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Evidence-based neighborhood greening and concomitant improvement of urban heat environment in the context of a world heritage site - Malacca, Malaysia

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ABSTRACT

Malacca, located on the west coast of the central part of the Malaysian Peninsula, has been designated as a UNESCO World Heritage Site. At present, the urban heat environmental condition is feared to gradually worsen in the future. By applying a new design that modifies the heat environment by creating organically linked neighborhood green spaces, which encourage pedestrian use, will assist in efforts to conserve and improve the town as a sustainable heritage site. In this research, areas with future greening potential are first extracted based on field surveys and the results of overlaid site appraisals that, by using computer simulations, account for pedestrian thermal comfort, visibility of the historical landscape, and movement. Based on the identified and extracted areas with greening potential, three neighborhood greening scenarios are established: case 1 is based on the existing conditions, case 2 is based on following existing conservation plans, and case 3 is based on maximizing green areas by implementing the proposed pedestrian walkway. A microclimate simulation was done for each scenario and the results are compared specifically from the viewpoint of where and how much each scenario contributes to mitigating the urban heat environment, focusing on changes in physiologically equivalent temperature distribution and numerical changes. From the results, we conclude that the streetscape conservation-oriented neighborhood greening approaches proposed herein should improve the urban heat environment in such historical towns in tropical regions.

1. Introduction

Malacca city, located on the west coast of the central part of the Malaysian peninsula, is a historical town that, after a period of colonial occupation by several countries, contains many historical buildings with multicultural influence in the inner-city townscape. The town was designated as a UNESCO World Heritage Site in 2008 and has since become one of Malaysia's most popular tourist destinations, attracting more than 12 million visitors annually from both inside and outside Malaysia in recent years (The Star online, 2016). With a mean monthly maximum temperature exceeding 32 °C, Malacca city is one of the hottest towns in the country. The district designated as historical heritage site is next to the central business district in downtown Malacca and, because of chronic traffic congestion and big commercial facilities nearby, is increasingly affected by exhaust heat from passing vehicles. Consequently, the urban heat environmental conditions are feared to gradually worsen over time (Asian Development Bank, 2014). As a result, the walking environment for pedestrians strolling around the historical area is rather unpleasant. In general, in a historical district where the townscape should be preserved, changing and improving building form or volume or street width or placement is a very difficult task. However, in the context of historical districts, the surrounding heat environment may be reasonably and effectively ameliorated by installing green spaces, which includes planting trees (Givoni, 1991; Jim, 2012; Bajsanski, Stojakovic, & Jovanovic, 2016). In its current condition, the historical area in Malacca contains few green spaces or open spaces, and those that do exist are small and widely dispersed.

Previous studies have examined the Southeast Asian region to look at how effective urban greening is to improve the heat environment, and some of these studies have focused on Malaysia and Singapore (Wong et al., 2007; Wong & Jusuf, 2008; Shahidan, Jones, Gwilliam, & Salleh, 2012; Yang, Wong, & Jusuf, 2013). However, to few fundamental findings are available and, in particular, insufficient reliable research and evidence are relevant to historical towns. In addition, the urban design studies of Malacca done to date (Amran & Rosli, 2006, Lee, Lim, & Nor'Aini, 2008) focus mainly on methods to conserve the entire

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historical district and on the value of the intangible historical and cultural aspects as one of preparatory activities for future UNESCO bids. To date, very little quantitative research has been done focusing on tangible or physical aspects such as street patterns or historical buildings as components of the heritage landscape. The overarching goal of this research project is to create a virtuous cycle in the future whereby improving the heat environment by neighborhood greening would promote pedestrian activity by local residents and tourists, thereby reducing the through traffic within and into the area, which would lead to further improvement in the heat environment and pedestrian activities, and so forth. Looking toward the future, such a virtuous cycle could contribute significantly to upgrading the town's value as a World Heritage Site.

Given this current condition, the primary aim of the present study is to develop methods for neighborhood greening, which facilitates pedestrian activity by improving both the landscape and the urban heat environment in the historical town in the hot and humid climate of Southeast Asia. Specifically, the first step of the study consists of a quantitative analysis and evaluation of the existing characteristics of the outdoor heat environment and landscape components in historical Malacca. Second, we examine the technical procedure to identify areas with future greening potential by combining the results of a multi-aspect analysis with the requirement of consistency with the existing urban conservation plans for Malacca. Finally, neighborhood greening scenarios are proposed based on the extracted areas with greening potential, and the contribution of such greening to urban cooling is objectively examined through a comparative study.

2. Methodology

As shown by the conceptual framework in Fig. 1, the analysis of the study area contains three major components that encompass (1) the outdoor microclimate from the viewpoint of pedestrian thermal comfort; (2) the urban design elements from the viewpoint of degree of linkage between each space over street network as an urban structure (connectivity), securing the pedestrian line-of-sight to historical buildings within the study area (visibility), and pedestrian movement patterns (human behavior); and (3) consistency with existing urban conservation plans. Second, the results of these analyses are integrated to semi-automatically identify areas with greening potential. By combining the extracted areas with greening potential and the existing urban conservation plans developed by local authorities, multiple neighborhood greening scenarios are proposed and implemented in the study area. Next, the cooling effects of each greening scenario are quantitatively verified. Finally, we discuss the effectiveness of the technical process for extracting areas with greening potential and the possibility of applying this proposal in similar conditions. To date, although several studies have objectively evaluated the impact of regional weather conditions or microclimate on tourism or recreation (Scott & McBoyle, 2001; Freitas, 2003), only a few have applied urban design methods and neighborhood greening by integrating an analysis of two major aspects such as microclimate and urban landscape components.

2.1. Study area

The study covered the central area of Malacca, Malaysia. The town of Malacca is located on the west coast of the Malaysian Peninsula and faces the Strait of Malacca. The town is rich in tangible and intangible remnants of diverse cultures from ancient times through the present day as a result of its long history as a colonial city occupied by different western countries (Portugal, the Netherlands, and Britain). Inherited historical buildings and streetscapes that reflect diverse cultures occupy the central area of the town, which was registered as a UNESCO World Heritage Site in 2008 (Fig. 2(a)). The designated heritage site contains two zones: the core zone (0.37 km^2) and a buffer zone (1.69 km^2) surrounding the core zone. This study narrows the study area to an area measuring 480 m × 320 m, including the Malacca River that flows through the town center for further micro-scale consideration (Fig. 2(b)). The core zone encompasses mostly so-called shophouses, which are two-to-three story structures and six-to-nine meters high, as shown in Fig. 2(c).

2.2. Analysis of neighborhood outdoor heat environment

To assess the outdoor heat environment in a three-dimensional space, we use the microclimate model ENVI-met (Bruse & Fleer, 1998; Bruse, 2016.) as a main tool in this study. The ENVI-met software is widely used to simulate microclimate environments, particularly on

