greenery coverage and urban cooling.

4.2 PART 1: PROTOTYPE SCREENING

Nine greening prototypes were developed by exploring the possible landscape spatial arrangements, resulting in different green coverage ratios, compositions, and configurations. Since the research area was situated within a historic district with many profound traditional architectural assets, the greening strategy was limited to street canyons without modifying the existing structure layout and building surfaces.

4.2.1 Methodology

In this case, except for car lanes, all open surfaces on the street level should be greening and added with a maximum number of trees in a reasonable interval distance. The greening consisted of four elements: trees, planting strip, green sidewalks and green parking, respectively, which associated with the following conditions:

a. Trees: The tree-to-tree distance should be at least equal to the tree's diameter to balance the visibility between greenery and traditional building facades—for example, a 5-meter interval between 5-meter tree crowns. Furthermore, the distance between tree trunks and buildings must be not less than the tree crown radius. Trees were mainly planted on the planting strip. In case that there is no space to locate a planting strip, the tree can be planted at the sidewalk's edge with a minimum width of 2.5 meters.

b. Planting strip: The width of the strip should be maintained at a minimum of one meter in width.

c. Green sidewalks and green parking: The sidewalk should be at least 2m in width on secondary roads and 1.5m for other road types. With the name of "green", both sidewalk and parking areas promoted green paving, in which the void-structured bricks or concrete blocks were installed and filled with turf soil. Nowadays, the green paving design and technology are relatively mature, minimising the impediment to pedestrian and vehicular areas. It improved the traditional paving, allowing water to pass through artificial surfaces and expand the green area without adding extra spacer for vegetation.

There were several possible spatial layout designs (prototypes) in the study model for primary roads, secondary roads, tertiary roads, and non-motorised roads. In the secondary road, it was further divided into two types of layout patterns: one-way and two-way circulation. Each prototype design had its specific trait and priority at the planting range, walking range or driving range. They were carried out based on the area ratio allocating for trees, planting zone, pedestrian walkway, car lanes and parking lot, as elaborated in Table 4.1 (see the plans and sections in Figures 4.1 and 4.2). The procedure to compute green coverage area was by taking the total area of uncovered vegetation in the plane dimension. This calculation method avoided double-counting the overlapping areas formed by those tall tree crowns and the underlying greenery like shrub hedges and grass cover.

Table 4.1. Prototypes description.

Prototypes	Types of roads	Traffic requirements	Descriptions
1a	Primary road *-typically, 15m in width-*	• Allow maximum vehicular circulation by providing a minimum of three one-way car lanes (3.25m-wide per lane). • No parking is allowed.	Give priority to pedestrian access
1b			Give priority to planting strips
2a	Secondary road (type I) *-typically, 15m in width-*	• Allow one-way vehicular circulation by providing one 5m-wide car lane. • Allow for parking.	Give priority to pedestrian access
2b			Give priority to parking availability
2c			Give priority to planting strips
3a	Secondary road (type II) *-typically, 15m in width-*	• Allow two-way vehicular circulation by providing two car lanes (3.25m-wide per lane). • Allow for parking.	Give priority to planting strips
3b			Give priority to pedestrian access
4	Tertiary road *-typically, 5m in width-*	• Refer to single lane and backlane (type I). • At least 3.25m remain for vehicle access. • No parking is allowed.	Give priority to pedestrian access
5	Non-motorised road *-typically, 3.5m in width-*	• Refer to backlane (type II) and alley within the building cluster. • Not available for vehicle access and parking.	Give priority to pedestrian access

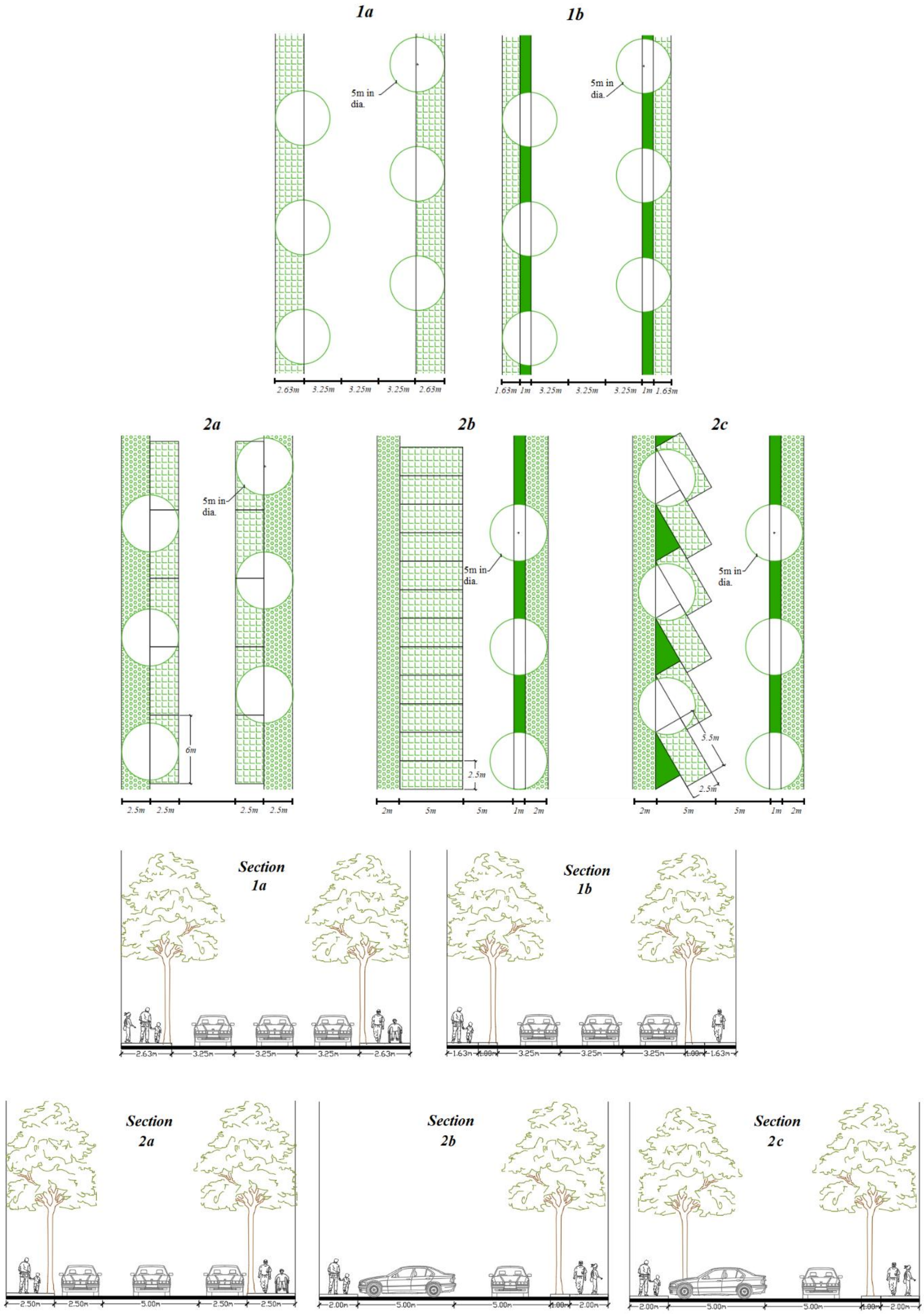


Fig.4.1. Plans and Sections of Prototypes 1 and 2.

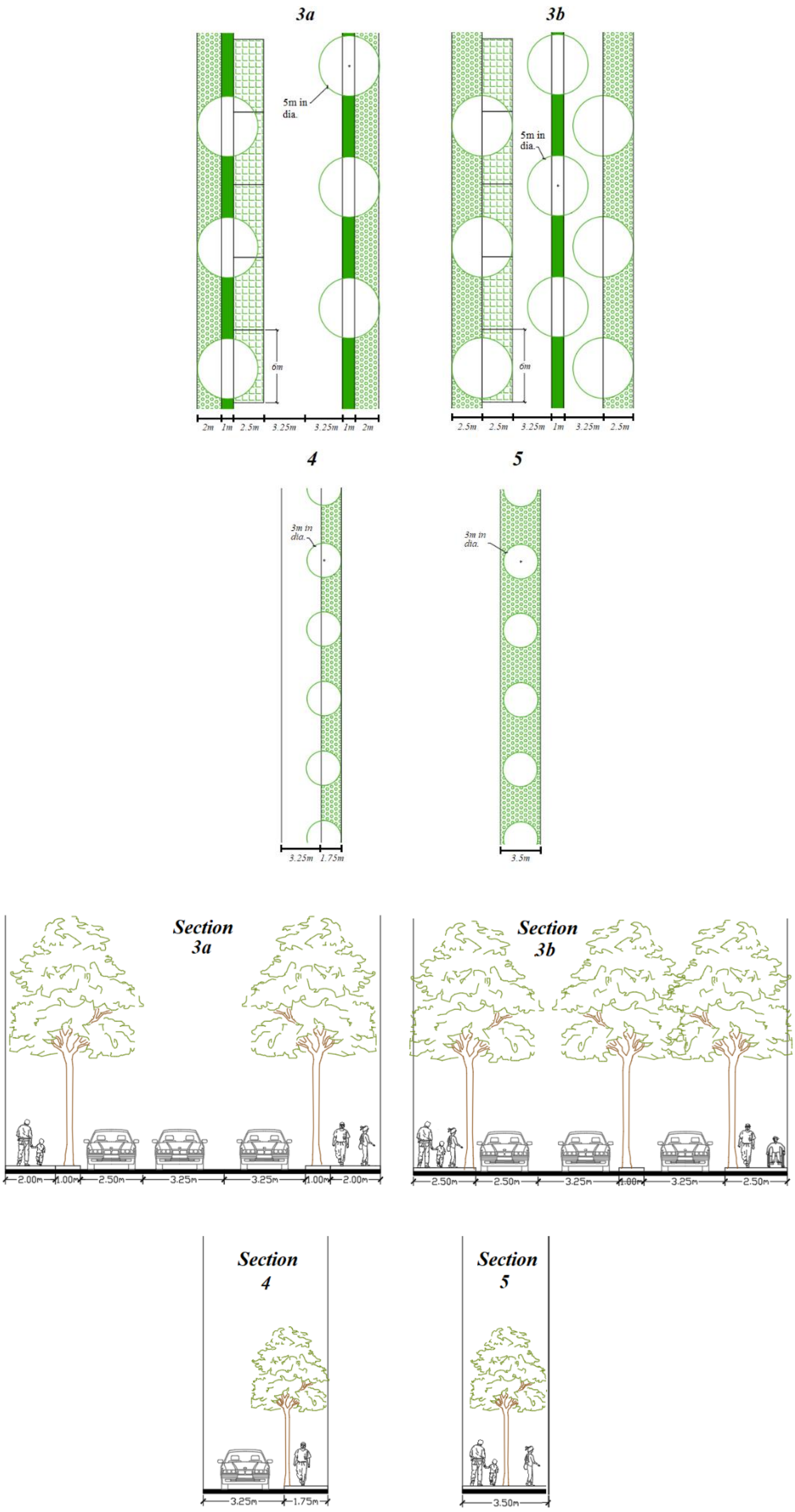


Fig.4.2. Plans and Sections of Prototypes 3, 4 and 5.

4.2.2 Results and Discussion

Table 4.2 summarised the overall performance of prototypes depicted in Section 4.2.1, presenting the spatial allocations for vegetation, pedestrian and vehicular use. From there, the walkway area was then further analysed regarding the potential shading coverage in the pedestrian walking zone, as shown in Table 4.3.

The result showed that the tertiary road in Ipoh (Prototype 4) had the least effect on the greenery coverage. It only possessed a green coverage ratio of 33.40%, having the lowest ratio, and only a maximum of one-third of the model area could be converted into the green area. Its greenery coverage area (51.77m^2) was even smaller than that of non-motorised roads (71.92 m^2). In contrast, the non-motorised road had more significant impacts on greenery coverage when up to two-thirds of the model area (66.29%) was potentially turned into green areas. Despite its contribution to the overall greenery coverage was limited due to its size, it was the prototype with the highest green coverage ratio in this study.

Although Prototypes 1 - 3 had the same total area, their greening quotas were different. Prototypes 1, as expected, performed the worst because open spaces were most allocated with car lanes. Prototypes 2 had the least allocation for car lanes, but they had more parking spaces than Prototypes 3, affecting greening quotas to some extent. The comparison showed that the green coverage did not fully depend on the size of open areas and non-vehicle spaces, but also their spatial composition.

Despite that, the road size impacted the selection of trees. For tertiary and non-motorised roads, we could only plant those trees with a maximum of 3m tree crown, whereas it was possible to plant trees with a bigger tree crown at the typical 15m-wide road on site. However, the spatial arrangement, composition and allocation between planting, vehicular and walking zones did impact the site capacity to accommodate trees, resulted in different patterns of tree distribution. For example, Prototype 2b resulted in insufficient space for tree planting compared to Prototypes 2a and 2c. Also, Prototype 3b allowed more tree planting than Prototype 3a.

In addition, green walkways did contribute to overall green coverage meanwhile providing proper walking spaces for pedestrians. However, to consider pedestrian thermal comfort, it was found that tree shade coverage areas on the walkways should be taken into account. As summarised in Table 4.3, it turned out that there will be a loophole if the overall green coverage is assumed to be linearly correlated with pedestrian thermal comfort. In view of that, all prototypes (except for Prototypes 4 and 5) were further reviewed and compared in two dimensions. On the one hand, the priority of selection was still placed on the greening extent on the street level. The greening extent was according to the allocations to trees, shrubs and green walkways. In this case, in addition to considering the overall green coverage ratio (GCR), the coverage ratio of trees (TCR) was equally important. On the other hand, these prototypes were evaluated by their advantages over pedestrian-oriented development. It would be in accordance with their allocation ratio for walkways and the potential shading coverage ratio at the walking zone. The ratio calculation methods were demonstrated respectively, as below:

- The coverage ratio calculation of trees was shown in the following:

$$\text{Ratio} = \frac{\text{Total area of trees}}{\text{Total area of prototype}} \times 100$$

- The coverage ratio calculation of planting strip, walkway, and parking was shown in the following:

$$\text{Ratio} = \frac{\text{Total uncovered area (planting strip, walkway, or parking)}}{\text{Total area of prototype}} \times 100$$

- The coverage ratio calculation of the overall walkway was shown in the following:

$$\text{Ratio} = \frac{\text{Total walkways area}}{\text{Total area of prototype}} \times 100$$

- The coverage ratio calculation of shading was shown in the following:

$$\text{Ratio} = \frac{\text{Total shaded walkways area}}{\text{Total walkways area}} \times 100$$

Table 4.2. Summary of prototype performance in various aspects.

Prototype	AREA (m²)									Planting range		Driving range		Walking range	
	Trees*1	Planting strip		Green Walkway*2		Green Parking*2		Total							
		Uncovered	Total	Uncovered	Total	Uncovered	Total	Green Coverage	Overall	Green coverage ratio (%)	Tree no.	Parking lot no.	Car lane no. x width (m)	Lane no. x width (m)	Total in width (m)
1a	117.81	-	-	49.98	162.75	-	-	167.78	465	36.08	6	-	3 x 3.25	2 x 2.63	5.26
1b	117.81	32.54	62	33.72	100.75	-	-	184.07	465	39.58	6	-	3 x 3.25	2 x 1.63	3.26
2a	117.81	-	-	47.53	155	46.01	150	211.34	465	45.45	6	10	1 x 5	2 x 2.50	5
2b	58.91	16.11	31	50.49	124	85.25	85.25	210.75	465	45.32	3	12	1 x 5	2 x 2.00	4
2c	117.81	33.32	64.38	44.25	124	27.29	82.5	222.67	465	47.89	6	6	1 x 5	2 x 2.00	4
3a	117.81	32.21	62	39.44	124	26.35	75	215.81	465	46.41	6	5	3 x 3.25	2 x 2.00	4
3b	176.72	16.10	31	47.99	155	22.70	75	263.50	465	56.67	9	5	3 x 3.25	2 x 2.50	5
4	35.34	-	-	16.42	54.25	-	-	51.77	155	33.40	5	-	1 x 3.25	1 x 1.75	1.75
5	35.34	-	-	36.58	108.50	-	-	71.92	108.50	66.29	5	-	-	1 x 3.50	3.5

[1] Size of tree: 5m crown for prototypes 1, 2 and 3; 3m crown for prototypes 4 and 5.
[2] Green coverage area = half of the total uncovered area (due to void (turf) and non-void (concrete or brick) surfaces presented in a green paver structure)

Table 4.3. Calculation of prototype performance in shading coverage at the walkway area.

Prototype area (m²)	**1a**	**1b**	**2a**	**2b**	**2c**	**3a**	**3b**	**4**	**5**
Total walkway (A)	162.75	100.75	155	124	124	124	155	54.25	108.5
Unshaded walkway (B) *	99.95	67.44	95.05	100.98	88.50	78.88	95.98	32.85	73.16
Shaded walkway area (A-B)	62.8	33.31	59.95	23.02	35.5	45.12	59.02	21.4	35.34

** equal to uncovered walkway area*

For the primary road situation (refer to Table 4.4), prototypes 1a and 1b obtained the same score in tree coverage ratio. However, prototype 1b scored the highest greenery coverage ratio by providing planting strips. The comparison showed that the removal of planting strip to increase green walkways area remained a significant discrepancy in greenery coverage, highlighting the importance of planting reserve area to secure greenery coverage on urban street level. Therefore, the street planting strip shall not be replaced for any other functions on the street unless the greenery can be remained at the same quantity and quality alternatively.

However, the only 1.63m-wide sidewalk of prototype 1b is insufficient for high pedestrian flow, becoming a disadvantage for pedestrian-priority development. Moreover, a higher ratio of shading coverage was found in prototype 1a, suggesting that prototype 1a was more suitable for pedestrian-priority development.

In order to maintain a balance between greening and pedestrian development, there were two suggestions, as follows:

- Prototype 1b is recommended for most primary roads in Ipoh downtown, except for those that also become the primary access for pedestrians.
- Under exceptional conditions, prototype 1a will be executed to maintain the smooth flow of pedestrians.

Table 4.4. Analysis of prototypes 1.

Criteria		1a	1b
Greenery priority (*all ratios are obtained based on AREA mentioned in Table 4.2)*	**Tree coverage ratio (%)**	**25.34**	**25.34**
	Planting strip coverage ratio (%)	-	7.00
	Walkway coverage ratio (%)	10.75	7.25
Total green coverage ratio (%)		**36.08**	**39.58**
Most recommended			/
Pedestrian priority (*all ratios are obtained based on A and A-B in Table 4.3)*	**Overall walkway ratio (%)**	35	21.67
	Shading coverage ratio (%)	38.58	33.06
Most recommended		/	

For the one-way secondary road situation (refer to Table 4.5), despite only a small green coverage ratio discrepancy between the subsets, prototype 2c scored the highest index. However, in terms of tree coverage ratio, prototypes 2b were much lowered than prototypes 2a and 2c, representing that its cooling effect could not be assumed the same as the other two subsets due to the gap in the amount of tree shade.

From a pedestrian-priority viewpoint, the situation of 2a was similar to prototypes 1a where the allocation in the planting strip area had relatively reduced the allocation in the walkway and parking area. Prototype 2a became more dominant in walkway coverage and shading coverage, making it the most appropriate model for pedestrian-priority development.

Again, in order to maintain a balance between greening and pedestrian development, there were two suggestions, as follows:

- Prototype 2c is recommended for most one-way secondary roads in Ipoh downtown, except for those that also become the primary access for pedestrians.
- Under exceptional conditions, prototype 2a will be executed to maintain the smooth flow of pedestrians.

Table 4.5. Analysis of prototypes 2.

Criteria		**2a**	**2b**	**2c**
Greenery priority *(*all ratios are obtained based on Table 4.2)*	**Tree coverage ratio (%)**	**25.34**	**12.67**	**25.34**
	Planting strip coverage ratio (%)	-	3.46	7.17
	Walkway coverage ratio (%)	10.22	10.86	9.52
	Parking coverage ratio (%)	9.89	18.33	5.87
Total green coverage ratio (%)		**45.45**	**45.32**	**47.89**
Most recommended				✓
Pedestrian priority *(*all ratios are obtained based on Table 4.3)*	**Overall walkway ratio (%)**	33.37	26.67	26.67
	Shading coverage ratio (%)	38.68	18.56	28.63
Most recommended		✓		

For the two-way road situation, there was relatively a significant variation between the subsets of prototypes 3. Prototype 3b performed the best in both greenery and pedestrian consideration. Besides, it scored the highest tree coverage ratio, where up to nine trees (contributed a total of 38% in the coverage ratio for greenery) could be accommodated on-site. It was also the only prototype that provided up to a 2.5m-wide walkway for pedestrians without affecting the green coverage ratio, becoming the most prominent prototype in this study.

Table 4.6. Analysis of prototypes 3.

Criteria		3a	3b
Greenery priority *(*all ratios are obtained based on Table 4.2)*	**Tree coverage ratio (%)**	**25.34**	**38**
	Planting strip coverage ratio (%)	6.93	3.46
	Walkway coverage ratio (%)	8.48	10.32
	Parking coverage ratio (%)	5.67	4.88
Total green coverage ratio (%)		**46.41**	**56.67**
Most recommended			
Pedestrian priority *(*all ratios are obtained based on Table 4.3)*	**Overall walkway ratio (%)**	26.67	33.37
	Shading coverage ratio (%)	36.39	38.08
Most recommended			✓

In summary, prototypes 1b, 2c and 3b were recommended as the optimal threshold for greenery coverage on mitigating the urban thermal environment of the study area, except for the exceptional condition. In the comparison between prototypes 2c and 3b, it recommended converting some secondary roads from one-way to two-way traffic. This suggestion was made mainly because of three reasons, as follows:

- The two-way prototype could significantly increase the greenery coverage in the street canyon.
- The two-way prototype could allocate more pedestrian areas (walkways) in the street canyon.
- The two-way prototype could provide more tree shading to pedestrians on the street level.

In addition to its advantages in green coverage and pedestrian aspect, the suggestion was supported by Baco (2009) and Gayah (2012). Compared with the one-way traffic network that prioritised the needs of automobile drivers above all others, Baco (2009) opted for two-way traffic as a preservation and downtown revitalisation tool. Through a case study of Upper King Street in Charleston, South Carolina, she concluded that the two-way road network had reduced car speed, improved pedestrian experience, and increased the visibility of commercial storefronts. The improvement had ultimately revitalised street life, increasing the old property values of downtowns. On the other hand, Gayah (2012) recommended a two-way traffic network for downtown areas based on his broader view regarding pedestrians, economic activity and liveability, traffic and transit, as elaborated in Table 4.7.

Table 4.7. Benefits of using a two-way network system in the downtown area (source: Gayah, 2012).

Aspect	Benefits of two-way roads
Pedestrians	Reduced vehicle-moving capacities, flow, and travel speed to make the roads safer for pedestrians to cross at the intersection.
	Increased levels of driver attention and drivers tend to drive more slowly.
Economic activity and liveability	Allow more pass-by traffic, increasing prosperity and liveability.
	Make more frequent stops for vehicles, giving drivers more exposure to local businesses.
Traffic	Drivers have less confusion because they can easily approach their destination from any direction.
	Allow drivers to take the most direct routes from origin to destination, resulted in decreased vehicle miles travelled (VMT). Decreased VMT reduced fuel consumption, emissions, and exposure to accidents as well.
Transit	Make locating the transit stop for a return trip in the downtown easier.

4.3 PART 2: SCENARIO MODEL SCREENING

After deciding the model study prototypes, this section applied the prototypes into a pilot model (a 350m x 350m model extracted from the shophouse district in Ipoh). As defined in the prototypes, the green coverage and sidewalks were allocated according to road types and traffic systems of the model. In the process, the model design would be modified to increase the greening and pedestrian's benefits. In addition, it came up with another scenario model by considering the heritage visibility at the street level. The selection of models would finally depend on simulated thermal performance and overall integration.

4.3.1 Model Building and Simulation

Based on the criteria concerned in the last paragraph, a total of three scenario models were built and simulated in this chapter:

Scenario 1 (Figure 4.3) replicated the existing condition of the pilot model. It acted as the baseline model, mainly used to capture the existing thermal condition and enable the comparison between original and modified baseline models.

Scenario 2 (Figure 4.4) was designed to achieve maximum greening for the pilot model. In this case, all open roads and sidewalks were assumed to be modifiable, maximally adding trees and vegetation along the streets and changing the existing impervious surface to optimum natural-based groundcover. In this model, there was an attempt to increase greenery and pedestrian zone by changing a specific part of roads into non-motorised areas. The transformation was most inspired by the current downtown tour route and popular visitor spots, considering an effective pedestrian network designed for tourists.

Scenario 3 (Figure 4.5) coincided with Scenario 2, but it has been modified with the condition that we need to secure and prioritise the views of heritage buildings and murals. This scenario aimed to conserve the heritage streetscape of Ipoh old town in terms of visibility. The heritage facades and murals were referred to as point-of-interest (POI) in the study. Plants, especially trees, should not block the views of these POIs at the pedestrian level (Figure 4.6).

Fig. 4.3. The baseline model used for climate simulation (Scenario 1): above-ground layer(left) and ground layer (right)

Fig. 4.4. The maximum greening model used for climate simulation (Scenario 2): above-ground layer(left) and ground layer (right)

Fig. 4.5. The conditional greening model used for climate simulation (Scenario 3): above-ground layer(left) and ground layer (right)

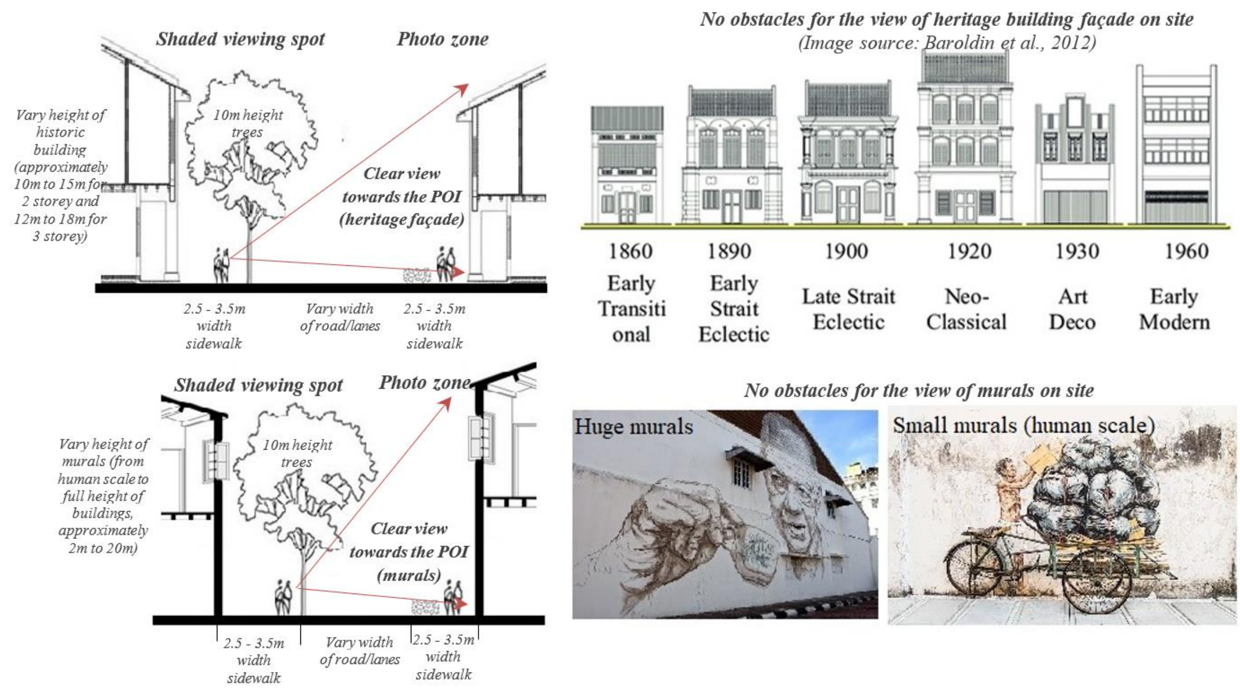


Fig. 4.6. Greening recommendation for POI and adjacent areas (according to Scenario 3).

For design and simulation, trees with 3m and 5m canopies were set at the height of 6m and 10m, while the shrubs and grass were kept at 1m and 0.1m, respectively. No specific plant species were studied. In this study, green paving was introduced for pedestrian walkways and parking areas. Since the paver block used for green paving is void-structured and mostly filled by grass and turf soil, it was considered the same as "grass" in the simulation. In ENVI-met, it was simulated in a 350 m x 350m x 70m model, with a model grid resolution of 2m x 2m x2.5m in dx, dy, and dz directions, respectively. The overall operation procedure was explained in section 3.3 of the last chapter.

Table 4.8 showed the greenery and walkway coverage ratio of each scenario in this study. They are calculated in two contexts: overall and open area. 'Overall' meant to include the entire surface of the model, whereas the 'open area' meant to exclude the building footprint area in the model. Before the simulation stage, we have seen that the walking area ratio has risen from approximately 15% to 25%, significantly increasing the walking area for pedestrians in the total open area. Scenario 2 scored the highest ratio in terms of greenery coverage, showing that it is possible to turn up to 57.21% of the total open area into green using the maximum greening strategy. It was followed by Scenario 3 with a 0.18% difference. Through the simulation, it was to examine the thermal pattern and discrepancy between Scenario 2 (maximum greening model) and 3 (conditional greening model), as well as how effective they improved the thermal environment by comparing with Scenario 1 (the baseline model).

Table 4.8. Summary of coverage area calculation between scenarios.

Coverage area	**Greenery**		**Pedestrian walkway**	
	Count (no. of raster cell)	**Percentage (%)**	**Count (no. of raster cell)**	**Percentage (%)**
CASE I: OVERALL				
Scenario 1	2371	7.65	2426	7.83
Scenario 2	8959	28.92	3892	12.56
Scenario 3	8903	28.74	3892	12.56
*Total Open Area	15659	50.55	15659	50.55
Total	30976	100	30976	100
*** CASE II: OPEN AREA ONLY *(excluded buildings)***				
Scenario 1	2371	15.14	2426	15.49
Scenario 2	8959	57.21	3892	24.85
Scenario 3	8903	56.86	3892	24.85
Total	15659	100	15659	100

4.3.2 Results and Discussion

4.3.2.1 Microclimate aspect

Table 4.9. Comparison of climatic factors between scenarios.

Factors	***Scenario 1 (baseline model)***			***Scenario 2 (maximum greening model)***			***Scenario 3 (conditional greening model)***		
	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max
Air temperature (°C)	30.70	31.99	34.62	29.73	31.43	34.05	29.79	31.43	34.05
Surface temperature (°C)	22.98	41.72	54.19	21.57	36.10	53.47	21.76	36.30	53.76
Mean radiant temperature (°C)	32.44	55.59	64.31	26.88	48.99	62.03	27.20	49.46	62.14
Air velocity (m/s)	0.01	0.55	2.40	0.01	0.46	1.99	0.01	0.46	1.99
Relative humidity (%)	52.60	61.39	65.73	54.05	64.75	70.06	54.05	64.68	69.77

In this section, we first assessed and compared the climate performance in the aspects of air temperature, mean radiant temperature, surface temperature, air velocity, and relative humidity. According to Table 4.9, all climatic factors have been improved at certain degrees through the proposed landscape models, proving that a climate-led landscape plan can indeed effectively ameliorate the local microclimate. Overall, the design outcomes were in line with the expectations discussed in the previous chapter. In other words, the greening strategy formulated in this chapter abled to increase site humidity and reduced the temperatures and air velocity effectively. This result would lead to a lower physiological equivalent temperature (PET), thereby positively improving local thermal comfort. By using mappings and graphs, the simulation output was further analysed along with the microclimate distribution patterns - before and after designs -. This process was to examine the effectiveness of climate-led landscape in microclimate improvement visually.

a. Air Temperature

Figure 4.7 showed an average drop of 0.56°C and a lower temperature range before and after design. The colour changing in the distribution maps from Scenario 1 to Scenarios 2 and 3 clearly illustrated the decline. All areas in the model have been dropped to lower temperatures, with the most apparent improvement happened in open spaces locating at the northwest and northeast of the model. It should be noted that the changes of half of a degree may not be significant in terms of numerical value, but it will be crucial in the realm of climatology. The rapid climate change today is the result of an increase of 1°C on average global temperatures on the Earth since the 19th century, and nowadays, most countries are committed to keeping it at no more than 1.5°C above preindustrial levels, instead of the 2°C in estimation.

There was no significant discrepancy in the distribution pattern between Scenarios 2 and 3. Likewise, as shown in Scenario 2, there was no disparity in air temperature performance between prototypes 1b, 2c and 3b that have been integrated into the model. The result turned out that the differences between these two scenarios were insignificant to affect the overall atmospheric temperatures, and the same went for the case between the prototypes.

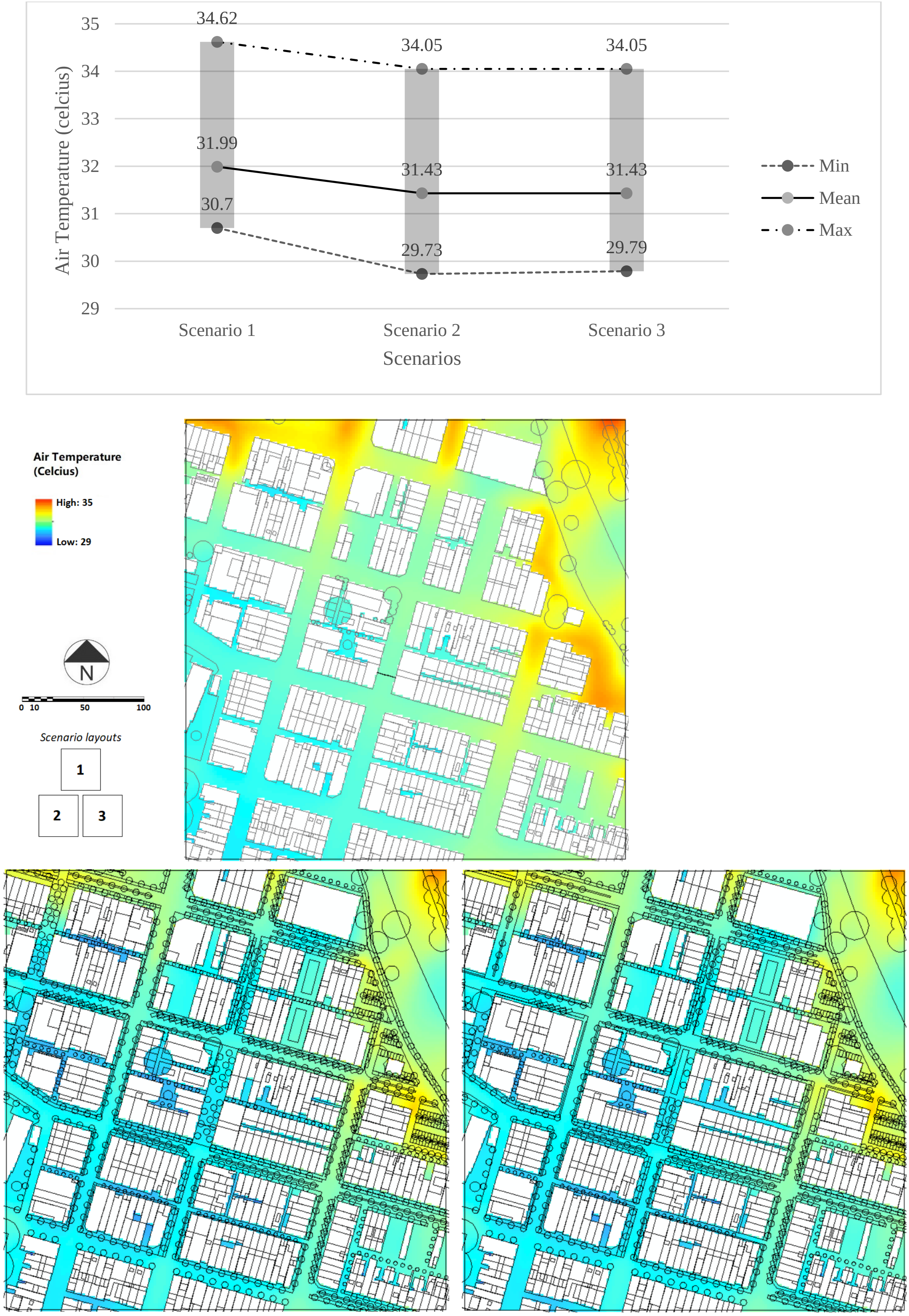


Fig. 4.7. Air temperature distribution between scenarios.

b. Surface Temperature

Unlike air temperatures, surface temperatures changed dramatically before and after designs (Figure 4.8). The average surface temperature reduced about 5°C, from 41.72°C to 36.1°C in Scenario 2 and 36.3°C in Scenario 3, immensely cooling the urban surfaces. However, there were fewer changes in the temperature range because many asphalt roads were still inevitably exposed to the sun. The maps showed that the shaded areas in Scenarios 2 and 3 could reduce surface temperatures to the maximum level (as shown in blue on the maps). Meanwhile, the temperature of areas covered by shrubs or grass (including green paving areas) also dropped drastically to an acceptable level (as shown in green on the maps). The gap in cooling performance between trees, shrubs, and grass have led to significant discrepancies at POI areas between scenarios.

The diverse composition of land cover materials between prototypes also resulted in different surface temperature performances. Scenario 2 clearly illustrated that Prototype 3b performed the best, followed by Prototype 2c and then Prototype 1b. Using the green coverage ratio to predict land surface cooling efficiency, in this case, is justified. Lastly, replacing asphalt with brick pavers was practical to reduce the heat on open roads. Brick pavers not only have advantages in surface cooling but are also helpful in increasing driver attention and reducing driving speed.

c. Mean Radiant Temperature

Based on Figure 4.9, mean radiant temperatures were most decreased before and after design, more than 6°C on average. Their maximum extent was similar, but the minimum extent has been reduced sharply from 32.44°C to 26.88°C in Scenario 2 and 27.2°C in Scenario 3. However, most areas still had high temperatures on average (up to 48.99°C in Scenario 2 and 49.46°C in Scenario 3), except for treed areas.

The diverse performance between prototypes (see Scenario 2) showed that mean radiant temperature could only be significantly improved by trees. Prototype 3b, which had more trees than the other two prototypes, performed best in this section. Likewise, there were no significant changes in the distribution patterns between Scenario 2 and 3, except for the POI area. The lower degree in Scenario 2 was also contributed by the higher ratio of trees. This finding supported the use of tree coverage ratio in predicting ambient temperature performance as well.

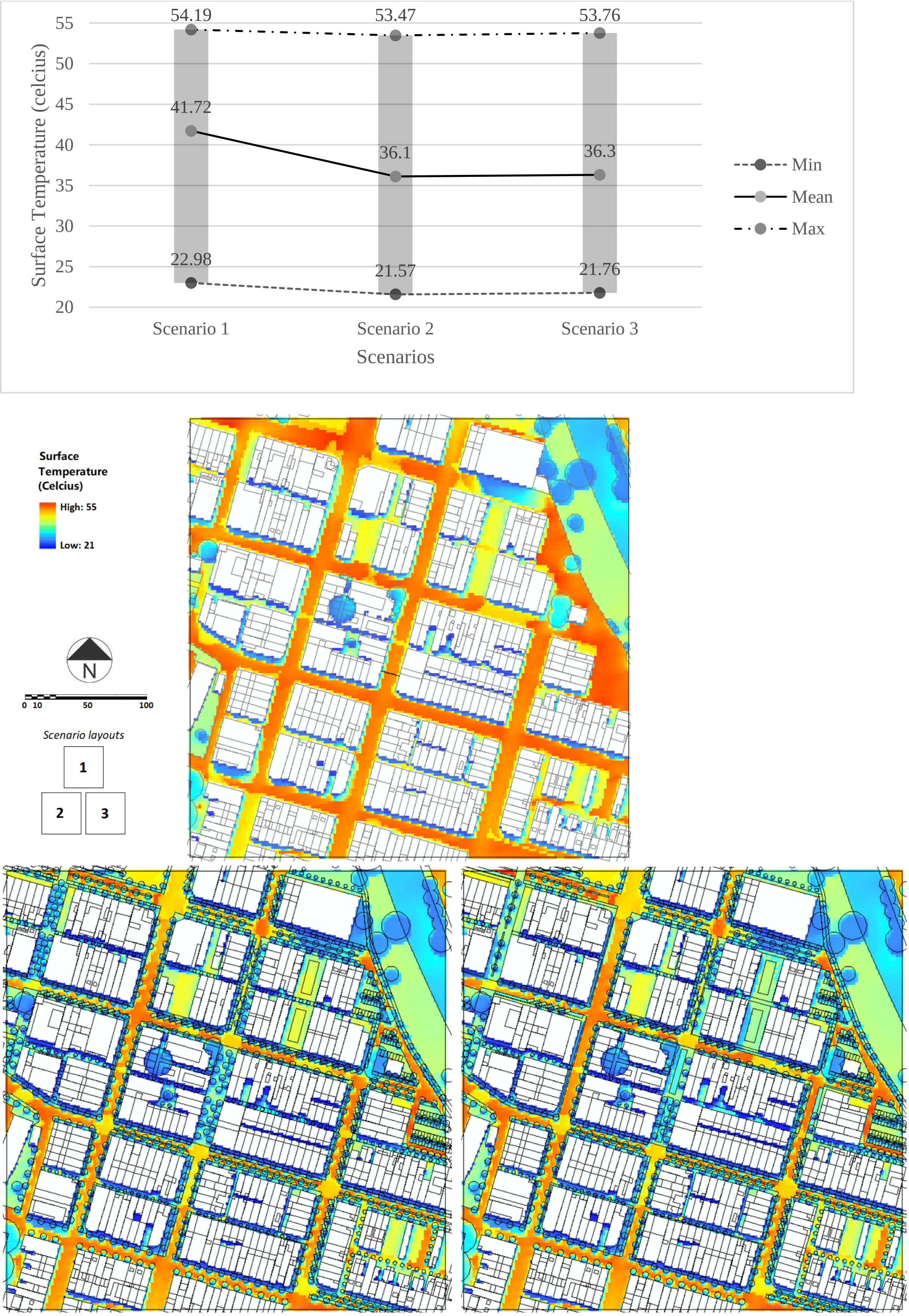


Fig. 4.8. Surface temperature distribution between scenarios.

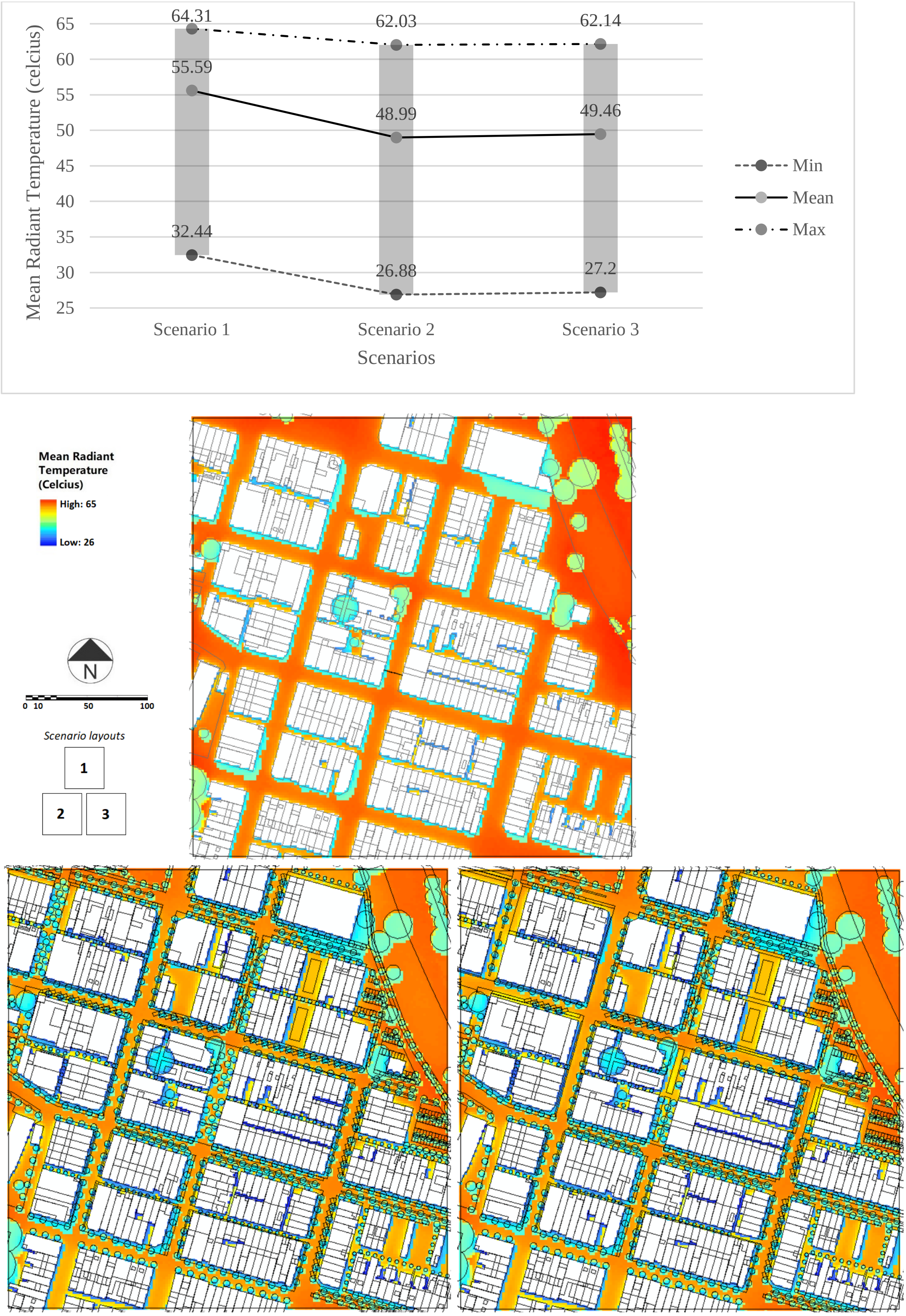


Fig. 4.9. Mean radiant temperature distribution between scenarios.

d. Wind Speed

The result turned out that the arrangement of trees in this chapter could positively influence wind pattern and speed, shrinking the wind speed range from the maximum of 2.4m/s to 1.99m/s. As shown in Figure 4.10, Scenarios 2 and 3 hold the same average wind speed at 0.44m/s, maintaining the range at 0.01-1.99m/s. Their difference was only found in the POI areas, showing that only trees could impact the wind pattern.

The North-South oriented streets remained as air tunnels in the downtown but at a smaller span and lower wind speed. The consistent and continuous tree planting along streets has stabilised and reduced the wind flow at the pedestrian level, giving a relative lower wind speed along the sidewalks. Other than that, the addition of trees has also effectively ameliorated the "downdraught effect" (mentioned in section 3.5.4) happening at the high-rise buildings.

In this section, all prototypes were constructive on wind performance. However, due to the road orientation and diverse building layout patterns in the model, it was not easy to compare the differences in wind effects between prototypes.

e. Relative Humidity

Figure 4.11 showed a positive change in relative humidity mean before and after design, from 61.39% to 64.75% in Scenario 2 and 64.68% in Scenario 3. The relative humidity range also improved from 52.6-65.73% to 54.0-70.06% in Scenario 2 and 54.05-69.77% in Scenario 3. The colour changing in the distribution maps from Scenario 1 to Scenarios 2 and 3 clearly illustrated the intensification.

The comparison at POI showed that the treed areas in Scenario 2 had higher air moisture than the area with only shrubs or grass in Scenario 3. Likewise, prototype 3b impacted relative humidity the most, followed by prototype 2c and then prototype 1b, following their tree ratio and greenery coverage. In other words, it proved that the numbers of trees and the quantity of vegetation play a crucial regulating role in air moisture level for site cooling. The result also supported the use of tree coverage ratio and green coverage ratio in predicting site humidity performance.

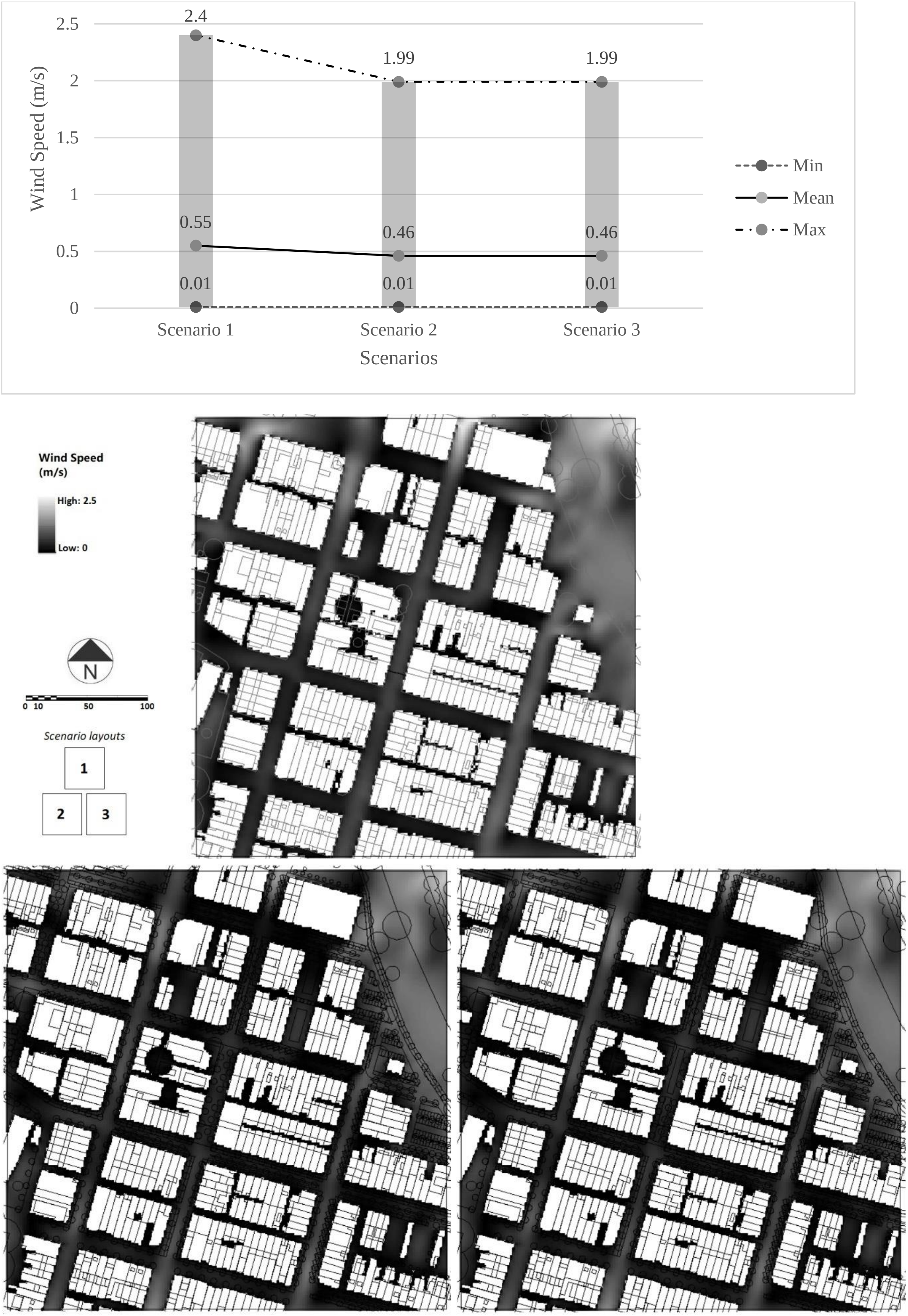


Fig. 4.10. Wind speed distribution between scenarios.

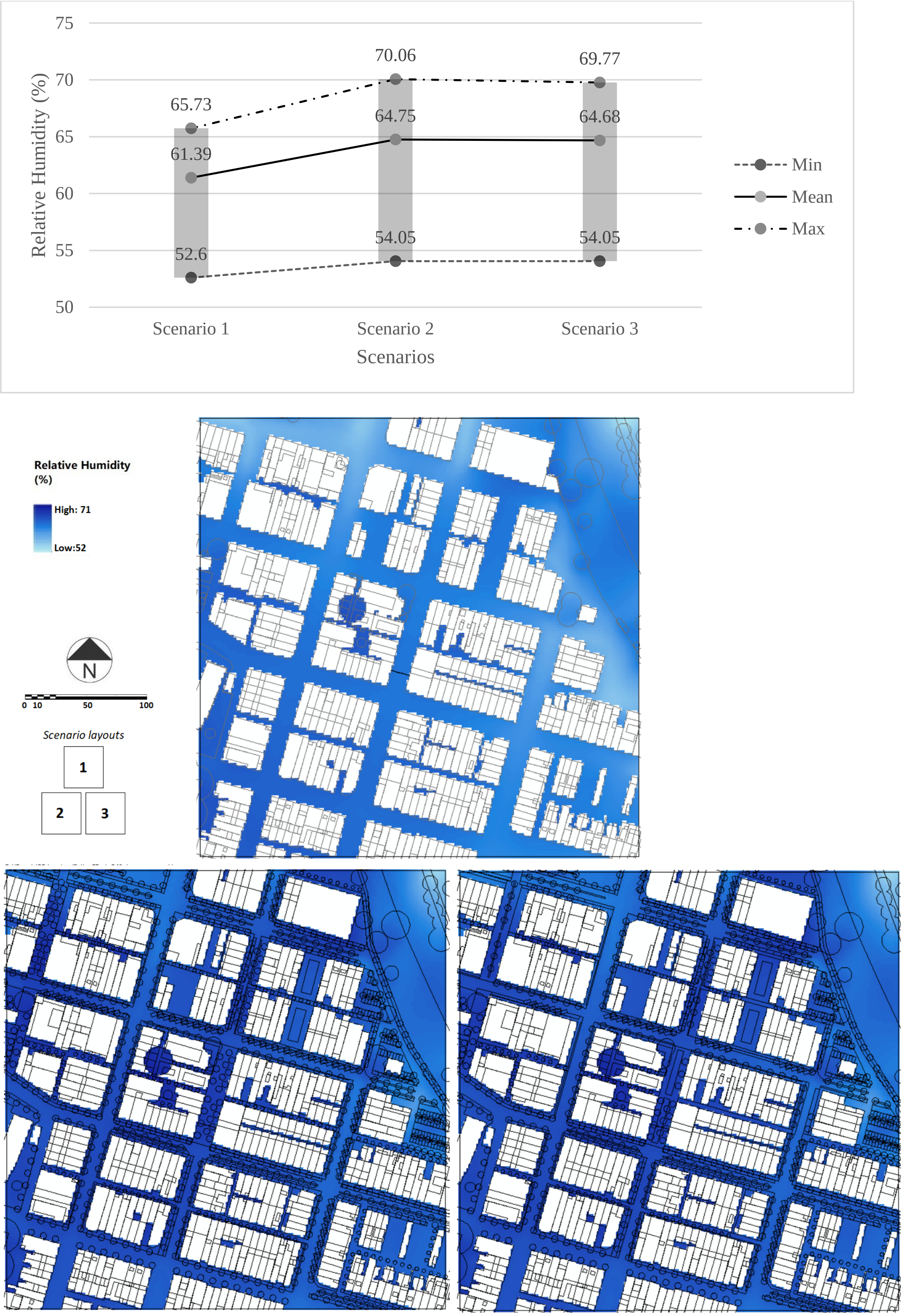


Fig. 4.11. Relative humidity distribution between scenarios.

4.3.2.2 Thermal comfort aspect

In consideration of pedestrian comfort, this section analysed the climate-led landscape plans for human thermal comfort. Overall, the physiological equivalent temperature (PET) was reduced about 3-4°C on average, from 44.72°C to 40.85°C in Scenario 2 and 41.11°C in Scenario 3 (Table 4.10). In this case, the average thermal comfort had been improved from 'very hot' (>42°C) to 'hot' condition (38 - 42°C) before and after design, which could be considered a significant improvement at the hottest hour of the day (refer to Table 3.7). Furthermore, the PET range has also been lowered from 32.7 - 51.3°C to 29.4 - 49.5°C in Scenario 2 and 29.6 - 49.5 °C in Scenario 3. In both cases, the minimum PET index was successfully reduced to a "slightly warm" condition, which was a major leap in ameliorating thermal comfort conditions, turning from "uncomfortable" to "comfortable" levels.

Table 4.10. Comparison between the thermal comfort level

PET (°C)	Scenario 1 (A)	Scenario 2 (B)	B - A	Scenario 3 (C)	C-A
Mean	44.72	40.85	-3.87	41.11	-3.61
Maximum	51.3	49.5	-1.8	49.5	-1.8
Minimum	32.7	29.4	-3.3	29.6	-3.1

The distribution changes of PET (Figure 4.12) and thermal comfort level (Figure 4.13) illustrated that thermal comfort was mainly improved by the tree planting along the streets. The result also showed that the cooling magnitude was proportional to the allocation and density of street trees. There was at least one row of trees at small lanes, two rows of trees for one-way roads, three rows of trees for two-way roads, maximising the shading coverage for pedestrian comfort. Prototype 3c, which offered the most spaces for tree planting, was undoubtedly the most excellent prototype for this study. Likewise, the higher tree coverage ratio made Scenario 2 performed slightly better than Scenario 3. Under these treed areas, thermal comfort level dropped rapidly from 'very hot' to 'warm' or even 'slightly warm' condition, helped to relieve pedestrian thermal discomfort to a great extent.

In the comparison between Figures 4.12 and 4.13, the conclusion was that even though shrub and grass did impact PET, unfortunately, the small degree of improvement did not have sufficient influence on thermal comfort perception.