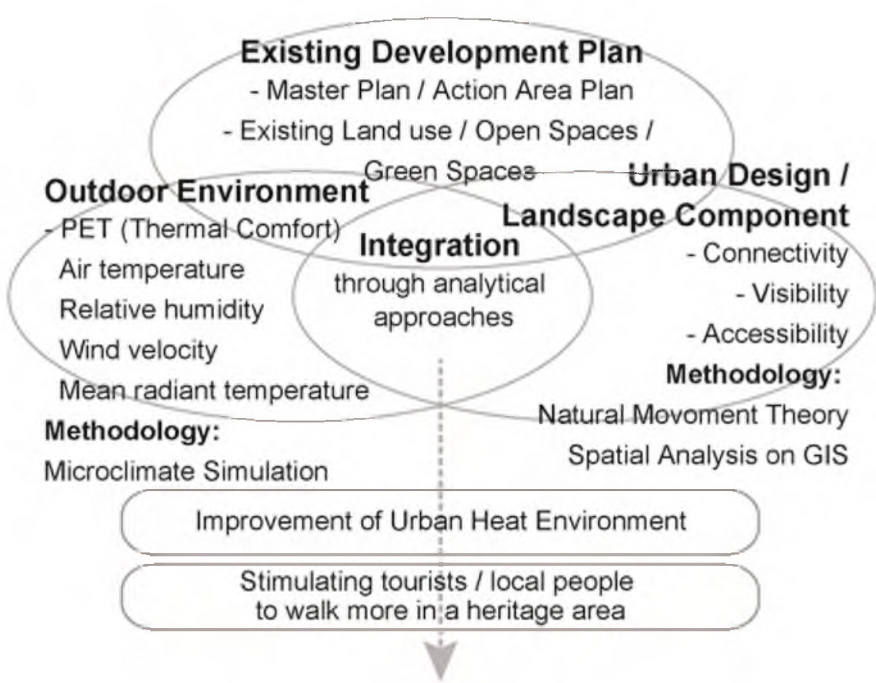
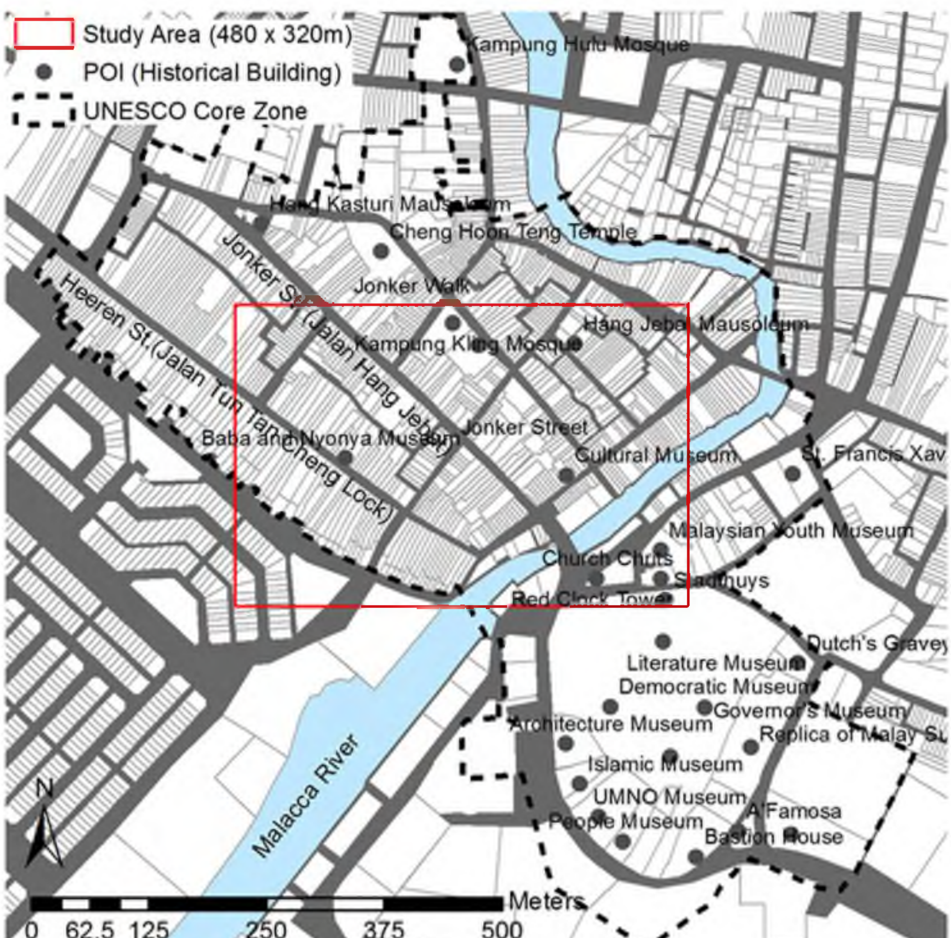


Fig. 1. Conceptual framework for evidence-based neighborhood greening.

(a) UNESCO-designated historical area.



(b) UNESCO core zone and study area.

Fig. 2. Malacca UNESCO-designated historical area.

(c) Building height (m)

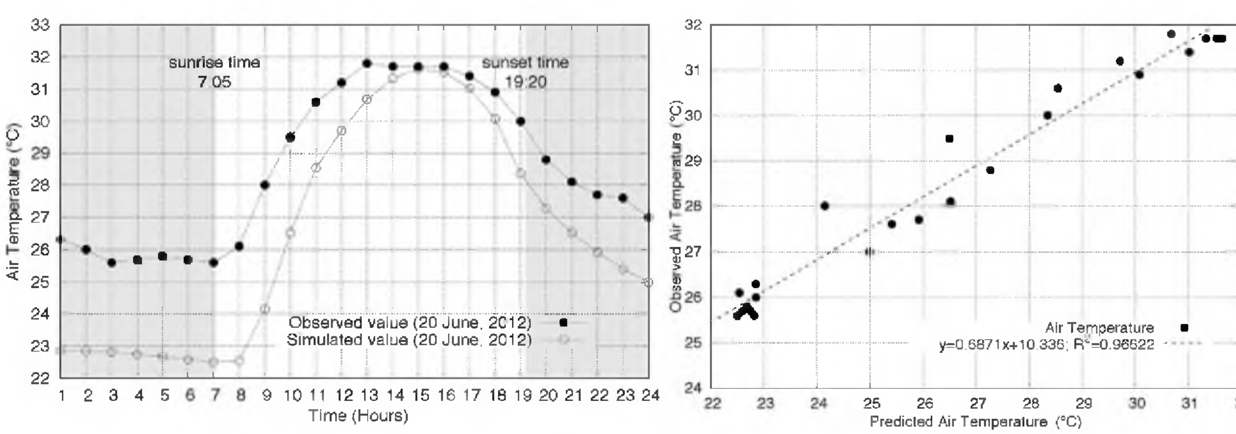
Fig. 2 (*continued*).

the scale of neighborhoods, and has proven to be reliability analysis tool. Quantitative results from simulations by ENVI-met have been accumulated not only in European countries where the software was developed but also in Southeast Asian countries including in towns with a hot-humid climate similar to that of Malacca. In previous research (Saito, Said, & Shinozaki, 2015), the individual index such as air temperature and wind velocity were used to analyze the neighborhood microclimate. Based on those findings, the present study focuses on PET, which is defined as the physiological equivalent temperature at any given place (outdoors or indoors) and is equivalent to the air temperature at which, in a typical indoor setting, the heat balance of the human body is maintained with the core and skin temperatures equal to those under the conditions being assessed (Mayer & Höppe, 1987; Höppe, 1999) as an index for evaluating the heat environment on the scale of neighborhoods, so that the impact on pedestrian activity of modifying the heat environment can be directly understood by integrating the various aspects evaluated by individual indices related to microclimate conditions. In the previous researches on urban heat island (UHI) mitigation strategies using the combination of the ENVI-met model and PET as a human thermal comfort index, Wang, Berardi, & Akbari, 2016 have confirmed the effect of greenery in urban environments with strategies such as roadside tree planting with different densities in Toronto, Canada. Berardi, 2016, Peng & Jim, 2013 have reported that a green-roof installation will have a significant impact on the thermal comfort level at the rooftop level and a slight cooling effect at the pedestrian level in the context of Canada and Hong Kong, respectively. Furthermore, Ghaffarianhoseini, Berardi, & Ghaffarianhoseini, 2015 have confirmed that the proper design of courtyards, including greenery strategies, can improve the microscale thermal environment present in the hot and humid climate of Malaysia. Several indices are available to evaluate the heat environment: predicted mean vote (PMV), PET,

Table 1
Initial parameters for microclimate simulation.

Date	June 21, 2012[a]
Duration	24 h (6 pm June 20 to 6 pm June 21)
Wind velocity	1.8 m/s[b] at 10 m above the ground
Wind direction	45°[b] (from North-East)
Temperature	301.3 K[c] (28.1 °C)
Relative humidity	80.5%[c]

[a] The day of the summer solstice in 2012, Malacca. The similar previous research under hot and humid climate in Hong Kong also used the same day for microclimate simulation using the ENVI-met model (Chen & Ng, 2013).
[b] Yearly prevailing wind and direction in 2012, Malacca.
[c] Monthly mean value in June 2012, Malacca. The variation range of the monthly mean temperature in 2012 is within 1.5 °C, and there are no significant seasonal changes in this region.



(a) (b)

Fig. 3. Validation of the ENVI-met model: comparison between measured and predicted air temperatures for the same day in the context of Malacca, Malaysia.

Table 2
Classification of thermal perceptions for tropical region (Lin & Matzarakis, 2008).

Thermal perception	Classification for tropical region (°C PET)
Very cold	<14
Cold	14–18
Cool	18–22
Slightly cool	22–26
Neutral	26–30
Slightly warm	30–34
Warm	34–38
Hot	38–42
Very hot	>42

and standard effective temperature (SET*). This study uses the PET because of it is appropriate for evaluating changes in the outdoor heat environment after neighborhood greening, including street planting, and the facility to translate it into sensory perception by people in the environment, which should be useful for implementing these results in future designs (Matzarakis, Mayer, & Iziomon, 1999). Previous work on thermal comfort in Malaysia also showed the effectiveness of using PET as an index for judging comfort level (Makaremi et al., 2012). Because PET has been used to study the heat environment particularly in Europe, Lin and Matzarakis (2008) tuned it for use in tropical and subtropical regions by taking into account the differences in thermal perception of local people such regions. This modified PET was used in the aforementioned research, which studied conditions in the hot-humid climate of Malaysia and demonstrated that Malaysians have significantly different perception of the climatic conditions in Malaysia than foreigners (Makaremi et al., 2012). This study also used a thermal comfort classification for tropical regions in which a scale factor was applied to the PET. The PET distribution is calculated by using the ENVI-met combined with the Rayman model (described below), and the results are stored with other layers in a graphic information system (GIS) database.

2.2.1. Microclimate simulation

We now discuss the microclimatic simulation of the 480 m × 320 m area in the core area of the Malacca heritage site. The model considers mainly the building height, tree height, and existing land-cover conditions in a three-dimensional space by using an ENVI-met simulation model. Table 1 lists the initial settings used in the simulation. The grid size (2 m × 2 m × 2.5 m) and the number of grid elements (240 × 160 × 20; x, y, z) are fixed. The grid size used here is determined by referring to the grids used in previous researches dealing with PET as an index for thermal environment studies in a similar neighborhood scale (a 3-m grid was used in Chen & Ng, 2013; a 2-m grid in Müller, Kuttler, & Barlag, 2013; a 2-m grid in Peng & Jim, 2013; and a 3-m grid in Wang et al., 2016). Three types of land cover are considered: soil (albedo = 0), concrete (0.4), and asphalt (0.2). The buildings (wall albedo: 0.25, roof albedo: 0.3), grass (height: 0.1 m), and trees (height: 10 m, canopy width: 5 m) are located on these three types of land covers. Although the ENVI-met model has been extensively employed to examine the thermal environment, it has several limitations that should be noted. The model does not consider heat emission from HVAC (Heating, ventilation, and air conditioning) as well as transportation-related heat fluxes (Wang et al., 2016). It also does not take heat storage of building facades into account in the energy balance, which could result in an underestimation of the surface temperature of walls and the ambient air temperature near the buildings (Wu, Kong, Wang, Sun, & Chen, 2016).

2.2.2. Validation of the ENVI-met model

The reliability of the ENVI-met model for simulating the thermal performance of outdoor spaces in hot and humid climate regions has been reported in previous researches (Peng & Jim, 2013, GhaffarianHoseini et al., 2015). Fig. 3 shows the validation of the ENVI-met model through a comparison between measurements and simulation results of the air temperature for the same day in the context of Malacca, Malaysia. The measurement data were derived from the governmental weather station database. The difference between the measured and the predicted air temperatures is approximately 2.6 °C during sunrise-to-sunset and 1.5 °C during sunrise-to-sunset on average (Fig. 3(a)). A similar tendency has been confirmed in the previous research conducted in the humid tropics (Emmanuel, Rosenlund, & Johansson, 2007). Berardi, 2016 indicated that this discrepancy could be explained by the inaccuracies in the input parameters for the simulation, such as surface material or vegetation, or because the data does not include anthropogenic heat. Fig. 3(b) shows a high correlation (R^2 = 0.97) between simulated and measured air temperatures, demonstrating the validity of the ENVI-met model.

2.2.3. Calculation of PET

The PET can be calculated using the Rayman model. The physical basis, abilities, and limitations of the Rayman model have been

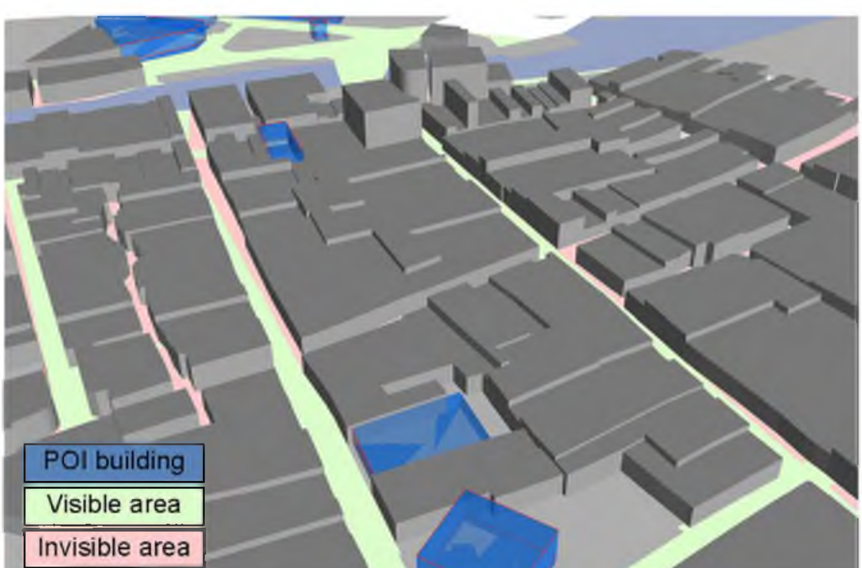


Fig. 4. Visibility calculation with viewshed analysis in three-dimensional spaces.

Table 3
Key spatial data stored in the database.

Category	Type	Source from
2D Vector (polygon)	Cadastral data (lot)	Local authority
	Existing land use	Local authority
	Block	Original (based on the Cadastral data)
	Building footprint	Original (based on the Cadastral data + Field survey)
	Building height	Original (based on Field survey + Panoramic facade)
2D Vector (line)	Road	Local authority
	River	Local authority
2D Vector (point)	Trees	Field survey + Aerial photos
Image data	Aerial photos	Local authority + Google Earth
Observatory data (meteorological data)	24 Hour mean temperature	Malaysian Meteorological Department
	Wind rose (2012)	Malaysian Meteorological Department

introduced by Matzarakis et al., 2007 and 2010. The necessary meteorological input variables such as air temperature (°C), relative humidity (%), wind speed (m/s), and mean radiant temperature (°C) are obtained from the ENVI-met microclimate simulation (Peng & Jim, 2013). Other required input data (Matzarakis et al., 1999) are the heat-transfer resistance of the clothing: 0.3 (clo) and the internal heat production: 93 (W) (Yang et al., 2013, Bruse, 2016), where the parameter values are taken from the previous study on thermal comfort of tourists strolling at low speed in the hot-humid climate of Southeast Asia. To evaluate neighborhood thermal conditions based on the distribution of the calculated results, the aforementioned modified PET classification for tropical regions (Lin & Matzarakis, 2008) are used, as described in Table 2. For the following analysis and the interpretation of the heat environment based on PET, we use 34 °C PET as the threshold for defining the “acceptable” upper limit for thermal comfort, as in the previous studies (Lin & Matzarakis, 2008; Makaremi et al., 2012).

2.3. Analysis of urban configuration and landscape component

The elements of urban design and landscape are quantitatively analyzed from the viewpoint of “visibility,” especially for historical buildings, “connectivity” of spaces over street network, and theoretical “pedestrian behavior.” These three indices are regarded as key indicators in research on tourism climatology, specifically for studying thermal comfort in tourist destinations (Scott & McBoyle, 2001). The present study also uses the same three indicators for analysis.

2.3.1. Securing visibility for historical buildings

Obtaining greener neighborhoods it is considerably important to secure pedestrian visibility of historical buildings and townscapes for not only from the point of view of improving the heat environment but also to conserve the landscape's local identity and character. Taking photographs and drawing sketches is used to record and analyze the visual environment, such as the scenery of townscapes from pedestrians (Yang, Putra, & Li, 2007). In the present study the visible and invisible areas for pedestrians near historical buildings are considered based on the geometry of three-dimensional buildings stored in the GIS database. The visible and invisible areas on the ground and the visible outline of point-of-interest (POI) buildings can be calculated based on a viewshed analysis in the GIS application (Fig. 4). The invisible areas found in this analysis are regarded as active areas for future greening, including street planting, since this would not interrupt the pedestrian line-of-sight.