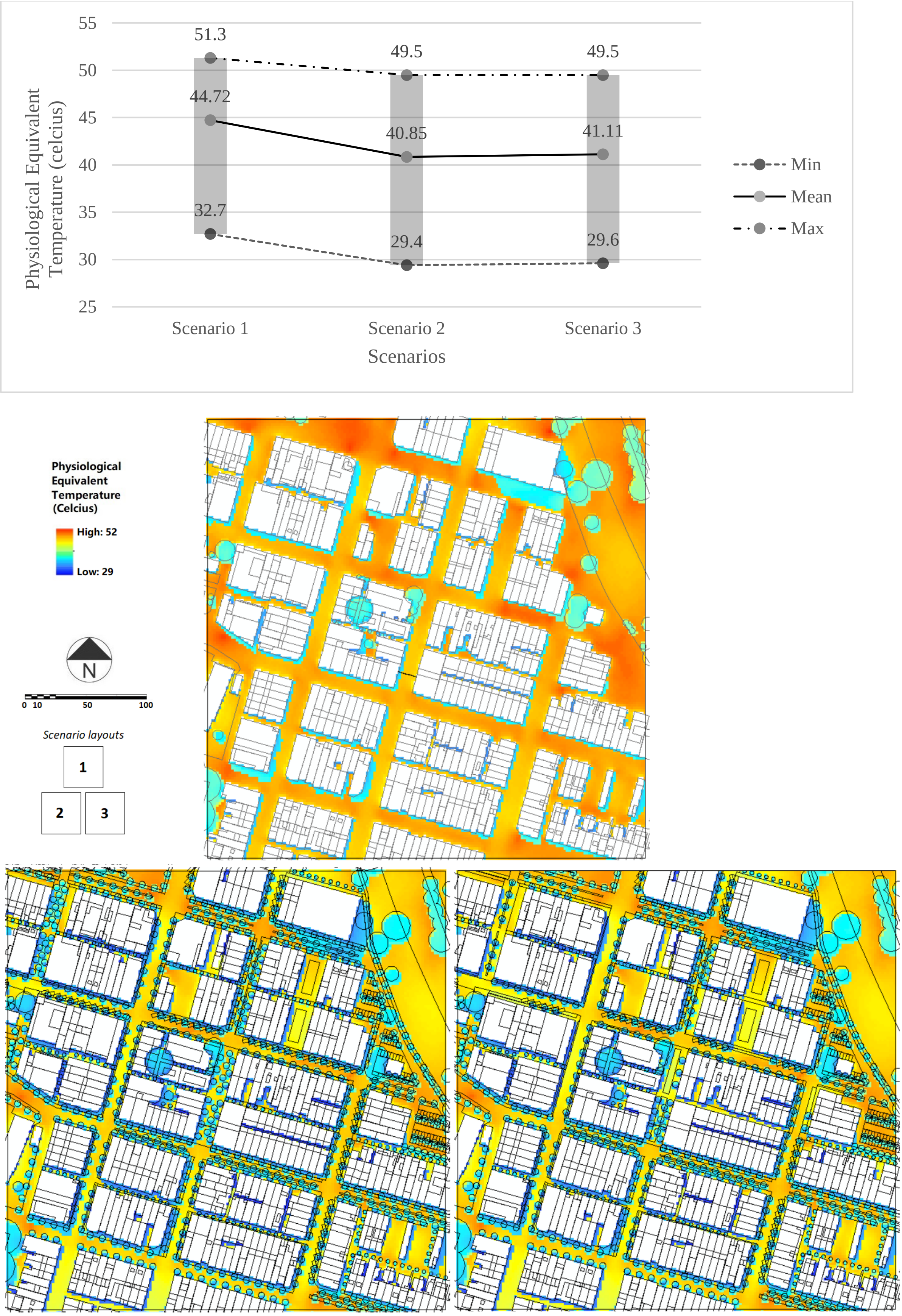


Fig. 4.12. PET distribution between scenarios.

Fig. 4.13. Comparison between thermal comfort level.

Overall, both scenarios have significantly increased the comfort zone coverage ratio:

a. In the overall coverage dimension, it increased from 57.71% to 62.40% in Scenario 2 and 62.25% in Scenario 3 (Table 4.11).
b. In the open area coverage dimension, it increased from 1.33% to 12.29% in Scenario 2 and 11.92% in Scenario 3 (Table 4.12).

Table 4.11. Summary of thermal comfort coverage area between scenarios (case I).

Overall Coverage ratio （%）		**Scenario 1**	**Scenario 2**		**Scenario 3**	
Level	**Classification**	**Coverage A2**	**Coverage B2**	**Comparison B2 – A2**	**Coverage C2**	**Comparison C2 – A2**
Comfort	Inside building	57.14	57.14	0.00	57.14	0.00
	0 (neutral)	0.00	0.04	0.04	0.03	0.03
	1 (slightly warm)	0.57	5.22	4.65	5.08	4.51
Acceptable *(adaptation)*	2 (warm)	7.61	11.50	3.89	10.60	2.98
Discomfort	3 (hot)	1.80	4.03	2.22	3.72	1.91
	4 (very hot)	32.88	22.07	-10.81	23.44	-9.43
Summary						
Comfort		57.71	62.4	4.69	62.25	4.54
Acceptable		7.61	11.5	3.89	10.6	2.99
Discomfort		34.68	26.1	-8.58	27.15	-7.53
Greenery available		7.65	28.92	+21.27	28.74	+21.09

Table 4.12. Summary of thermal comfort coverage area between scenarios (case II).

Open area Coverage ratio （%）		**Scenario 1**	**Scenario 2**		**Scenario 3**	
Level	**Classification**	**Coverage A1**	**Coverage B1**	**Comparison B 1- A1**	**Coverage C1**	**Comparison C1 – A1**
Comfort	0 (neutral)		0.09	0.09	0.06	0.06
	1 (slightly warm)	1.33	12.2	10.87	11.86	10.53
Acceptable *(adaptation)*	2 (warm)	17.76	26.83	9.07	24.72	6.96
Discomfort	3 (hot)	4.21	9.4	5.19	8.67	4.46
	4 (very hot)	76.7	51.48	-25.22	54.69	-22.01
Summary						
Comfort		1.33	12.29	10.96	11.92	10.59
Acceptable		17.76	26.83	9.07	24.72	6.96
Discomfort		80.91	60.88	-20.03	63.36	-17.55
Greenery available		15.14	57.21	+42.07	56.86	+41.72

The PET results showed that the majority area was still not in the range of comfort zones, but the range of extreme conditions was significantly reduced. As showed in Table 4.12, the ratio of 'very hot' area (above 42°C) was declined from 76.70% to 51.48% in the maximum greening model (Scenario 2) and 54.69% in the conditional greening model (Scenario 3). In other words, more than 22% of the PET coverage area (that is, the total open area) has been improved and cooled in the study, proving that their capacities in alleviating thermal discomfort in Ipoh old town.

At the same time, the "warm" area has been dramatically increased and occupied approximately 25% of the PET coverage area (26.83% in Scenario 2 and 24.72% in Scenario 3). This achievement was worth mentioning because the past thermal comfort studies in Malaysia have indicated that the respondents could adapt to the "warm" condition rather than the "comfortable" range of PET, and they viewed "warm" as an acceptable thermal condition (Makaremi et al., 2012; Nasir et al., 2012). Finally, most comfort and acceptable zones fall in the pedestrian area after climate-led design, indicating that the goal of providing pedestrians with optimal thermal comfort was ultimately achieved. Through the sectional perspective (Figure 4.14), we could directly differentiate the degree of thermal comfort improvement before and after climate-led design. All outcomes showed that both proposed landscape models were practical for alleviating thermal discomfort in Ipoh old town.

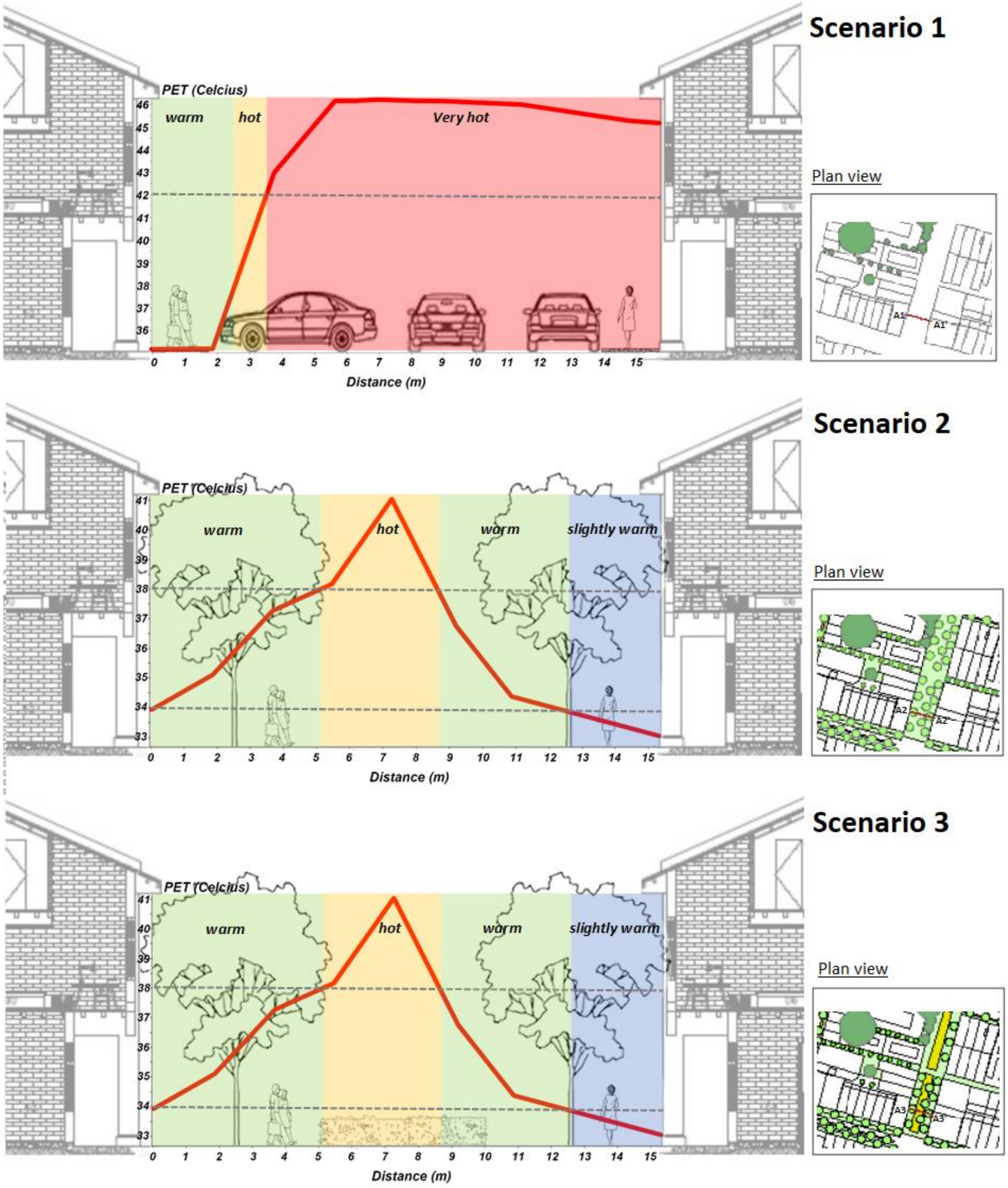


Fig. 4.14. The cross-section showed the thermal comfort improvement (at the pedestrian level of 1.75m) after a road was transformed into a vegetated pedestrian zone.

4.4 CONCLUSION AND RECOMMENDATIONS

This chapter proved that the planting scheme of landscape design for urban thermal improvement could be evidence-based planned. As shown in Section 4.2, this study tested several greening schemes (prototypes) before the scenario design to obtain the optimum tree and green coverage ratio. It included situatednesses in the scenario building process. Other than maximising greenery coverage to improve microclimate and thermal comfort conditions, the design models have been repetitively revised to make them more coherent to the site context and fulfil various pedestrian needs. The scope of consideration ranged from spatial allocation to overall network connectivity and their visibility to the historic downtown streetscape.

Besides, this chapter had referred to the findings and recommendations in Chapter 3 as design guidelines. Through the pilot model simulation, it turned out that they were practical and useful to improve microclimate and thermal comfort conditions, making the prototypes more convincing to be applied in master planning. For example, it was true that within the high built area with limited green spaces, street tree planting did play a crucial role in regulating the local microclimate and thermal comfort.

The scenario simulation also affirmed that the cooling magnitude correlated to the green and tree coverage ratios (GCR and TCR). Among these ratios, it would be more accurate by using the tree coverage ratio because the effect of trees was clearly reflected in all microclimate and thermal comfort aspects. By contrast, the effect of shrub and grass was less reflected in mean radiant temperature, wind and thermal comfort performance, thereby somewhat affecting the use of green coverage ratio to determine the cooling magnitude. This finding did enhance using trees as the most useful measure to improve the microclimate and thermal comfort in tropical cities like Ipoh. As for shrub and grass, perhaps their significance in cooling magnitude and thermal comfort had to be further identified using a more significant coverage ratio gap.

At last, to determine the most suitable model for climate-led landscape design and planning in this research, it first looked at the cooling effect in terms of microclimate and thermal comfort. In prototypes comparison, prototype 3b, which had the highest tree coverage ratio and green coverage ratio, cooled the area the most, followed by prototype 2c and then prototype 1b. Likewise, in the comparison between scenarios, Scenario 2 (maximum greening model), which also had the highest tree coverage ratio and green coverage ratio, performed more prominently than Scenario 3. The weakness of Scenario 3 indeed occurred around POI, where having less or no trees.

However, despite Scenario 2 performing better in thermal improvement, Scenario 3 provided more positive and comprehensive countermeasures for a historical urban environment, ranging from thermal improvement to pedestrians experience and heritage visibility. More importantly, the simulation results did not find a notable discrepancy in the overall performance between Scenario 2 and 3. Their difference, in this case, was not worth mentioning. Therefore, this chapter concluded and recommended Scenario 3 as the appropriate reference used for climate-led landscape redevelopment in the following chapters.

CHAPTER 5
CLIMATE-LED LANDSCAPE DESIGN AND PLANNING

5.1 INTRODUCTION

Further to site thermal assessment and greening prototypes development studied in Chapters 3 and 4, this chapter proceeded to the landscape design and planning for the full-scale study model. The chapter firstly focused on the formulation of landscape designs in response to the findings and results obtained in the previous chapters. The design concepts and ideas mainly were elaborated through diagrams or plans. This chapter would proceed with two design versions: an optimal plan and a basic plan, as explained in the following:

a. The optimal plan would imitate the prototypes studied in the previous chapter. On the basis of the optimal greening strategy, this version also considered the completion of pedestrian networks, the organisation of visitor trails, the development of full pedestrian zones and cycling routes. This version had a far-reaching objective, aiming to reduce artificial heat and pollutant emissions by minimising motorcar use during short trips in downtown. The version also expected a positive pedestrian-oriented development by allocating some car-free zones connected by intensive walking and cycling network.
b. The basic plan would be relatively simple and conventional, with minimal interruption to the existing vehicular accessibility, including car parks. Contrary to the optimal plan, the basic plan only provided an essential pedestrian network and facilities for residents and visitors. This version did not consider creating car-free zones and cycling routes, in view that these initiatives highly depended on the local authority's willingness and budget.

These two full-scale design versions would then be built as scenario models and simulated on the macro-scale. After completing the simulations, all outputs would be analysed and compared between models. This chapter followed the assessment methods used in Chapters 3 and 4 to examine the effects of proposed models in microclimate and thermal comfort. All results and comparisons would be discussed and concluded with relevant appraisals.

5.2 DESIGNS AND METHODS

5.2.1 Concept and Procedure

The master plan was firstly developed in the following sequences:

a. Development of full pedestrian zone

The potential areas for street-to-plaza development were sorted out according to the site history, social culture and traits. The street-to-plaza idea was to transform specific road segments from typical car routes to semi or full pedestrian areas for local business and cultural activities, promoting walking culture by providing pedestrians with a more diverse walking experience in the town. It was also an extra effort to increase the green area throughout the model. The creation of car-free zones would give merits to the site attractiveness, stimulating local vitality and the social economy of the historic district.

b. Replanning the traffic network system on-site.

As recommended in Section 4.2.2 of the previous chapter, this chapter tried to identify potential one-way roads and converted them into two-way functions. It started from the premise that the modified traffic circulation changed the road pattern but did not disrupt the existing traffic system much, especially at the primary access (main roads). The conversion was not only to increase the green coverage on the streets but also to promote traffic calming in the core zone of Ipoh downtown, trying to improve the safety and comfort of pedestrians.

c. Organising visitor trails

Other than the typical walking route along the shophouses, the design also organised a proper sightseeing trail for walking visitors. It covered all attractions within the Ipoh downtown, such as the heritage buildings, murals, cuisines, open spaces and natural resources, meanwhile connected with the local amenities like railways station, bus terminal, mosque, tourists centre and the local markets. Along the trail, it would try to minimise the car-human conflicts and accessibility barriers to pedestrians. Different from typical walkways, the size of walkways within the visitor trails would be enlarged to accommodate a higher volume of walking visitors. The enlargement would give higher green coverage areas on the street level as well.

d. Trees and vegetation arrangement on-site.

The road type would determine the greening scheme adopted. It was mainly to locate the trees and vegetation along the streets and abandoned open spaces of Ipoh downtown. To achieve optimal greenery coverage ratio in the study model, it followed the greening strategy introduced in the prototypes, whereby consisted of four elements: trees, planting strip, green sidewalks and green parking (refer to 4.2.1).

As mentioned in 4.3.1, the tree arrangement should secure and prioritise the views of heritage buildings and murals to conserve the visibility of heritage streetscape in Ipoh downtown. The street trees should never intercept these historic facades and murals at the pedestrian level in this case.

Simultaneously, the completion of new sidewalks would also facilitate a coherent walking trail, providing the basic amenity for residents and visitors walking around the downtown.

e. Development of cycling route

Other than the greening strategy, climate-led design planning also considered the reduction of exhaust emissions from motorcars. Nowadays, many developed countries in Europe sought to increase non-motorised transport to improve sustainable mobility in cities. As one of the greenest or cleanest transportations, cycling has been highly recommended as one of the most climate-friendly transport modes in urban areas. In the city of Copenhagen, it was 50% of residents remote to work or school by bicycle, giving the city the name of City of Cyclists (Gössling, 2013). Cycle culture is strongly promoted in the European Commission as well. Other than providing complete guidance for cycling projects in Europe on their website (the complete information and details was presented in the following link: https://ec.europa.eu/transport/themes/urban/cycling/guidance-cycling-projects-eu_en), European Commission has also funded more than 20 cycle projects since the year 2006 (the details and websites of projects were listed in the following link: https://ec.europa.eu/transport/themes/urban/cycling/guidance-cycling-projects-eu/eu-funded-cycle-projects_en).

Moreover, based on Vandy (2020), the coronavirus pandemic did impact urban mobility. It resulted in a surge in the number of cyclists and boosted unprecedented investments in cycling across Europe. Rowlatt's report (2020) also showed that the pandemic lockdown has made people rediscover the joys of walking and cycling in the United Kingdom, raising the public's willingness to create more car-free zones in cities. The change would propel a revolution in urban travel when the local governments shifted to encourage people to take up cycling instead of taking public transport like buses and rails. The influence could be far-reaching and global.

From a multi-dimension perspective, this study, therefore, considered to proposed a systematic cycling route to the study model. The idea was not groundless because the entire special area of Ipoh is within a circle of less than 2km. It has enormous potential to develop a designated cycling route for residents to move around the neighbourhood by bicycle. Besides, a safe and friendly cycling environment could also offer an exciting sightseeing mode for tourists in Ipoh downtown. Lastly, back to the greening viewpoint, converting roads into bicycle lanes helped achieve the optimal greening effect when the lanes were integrated into green zones in the model. Similar to green walkways and car parks, additional trees and green paving would be applied along the cycling trail to increase cyclists' safety and comfort.

5.2.2 Schematic Design and Planning

This section introduced the design ideas and details to improve the microclimate and thermal comfort of the study model, mainly through the greening and reorganisation of open spaces. The optimal model design process would fully follow the sequence elaborated in 5.5.1 (from (a) to (e)), whereas the basic model would only proceed from (b) to (d) in the same section.

5.2.2.1 Optimal model design

The traffic system was modified starting from this model. It first identified the potential car-free areas for pedestrian zone development, followed by converting particular roads into two-way systems (Figure 5.1). There are a total of five pedestrian zone areas being determined, which are explained in Table 5.1. These areas would become the core nodes in the downtown areas and are connected by a comprehensive visitor trail. Those walkways included in the designated visitor trails would be designed in a larger size to accommodate higher volumes of pedestrian flow. The enlarged walkways mainly were found along *Jalan Sultan Iskandar, Jalan Yat Tet Shin, Jalan Laxamana, Jalan Lahat* and *Jalan Bandar Bijih Timah.* Since *Jalan Sultan Iskandar* functioned as the main road for vehicle access, there were limited spaces for pedestrian use. In this case, prototype 1a was applied instead of prototype 1b (refer to Figure 4.1, and see the explanation in 4.2.2 and Table 4.4).

Table 5.1. The potential semi or full pedestrian zones in the landscape design plan.

No.	Area	Reason	Potentials
1a	Jalan *Sheikh Adam*	• It is located at the centre with many points of interest (POIs): Ipoh Padang, Ipoh Mural no. 1&2, and three declared heritage buildings. • It is the most direct access connected to the existing pedestrian network (from Railway Station to Concubine Lane).	• Full pedestrian zone: Tin-mining Heritage Court ➢ This area was full of murals, heritage and cultural assets, made it suitable to be developed for various historical and cultural events and activities. ➢ The heritage and cultural theme design could help to enhance the heritage and cultural identity of Ipoh Oldtown.
1b	One segment in *Jalan Bandar Bijih Timah*	• It is next to Concubine Lane. • It is next to the new attraction of Oldtown: Plan B, an adaptation use of old building into café and art market. • There are various Ipoh Chinese cuisine and souvenir shops along the street.	
2	One segment in *Jalan Koo Chong Kong*	• The area is famous for Chinese-styled coffee shops, similar to Area 1b. • It is located between the Indian and Chinese quarters in Oldtown, surrounded by traditional Chinese and Indian ethnic shops. Their businesses included grocery, snacks, clothing and accessories, ritual necessities, etc.	• Full pedestrian zone: Little India and Chinese Plaza ➢ This area was combined with the alleys and triangle open space in Little India to become a full pedestrian zone for enhancing the Indian and Chinese culture of Ipoh. ➢ The ethnic theme design could help to conserve the local ethnic business cultures.
3a	One segment in *Jalan Dato Tahwil Azar*	• It is a famous spot with diverse Ipoh Chinese cuisine restaurants, café, snacks and souvenir shops along the street. • It is also the location for a daily night market named *Gerbang Malam*.	• Full pedestrian zone: Ipoh Open Market and Café Street ➢ Area no. 3a was the platform with the Open Café concept, where allow people to enjoy outdoor dining.

3b	One segment in *Jalan Mustapha Al-Bakri*	• It is next to the local food court and cuisine street (Area no.3a). • It is the most direct access connecting to local markets and shopping malls.	➢ Change the night market to a full-day bazaar. The bazaar would be re-organised, where Area no.3a is mainly for food and beverage business and Area no. 3b for non-food business.
4	One segment in *Jalan Masjid*	It is located between the Mural Art Lane and Masjid Panglima Kinta (a heritage mosque established in 1898).	• Semi pedestrian zone: Open Gallery on Art and Culture ➢ The Mural Art Lane turned into a car-free zone. ➢ The mosque's front becomes a car-free zone during the mosque festivals, weekly Muslim bazaar and Ramadan month.
5	One segment next to the Kinta River	The area was in the future redevelopment plan of Ipoh for heritage waterfront and jetty (Refer to Sections 5.3 and 5.4 in the Ipoh Special Area Plan 2020), extending the pedestrian network from Oldtown to Newtown.	• Full pedestrian zone: Heritage riverfront ➢ It is a core node to connect the pedestrian and cycling network between Oldtown and Newtown, minimising their conflict with cars.

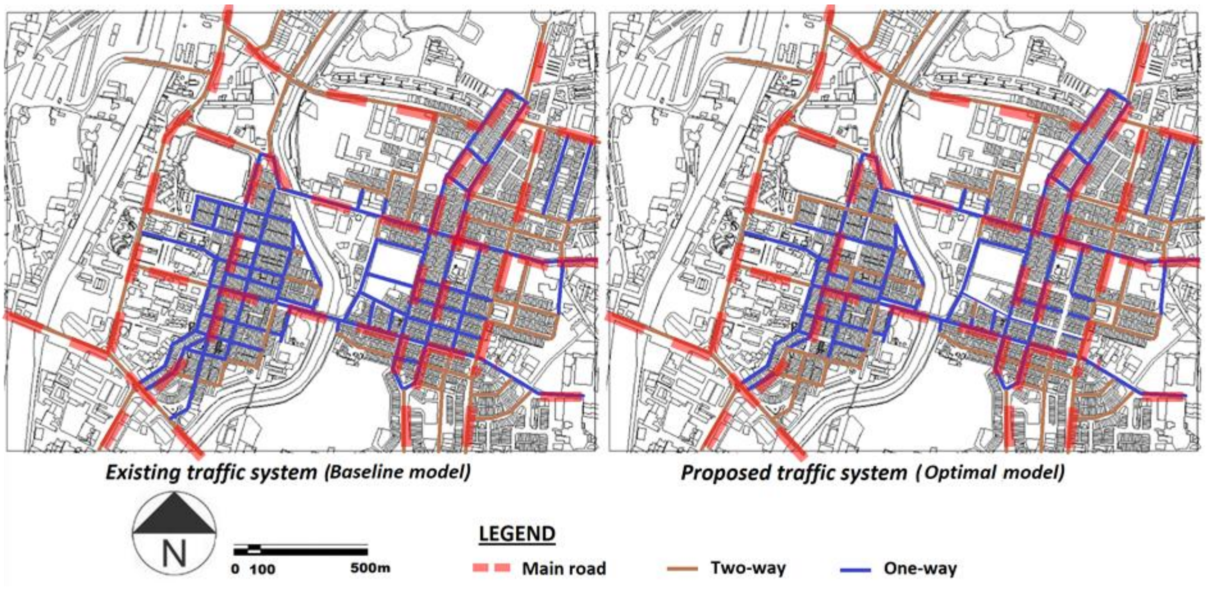


Fig.5.1. The changes in the traffic system before and after optimal design.

Next, walkways, car parks, trees and non-trees vegetation were inserted into the rest area of the model accordingly based on road types and sizes. It was worth mentioning that the road size in Newtown was averagely larger than in Oldtown, and they were enough to allocate space for pedestrian access. Moreover, according to the thermal performance assessment in Chapter 3, service lanes in Newtown were not as ideal as those in Oldtown. Due to the different thermal effects of service lanes between Oldtown and Newtown, only service lanes in the Oldtown area were suggested to be converted into full pedestrian lanes.

In planning the cycling route, bicycle lanes were preferred to be allocated at the service lanes to secure the cyclist's safety and comfort, minimising their conflicts with cars. However, this approach was only applicable in the East-West oriented streets in New Town. There was a lack of service lanes laid in North-South orientation in this model. In this case, for the North-South direction, the cycling lanes would follow the routes recommended for visitor trail. It recommended turning the existing car-park spaces into cycling lanes to reduce the interruption to the traffic system.

Besides, Old Town East-West oriented service lanes were relatively small, and most of them have been fully occupied for pedestrian access. It found that part of the cycling route from Ipoh Railway Station to Newtown would be interrupted. To fix the problem, it suggested allocating the bicycle lanes at *Jalan Market*, which become parallel to the existing pedestrian route. The lane would occupy the spaces that were initially allocated for car parks. *Jalan Market* was recommended mainly because the road was the most treed area in the heritage zone after converting into two-way systems, which should be safer and comfort for cyclists.

Unlike the visitor trail that only laid in the core zone, the cycling route was further extended to the buffer zone in Ipoh Special Area. By connecting the downtown with those residential neighbourhoods located at the fringe of downtown, it could help to encourage the use of bicycles as a local mode of transportation. At the same time, it allowed cyclists to further explore nearby attractions such as Memory Lane (a weekly second-hand bazaar located in the buffer zone) and the largest green space in Ipoh downtown (DR Seenivasagam recreational park). The overall design idea was illustrated as a schematic diagram shown in Figure 5.2.

Fig.5.2. The schematic diagram of the optimal model design.

5.2.2.2 Basic model design

This model basically was a simplified version of the optimal model. It first restored all the pedestrian zones mentioned in Table 5.1 back into vehicle roads, followed by the conversion of roads into two-way systems (Figure 5.3). However, it considered and gave priority to the higher volumes of pedestrians in Jalan Bandar Bijih Timah (refer to Area 1b in Table 5.1), the cuisine street and night market at *Jalan Dato Tahwil Azar* (refer to Area 3a in Table 5.1), and also around the local markets. All walkways in these areas would turn out to be larger, occupying half of the open street or at least 5m in width to accommodate the high pedestrian flow. As for visitor trail planning, all attraction spots (known as POI - points of interest) were connected in an orderly direction, similar to the optimal model design.

The design was continued with the greening installation based on the road types and sizes. Since this model applied minimal interruption to the existing vehicular accessibility, car parks' surface material was not modified into green paving. The greening areas, therefore, only focused on walkways and planting strips. Compared with asphalt, using green paving for car parks did have several disadvantages from a traffic perspective, such as higher construction costs and higher maintenance. Also, the road system cannot be easily changed anymore. These disadvantages made car parking spaces to be excluded as green areas in this model. Lastly, all spaces designed for cycling trails in the optimum model were restored as car parks in this model, except for those service lanes. As for service lanes, it followed the strategy applied in the optimal model. That is, only the service lanes in Oldtown were converted into full pedestrian lanes. The service lanes in Newtown remained for service purposes. The overall design idea was illustrated as a schematic diagram shown in Figure 5.4.

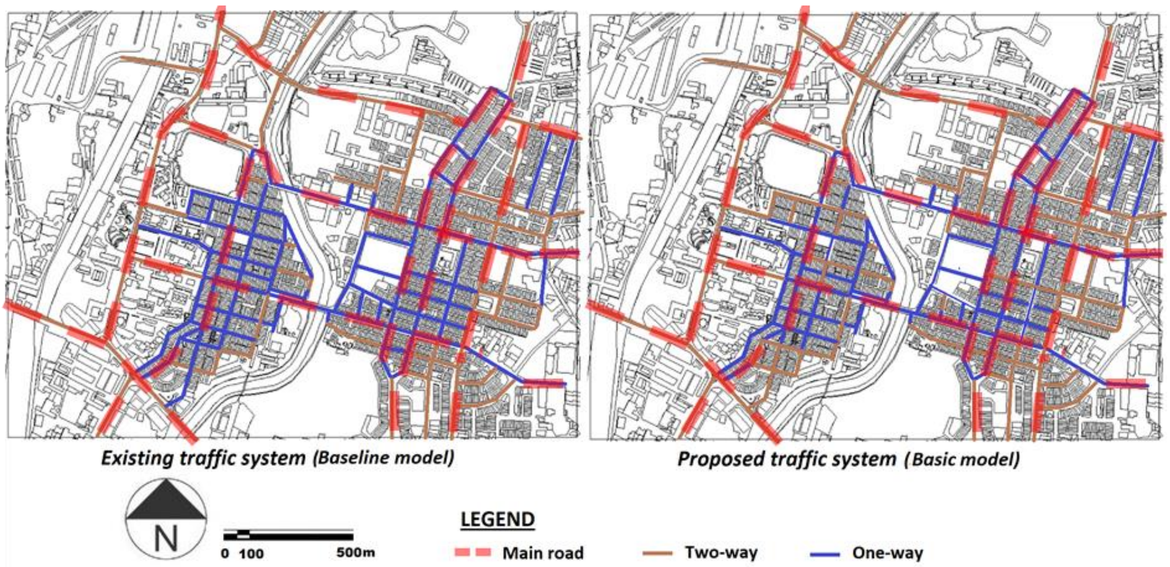


Fig. 5.3 The changes in the traffic system before and after basic design.

Fig.5.4. The schematic diagram of the basic model design.

5.3 MODEL BUILDING AND SIMULATION

The overall operation procedure was explained in Section 3.3 of Chapter 3. Figure 5.5 presented the workflow of model building and simulation (inside the dotted box) and the link with other sections in this chapter.

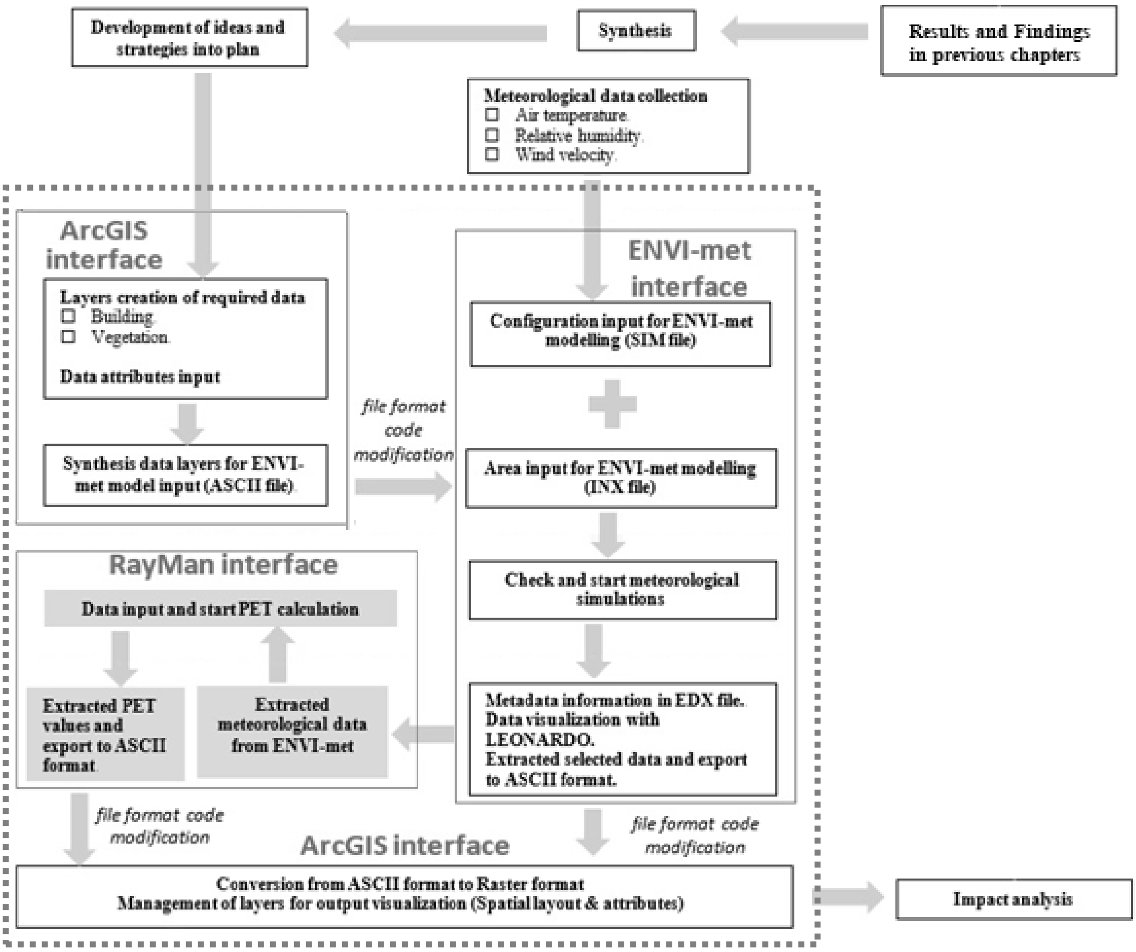


Fig. 5.5. The study workflow

5.3.1 Model Building in ArcGIS

Based on the designs formulated in the last section, three scenario models were built and simulated: the baseline model, the basic model and the optimal model.

a. Scenario 1 (Figure 5.6) was the baseline model (the same model in Chapter 3), replicating the existing site condition to enable the comparison between original and proposed models.
b. Scenario 2 (Figure 5.7) was the basic model, following the design concept in Section 5.2.2.2.
c. Scenario 3 (Figure 5.8) was the optimal model, following the design concept in Section 5.2.2.1.

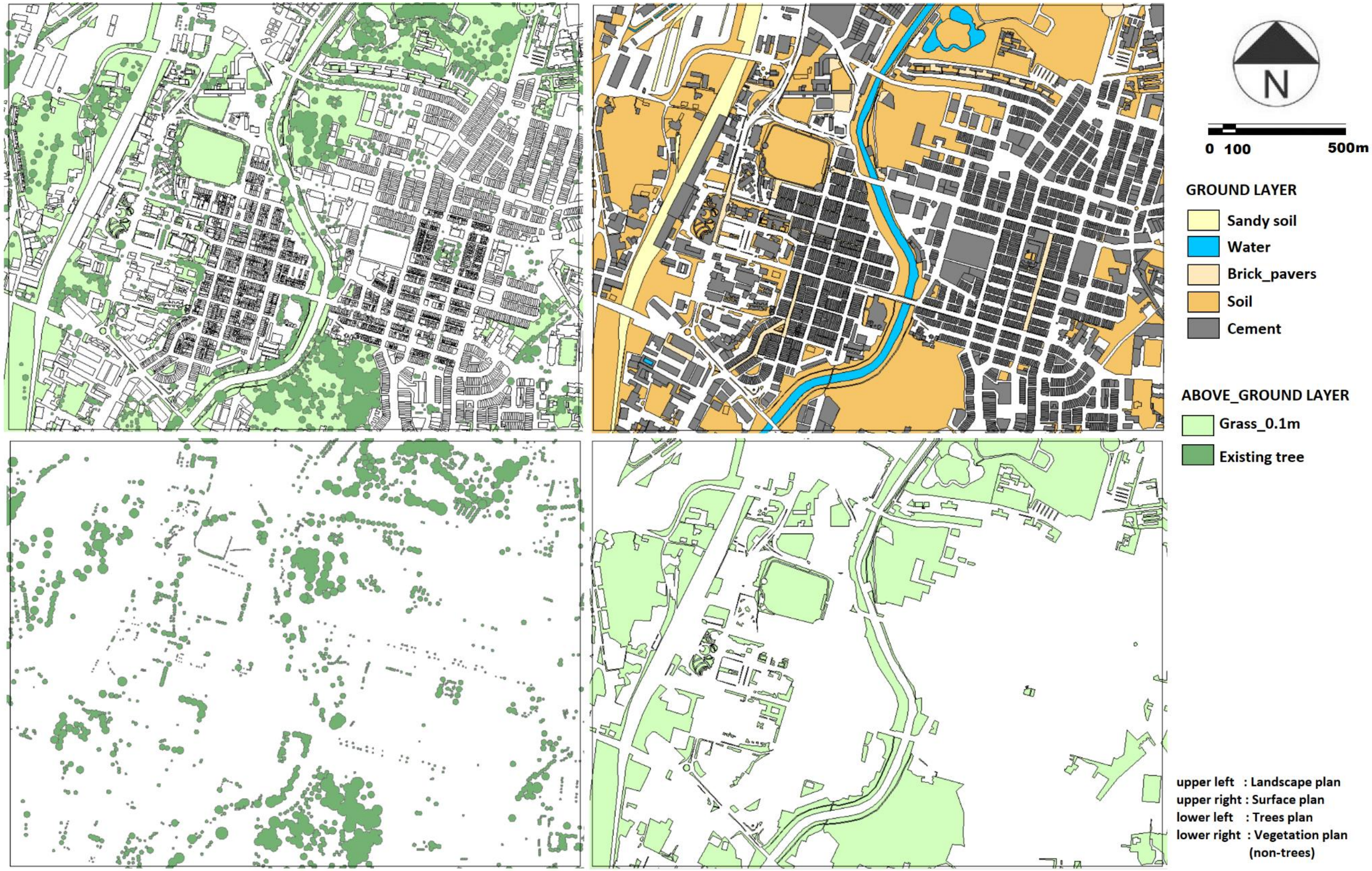


Fig.5.6. The overall plans for the baseline model (Scenario 1).

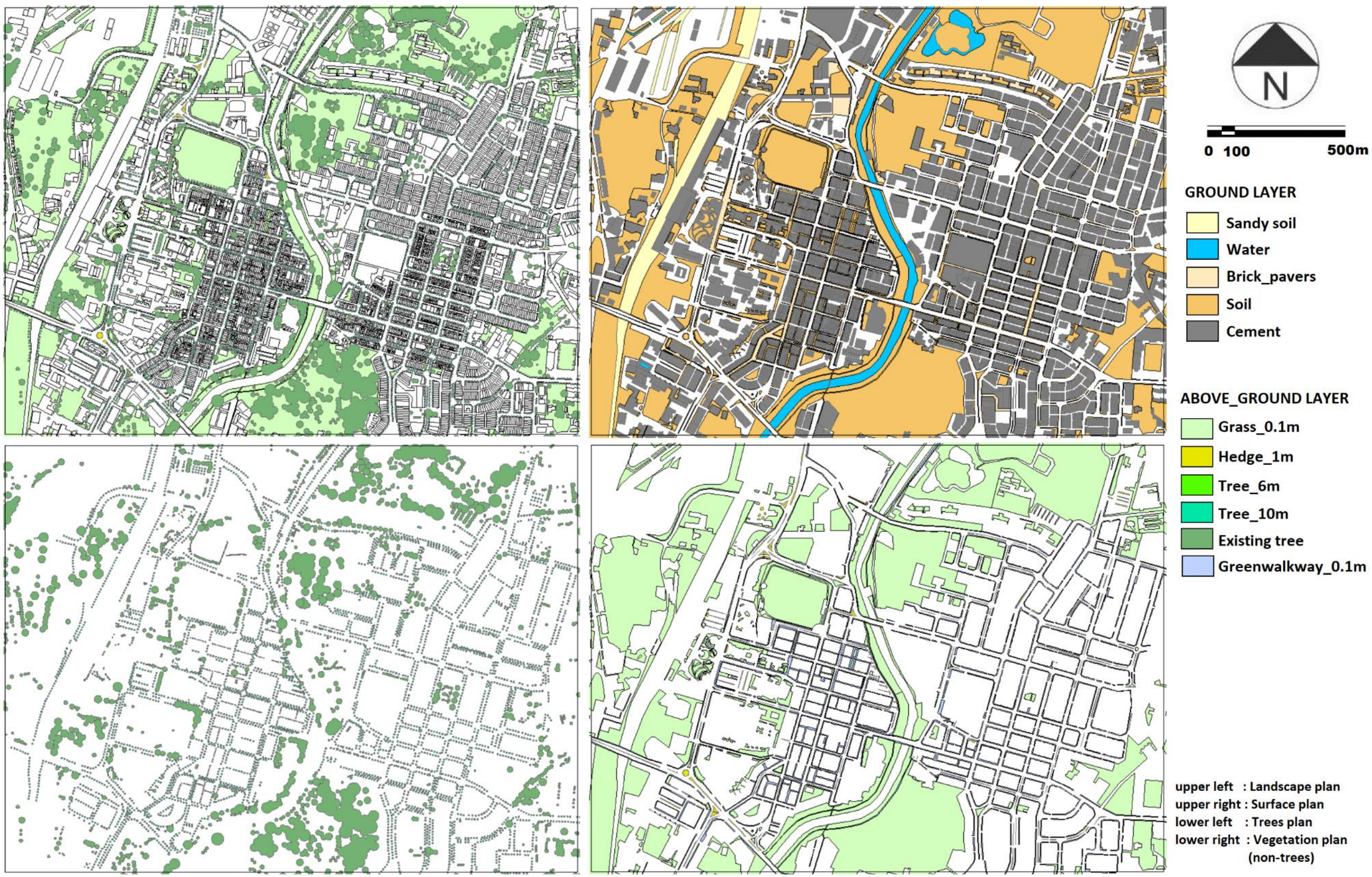


Fig.5.7. The overall plans for the basic model (Scenario 2).

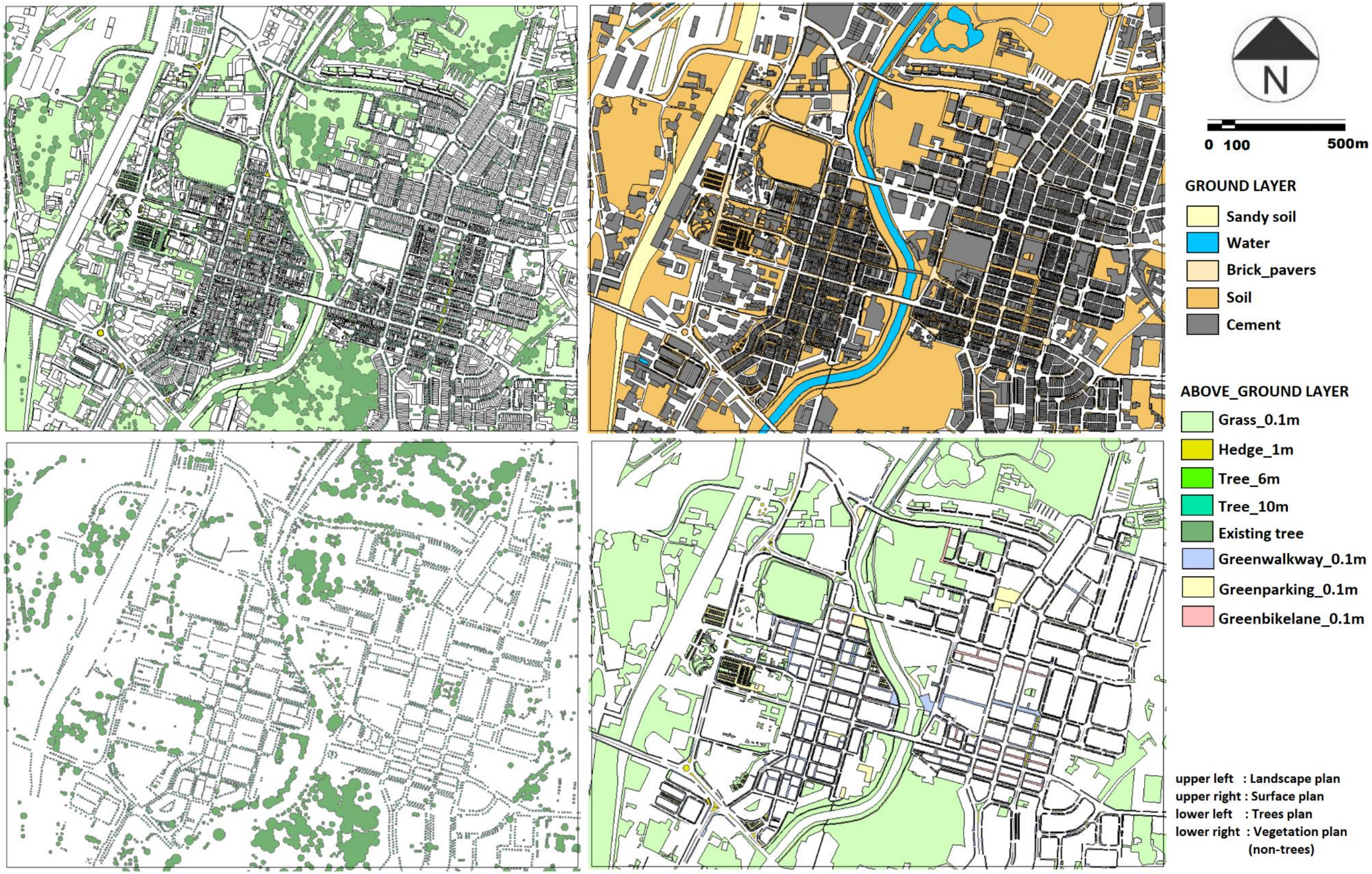


Fig.5.8. The overall plans for the optimal model (Scenario 3).

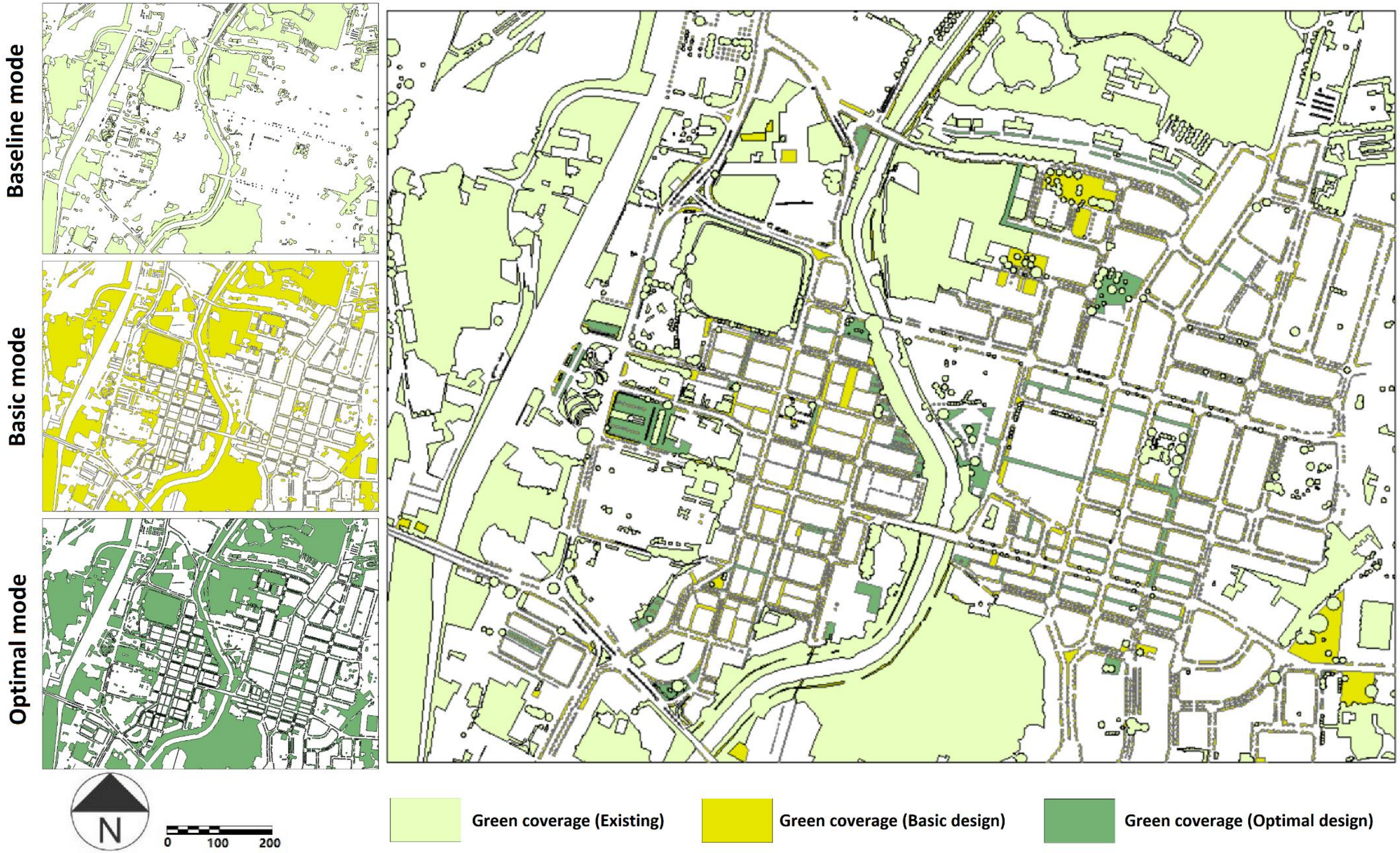


Fig.5.9. The increase of green coverage area from baseline mode, basic mode to optimal mode.

Table 5.2. Summary of coverage area calculation between scenarios.

Total	Scenario 1 (Baseline mode)				Scenario 2 (Basic mode)				Scenario 3 (Optimal mode)			
	Area (m^2)	**Percentage (%)**	**No. of raster cell**	**Percentage (%)**	**Area (m^2)**	**Percentage (%)**	**No. of raster cell**	**Percentage (%)**	**Area (m^2)**	**Percentage (%)**	**No. of raster cell**	**Percentage (%)**
Study Area (A)	2961062	100	118503	100	2961062	100	118503	100	2961062	100	118503	100
Building Area (B)	824467	27.84	32991	27.84	824467	27.84	32991	27.84	820929	27.72	32846	27.72
Open Area (A-B)	2136595	72.16	85512	72.16	2136595	72.16	85512	72.16	2140133	72.28	85657	72.28
CASE I: OVERALL												
Green coverage (C)	878025	29.65	35132	29.65	1071524	36.19	42965	36.26	1154892	39.00	46280	39.05
Tree coverage (D)	310546	10.49	12455	10.51	401780	13.57	16124	13.61	407671	13.77	16372	13.82
Non-tree coverage (C-D)	567479	19.16	22677	19.14	669744	22.62	26841	22.65	747221	25.23	29908	25.24
CASE II: OPEN AREA ONLY												
Green coverage (C)	878025	41.09	35132	41.08	1071524	50.15	42965	50.24	1154892	53.96	46280	54.03
Tree coverage (D)	310546	14.53	12455	14.57	401780	18.80	16124	18.86	407671	19.05	16372	19.11
Non-tree coverage (C-D)	567479	26.56	22677	26.52	669744	31.35	26841	31.39	747221	34.91	29908	34.92

The green coverage pattern was dramatically changed before and after design, as showed in Figure 5.9. The changes were attributed to the greening elements added by stages. In the basic model, the main elements were trees, non-trees vegetation (hedge and grass) and green walkways, whereas green car parks, green bicycle lanes and more green open spaces (car-free zones) were only introduced in the optimal model.

All three models' coverage areas were calculated and summarised in Table 5.2. As shown in the table, the coverage ratio was measured in two modes: vector (unit in meter square) and raster (unit in no. of cells). This step was mainly to examine the data fidelity of simulation models after the process of rasterisation. Overall, the ratio difference was less than 0.1%, indicating high fidelity in all models. There are 72.16% of open areas in the baseline model, but it increased to 72.28% in the optimum model after demolished some scattered buildings at the proposed riverfront site. The green coverage ratio has been increased through the greening strategies proposed in the previous chapter, from 41% of open areas to 50% (basic model) and 54% (optimal model), with the remaining areas for essential traffic use or under private compounds. With the consideration of heritage building visibility, all models considered tree intervals and the use of standard 5m and 3m crown street trees throughout the models. Thus, the increase of tree coverage ratio was relatively small, from 15% of open areas (basic model) to 19% (optimal model). In other words, most green coverage ratios were contributed by non-trees vegetation, from 27% of open areas to 31% (basic model) and 35% (optimal model). Overall, the greening strategies introduced have converted up to 39% of the study area into green areas. It was an increment of about 10% compared to the baseline model. As for the basic model, the green coverage ratio could reach 36% of the total area. On the other hand, the results also showed the limitation of landscape greenery strategies recommended in this study when the optimal strategy only could boost up 10% of greenery in the total area. However, this index could also become a benchmark for the local authority to achieve, as well as a threshold for future design studies to transcend.

5.3.2 Model Building and Simulation in ENVI-met and RayMan

The raster models (Figures 5.10 and 5.11) were finally imported to ENVI-met for simulation. The models covered an area of 1995 m x 1485m, running in the 399 m x 297m x 75m model with a grid resolution of 5m x 5m x2.5m in dx, dy, and dz directions, respectively. The modelling and simulation process has been explained in Sections 3.3.3 and 3.3.4 of Chapter 3.

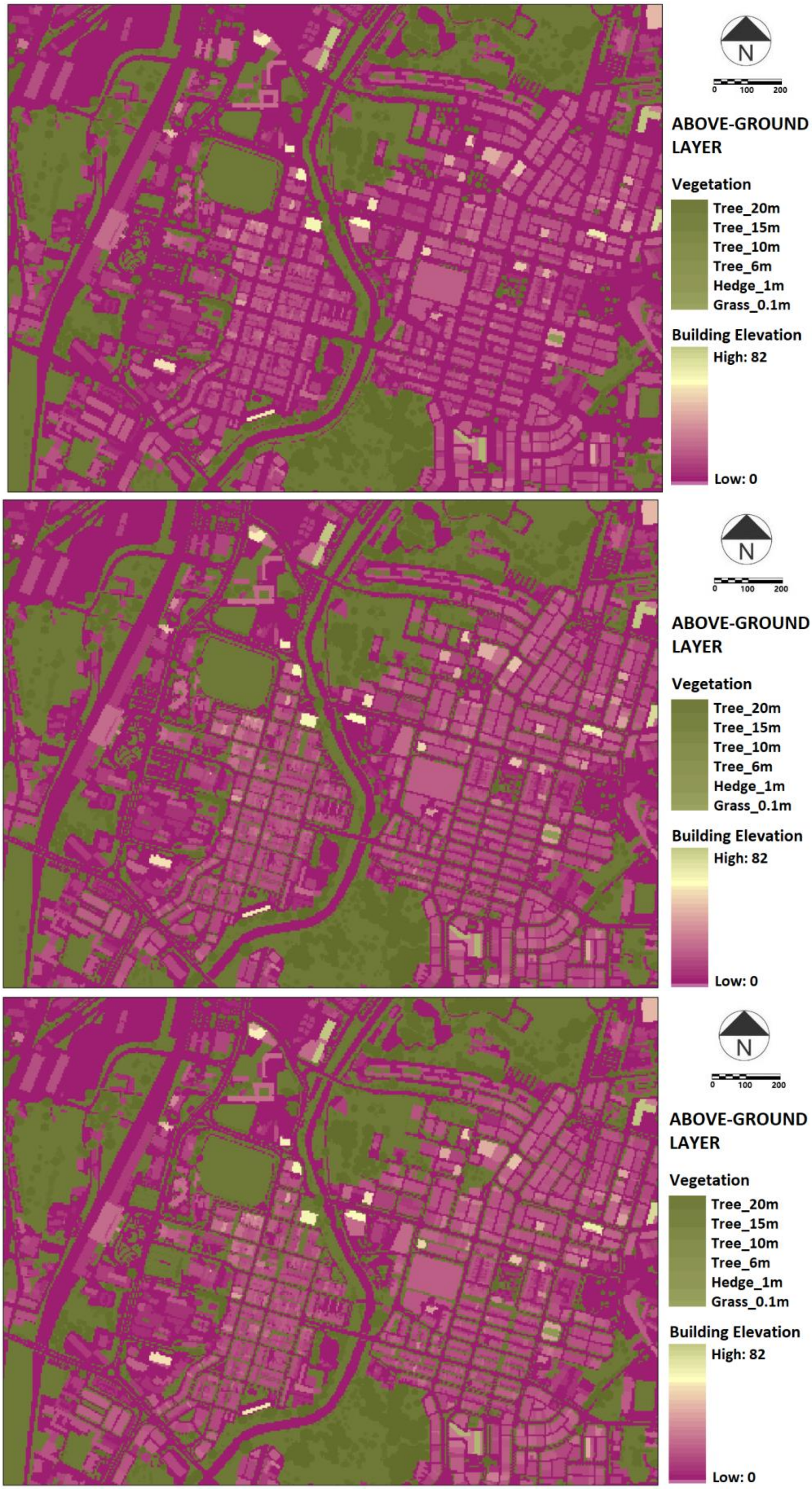


Fig.5.10. The evolution of the above-ground raster layer through the scenarios (from upper to lower: the baseline model, the basic model, and the optimal model).