2.3.2. Human behavior

In this study, neighborhood greening is done so as to improve the facility for tourists to get around. Thus, we expect neighborhood greening to contribute to reducing traffic, which would lead to further improvements in the urban heat environment and more aggressive greening in the future. From this viewpoint, the extent of inter-visibility between certain location within the study area is analyzed based on the “Through Vision” indicator, which is part of the space syntax technique of visibility graph analysis (VGA) (Turner, Doxa, O'Sullivan, & Penn, 2001). Through Vision is the sum of all visibility lines for each location on a visibility graph grid and correlates well with pedestrian behavior in urban areas as per agent-based simulations (Turner, 2001, 2007; Ferguson, Friedrich, & Karimi, 2012). Mahmoud and Omar (2015) also confirmed the effectiveness of space syntax techniques of visibility graph analysis for supporting assessments of planting design, especially at the level of pedestrian movement. Based on this, the areas with low Through Vision are regarded as relatively non-active areas from the viewpoint of inter-visibility, but are considered potentially conducive areas for easing pedestrian movement within the proposed neighborhood green network. DepthmapX (Turner, 2001) is used to calculate Through Vision.

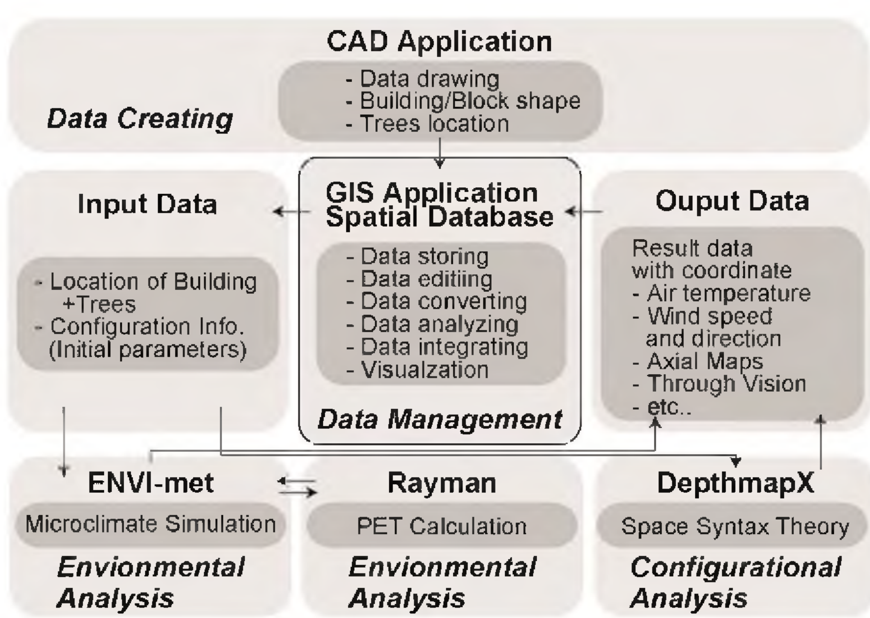


Fig. 5. Key components and data flow in the system.

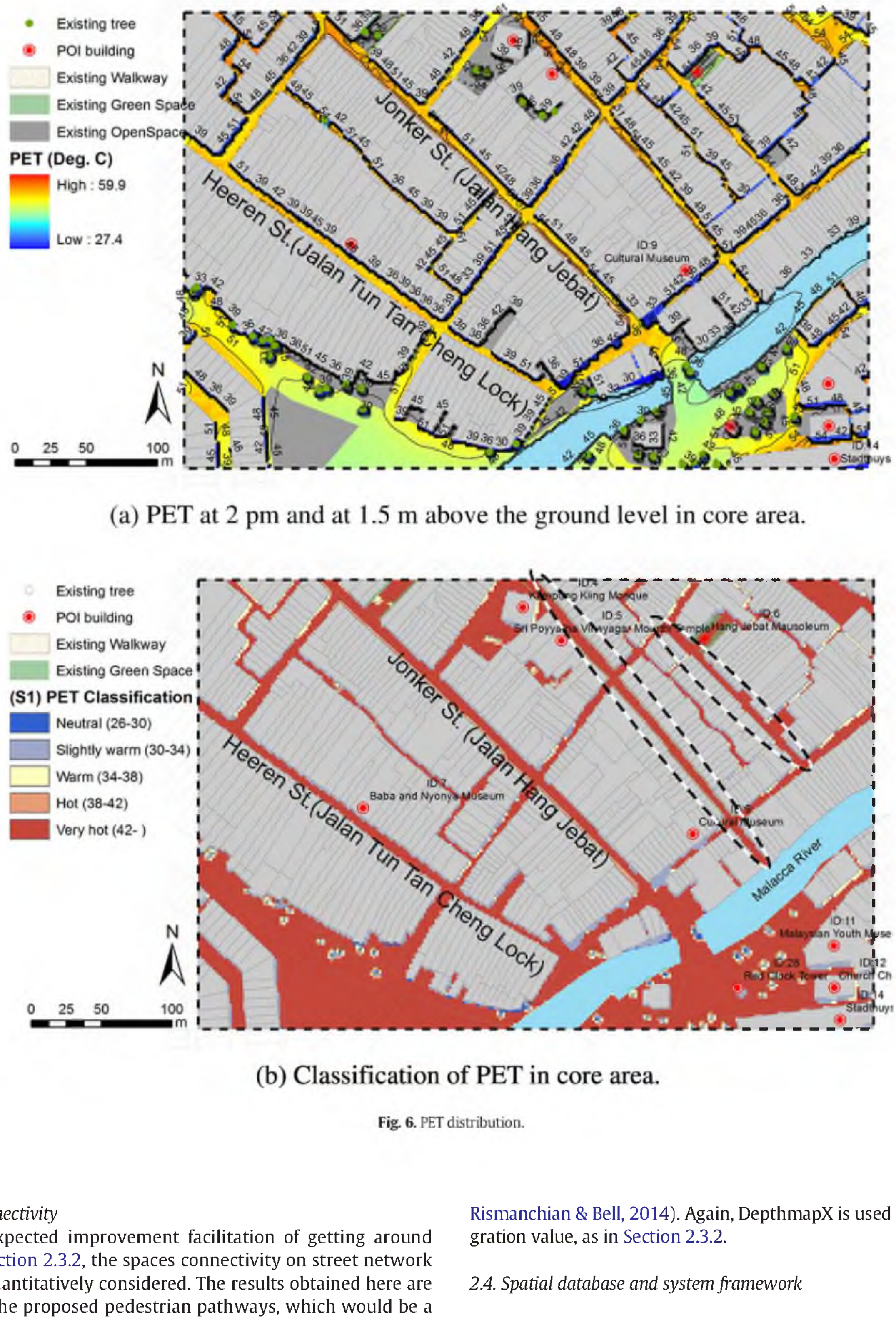


Fig. 6. PET distribution.

2.3.3. Space connectivity

With the expected improvement facilitation of getting around discussed in Section 2.3.2, the spaces connectivity on street network must also be quantitatively considered. The results obtained here are used to guide the proposed pedestrian pathways, which would be a part of the future neighborhood green network. The integration value, which is one of the core indicators of the space syntax technique, is used to analyze how well integrated or, how closely or distantly each space is accessible from all other spaces, where higher integration value means more connection to the network (Hillier, Penn, Hanson, Grajewski, & Xu, 1993). The effectiveness of space syntax technique, and in particular the application of integration value as a reference indicator on which to base urban design, has been confirmed as an evidence-based design approach in previous studies (Karimi, 2012; Rismanchian & Bell, 2014). Again, DepthmapX is used to calculate integration value, as in Section 2.3.2.

2.4. Spatial database and system framework

Table 3 summarizes the key data sources used in the present study, which include digital and non-digital spatial data and official climatic observations. The most significant basement data for this study, such as cadastral data and existing land use, have been developed by the local authorities, and several data required for the analysis, such as building footprint and height and tree location, were acquired through on-site field studies.

The series of spatial data stored in the GIS database (ESRI ArcGIS) appears in the middle of Fig. 5, which shows the flow of the key input and

Fig. 7. Viewshed analysis from each POI (Historical buildings).

output data from each stand-alone analytical tool and the overall system framework for data editing, management, analysis, and seamless visualization.

3. Analysis of heritage site and integration of multiple aspects

To analyze the current conditions, the three main perspectives shown in Fig. 1 are analyzed objectively, particularly with regard to the outdoor neighborhood environment and urban configuration. The results from each perspective are evaluated by applying the theories and results of previous research.

3.1. Thermal comfort

Fig. 6(a) shows the PET distribution at 1.5 m above the ground for 2 pm. The PET on streets is relatively low, with approximately 32 °C occurring at areas near south façades of buildings that are themselves shaded by buildings at that time. A similar low PET also occurs around existing trees. Near north-facing building façades, around intersections, and on most of the streets, a high PET occurs (over 50 °C). The PET classification shown in Fig. 6(b) indicates that a large part of study area is categorized as above "warm" (i.e., the thermal perception of pedestrians exceeds 34 °C in PET). This means that many pedestrians feel or begin to feel thermal discomfort in most of study area at 2 pm. In addition, back streets marked by dashed lines in Fig. 6(b) are relatively narrow (about 6 m wide at most) and on-street parking is common there. The PET level for these streets is "very hot." These results indicate that visitors are far from comfortable in this environment. With regard to the shadow effects by the building height, the previous research that focused on the relation between the surrounding building height and the thermal performance in a courtyard in Malaysia context has reported that irrespective of the height of the enclosing wall, the thermal performance of the courtyard is extremely poor, especially during critical time periods of the day (12:00 and 14:00), and highlighted the necessity of application

Fig. 8. Classification of Through Vision in core area.

Fig. 9. Classification of integration value.

of shading devices or greeneries for providing comfortable spaces during these particular periods (GhaffarianHoseini et al., 2015). Thus, the shadow effects to decrease the ambient temperature are considered limited especially at the critical time period at 14:00 in this study area, which encompasses two- to three-story (six-to-nine meters high) low-rise buildings (Fig. 2(c)).

3.2. Urban configuration

Second, to analyze the urban configuration, we use viewshed analysis in the GIS application, and visibility graph analysis and axial line analysis based on the space syntax theory. The 2 m × 2 m grid is used here, which is the same size for microclimate simulations (see Section

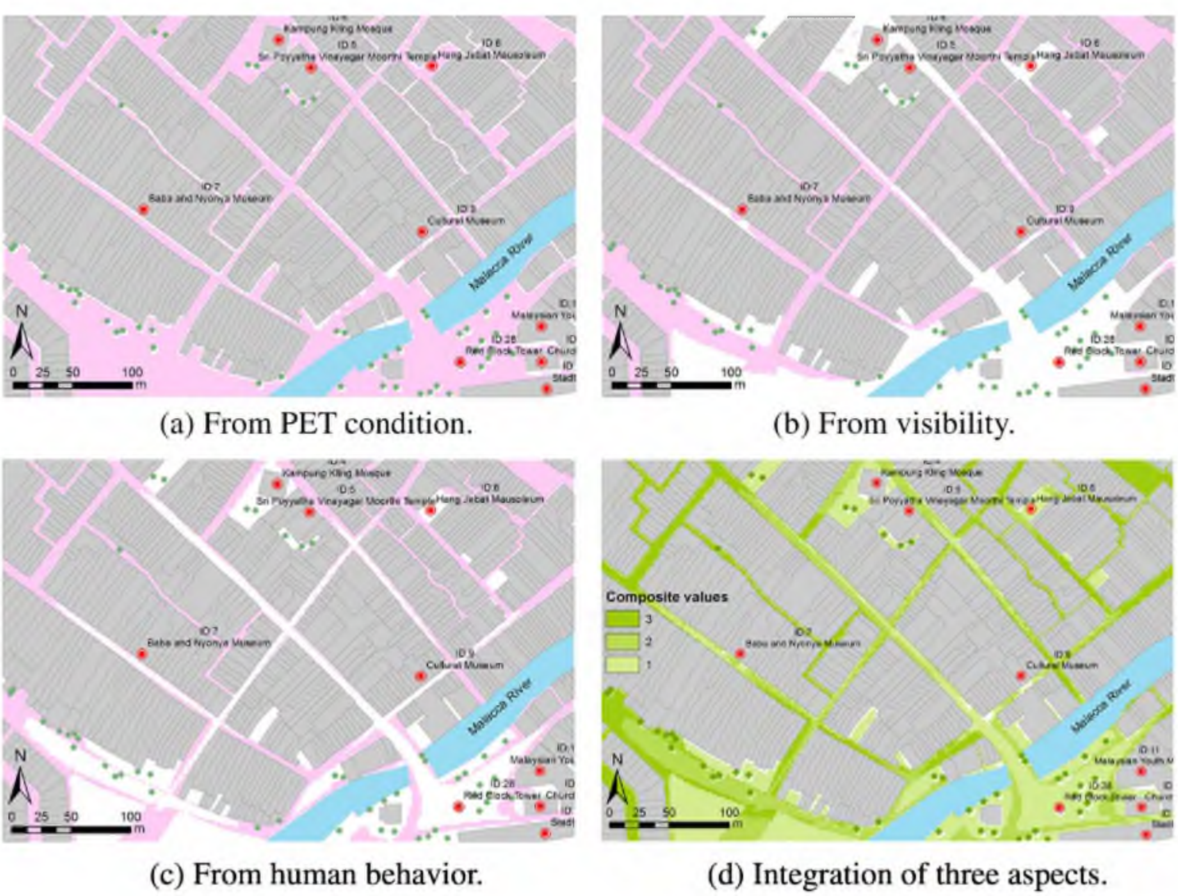


Fig. 10. Potential areas from each aspect and from integration.

Fig. 11. Areas that have a potential for future neighborhood greening.

3.1). The results of this study are stored with other layers in the GIS database.

3.2.1. Visibility condition

Fig. 7 shows results of the viewshed analysis applied to areas that are visible and invisible from historical buildings, which are some of the key POIs within the urban landscape. The white areas provide unobstructed views of at least one POI (shown as red dots in the figure) in the study area. Although the streets within the dashed lines and running perpendicular to the major streets are 6 to 9 m wide, no POI may be observed from these streets because of their physical and positional relationship in space.

Table 4
Summary of neighborhood greening scenarios.

	Basic concepts and directions	Detail plan and actions
Case 1 (C1)	Existing condition	–
Case 2 (C2)	Following the existing conservation plan and detailed guideline (Melaka Town and Country Planning Department, 2000, 2008a and 2008b)	1. Replacing existing on-street parking zone with Green walkway (covered by permeable surface using grasscrete paver) 2. Potted plant (Not included in the models and microclimate simulation)
Case 3 (C3)	Proposing walkway extension, roadside trees and neighborhood pathways	1. Walkway extension (Covered by Terracotta Tiles) with 1.5 m in width along the shophouses especially on 9 m width road 2. Roadside trees and Car parking zone with 2.4 m in width along the extended walkway. The tree pairs are proposed in alignment with the party walls of the shophouses (5–6 m varies) so that the building façade could be opened to the frontal walkway and road (Refer to Figs. 12 and 13). 3. Three new neighborhood pathways for connecting a major street with an inner-street (back lane). 4. Replacing existing unutilized back-lane with Green walkway (covered by grasscrete paver)

3.2.2. Human behavior

Fig. 8 shows the distribution of Through Vision obtained by visibility graph analysis after division into five classes based on the Through Vision value in GIS, as obtained by using the natural-break method. In particular, one of the major streets (Jonker Street), which runs through the middle of the town shows, has the highest Through Vision values. This result is consistent with the crowded and lively situation due to visitors on site. Lower Through Vision values occur on the relatively narrow streets surrounding the major key streets. Although several POIs (historical buildings) are located along these secondary streets, the distribution of Through Vision predicts little visitor movement because of the low inter-visibility between surrounding buildings and blocks.

3.2.3. Space connectivity

Fig. 9 shows the results for the local integration (R3) obtained by applying an axial lines analysis based on the space syntax technique. This result shows the extent of space connectivity within the street network. By using the natural-break method, the results are divided into five classes based on the value in GIS. The major streets and other perpendicular streets are indicated by red and are in the highest integration class. In contrast, relatively narrow streets between inner-blocks have lower integration than the surrounding major streets.