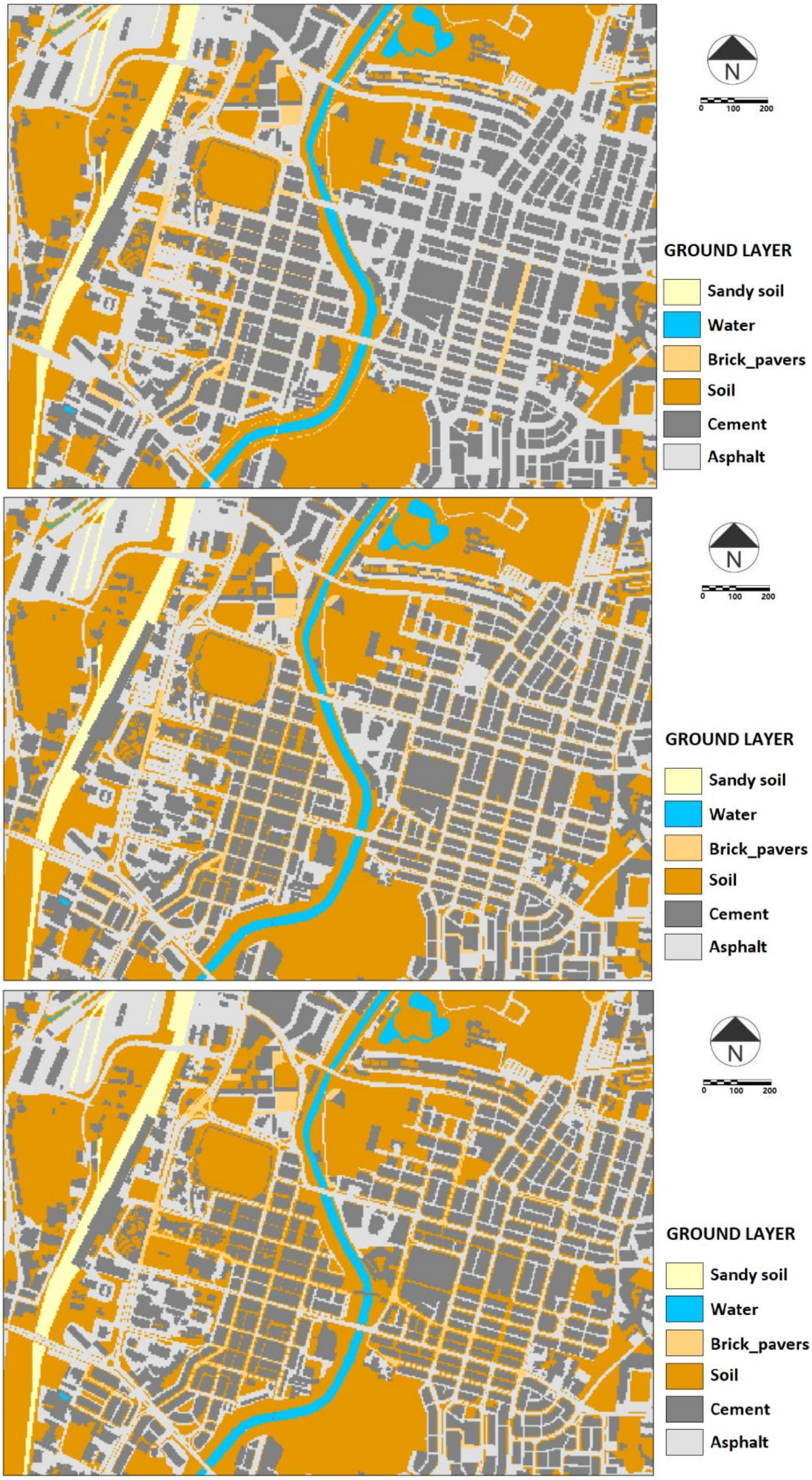


Fig.5.11. The evolution of the ground raster layer through the scenarios (from upper to lower: the baseline model, the basic model, and the optimal model).

5.4 RESULTS AND DISCUSSION

5.4.1 Microclimate Aspect

Table 5.3. Comparison of climatic factors between scenarios.

Factors	***Scenario 1 (baseline model)***			***Scenario 2 (basic model)***			***Scenario 3 (optimal model)***		
	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max
Air temperature (^oC)	30.43	31.92	34.43	30.13	31.74	34.4	30.04	31.66	34.38
Surface temperature (^oC)	23.76	40.66	54.46	22.99	39.30	54.28	22.78	38.72	54.24
Mean radiant temperature (^oC)	36.99	58.18	65.94	31.98	56.02	64.7	31.6	55.73	64.55
Wind speed (m/s)	0.01	0.84	2.75	0.01	0.78	2.79	0.01	0.78	2.81
Relative humidity (%)	52.94	63.31	73.27	53	64.29	74.95	53.02	64.68	75.33

This section reviewed the overall climate performance from air temperature to mean radiant temperature, surface temperature, wind speed and relative humidity. Table 5.3 showed that all climatic factors of the design models had been ameliorated at certain degrees, in line with the performance of prototypes created in the previous chapter. The result proved that local microclimate could be improved through climate-led landscape design and planning, and the effectiveness highly relied on the level of greening.

In the last section, this study discussed the greening level from two dimensions: the green coverage ratio and tree coverage ratio. According to Table 5.2, it was given that Scenarios 2 and 3 resulted in a similar tree coverage ratio (both occupied about 14% in the study area context and 19% in the open area context). In this case, the additional 3% of non-trees vegetations and the insignificant new trees in the green coverage ratio of Scenario 3 thus hold a determining position to distinguish the overall performance between Scenarios 2 and 3. With the same tree coverage ratio, it showed that Scenario 3 did have advantages over Scenario 2, resulting in a higher degree of improvement in all discussed climate aspects. To determine the effectiveness of each model more specifically, this section further analysed the differences between the models through the comparisons of microclimate distribution patterns.

a. Air Temperature

In Figure 5.12, the graph showed a significant drop of the air temperature range before and after design, especially in the minimum index where 0.3 ^{o}C and 0.39 ^{o}C of reduction were found in Scenario 2 and 3, respectively. The continuous drop of mean index values from Scenarios 1 to 3 indicated that the cooling level was affected by both green and tree coverage ratios. However, the cooling magnitude was not linearly proportional to the green coverage and tree coverage ratios.

From the air temperature maps, there were no significant differences between models in terms of distribution patterns. However, the colour changes in the distribution maps from Scenarios 1 to 3 illustrated that they have averagely dropped to lower temperatures in the entire downtown area. The most apparent changes happened from Scenarios 1 to 2. This result turned out that the basic model concept developed in this chapter (Scenario 2) had been able to play an influential role in cooling the model atmosphere. The optimal model (Scenario) 3 has further strengthened the cooling effect, especially at the large open car parks, the proposed riverfront, and those streets laid in the shophouse zone centre area of Oldtown and Newtown. The result proved that the amount of non-trees vegetation did affect air temperature with the presence of trees.

b. Surface Temperature

The average temperature has decreased by 1.36 ^{o}C and 1.94 ^{o}C in Scenarios 2 and 3, respectively. The minimum index also dropped from 23.76 ^{o}C to 22.99 ^{o}C and 22.78 ^{o}C in Scenario 2 and 3, indicating the effectiveness of greening strategies applied on landscape surface materials. From the result, it did not find any linear relationship between the cooling magnitude with green coverage or tree coverage ratios, even though it has been proved that the land surface temperatures were negatively proportional to the greening ratios.

With the increasing shades of trees and non-trees vegetation land cover, the distribution pattern was clearly changed in the downtown area before and after designs, immensely cooling the urban surfaces from Scenarios 1 to 3 (Figure 5.13). Also, the cooling magnitude between trees and non-trees vegetations was best illustrated in the maps. Treed areas reduced the surface temperature to the maximum level (as shown in blue colour). In contrast, the non-trees vegetation area could only decrease the temperature to an acceptable level (as shown in green colour). The high use of brick pavers in Scenario 3 for traffic calming has also greatly improved road surfaces' thermal condition than Scenario 2, turning the temperature colour from orange to yellow.

c. Mean Radiant Temperature

Unlike air temperatures and surface temperature, the mean radiant temperature index changed the most before and after designs, especially the minimum index, which decreased dramatically by more than 6 °C (Figure 5.14). It dropped from 36.99 to 31.98 and 31.6 un Scenarios 2 and 3 in respectively. The average index has also reduced sharply from 58.18°C to 56.02°C and 55.73°C in Scenarios 2 and 3, but it remained relatively high in temperature during hot hours.

Similar to air temperature maps, there were no significant differences between models in terms of distribution patterns. However, the hot colour fading in the distribution maps indicated a positive cooling trend from Scenarios 1 to 3. Different from prototypes, the result turned out that mean radiant temperature was impacted not only by trees but also by non-trees vegetation that coexisted with trees. Trees still did impact the mean radiant temperature the most, regardless of their size and location.

d. Wind Speed

As shown in Figure 5.15, wind speed performed differently in mean, minimum and maximum indexes, not exactly the same pattern with the estimation made using prototypes. It kept a constant minimum wind speed at .01m/s in all three models. The wind speed dropped from the average of 0.84m/s to 0.78m/s between Scenario 1 and 2 and kept constant between Scenarios 2 and 3. Besides, there was no discrepancy between Scenarios 2 and 3 in the distribution maps as well. This result, again, proved that only trees could impact the speed and pattern of winds.

Contrary to the average wind speed, maximum wind speed instead increased in Scenarios 2 and 3, from 2.75m/s to 2.79 m/s and 2.81m/s. This situation was not in expectation as it was supposed to be reduced as well. In this case, the maps showed that wind speed increased at those North-South oriented primary roads, railway and river that functioned as air tunnels. Their openness was decreased after placing consistent and continuous trees along both sides of these air tunnels. Such a situation has ultimately intensified the speed of passing airflow, similar to the wind effect in shallow street canyons. However, the increasing maximum index did not affect the overall wind trend tending to a lower average. The decelerating trend still met the conditions for creating a lower physiological equivalent temperature (PET) (refer to Section 3.5.5). Last but not least, the situation also explained and strengthened the function of trees as windbreaks in urban areas.

Lastly, as expected, tree planting along streets has reduced the wind flow at the pedestrian level, especially at the shophouse zones. Simultaneously, most "downdraught effect" (mentioned in section 3.5.4) happening at the high-rise buildings was ameliorated to a lower magnitude.

e. Relative Humidity

Figure 5.16 showed an increase of relative humidity in mean before and after design, from 63.31% to 64.29% and 64.68% in Scenarios 2 and 3. The relative humidity range also considerably improved in overall, from 52.94 - 73.27% to 53 -74.95% in Scenario 2 and 53.02 - 75.33% in Scenario 3.

The colour changing in the distribution maps from Scenarios 1 to 3 also clearly illustrated the intensification, especially between Scenarios 1 and 2. The advantage of Scenario 3 over Scenario 2 was most reflected at the car parks, indicating that the greening paving did affect the relative humidity significantly. The result proved that non-trees vegetation also played an essential regulating role in air moisture level for site cooling.

In summary, except for wind speed, all results in this section supported using green coverage ratio in climate-led design and planning for predicting microclimate performance. As for wind performance, the tree coverage ratio will be a more accurate indicator of its performance prediction.

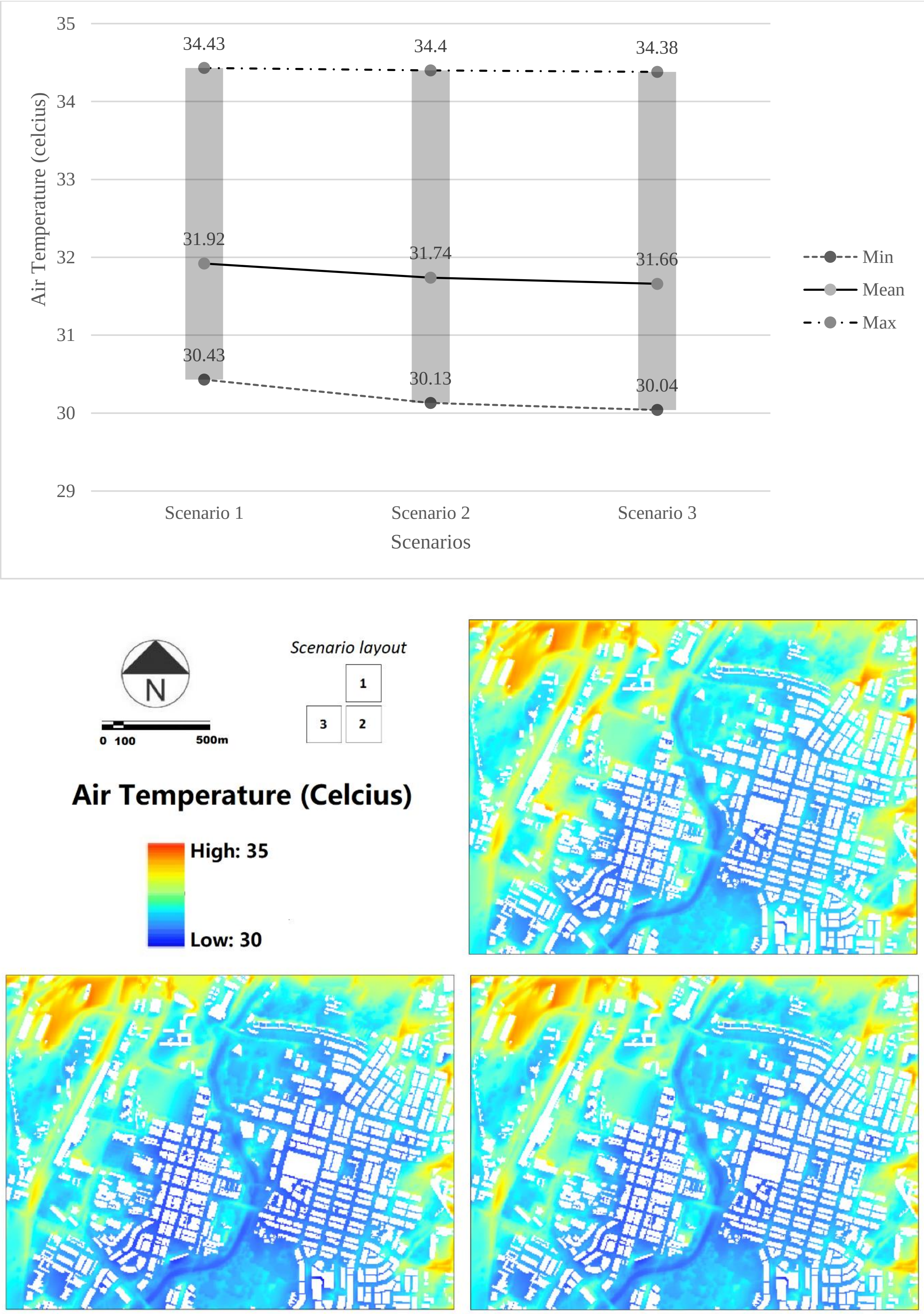


Fig. 5.12. Air temperature distribution between scenarios (1 = baseline model; 2 = basic model; 3 = optimal model).

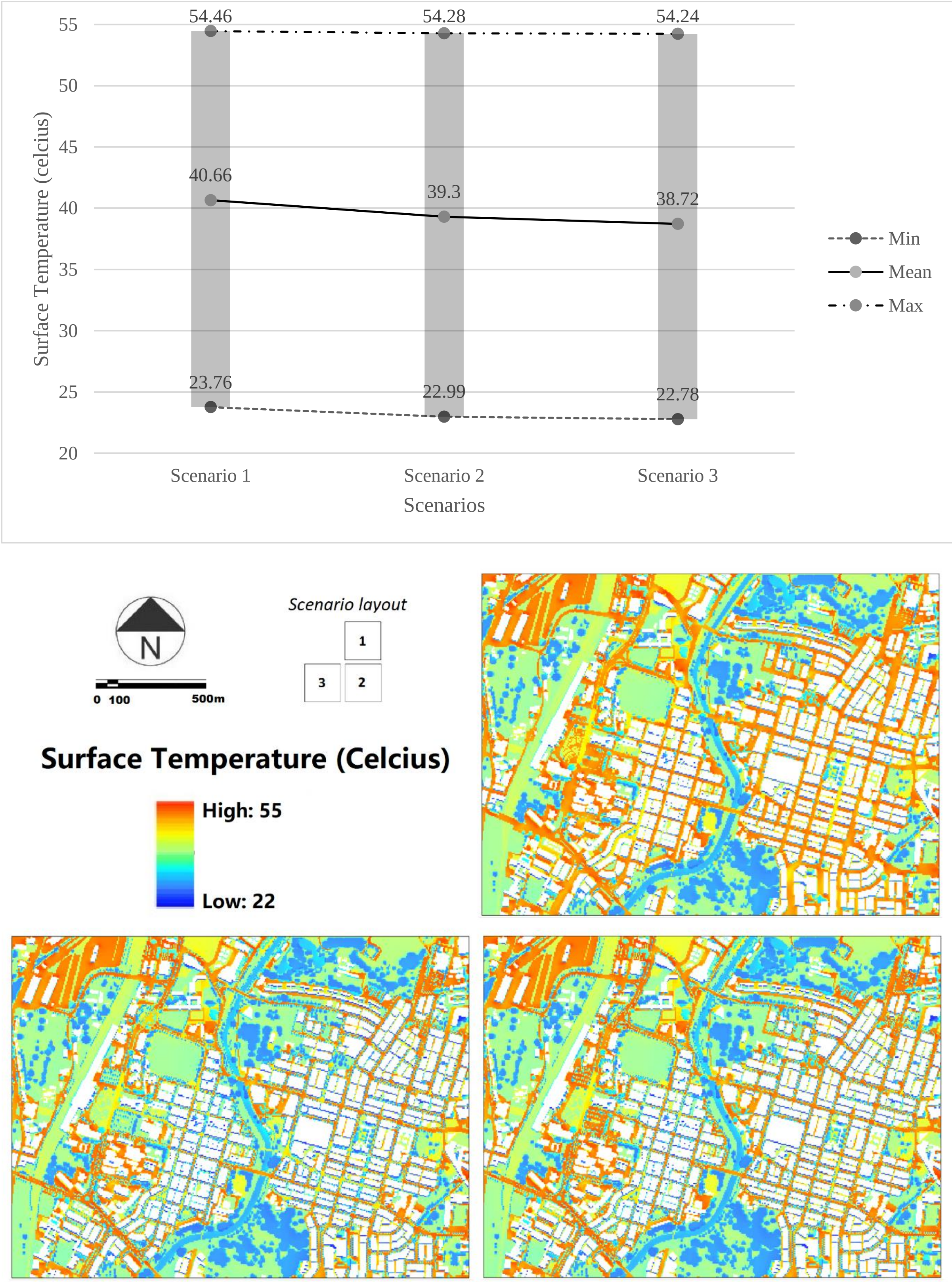


Fig. 5.13. Surface temperature distribution between scenarios (1 = baseline model; 2 = basic model; 3 = optimal model).

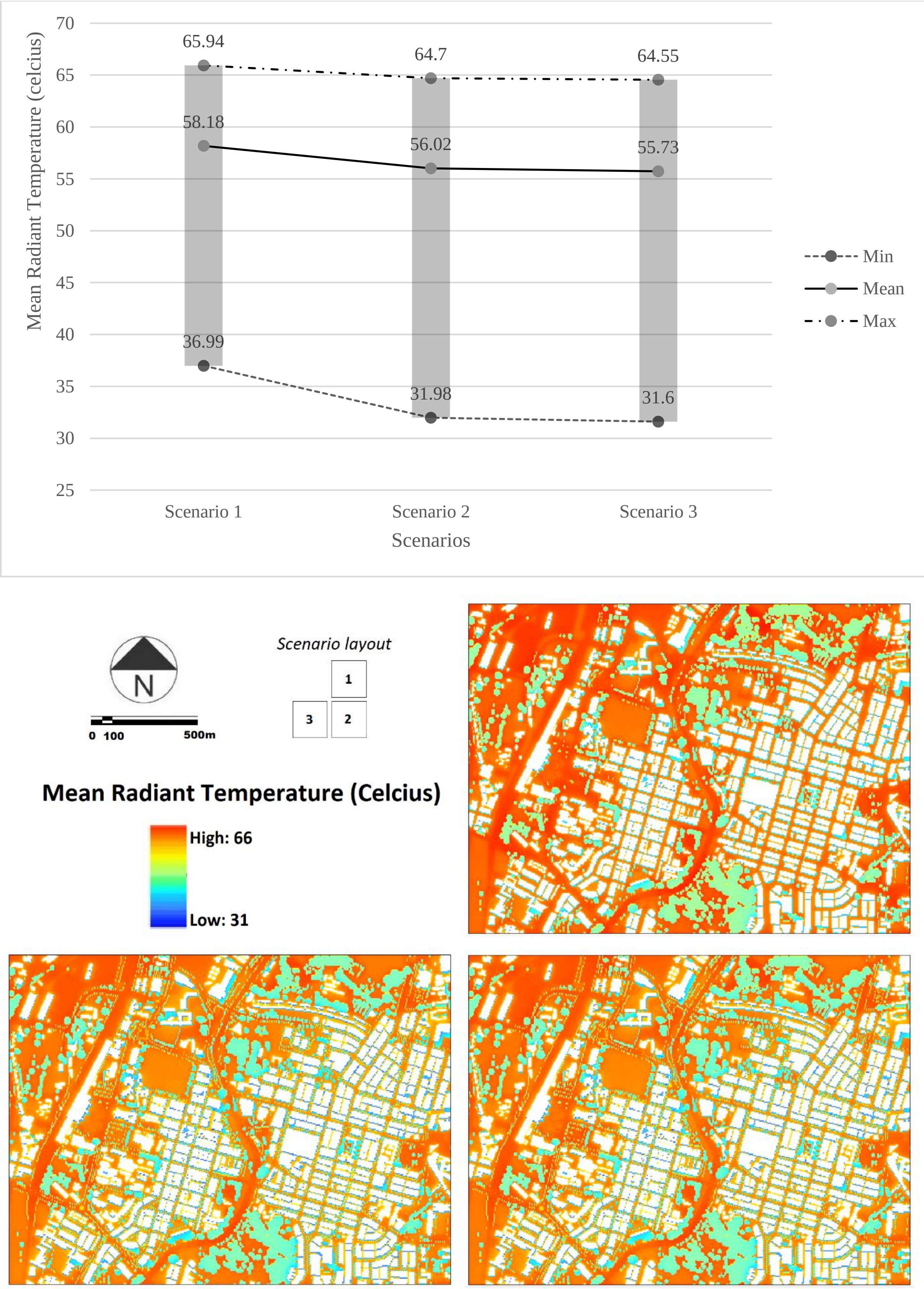


Fig. 5.14. Mean radiant temperature distribution between scenarios (1 = baseline model; 2 = basic model; 3 = optimal model).

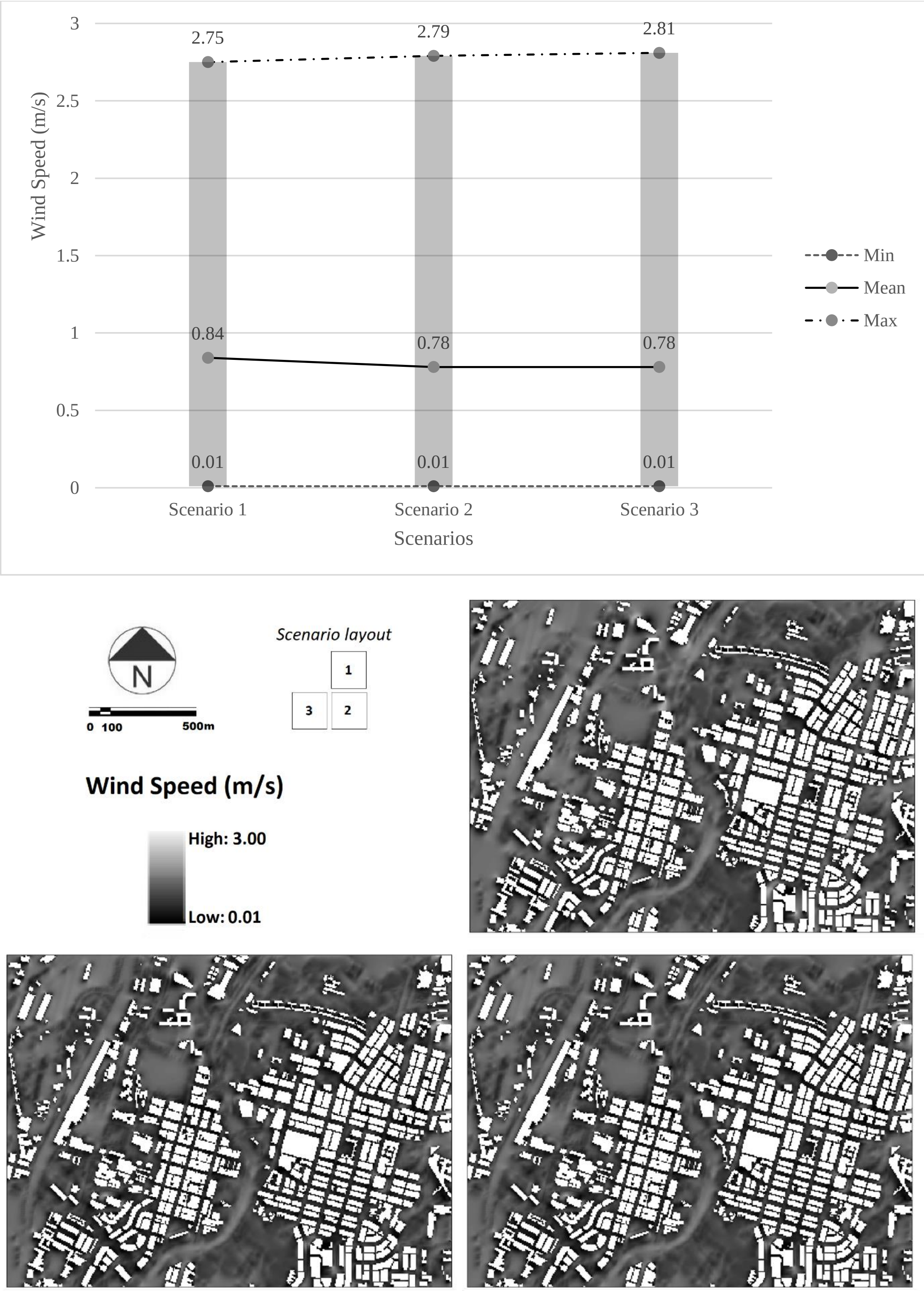
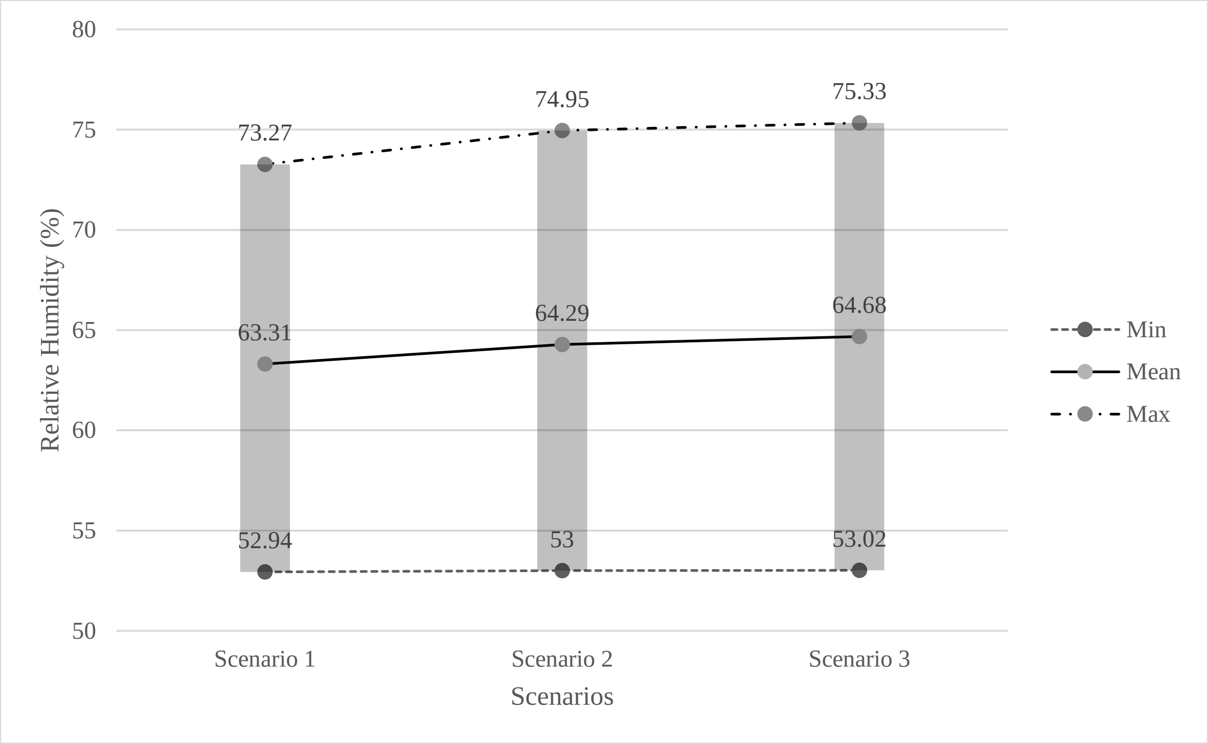


Fig. 5.15. Wind speed distribution between scenarios (1 = baseline model; 2 = basic model; 3 = optimal model).



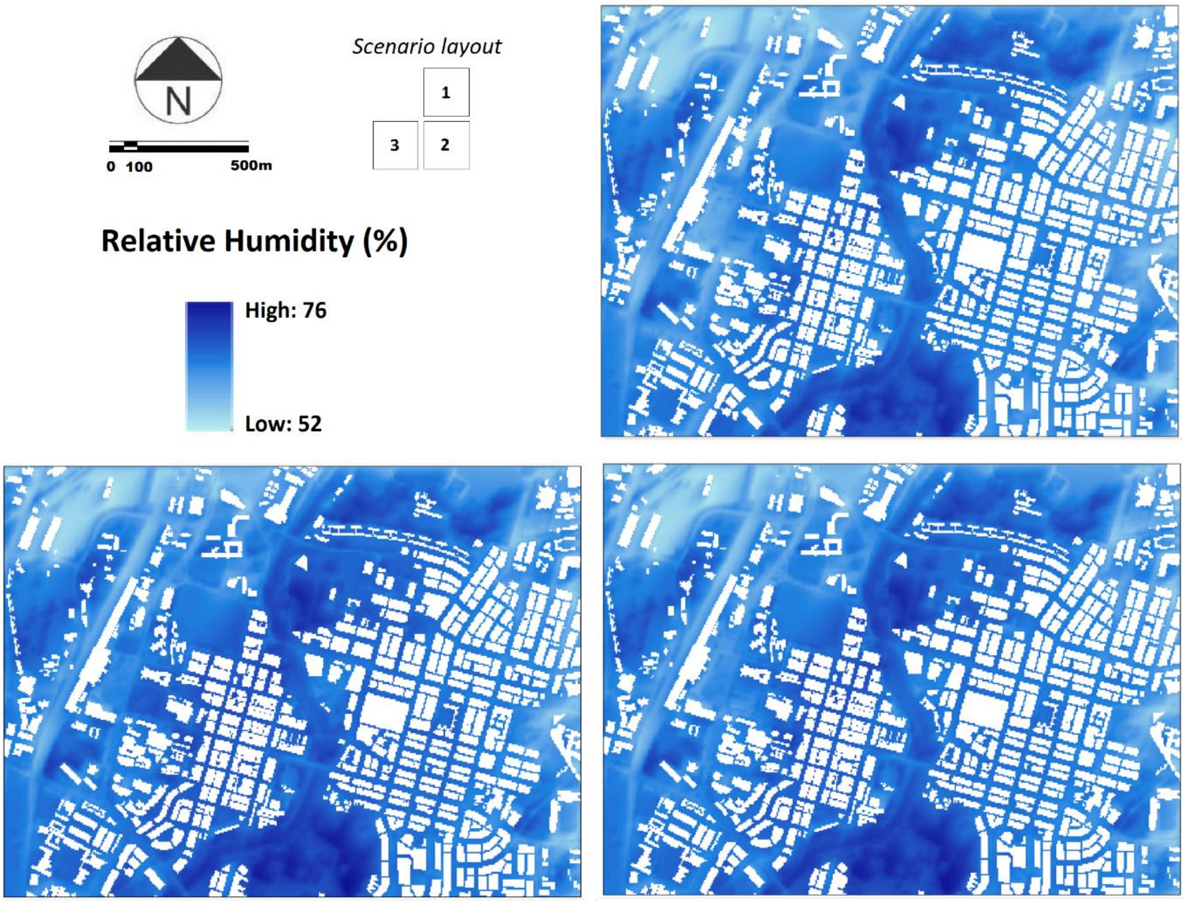


Fig. 5.16. Relative humidity distribution between scenarios (1 = baseline model; 2 = basic model; 3 = optimal model).

5.4.2 Thermal Comfort Aspect

This section analysed the climate-led landscape plans in terms of human thermal comfort. Overall, the average physiological equivalent temperature (PET) declined 1.19^{o}C in Scenario 2 and 1.39^{o}C in Scenario 3 (Table 5.4 and Figure 5.17). In this case, the average thermal comfort was improved, but it remained at a 'very hot' (>42^{o}C) condition during the hottest hour of the day (refer to Table 3.7). Compared to the minor change of mean and maximum values, the PET minimum index was relatively much improved, dropping from 34^{o}C to 31.2^{o}C in Scenario 2 and 30.9^{o}C in Scenario 3. Despite that, the minimum index was still in the ' slightly warm' condition, unchanging the thermal comfort perception at all. Compared with the prototype model of the previous chapter, the full-scale models were less performed on the macro scale.

The difference between Scenarios 2 and 3 was small, reducing 0.2^{o}C in the mean index, 0.1^{o}C in the maximum index and 0.3^{o}C in the minimum index. As shown in Figures 5.17 and 5.18, PET improvement most occurred in the area used for pedestrian and bicycle activities (where the new additional trees were located in Scenario 3). This result proved that outdoor thermal comfort was proportional to the tree coverage ratio. Non- trees vegetations could reduce the PET, but the small degree of improvement did not significantly influence thermal comfort perception. However, the maps showed that green paving enhanced trees cooling effect that helped the thermal comfort level at large open car parks. This finding could be an essential guideline in the design of large-scale car parks in tropical cities.

Table 5.4. Comparison between the physiological equivalent temperature

PET (^{o}C)	Scenario 1 (A)	Scenario 2 (B)	B - A	Scenario 3 (C)	C-A	C-B
Mean	45.22	44.03	-1.19	43.83	-1.39	-0.2
Maximum	51.5	51	-0.5	50.9	-0.6	-0.1
Minimum	34	31.2	-2.8	30.9	-3.1	-0.3

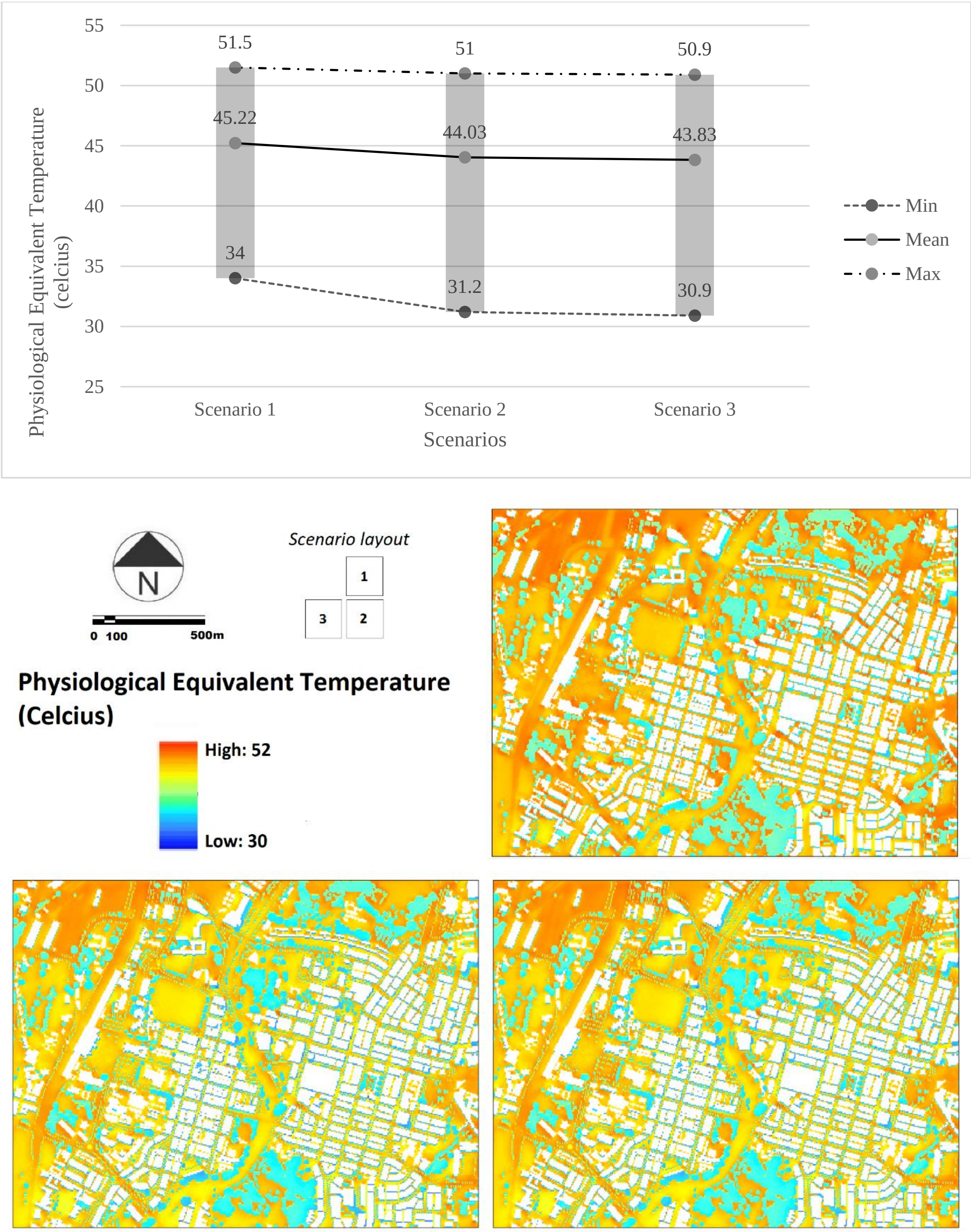


Fig. 5.17. PET distribution between scenarios (1 = baseline model; 2 = basic model; 3 = optimal model).

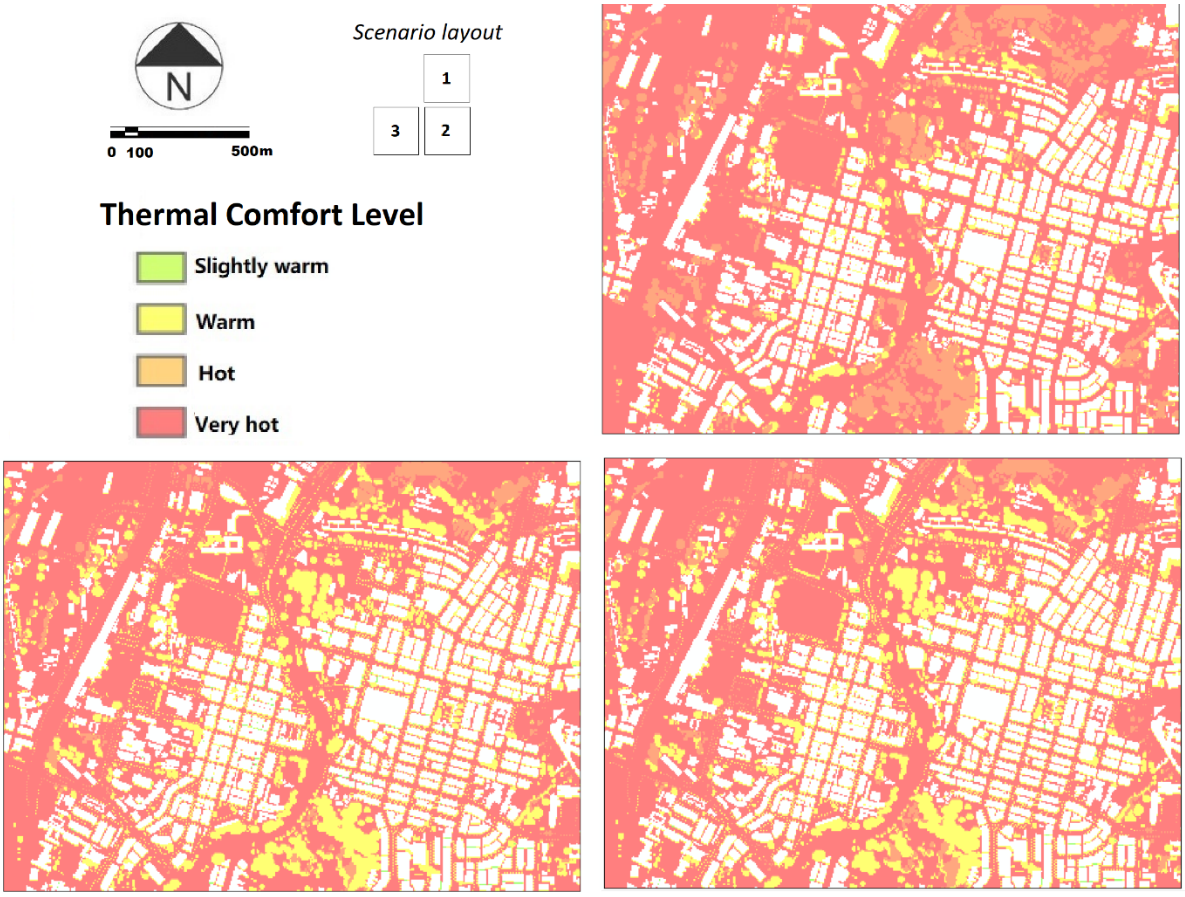


Fig. 5.18. Thermal comfort level between scenarios (1 = baseline model; 2 = basic model; 3 = optimal model).

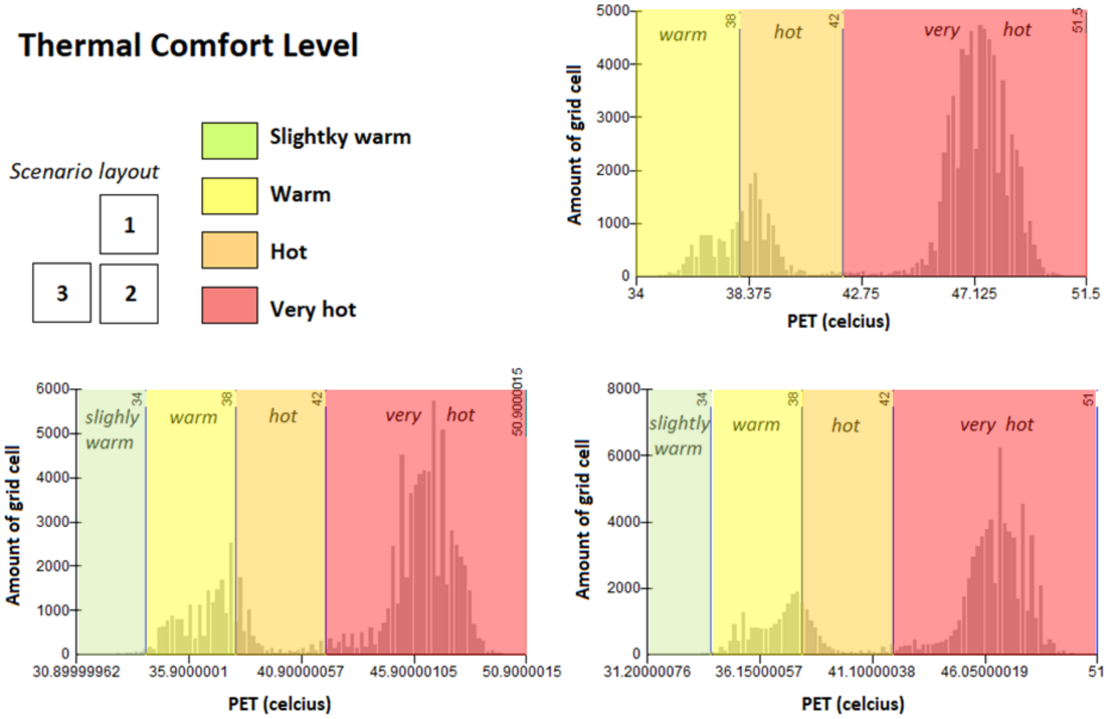


Fig. 5.19. Overall PET statistical diagram (1 = baseline model; 2 = basic model; 3 = optimal model).

Due to the unhelpful findings in terms of mean, maximum and minimum index, this study, in turn, reviewed and compared the index trends of PET between models, as shown in Figure 5.19. the figure was also in line with the information provided in Table 5.6. It was significant to see that thermal comfort level has dramatically shifted from 'very hot' to cooler conditions, made the PET indexes more falling in the range of 'warm' conditions. The 'very hot' area ratio was decreased from 76.98% (Scenario 1) to 72.71% (Scenarios 2 and 3), whereas the 'warm' area ratio was increased from 9.44% (Scenario 1) to 19.81% (Scenarios 2) and 21.02% (Scenario 3). Besides, the range for 'slightly warm' was also enlarged in Scenarios 2 and 3. It was from an insignificant ratio (0% in Scenario 1) to 0.15% and 0.28% in Scenarios 2 and 3, respectively. The positive trend change indicated that the design models did have a tremendous impact on improving outdoor thermal comfort.

Overall, both scenarios have increased the comfort and acceptable zone coverage ratio, as analysed in the following:

a. In the overall coverage dimension (Table 5.5).
    i. With an additional 6% green coverage ratio, Scenario 2 increased 0.11% of comfort area and 7.52% of acceptable areas.
    ii. With an additional 9% green coverage ratio, Scenario 3 increased 0.2% of comfort area and 8.4% of acceptable areas.
    iii. Scenario 3 (which had an extra 3% of green coverage area than Scenario 2) increased 0.09% of comfort area and 0.88% of acceptable areas compared to Scenario 2.

b. In the open area coverage dimension (Table 5.6).
    i. With an additional 10% green coverage ratio, Scenario 2 increased 0.15% of comfort area and 10.37% of acceptable areas.
    ii. With an additional 14% green coverage ratio, Scenario 3 increased 0.28% of comfort area and 11.58% of acceptable areas.
    iii. Scenario 3 (which had an extra 4% green coverage area than Scenario 2) increased 0.13% of comfort area and 1.21% of acceptable areas compared to Scenario 2.

The result indicated that the cooling magnitude was positively proportional to the green coverage ratio, but their relationship is not linear. Compared with the prototype model of the previous chapter, the full-scale models, again, were less performed on the macro scale. However, despite it not being a presentable cooling index in the overall context, Figure 5.18

showed that the coverage of 'slightly warm' (comfort zone) and 'warm' (acceptable zone) conditions most found in pedestrian areas. This situation indicated that at least the design models still successfully protected the walking people from exposure to extreme sun heat during hot hours.

Table 5.5. Summary of thermal comfort coverage area between scenarios (case I).

Overall Coverage ratio （%）		**Scenario 1**	**Scenario 2**		**Scenario 3**		
Level	**Classification**	**Coverage A1**	**Coverage B1**	**B1 – A1**	**Coverage C1**	**C1 – A1**	**C1– B1**
Comfort	Inside building	27.48	27.48	0.00	27.48	0.00	0.00
	0 (neutral)						
	1 (slightly warm)		0.11	0.11	0.20	0.20	0.08
Acceptable *(Adaptation)*	2 (warm)	6.85	14.37	7.52	15.25	8.40	0.88
Discomfort	3 (hot)	9.85	5.31	-4.53	4.73	-5.11	-0.58
	4 (very hot)	55.82	52.73	-3.10	52.34	-3.49	-0.39
Total							
Comfort		27.48	27.59	0.11	27.68	0.2	0.09
Acceptable		6.85	14.37	7.52	15.25	8.4	0.88
Discomfort		65.67	58.04	-7.63	57.07	-8.6	-0.97
Greenery available		30	36	6	39	9	3

Table 5.6. Summary of thermal comfort coverage area between scenarios (case II).

Open area Coverage ratio （%）		**Scenario 1**	**Scenario 2**		**Scenario 3**		
Level	**Classification**	**Coverage A2**	**Coverage B2**	**B2 – A2**	**Coverage C2**	**C2 – A2**	**C2 – B2**
Comfort	0 (neutral)						
	1 (slightly warm)		0.15	0.15	0.28	0.28	0.13
Acceptable *(Adaptation)*	2 (warm)	9.44	19.81	10.38	21.02	11.58	1.21
Discomfort	3 (hot)	13.58	7.33	-6.25	6.53	-7.05	-0.8
	4 (very hot)	76.98	72.71	-4.27	72.17	-4.81	0
Total							
Comfort			0.15	0.15	0.28	0.28	0.13
Acceptable		9.44	19.81	10.37	21.02	11.58	1.21
Discomfort		90.56	80.04	-10.52	78.7	-11.86	-1.34
Greenery available		40	50	10	54	14	4

Lastly, this section tried to sort out the PET and thermal comfort differences between models, which were summarised as follows:

a. Between Scenarios 1 and 2 (see Figure 5.20)
   Diagram (a) showed that the changes most happened from -2^{o}C to 1^{o}C, with an average at -1.2^{o}C. It could be a maximum drop of 13.6^{o}C in this case. Diagram (b) indicated a drop of >1^{o}C for the majority area, with a small portion in the range of >2^{o}C. Diagram (c) illustrated that most model areas have remained at the same thermal comfort level, followed by the one-level-decline (-1). The declining area was most found at the existing treed area, indicating that the additional greening helped strengthen the cooling magnitude of existing greenery. It was up to two-levels-decline (-2) in this case. For example, the decline from 'very hot' to 'warm' conditions, most found at the new treed area.

b. Between Scenarios 1 and 3 (see Figure 5.21)
   Diagram (a) showed that the changes most happened from -3^{o}C to 1^{o}C, with an average at -1.39^{o}C. It could be a maximum drop of 13.8 ^{o}C in this case. Diagram (b) indicated a drop of >1^{o}C for the majority area, with a considerable portion in the range of >2^{o}C. Similar to the last comparison, diagram (c) illustrated that most model areas have remained at the same thermal comfort level, followed by the one-level-decline (-1). It was up to three-levels-decline (-3) in this case. For example, the decline from 'very hot' to 'slightly warm' conditions, most found at the new treed area. It proved that optimum greening did have a higher cooling effect in the model.

c. Between Scenarios 2 and 3 (see Figure 5.22)
   Diagram (a) showed that the changes most happened from -1^{o}C to 0^{o}C, with an average at -0.21^{o}C. It could be a maximum drop of 12.2 ^{o}C in this case. Diagram (b) indicated a drop of >1^{o}C for the majority area. It found that those large open car parks have significantly dropped about another 1^{o}C, indicating that non-trees vegetation also positively impacted the cooling magnitude. However, diagram (c) illustrated that most model areas have remained at the same thermal comfort level. Only some areas experienced the one-level-decline (-1) or two-level-decline (-2) in this case. The -1 situation was primarily found in the open green spaces, whereas the -2 situation was most found along the streets in the shophouse zone. Again, it proved that Scenario 3 did have more advantages over Scenario 2.

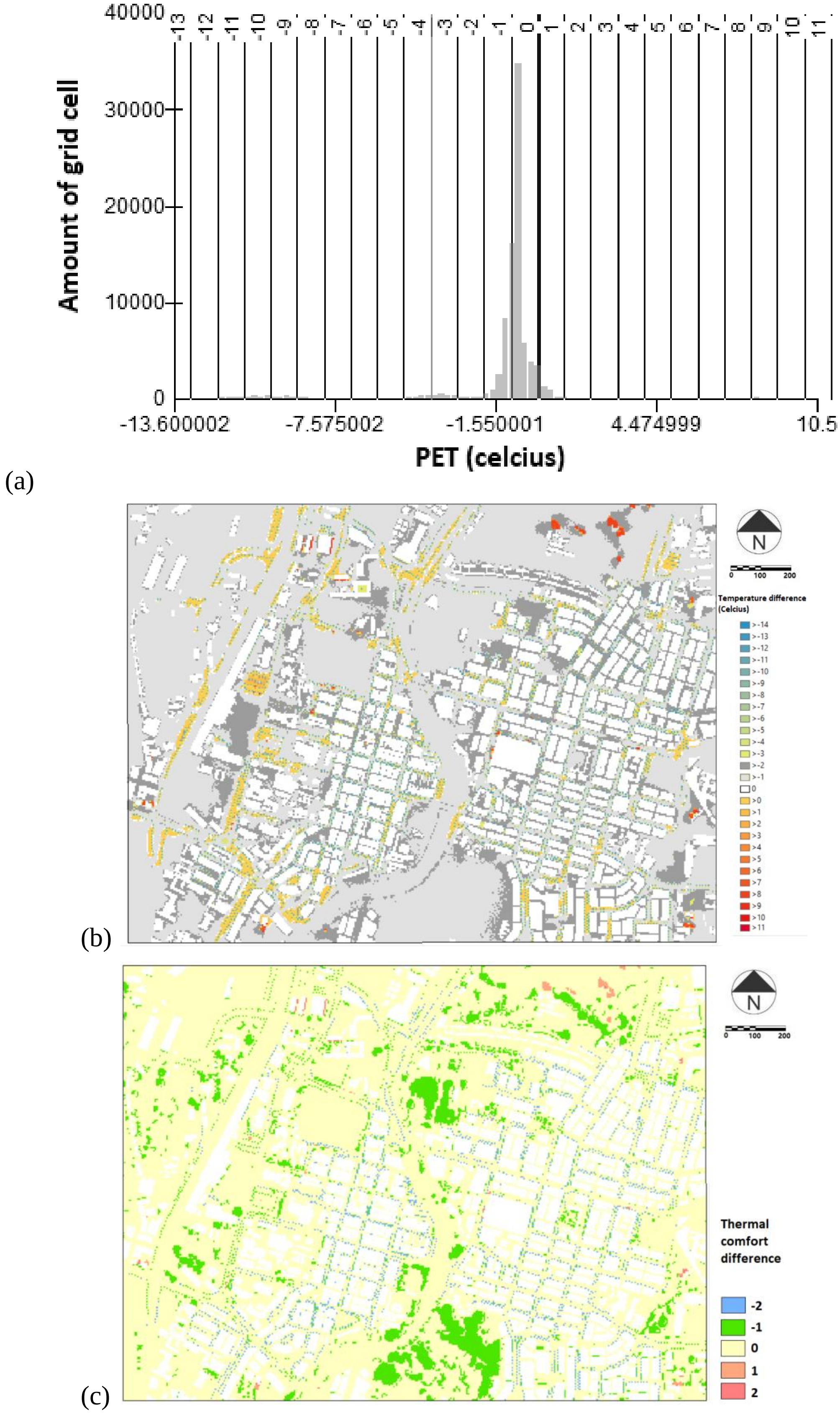


Fig. 5.20. The PET and thermal comfort level differences between Scenarios 1 and 2.

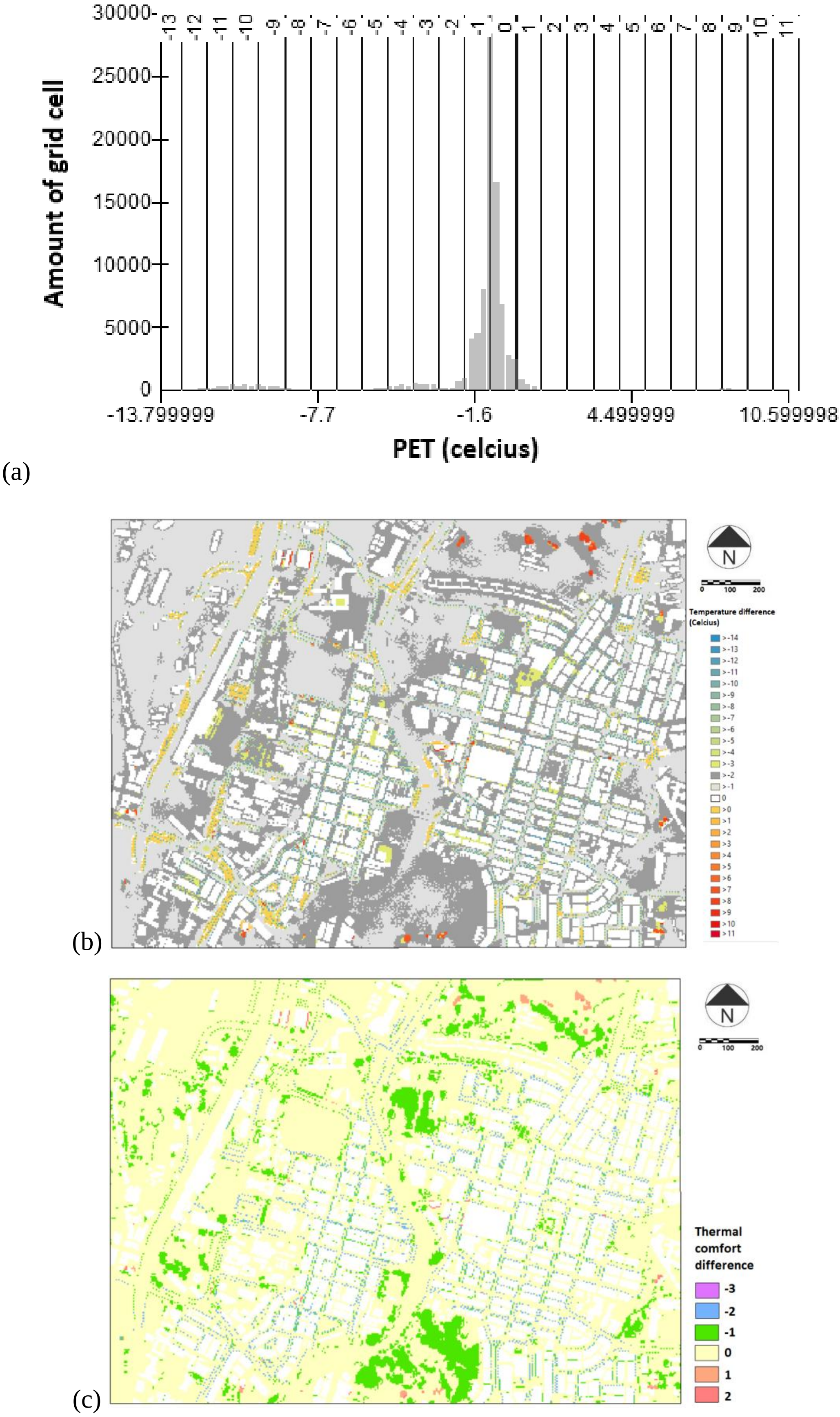


Fig. 5.21. The PET and thermal comfort level differences between Scenarios 1 and 3.

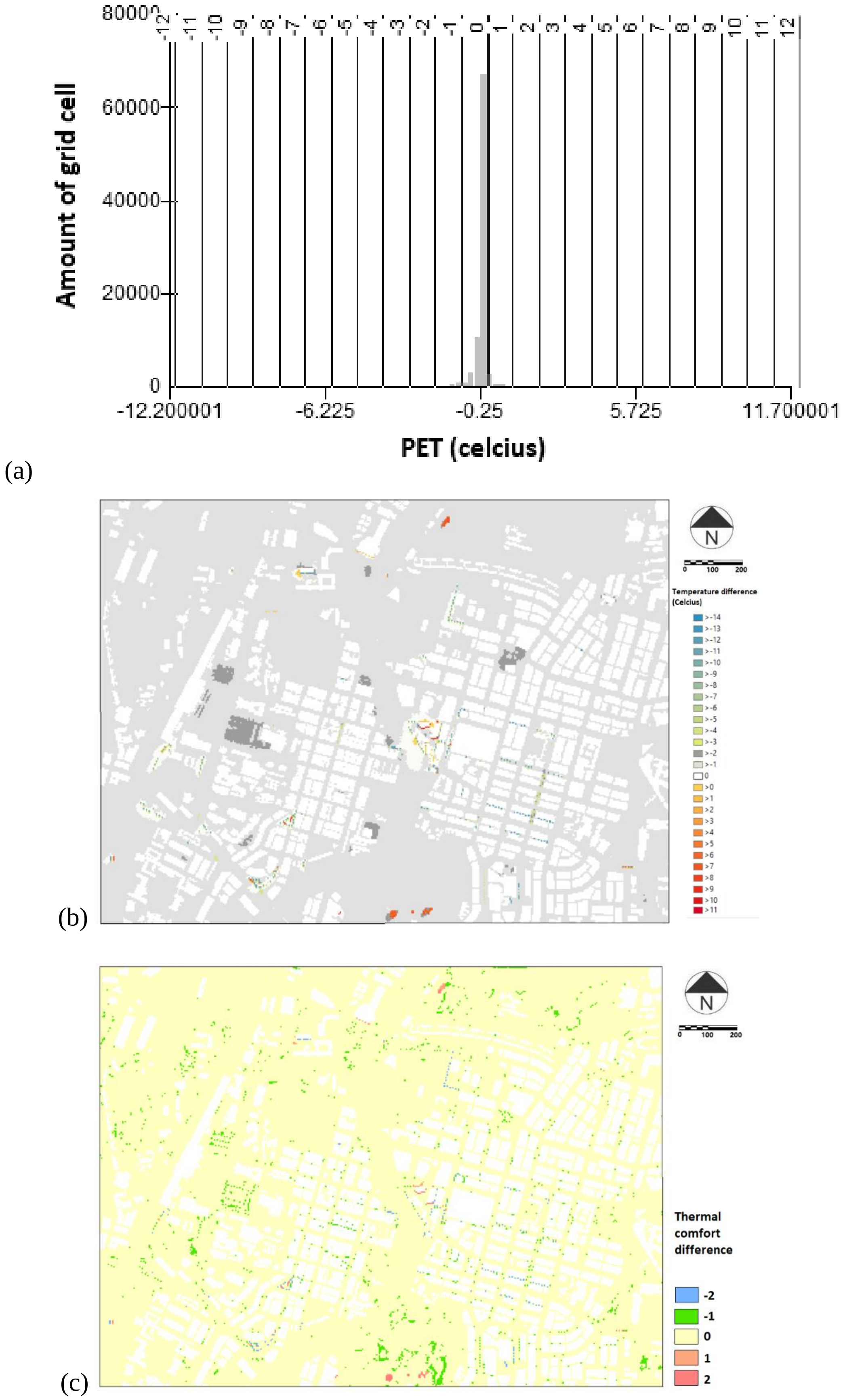


Fig. 5.22. The PET and thermal comfort level differences between Scenarios 2 and 3.