3.3. Identifying potential areas for future greening

Proposing future neighborhood green spaces requires identifying areas with high potential by combining the results from each perspective analyzed above. Fig. 10(a)–(c) show the areas considered suitable for future neighborhood greening from each perspective and before overlaying. Fig. 10(a) shows areas with PET > 34 °C, which exceeds the acceptable range of thermal comfort. Fig. 10(b) shows the invisible areas based on the viewshed analysis from each POI. Fig. 10(c) shows the areas identified by low and very low Through Vision as determined by the visibility graph analysis.

Herein, the pink-colored areas in each of the three layers (a), (b), and (c) have the same numerical pixel value of 1 and are simply overlaid and summed using a raster calculator in the GIS. The results are shown in Fig. 10(d) as a composite map, which represents the importance based on the layering frequency in three levels, ranging from 1 to 3. In

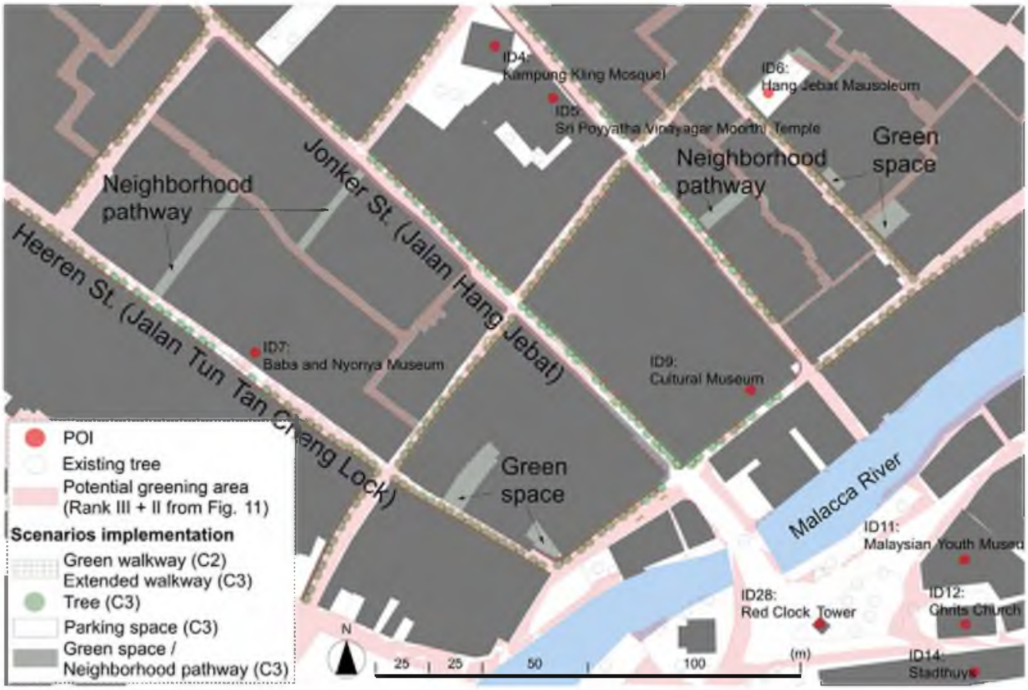


Fig. 12. Neighborhood greening scenario based on areas with higher potential (as determined by combining ranks III and II on Fig. 11).

addition to these levels, the results of the integration, which extracts two classes from the lower value and is represented by lines (see Section 3.2.3), are also overlaid on the other layers. Consequently, the particular areas that take into account four aspects (thermal comfort, visibility, human behavior, and street integration) can be identified. The calculated potential areas shown in Fig. 11 show that the one of the major street in the study area (Jonker Street) has lower importance than the other streets. Conversely, the areas covered by the narrow inner streets (indicated A and B in Fig. 11) have the highest importance and lower or the lowest value for street connectivity. Those areas thus require additional connections in the form of new neighborhood pathways to major surrounding streets. The zone labeled C in the figure has relatively higher importance, which indicates that alterations to improve pedestrian access are required even if an area is closely connected with a major street, such as Heeren Street.

4. Proposed neighborhood greening scenarios and models

Based on the potential greening areas identified by considering the aspects discussed above, scenarios for future neighborhood greening are proposed, following which the urban model is prepared for verification. For this, three types of greening scenarios are prepared: a scenario based on the current conditions, a reality-oriented scenario based on the existing urban conservation plan, and a maximum-greening scenario whose focus is on verifying the relationship between degree of greening and its effect rather than on feasibility of future implementation.

4.1. Greening scenarios

Initially, the scenarios for neighborhood greening models are constructed. This work uses three different scenarios: case 1 is based on existing conditions and is regarded as a baseline model for comparative analysis. Next, case 2 is the minimum greening model and follows the existing conservation and management plan (Melaka Town and Country Planning Department, 2000, 2008a, and 2008b). These conservation plans do not include a detailed prescriptive design code or regulation with regard to the landscape treatment or urban design. Thus, in case 2, we selectively followed two associated guidelines and applied them, viz., 1) application of a permeable surface material for a pedestrian walkway and 2) only minimal application through the planting of ornamental trees/shrubs or potted plants to be allowed owing to the limited space in the existing streets. Finally, case 3 is the maximum greening model and includes a walkway extension, newly planted trees along the extended walkway, and neighborhood pathways connecting major streets with back lanes covered by permeable surface materials, designed in accordance with the urban configurational aspect such as built form, street width and layout, and open-space distribution. As a key basic concept, both case 2 and case 3 contain enhancements to walkability within the study area through neighborhood greening. Case 3 in particular prioritizes a quantitative measurement of the extent to which the urban heat environment is mitigated by greening and implementing neighborhood pathways, rather than considering the feasibility of implementing the scenario in the future. The details of each proposed scenario are summarized in Table 4.

Through these scenarios, we expect the greening to make the following positive impacts to the area:

- Improved walkability (ease of pedestrian access) because of continuously connected pedestrian walkways.
- Mitigation of urban heat environment, especially with regard to pedestrian thermal comfort, by providing areas shaded by newly planted trees (currently the study area contains 49 trees).
- Less on-street parking because of planted trees and the installation of a designated car park, thereby reducing parking over twofold with respect to the current situation.

4.2. Implementation of greening scenarios

Second, the proposed greening scenarios must be implemented within the study area. Here, the potential areas for future greening identified in Fig. 11 are referenced as a basis. Fig. 12 shows the areas that have implemented the neighborhood greening plan by the following scenario-based neighborhood greening proposed above (refer to “Detail plan and actions” in Table. 4). The implemented areas are shown by