5.5 CONCLUSION

The primary outcome in this chapter was the optimal and basic models proposed for climate-led landscapes in Ipoh downtown. Both models facilitated to achieve the maximum green coverage in tropical cities by using different design principles. The optimal climate-led landscape design concept presented in this chapter was far beyond the typical planting strategy. In addition to optimising the greening by trees and vegetations, it integrated various considerations related to climate change mitigation and adaptation, ranging from non-motorised mobility to green technology and sustainable development planning. The design model first introduced full-pedestrian zones to attract and increase the public's willingness to travel by walk. Considering pedestrian comfort and safety, it continued to the traffic reorganisation and designed pedestrians and cycling networks. Compared to the basic model, the optimal model had more far-reaching objectives. It deliberated over the reduction of heat, pollutants and exhaust emissions from cars, the psychological adaptation in outdoor thermal comfort, and the pedestrian-oriented development. These factors were not evaluated in this study but were essential for mitigating and adapting to climate change. The basic climate-led landscape model was relatively designed in a typical way, only aiming to reach the maximum green coverage in the existing open space and improve walkway connection. The degree of site modification was relatively low. Despite that, similar to the optimal model, all greening designs applied in the basic model were also evidence-based. Both design models were evaluated using microclimate and thermal comfort simulation.

The full-scale model study affirmed that the cooling magnitude was correlated to the green coverage ratio and tree coverage ratio, in line with the results of prototypes models in the previous chapter. However, the outcomes of this chapter lastly suggested using the green coverage ratio to predict microclimate performance, except for the wind. The main reason was that this chapter realised that non-trees vegetation that coexisted with trees also highly impacted the microclimate and thermal comfort, especially in large open areas. Nevertheless, trees were still the most effective measure to improve the microclimate and thermal comfort in this model. In conclusion, until this chapter, this research has provided a complete roadmap of climate-led landscape design and planning for tropical cities. Throughout the process, it indicated that the landscape-based approach was practical in leading urban climate-responsive development. This approach is multi-dimensional, integrated and flexible in implementation. It included but was not limited to the factors or aspects considered in this research, giving the climate-led landscape more room for development with local conditions.

CHAPTER 6
ZONING DESIGN ASSESSMENT AND DETERMINATION OF PRIORITY IN CLIMATE-LED LANDSCAPE DEVELOPMENT

6.1 INTRODUCTION

This chapter was an extension study of Chapter 5 to explore the proposed design model details on a micro-scale. It followed the sub-model division created in Chapter 3 and replicated the design concepts used in Chapter 4. Throughout the study, the focus was mainly placed on the microclimate and thermal comfort comparison between sub-models. It was mainly to answer the following research questions:

Under the premise of using the same climate-led design strategy, do the greening, as well as the cooling magnitude, be the same between sub-models? To what extent do they perform differently? Do all models achieve the desired climate and thermal comfort condition? How to determine the priority of development between sub-models?

Furthermore, in the previous chapter, the macro-scale raster model with decreased resolution had led to the loss of landscape design details, mostly when the size of landscape components was smaller than the size of raster cells. For example, within a 5m pixel grid model (macro-scale study), it was impossible to completely project a 1m wide planting strip and a 2.5m wide parking lot or walkways. Likewise, some trees with a 3m crown (which were mostly located at those small lanes) might not be projected into the macro model, too. The loss of details resulted in fewer differences between the scenarios, affecting the accuracy of study outcomes. To minimise the deficiency, all sub-models in this chapter were simulated and analysed again with higher resolution, giving a more precise projection between zonings and scenarios. Similar to the macro model, each sub-model was studied under two scenarios: the basic design (refer to Section 5.2.2.2) and the optimal design (refer to Section 5.2.2.2). It first compared the sub-models between zonings, followed by the comparison between scenarios. Lastly, all outcomes would be discussed in the interest to determine the priority of development.

6.2 SUB-MODELS BUILDING AND SIMULATION

This section extracted four sub-models (Figure 6.1) from each macro model formulated in the previous chapter: the baseline model, the basic model and the optimal model (refer to Section 5.3.1). A total of 12 set models were built in this case. In other words, each zone had three scenarios. For example, for Zone 1, Model 1a represented the baseline model, Model 1b for the basic greening model and Model 1c for the optimal greening model. The same applied to other models for Zones 2, 3 and 4. By comparing Figures 6.2 to 6.5, we can see the differences between study models regarding the nature of model context, design principles, and greening level. The raster models (Figures 6.6 and 6.7) were then imported to ENVI-met for simulation. The simulation procedure has been explained by Sections 3.3.3 and 3.3.4 in Chapter 3. In this case, all models were built in the grid resolution of 2m x 2m x 2.5m in dx, dy, and dz directions, respectively, in which:

a. Models 1a, 1b and 1c with an area of 400m x 400m (200m x 200m x 75m in the model).
b. Models 2a, 2b and 2c with an area of 540m x 500m (270m x 250m x 75m in the model).
c. Models 1a, 1b and 1c with an area of 500m x 400m (250m x 200m x 75m in the model).
d. Models 1a, 1b and 1c with an area of 400m x 500m (200m x 250m x 75m in the model).

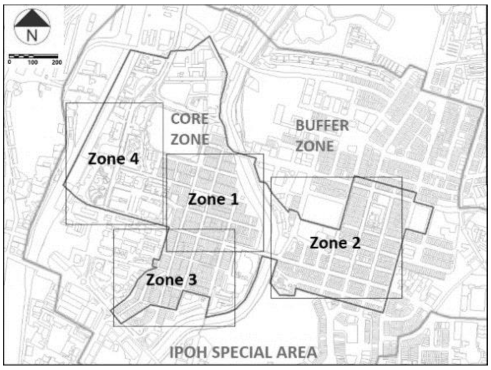


Fig.6.1. The zoning plan indicated the location of zones for sub-models.

Lastly, to compare the degree of implementation of climate-led landscape design between zonings, this section calculated the area and ratio of open area coverage, green coverage, tree coverage, and non-trees coverage for each zoning, as shown in Appendices 6.1 to 6.4. Since the simulation outputs were all in the raster unit, the coverage ratios based on the numbers of raster cells in each zoning model were calculated, too.

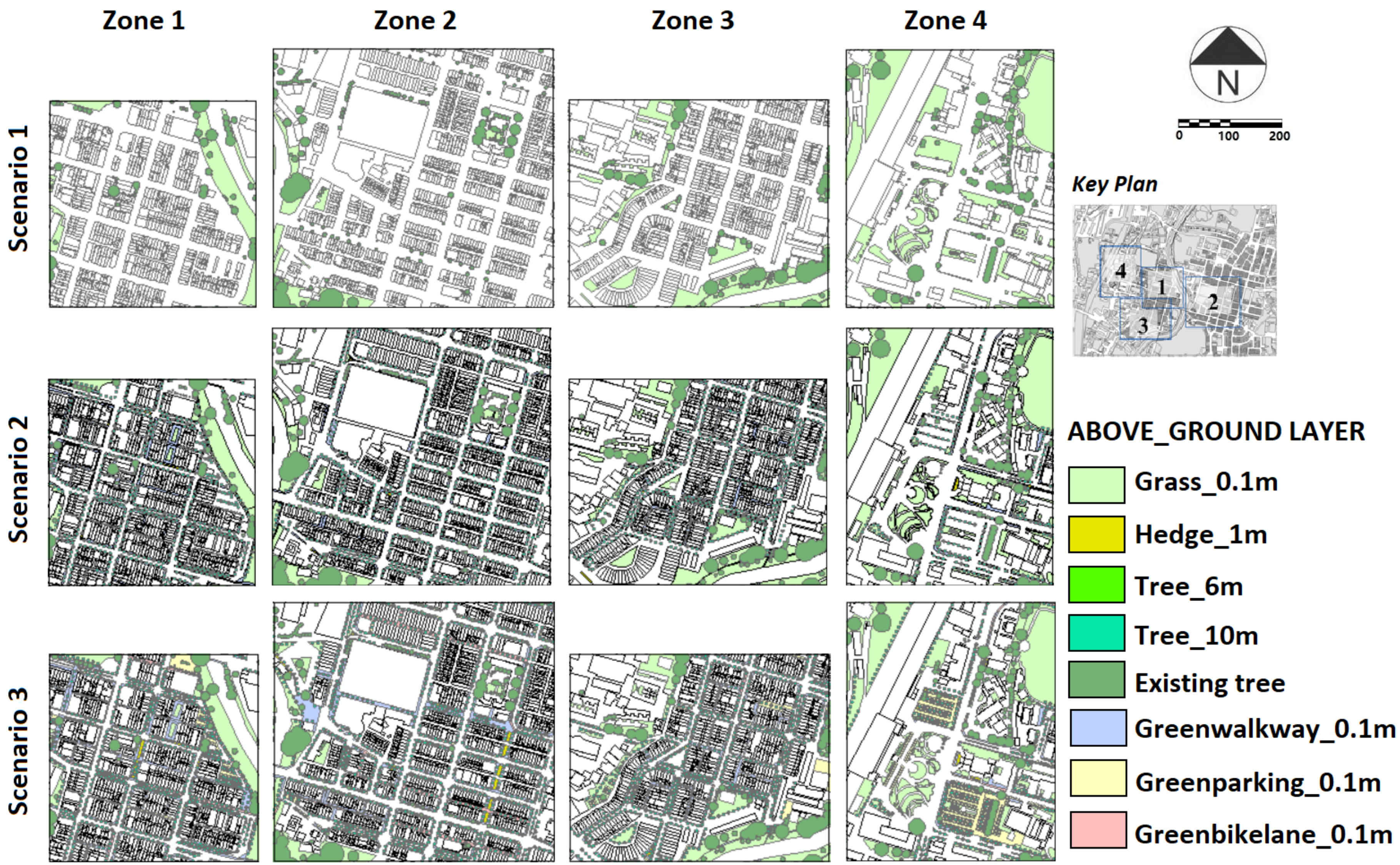


Fig.6.2. The evolution of landscape plan throughout the scenarios and between zonings.

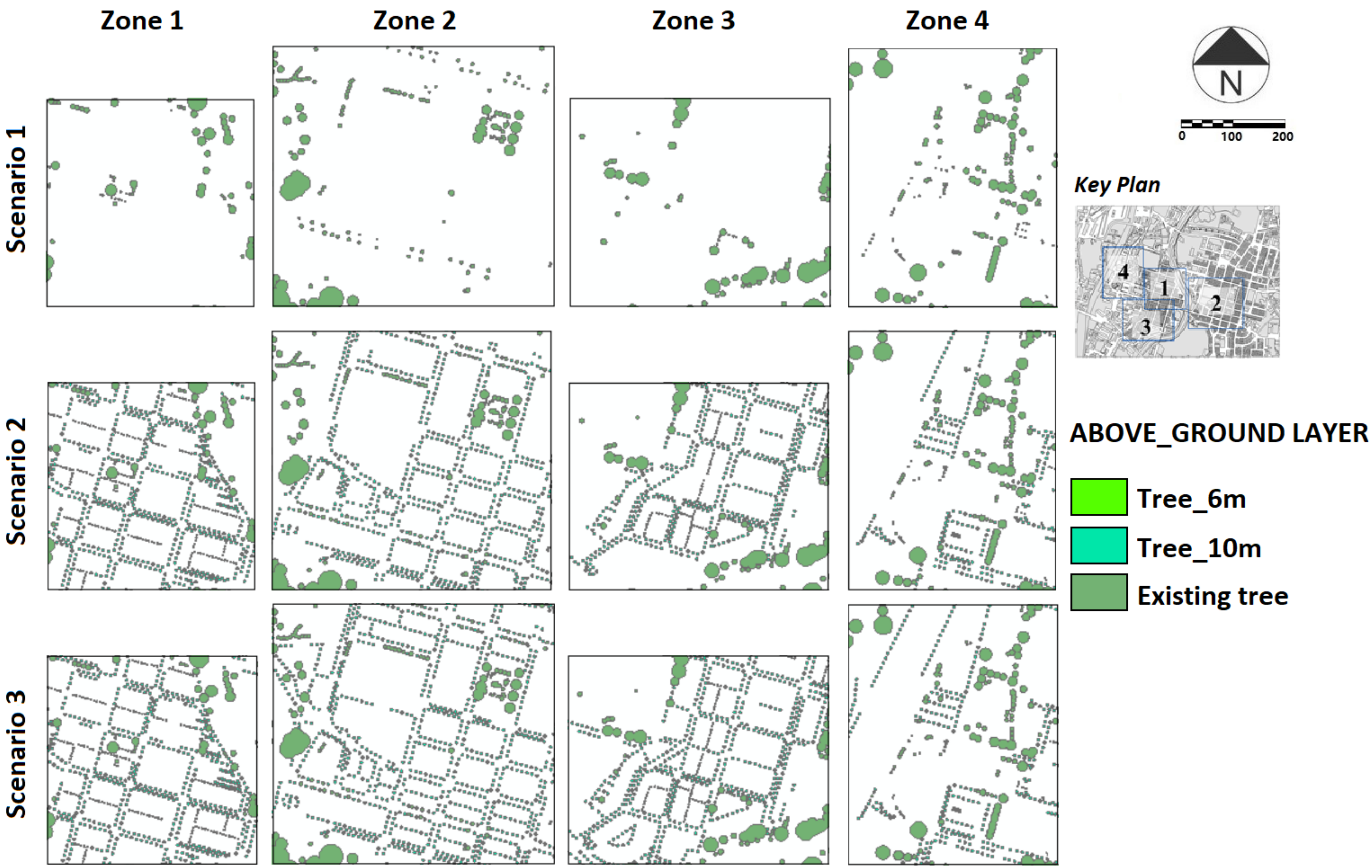


Fig.6.3. The evolution of trees distribution pattern throughout the scenarios and between zonings.

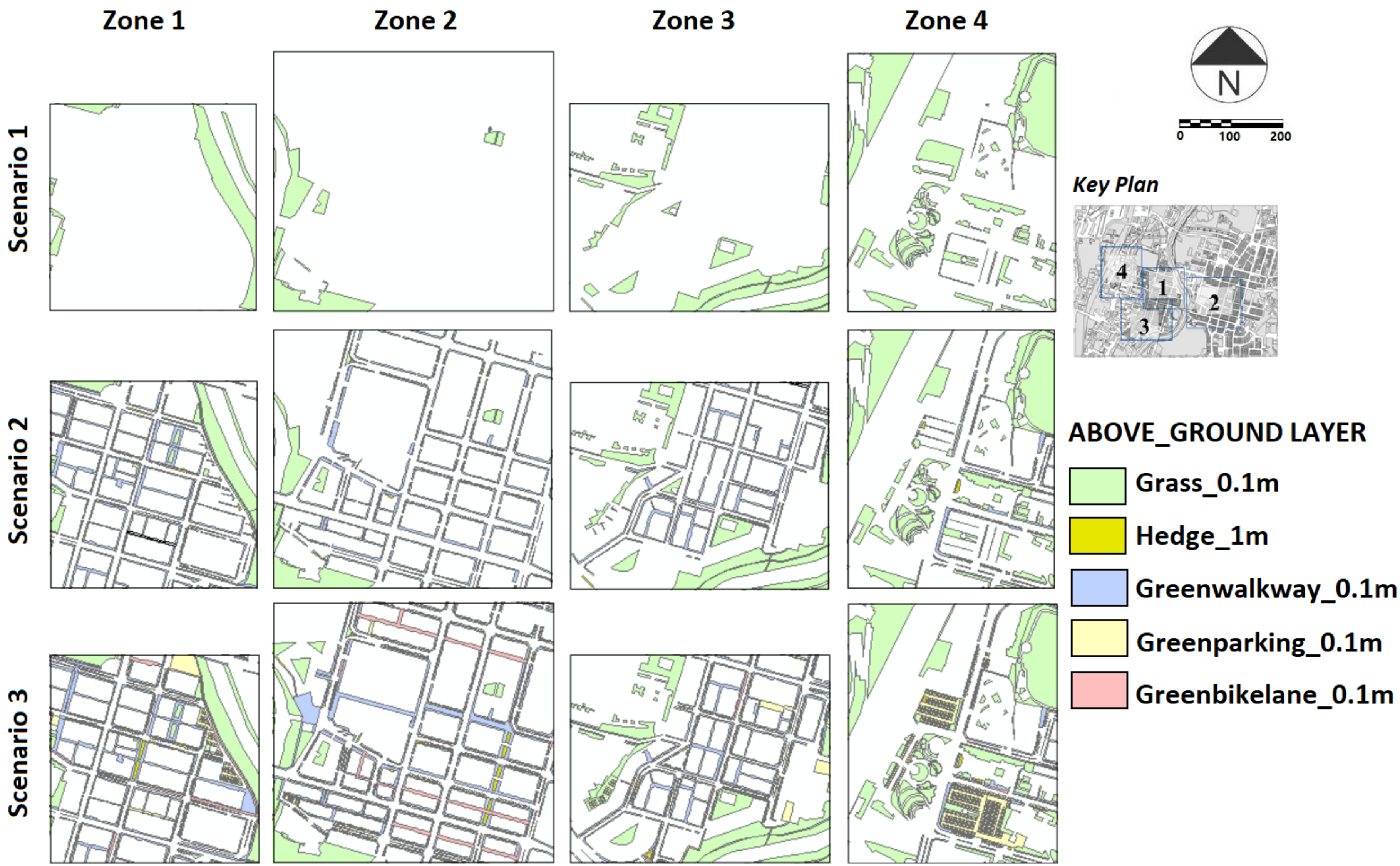


Fig.6.4. The evolution of vegetations (non-trees) distribution pattern throughout the scenarios and between zonings.

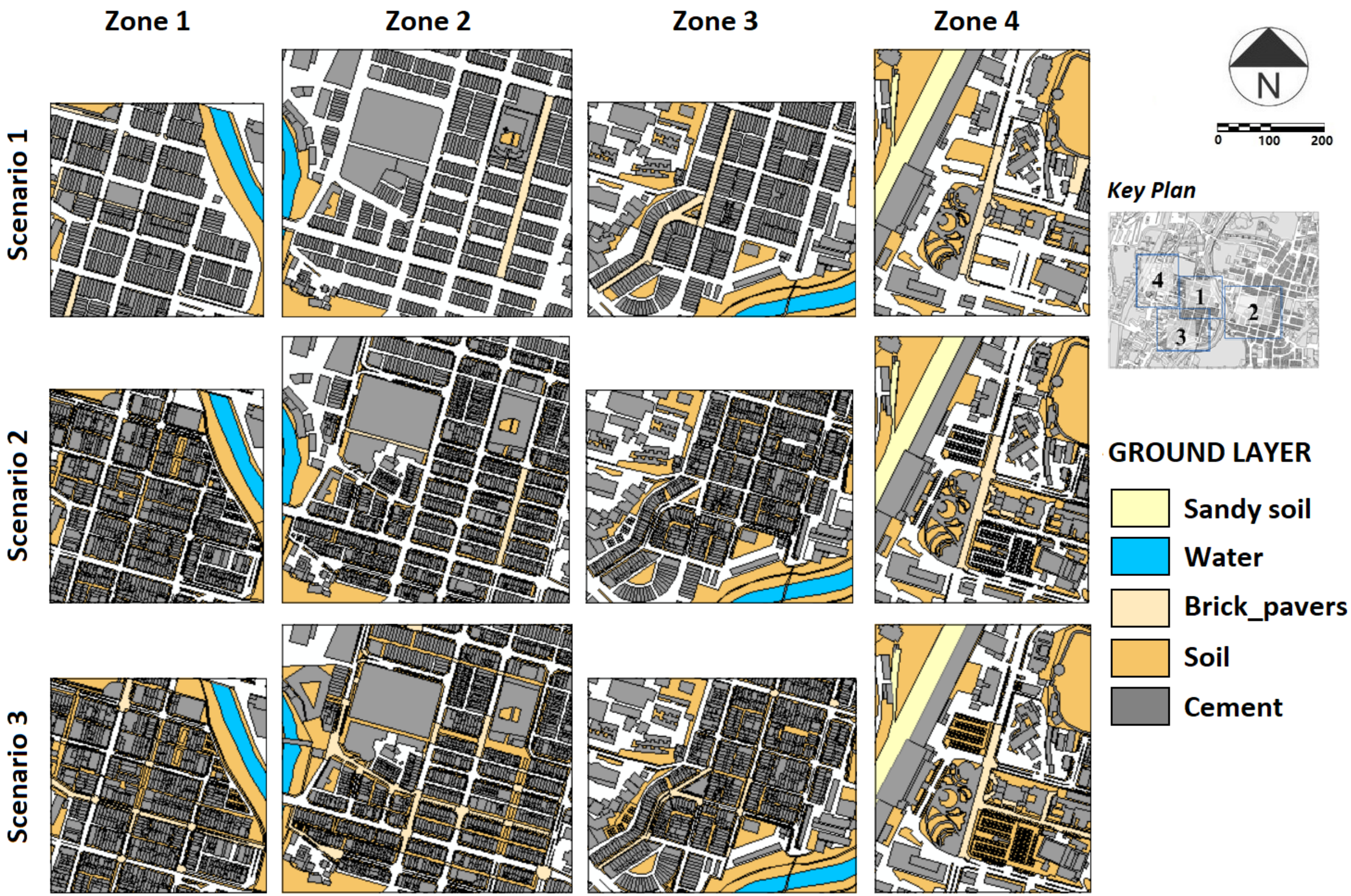


Fig.6.5. The evolution of surface materials throughout the scenarios and between zonings.

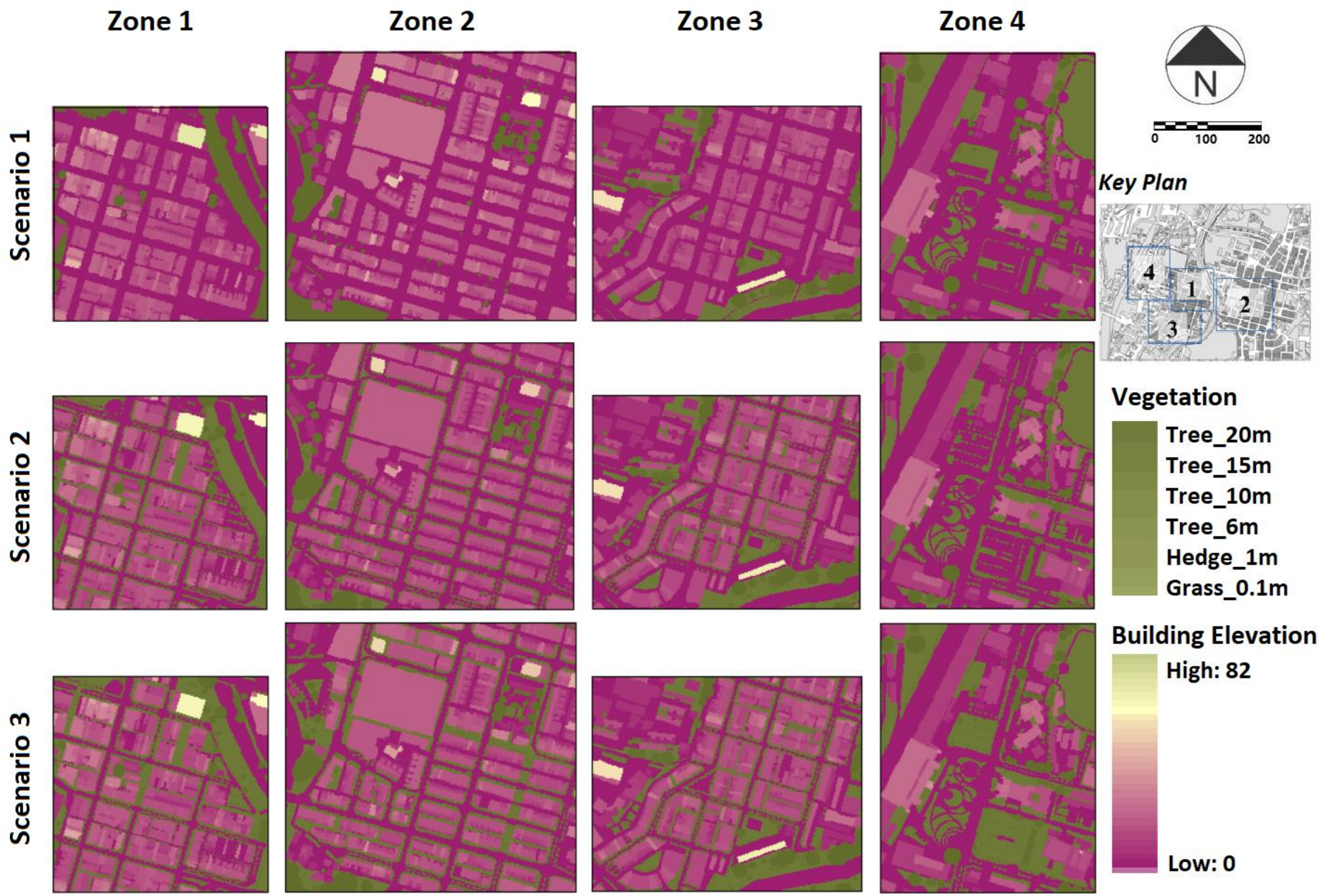


Fig.6.6. The evolution of the above-ground layer (raster) throughout the scenarios and between zonings.

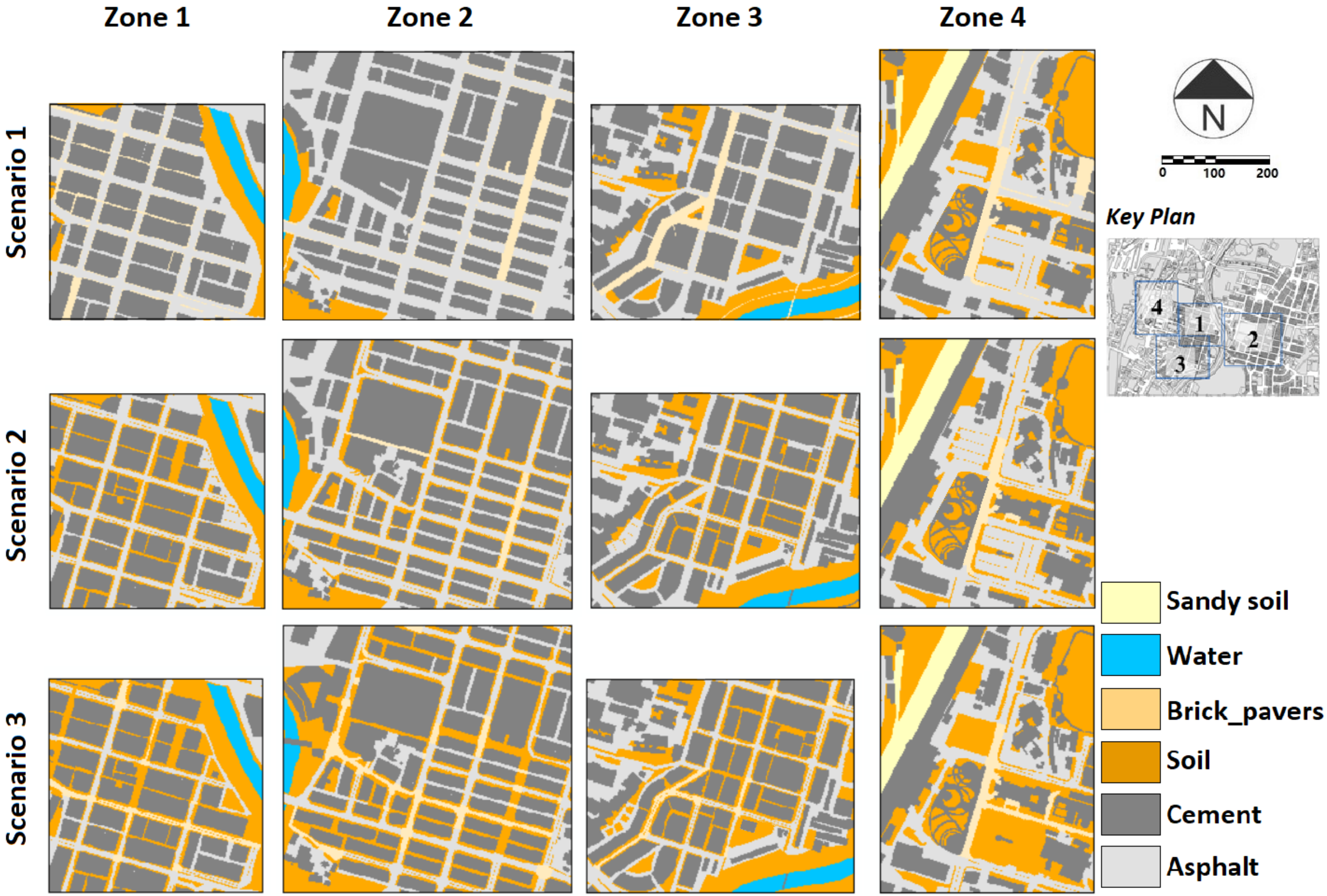


Fig.6.7. The evolution of the ground layer (raster) throughout the scenarios and between zonings.

6.3 RESULTS AND DISCUSSION

6.3.1 Degree of Implementation: GCR and TCR

First, this section examined the degree of implementation by comparing the green coverage ratio (GCR) and tree coverage ratio (TCR) before and after climate-led landscape designs. Since all simulation output data were in the raster unit, only raster coverage ratios were extracted from Appendices 6.1 to 6.4 and summarised in Table 6.1 for comparison.

Table 6.1. Comparison of green and tree coverage ratio between scenarios and zonings.

Index	Model	Scenario 1 (A)	Scenario 2 (B)	B-A	Scenario 3 (C)	C-A	C-B
CASE I: OVERALL AREA (raster)							
Green coverage ratio (%)	Zone 1	11.13	27.1	15.97	32.27	21.14	5.17
	Zone 2	7.64	18.64	11	26.92	19.28	8.28
	Zone 3	13.71	23.99	10.28	27.76	14.05	3.77
	Zone 4	27.44	30.05	2.61	37.75	10.31	7.7
Tree coverage ratio (%)	Zone 1	3.97	11.13	7.16	11.51	7.54	0.38
	Zone 2	5.17	10.1	4.93	11.38	6.21	1.28
	Zone 3	5.48	10.62	5.14	11.56	6.08	0.94
	Zone 4	7.2	9.41	2.21	9.84	2.64	0.43
CASE II: OPEN AREA ONLY*(raster)							
Green coverage ratio (%)	Zone 1	20.01	48.48	28.47	57.74	37.73	9.26
	Zone 2	14.53	35.2	20.67	49.63	35.1	14.43
	Zone 3	24.32	42.36	18.04	49.01	24.69	6.65
	Zone 4	37.45	40.65	3.2	51.07	13.62	10.42
Tree coverage ratio (%)	Zone 1	7.13	19.91	12.78	20.6	13.47	0.69
	Zone 2	9.83	19.06	9.23	20.98	11.15	1.92
	Zone 3	9.72	18.76	9.04	20.41	10.69	1.65
	Zone 4	9.83	12.73	2.9	13.31	3.48	0.58

Note:
*Total open area ratios in overall area: **56% (zone 1), 53-54% (zone 2) [a], 57% (zone 3), and 74% (zone 4)**
[a] The increase from 53% to 54% was because of the removal of some scattered buildings in Zone 2.

Zone 4, where had the largest open area (74%), held the highest GCR (27.44%) and TCR (7.2%) in the existing condition (Scenario1). However, in Scenarios 2 and 3, the increase of GCR and TCR was relatively low, resulting in only 30.05% (GCR) and 9.41%(TCR) in Scenario 2 meanwhile 37.75% (GCR) and 9.84% (TCR) in Scenario 3. In other words, the degree of implementation in Zone 4 was the lowest, with only +2.61% (GCR) and +2.21% (TCR) in

Scenario 2, and also only +10.31% (GCR) and +2.64% (TCR) in Scenario 3. As a result, the GCR of Zone 4 remained the highest, but the TCR became the lowest in Scenario 3 at last. Also, in the case that considered the open area only (CASE II in Table 6.5), it found that Zones 2,3 and 4 had a similar TCR in the existing condition. However, Zone 4 resulted in an extremely low TCR in Scenarios 2 and 3, showing the impact of the lowest degree of implementation.

In contrast, Zone 1 (with only 56% of open area) had the highest degree of implementation. From 11.13% in GCR, it reached 27.1% in Scenario 2 and 32.27% in Scenario 3. As for TCR, it increased from 3.97% to 11.13% in Scenario 2 and 11.51% in Scenario 3. Both have increased the most, up to 15.97% (Scenario 2) and 21.14% (Scenario 3) for GCR, and 7.16% (Scenario 2) and 7.54% (Scenario 3) for TCR. The decline was mostly contributed by the street planting and additional planting areas created at pedestrian zones and open car parks in the area (Figures 6.2 and 6.3). Zone 1 still produced a higher-than-average GCR for Case II, which held 48.48% in Scenario 2 and 57.74% in Scenario 3, indicating that around half of the open area turned green. In this case, the TCR has also risen about three times, from 7.13% to 19.91% and 20.6% in Scenarios 2 and 3.

Zone 2, with the smallest open area (53-54%), was the second most performed area in the degree of implementation. Its GCR increased from 7.64% to 18.64% (+11%) in Scenario 2 and 26.92% (+ 19.28%) in Scenario 3. As for TCR, it also increased from 5.17% to 10.1% (+4.93%) in Scenario 2 and 11.38% (+ 6.21%) in Scenario 3. The improvement of GCR and TCR was also most contributed by the elements mentioned in Zone 1. Zone 3 (57% of open area) had the same degree of implementation as Zone 2 in TCR, where it increased from 5.48% to 10.62% (+5.14%) in Scenario 2 and 11.56% (+ 6.08%) in Scenario 3. It less performed in GCR, where increased from 13.71% to 23.99% (+10.28%) in Scenario 2 and 27.76% (+ 14.05%) in Scenario 3.

In summary, Scenario 2 and Scenario 3 performed almost the same in terms of TRC. However, through Scenario 3, at least half of the total open area could be turned green when GCR reached a minimum of 49%. This advantage would make Scenario 3 more effective than Scenario 2 in cooling. Besides, the results showed that GCR or TCR was not definitely correlated to the ratio of open areas, but also relied on the area context and degree of implementation. The trends of GCR and TCR were finally shown in Figure 6.8 (for the overall area) and Figure 6.9 (for the open area only). The ranking of GCR and TCR between zonings was determined from highest to lowest for comparison in the following sections, as follows:

a. GCR: CASE I (the overall area)

i. For Scenario 1, Zone 4 (27.44%) – Zone 3 (13.71%) – Zone 1 (11.13%) – Zone 2 (7.64%)
ii. For Scenario 2, Zone 4 (30.05%) – Zone 1 (27.1%) – Zone 3 (23.99%) – Zone 2 (18.64%)
iii. For Scenario 3, Zone 4 (37.75%) – Zone 1 (32.27%) – Zone 3 (27.76%) – Zone 2 (26.92%)

b. GCR: CASE II (the open area only)

i. For Scenario 1, Zone 4 (37.45%) – Zone 3 (24.32%) – Zone 1 (20.01%) – Zone 2 (14.53%)
ii. For Scenario 2, Zone 1 (48.48%) – Zone 3 (42.36%) – Zone 4 (40.65%) – Zone 2 (35.2%)
iii. For Scenario 3, Zone 1 (57.74%) – Zone 4 (51.07%) – Zone 2 (49.63%) – Zone 3 (49.01%)

c. TCR: CASE I (the overall area):

i. For Scenario 1, Zone 4 (7.2%) – Zone 3 (5.48%) – Zone 2 (5.17%) – Zone 1 (3.97%)
ii. For Scenario 2, Zone 1 (11.13%) – Zone 3 (10.62%) – Zone 2 (10.1%) – Zone 4 (9.41%)
iii. For Scenario 3, Zone 3 (11.56%) – Zone 1 (11.51%) – Zone 2 (11.38%) – Zone 4 (9.84%)

d. TRC: CASE II (the open area only)

i. For Scenario 1, Zone 2 / Zone 4 (9.83%) – Zone 3 (9.72%) – Zone 1 (7.13%)
ii. For Scenario 2, Zone 1 (19.91%) – Zone 2 (19.06%) – Zone 3 (18.76%) – Zone 4 (12.73%)
iii. For Scenario 3, Zone 2 (20.98%) – Zone 1 (20.6%) – Zone 3 (20.41%) – Zone 4 (13.31%)

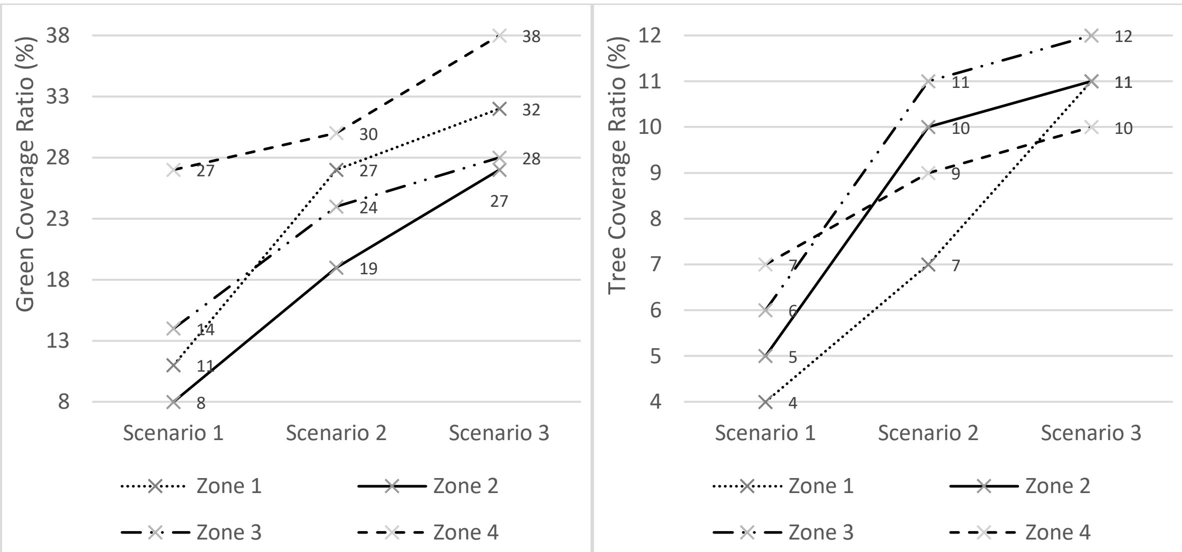


Fig.6.8. The trend of GCR (left) and TCR (right) between zonings for the overall area.

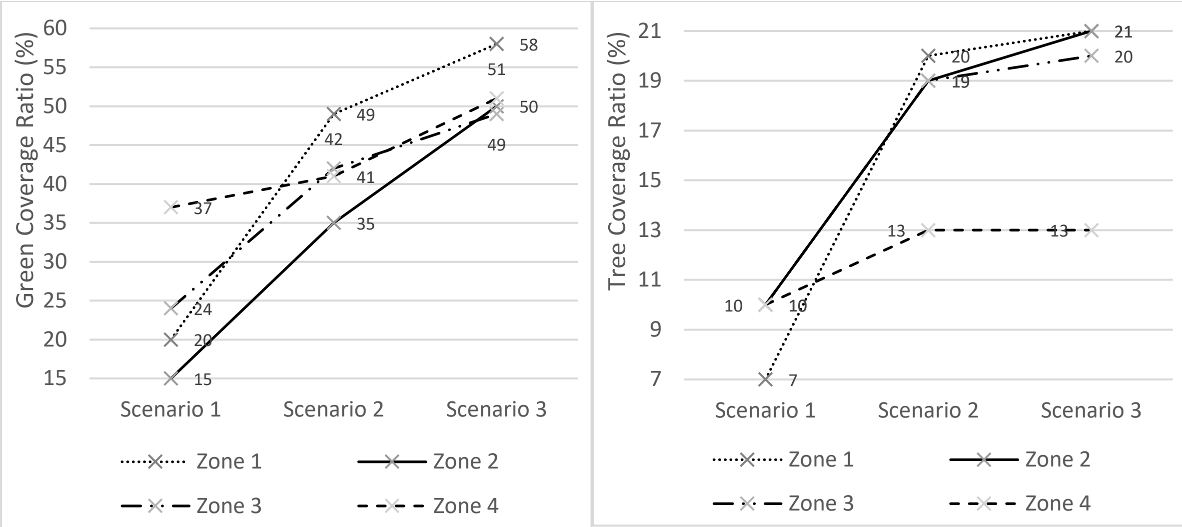


Fig.6.9. The trend of GCR (left) and TCR (right) coverage ratios between zonings for the open area only.

6.3.2 Microclimate Aspect

a. <u>Air Temperature</u>

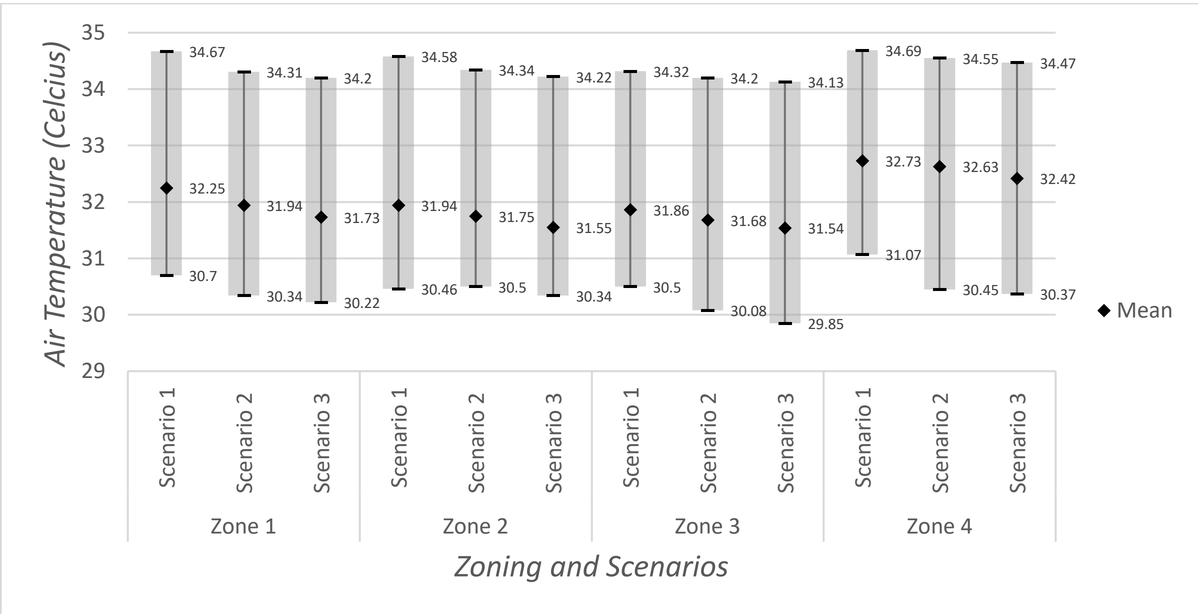


Fig.6.10. The means and the ranges of air temperature between zonings and their scenarios (Table refer to Appendix 6.5).

Figure 6.10 showed that the air temperature range and mean have significantly dropped from Scenarios 1 to 3 in all study zones. It also found that the air temperature range and mean held in the same ranking order throughout the study: from Zone 4 (highest) to Zone 1, Zone

2 and Zone 3 (lowest). The mean indexes in Zone 4 remained at a much higher range than other zonings before and after design.

Based on the calculation in Appendix 6.5, the degree of decline was not the same on average between zonings. Zone 1 experienced the greatest decline (-0.31^{o}C in Scenario 2 and -0.52^{o}C in Scenario 3), followed by Zone 2 (-0.19^{o}C in Scenario 2 and -0.39^{o}C in Scenario 3) and Zone 3 (-0.18^{o}C in Scenario 2 and -0.32^{o}C in Scenario 3). Whereas Zone 4 had the smallest changes between scenarios with only -0. 1^{o}C in Scenario 2 and -0.31^{o}C in Scenario 3. By comparing Appendix 6.5 with Table 6.1, it found that the trend and degree of air temperature decline were not correlated to GCR but responded to the degree of implementation for GCR, as summarised in Table 6.2. However, their relationship was not proportional. The non-proportional relationship was further verified in the comparison between Scenarios 2 and 3. In this case, Zone 1 had a similar GCR variance with Zone 3, but it achieved a similar air temperature variance with Zone 4, which had a relatively higher GCR variance. Also, Zones 1, 2 and 4 resulted in a similar air temperature variance with different GCR variances.

Table 6.2. The relationship between the air temperature variance and the GCR variance.

Zone	Air temperature variance between Scenarios 1 and 2 (^{o}C)	GCR variance between Scenarios 1 and 2 (%)	Air temperature variance between Scenarios 1 and 3 (^{o}C)	GCR variance between Scenarios 1 and 3 (%)	Air temperature variance between Scenarios 2 and 3 (^{o}C)	GCR variance between Scenarios 2 and 3 (%)
1	-0.31	15.97	-0.52	21.14	-0.21	5.17
2	-0.19	11	-0.39	19.28	-0.2	8.28
3	-0.18	10.28	-0.32	14.05	-0.14	3.77
4	-0.1	2.61	-0.31	10.31	-0.21	7.7

b. <u>Surface Temperature</u>

Figure 6.11 showed that the change in surface temperature range was not the same between zonings before and after designs. Zones 1 and 3 had similar patterns, where the temperature range dropped significantly from Scenarios 1 to 2 to a lower degree, but then remained within the range from Scenarios 2 to 3. In Zone 2, the temperature range was continuously dropped to lower degrees from Scenarios 1 to 3. Zone 4 almost remained at a similar range of temperature between scenarios.

In contrast, the mean indexes in each zone have declined dramatically from Scenarios 1 to 3. The different degrees of decline made them resulted in different ranking order before and after design, as follows:

i. For Scenario 1, Zone 2 (highest) – Zone 4 – Zone 1 – Zone 3 (lowest)
ii. For Scenario 2, Zone 4 (highest) – Zone 2 – Zone 3 – Zone 1 (lowest)
iii. For Scenario 3, Zone 4 (highest) – Zone 3 – Zone 2 – Zone 1 (lowest)

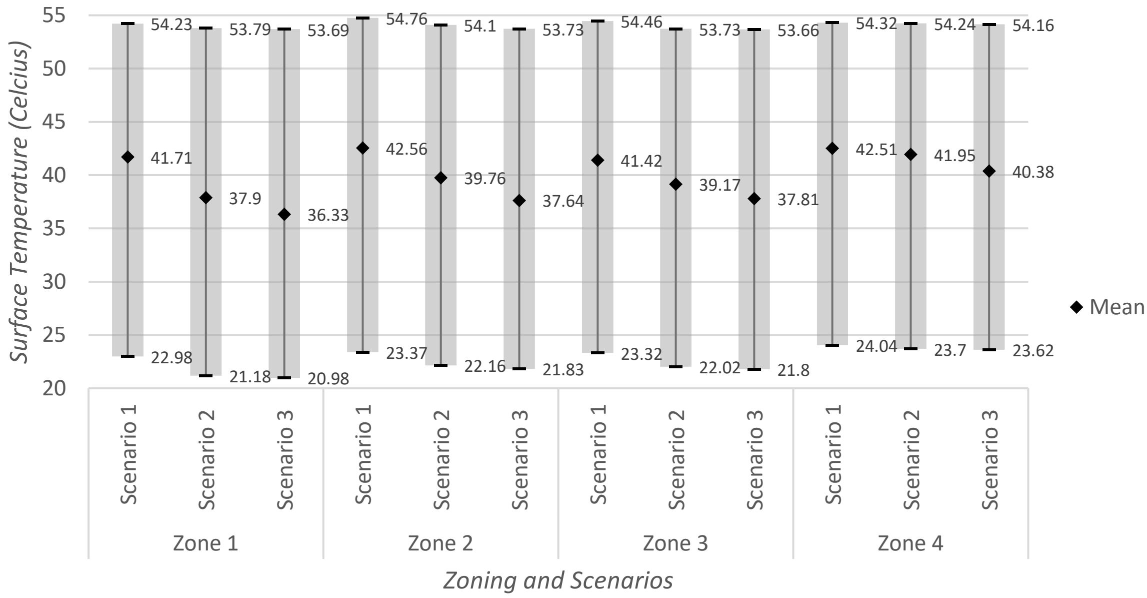


Fig.6.11. The means and the ranges of surface temperature between zonings and their scenarios (Table refer to Appendix 6.6).

Based on the calculation in Appendix 6.6, Zone 1 experienced the greatest decline (-3.81^{o}C in Scenario 2 and -5.38^{o}C in Scenario 3), followed by Zone 2 (-2.8^{o}C in Scenario 2 and -4.92^{o}C in Scenario 3) and Zone 3 (-2.25^{o}C in Scenario 2 and -3.61^{o}C in Scenario 3). Whereas Zone 4 had the smallest changes between scenarios with only -0. 56^{o}C in Scenario 2 and -2.13^{o}C in Scenario 3. Similar to air temperature, the trend and degree of surface temperature decline were also positively correlated to the degree of implementation for GCR, as summarised in Table 6.3. Also, the relationship was not proportional. The greatest GCR variance in Zone 1 made it the zone with the lowest surface temperature after design.

Lastly, compared to other microclimate parameter variances, the surface temperature variances between Scenarios 2 and 3 were the most significant. The results proved the significance of Scenario 3 in the thermal improvement of urban land surfaces.

Table 6.3. The relationship between the surface temperature variance and the GCR variance.

Zone	Surface temperature variance between Scenarios 1 and 2 (°C)	GCR variance between Scenarios 1 and 2 (%)	Surface temperature variance between Scenarios 1 and 3 (°C)	GCR variance between Scenarios 1 and 3 (%)	Surface temperature variance between Scenarios 2 and 3 (°C)	GCR variance between Scenarios 2 and 3 (%)
1	-3.81	15.97	-5.38	21.14	-1.57	5.17
2	-2.8	11	-4.92	19.28	-2.12	8.28
3	-2.25	10.28	-3.61	14.05	-1.36	3.77
4	-0.56	2.61	-2.13	10.31	-1.57	7.7

c. <u>Meant Radiant Temperature</u>

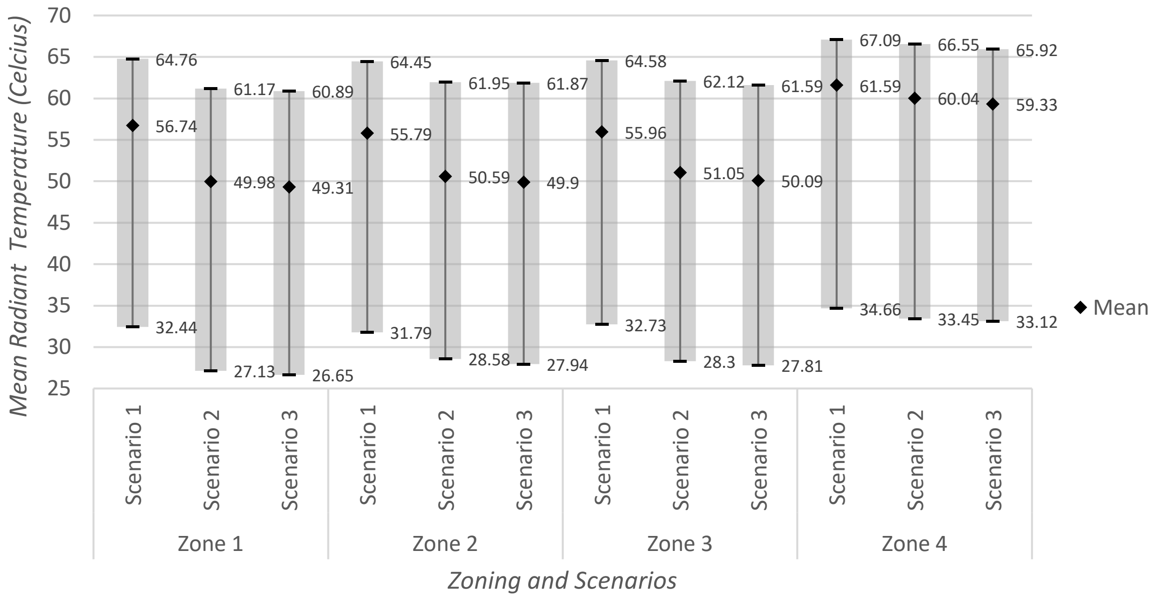


Fig.6.12. The means and the ranges of mean radiant temperature between zonings and their scenarios (Table refer to Appendix 6.7).

Figure 6.12 showed that the mean radiant temperature range changes were similar between zonings, except Zone 4. Zone 4 almost remained in the same temperature range. On the contrary, the temperature ranges in Zones 1-3 were dramatically dropped to lower degrees from Scenarios 1 to 2, but then remained in a similar range from Scenarios 2 to 3.

The same pattern of change was found in the mean index: Zone 4 almost remained at a similar mean index between scenarios. As for Zones 1- 3, the sharp drop was only found between Scenarios 1 and 2, indicating that the change of GCR from Scenarios 2 to 3 did not significantly reduce mean radiant temperature. Furthermore, Zone 4 remained at a much higher mean than other zonings before and after design, showing that the designs in Scenarios 2 and 3 were less effective for Zone 4 context as well.

Based on the calculation in Appendix 6.7, the ranking order was different before and after design, as follows:

i. For Scenario 1, Zone 4 (highest) – Zone 1 – Zone 3 – Zone 2 (lowest)
ii. For Scenario 2, Zone 4 (highest) – Zone 3 – Zone 2 – Zone 1 (lowest)
iii. For Scenario 3, Zone 4 (highest) – Zone 3 – Zone 2 – Zone 1 (lowest)

From the ranking, we can know that Zone 1 experienced the most significant decline (-6.76°C in Scenario 2 and -7.43°C in Scenario 3), followed by Zone 2 (-5.2°C in Scenario 2 and -5.89°C in Scenario 3) and Zone 3 (-4.91°C in Scenario 2 and -5.87°C in Scenario 3). Whereas Zone 4 had the smallest changes between scenarios with only -1.55°C in Scenario 2 and -2.26°C in Scenario 3.

By comparing Appendix 6.7 with Table 6.1, it found that the trend and degree of mean radiant temperature decline were still correlated to the degree of implementation for GCR, as summarised in Table 6.4. Also, the variances between the mean radiant temperature and GCR were not proportional.

Table 6.4. The relationship between the mean radiant temperature variance and the GCR variance.

Zone	Mean radiant temperature variance between Scenarios 1 and 2 (°C)	GCR variance between Scenarios 1 and 2 (%)	Mean radiant temperature variance between Scenarios 1 and 3 (°C)	GCR variance between Scenarios 1 and 3 (%)	Mean radiant temperature variance between Scenarios 2 and 3 (°C)	GCR variance between Scenarios 2 and 3 (%)
1	-6.76	15.97	-7.43	21.14	-0.67	5.17
2	-5.2	11	-5.89	19.28	-0.69	8.28
3	-4.91	10.28	-5.87	14.05	-0.96	3.77
4	-1.55	2.61	-2.26	10.31	-0.71	7.7

d. Wind Speed

Figure 6.13 showed that there were inconsistent wind speed ranges between zonings. However, they had some similarities at the same time. The minimum index remained at 0.01m/s in all models. Except for Zone 1, all maximum indexes decreased to lower degrees in Scenario 2 but then increased 0.01m/s from Scenarios 2 to 3. In Zone 1, the wind speed range never changed between scenarios, and the maximum values were maintained at the highest index (3m/s).

Overall, the wind speed range and mean stayed in the same ranking order from Scenarios 1 to 3, from Zone 4 (highest), Zone 1, Zone 3 to Zone 2(lowest). It should be noted that Zones 3 and 4 had a lower wind speed range, but instead, their mean indexes were higher than the other two zones. In particular, Zone 4 had the lowest wind speed range, but at the same time, it held the highest mean indexes, and the index degrees were relatively high compared to other zonings.

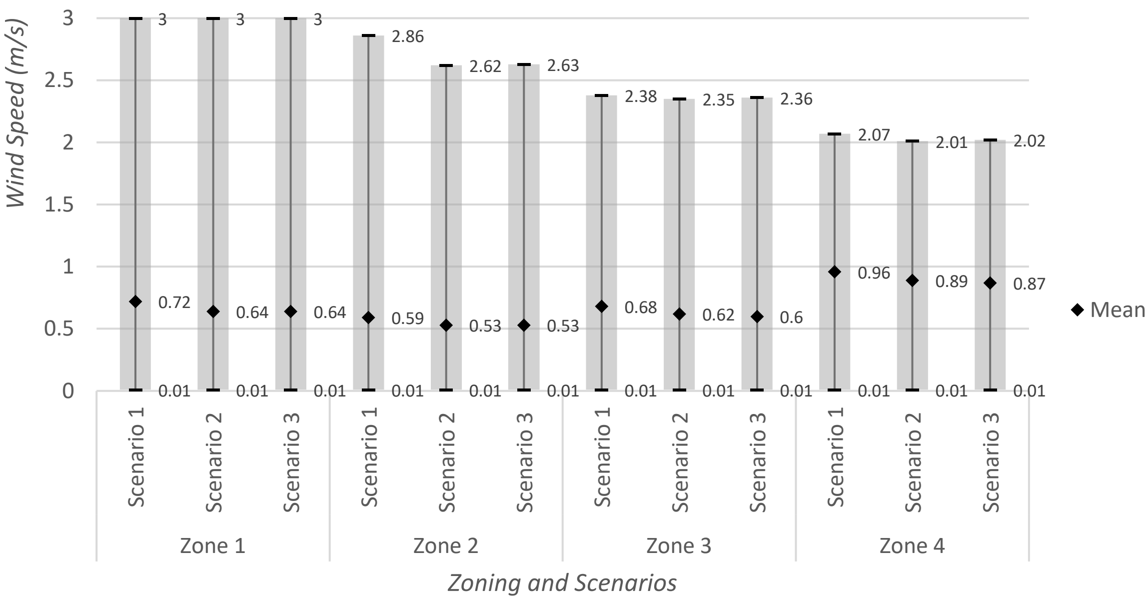


Fig.6.13. The means and the ranges of wind speed between zonings and their scenarios (Table refer to Appendix 6.8).