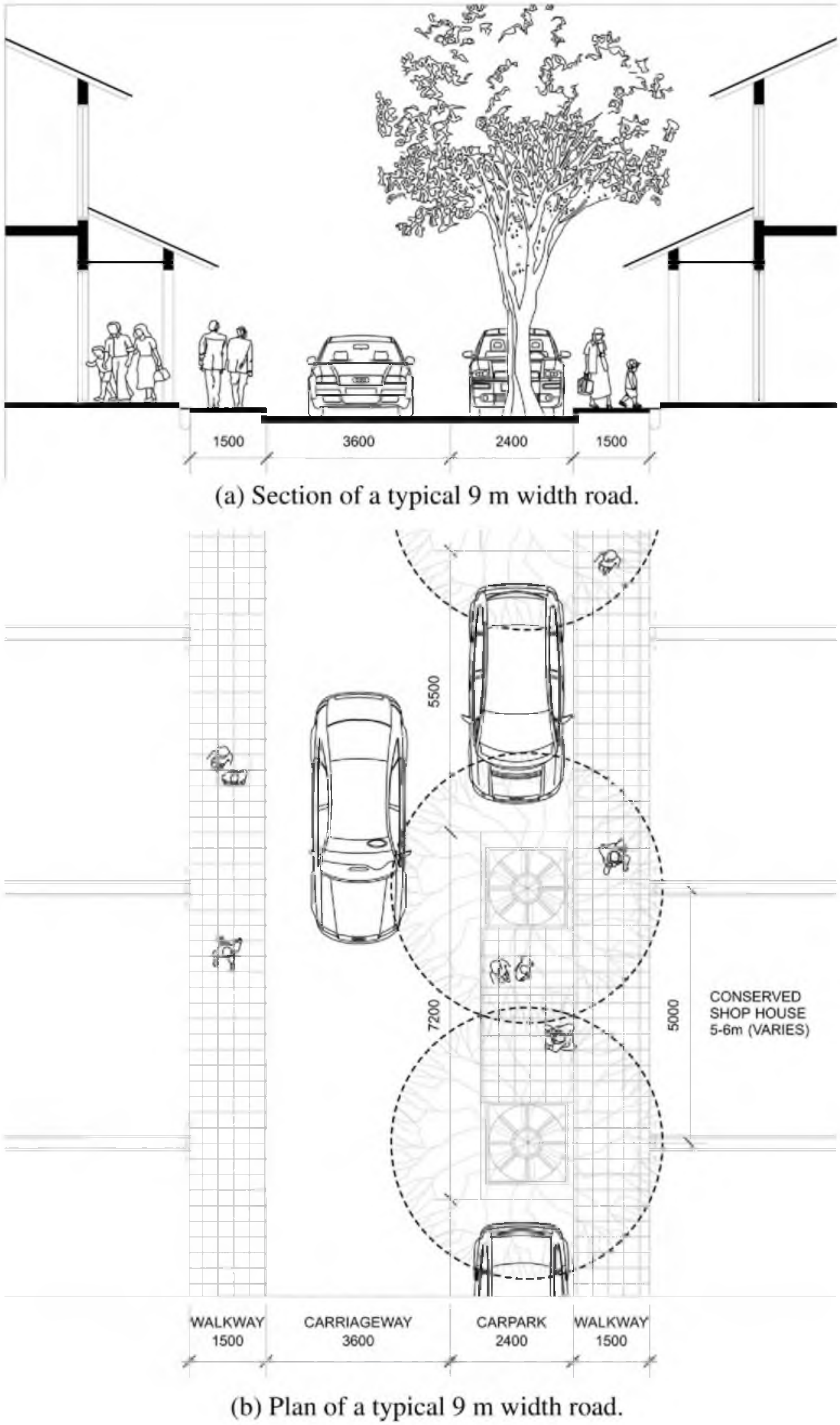


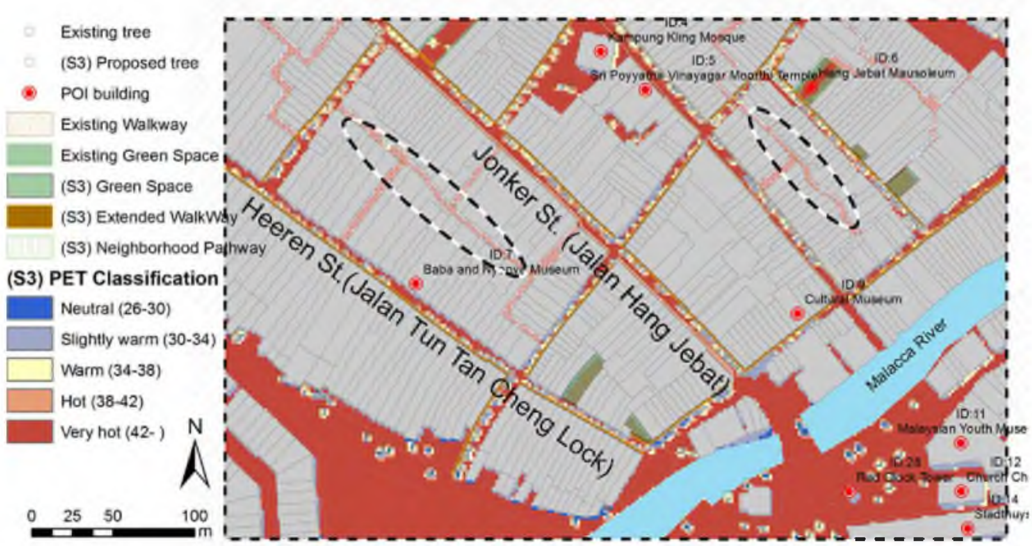
Fig. 13. Detail plan for urban greening (case 3) (Adapted from Melaka Town and Country Planning Department, 2008b and URA Singapore, 1997).

pink in Fig. 12 and derive from the areas that combined the top two potential areas for future greening (rank III and II; the areas that contain at least two aspects from analyzed factors, as shown in Fig. 11).

Additionally, case 3 proposes three neighborhood pathways exclusively for pedestrians (see Fig. 12). These are intended to connect major streets and narrow back lanes that connect with low or very-

Fig. 14. Image of street planting and parking spots based on the case 3.

(a) PET classification at 2 pm and at 1.5 m above the ground level (case 2).



(b) PET classification at 2 pm and at 1.5 m above the ground level (case 3).

Fig. 15. PET distribution for cases 2 and 3.

(a) Case 1 compared with case 2.

(b) Case 1 compared with case 3.

Fig. 16. Changes of PET classification in thermally acceptable areas.

Table 5
PET classifications for the various scenarios.

	Acceptable range (PET < 34 °C)		Unacceptable range (34 °C < PET)			**Total PET calculated area (m²)**	**Total acceptable condition area (m²)**
	Neutral (m²)	**Slightly warm (m²)**	**Warm (m²)**	**Hot (m²)**	**Very hot (m²)**		
Case 1	**244** (0.5%)	**5864** (12.6%)	**2132** (4.6%)	**516** (1.1%)	**37,764** (81.2%)	**46,520** (100%)	**6108** ±0%
Case 2	**248** (0.5%)	**6156** (13.2%)	**1840** (4.0%)	**520** (1.1%)	**37,756** (81.2%)	**46,520** (100%)	**6404** +4.8%
Case 3	**356** (0.8%)	**8712** (18.4%)	**3564** (7.5%)	**1944** (4.1%)	**32,724** (69.2%)	**47,300** (100%)	**9068** +48.5%

Table 6
Breakdown of green spaces and GCR.

	Existing setting		Proposed neighborhood greening				Total green coverage area (m^2)	Total study area (480 x 320 m) (m^2)	GCR (%)
	Trees coverage area (m^2)	Green spaces (m^2)	Trees coverage area (m^2)	Green walkway (m^2)	Neighborhood pathway (m^2)	Green spaces (m^2)			
	(A)		(B)				(C) = (A) + (B)	(D)	(C) / (D) * 100
Case 1	962.1	373.5	0.0	0.0	0.0	0.0	1335.6	153,600.0	0.9
Case 2	962.1	373.5	0.0	3015.3	0.0	0.0	4350.9	153,600.0	2.8
Case 3	962.1	373.5	5360.3	0.0	4,559.2	718.6	11,973.7	153,600.0	7.8

low integration and are supported by an improved integration based on the space syntax technique combined with the conditions of existing buildings along the streets observed during the on-site survey. In addition, the existing walkways are extended along the streets and covered with terracotta tiles [see Fig. 13(a) and (b)]. These extended walkways are provided on both sides of the street (for 9-m-wide streets) and on one side (for 6-m-wide streets). In addition, planting trees on the vacant spaces created by reducing the number of existing on-street parking are uninterrupted seen on site to less than half, and 273 new trees will be planted on one side of the streets due to space limitations, regardless of street width. Detailed information on the design components and dimensions are given in Table 4 and in Fig. 13(a) and (b), and Fig. 14 shows an image of the future street with trees and parking spots. Digital models after implementation of all greening actions for each scenario are converted to the GIS format and stored with other layers in the spatial database.

5. Results and discussions

In this section, we discuss the simulation of the microclimate, which is done by using digital data from the scenarios of neighborhood greening presented in Section 4.2. The simulation uses the same initial setting described in Section 2.2.1. To verify the effectiveness of neighborhood greening methods, the comparative analysis of the numerical results of the simulation focuses especially on changes in PET.

5.1. Changes in PET distribution

Based on the simulation results, we focus here on changes in the PET distribution after neighborhood greening as per the scenarios discussed above. In particular, we investigate quantitatively where the urban heat environment improves from the viewpoint of thermal comfort for the three greening scenarios (including the current conditions). We start by looking at the PET distribution for case 2, which follows the existing urban conservation plan. No significant difference appears upon comparing the PET distributions in Figs. 15(a) and 6(b) (the latter shows the current condition of case 1). Next, we consider the PET distribution of case 3 [Fig. 15(b)]: upon comparison with case 1 the differences in PET distribution appear clearly, especially under the canopy of the newly planted trees. The distribution of low PET for case 2 is narrowly and linear, whereas, for case 3, those fragmented effects overlap each other and spread to adjacent areas. In terms of the PET distribution on the green back-lane walkway [indicated by the dashed line in Fig. 15(b)] and in the newly proposed green spaces, no significant changes occur, as for case 2.

5.2. Verification of changes in PET classification

Next, we verify the changes in PET classification for each neighborhood greening scenario. For this purpose, we extract only the areas with PET classification of "slightly warm" and "neutral," which fall under the "acceptable range," meaning they are thermally comfortable areas for pedestrians. We look for change in thermally acceptable areas between cases 1 and 2 [see Fig. 16(a)]. Some areas on part of the proposed green walkway indicated by the dashed line in Fig. 16 improve one class from "warm" to "slightly warm." However, as per the numerically results in Table 5, the observed changes are very limited and cover less than 1% of the total study area. In addition, no change occurs in the areas near northeast-facing building façades, even on the proposed green walkway.

Next, we look at the change in thermally acceptable area between cases 1 and 3 [see Fig. 16(b)]. Some areas under the proposed trees improve significantly (three classes from "very hot" to "slightly warm"), as indicated by the orange color in the figure. This is the case in particular around the intersection on the major street in A zone, and on the relatively narrow streets with a lot of on-street parking in the B zone. As shown in Table 5, the area classified as "slightly warm" is 18.4% of the total area, which is an increase of 5.8% with respect to the current condition (case 1). Approximately 6%–7% of the area classified as "very hot," which is over 80% of the total area for cases 1 and 2, improve and become thermally acceptable. Although the improvement is insufficient to reach the acceptable condition (PET < 34 °C), approximately 6% of the total area improves from "very hot" to "hot" or "warm." As shown in Table 5, the total thermally acceptable area in the study area increases 4.8% and 48.5% for cases 2 and 3, respectively, with respect to case 1. These results indicate that the proposed street planting in the case 3 makes a huge contribution to the improvement of neighborhood urban heat environment.

5.3. Changes in PET on pedestrian walkway on each scenario and green coverage

Finally, Table 6 breaks down the green spaces and the green coverage ratio (GCR) to better understand and measure the green space

Table 7
Change in PET on the pedestrian walkway.

	Material of pedestrian walkway	Total length within study area (m)	Average PET (C°)*	Average PET classification	GCR (%)
Case 1	Terracotta tiles	1597.7	47.4	Very hot	0.9
Case 2	Permeable surface (Grasscrete paver)	3091.2	42.8 (−4.6)	Very hot	2.8
Case 3	Terracotta tiles under the trees	3127.6	35.9 (−11.5)	Warm	7.8

* 1.5 m above the ground level.

distribution over the whole study area in each scenario. The GCR increases from 0.9% to 2.8% and to 7.8% for cases 1, 2, 3, respectively. Given this, we now focus on the relationship between PET change on the pedestrian walkways and GCR for each greening scenario. Table 7 lists the possible surface materials for the pedestrian walkway, the total length, average PET, average PET classification on the walkway, and GCR. The pedestrian walkway partially exists in the current condition (case 1), whereas case 2 (i.e., the neighborhood greening scenario that follows the existing town conservation plan) proposes that the length of the pedestrian walkway doubles and that the walkway be covered by a permeable material. Consequently the GCR for case 2 increases by 2% in the study area. However, the thermal conditions remain "very hot," which is most uncomfortable for the pedestrian walkway, although the average PET on the walkway has declined by approximately 4.6 °C. Next, in case 3, which aims for maximum greening, the total length of pedestrian walkway is doubled with respect to case 2 and it is covered by terracotta tiles (the current material). In addition, increased street planting and reduced on-street parking along the walkway are proposed. Consequently, the GCR for case 3 increases 7.8%. As a result, the average PET on the pedestrian walkway drops considerably by 11.5 °C with respect to the current situation. Although the thermal conditions do not reach the acceptable range, they improve to "warm."

5.4. Discussion

The analysis of PET changes confirms that case 2 neighborhood greening scenario improves the urban heat environment in the same location as current condition by increasing the GCR by 2%. However, the improvement covers $<1\%$ of the entire area, which means that the effect is severely limited. This result means that, although the proposed pedestrian green walkway separated from the road might provide a safer walking zone for pedestrians, the walkway would not be a thermally acceptable environment for pedestrians, even if it is covered with a permeable material. In case 3, the GCR of the entire study area increases by approximately 7%, which is due to the proposed green walkway and shaded spaces created by street planting. Consequently, the thermally acceptable area of walkway increases significantly by 48.5% with respect to the current conditions. In addition, the obtained thermally comfortable areas are connected uninterrupted from one block to another because the PET acceptable areas are spread to the corners near intersections. Previous studies have also has pointed out that, as a result of protection from direct sunlight, the creation of areas shaded by trees and vegetation could reduce the PET (Makaremi et al., 2012). The present study also confirms that the urban heat environment improves as a result of street planting, which should stimulate more pedestrian activity in the affected areas. Additionally, 6% of the study area improved one or two PET classes from "very hot," although they did not reach the acceptable range. However, such improvement should not be ignored because these areas could be the target of further improvements in the future.

6. Conclusion

This study proposes an efficient method for extracting potential areas for future neighborhood greening that aims to improve the urban heat environment and thereby encourage pedestrian activity. The proposals conserve the historical landscape that gives the town its identity and limits remnant open spaces. The results of the objective analysis of PET distribution and changes in average PET on pedestrian walkways show that the proposed method and process of neighborhood greening are functional. As a result of improving the urban heat environment, as assessed by PET, the proposed pedestrian walkway covered by permeable materials that conforms to the existing town conservation plan slightly improves the urban heat environment. However, the effects are extremely local and not significant over the entire area (an average reduction of PET on the pedestrian walkway up to 4.6 °C with GCR increases by approximately 2% in case 2). The extensive neighborhood greening, including street planting, in case 3 proposes a green corridor for connecting one point and one block to another in the study area. Consequently, the thermally acceptable area increases by approximately 50% with respect to the current condition (i.e., case 1) (An average reduction of PET on the pedestrian walkway up to 11.5 °C with GCR increases by approximately 7% in case 3). These results should encourage visitors to partake in more pedestrian activities in the future.

The Malacca historical district has a high building-coverage ratio and relatively narrow streets, so heat radiated (as indicated by the mean radiant temperature) from the surrounding buildings and road surface make a significant contribution to the urban heat environment. For this reason, it is not realistic to expect a profound improvement in thermal comfort for pedestrians with greening confined to limited space. However, this study confirms that neighborhood greening by street planting, which blocks direct sunlight, could improve the thermal conditions. In addition, this study shows the importance and effectiveness of properly determining the locations and sizes of street planting, rather than using arbitrary planting. The planting strategy should be based on the result of a quantitative analysis that considers pedestrian visibility of historical buildings and townscape, which is an important part of the town's heritage and identity.

This study extends the previous study that investigates microclimate conditions by using individual indices such as air temperature and wind speed (Saito et al., 2015) by using PET as an indicator of the urban heat environment. This modification allows us to incorporate a human physiological perception of the urban heat environment based on the relationship with other indicators that could not be understood by using an individual index. This approach is more appropriate for this particular study and should help increase pedestrian activities through neighborhood greening. It is also more efficient for extracting areas with greening potential because it considers the actual physical and psychological conditions experience by pedestrians.

In conclusion, this study confirms the effectiveness of the proposed neighborhood greening methods by combining diversified viewpoints with computational techniques and dedicated tools for improving the urban heat environment and conservation the urban landscape of this unique UNESCO World Heritage Site. The results show that these methods are efficient and can be used to understand the current conditions of a town and to aid in the design process for future neighborhood greening. The aspects proposed by us throughout this study, such as securing visibility of the historical townscape from pedestrian and roadside tree planting, including parking space, are not included in the existing conservation plan. Hence, the proposal for a future neighborhood greening in consideration of heritage sites under a hot and humid tropical climate could be expected to be incorporated into a future plan or design guideline. We mainly focused on the quantitative analysis of the physical environment and its supportive tools and techniques throughout this study. However, to fit the proposed greening methods more effectively into the context of Malacca City, for instance, it will be necessary to take into account opinions from relevant stakeholders and visitor's feedback based on their preference for determining the priority of aspects to be considered (we examined three aspects in this study: PET condition, visibility, and human behavior) for their integration and for the identification of potential areas for future greening. Further research should investigate in more detail the extent of cooling effects on the physical environment and consider changing the profile of green walkways or open spaces, and how cooling effects spread. The outcome of such research should lead to more effective neighborhood greening in tropical areas and more comfortable habitation.

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