Based on the calculation in Appendix 6.8, Zones 1 and 2 changed differently with Zones 3 and 4 in the aspects of mean indexes. In Zones 1 and 2, mean indexes have dropped to lower degrees from Scenarios 1 to 2, but they were unchanged from Scenarios 2 to 3. As for Zones 3 and 4, mean indexes were continuously dropped to lower degrees from Scenarios 1 to 3. However, the decline degree (0.02 m/s) was too little and had no significance.

By comparing Appendix 6.8 with Table 6.1, it is found that the trend and degree of wind speed decline had no direct correlation with GCR, TCR or the degree of implementation. In this case, it implied that some other urban factors had also affected the wind speed simultaneously, including canyon depth, road size, building layout and composition, or urban layout patterns. Nevertheless, the results showed that at least Scenarios 2 and 3 did have similar effects on reducing wind speed in all zonings.

e. Relative Humidity

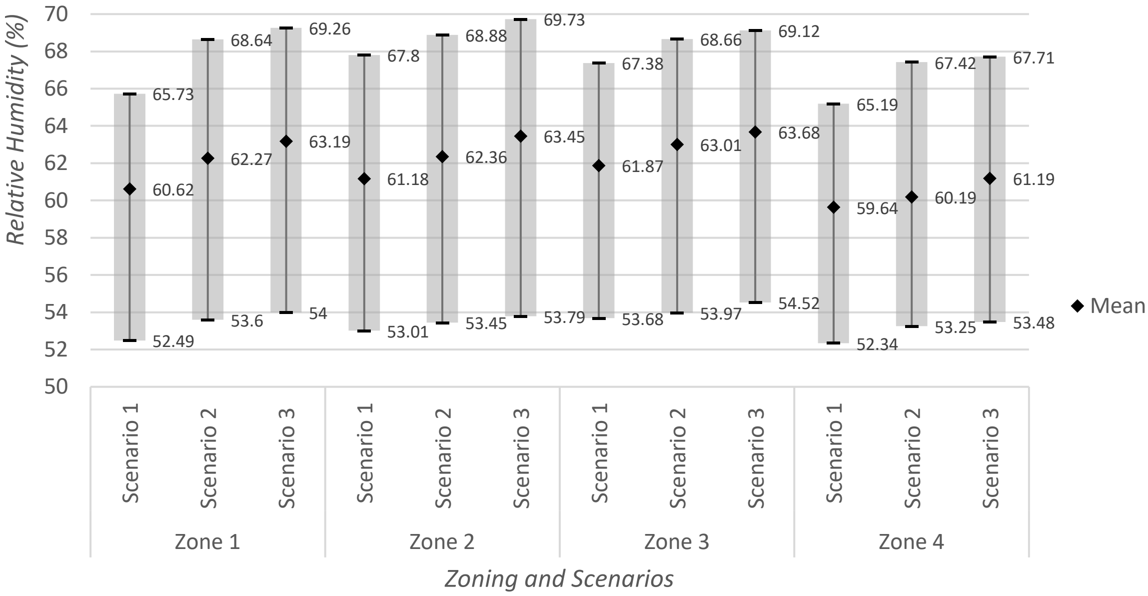


Fig.6.14. The means and the ranges of relative humidity between zonings and their scenarios (Table refer to Appendix 6.9).

Figure 6.14 showed that both relative humidity range and mean have significantly increased from Scenarios 1 to 3 in all zonings. It also found that the relative humidity stayed in the same ranking order on average throughout the study: from Zone 3 (highest) to Zone 2, Zone 1 and Zone 4 (lowest). The mean indexes in Zone 4 remained at much lower degrees than other zonings before and after design.

Table 6.5. The relationship between the relative humidity variance and the GCR variance.

Zone	Relative humidity variance between Scenarios 1 and 2 (%)	GCR variance between Scenarios 1 and 2 (%)	Relative humidity variance between Scenarios 1 and 3 (%)	GCR variance between Scenarios 1 and 3 (%)	Relative humidity variance between Scenarios 2 and 3 (%)	GCR variance between Scenarios 2 and 3 (%)
1	1.65	15.97	2.57	21.14	0.92	5.17
2	1.18	11	2.27	19.28	1.09	8.28
3	1.14	10.28	1.81	14.05	0.67	3.77
4	0.55	2.61	1.55	10.31	1	7.7

Based on the calculation in Appendix 6.9, Zone 1 experienced the greatest improvement (1.65% in Scenario 2 and 2.57% in Scenario 3), followed by Zone 2 (1.18% in Scenario 2 and 2.27% in Scenario 3) and Zone 3 (1.14% in Scenario 2 and 1.81% in Scenario 3).

Whereas Zone 4 had the smallest changes between scenarios with only (0.55% in Scenario 2 and 1.55% in Scenario 3). Similar to air temperature, it found that the trend and degree of relative humidity decline were correlated to the degree of implementation for GCR, as summarised in Table 6.5. Also, their relationship was not proportional.

Lastly, the distribution patterns of microclimate parameters were as shown in Figures 6.15 - 6.19. These figures have helped verify and enhance the findings presented in Parts (a) to (e) of this section. For example:

- Figure 6.15 showed that Zone 4 was indeed much hotter and less improved than the other three zones from Scenarios 1 to 3, in line with the air temperature range and the mean pattern shown in Figure 6.10.
- Figure 6.16 showed that all zonings had considerable thermal colour changes from Scenarios 1 to 3, except Zone 4. It also reflected the significant gap in GCR and surface temperature variances between Zone 4 and other zonings, as shown in Table 6.3.
- Figure 6.17 has illustrated the remarkable cooling between Scenarios 1 and 2 and the unchanged condition from Scenarios 2 to 3 in Zones 1-3. At the same time, it also showed a relatively low improvement in Zone 4 compared to others. They were as discussed in Part (c).
- Figure 6.18 showed that each zone performed different wind patterns, proving that wind speeds were strongly manipulated by both landscape and non-landscapes elements in the site, especially buildings. However, they all showed a decreasing trend from Scenarios 1 to 2 and an insignificant change between Scenarios 2 and 3.
- Figure 6.19 showed a remarkable improvement of relative humidity from Scenarios 1 to 3 in all zoning. It also highlighted the importance of green coverage in increasing the relative humidity level in open spaces.

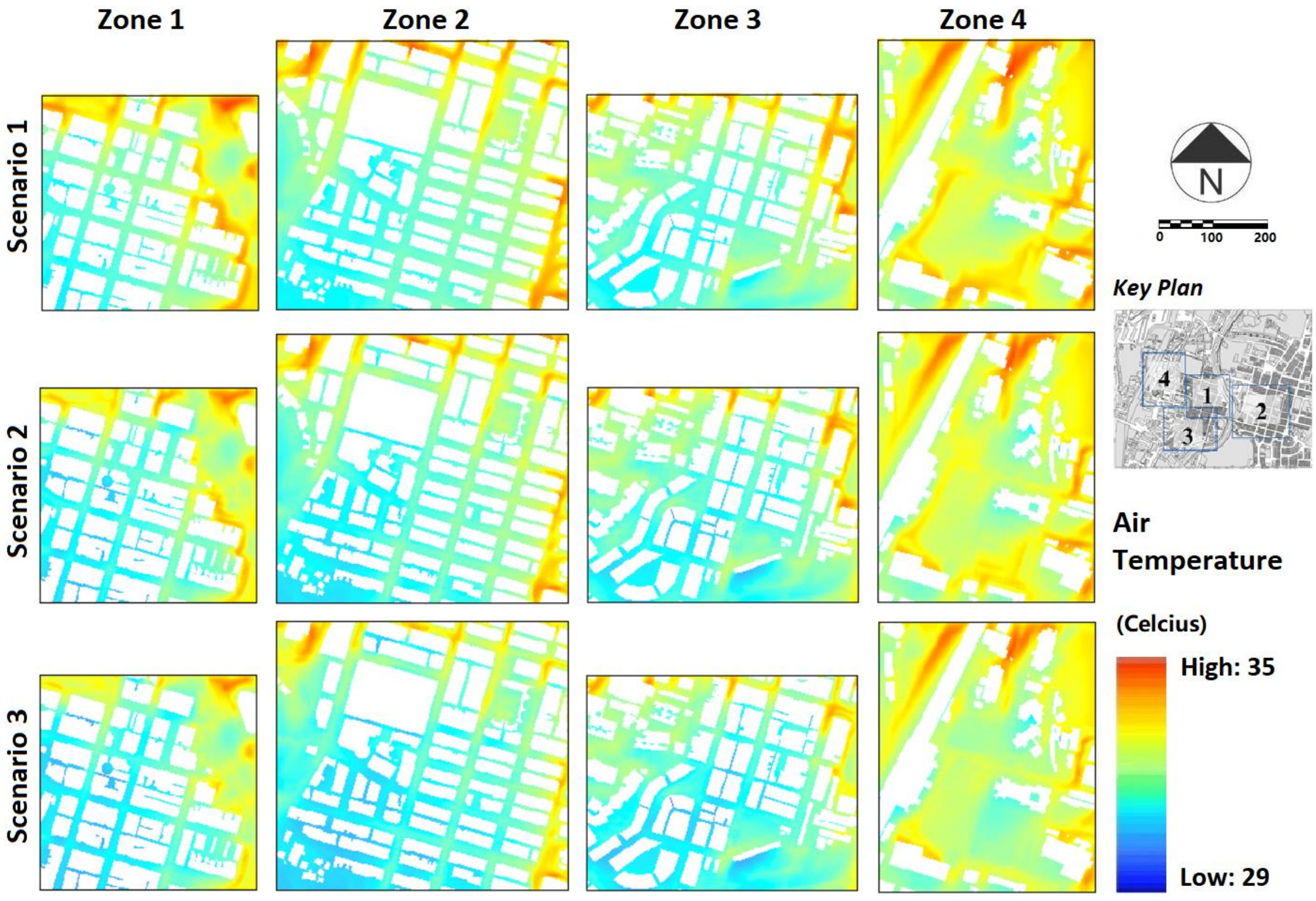


Fig. 6.15. Air temperature distribution between scenarios and zonings.

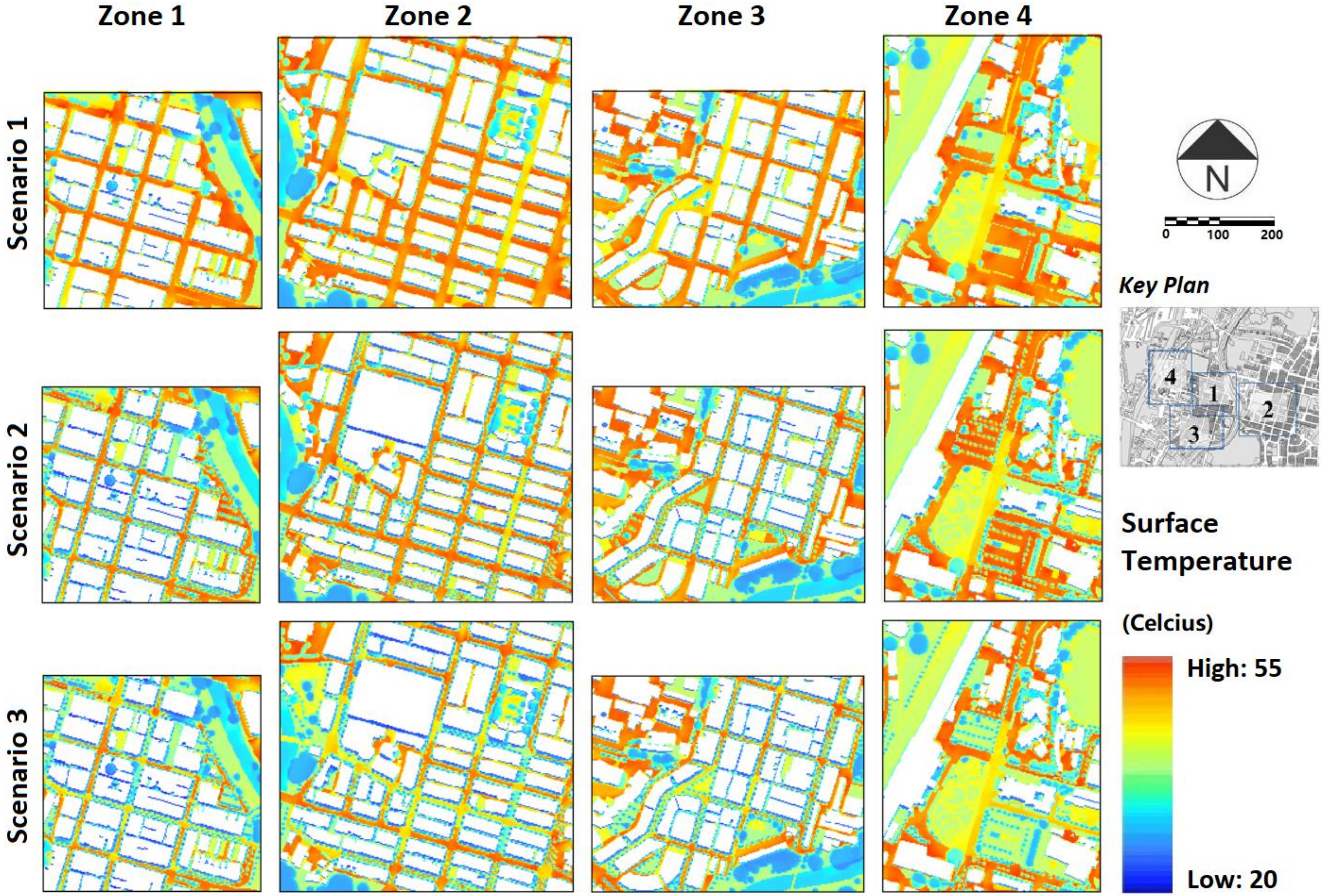


Fig. 6.16. Surface temperature distribution between scenarios and zonings.

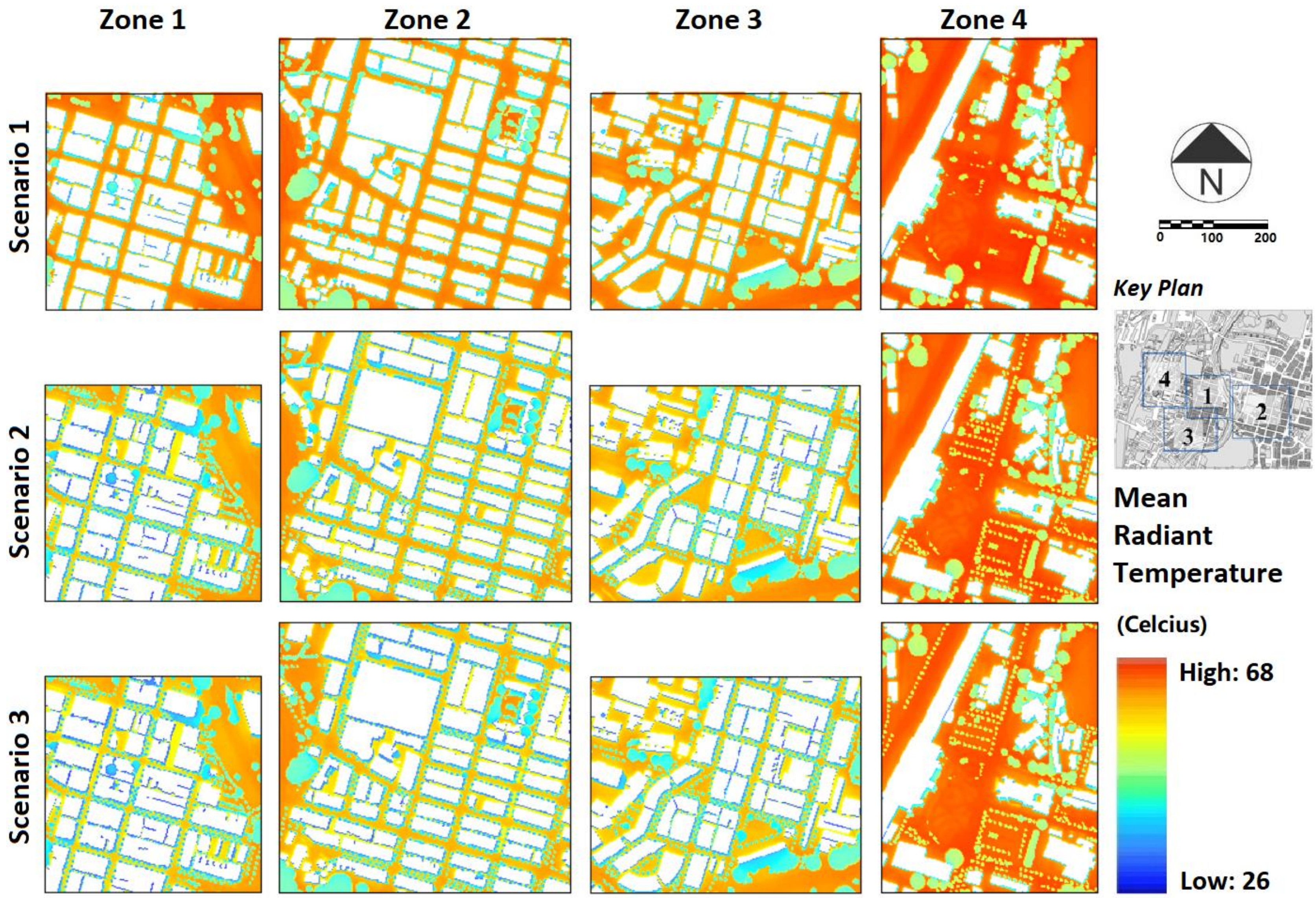


Fig. 6.17. Mean radiant temperature distribution between scenarios and zonings.

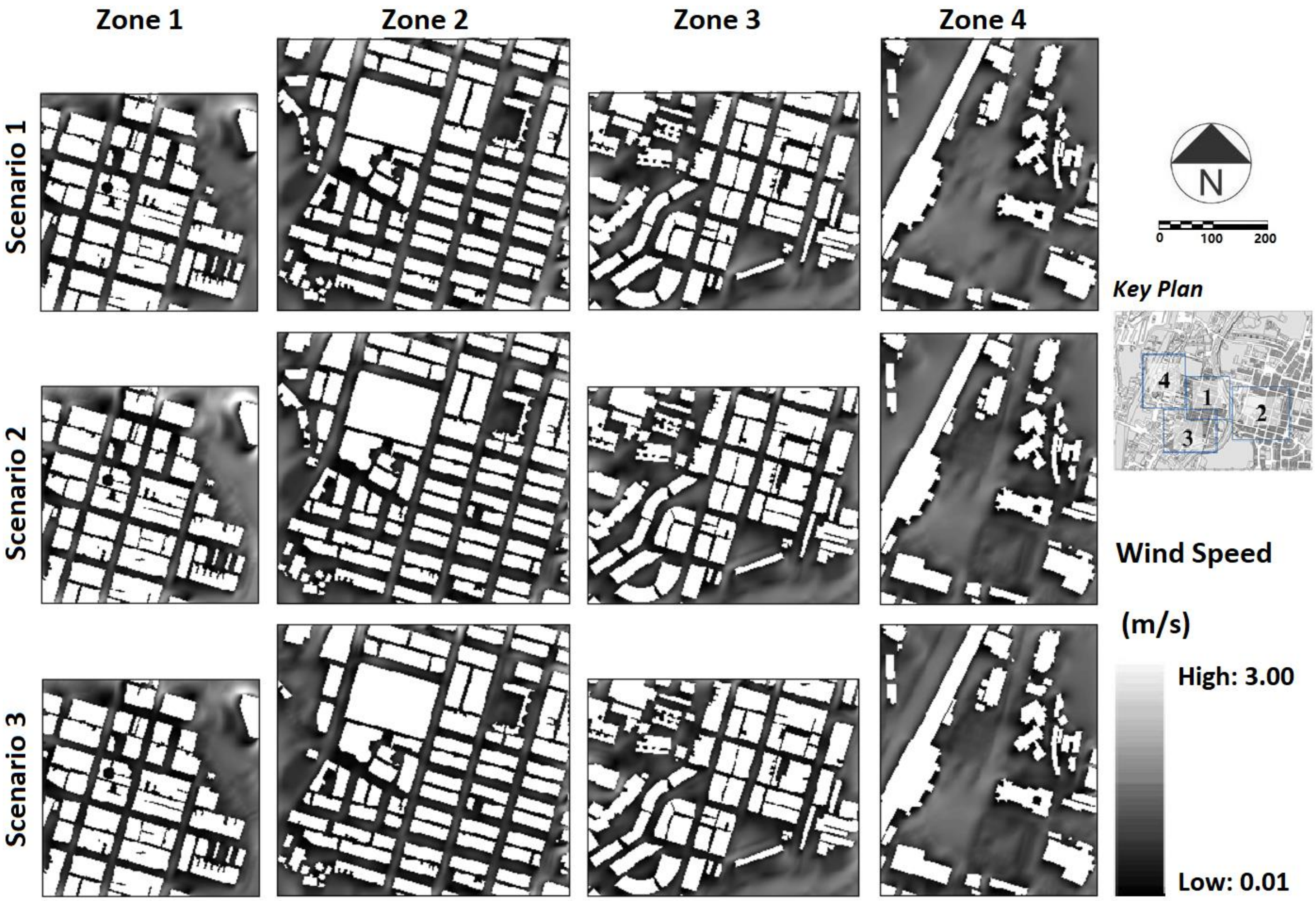


Fig. 6.18. Winds speed distribution between scenarios and zonings.

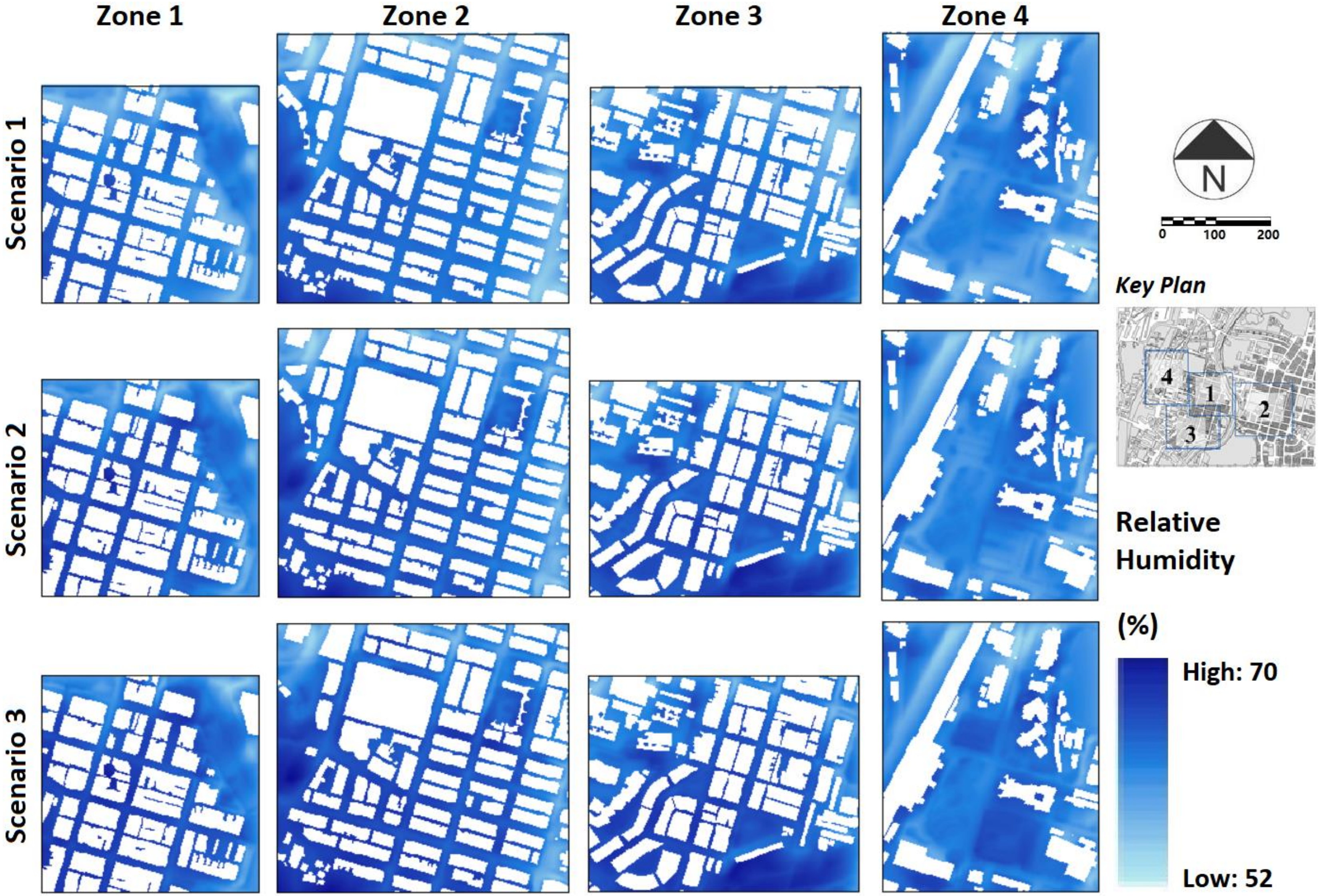


Fig. 6.19. Relative humidity distribution between scenarios and zonings.

6.3.3 Thermal Comfort Aspect

This section analysed and compared the zoning scenarios in terms of human thermal comfort. Overall, all zonings had similar changing patterns in physiological equivalent temperature (PET). Figures 6.20 and 6.21 showed that the PET range and mean indexes dropped significantly from Scenarios 1 to 2 but then remained within the range from Scenarios 2 to 3. However, Zone 4 remained at a much higher range and mean indexes than other zonings, becoming the only zone in 'very hot' condition (> 42°C) on average after design. For other zonings, the PET was averagely reduced from > 42°C to ≤ 42 °C, improving from 'very hot' condition to 'hot' condition.

It also found that the different degrees of decline made PET resulted in different ranking orders before and after design, as follows:

i. For Scenario 1, Zone 4 (highest) – Zone 1 – Zone 2 – Zone 3 (lowest)
ii. For Scenario 2, Zone 4 (highest) – Zone 2 – Zone 3 – Zone 1 (lowest)
iii. For Scenario 3, Zone 4 (highest) – Zone 2 – Zone 3 – Zone 1 (lowest)

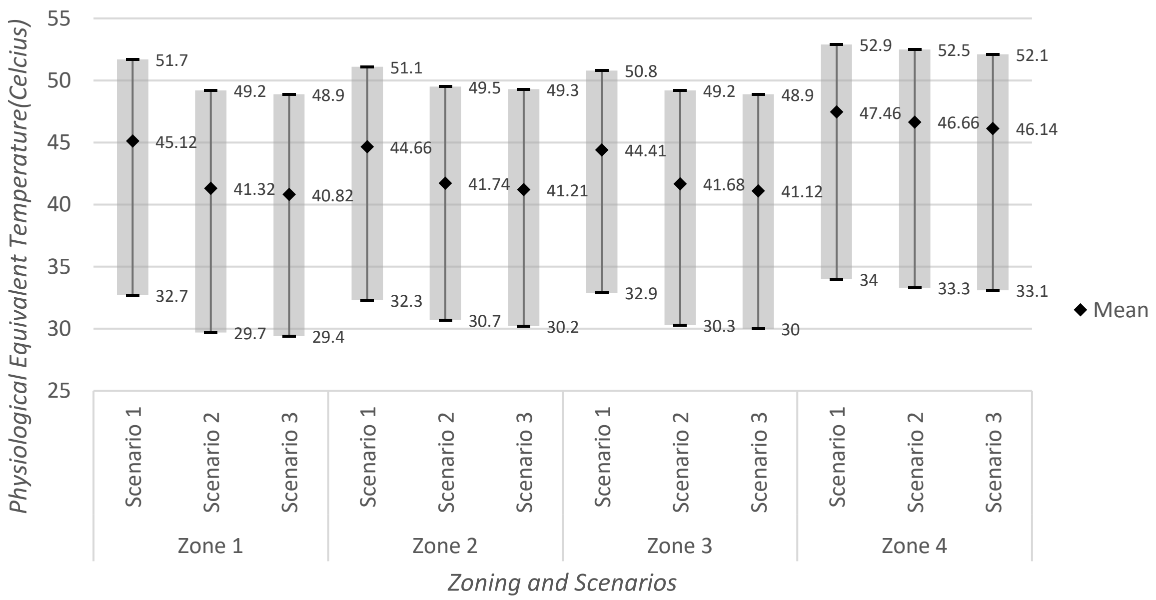


Fig.6.20. The means and the ranges of PET between zonings and their scenarios.

Based on the calculation in Appendix 6.10, Zone 1 experienced the most significant decline (-3.8°C in Scenario 2 and -4.3°C in Scenario 3), followed by Zone 2 (-2.92°C in Scenario 2 and -3.45°C in Scenario 3) and Zone 3 (-2.73°C in Scenario 2 and -3.29°C in Scenario 3). Whereas Zone 4 had the smallest changes between scenarios with only -0. 8°C in Scenario 2 and -1.32°C in Scenario 3. Similar to microclimate parameters, the trend and degree of PET decline were positively correlated to the degree of implementation for GCR, as summarised in Table 6.6. Also, the relationship was not proportional.

Table 6.6. The relationship between the PET variance and the GCR variance.

Zone	PET variance between Scenarios 1 and 2 (%)	GCR variance between Scenarios 1 and 2 (%)	PET variance between Scenarios 1 and 3 (%)	GCR variance between Scenarios 1 and 3 (%)	PET variance between Scenarios 2 and 3 (%)	GCR variance between Scenarios 2 and 3 (%)
1	-3.8	15.97	-4.3	21.14	-0.5	5.17
2	-2.92	11	-3.45	19.28	-0.53	8.28
3	-2.73	10.28	-3.29	14.05	-0.56	3.77
4	-0.8	2.61	-1.32	10.31	-0.52	7.7

Despite Figure 6.21 showing that most PET had been declined to lower degrees, Figure 6.22 indicated that the decline degree was not significant in changing the thermal comfort perception in the majority areas, except for treed areas. Figure 6.23 showed at least a one-level-decline (-1) at treed areas, up to a four-level decline (-4) at most.

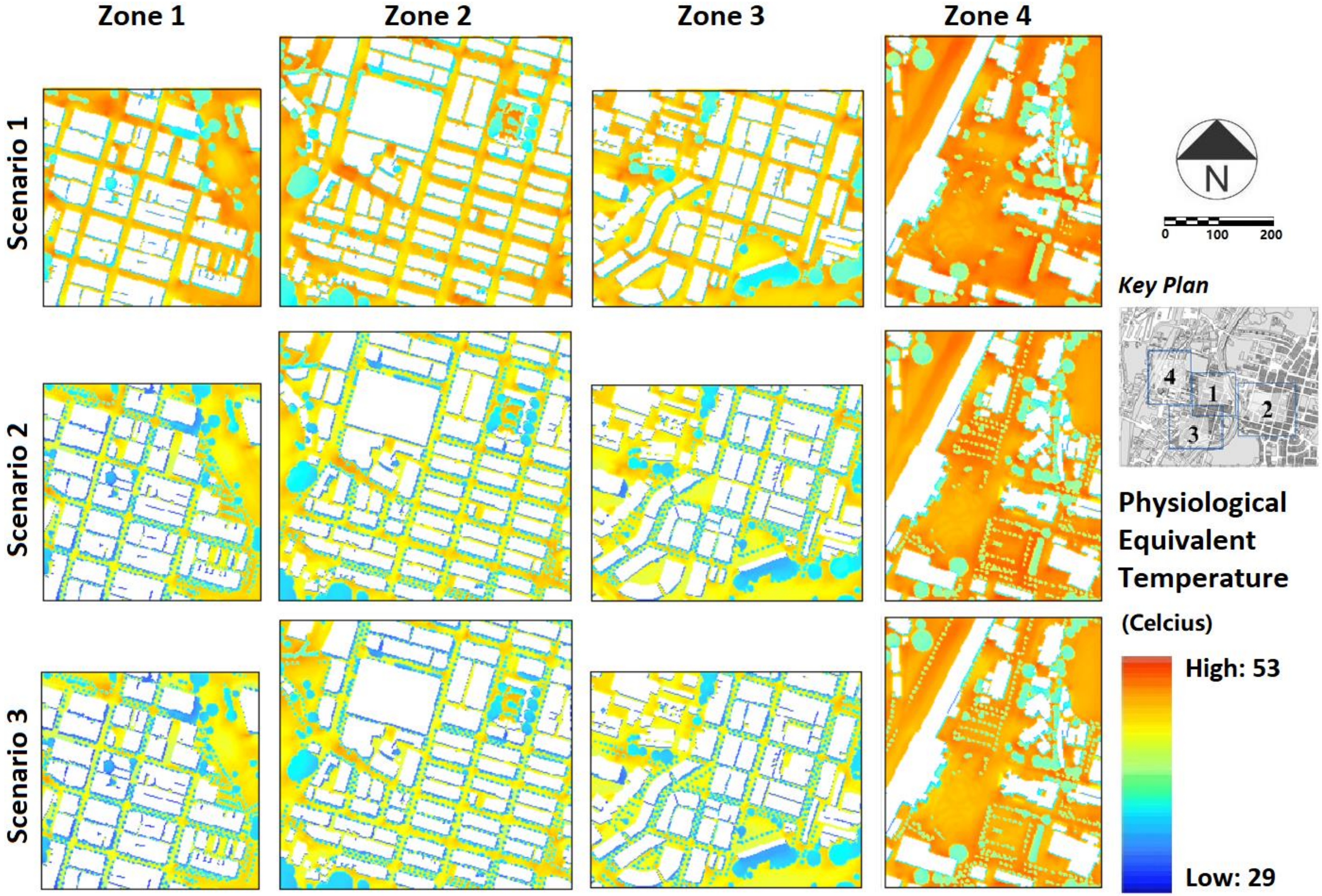


Fig. 6.21. PET distribution between scenarios and zonings.

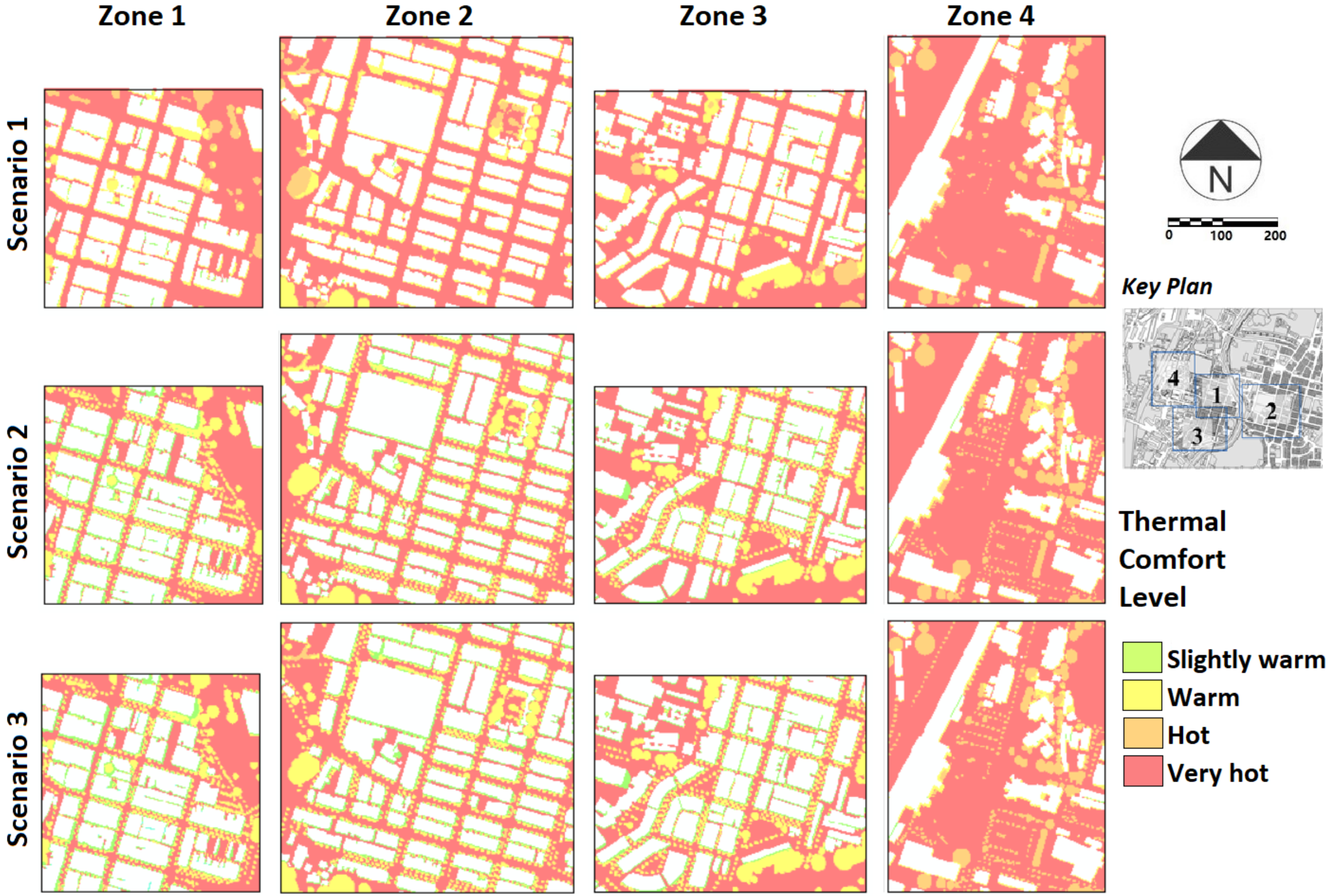


Fig. 6.22. Thermal comfort level distribution between scenarios and zonings.

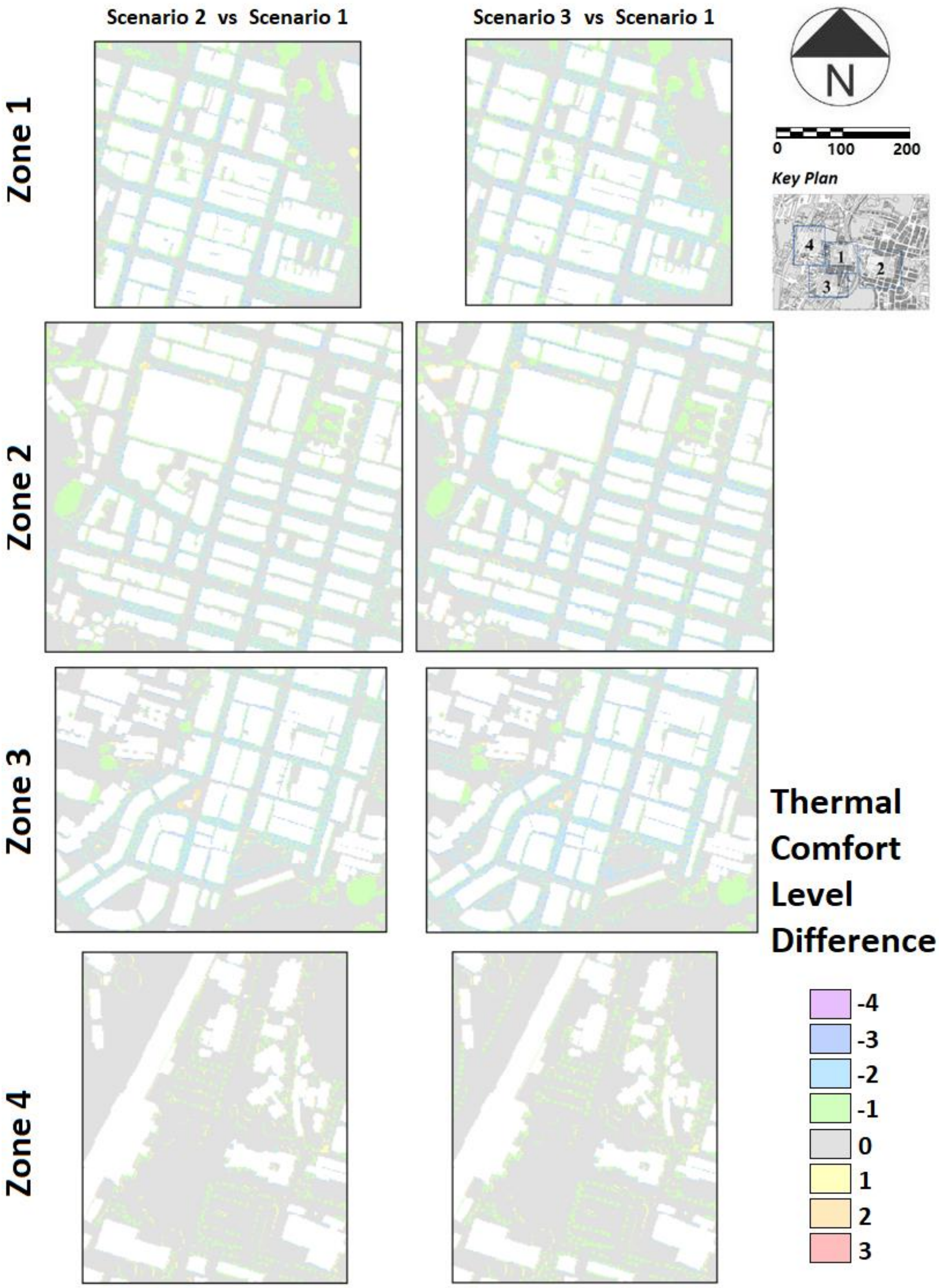


Fig. 6.23. The differences in thermal comfort level distribution between scenarios and zonings.

Lastly, to compare differences in thermal comfort before and after designs, it sorted out thermal comfort coverage ratios based on thermal comfort perceptions (ranged from neutral to very hot), as shown in Table 6.7. It could be found that, except for the 'very hot' condition, the coverage area of all other thermal comfort perceptions have increased in Zones 1- 4, which implied a cooling trend in all zoning. It can be found that Zone 1 improved the most, and it was the only zone having "neutral" conditions after design. Derived from Table 6.7, Table 6.8 compared and proved a positive correlation between GRC variances and comfort area ratio, but they were not in a proportional relationship.

Table 6.7. Thermal comfort coverage ratio between zonings and scenarios (open area only).

%	PET	Model	Scenario 1 (A)	Scenario 2 (B)	B-A	Scenario 3 (C)	C-A	C-B
COMFORT ZONE	0 (neutral)	Zone 1		0.12	0.12	0.31	0.31	0.19
		Zone 2						
		Zone 3						
		Zone 4						
	1 (slightly warm)	Zone 1	1.13	12.38	11.25	14.07	12.94	1.69
		Zone 2	0.15	9.36	9.21	12.21	12.06	2.85
		Zone 3	0.62	8.72	8.1	10.8	10.18	2.08
		Zone 4	0.17	0.34	0.17	0.45	0.28	0.11
ACCEPTABLE ZONE	2 (warm)	Zone 1	13.85	21.75	7.9	22.09	8.24	0.34
		Zone 2	18.79	23.34	4.55	23.48	4.69	0.14
		Zone 3	17.96	22.92	4.96	24.48	6.52	1.56
		Zone 4	3.12	4.09	0.97	4.7	1.58	0.61
DISCOMFORT ZONE	3 (hot)	Zone 1	6.24	7.05	0.81	6.45	0.21	-0.6
		Zone 2	5.33	6.28	0.95	6.04	0.71	-0.24
		Zone 3	4.74	6.01	1.27	5.3	0.56	-0.71
		Zone 4	11.94	14.46	2.52	15.38	3.44	0.92
	4 (very hot)	Zone 1	78.78	58.7	-20.08	57.08	-21.7	-1.62
		Zone 2	75.73	61.02	-14.71	58.27	-17.46	-2.75
		Zone 3	76.68	62.35	-14.33	59.42	-17.26	-2.93
		Zone 4	84.77	81.11	-3.66	79.47	-5.3	-1.64

Table 6.8. Summary of thermal comfort coverage ratio between zonings and scenarios.

(%)	Scenario 1	Scenario 2		Scenario 3		
	Area coverage	*Area coverage*	***Variance***	*Area coverage*	***Variance***	***Variance***
	A	*B*	***B - A***	*C*	***C - A***	***C - B***
GREEN COVERAGE RATIO VARIANCE						
Zone 1	11.13	27.1	15.97	32.27	21.14	5.17
Zone 2	7.64	18.64	11.00	26.92	19.28	8.28
Zone 3	13.71	23.99	10.28	27.76	14.05	3.77
Zone 4	27.44	30.05	2.61	37.75	10.31	7.70
COMFORT AREA RATIO						
Zone 1	0.63	7	6.37	8.05	7.42	1.05
Zone 2	0.08	4.96	4.88	6.59	6.51	1.63
Zone 3	0.35	4.97	4.62	6.16	5.81	1.19
Zone 4	0.13	0.25	0.12	0.33	0.20	0.08
ACCEPTABLE AREA RATIO						
Zone 1	7.76	12.18	4.42	12.37	4.61	0.19
Zone 2	9.96	12.37	2.41	12.68	2.72	0.31
Zone 3	10.24	13.06	2.82	13.95	3.71	0.89
Zone 4	2.31	3.03	0.72	3.48	1.17	0.45
DISCOMFORT AREA RATIO						
Zone 1	47.61	36.82	-10.79	35.58	-12.03	-1.24
Zone 2	42.96	35.67	-7.29	34.73	-8.23	-0.94
Zone 3	46.41	38.97	-7.44	36.89	-9.52	-2.08
Zone 4	71.57	70.72	-0.85	70.19	-1.38	-0.53

Note:
The calculation was based on the zoning open area coverage in overall area: 56% (zone 1), 53-54% (zone 2)*, 57% (zone 3), and 74% (zone 4). Formula = (a /100) x b, where a is the coverage ratio in Table 6.17 and b is zoning open area coverage in the overall area
*(*The increase from 53% to 54% was because of the removal of some scattered buildings in Zone 2)*

Overall, the positive trend change indicated that the design models did have a tremendous impact on improving outdoor thermal comfort. However, it found that although Zone 4 has the highest GCR, its cooling rate was extremely low compared to other zones. In view that the average PET in Zone 4 after designs remained extremely high, this chapter tried to enhance the planting scheme, as shown in the next section.

6.4 ADDITIONAL SCENARIO: ZONE 4

6.4.1 Models Building and Simulation

The additional design model, Scenario 4, was the extension model of Scenario 3. This model suggested denser tree planting. It would reduce the tree distance with the point of interest (POI), with a premise that it should remain the clear view towards POIs but in a shorter interval. It would also reduce the tree interval from 10m to 5m. Besides, the greening scheme was extended to the open compounds of institutional buildings in Zone 4. Additional tree rows were also added in the secondary road to increase the green coverage ratio maximumly. Considering the surface material's thermal properties, the model also increased the use of brick-pavers on the roads. The overall design and model layout was presented in Figure 6.24.

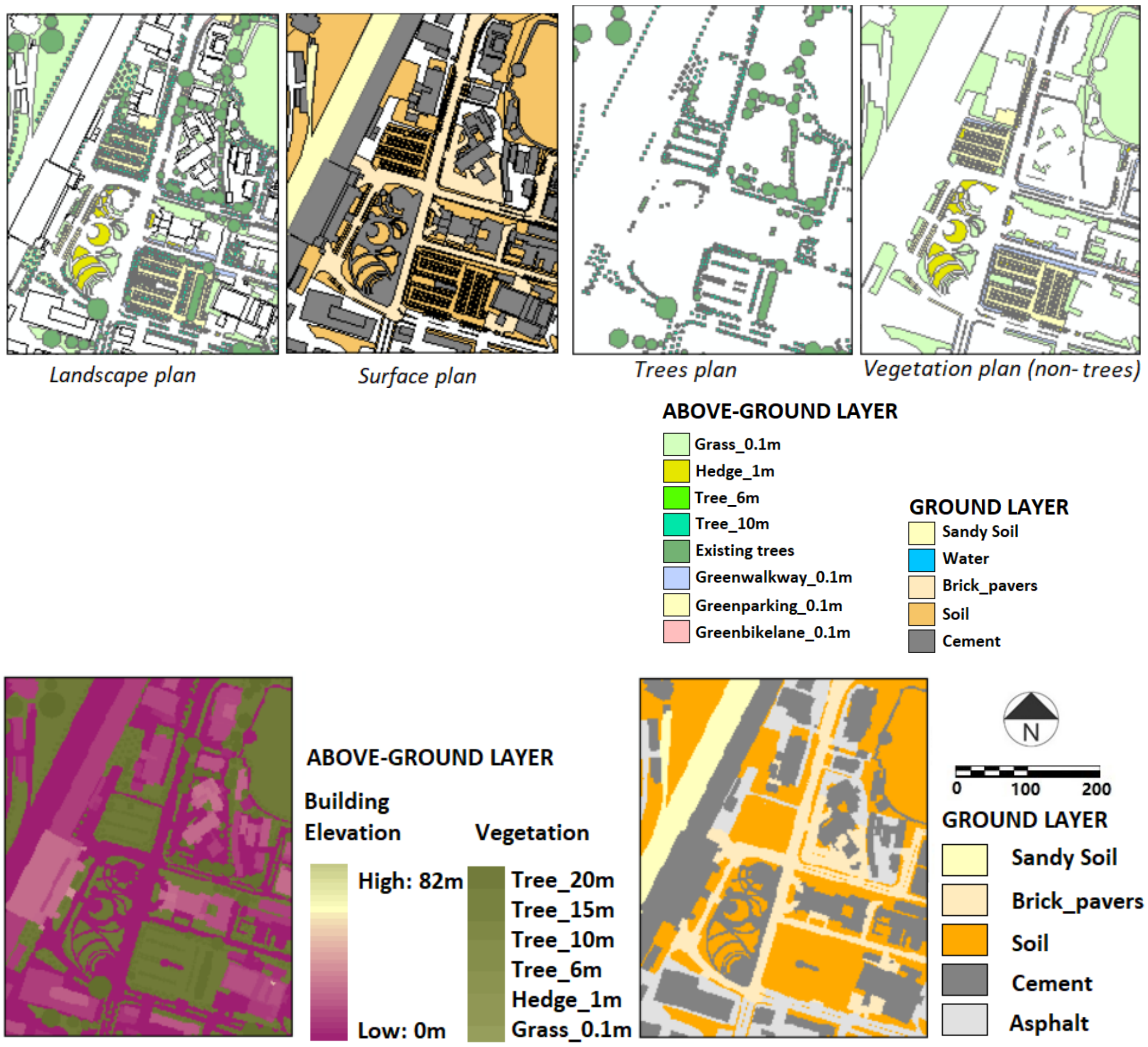


Fig.6.24. The overall plans for the additional model of Zone 4 (Scenario 4).

6.4.2 Results and Discussion

Based on Table 6.9, there was only a 1.71% increase in the additional design, reaching 39.46% of GCR in Scenario 4. However, there was a significant increase in TCR, from only 2.64% in Scenario 3 to 5.51% in Scenario 4. Considering the open area only, GCR and TCR also increased from 51.07% to 53.38% and 13.31% to 17.20%. The increase of total green coverage was still relatively low due to the nature of the site context. A large portion of open areas in Zone 4 was allocated for transportation purposes (roads and railway) and *padang* (local open field for recreational and event use), resulting in limited spaces for greening.

Table 6.9. Comparison of green and tree coverage ratio between scenarios in Zone 4.

Scenario	**1**	**3**		**4**		
	A	**C**	**C-A**	**D**	**D-A**	**D-C**
CASE I: OVERALL AREA (raster)						
Green coverage ratio (%)	27.44	37.75	10.31	39.46	12.02	1.71
Tree coverage ratio (%)	7.2	9.84	2.64	12.71	5.51	2.87
CASE II: OPEN AREA ONLY*(raster)						
Green coverage ratio (%)	37.45	51.07	13.62	53.38	15.93	2.31
Tree coverage ratio (%)	9.83	13.31	3.48	17.20	7.37	3.89

Table 6.10. Comparison of mean variances between scenarios in Zone 4.

Scenario	**1**	**3**		**4**		
Parameters	**A**	**C**	**C-A**	**D**	**D-A**	**D-C**
Air temperature (°C)	32.73	32.42	-0.31	32.21	-0.52	-0.21
Surface temperature (°C)	42.51	40.38	-2.13	39.03	-3.48	-1.35
Mean Radiant Temperature (°C)	61.59	59.33	-2.26	57.66	-3.93	-1.67
Wind Speed (m/s)	0.96	0.87	-0.09	0.81	-0.15	-0.06
Relative Humidity (%)	59.64	61.19	1.55	62.09	2.45	0.9
Physiological Equivalent Temperature (°C)	47.46	46.14	-1.32	45.19	-2.27	-0.95

Table 6.10 and Figure 6.25 showed an average positive trend in all microclimate and thermal comfort parameters from Scenarios 3 to 4. However, the degree of improvement in PET was

still relatively low, and the final PET (45.19 ^{o}C) ultimately could not change the thermal comfort perception to cooler classification.

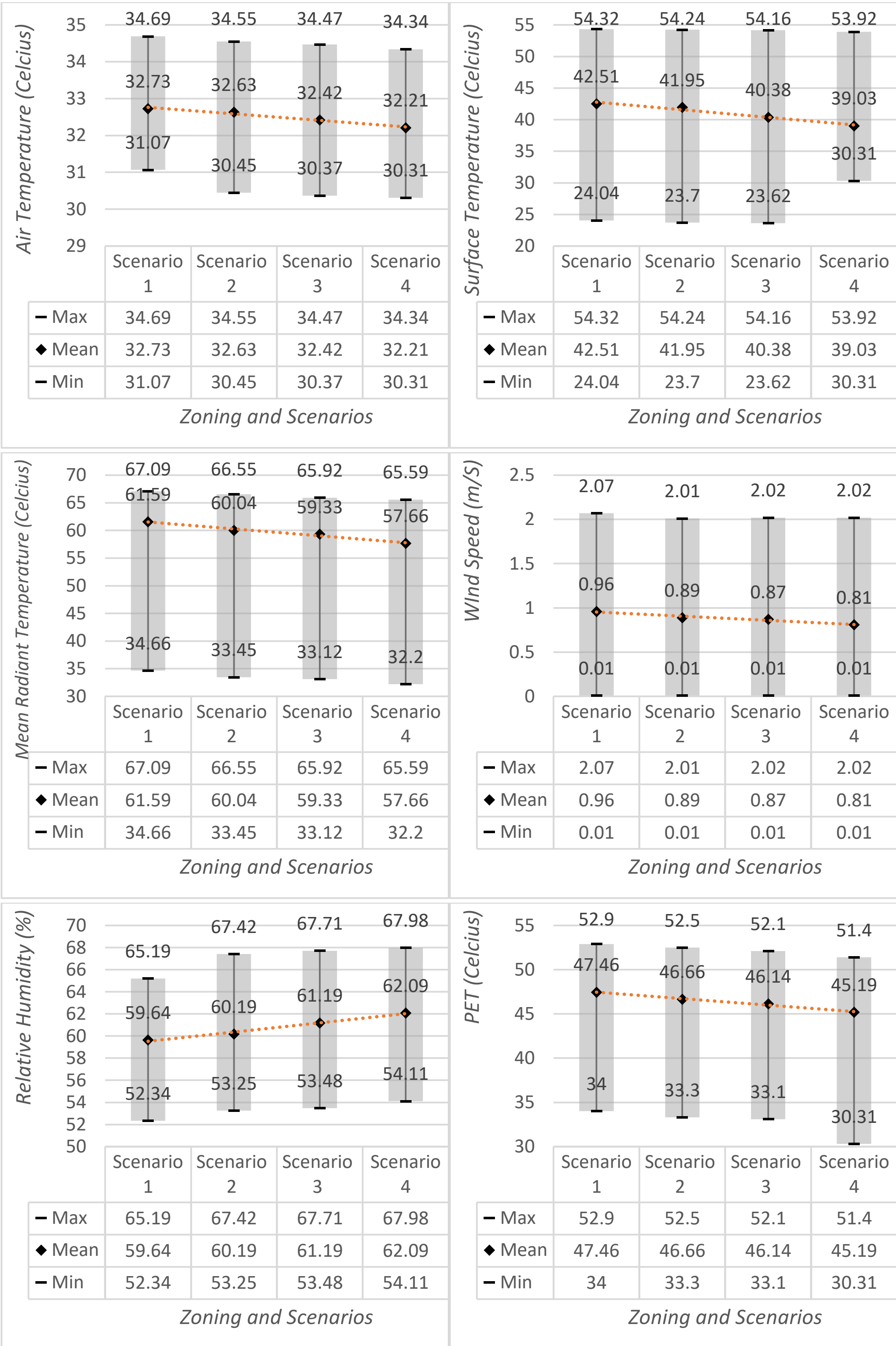


Fig. 6.25. All measured parameters distribution between scenarios in Zone 4.

Table 6.11. The relationship between the PET variance and the TCR variance.

PET variance between Scenarios 1 and 3 (°C)	TCR variance between Scenarios 1 and 3 (%)	PET variance between Scenarios 1 and 4 (°C)	TCR variance between Scenarios 1 and 4 (%)	PET variance between Scenarios 3 and 4 (°C)	TCR variance between Scenarios 3 and 4 (%)
-1.32	2.64	-2.27	5.51	-0.95	2.87

Besides, by comparing Tables 6.9 and 6.10, it found that the decline degree of PET in Zone 4 instead responded to TCR, not GCR in this case. As summarised in Table 6.11, when TCR variance increased, PET declined relatively but not proportionally. Based on the trend of PET variances in Table 6.11, it was found that Zone 4 required a much higher TCR than Scenario 4 to reduce the PET to a 'hot' condition (<42°C).

From a practice viewpoint, this case implied that it would be difficult to improve the thermal comfort in Zone 4 using TCR. Even under the assumption that there is a proportional equation correlating PET and TCR, it required at least 2.87%% in TCR variance to reduce about 0.95°C in PET (refer to Table 6.11). In this case, to change the thermal comfort perception in Zone 4, it needs to reduce about 6°C in PET, which is required about 18.13 % in TCR variance. In other words, it required a minimum of 26% in TCR to improve the average PET in Zone 4. This is not easy to be achieved in reality because the TCR so far could only reach 12.71% at most after being tested using Scenario 4. Otherwise, most open areas (the *padang*, roads and railway) had to be converted into green spaces for tree planting to achieve the target.

However, referring to Figures 6.26-6.31, Scenario 4 has significantly improved all studied temperatures, wind and relative humidity, which could immensely reduce pedestrian thermal discomfort during hot hours. The dramatic colour change showed that the cooling performance of Scenario 4 was much stronger than Scenario 3. In Figure 6.32, even though most areas still stayed in 'very hot' condition, it can be seen that the design has focused on pedestrians-active-areas to guarantee pedestrians most stayed in the cooler zone. From a pedestrian planning perspective, it can be said that Scenario 4 has already effectively ameliorated pedestrian thermal comfort in Zone 4. Therefore, Scenario 4 should be recommended for Zone 4 instead of Scenario 3.

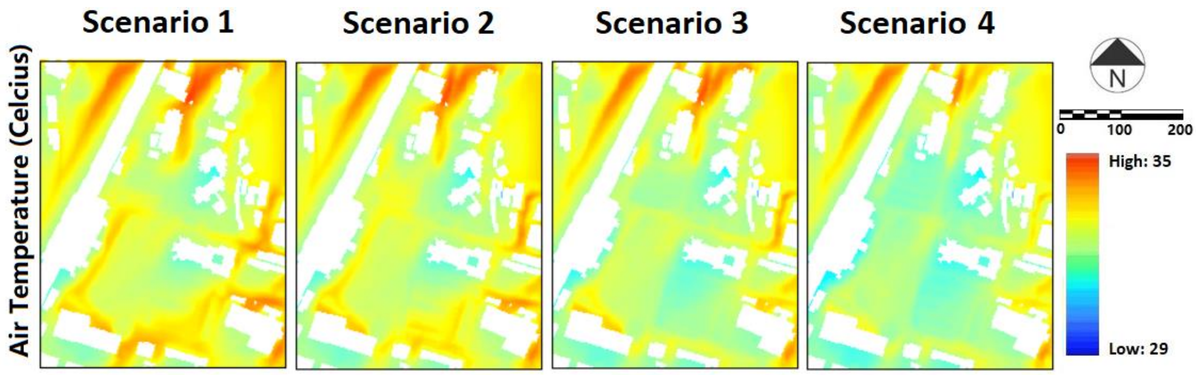


Fig. 6.26. Air temperature distribution between scenarios in Zone 4.

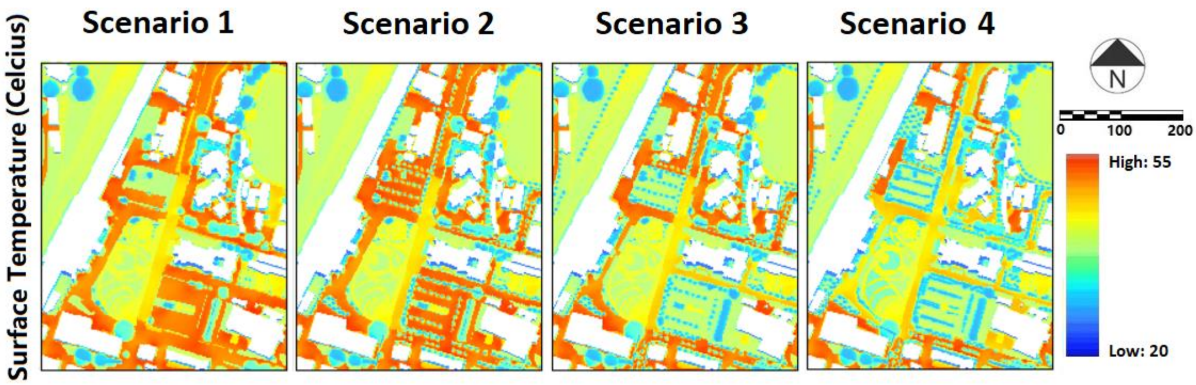


Fig. 6.27. Surface temperature distribution between scenarios in Zone 4.

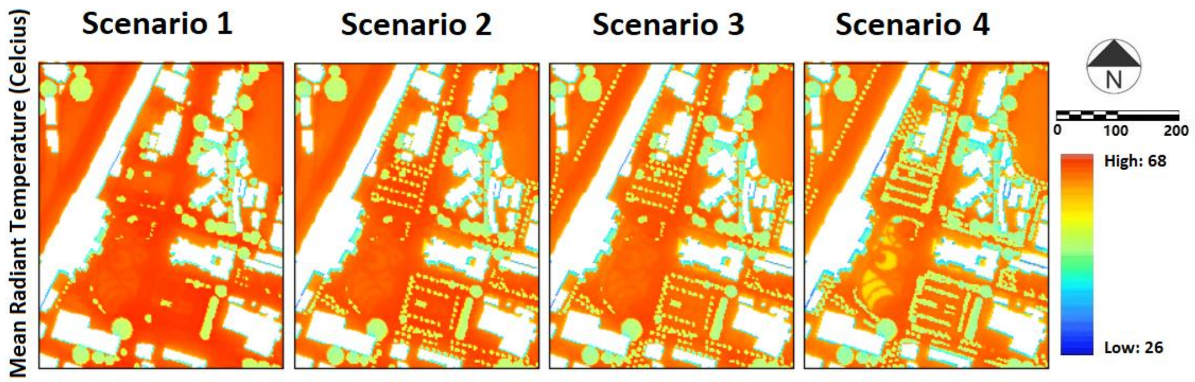


Fig. 6.28. Mean radiant temperature distribution between scenarios in Zone 4.

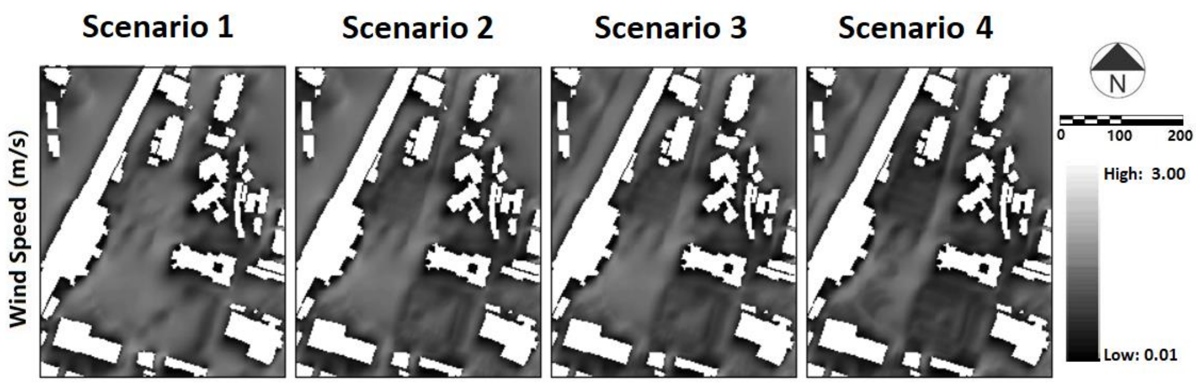


Fig. 6.29. Wind speed distribution between scenarios in Zone 4.

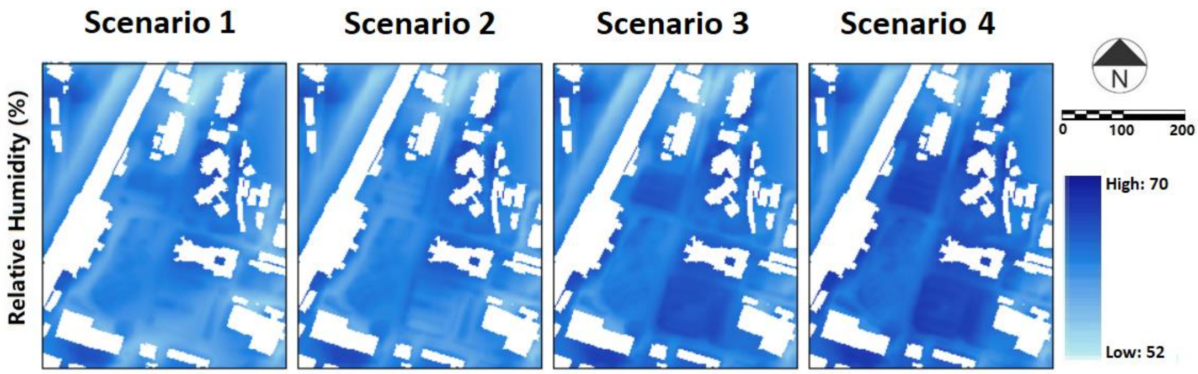


Fig. 6.30. Relative humidity distribution between scenarios in Zone 4.

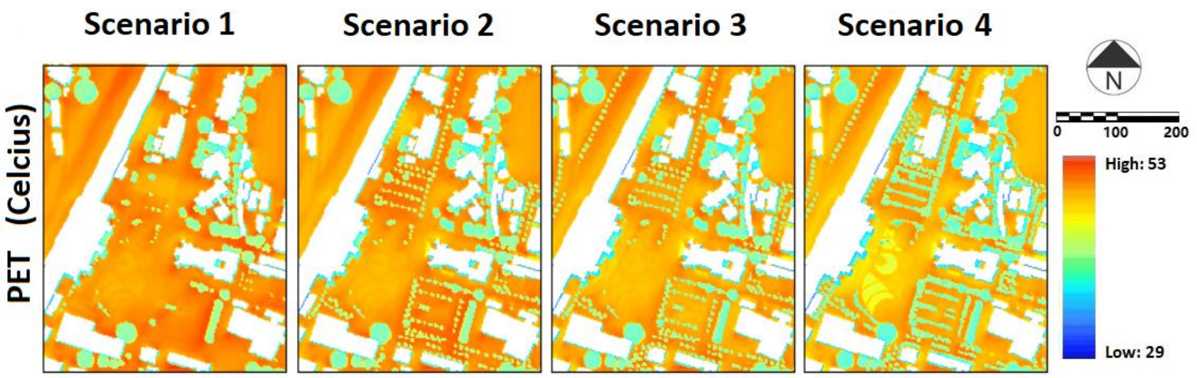


Fig. 6.31. PET distribution between scenarios in Zone 4.

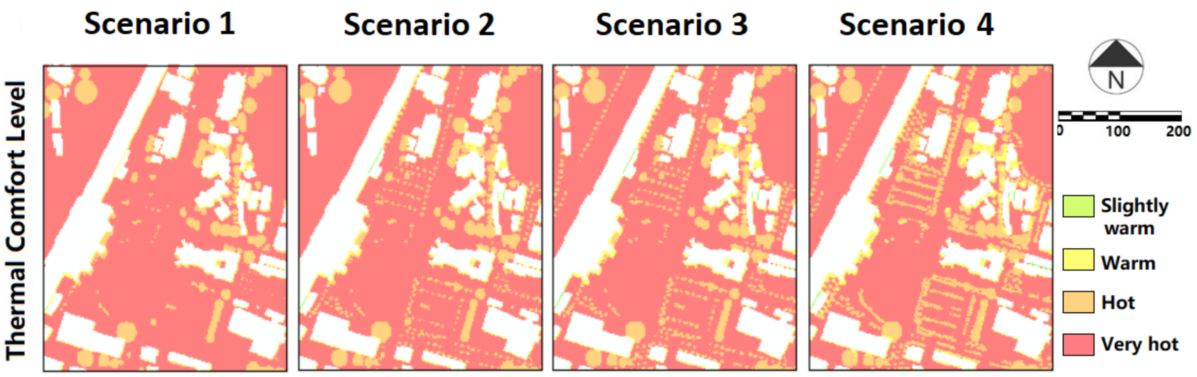


Fig. 6.32. Thermal comfort level distribution between scenarios in Zone 4.

6.5 CONCLUSION

In summary, this chapter has provided an in-depth analysis of the simulated outcomes of climate-led design and planning. There were various insights and findings through the comparisons between the zonings and scenarios, as shown in the following sections.

6.5.1 The Correlation between Climate-Led Landscape Greening, Microclimate and Thermal Comfort

The greening schemes were the core of the climate-led landscape design and planning in this research. The green coverage ratio (GCR) and the tree coverage ratio (TCR) were thereby expected to determine the greening level and the degree of impact on microclimate and thermal comfort. The measured parameter included air temperatures, surface temperatures, mean radiant temperatures, wind speed, relative humidity, PET and thermal comfort level. First, it found that the open area coverage ratio (OACR) did not affect the GCR and TCR. However, a high OACR implied a high openness on site, which has adverse effects on thermal performance and influenced the greening effectiveness as well. Given that Zone 4 remained disadvantaged overall due to its openness, it suggested that the climate-led design and studies also need to consider the ratio and composition pattern of open areas in tropical cities.

In the comparison between zonings, it also revealed that the performance of the measured parameter was highly based on the nature of zoning rather than the value indexes of GCR or TCR. Under different study contexts, the same/similar GCR/TCR would not definitely have proportional effects. Likewise, the same/similar effects could be achieved by using different GCR/TCR indexes. Also, the highest GCR did not definitely lead to the greatest improvement when compared in different zoning contexts. Zone 4 presented itself as the most appropriate portrayal in this case. Despite having a much higher GCR index than other zonings, the thermal performance of Zone 4 was not outstanding in any measured parameter evaluation, and even the worst of all. In contrast, although the GCR of Zone 2 remains the lowest, this did not place Zone 2 at the worst ranking throughout the study.

To investigate the correlation between the GCR/TCR and the measured parameter value indexes, this chapter analysed and studied the effects of delta value (Δ) of GCR/TRC between scenarios. From there, it was found that ΔGCR (also known as the degree of implementation) was always correlated to Δmeasured parameter indexes (the degree of improvement). Therefore, the degree of variance in the ΔGCR determined the degree of improvement in microclimate and thermal comfort. It even could affect the zoning ranking order before and after designs. Throughout the comparisons, it concluded that the correlation was not in a proportional relationship.

On the other hand, when comparing different scenarios within the same context, it was found that the improvement was correlated to GCR. A higher GCR always had more positive impacts on the measured parameters, resulting in a higher degree of improvement. In this case, ΔGCR was also positively correlated to the degree of improvement in a non-proportional relationship.

6.5.2 Responses to Research Questions

Based on the results, the last section answered the research questions mentioned in Section 6.1. Under the premise of using the same climate-led design strategy, all questions were responded, as follows:

a. Question 1: Do the greening, as well as the cooling magnitude, be the same between sub-models?

   No. Table 6.5 showed that the greening indexes (GCR and TCR) were uneven between zonings even under the same scenario design. The differences were because of discrepancies between the zoning context in terms of site openness, building layout and composition, road pattern and size, and landscape design.

   Also, the result presented in Sections 6.3.2 and 6.3.3 showed different cooling magnitudes between sub-models. The cooling magnitude was highly based on the nature of the zoning context. In this case, it was beyond the relationship between landscape greening, microclimate and thermal comfort.

   However, under the same zoning context, the cooling magnitude was mainly influenced by the GCR in the area. For example, the additional study on Zone 4 presented a limitation in landscape greening, and the limited greening areas directly affected the cooling magnitude. This finding also showed the limitations of applying climate-dominant concepts only in the landscape domain. For a more effective urban cooling mechanism, it suggested that the notion of climate-led designs introduced in this research should be integrated and expanded to the overall context of urban planning. At the same time, the climate-led concept and method could also be applied to the designs and decision-making in urban composition.

b. Question 2: To what extent do the sub-models perform differently?

   The performance degree was highly based on the nature of zonings. The results showed that Zone 4 were much different from the other three zonings. It always was the last in most rankings and had a big gap with others. Zones 1 – 3 were relatively similar in performance. However, in most design scenarios (Scenarios 2 and 3), Zone 1 usually came out at the top in those rankings related to temperatures. The dominance was because Zone 1 had the highest degree of implementation in Scenarios 2 and 3, and resulted in the highest degree of improvement. Therefore, despite the existing thermal conditions (Scenario 1) of Zones 2 and 3 were better than Zone 1, they lost their dominant positions at some rankings in Scenarios 2 and 3.

c. Question 3: Do all models achieve the desired climate and thermal comfort condition?

No. Despite a huge improvement in all zoning scenario models, most open areas were still under undesired microclimate and thermal comfort conditions. Nevertheless, the comfort zone has increased in Zones 1-3, and they were mostly in the pedestrian zone (refer to Table 6.18). The outcome, therefore, still complied with the study objectives.

d. Question 4: How to determine the priority of development between sub-models?

Based on the analysis, there were several ways to determine the priority of development between zonings. It could be based on four criteria, as explained in the following:

i. Based on Scenario 1: from the worse thermal comfort condition in the existing condition.

Zone 4 (the most priority) – Zone 1 – Zone 2 – Zone 3 (the least priority)

ii. Based on Scenario 2 and 3: for the best thermal comfort improvement.

Zone 1 (the most priority) – Zone 3 – Zone 2 – Zone 4 (the least priority)

iii. Based on Scenario 2 and 3: for maximum comfort area and acceptable area ratio

Zone 1 (the most priority) – Zone 3 – Zone 2 – Zone 4 (the least priority)

iv. Non-thermal consideration: based on the significances of heritage and attractions

Zone 4 (the most priority) – Zone 1 – Zone 2 – Zone 3 (the least priority)

By comparing (i) – (iv), it was found that (i) and (v) had higher significance in terms of pedestrian-oriented consideration. As a conclusion, this chapter recommended developing the zonings in the following order:

Zone 4 (the most priority) – Zone 1 – Zone 2 – Zone 3 (the least priority)

CHAPTER 7
EVALUATION OF BUFFER GREENING

7.1 INTRODUCTION

This chapter was another extension study of Chapter 5. In this research, the study model itself was the area designated for Ipoh Special Area Planning, which has been divided into two parts: the core zone and the buffer zone (Figure 7.1). The buffer zone surrounded the core area on all sides. In this case, it formed a matching experimental context for the research to study whether any landscape changes in the buffer zone would affect the microclimate and thermal comfort in the core area. In other words, it was to identify the role and significances of buffer greening in urban cooling magnitude.

In order to confirm whether buffer greening did have impacts on the target area, this chapter re-manipulated the level of greening in the core zone and the buffer zone, respectively. Continued with the scenario designs formulated in Chapter 5, the testing models were created based on the baseline and the other two design models (i.e., the basic and optimal models). Each scenario model was studied under two assumptions: with and without greening in the buffer zone. Similar to Chapter 6, the focus was mainly on the microclimate and thermal comfort comparison between scenario models. In this process, four additional scenarios were created to compare with the three master models. Lastly, all outcomes would be discussed and concluded with concern on urban expansion and deforestation.

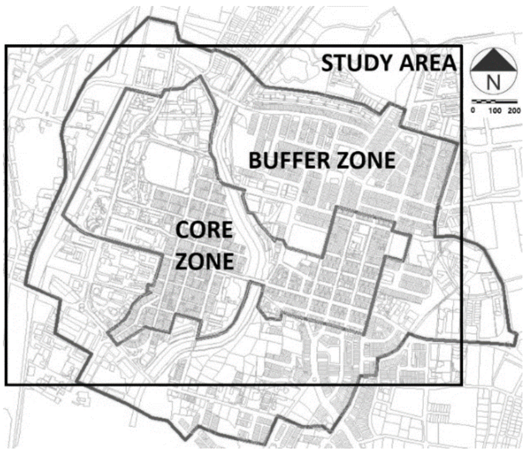


Fig.7.1. The zoning plan of Ipoh Special Area Planning.

7.2 SCENARIO MODELS BUILDING AND SIMULATION

There was a total of seven models studied in this chapter. Other than the three master models used in Chapter 5 (Scenarios 1, 3b and 4c), there was one modified by combining the baseline model and the basic model (Scenario 2), one modified from the basic model (Scenario 3a), and two modified from the optimal model (Scenarios 4a and 4b). Each scenario model adopted different design approaches in the core and buffer zones, as explained in Table 7.1. Scenarios 1, 3a and 4a were not equipped with any buffer greening, whereas Scenarios 2, 3b, 4b and 4c had either basic or optimal greening at the buffer zone.

Table 7.1. The design attributes of scenario models in Chapter 7.

Scenario	Core zone	Buffer zone
1	Baseline	Baseline
2	Baseline with the following designs: • Hedge shrub planting (same design as the basic model) • Walkway system (following the design of the basic model but using brick paving)	Basic model design
3a	Basic model design	Baseline
3b	Basic model design	Basic model design
4a	Optimal model design	Baseline
4 b	Optimal model design	Basic model design
4c	Optimal model design	Optimal model design

Note: Baseline - no design at all; Basic model design - refer to Section 5.2.2.2; Optimal model design - refer to Section 5.2.2.1.

Following the landscape design approaches shown in Table 7.1, the physical changes between scenarios could be found in the landscape design pattern, the planting densities (trees and non-trees), and the land cover, as illustrated in Figures 7.2 7.5. For simulation purposes, all models were rasterised with a grid resolution of 5m x 5m x 2.5m in dx, dy, and dz directions, respectively (Figures 7.6 - 7.7). However, different from the previous chapters, the buffer zone only acted as an off-site factor. All simulation data in the buffer zone was not included as output for measurement. In other words, in this case, only the core area output was extracted for comparison and analysis.

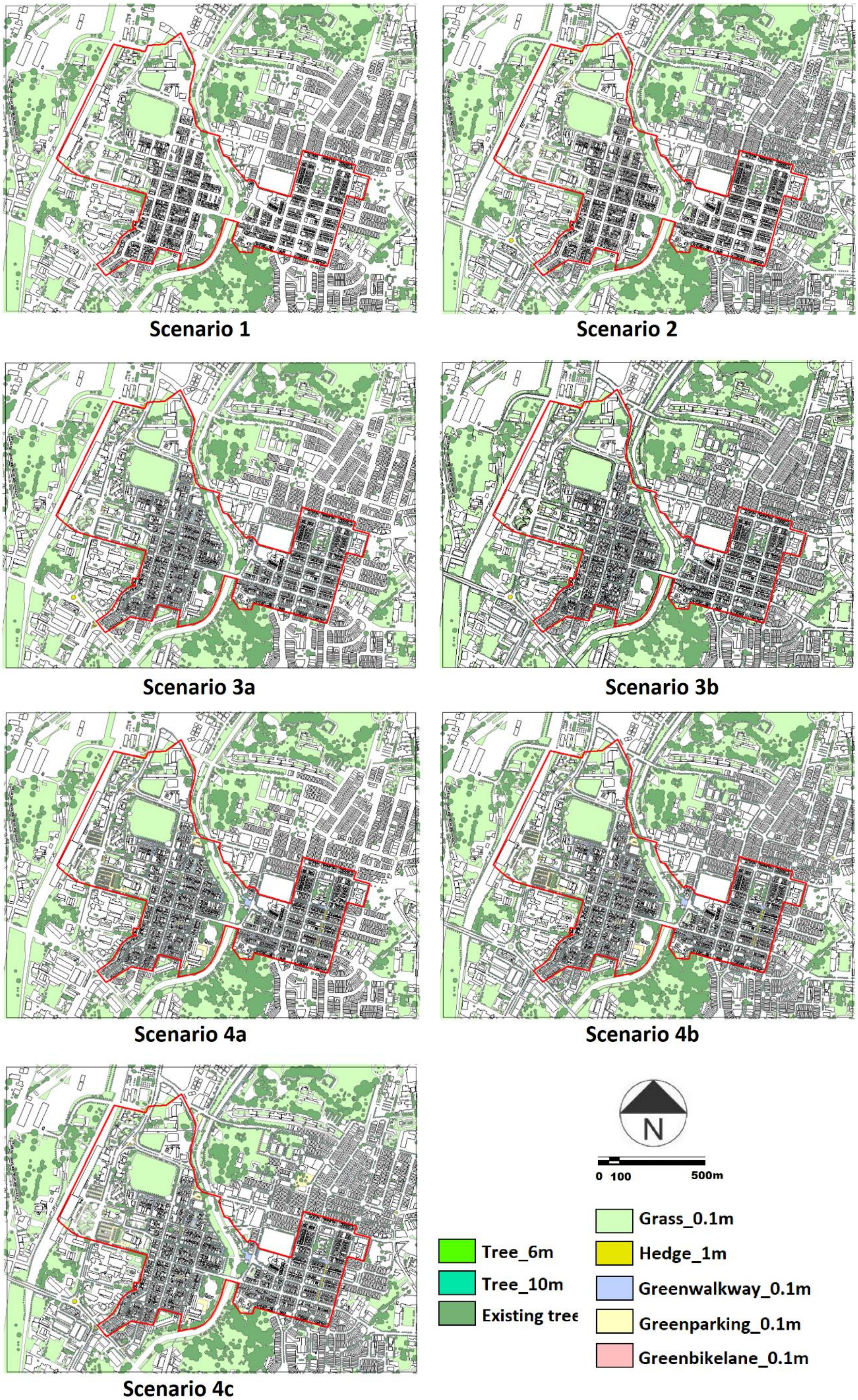


Fig.7.2. The variation in landscape plan between models.

Fig.7.3. The variation in trees density and distribution pattern between models.

Fig.7.4. The variation in vegetation (non-trees) density and distribution pattern between models.

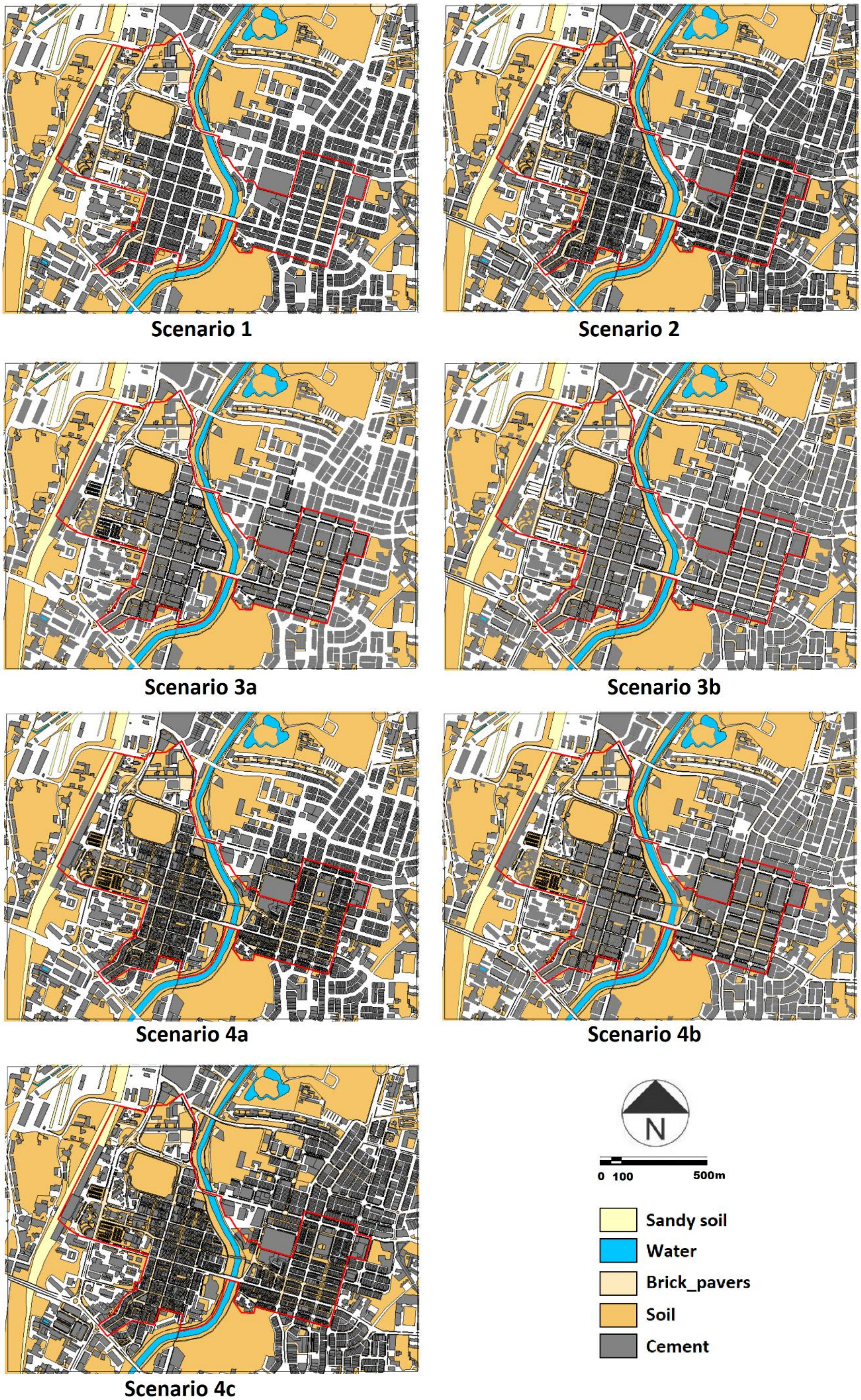


Fig.7.5. The variation in land cover between models.

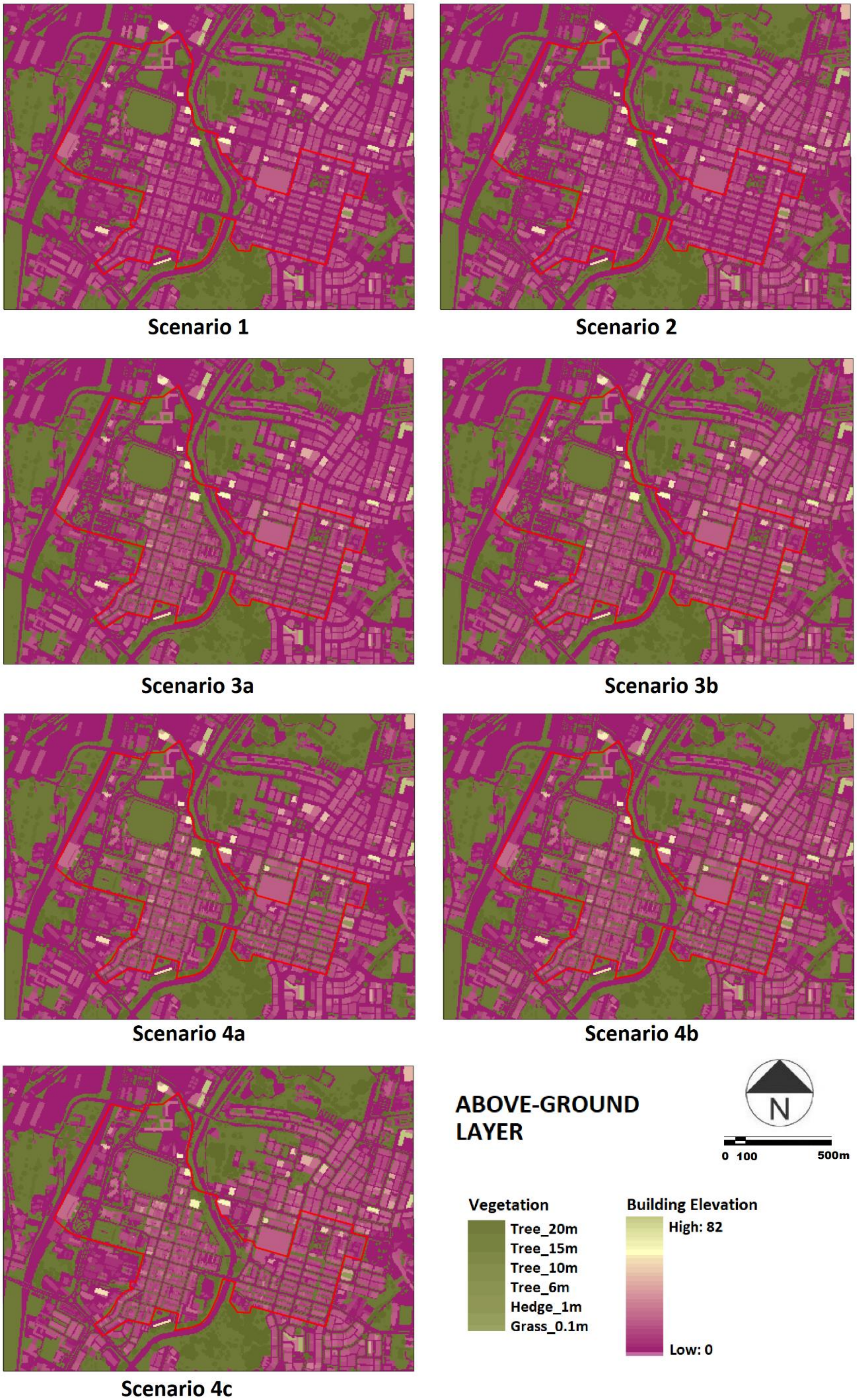


Fig.7.6. The variation in the above-ground layer (raster) between models.

Fig.7.7. The variation in the ground layer (raster) between models.

7.3 RESULTS AND DISCUSSION

From Table 7.1, it can be seen that there were multiple possible sets for comparison. To enable one-to-one and group-to-group comparisons, this section would present the variances (Δ) in mean, minimum and maximum value indexes through matrix tables for readable evaluation. The comparison included: between scenario groups (Scenarios 1, 2, 3 and 4) and within scenario group (between 1 and 2, between 3a and 3b, or between 4a, 4b and 4c).

7.3.1 Microclimate Aspect

a. Air Temperature

Air temperature resulted in a continuous decline from Scenarios 1 to 4c, as shown in Figure 7.8 and Table 7.2. The results indicated the advantage of the optimal design models (Scenarios 4) over the other models, as well as the basic design models (Scenarios 3) over the baseline-based models (Scenarios 1-2).

More importantly, the comparisons within scenario groups showed that all models with buffer greening have lower average air temperature degrees than those without buffer greening. However, a wider range of temperatures was found in those models with buffer greening. Compared with those without buffer greening, their minimum values dropped to lower degrees, but at the same time, the maximum values also have risen to higher degrees (see those positive maximum values in Table 7.2). Nevertheless, the degree of warming was relatively less than the degree of cooling. They did not affect the overall decreasing air temperature when all mean values were showed as negative numbers in the table.

Even though there were no additional trees and green paving in the core area, the mean, minimum and maximum indexes in Scenario 2 were still slightly lower than Scenario 1. By comparing them in Figure 7.13, it can be found that those open areas close to the buffer zone have improved the most. In this regard, Figure 7.3 showed a large number of trees in the corresponding buffer zone in Scenario 2. Likewise, there was a similar pattern of decline in groups of Scenarios 3 and 4. The result has clearly illustrated the effectiveness of off-site greening in cooling on-site air temperature.

In addition, the variance between Scenarios 4b and 4c was minimal, which indicated that when the core area was in the optimal design mode, the buffer zone variance in green coverage ratio (GCR) had less effect on the core area.

Table 7.2. Air temperature variance between scenarios.

AT (°C)		**Variance in maximum and minimum index (Δ_{max} & Δ_{min})**						
		1	**2**	**3a**	**3b**	**4a**	**4b**	**4c**
Variance in mean index (Δ_{mean})	**1**	0	Δ_{max}: -0.14 Δ_{min}: -0.09	Δ_{max}: -0.2 Δ_{min}: -0.23	Δ_{max}: -0.16 Δ_{min}: -0.3	Δ_{max}: -0.31 Δ_{min}: -0.28	Δ_{max}: -0.24 Δ_{min}: -0.37	Δ_{max}: -0.24 Δ_{min}: -0.39
	2	-0.08	0	Δ_{max}: -0.06 Δ_{min}: -0.14	Δ_{max}: -0.02 Δ_{min}: -0.21	Δ_{max}: -0.11 Δ_{min}: -0.05	Δ_{max}: -0.04 Δ_{min}: -0.14	Δ_{max}: -0.1 Δ_{min}: -0.3
	3a	-0.15	-0.07	0	Δ_{max}: 0.04 Δ_{min}: -0.07	Δ_{max}: -0.11 Δ_{min}: -0.05	Δ_{max}: -0.04 Δ_{min}: -0.14	Δ_{max}: -0.04 Δ_{min}: -0.16
	3b	-0.21	-0.13	-0.06	0	Δ_{max}: -0.15 Δ_{min}: 0.02	Δ_{max}: -0.08 Δ_{min}: -0.07	Δ_{max}: -0.08 Δ_{min}: -0.09
	4a	-0.26	-0.11	-0.11	-0.15		Δ_{max}: 0.07 Δ_{min}: -0.09	Δ_{max}: 0.07 Δ_{min}: -0.11
	4b	-0.33	-0.18	-0.18	-0.12	-0.07	0	Δ_{max}: 0 Δ_{min}: -0.02
	4c	-0.34	-0.26	-0.19	-0.13	-0.08	-0.01	0

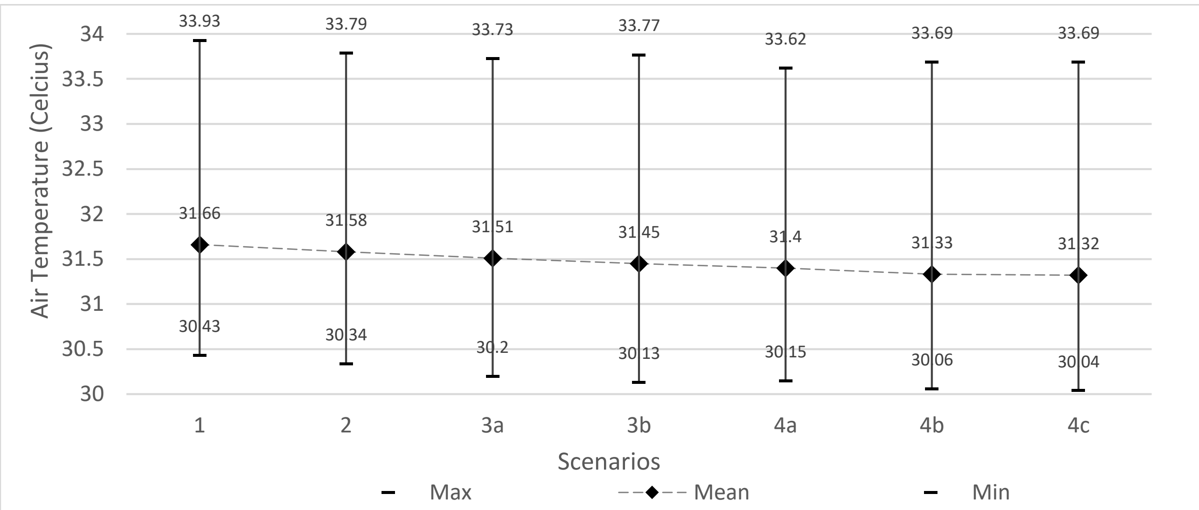


Fig.7.8. Air temperature trend between scenarios.

b. Surface Temperature

The average surface temperature continued to decrease from Scenarios 1 to 4c, as shown in Figure 7.9 and Table 7.3. However, the reduction in the temperature range was relatively small, keeping it between 22-54°C. Despite that, variances between scenario groups (1°C and above) were larger than variances within the same scenario group (less than 0.15°C). The results indicated that surface temperatures were more affected by the on-site land cover instead of off-site greening. Figure 7.14 also showed that the major changes in surface temperature mainly occurred at the parts where have been modified on-site. There was no significant indication to show that the decline related to off-site buffer greening.

Table 7.3. Surface temperature variance between scenarios.

ST (°C)		**Variance in maximum and minimum index (Δ_{max} & Δ_{min})**						
		1	**2**	**3a**	**3b**	**4a**	**4b**	**4c**
Variance in mean index (Δ_{mean})	**1**	0	Δ_{max}: -0.19 Δ_{min}: -0.49	Δ_{max}: -0.3 Δ_{min}: -0.53	Δ_{max}: -0.45 Δ_{min}: -0.77	Δ_{max}: -0.33 Δ_{min}: -0.58	Δ_{max}: -0.51 Δ_{min}: -0.96	Δ_{max}: -0.52 Δ_{min}: -0.98
	2	-0.49	0	Δ_{max}: -0.11 Δ_{min}: -0.04	Δ_{max}: -0.26 Δ_{min}: -0.28	Δ_{max}: -0.03 Δ_{min}: -0.05	Δ_{max}: -0.21 Δ_{min}: -0.43	Δ_{max}: -0.33 Δ_{min}: -0.49
	3a	-2.14	-1.65	0	Δ_{max}: -0.15 Δ_{min}: -0.24	Δ_{max}: -0.03 Δ_{min}: -0.05	Δ_{max}: -0.21 Δ_{min}: -0.43	Δ_{max}: -0.22 Δ_{min}: -0.45
	3b	-2.27	-1.78	-0.13		Δ_{max}: 0.12 Δ_{min}: 0.19	Δ_{max}: -0.06 Δ_{min}: -0.19	Δ_{max}: -0.07 Δ_{min}: -0.21
	4a	-3.62	-1.48	-1.48	-1.35		Δ_{max}: -0.18 Δ_{min}: -0.38	Δ_{max}: -0.19 Δ_{min}: -0.4
	4b	-3.66	-1.52	-1.52	-1.39	-0.04		Δ_{max}: -0.01 Δ_{min}: -0.02
	4c	-3.67	-3.18	-1.53	-1.4	-0.05	-0.01	0

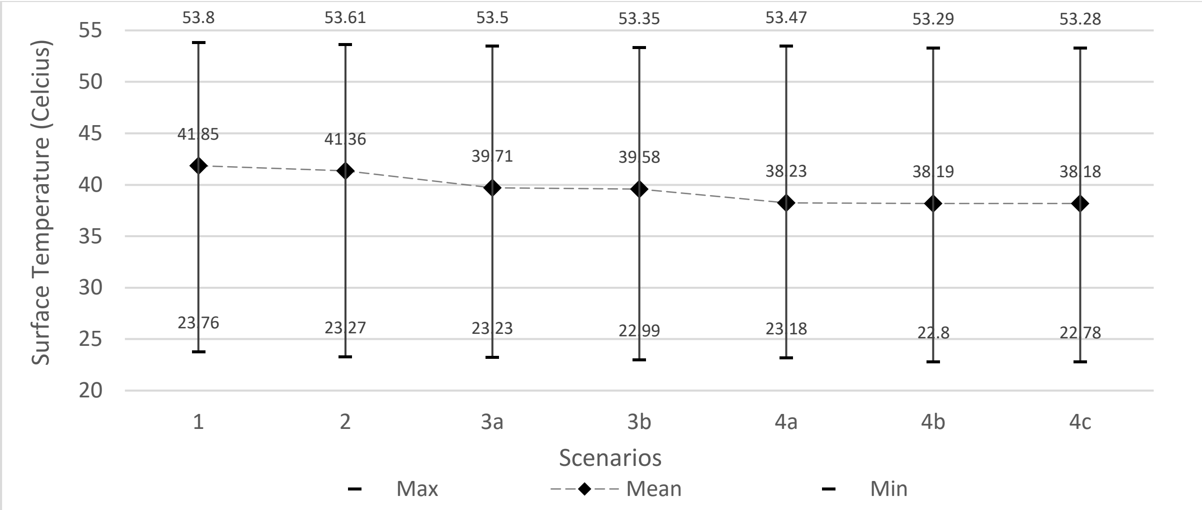


Fig.7.9. Surface temperature trend between scenarios.

c. Mean Radiant Temperature (MRT)

As shown in Figure 7.10 and Table 7.4, mean radiant temperature (MRT) resulted in a continuous decline in mean, minimum and maximum value indexes from Scenarios 1 to 4c, except between Scenarios 3b and 4a. It showed that Scenario 3b (basic model but with buffer greening) has lower MRT degrees than Scenario 4a (optimal model without buffer greening).

Other than that, through the comparisons within scenario groups, it also found that the overall MRT in those design models with buffer greening (Scenarios 2, 3b, 4b and 4c) were lower than those without buffer greening (Scenarios 1, 3a and 4a). All outcomes have best explained the importance of buffer greening to reduce MRT.

Besides, by comparing Scenarios 1 and 2 in Figure 7.15, a significant drop in MRT at hedge planting areas was found. Meanwhile, even though its variances in maximum and minimum indexes (Δmax: -0.53 & Δmin: -4.76) were similar with Scenario 3a (Δmax: -0.4 & Δmin: -4.99) when compared to the baseline model, their difference in mean indexes was relatively big (Δmean: -0.81 in Scenario 2 and Δmean: -2.13 in Scenario 3a). These results indicated that on-site greening still has a conclusive influence on MRT at the same time.

Lastly, similar to air temperature, the MRT variance between Scenarios 4b and 4c was minimal, indicating that the buffer zone variance in green coverage ratio (GCR) had less effect on the core area under this scenario.

Table 7.4. MRT variance between scenarios.

MRT (°C)		Variance in maximum and minimum index (Δ_{max} & Δ_{min})						
		1	**2**	**3a**	**3b**	**4a**	**4b**	**4c**
Variance in mean index (Δ_{mean})	**1**	0	Δ_{max}: -0.53 Δ_{min}: -4.76	Δ_{max}: -0.4 Δ_{min}: -4.99	Δ_{max}: -1.05 Δ_{min}: -5.69	Δ_{max}: -0.63 Δ_{min}: -5.13	Δ_{max}: -1.31 Δ_{min}: -6.03	Δ_{max}: -1.36 Δ_{min}: -6.07
	2	-0.81	0	Δ_{max}: -0.13 Δ_{min}: -0.23	Δ_{max}: -0.52 Δ_{min}: -0.93	Δ_{max}: -0.23 Δ_{min}: -0.14	Δ_{max}: -0.91 Δ_{min}: -1.04	Δ_{max}: -0.83 Δ_{min}: -1.31
	3a	-2.13	-1.32	0	Δ_{max}: -0.65 Δ_{min}: -0.7	Δ_{max}: -0.23 Δ_{min}: -0.14	Δ_{max}: -0.91 Δ_{min}: -1.04	Δ_{max}: -0.96 Δ_{min}: -1.08
	3b	-2.81	-2	-0.68		Δ_{max}: 0.42 Δ_{min}: 0.56	Δ_{max}: -0.26 Δ_{min}: -0.34	Δ_{max}: -0.31 Δ_{min}: -0.38
	4a	-2.46	-0.33	-0.33	0.35		Δ_{max}: -0.68 Δ_{min}: -0.9	Δ_{max}: -0.73 Δ_{min}: -0.94
	4b	-3.22	-1.09	-1.09	-0.41	-0.76		Δ_{max}: -0.05 Δ_{min}: -0.04
	4c	-3.28	-2.47	-1.15	-0.47	-0.82	-0.06	0

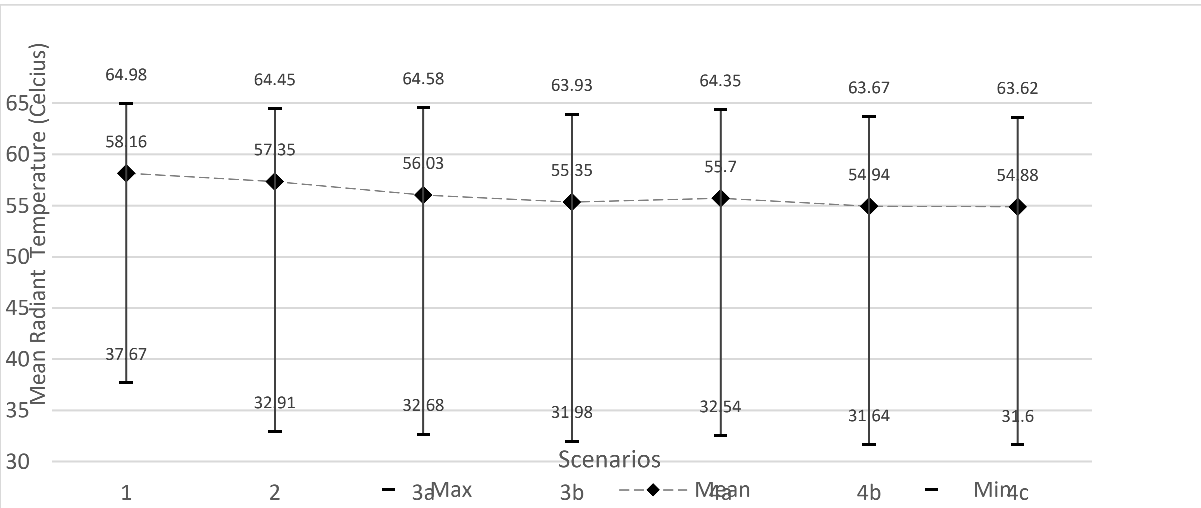


Fig.7.10. MRT trend between scenarios.

d. Wind Speed

Compared to other microclimate parameters, the variances between scenario groups and within scenario groups were relatively small, less than 0.1m/s (Figure 7.11 and Table 7.5). Figure 7.16 also showed an improved but similar wind distribution pattern throughout the scenario study.

The only finding was that the maximum index in all design scenarios was decreased to the same level (0.28-0.29m/s). Scenario 2, with no additional trees in the core area, has a lower variance in the maximum index than others, indicating the wind speed was still highly affected by trees on-site. Off-site greening, including trees, had no impacts on wind performance on-site in this case.

Table 7.5. Wind speed variance between scenarios.

WS (m/s)		**Variance in maximum and minimum index (Δ_{max} & Δ_{min})**						
		1	**2**	**3a**	**3b**	**4a**	**4b**	**4c**
Variance in mean index (Δ_{mean})	**1**	0	Δ_{max}: -0.19 Δ_{min}: 0	Δ_{max}: -0.28 Δ_{min}: 0	Δ_{max}: -0.29 Δ_{min}: 0	Δ_{max}: -0.28 Δ_{min}: 0	Δ_{max}: -0.28 Δ_{min}: 0	Δ_{max}: -0.28 Δ_{min}: 0
	2	-0.006	0	Δ_{max}: -0.09 Δ_{min}: 0	Δ_{max}: -0.1 Δ_{min}: 0	Δ_{max}: 0 Δ_{min}: 0	Δ_{max}: 0 Δ_{min}: 0	Δ_{max}: -0.09 Δ_{min}: 0
	3a	-0.077	-0.071	0	Δ_{max}: -0.01 Δ_{min}: 0	Δ_{max}: 0 Δ_{min}: 0	Δ_{max}: 0 Δ_{min}: 0	Δ_{max}: 0 Δ_{min}: 0
	3b	-0.078	-0.072	-0.001		Δ_{max}: 0.01 Δ_{min}: 0	Δ_{max}: 0.01 Δ_{min}: 0	Δ_{max}: 0.01 Δ_{min}: 0
	4a	-0.085	-0.008	-0.008	-0.007		Δ_{max}: 0 Δ_{min}: 0	Δ_{max}: 0 Δ_{min}: 0
	4b	-0.086	-0.009	-0.009	-0.008	-0.001		Δ_{max}: 0 Δ_{min}: 0
	4c	-0.087	-0.081	-0.01	-0.009	-0.002	-0.001	0

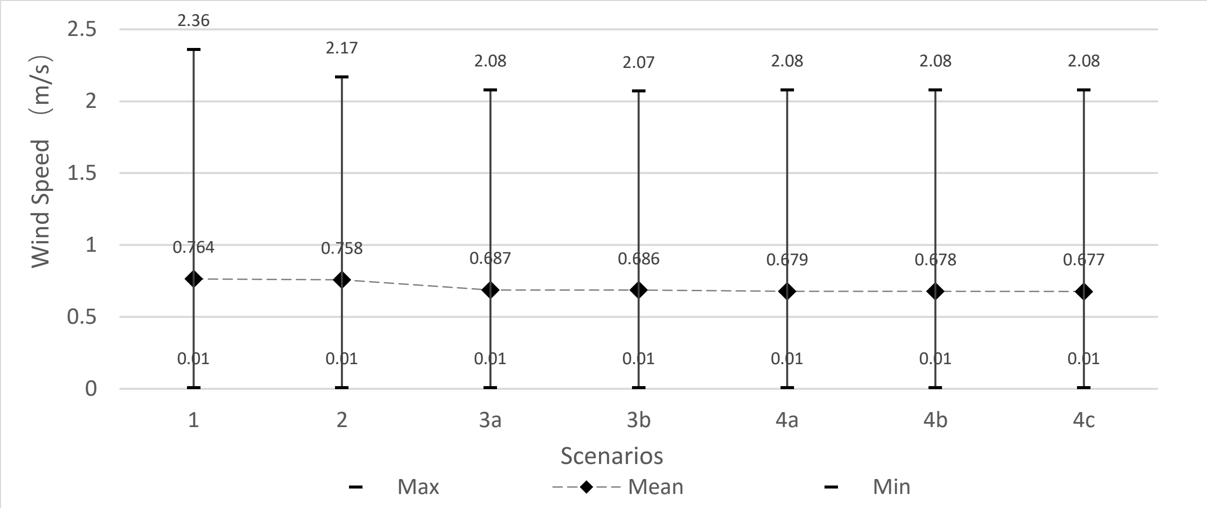


Fig.7.11. Wind speed trend between scenarios.

e. Relative Humidity

Relative humidity continued to increase from Scenarios 1 to 4c, as shown in Figure 7.12 and Table 7.6. Similar to air temperature, the highest average degree was found in optimal design models (Scenarios 4), followed by the basic design models (Scenarios 3), and then Scenario 2 and the baseline model (Scenario 1). The relative humidity range had a relatively small change, in which the minimum was maintained at 55-56%, and the maximum was maintained at 70-71%.

Likewise, as shown in Figure 7.17, all models with buffer greening have higher average relative humidity degrees than their corresponding model with no buffer greening, including Scenario 2. In the absence of any additional trees and green paving, the relative humidity in Scenario 2 was still improved by buffer greening throughout the entire core area. All result has clearly illustrated the effectiveness of off-site greening in improving on-site relative humidity.

Lastly, the variance between Scenarios 4b and 4c was still relatively insignificant in the overall study. In other words, for an optimal design model, the variance of green coverage ratio (GCR) in the buffer zone less impacted the relative humidity.

Table 7.6. Relative humidity variance between scenarios.

RH (%)		**Variance in maximum and minimum index (Δ_{max} & Δ_{min})**						
		1	**2**	**3a**	**3b**	**4a**	**4b**	**4c**
Variance in mean index (Δ_{mean})	**1**	0	Δ_{max}: 0.4 Δ_{min}: 0.09	Δ_{max}: 0.77 Δ_{min}: 0.17	Δ_{max}: 1.13 Δ_{min}: 0.16	Δ_{max}: 1.11 Δ_{min}: 0.56	Δ_{max}: 1.54 Δ_{min}: 0.43	Δ_{max}: 1.59 Δ_{min}: 0.44
	2	0.41	0	Δ_{max}: 0.37 Δ_{min}: 0.08	Δ_{max}: 0.73 Δ_{min}: 0.07	Δ_{max}: 0.34 Δ_{min}: 0.39	Δ_{max}: 0.77 Δ_{min}: 0.26	Δ_{max}: 1.19 Δ_{min}: 0.35
	3a	1	0.59	0	Δ_{max}: 0.36 Δ_{min}: -0.01	Δ_{max}: 0.34 Δ_{min}: 0.39	Δ_{max}: 0.77 Δ_{min}: 0.26	Δ_{max}: 0.82 Δ_{min}: 0.27
	3b	1.3	0.89	0.3		Δ_{max}: -0.02 Δ_{min}: 0.4	Δ_{max}: 0.41 Δ_{min}: 0.27	Δ_{max}: 0.46 Δ_{min}: 0.28
	4a	1.6	0.6	0.6	0.3		Δ_{max}: 0.43 Δ_{min}: -0.13	Δ_{max}: 0.48 Δ_{min}: -0.12
	4b	1.98	0.98	0.98	0.68	0.38		Δ_{max}: 0.05 Δ_{min}: 0.01
	4c	2.04	1.63	1.04	0.74	0.44	0.06	0

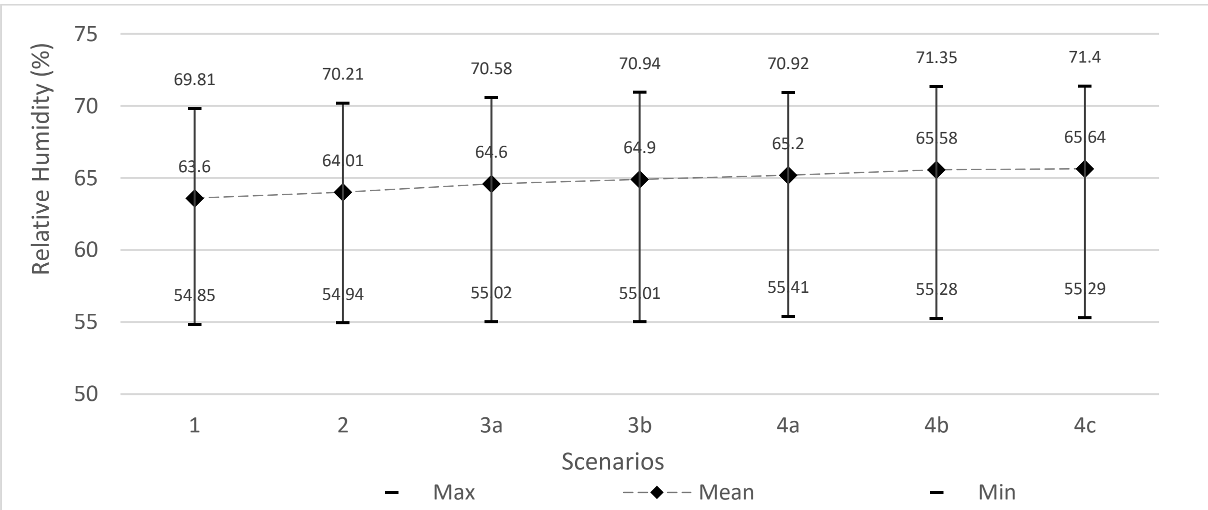


Fig.7.12. Relative humidity trend between scenarios.

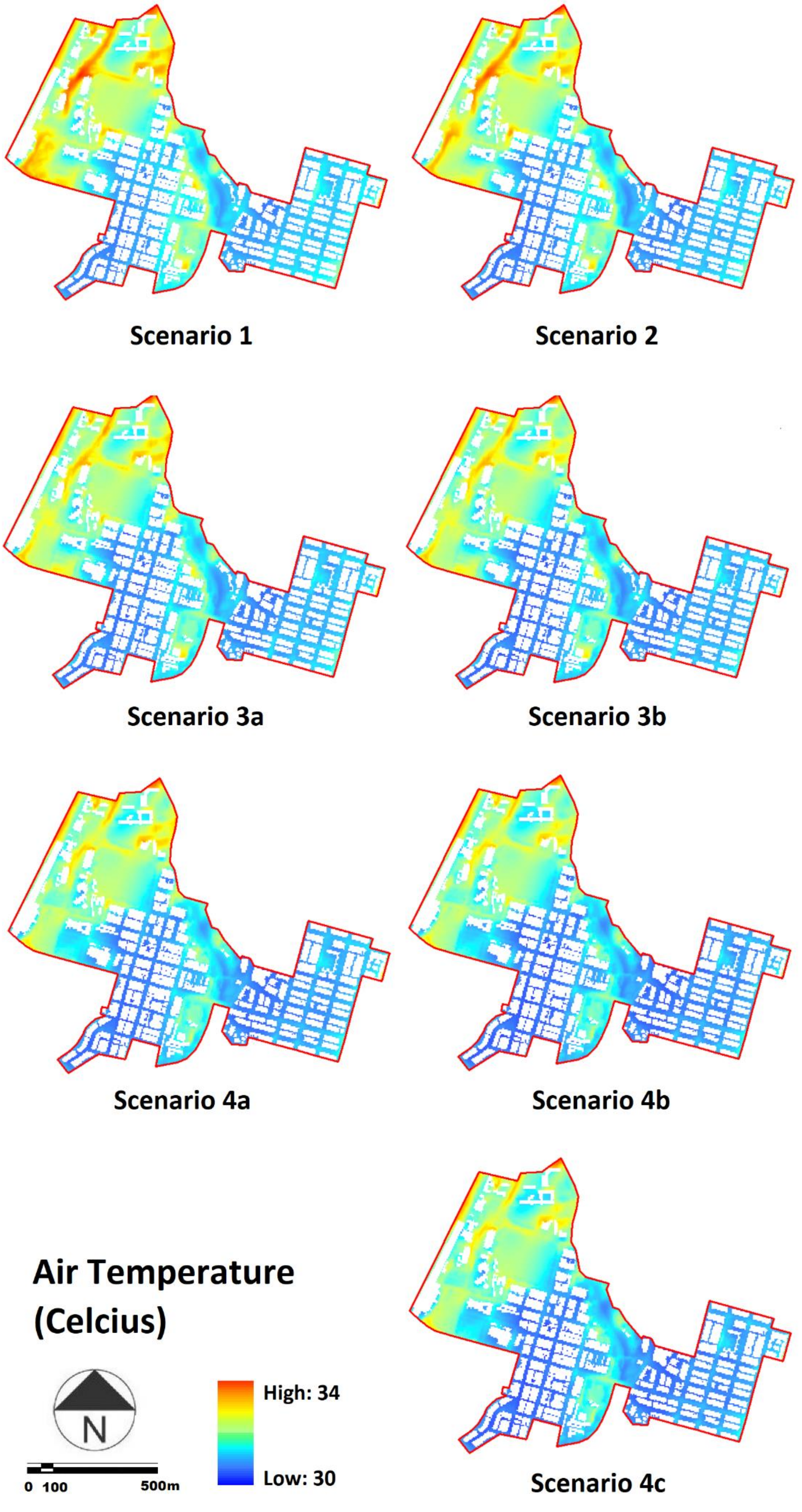


Fig. 7.13. Air temperature distribution between scenarios

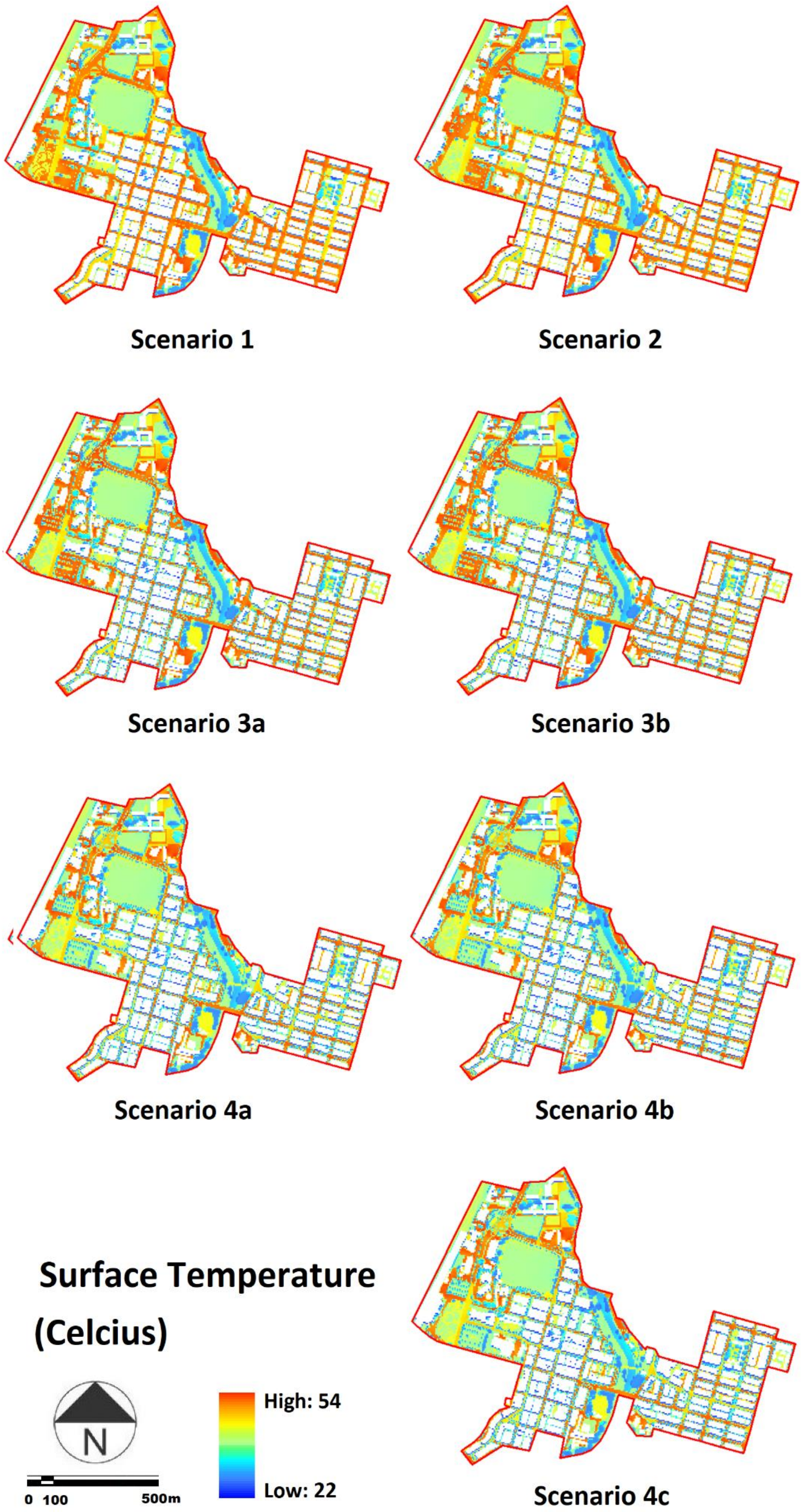


Fig. 7.14. Surface temperature distribution between scenarios.

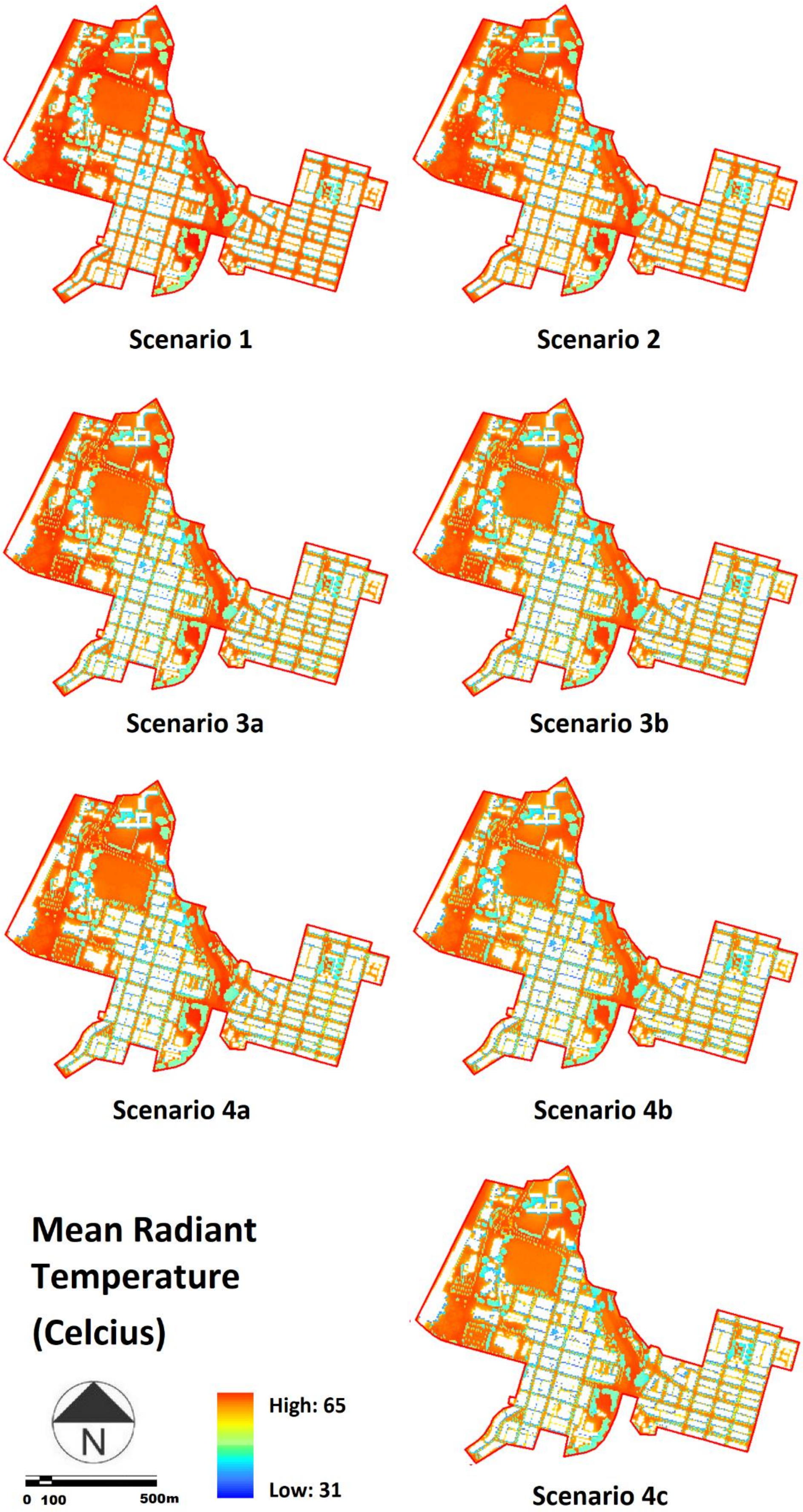


Fig. 7.15. MRT distribution between scenarios.

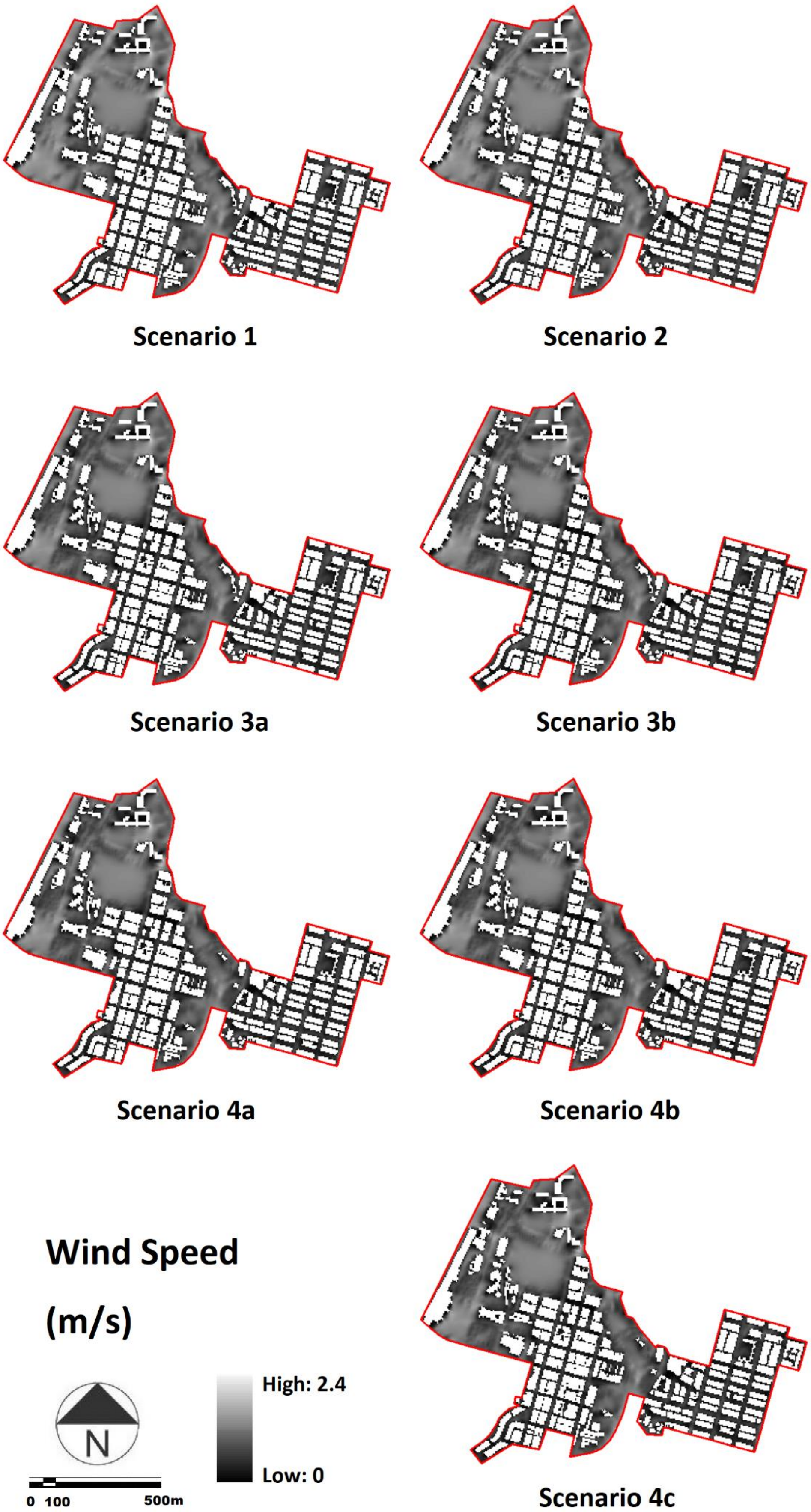


Fig. 7.16. Wind speed distribution between scenarios.

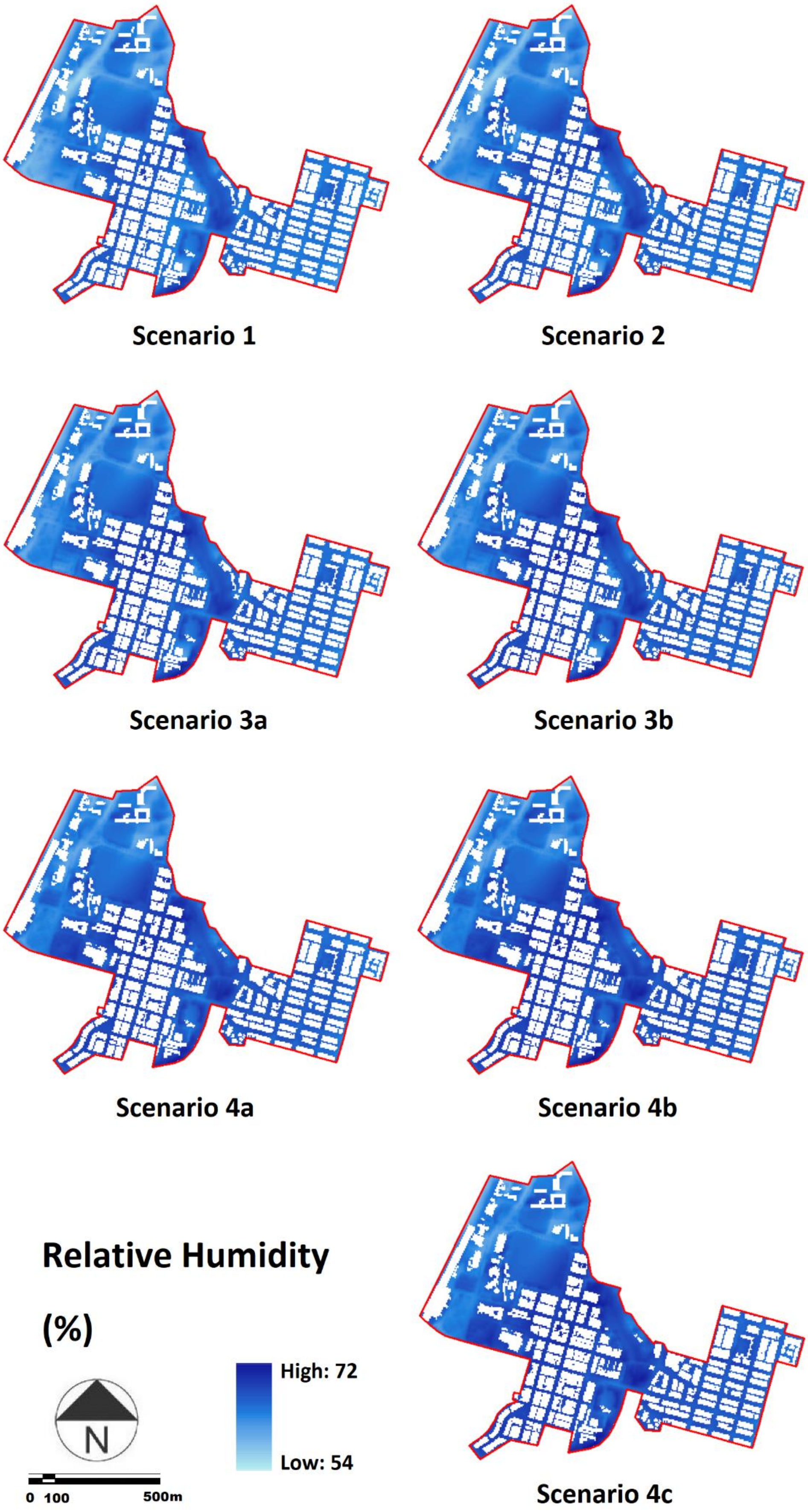


Fig. 7.17. Relative humidity distribution between scenarios.

7.3.2 Thermal Comfort Aspect

In terms of human thermal comfort, physiological equivalent temperature (PET) followed the trend of MRT. As shown in Figure 7.18 and Table 7.7, PET continued to decline in mean, minimum and maximum value indexes from Scenarios 1 to 4c, except between Scenarios 3b and 4a.

Based on the output, Scenario 4a (optimal model without buffer greening) has higher PET degrees than Scenario 3b (basic model but with buffer greening). The finding indicated that the basic model (with buffer greening) did have advantages over the optimal model (without buffer greening) in the core zone. At the same time, within the same scenario groups, the overall PET in those design models with buffer greening (Scenarios 2, 3b, 4b and 4c) was also lower than those without buffer greening (Scenarios 1, 3a and 4a). All PET outcomes indicated that buffer greening helped to reduce thermal discomfort in the target area.

On the other hand, the comparison between Scenarios 1 and 2 found a significant PET decline (-0.52^{o}C) throughout the core zone (refer to Figure 7.19 and Table 7.7). However, compared to the variance between Scenarios 1 and 3a (-1.11^{o}C), it showed that the effectiveness of buffer greening in PET improvement was relatively weak. By contrast, on-site greening was still the decisive factor for reducing PET.

Overall, Figure 7.19 has shown notable variances in PET between scenarios with and without buffer greening. Nevertheless, the PET decline degree was not significant in changing thermal comfort perception. The variances in thermal comfort level became relatively small, as resulted in Figure 7.20. In order to examine the degree of improvement in thermal comfort level between scenarios, the variances in thermal perception were sorted out, which included:

a. Between Scenario 1 (the baseline) and other scenarios (Figure 7.21).
b. Between Scenarios 2 and 3a (Figure 7.22).
c. Within Scenarios 3 group - the basic design (Figure 7.22).
d. Between Scenarios 3b and 4a (Figure 7.22).
e. Within Scenarios 4 group - the optimal design (Figure 7.22).

Table 7.7. PET variance between scenarios.

PET (°C)		Variance in maximum and minimum index (Δ_{max} & Δ_{min})						
		1	**2**	**3a**	**3b**	**4a**	**4b**	**4c**
Variance in mean index (Δ_{mean})	**1**	0	Δ_{max}: -0.2 Δ_{min}: -2.6	Δ_{max}: -0.1 Δ_{min}: -2.8	Δ_{max}: -0.5 Δ_{min}: -3.2	Δ_{max}: -0.2 Δ_{min}: -3	Δ_{max}: -0.7 Δ_{min}: -3.4	Δ_{max}: -0.7 Δ_{min}: -3.5
	2	-0.52	0	Δ_{max}: -0.1 Δ_{min}: -0.2	Δ_{max}: -0.3 Δ_{min}: -0.6	Δ_{max}: -0.1 Δ_{min}: -0.2	Δ_{max}: -0.6 Δ_{min}: -0.6	Δ_{max}: -0.5 Δ_{min}: -0.9
	3a	-1.11	-0.59	0	Δ_{max}: -0.4 Δ_{min}: -0.4	Δ_{max}: -0.1 Δ_{min}: -0.2	Δ_{max}: -0.6 Δ_{min}: -0.6	Δ_{max}: -0.6 Δ_{min}: -0.7
	3b	-1.54	-1.02	-0.43	0	Δ_{max}: 0.3 Δ_{min}: 0.2	Δ_{max}: -0.2 Δ_{min}: -0.2	Δ_{max}: -0.2 Δ_{min}: -0.3
	4a	-1.35	-0.24	-0.24	0.19	0	Δ_{max}: -0.5 Δ_{min}: -0.4	Δ_{max}: -0.5 Δ_{min}: -0.5
	4b	-1.83	-0.72	-0.72	-0.29	-0.48	0	Δ_{max}: 0 Δ_{min}: -0.1
	4c	-1.87	-1.35	-0.76	-0.33	-0.52	-0.04	0

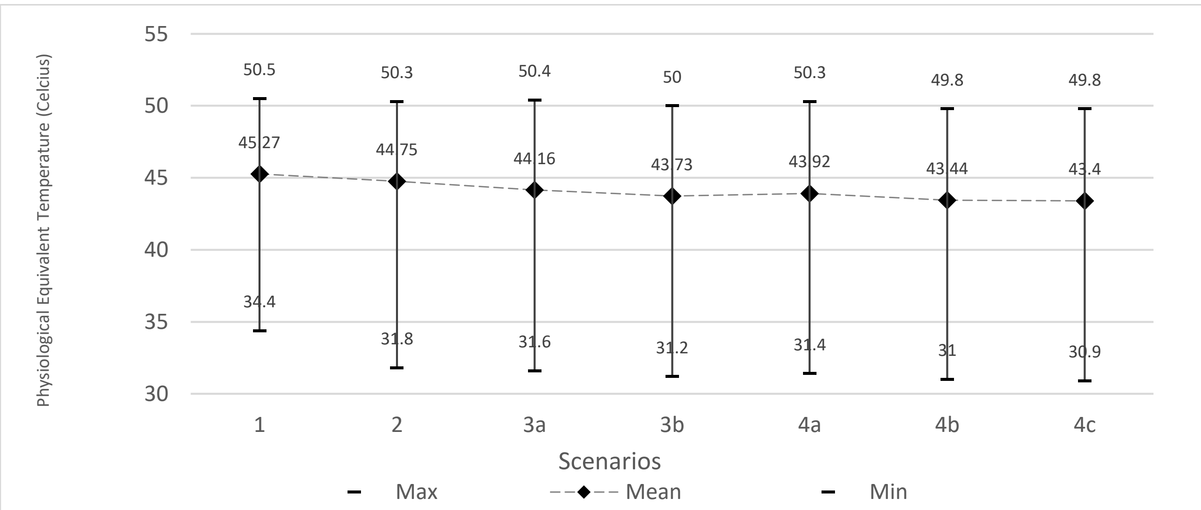


Fig.7.18. PET trend between scenarios.

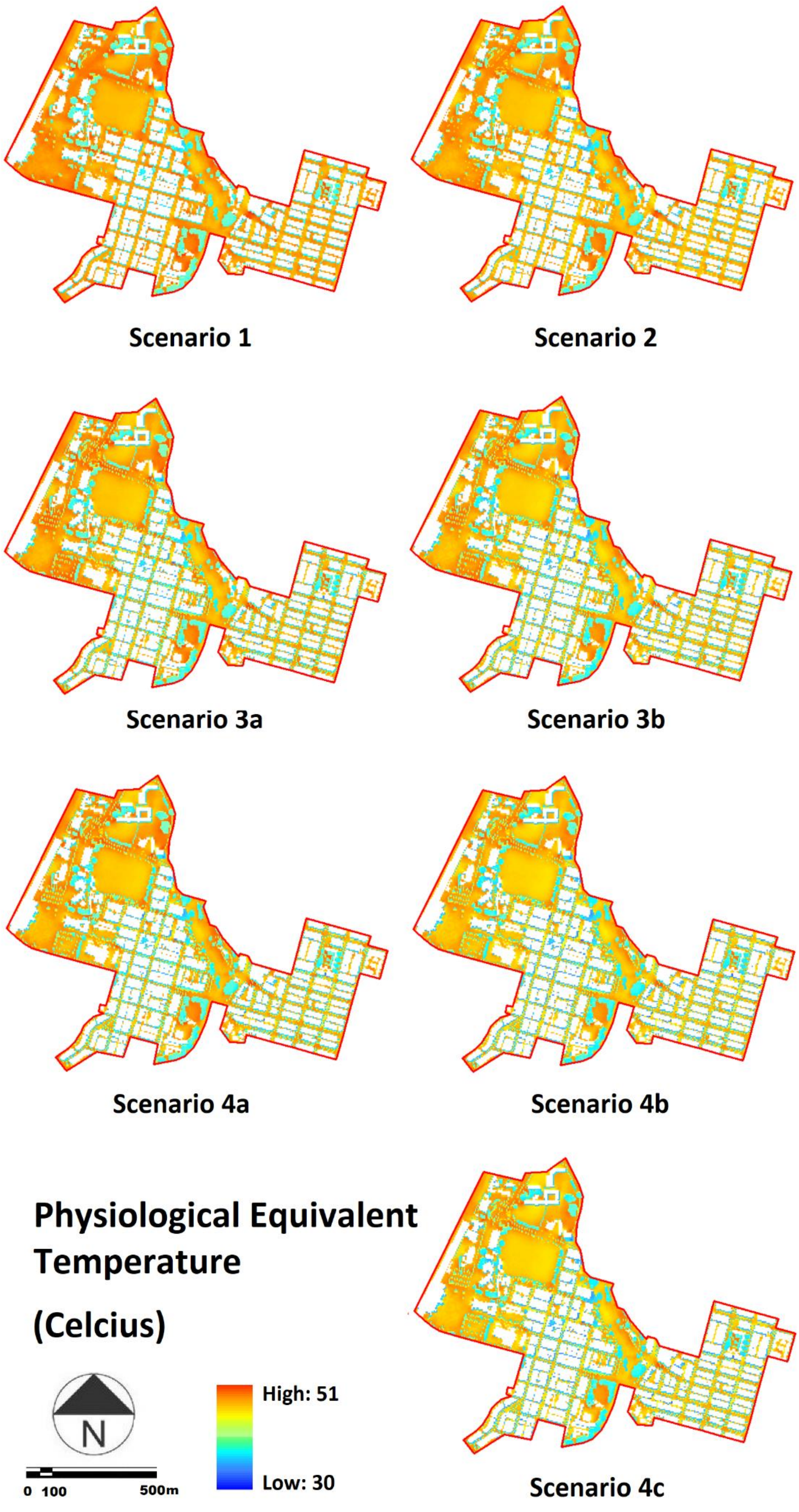


Fig. 7.19. PET distribution between scenarios.

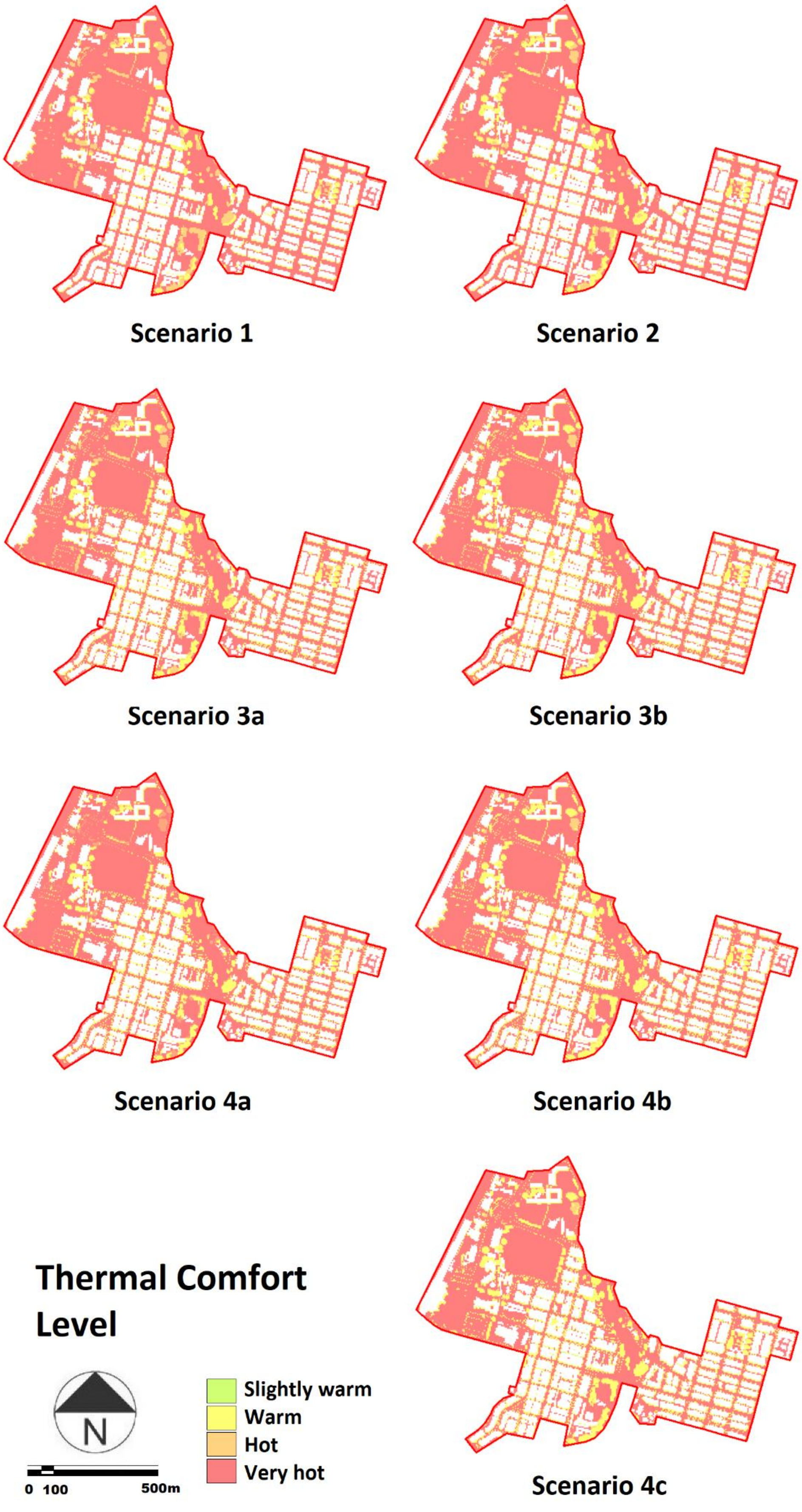


Fig. 7.20. Thermal comfort level distribution between scenarios.

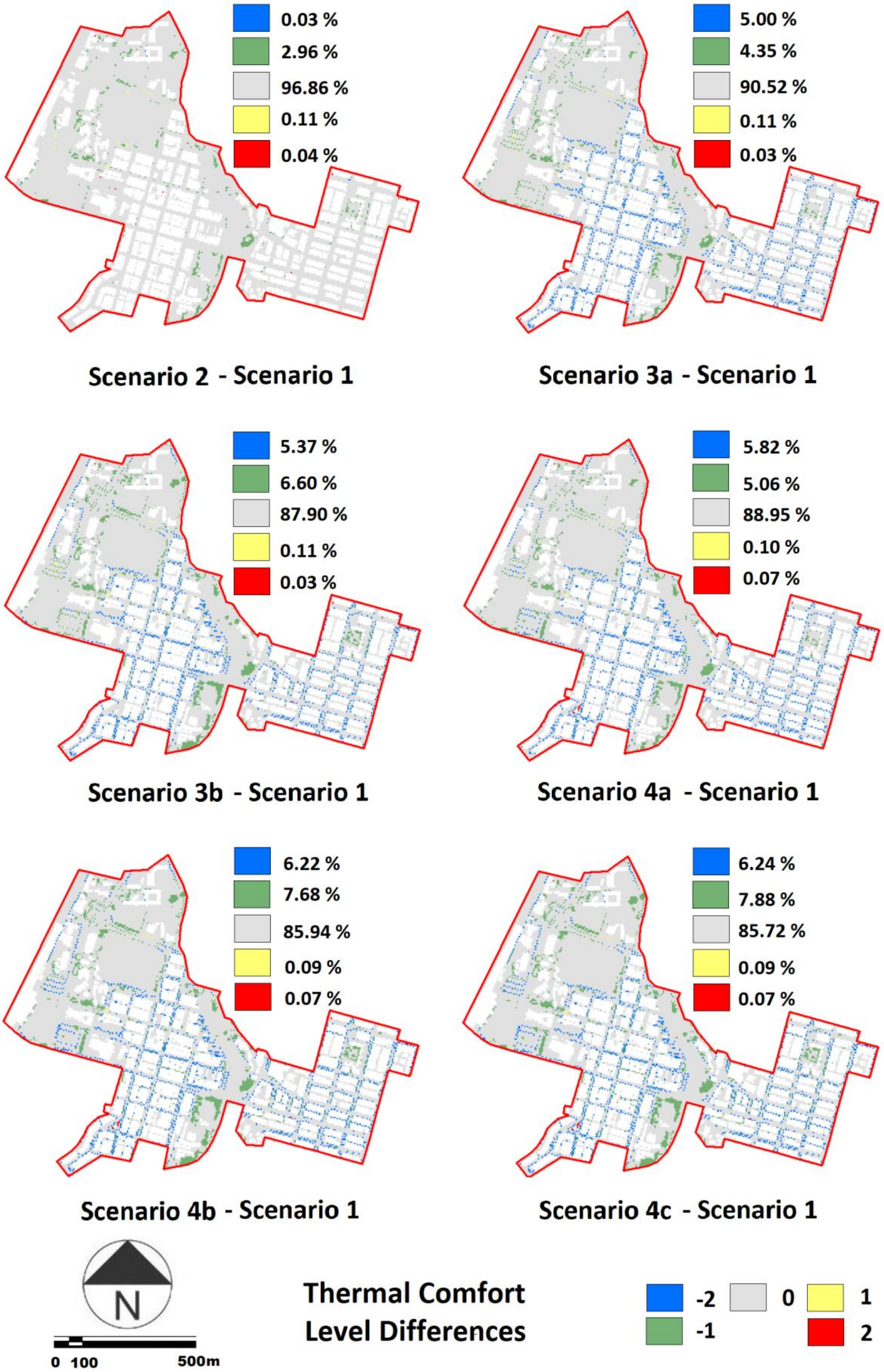


Fig. 7.21. Thermal comfort level variance between Scenario 1 and other scenarios(map).

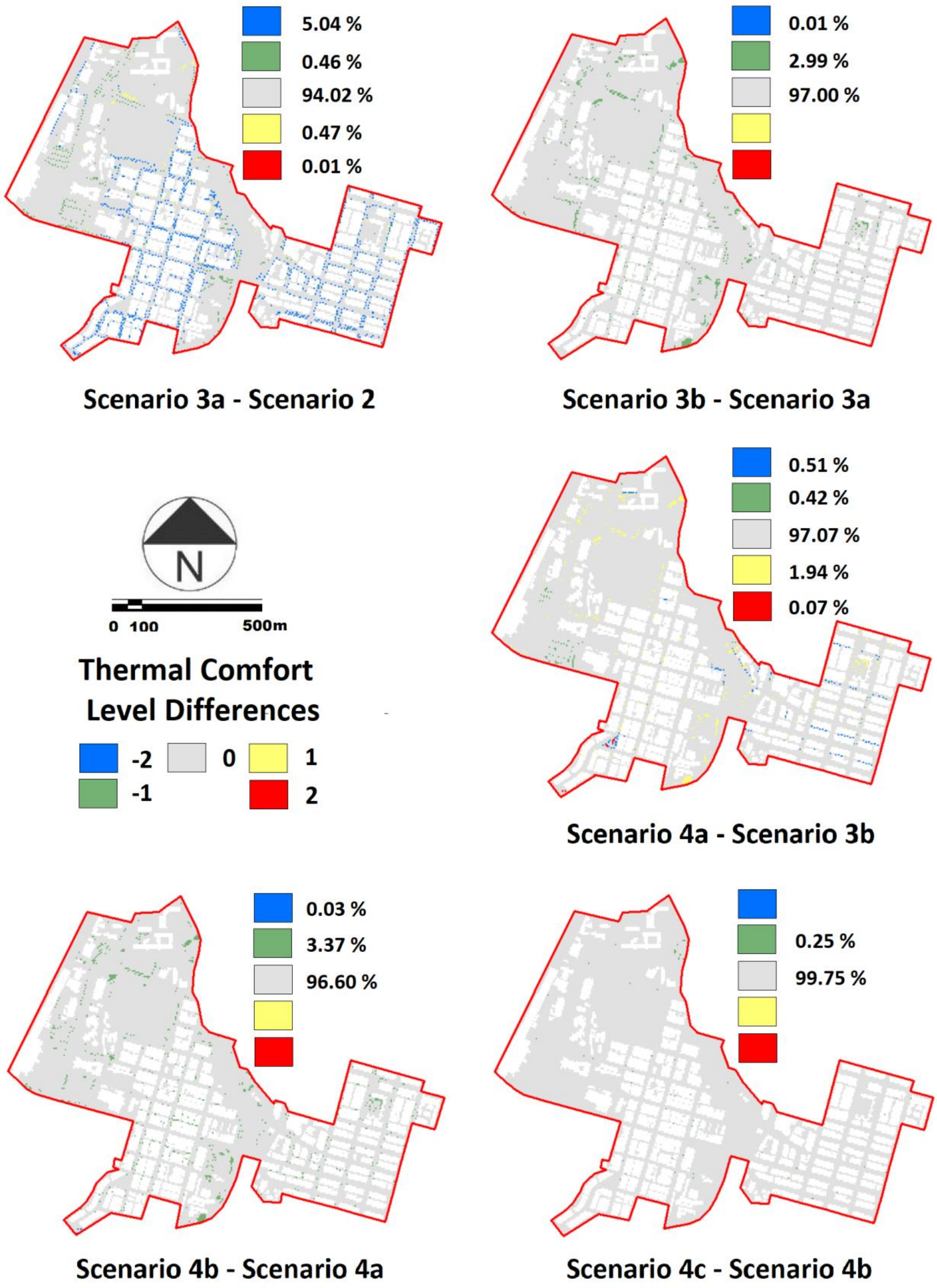
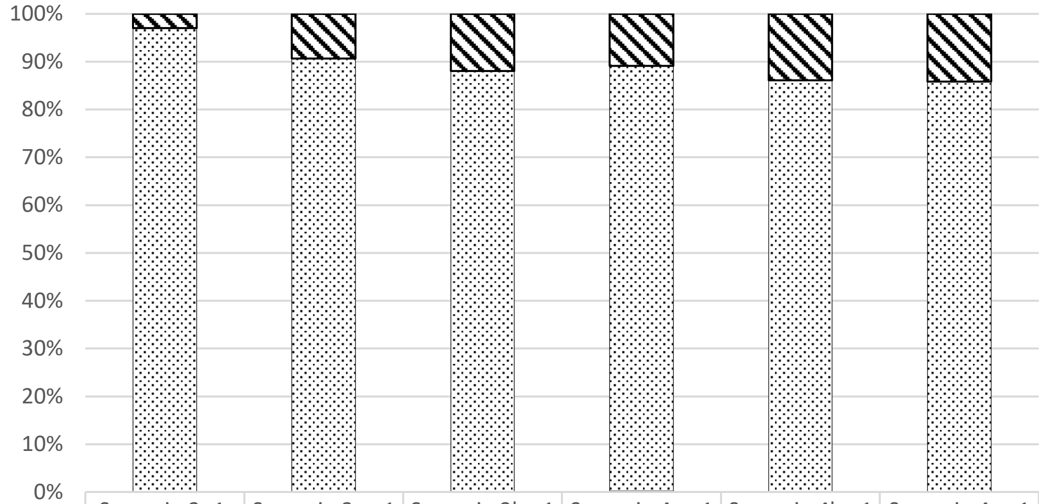
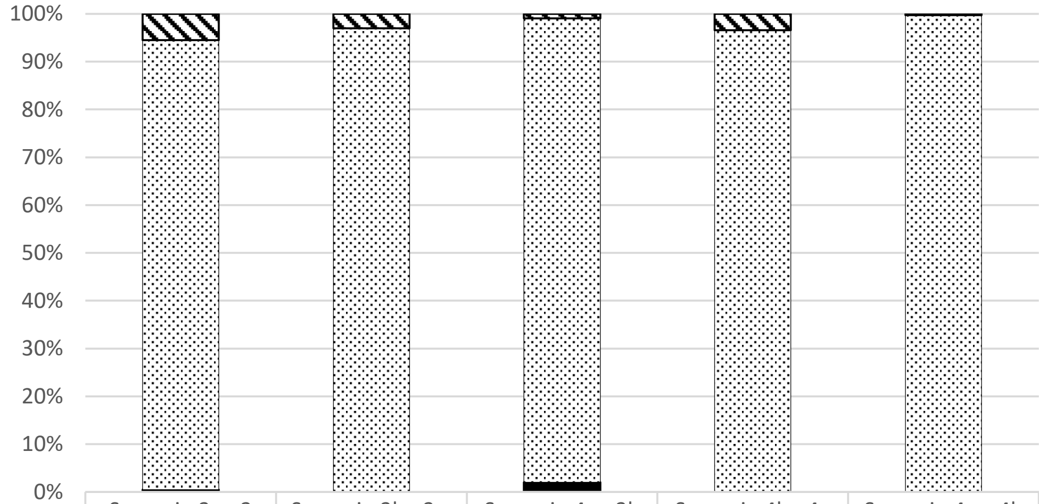


Fig. 7.22. Thermal comfort level variance between scenarios (map).



	Scenario 2- 1	Scenario 3a - 1	Scenario 3b - 1	Scenario 4a - 1	Scenario 4b - 1	Scenario 4c - 1
Cooling	2.99	9.34	11.97	10.88	13.9	14.13
Neutral	96.86	90.52	87.9	88.95	85.94	85.72
Warming	0.15	0.13	0.13	0.17	0.16	0.16

Fig. 7.23. Thermal comfort level variance between Scenario 1 and other scenarios (graph).



	Scenario 3a - 2	Scenario 3b - 3a	Scenario 4a - 3b	Scenario 4b - 4a	Scenario 4c – 4b
Cooling	5.5	3	0.92	3.4	0.25
Neutral	94.02	97	97.07	96.6	99.75
Warming	0.48		2.01		

Fig. 7.24. Thermal comfort level variance between scenarios (graph).

Figures 7.21 and 7.23 showed that all design scenarios tended to have more cooling areas when the ratio continued to increase from Scenarios 2 to 4c. The improvement could be up to a two-level-decline (-2) in thermal comfort level. In the cooling areas, the two-level-decline (-2) area ratio continued to increase from Scenarios 2 to 4c. The one-level-decline (-1) zone also increased continuously, except for from Scenarios 3b to 4a. The area ratio of one-level-decline (-1) in Scenario 4a was lower than in Scenario 3b, resulting in a higher cooling area ratio (11.97%) in Scenario 3b than in Scenario 4a (10.88%). In contrast, although some warming has occurred in all scenarios, the ratio was too small and negligible.

Based on Figures 7.22 and 7.24, there were four main findings as well, as follows:

a. There was no warming within the Scenario 3 group and Scenario 4 group, affirming the additional buffer greening would only promote cooling to the target area.
b. In comparison to Scenario 2, Scenario 3 provide a 5.5% more cooling area in the core area. The variance indicated that the thermal comfort in the core area cannot solely rely on buffer greening and must be effectively improved with more tree planting on-site.
c. The warming area ratio (2.01%) was more than the cooling area ratio (0.92%) in the comparison of Scenario 4a with Scenario 3b, highlighting the effectiveness of buffer greening in Scenario 3 in ameliorating thermal comfort. It turned out that the degree of cooling does not fully depend on the on-site green coverage rate (GCR) but also the off-site factors like buffer greening.
d. The cooling area ratios between Scenarios 1-2, 3a-3b, and 4a-4b were similar: 2.99%, 3% and 3.4%, respectively. It indicated that regardless of the design mode in the core area, the basic design in the buffer zone would make approximately 3% of the core area cooler in this study.
e. The area ratio variance between Scenario 4b and 4c remained minimal (0.25%), which proved that the optimal buffer greening has no significant advantage over the basic buffer greening in case that the optimal design has been applied in the core area.

7.4 CONCLUSION

In summary, this chapter has assessed seven scenarios to determine whether buffer greening could ameliorate microclimate and thermal comfort conditions. Throughout the study, it affirmed that buffer greening made a positive impact on the target area, mainly by improving air temperature, mean radiant temperature, relative humidity, and thermal comfort level. As for the surface temperature and wind performance, the output has not shown any definite correlation between buffer greening and these parameters.

As expected, the outcomes revealed that buffer greening was a booster or supplementary strategy at most. The degree of thermal improvement was relatively low if only with buffer greening, as shown in Scenario 2. Despite the fact that buffer greening will not be the core of the solution, it is undoubtedly indispensable for urban microclimate and thermal comfort improvement. Without buffer greening, the design model could not achieve optimal cooling, as shown in Scenarios 3a and 4a. In other words, to expect the optimal degree of thermal improvement, it required both buffer greening and core greening. The affirmation also reinforced the conclusion of Chapter 3, which showed that the existing greenery in and around New Town has a cooling effect on the thermal performance of New Town.

Lastly, this chapter suggested buffer greening as one of the vital strategies in improving on-site microclimate and thermal comfort. Meanwhile, it also implied the significance of green space and natural environment in and around the city. The conclusion has strengthened the necessity of green and nature conservation in the urban and adjacent regions. The local authority should consider a range of environmental risk assessments and thermal environment evaluations before any development plan is allowed at undeveloped lots. In particular, urban expansion and deforestation activities should be carried out more strictly and cautiously to prevent a substantial loss of vegetation and trees.

CHAPTER 8
DISCUSSIONS

8.1 THE FINAL FRAMEWORK REPRESENTING CLIMATE-LED CONCEPT AND APPROACH

The climate-based design concept is not something new in the field. There are currently plenty of design themes on this subject, such as “Climate-responsive”, “Climate-sensitive”, “Climate-proof”, and so on. These concepts, in fact, commonly share an ultimate goal but with different objectives, scopes and approaches, for example:

- ‘Climate-responsive’, which originated from architecture, aimed to “minimize environmental impacts of buildings through selecting an appropriate response to the climate” (Hyde, 2000). In the scope of urban planning, its main objective is to reduce the environmental impacts of urban design through selecting an appropriate response to the climate. Usually, the scope of works includes the layout design of buildings and streets, the selection of surface materials, etc.
- ‘Climate-sensitive’ is also related to building design, mainly considering the impacts of buildings on the surrounding microclimate, especially the carbon dioxide emission or any human-induced warming (Humphreys, 2017). Likewise, it also aims to reduce the negative impacts of urban development on the local climate.
- ‘Climate-proof’ is more for urban policy planning instead of urban design. It often refers to the urban capacity on vulnerability, risk potentials, climate change mitigation and adaptation from a regional perspective (Albers et al., 2015).

Instead of using those existing design concepts for climate solutions, this research suggested using a new concept, called the ‘climate-led’ design, for urban landscape design and planning. It is necessary to highlight that the new concept is similar but ahead of the existing climate-based design concepts. As mentioned in Chapter 1.3, the climate-led approach is not a passive but an active countermeasure in design implementation. In addition to improving the urban thermal conditions, it is also committed to changing the local lifestyle and transportation preferences through landscape solutions.

As a result, it can be seen from Figure 8.1 that the so-called climate-led approach has been extended from the scope of pure urban thermal solutions. The ultimate goal has gone beyond the considerations of improving microclimate and human comfort, aiming to take a broad and active approach to support and optimize urban resilience and sustainability. It has a more holistic landscape dimension, which not only is highly compatible with the pedestrian-oriented concept but also in harmony with the local economic and social redevelopments. Most importantly, all these non-thermal solutions will eventually help walking in the tropical cities and towns more enjoyable, meaningful and easier. The emphasis on walking and walkable communities will help reduce automobile use, which will be a favourable turning point for the local microclimate improvement at last.

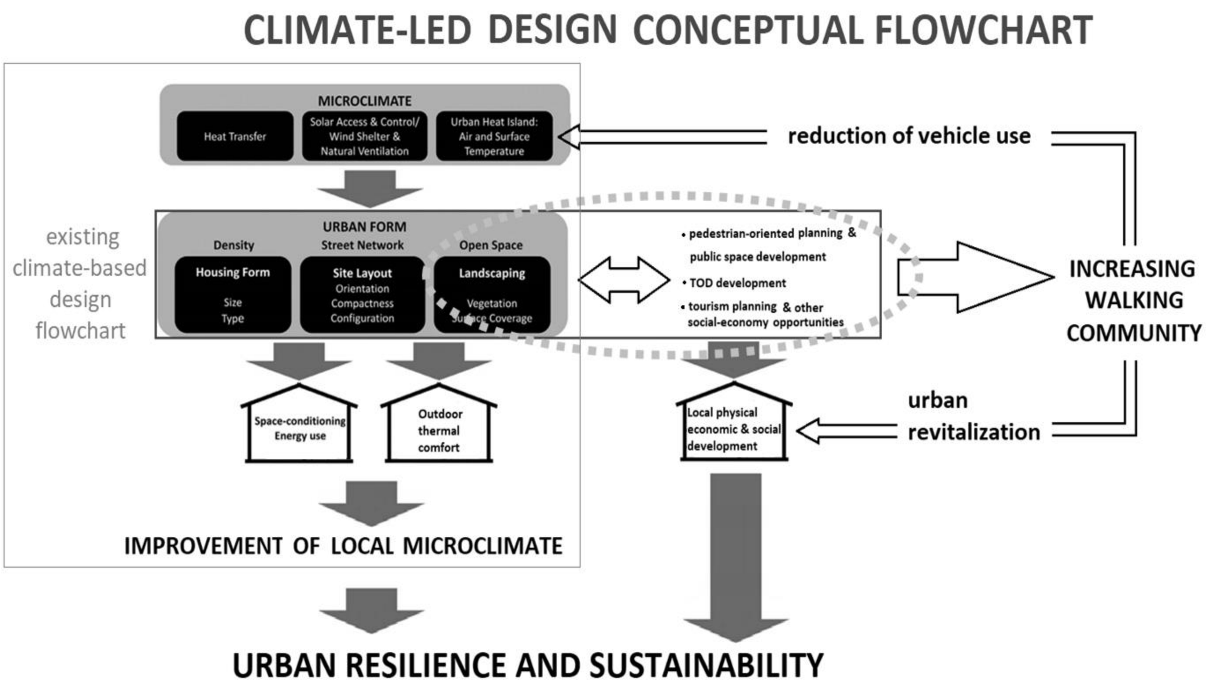


Fig.8.1. The conceptual diagram demonstrated the extension of climate-led considerations, showing the differences between existing climate-based design flowchart with climate-led design flowchart.

Hence, compared to the existing climate-based design concepts, the objectives and approaches of the climate-led design are relatively far-reaching and practical to deal with urban heat issues in existing cities, not dealing with problems on an ad hoc basis. Moreover, a climate-led framework is relatively more open and flexible to lead urban designers and planners towards a more comprehensive, integrated and multi-dimensional redevelopment goal in the era of climate change. Taking the Ipoh case study as an example, the climate-led approach has integrated landscape redevelopment for thermal improvement, local development and heritage conservation. In practice, it will include but not be limited to the factors or aspects considered in this research. In other words, more considerations can be added based on the local context, giving the climate-led urban landscape more room for development.

Next, technically speaking, with the support of computing tools, this research has ultimately formed an integrated method that can repeatedly monitor and assess the climate condition and thermal comfort level of a given model throughout the analysis and design process. Continued from Figures 3.17 and 5.5, Figure 8.2 has clearly illustrated a complete loop of the overall workflow and methods used in a climate-led model, further explaining the initial concept shown in Figure 1.2 in Chapter 1. Throughout the process, each design and planning decision is made with inferences and evaluations.

Finally, it should be noted that no design solution is universal. Within this framework paradigm, the climate-led approach particularly stresses site-based solutions. With changes in physical characteristics of the target area (input data), such as geographic location, climate conditions and spatial layout, the correlation between thermal parameters and thermal comfort index would be changed as well. The strength of the climate-led framework lies in its applicability and feasibility in different study contexts. The design solutions or insights for thermal improvement would vary depending on the study context. For example, due to the study location and wind characteristics, the correlation between wind and thermal comfort in Ipoh was weak and even negative. The proposed design, therefore, less considered the influence of trees arrangement on wind flow. In other cases, if the wind is a dominant contributor to thermal comfort, it should have other design solutions to increase thermal comfort without disturbing wind flow.

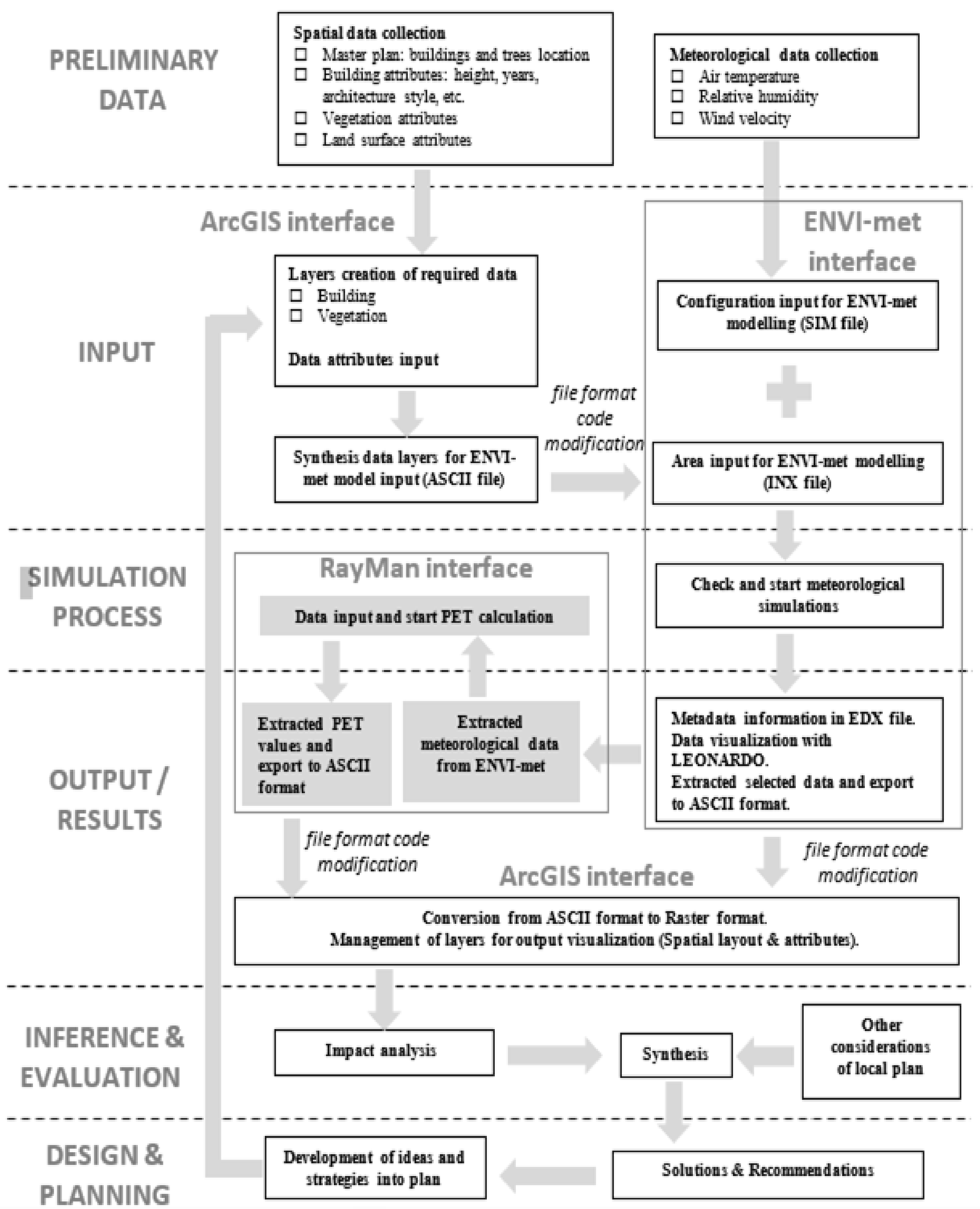


Fig.8.2. The climatology data-driven analysis and design framework used in the climate-led landscape design and planning.

8.2 THE INTEGRATION OF CLIMATE-LED FRAMEWORK INTO CURRENT URBAN DESIGN AND PLANNING CONTEXT

As explained in the last section, the strategies applied climate-led framework has been beyond the pure climate and thermal comfort improvement. As shown in Figure 8.3, the climate-led landscape approach has increased the priority of climate-spatial assessment, pedestrian-oriented development and local considerations in the overall urban master planning. The strategy adopted in the climate-led approach is rather bottom-up and places the landscape in a more dominant position in the overall spatial layout design.

Besides, the climate-led framework also shaped a more comprehensive greening strategy for most existing cities and towns in Malaysia where there are no greens on the street level. The greening scope is relatively more complex than typical street planting strategies. The extended landscape coverage area is attributed by modifying existing road types and sizes (the modification might also include buildings and infrastructures, depending on the extent of the study). Also, landscape greening can become more dominant in urban redevelopment, far beyond its supplementing role in previous urban and town planning. It has a determinant position to provide high-quality pedestrian spaces, or in other words, it is the leading indicator of a successful walkable city.

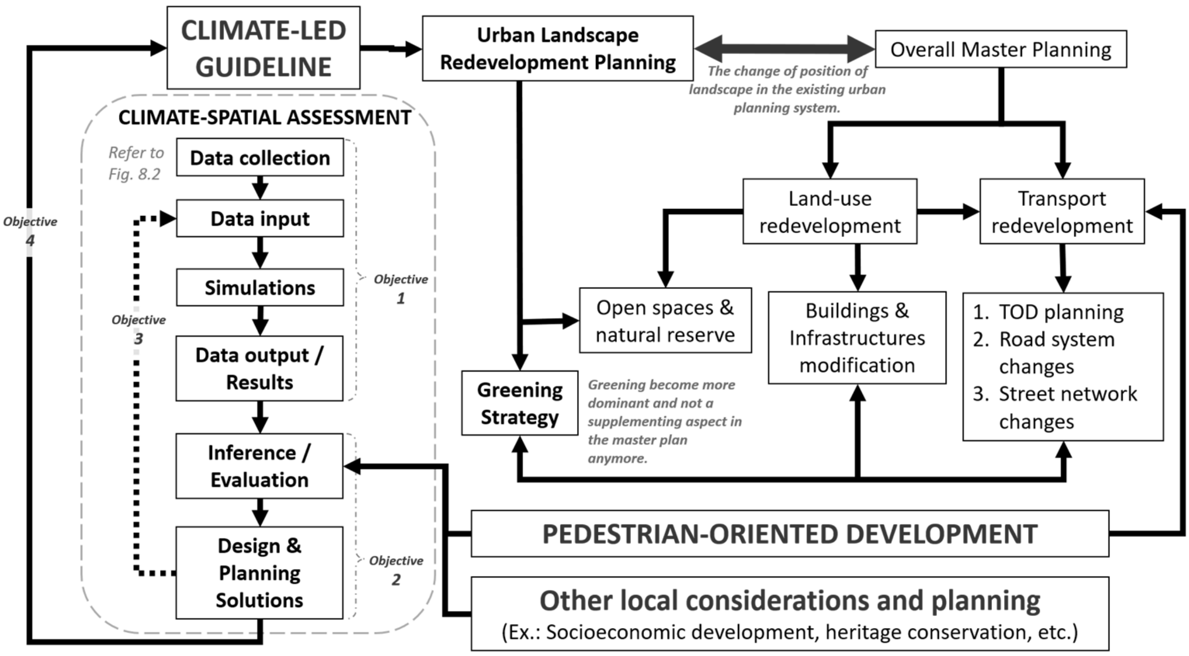


Fig.8.3. The implementation of the climate-led framework into the current urban design and planning context.

In conclusion, the resulting outcomes showed that the objectives designed in the early research stage (as explained in Section 1.3 in Chapter 1) are essential to creating a logical framework to implement a climate-led concept and approach. The four objectives contributed to the development of practical landscape-based solutions to address climate and thermal comfort issues induced by the physical configuration and routine activities of a particular city. The coverage throughout the aspects of analysis, design, evaluation and decision-making has also offered a relatively comprehensive and long-term solution of climate change mitigation and adaptation for existing cities in the tropics. All these become the novelty of this research.

In summary, this study has extended the boundary of urban thermal studies, incorporating microclimate and thermal comfort considerations into urban design and planning. The study demonstrated the possibility of integrating thermal data with other urban data through the advantage of the modelling and simulation approach. This approach will enlarge the breadth of views in urban design and planning, contributing to a more comprehensive physical development outlook in tropical cities.

CHAPTER 9
OVERALL CONCLUSION

9.1 SUMMARY AND MAIN FINDINGS

This research mainly studied the microclimate and human thermal comfort for tropical urban landscape planning and design. The motivation was mainly due to the rising warming issues in cities worldwide, which has increased the risks in public health and degraded urban quality and sustainability. Besides, a thermally comfortable outdoor environment was undoubtedly a requisite to support the New Urbanism development in tropical regions. It is a new urban growth model that emphasises pedestrian- and transit-oriented neighbourhood design and mixed-use development. However, there are currently three main problems that lead to weak awareness and execution in the implementation of climate-based knowledge into urban design and landscape planning: (i) the rookie's attitude and the weak bond between climatology and planning; (ii) the gap in scholars-practitioners' perspective; and (iii) the capacity deficit and technical challenges in implementation.

In response to the climate-responsive design principle, this research aimed to develop a comprehensive climate data-driven design framework for tropical urban landscape planning. The framework covered the entire landscape design and planning process in practice, including analysis, design, evaluation and decision making. In addition, this research suggested using "climate-led" as an active-response strategy to promote a climate-responsive design in landscape planning, in conjunction with new urbanism principles. The case study area was Ipoh, Malaysia, mainly because of its compatible context that fit the research theme. The study was based on a modelling and simulation approach. Other than the introduction and conclusion, there was a total of seven body sections in this research, including theoretical review, methodology (based on baseline model creation and assessment), pilot study, full-scale design and evaluation, zoning design and evaluation, buffer design and evaluation, and discussions.

In the literature review process, this research first explored the history and trend in thermal comfort studies. This part was mainly to figure out the evolution of thermal comfort concepts as well as the core disciplines advocated by seminal scholars (including A.P. Gagge, P.O. Fanger, H. Mayer and P. Höppe, G.S. Brager and R. de Dear). Given that most thermal comfort concepts are grounded in an indoor context, the comfort discrepancy between indoors and outdoors was then discussed to redefine the implications of outdoor thermal comfort. The comparison included human-level control, time of exposure, physical and psychological perception, and spatial efficiency. For an objective urban thermal evaluation using modelling and simulation, the review section also accumulated the underpinning parameters, indices, methods and tools used to study environmental thermal research. To consolidate the novelty of this research, this section lastly made a detailed analysis of urban microclimate studies conducted in Malaysia.

Throughout the theoretical review, it found that most studies still primarily focused on field observation, measurement and evaluation. The use of scenario functions in the modelling and simulation approach thus remained many possibilities to be developed into the design and planning stage. The adopted parameters, indices, methods and tools were highly correlated to the local information and scope of the study. It was usually using a multi-methods or mixed-methods approach in linking thermal-spatial factors altogether for evaluation purposes. Likewise, the same for design and planning. Overall, this review chapter provided a clear direction for the position and significance of this research in the field of urban microclimate and thermal comfort research.

Chapter 3 developed a simulation-based assessment framework to examine outdoor thermal resilience and comfort using integrated computational modelling and simulation. It first explained the shortcomings of ENVI-met application for urban-scale thermal study, followed by an agenda for solutions – integrating ENVI-met with GIS and Rayman (thermal comfort) tools. After that, it demonstrated the procedure of building the baseline model using the GIS tool, the conversion between GIS and ENVI-met tools, the simulation in ENVI-met and RayMan software, and the simulation data interpretation in the GIS tool. In the process, the microclimate and thermal comfort simulation data were be decoded and assembled into a GIS platform to perform an integrated climate-spatial analysis and evaluation. The validation test showed a high correlation between the simulated data and the measured data obtained from the local weather station. The measured parameters included air temperature, mean radiant temperature (MRT), wind speed, relative humidity and physiological equivalent temperature (PET). In view of significant thermal impacts on urban surfaces created by land cover and land use (LCLU), the surface temperature was evaluated altogether with MRT, even though it was not the parametric factor of human comfort.

All results were extracted from a 24-hours simulation cycle at the height of 1.75m at 14:00, the hottest hour recorded by the local weather station. The outcomes showed that Ipoh possessed the typical characteristics of tropical regions, with a high air temperature in 30.43-34.43^{o}C, low wind speed at an average of 0.77m/s, and high relative humidity at 53.6 - 73.27%. According to the result, there was a considerable variation in surface temperature and MRT, approximately 30^{o}C. The variations were mainly due to trees, building aspect ratio, street pattern, and land cover or surface material, highly in line with the key findings of previous studies in Malaysia. Through the sub-model (zoning) comparison, it was found that the discrepancy in urban geometry and vegetation abundance has made them result in different degrees of thermal resilience.

Moreover, based on the multivariate correlation analysis outcomes, MRT was most correlated with PET (0.98), emphasising the radiant heat created in the urban environment. Also, there was a possibility that wind was not conducive to thermal comfort in the site context of this research. The insights derived from this section has become the basic guidelines or design foundation for climate-led landscape design in the later sections.

In Chapter 4, a pilot model study was conducted. Prior to that, it emphasised the greening threshold in terms of feasibility in design and planning. A total of nine greening prototypes were developed based on road types in the study area. All design prototypes were firstly screened in terms of green coverage ratio and pedestrian priority. The selected prototypes would be replicated into a pilot model for testing. In the process, two scenarios were created: one focused on maximum greening and another further considering the Ipoh downtown's heritage visibility. Both models considered the spatial allocation for pedestrian network connectivity. The design scenarios were simulated and compared with the baseline model to examine the degree of improvement. The decision was made by the comparison of their thermal performance and design integrity at last.

The simulation outcomes proved that the urban landscape planting could be evidence-based planned for urban thermal improvement. There was a significant improvement in thermal comfort by referring to the findings and recommendations in the previous section, especially in the highlight of the street planting strategy. Using scenario simulations also helped affirm the positive correlation between cooling magnitude and green coverage ratio, particularly in relation to tree coverage ratio. The effect of shrub and grass was relatively less reflected in MRT, wind and thermal comfort levels. Since there was no significant divergence between the design scenarios, the model encompassing most considerations for a historical urban environment like Ipoh was selected as design prototypes for the full-scale model. The recommended prototype considered a balance between thermal improvement, pedestrians experience, and heritage visibility.

Chapter 5 was a resultant of all studies made in the previous sections. It basically converted all feedbacks and recommendations presented in Chapters 3 and 4 into full-scale designs. Similarly, two scenarios were created based on different design approaches in practice. One was designed with only greening and essential pedestrian amenities. Another was the optimal design scheme, including developing full pedestrian zones, reorganising traffic networks, organising visitor trails and building bicycle routes. These additional efforts were not only to upgrade the walkability of the site but also to increase the spatial allocation for greenery. They were assessed and compared in terms of degrees of improvement in microclimate and thermal comfort. In the process, the study also correlated the cooling magnitude with the green coverage ratio and tree coverage ratio, enhancing the greening significance in urban thermal improvement.

The study showed that the statistic outcomes have less reflected the improvement compared with the maps. The changes in the parameter distribution were relatively apparent. Statistically, only 0.11% of the basic design model area and 0.2% of the optimal design model area were converted from thermal discomfort to thermal comfort during the hottest hour. Nevertheless, a remarkable rise was found in the acceptable thermal comfort range(warm condition), from only 6.85% to 14.37% (basic design model) and 15.25% (optimal design model). The slight discrepancy between the design models was mainly due to the low difference in the tree coverage ratio, which again affirmed the high dependence of thermal comfort on trees' function. Despite only having a little more thermal advantages than the basic design model, the optimal model embodied more far-reaching objectives. It strongly encouraged walking and cycling as the primary mode of mobility in the study area by providing a more pedestrian-friendly outdoor environment. Its effects have indirectly impacted the reduction of heat, pollutants and exhaust emissions from cars, the psychological adaptation in outdoor thermal comfort, the pedestrian-oriented development and urban revitalisation. These long-term impacts were considerable for mitigating and adapting to climate change.

Continued from Chapter 5, Chapter 6 further studied the zoning' thermal performances using micro-scale and higher resolution. This section continued the thermal comparisons between zonings and scenarios to determine their differences and development priorities under the same design approaches.

There are three main findings from this section. First, the open area coverage ratio (OACR) highly affected thermal comfort as well as greening effectiveness. High OACR would increase PET and lower the effectiveness of trees and vegetation. Second, microclimate and thermal comfort highly depended on the nature of site context instead of the ratio value of GCR and TCR. A higher GCR or TCR did not guarantee the greater improvement can be achieved. Likewise, the same GCR or TCR did not definitely bring the same effects or degree of improvement as well. Third, the ΔGCR (also known as the degree of implementation) was consistently correlated to Δmeasured parameter indexes (the degree of improvement) in a positive but non-linear relationship. The priority of development was finally determined by four criteria: from the worse thermal comfort condition in the existing condition; for the best thermal comfort improvement; for maximum comfort area ratio; and based on the significances of heritage and attractions.

Chapter 7 was another extension study of Chapter 5. It mainly explored the significance of buffer greening in urban cooling. By comparing four modified scenario models with another three primary models in Chapter 5, this section investigated whether greening created at the buffer zone did have thermal effects on the core area of the study area. The results showed that buffer greening was an effective booster or supplementary in the greening strategy. To expect the optimal degree of thermal improvement, both buffer greening and core greening were necessary. It implied greenery significance in and around the city, strengthening nature conservation in cities and adjacent regions.

Lastly, Chapter 8 mainly discussed the overall outcomes of the research, primarily focused on the final design framework of so-called climate-led landscape planning. This chapter distinguished the concept, objectives and approaches of climate-led design from other existing climate-based design ideas, such as climate-responsive. In summary, in addition to improving microclimate and human comfort, a climate-led model has a broad and active approach to support and optimise urban resilience and sustainability in the dimensions of physical, economic and social developments.

Overall, this research has demonstrated a quick-start guide on how the thermal consideration to be integrated into urban design and planning from a design point of view, beyond the contexts of pure climate physics and human physiological science. The workflow was consistent with the design science research (DSR) process widely used in the engineering field, with a collaborative mindset to increase the problem-solving intelligence for practical urban design activities. This study indicated that the use of modelling and simulation tools enable better exploration regarding climate effects and thermal comfort in the urban context. Simulating the microclimate has firstly provided necessary thermal information for the subsequent thermal comfort design and planning, whereas the scenarios simulations have helped to figure out the remedy to the case. In short, their main contribution was to define the site problem more precisely, assist in testing the hypothetical designs, and offer theoretical explanations of any phenomena related to designs. These result-oriented evaluations provided evidence-based insights for climate change mitigation and adaptation strategies in the planning design process, thereby minimising potential design failures during the implementation phase.

Most of the thermal sensation improvement was associated with vegetation, particular with the presence of trees. The trees layout, as well as their density, had a decisive influence on the degree of thermal improvement. Only continuous or dense tree canopies, especially along the roads and sidewalks, could create efficient shading and cooling, providing thermal comfort to the greatest extent at the pedestrian level. This research, finally, suggested that tree planting should be given priority in tropical urban landscape design and planning to accelerate urban thermal adaptability.

9.2 SIGNIFICANCES AND KEY LESSONS OF THE RESEARCH

9.2.1 Addressing Microclimate and Thermal Comfort at A Local Scale

This research has opened a window of opportunity for addressing microclimate and thermal comfort through street-level landscape design. Regarding climate-based design concepts, as discussed in Section 8.1 of the previous chapter, it can be found that the existing literature on climate and thermal comfort solutions are always too broad or too narrow. On the regional scale, more attention is placed on reducing carbon dioxide emissions, promoting green technologies, and improving energy management and consumer practices. On the micro-scale, the focus was relatively paid to climate-responsive architecture and green building design.

Although the landscape greening approach has also begun to receive attention in recent decades, it is still not a mainstream in urban design, especially in developing countries. Moreover, it is not difficult to notice that landscape design and greening are usually concentrated at squares, courtyards and parks only. By contrast, street-level greening has been rarely mentioned, even though streets occupy a substantial area of open spaces in urban areas.

This research, therefore, has particularly focused on street-level landscape design to increase the landscape position in climate change mitigation and adaptation at the local level. Urban landscapes act as a thermal responsive system in tune with the dynamics of outdoor environments. The key aspect of the landscape approach at the urban street level is comfort provision. It tends to maximise the shading by trees on the street level to provide optimal cooling to pedestrians and land surfaces.

9.2.2 Contribution to Pedestrian-oriented Development

Likewise, pedestrian-oriented development is usually discussed in a broad mission along with new urbanism and transit-oriented development. Implementing pedestrian-oriented design at the street level has always been a weakness in developing countries, including Malaysia. The landscape design and thermal comfort at the street level are often indispensable for a high-quality walkable street. Therefore, to promote this contemporary concept in the redevelopment plan of existing cities and towns, this study has regarded pedestrian-oriented design as the key indicator throughout the climate-led model development.

9.2.3 Contribution to Practices: a context-specific and integrated solution

Each region or city is unique in its physical, socio-economic and cultural characteristics, as well as its impacts on microclimate and human thermal comfort. This research framework, therefore, has strongly emphasised and promoted local and autonomous approaches. With the use of scientific means (computing modelling and simulation), this research has abled to:

a. recognise the local thermal problems in a more precise approach;
b. transform the climate-awareness insights into practical design solutions;
c. make the entire process of urban design, planning, and decision-making more evidence-based and result-oriented; and
d. integrate the climate solutions with the local development, adhere to the local potentials and promote sustainable development.

9.2.4 Contribution to Ipoh/Malaysia landscape design and planning: a climate-based study framework & design and planning guidelines

First of all, the study framework has involved and covered four phases of implementation: analysis, design, evaluation and decision making. Through the climate-led framework, this study formulated several measures and strategies for improving urban climate and pedestrian comfort in Ipoh, as well as other similar cities and towns in Malaysia. The core of these measures and strategies shading provision at the street level to minimise the degree and amount of solar radiation that could reach the outdoor ground and people, as summarised below:

a. Shading tree selection:
   - The recommended street tree size is 3-5 meters in crown size and 5-10 meters in height.
   - Tree species and the interval of trees should be studied, not only to ensure that it does not affect the tree growth but also to secure the visibility towards the historic building façade as well.

b. Spatial arrangement:
   - With full consideration to pedestrians, converting some one-way roads to two-way roads in Ipoh is recommended.
   - The roadside trees should be planted continuously to create efficient shading for pedestrians and land surfaces, avoiding scattered or clustered tree planting.

- It should be a minimum of two tree rows on the streets and along with sidewalks. An additional tree row at the road median should be considered for wide-open streets to maximise the green coverage area on streets.
- Without efficient building's shade, open spaces, such as parking spaces, must be planted with denser or larger trees.
- The conservation of the existing green zone is necessary. Those abandoned spaces with dense green should be protected and converted to be natural reserves. If they cannot be avoided for redevelopment, the green coverage ratio should be kept as much as possible in the new master plan.
- It should be additional greening along the open railway and riverfront.
- The development of full pedestrian zones at small lanes and alleys are encouraged.
- In case that tree shading is not sufficient, the combination of covered walkway and vegetation, or other semi-outdoor designs, is recommended.

Last but not least, this study has also highlighted the significance of buffer greening for urban thermal improvement. The outcomes, therefore, strongly supported off-site natural conservation. At the same time, it provided evidence of microclimate effects caused by land overexploitation and urban sprawl, calling to impose more controls and restrictions on such urban activities in order to minimise the thermal degradation in urban areas.

9.3 LIMITATIONS OF STUDY

Integrated urban thermal modelling and simulation-based research is still a relatively new technique in urban research and urban design. Throughout the study, limitations of software and time have been the primary constraints in this study. Since most relevant software tools are still in the development stage, there is an immensely limited choice of software for integrated urban thermal simulations. Also, even though ENVI-met software has been selected as the most appropriate tool to access outdoor microclimate, several constraints existed in model building for Ipoh. For example, it only supports flat-roof structures. In this case, other complex roof types, such as gable roofs and hipped roofs commonly found in tropical cities, could not precisely be replicated into the model for evaluation. Also, the limited resources in the existing database for planting species has increased the difficulty in identifying exact trees types for simulations.

Besides, ENVI-met typically supports small-scale models. Studying a city-size model using ENVI-met has resulted in an extremely long simulation time for each model. In this study, it took about 18-25 days for each macro-scaled model (full-scale studies in a model size of approximately 2km x 1.5km) and 7-15 days for each micro-scaled model (zoning studies with the model sizes ranged from 400m X 400m to 540m X 500m). The advancement of technology in computing equipment, including the processing unit and the volume amount of space and memory, was essential for the stability of simulations and the time consumed. Otherwise, the lengthy simulation-based assessment would eventually drag the whole design process, less efficient in actual practices.

Other than that, the far-reaching effects of a climate-led model so far cannot be quantitatively estimated by using modelling and simulation approaches. For example, the reduction of CO2 emission. Even though it is not the focus of this research, the implementation of the proposed model, to a certain extent, is foreseeable to reduce CO2 emissions by cars. Of course, that will be an evolutionary process. Currently, most of the open spaces in existing cities and towns are occupied by roads with cars. In such a condition, the greening magnitudes at the beginning of climate-led design and planning are significantly confined to the limited spaces at the current street level. However, this situation can be gradually improved after implementation.

Imagine that when the pedestrian-oriented system becomes more mature, and an increasing number of people prefer to walk instead of using cars, the demand for pedestrian spaces will increase accordingly. In contrast, the decline in the number of cars will relatively reduce the necessity of roads in cities and towns. In this case, more roads will be less used and converted for pedestrian uses. The increase of pedestrian spaces in cities and towns will promote more landscape greening. The resulting landscape greening and the decreased anthropogenic emissions will help restore the positive carbon cycle in cities and towns and eventually ameliorate urban heat island (UHI) and climate change effects of the region.

9.4 SUGGESTIONS FOR ACTUAL IMPLEMENTATION AND FUTURE STUDIES

Landscape elements, especially trees, is the crucial key to the success of a climate-led landscape strategy. Indeed, living design elements are not as easily handled as non-living design elements like building structures and hardscapes. Moreover, due to the cost consideration, many cities will purchase small trees at low prices in hopes of someday having large shade trees. The challenges of this kind of practice usually include that the trees may not grow in the expected height, size or shape in the end. Such a trend is somehow unavoidable, but urban designers/planners can minimise the possibilities that affect their growth. There are a few considerations for this aspect during the design and planning stage, including the tree species selection, the planting layout design and planning, the technique and technologies used.

- Tree species selection is the most crucial. The focus should be placed on the tree crown shape, root size, growth rate, life span, and vulnerability. In order to increase the survival rate and successfully meet the standard, it is also important to study and adopt local native species or species recommended by the local landscape department. Also, tree planting is something experimental, and you can never predict its growth precisely. In this case, mixed-species planting is more secure than monoculture practices, not only increasing the survival rate but also enhancing the resistance and resilience of trees, contributing to the stability of tree growth in the target area. In simulations, to produce more accurate results for reference, it is necessary to have more effort in simulating different tree models (by considering their 3D layout accurately).
- Next is the planting design layout. The spatial arrangement is important for tree growing. The distance of trees with people, vehicles, buildings, street lamp poles, road signs, fire hydrants, and so on will determine the stress on trees. In other words, the distribution pattern and coverage area should be designed and planned in tune with the living condition of selected species. Otherwise, unsatisfactory growth is expected. This topic can be another scope of studies, which is fundamental for street planting in urban areas
- Last is the site monitoring and maintenance. The techniques and technologies used will also affect the quality of trees and the time for them to grow. The local authority should have sufficient knowledge to deal with street tree planting and maintenance. For example, they should know how to deal with the possible stress over the root area

and other potential hazards caused by soil volume, quality and care (water, pruning, pest and diseases, etc.).

In conclusion, urban landscapes and greening are viable to secure urban thermal resilience and comfort, but they should be kept on close monitoring and observation. We should always expect the unexpected. In case that any unexpected has occurred, it should be handled through design adjustments (such as replacing the tree species, adding more trees by reducing tree intervals), or even a new planting strategy. Similarly, the study framework proposed in this thesis can be used to pre-evaluate new design decisions.

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APPENDIXES

Appendix 6.1. Summary of coverage area calculation between scenarios for Zone 1.

Total	Scenario 1 (Baseline mode)				Scenario 2 (Basic mode)				Scenario 3 (Optimal mode)			
	Area (m^2)	Percentage (%)	No. of raster cell	Percentage (%)	Area (m^2)	Percentage (%)	No. of raster cell	Percentage (%)	Area (m^2)	Percentage (%)	No. of raster cell	Percentage (%)
Study Area (A)	160000	100	40200	100	160000	100	40000	100	160000	100	40000	100
Building Area (B)	70629	44.14	17843	44.39	70629	44.14	17643	44.11	70629	44.14	17643	44.11
Open Area (A-B)	89371	55.86	22357	55.61	89371	55.86	22357	55.89	89371	55.86	22357	55.89
CASE I: OVERALL												
Green coverage (C)	17971	11.23	4473	11.13	43431	27.14	10839	27.10	51791	32.37	12908	32.27
Tree coverage (D)	6427	4.02	1594	3.97	17962	11.22	4451	11.13	18342	11.46	4604	11.51
Non-tree coverage (C-D)	11544	7.21	2879	7.16	25469	15.92	6388	15.97	33449	20.91	8304	20.76
CASE II: OPEN AREA ONLY												
Green coverage (C)	17971	20.11	4473	20.01	43431	48.60	10839	48.48	51791	57.95	12908	57.74
Tree coverage (D)	6427	7.19	1594	7.13	17962	20.10	4451	19.91	18342	20.52	4604	20.60
Non-tree coverage (C-D)	11544	12.92	2879	12.88	25469	28.50	6388	28.57	33449	37.43	8304	37.14

Appendix 6.2. Summary of coverage area calculation between scenarios for Zone 2.

Total	Scenario 1 (Baseline mode)				Scenario 2 (Basic mode)				Scenario 3 (Optimal mode)			
	Area (m^2)	**Percentage (%)**	**No. of raster cell**	**Percentage (%)**	**Area (m^2)**	**Percentage (%)**	**No. of raster cell**	**Percentage (%)**	**Area (m^2)**	**Percentage (%)**	**No. of raster cell**	**Percentage (%)**
Study Area (A)	270000	100	68021	100	270000	100	67500	100	270000	100	67500	100
Building Area (B)	127026	47.05	32281	47.46	127026	47.05	31760	47.05	124844	46.24	30880	45.75
Open Area (A-B)	142974	52.95	35740	52.54	142974	52.95	35740	52.95	145156	53.76	36620	54.25
CASE I: OVERALL												
Green coverage (C)	20727	7.68	5194	7.64	50374	18.66	12581	18.64	72684	26.92	18174	26.92
Tree coverage (D)	14689	5.44	3512	5.17	27692	10.26	6814	10.10	31220	11.56	7682	11.38
Non-tree coverage (C-D)	6038	2.24	1682	2.47	22682	8.40	5767	8.54	41464	15.36	10492	15.54
CASE II: OPEN AREA ONLY												
Green coverage (C)	20727	14.50	5194	14.53	50374	35.23	12581	35.20	72684	50.07	18174	49.63
Tree coverage (D)	14689	10.28	3512	9.83	27692	19.37	6814	19.06	31220	21.51	7682	20.98
Non-tree coverage (C-D)	6038	4.22	1682	4.70	22682	15.86	5767	16.14	41464	28.56	10492	28.65

Appendix 6.3. Summary of coverage area calculation between scenarios for Zone 3.

Total	Scenario 1 (Baseline mode)				Scenario 2 (Basic mode)				Scenario 3 (Optimal mode)			
	Area (m^2)	Percentage (%)	No. of raster cell	Percentage (%)	Area (m^2)	Percentage (%)	No. of raster cell	Percentage (%)	Area (m^2)	Percentage (%)	No. of raster cell	Percentage (%)
Study Area (A)	200000	100	50250	100	200000	100	50000	100	200000	100	50000	100
Building Area (B)	86783	43.39	21928	43.64	86783	43.39	21678	43.36	86783	43.39	21678	43.36
Open Area (A-B)	113217	56.61	28322	56.36	113217	56.61	28322	56.64	113217	56.61	28322	56.64
CASE I: OVERALL												
Green coverage (C)	27433	13.72	6888	13.71	47623	23.81	11997	23.99	55897	27.95	13882	27.76
Tree coverage (D)	10965	5.48	2752	5.48	21176	10.59	5313	10.62	23040	11.52	5781	11.56
Non-tree coverage (C-D)	16468	8.24	4136	8.23	26447	13.22	6684	13.37	32857	16.43	8101	16.20
CASE II: OPEN AREA ONLY												
Green coverage (C)	27433	24.23	6888	24.32	47623	42.06	11997	42.36	55897	49.37	13882	49.01
Tree coverage (D)	10965	9.68	2752	9.72	21176	18.70	5313	18.76	23040	20.35	5781	20.41
Non-tree coverage (C-D)	16468	14.55	4136	14.60	26447	23.36	6684	23.60	32857	29.02	8101	28.60

Appendix 6.4. Summary of coverage area calculation between scenarios for Zone 4.

Total	Scenario 1 (Baseline mode)				Scenario 2 (Basic mode)				Scenario 3 (Optimal mode)			
	Area (m^2)	Percentage (%)	No. of raster cell	Percentage (%)	Area (m^2)	Percentage (%)	No. of raster cell	Percentage (%)	Area (m^2)	Percentage (%)	No. of raster cell	Percentage (%)
Study Area (A)	200000	100	50451	100	200000	100	50000	100	200000	100	50000	100
Building Area (B)	52086	26.04	13489	26.74	52086	26.04	13038	26.08	52086	26.04	13038	26.08
Open Area (AB)	147914	73.96	36962	73.26	147914	73.96	36962	73.92	147914	73.96	36962	73.92
CASE I: OVERALL												
Green coverage (C)	54677	27.34	13843	27.44	60209	30.10	15025	30.05	75581	37.79	18876	37.75
Tree coverage (D)	14469	7.24	3632	7.20	18790	9.39	4705	9.41	19607	9.80	4919	9.84
Non-tree coverage (C-D)	40208	20.10	10211	20.24	41419	20.71	10320	20.64	55974	27.99	13957	27.91
CASE II: OPEN AREA ONLY												
Green coverage (C)	54677	36.97	13843	37.45	60209	40.71	15025	40.65	75581	51.10	18876	51.07
Tree coverage (D)	14469	9.78	3632	9.83	18790	12.71	4705	12.73	19607	13.26	4919	13.31
Non-tree coverage (C-D)	40208	27.19	10211	27.62	41419	28.00	10320	27.92	55974	37.84	13957	37.76

Appendix 6.5. Comparison of air temperature between scenarios and zonings (mean, minimum and maximum).

AT (ºC)	Model	Scenario 1 (A)	Scenario 2 (B)	B-A	Scenario 3 (C)	C-A	B-C
Maximum	Zone 1	*34.67*	*34.31*	-0.36	*34.2*	-0.47	-0.11
	Zone 2	*34.58*	*34.34*	-0.24	*34.22*	-0.36	-0.12
	Zone 3	*34.32*	*34.2*	-0.12	*34.13*	-0.19	-0.07
	Zone 4	*34.69*	*34.55*	-0.14	*34.47*	-0.22	-0.08
Mean	Zone 1	*32.25*	*31.94*	-0.31	*31.73*	-0.52	-0.21
	Zone 2	*31.94*	*31.75*	-0.19	*31.55*	-0.39	-0.2
	Zone 3	*31.86*	*31.68*	-0.18	*31.54*	-0.32	-0.14
	Zone 4	*32.73*	*32.63*	-0.1	*32.42*	-0.31	-0.21
Minimum	Zone 1	*30.7*	*30.34*	-0.36	*30.22*	-0.48	-0.12
	Zone 2	*30.46*	*30.5*	0.04	*30.34*	-0.12	-0.16
	Zone 3	*30.5*	*30.08*	-0.42	*29.85*	-0.65	-0.23
	Zone 4	*31.07*	*30.45*	-0.62	*30.37*	-0.7	-0.08

Appendix 6.6. Comparison of surface temperature between scenarios and zonings (mean, minimum and maximum).

ST (ºC)	Model	Scenario 1 (A)	Scenario 2 (B)	B-A	Scenario 3 (C)	C-A	B-C
Maximum	Zone 1	54.23	53.79	-0.44	53.69	-0.54	-0.1
	Zone 2	54.76	54.1	-0.66	53.73	-1.03	-0.37
	Zone 3	54.46	53.73	-0.73	53.66	-0.8	-0.07
	Zone 4	54.32	54.24	-0.08	54.16	-0.16	-0.08
Mean	Zone 1	41.71	37.9	-3.81	36.33	-5.38	-1.57
	Zone 2	42.56	39.76	-2.8	37.64	-4.92	-2.12
	Zone 3	41.42	39.17	-2.25	37.81	-3.61	-1.36
	Zone 4	42.51	41.95	-0.56	40.38	-2.13	-1.57
Minimum	Zone 1	22.98	21.18	-1.8	20.98	-2	-0.2
	Zone 2	23.37	22.16	-1.21	21.83	-1.54	-0.33
	Zone 3	23.32	22.02	-1.3	21.8	-1.52	-0.22
	Zone 4	24.04	23.7	-0.34	23.62	-0.42	-0.08

Appendix 6.7. Comparison of mean radiant temperature between scenarios and zonings (mean, minimum and maximum).

MRT (ºC)	**Model**	**Scenario 1 (A)**	**Scenario 2 (B)**	**B-A**	**Scenario 3 (C)**	**C-A**	**B-C**
Maximum	Zone 1	64.76	61.17	-3.59	60.89	-3.87	-0.28
	Zone 2	64.45	61.95	-2.5	61.87	-2.58	-0.08
	Zone 3	64.58	62.12	-2.46	61.59	-2.99	-0.53
	Zone 4	67.09	66.55	-0.54	65.92	-1.17	-0.63
Mean	Zone 1	56.74	49.98	-6.76	49.31	-7.43	-0.67
	Zone 2	55.79	50.59	-5.2	49.9	-5.89	-0.69
	Zone 3	55.96	51.05	-4.91	50.09	-5.87	-0.96
	Zone 4	61.59	60.04	-1.55	59.33	-2.26	-0.71
Minimum	Zone 1	32.44	27.13	-5.31	26.65	-5.79	-0.48
	Zone 2	31.79	28.58	-3.21	27.94	-3.85	-0.64
	Zone 3	32.73	28.3	-4.43	27.81	-4.92	-0.49
	Zone 4	34.66	33.45	-1.21	33.12	-1.54	-0.33

Appendix 6.8. Comparison of wind speed between scenarios and zonings (mean, minimum and maximum).

WS (m/s)	**Model**	**Scenario 1 (A)**	**Scenario 2 (B)**	**B-A**	**Scenario 3 (C)**	**C-A**	**B-C**
Maximum	Zone 1	3	3	0	3	0	0
	Zone 2	2.86	2.62	-0.24	2.63	-0.23	0.01
	Zone 3	2.38	2.35	-0.03	2.36	-0.02	0.01
	Zone 4	2.07	2.01	-0.06	2.02	-0.05	0.01
Mean	Zone 1	0.72	0.64	-0.08	0.64	-0.08	0
	Zone 2	0.59	0.53	-0.06	0.53	-0.06	0
	Zone 3	0.68	0.62	-0.06	0.6	-0.08	-0.02
	Zone 4	0.96	0.89	-0.07	0.87	-0.09	-0.02
Minimum	Zone 1	0.01	0.01	0	0.01	0	0
	Zone 2	0.01	0.01	0	0.01	0	0
	Zone 3	0.01	0.01	0	0.01	0	0
	Zone 4	0.01	0.01	0	0.01	0	0

Appendix 6.9. Comparison of relative humidity between scenarios and zonings (mean, minimum and maximum).

RH (%)	Model	Scenario 1 (A)	Scenario 2 (B)	B-A	Scenario 3 (C)	C-A	B-C
Maximum	Zone 1	65.73	68.64	2.91	69.26	3.53	0.62
	Zone 2	67.8	68.88	1.08	69.73	1.93	0.85
	Zone 3	67.38	68.66	1.28	69.12	1.74	0.46
	Zone 4	65.19	67.42	2.23	67.71	2.52	0.29
Mean	Zone 1	60.62	62.27	1.65	63.19	2.57	0.92
	Zone 2	61.18	62.36	1.18	63.45	2.27	1.09
	Zone 3	61.87	63.01	1.14	63.68	1.81	0.67
	Zone 4	59.64	60.19	0.55	61.19	1.55	1
Minimum	Zone 1	52.49	53.6	1.11	54	1.51	0.4
	Zone 2	53.01	53.45	0.44	53.79	0.78	0.34
	Zone 3	53.68	53.97	0.29	54.52	0.84	0.55
	Zone 4	52.34	53.25	0.91	53.48	1.14	0.23

Appendix 6.10. Comparison of PET between scenarios and zonings (mean, minimum and maximum).

PET	Model	Scenario 1 (A)	Scenario 2 (B)	B-A	Scenario 3 (C)	C-A	B-C
Maximum	Zone 1	51.7	49.2	-2.5	48.9	-2.8	-0.3
	Zone 2	51.1	49.5	-1.6	49.3	-1.8	-0.2
	Zone 3	50.8	49.2	-1.6	48.9	-1.9	-0.3
	Zone 4	52.9	52.5	-0.4	52.1	-0.8	-0.4
Mean	Zone 1	45.12	41.32	-3.8	40.82	-4.3	-0.5
	Zone 2	44.66	41.74	-2.92	41.21	-3.45	-0.53
	Zone 3	44.41	41.68	-2.73	41.12	-3.29	-0.56
	Zone 4	47.46	46.66	-0.8	46.14	-1.32	-0.52
Minimum	Zone 1	32.7	29.7	-3	29.4	-3.3	-0.3
	Zone 2	32.3	30.7	-1.6	30.2	-2.1	-0.5
	Zone 3	32.9	30.3	-2.6	30	-2.9	-0.3
	Zone 4	34	33.3	-0.7	33.1	-0.9	-0.2

RESPONSES TO EXAMINER'S COMMENTS

Examiner 1: Prof. Shunji Suzuki

PART I: Questions/Comments during presentation

1. **How do you expect the tree condition be consistent? For example, the tree size. As landscape is some living things and changing, how do you set the standard and how do you monitor that? The assumption has no problem as long as when you take this as the precondition of your simulation.**
   Response:
   Please refer to Section 9.4 of the thesis.

PART II: Questions/Comments by email dated 14th May 2021:

1. **Traffic (partially discussed in the presentation session)**
   You suggested to change some one-way traffic to two-ways, mainly because you can plant more trees, but it will not be good to make a walkable city, as wide streets will bring in more through traffic and divide town centers. People will not walk on street just because it is shaded.
   Response:
   Please refer to the response for question/comment no.1. in Part III.

2. **Zone setting**
   How did you set the four zones? What are the reasons and characteristics of each zone? It needs to be explained as preconditions to discuss on the priority of policy application.
   Response:
   Basically, I set these 4 zones based on site characters in terms of built form layout patterns, heritage valued and attractions (main activities on-site). But based on your comments in Part III question/comment no.4., it was lack of information explaining the setup of their boundaries, size, shape. Hence, I have created one more section in Chapter 3 to add in the sub-model description. Please refer to Section 3.3 of the thesis.

3. **Building Coverage, and materials**
   As mentioned in your presentation, ground coverage by building - area, material - matters in discussing "heat island". I understand that your main interest is not on that, but you may refer to it more precisely as a task for future studies.
   Response:
   Well noted.
   It is also worth noting even though urban heat island (UHI) is not exactly mentioned, nor comparison between the UHI intensity of daytime and night time in this study, the warming effects created by building and ground materials during the day was emphatically considered, and reflected in monitoring and improving land surface temperature.

In addition, it is well known that the intensity of heat retained and released at night mainly depends on the heat absorbed and stored by roads, buildings and other structures during the day. From an urban design perspective, the ultimate solution must always be started from thermal improvement, or cooling, during the hot hours in the daytime. In this case, this is also why this research has consistently focused on building thermal resilience and comfort based on the daytime hot hour condition.

Please also refer to the last two paragraphs in new Chapter 9.3, where discussing the ultimate effects of climate-led approach in urban design.

4. <u>**Brick surface on street**</u>

   You should mention about the water permeability of the brick, and may consider the difference by the factor in your future studies. The permeability of brick surface will be reduced by age deterioration, which should be considered as well.

   <u>Response:</u>

   Thanks for the suggestion. However, this factor has beyond the scope of my design study using ENVI-met modelling and simulation. There are no such modules embedded in ENVI-met system taking into account the water permeability of bricks. In the simulation of ENVI-met, the land surfaces including brick pavement were only calculated in terms of soil profil, albedo, and emissivity. Since this subject is not the main focus of the thesis study, it may only be further explored in future studies.

5. **Latent heat**

   The air environment and PET may be influenced by latent heat, by the evaporation from leaves. It may not be easy to simulate the effect, however.

   <u>Response:</u>

   This part has been covered by ENVI-met system. Please refer to the additional Section 2.4.3.1 of the thesis.

<u>PART III: Questions/Comments by email dated 21st May 2021</u>

1. **In some of your street sections, the width of sidewalk is 2.5m or less, which is not considered wide enough for pedestrian activities. Generally, it should be wider than 3m. The width of tree plant strip should be at least 1.5m to house a medium or tall size trees. It can be "root container box", of which the horizontal size is larger than 1.5m x 1.5m.**

   <u>Response:</u>

   First, I am sorry for not clarifying this during presentation in advance. Undeniably, 1m-width median was used in the prototype stage. However, in the full-scale design (in Chapter 5), particularly at New Town and some part in Old Town where the building edge-to-edge distance was larger than 15m in width, the road median has been reset to 1.5m in width (same to some planting zone along the walkway). Hence, it should not become the main issue in design implementation at last. This is not explained before as the size difference did not much affect the simulation results (within the grid size of 2m and 5m).

Overall, I also agreed that the bigger is better, indeed. The reason of using 1m-width will be explained. To keep the number of car lanes in most of the small roads in the shophouse area, and to follow some restrictions in the local planning (such as standards on car lane size and parking lots dimension), the landscape dimensions had to be set to a minimum standard to explore possible greening prototypes.

Also, by referring to the local guidelines shown in Appendix 1 (Malaysia Federal Department of Town and Country Planning, 2012, pp.36-37), we can see that it is so far no median and tree planting zone recommended for 15m-road model (case I). As alternative solution, I adopted and modified the 20m-road model (cases II & III) for my greening prototype study. Due to the limited space, I had to reduce the pedestrian area/planting area (including the median area). In this case, I referred to case II in Appendix 1 and set the walkway size at 2.5m (or even less depending on the space available). The road median and planting strip size had to be reduced to a maximum extent, as long as it fit to the standard tree hole dimensions shown in Appendix 2 (Malaysia National Landscape Department, 2008, pp. 72-73). It is a weak point for not using a mature tree hole standard.

Lastly, the design itself is a variable. The recommended prototype/design model always requires further adjustment to be acceptable for implementation. It may have better ideas through real practices or direct dealing with local planners/designers.

2. **In your section 3b, you put 1m-width of tree planting median and say it is effective, but it is questionable if it works as you assumed. It will not be used as pedestrian space.**

   Response:

   For the question regarding 1m-width of tree planting median, please refer to my response in question/comment no.1 in Part III.

   Next, the median was a planting zone and not pedestrian space. Only the openings at the both end of road median (next to intersections) are used as pedestrian refuge island. In terms of size, the population and pedestrian volume in the small-scaled city like Ipoh is not as big as in those big cities like Tokyo. Furthermore, it should consider the length of the island instead of its width. The 1m-width island is not a problem to accommodate a small group of pedestrians crossing the multilane road at the same time when people usually wait and stand in a row with the road median.

3. **With reasons above, I have difficulty to agree with your opinion "two-way roads will be good to make a walkable city as it would slow down the traffic, increase pedestrian-friendliness and regenerate the town centers", simply because it has more green/pedestrian space than one-way traffic.**

   Response:

   Providing more green/pedestrian space is not the only reason for me to propose two-way roads. Please refer to my response in question/comment no.2 in Part III.

   Back to the design intention, changing one-way to two-way is mainly to make the road as two shorter one-way roads. After changed, there will be only one lane for each direction, so pedestrian just have to be aware of one single car at one-direction in one time. The 1m-width space acts as a safe harbour for pedestrian after managing one direction of traffic and before taking on the next. In other words, it provided staged crossing for pedestrians on the road. Other than that, there are many supporting literatures discussing on this subject, as shown in below. From there, it showed that more studies concluded that two-way system has advantages over one-way system for pedestrians and local communities.

- Gheorghe, C. (2017, October). Comparative analysis of the performance of One-Way and Two-Way urban road networks. In IOP Conference Series: Materials Science and Engineering (Vol. 252, No. 1, p. 012056). IOP Publishing.
- Gayah, V. V. (2012). Two-way street networks: More efficient than previously thought?. ACCESS Magazine, 1(41), 10-15.
- Baco, M. (2009). One-way to two-way street conversions as a preservation and downtown revitalization tool: The case study of Upper King Street, Charleston, South Carolina.
- Wazana, A., Rynard, V. L., Raina, P., Krueger, P., & Chambers, L. W. (2000). Are child pedestrians at increased risk of injury on one-way compared to two-way streets?. Canadian Journal of Public Health, 91(3), 201-206.
- https://www.cnu.org/publicsquare/2019/07/09/cities-benefit-one-way-two-way-conversions
- https://www.ayresassociates.com/one-way-or-the-other-two-way-traffic-conversion-requires-study/
- http://www.pedbikesafe.org/pedsafe/countermeasures_detail.cfm?CM_NUM=23

4. **Zone setting: You showed some characteristics of each zone in p.52, but the reason for setting up the boundaries, size, shape is not clear, so it is better to have more explanation.**

   Response:

   Please refer to my response in question/comment no.2 in Part II.

Examiner 2: Prof. Dr Tetsu Kubota

PART IV: The originality of this study

This point, for me, is still not so clear. I do agree and intend to tell you that the new title now is better - "climate-led" instead of "climate-responsive". And I believe that is the originality of your thesis. SO, what is the difference and the originality of that? Please clarify the climate-led planning method compared to the existing climate-responsive planning method.

Also, based on slide.no 15, I do not think design-based study is still something new. There are many literatures available, for instance, Hong Kong. Their team do this kind of research intensively and they also implement this kind of climate-oriented design for their urban planning in Hong Kong. Some books, such as "Climate Considerations in Building and Urban Design" and "The Urban Climatic Map", also proposed the idea of climate-responsive designs, not only for building but also urban areas. We can find many examples, and even the implementation. So, I think you should distinguish and clarify the difference.

The resulting climate-led design strategy method should be the final outcome of your study. But now you discuss this point in the conclusion. Why don't you discuss this in the main part in the discussion, and clarify your original point compared with the existing planning method, and the novelty.

And also, based on slide no.8, the specific objectives are not so understandable and better to improve that. For me, this is just an outline of your thesis, the outline of your planning method, the procedure of your planning and strategy, but not the specific objectives. For me, the objective is what to do for each of the chapter. Anyway, again, the most important is that the originality of your study should be clarified clearly in the early part, in the introduction and discussion, not conclusion.

And plus, this is just my suggestion: it is better to propose your idea on the top of the existing methods/existing framework. You should propose not only yours but also the whole planning framework. I believe it would be much better than you do now. You tried to explain it in the very early part in the slide no.9, but you should try to do this in the final outcomes.

Points:

- **Climate-responsive design vs Climate led-design: still too abstract.**
- **The originality should be shown in the flowchart.**

<u>Response:</u>
Please refer to the following sections in the thesis:

- Section 2.2: the last paragraph.
- The new Chapter 8.

PART V: The scientific basis

1. For some of the things, I am sorry to say it is not valid.

For instance, you just simulated the peak hour of the specific month. Do you think it is reasonable to propose overall master plan only based on the simulation results of a specific hour?
I know the conditions of the tropics that seasonal variation is less but it is still there. And now you don't consider the seasonal variation. You also do not consider the temperature variation as well. The night time condition is also important. For instance, UHI is intense especially at the night time and that may increase energy consumption for cooling, in particular in the case of tropics.
My message is that it is a bit dangerous to give proposal only based on the day time especially peak hour alone. The seasonal variation, temperature variation, and especially when we talked about the mitigation, I believe the night time is also important.
You said that open space is not so good and ineffective in reduction of the day time temperature and so on. But how about night time. You release the heat more actually if you have large open space. This also mean the resulting condition is different according to the time.

Response:
Yes. I agreed on the necessity of full consideration on temperature and seasonal variation. However, due to the time constraint and different objectives of study, I only focused at the hottest hour recorded in actual condition for full analysis. Please refer to question/comment no.3 in Part II, where related to this question/comment as well. However, the main study objective is to propose a microclimate and thermal comfort simulation-based study and design model for landscape redevelopment. In this case, the specific time study did not much affect the flow of study and analysis.

2. The simulation

I know this is not the science study but at least make sure the boundary condition, the thermal property, the building fabrics, the surface material and so on. The key is the trees. You better to discuss and explain/describe how do you simulate the trees. How you simulate the evaporation and so on. I think better to explain about the setting and methodology. For instance, the boundary condition, the nesting configuration, or the terminal models that you used. Otherwise, no one can reproduce your result.

Response:
Please refer to the following sections in the thesis, where responded to all above-mentioned questions:

- Table 3.5: provided all initial and boundary condition of simulation used in ENVI-met.
- Section 2.4.3.1: explained the basics of ENVI-met simulations and also how it simulates trees.

3. **The validation**
   a. **How do you simulate the cloud condition? Based on slide no. 23, now you said that this is good as the r square is high. But if you take a look at the left-hand side, why there is some inconsistency…what do you think? I believe the cloud cover was not well simulated based on my experience. Most probably, the observation result was a cloudy day (overcast condition) Anyway, in the tropics, cloud cover is very important, so better to clarify. Also, if possible, better to do the validation not only for air temperature but also other parameters, because you used other parameters in the analysis. Is this statistic or non-statistic? Please explain this after this.**

      Response:
      Yes. It is a clear sky setting in simulation.
      For validation, please refer to the amended Section 3.5 of the thesis.

   b. **The explanation for ENVI-met and PET are not enough…at least do explain the scientific basis behind, the governing equation and so on. Otherwise, it is too brief.**

      Response:
      Please refer to the Section 2.4.2 (PET) and Section 2.4.3.1(ENVI-met) of the thesis.

   c. **The multivariate analysis for PET. It is questionable when look at the result of multi-variate analysis at slide no.30. Basically, the relationship is not linear. So I think you should understand the basic principle of PET. They calculate heat transfer differently (the conditional transfer and then the radiant heat transfer and so on). And in your manual, there is no linear relationship between RH and PET, but now you tried to explain them linearly**
      You said velocity has a negative relationship. I don't think so. Even if the temperature is high, if you received the velocity in the tropics, that can contribute to the evaporation, so I think it is possible to reduce PET. So why we could not see the wind effect? I believe that the background wind is very low, so the wind effect is offset by probably the MRT.
      Most of the data are divided into two groups. What is the reason? Please explain later. These may have some reasons/should have some reasons, so better you reconsider the validation, if possible. At least, better to brush up the validation.

      Response:
      Please refer to the new Section 3.6.6 of the thesis.

PART VI: The location

I knew you have already mentioned somewhere in the thesis. But for instance, wind. Wind is weak and therefore we cannot see the effects. This is because Ipoh is an inland and I know the wind speed is particularly low because of the location. It makes sense in the case of Ipoh where the wind speed is very low and the shading tree is the best option. But what if in different cities, such as coastal cities like JB, Jakarta, where the wind is there?
Of course, the result will be different. So, in this case, I think you should discuss/point that at somewhere: I think greening is very effective partly because of the wind condition. If the for windy city, planting trees may block the wind. So, the proposal should do consider local climate condition.

Response:
Please refer to the last paragraph in new Chapter 8.1

PART VII: Quantify the effects of CO2 emission reduction, if possible.

Response:
Please refer to the last two paragraphs in new Chapter 9.3, where discussing the ultimate effects of climate-led approach in urban design.

Examiner 3: Prof. Dr Hitoshi Kuwata

PART VIII: Questions/Comments

1. **Explain more about the multivariate correlation in the thesis. It is multivariate so how many types of analysis?**

Response:
Please refer to the new Chapter 3.6.6

2. **In general, please give us some charts besides the table to easily understand your results. You made so many tables in your thesis. So, some graphical charts will be better, so add some charts please.**

Response:
A total of 16 Tables was amended.

- Changed from Tables to Figures:
    - Tables 3.9 have been changed as Figures 3.19
    - Tables 3.10 have been changed as Figures 3.22
    - Tables 3.11 have been changed as Figures 3.23
    - Tables 3.12 have been changed as Figures 3.29
    - Tables 3.13 have been changed as Figures 3.32
    - Tables 3.14 have been changed as Figures 3.36

- The following tables were not necessary in the main body of Chapter 6 and shifted to Appendixes:
    - Tables 6.1-6.4 are the database of Table 6.5.
    - Table 6.6 shared same information with Figure 6.10
    - Table 6.8 shared same information with Figure 6.11
    - Table 6.10 shared same information with Figure 6.12
    - Table 6.12 shared same information with Figure 6.13
    - Table 6.13 shared same information with Figure 6.14
    - Table 6.15 shared same information with Figure 6.20

3. **In your simulation, in terms of traffic, the one-way road and two-way road. I don't understand why you change one-way to two-way. You said about some prototypes before that. Is that you reduced some traffic lane to plant trees? Why you need to change the traffic (direction)?**

Response:

Explained and accepted during presentation.

Also, it was explained again to Prof Suzuki. Please refer to my response in his question/comment no. 2 &3 in Part III.

Examiner 4: Prof. Dr Hidetoshi Maeda

PART IX: Questions/Comments:

I have 2 advices and recommendation to your completion, which are both related to each other.

One is your conclusion. I think your conclusion is very sad compared to your work in the former chapters, in which you simulated it in detailed, and many understandings and findings in the former chapters. I expected that in your conclusion, I would have some design guidelines or guidelines for zoning. For example, to plant trees per 10m, or something like that.

I know you avoid the generalisation because you look at only one city. But if you can make clear why you selected the city in this thesis (for example, this city or this district is very meaningful to develop your idea or theory) and the meaning of your selection, you can make specific or more practical conclusions.

I think if you do that, your thesis will be more original. Now your conclusion is sound like too natural. Your conclusion is very clear, but too clear and too general to apply to real project. So, just make clear why you selected this district and you can go further about your conclusion to make it more practical~

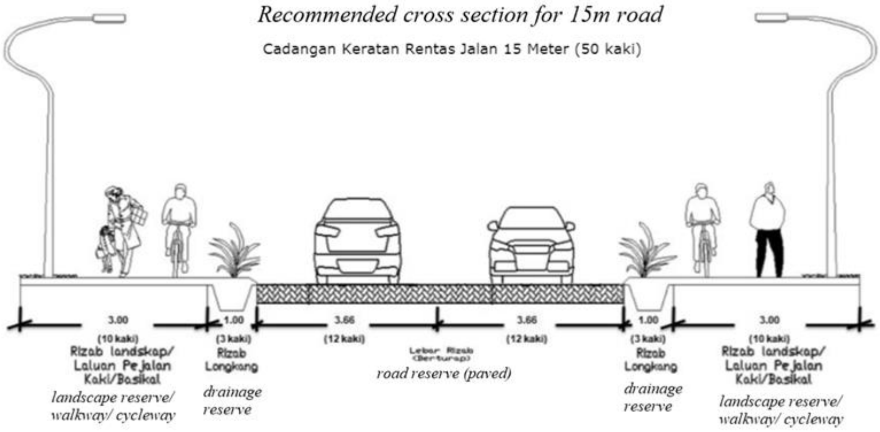
Response:

- Please refer to Chapter 1.5.1（site selection and reasons）
- Please refer to Chapter 9.2 (significances and key lessons of the research, especially Section 9.2.4)

Appendixes I

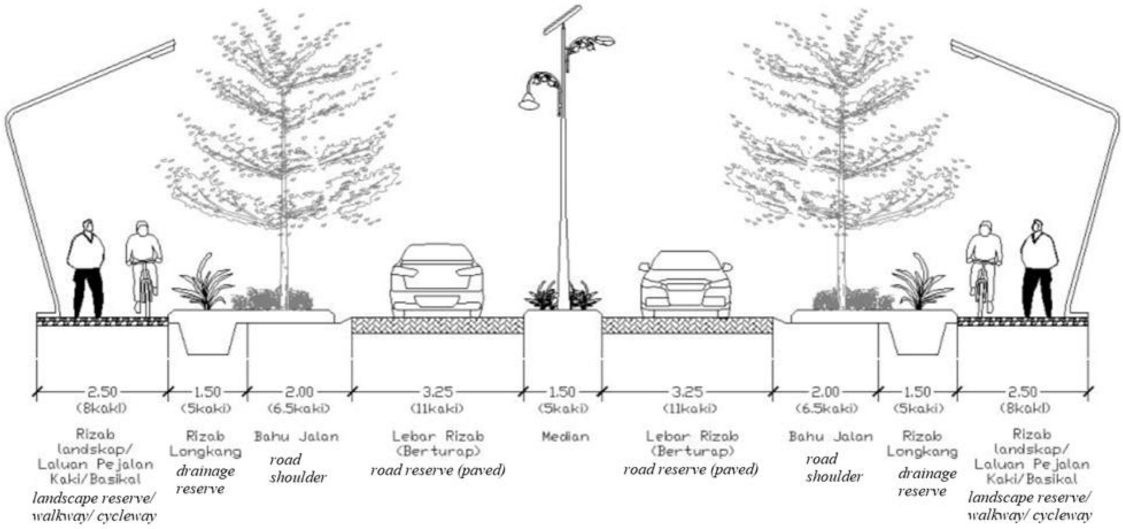
Case I *Recommended cross section for 15m road*

Cadangan Keratan Rentas Jalan 15 Meter (50 kaki)



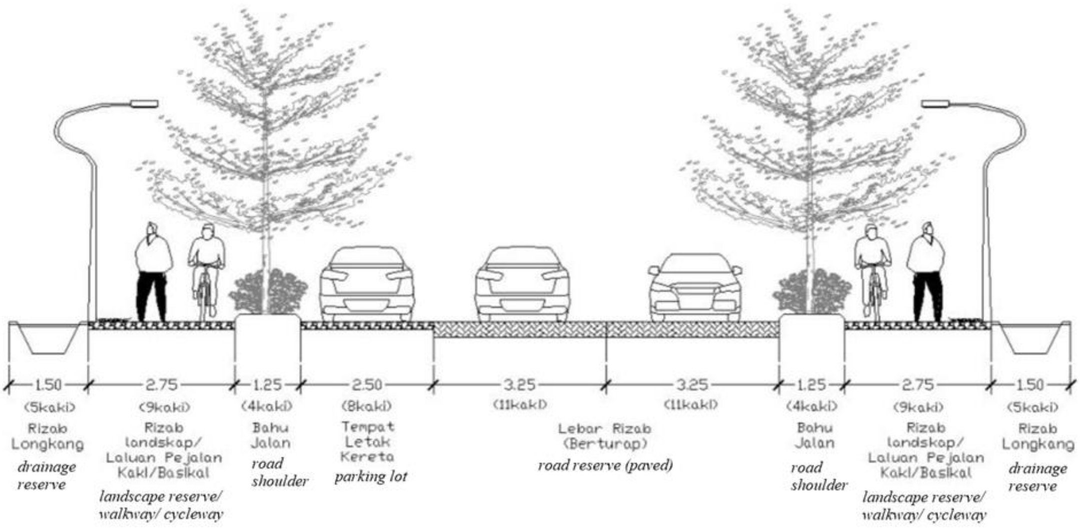
Case II *Recommended cross section for 20m road with median*

Cadangan Keratan Rentas Jalan 20 Meter (66 kaki) Dengan Penyediaan Median



Case III *Recommended cross section for 20m road with paved parking lot*

Cadangan Keratan Rentas Jalan 20 Meter (66 kaki) Dengan Tempat Letak Kereta Di Atas Turapan Jalan



Sumber : *JPBD, 2012. **Garis Panduan Perancangan Kejiranan Hijau**. Kuala Lumpur*

Source: Federal Department of Town and Country Planning (2012)

***Green neighborhood planning guidelines.** Kuala Lumpur.*

Appendixes II

Saiz Lubang Tanaman *(Plant Hole Size)*

The size of the planting hole is based on standard standards:

Saiz lubang tanaman adalah berdasarkan piawaian standard:

Tree / Palm

i. **Pokok utama / Palma** : 1m x 1m x 1

Shrubs

ii. **Pokok renek** : minimum 0.3m x 0.3m x 0.3m

Climbers (on the edge of wall/walkway&trellis/ ground area)

iii. **Pokok Pemanjat**

a. Di tepi tembok : 0.3m x 0.15m x 0.15m
b. Kawasan laluan / trellis : 0.2m x 0.15m x 0.15mm
c. Kawasan tanah : 0.15m x 0.15m x 0.15m

Ground cover

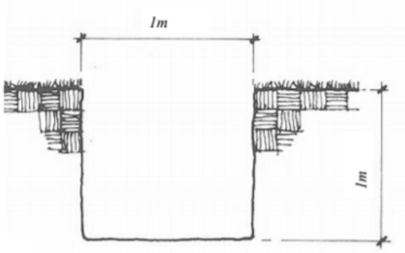
iv. **Penutup bumi** : 0.2m x 0.2m x 0.2m

Transplant tree: 2 times of root ball size

v. **Pokok 'transplant'** : 2 kali ganda dari saiz bebola akar (burlap)

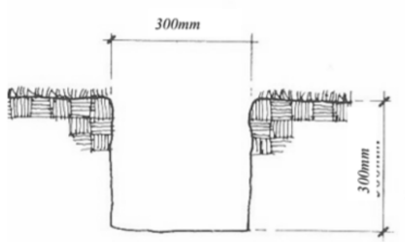
Mature tree

vi. **Pokok Matang** : minimum 1.5m x 1.5m x 1.5m.
Garispusat batang pokok yang melebihi 0.6m, saiz minimum lubang tanaman adalah 2m x 2m x 2m.
For >0.6m in tree trunk diameter, the minimum tree hole is 2m x2m x2m



Saiz lubang pokok utama dan palma

The hole size for tree and palm



Saiz lubang pokok renek

The hole size for shrub

Sumber: Jabatan Landskap Negara, 2008. ***Garis Panduan Landskap Negara Edisi 2.*** *Kuala Lumpur*
Source: Malaysia National Landscape Department, 2008. ***National Landscape Guidelines Edition 2.*** *Kuala Lumpur*